Constraining the Energy Density of the Universe Using Type 1a Supernovae as Standard Candles

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Abstract

Taking data from the Supernova Cosmology group at Berkley, we are able to expand their project to three dimensions by adding a radiation parameter to the total energy density of the universe. Using type 1a Supernova as standard candles (objects of known absolute magnitude), we are able to calculate their luminosity distance and hence, a value for the deceleration parameter (q_o). Doing a χ^2 contour plot of q_o as a function of the parameters of the energy density, omega matter (Ω_m), omega radiation (Ω_r), and omega vacuum (Ω_Λ), we get a "best fit" to our data. Unlike both the Supernova Cosmology Group and last year's candidate, Jason Farris, we are not constraining Ω_o[1] to be unity (a flat universe). We ended up with several models that are a good fit to the standard model of the universe.

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[1] The quantity $\Omega_o \equiv \rho_o/\rho_c$, where ρ_o is the present mass density of the Universe, and ρ_c is the critical density, $\rho_c \equiv 3H_o^2/8\pi G$ = 1.88 10-29h2gcm-3

1 Background Cosmology

1.1 Type 1a Supernova

Type 1a Supernova occur in binary star systems involving a main sequence star and a white dwarf, the end product of a main sequence star. The white dwarf is smaller in size, but is more dense and therefore more massive than the main sequence star. The white dwarf will pull material from its orbiting companion until it reaches it's critical mass, known as the Chandrasehkar Limit; at which point the dwarf violently explodes as a supernova. Type 1a Supernova are characterized by the presence of silicon lines in their spectra.

1.2 Standard Candles

A standard candle is a very useful class of objects in which there is a certain intrinsic brightness that links them all together; or in other words, once the luminosity of one nearby standard candle is known, the luminosity of all the other members of the same class is known. From this known luminosity, we can easily calculate the distance to these objects, which is quite possibly the most difficult variable to determine in astronomy today.

1.3 $\Omega_o = 1$

We observe, at least the matter portion of the energy density of the universe, to be nearly one, $\Omega_m \cong 0.3 \pm 0.1$. This implies that at the beginning of the universe, Ω_o must have been even closer to one. Imagine that for every Plank time frame ($5.4\ 10^{-44}$ sec), Ω_o changed so that it moved further away from its original value. If that original value had not been almost exactly one, Ω_o today would not be only one order of magnitude off from one.

1.4 $\Omega r < 0.3$

Radiation scales as $(1 + z)^4$ while matter scales as $(1 + z)^3$. As we increase redshift[2], or go back in time[3], radiation quickly takes over the matter-dominated universe that we live in today. If Ω_r is above 0.3, then this critical changing point is pushed forward in time and the universe as we know it would not have sufficient time to coalesce into the galaxy formations we see today.

2 Calculating Distance

High-z SNe 1a data is shown to the right where μ_o is given in units of distance moduli. The conversion to luminosity distance (D_L[4]) in Megaparsecs is:

$$\mu_o = m - M = 5\log(D_L) + 25 \qquad (1)$$

From here, we can expand out the luminosity distance in terms of the Hubble[5] constant (H_o), redshift (z), and the deceleration parameter (q_o):

$$D_L = H_o^{-1} z + H_o^{-1} z^2((1-q_o)/2) \qquad (2)$$

High-z SNe 1a Light Curve Parameters

SNe	z	Distance Modulus	Sigma
1996E	0.43	41.74	0.28
1996H	0.62	42.98	0.17
1996I	0.57	42.76	0.19
1996J	0.30	41.38	0.24
1996K	0.38	41.63	0.20
1996U	0.43	42.55	0.25
1997ce	0.44	41.95	0.17
1997cj	0.50	42.40	0.17
1997ck	0.97	44.39	0.30
1995K	0.48	42.45	0.17

The Hubble constant is difficult to pinpoint due to parametric dependence on cosmological parameters at high redshift, but at modest redshift (z 1), one may determine H_o: on a log z vs. log D_L, log H_o is the interception on the log z axis. The most recent value of H_o is 70±7 km/s/Mpc.

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[2] z = redshift, according to the Doppler Effect, the spectrum of an object moving away from a reference point will be shifted towards the red end.

[3] The further objects are from Earth, the more redshifted they seem to be. Also, the further away these objects are, the earlier they must have formed since the universe has been continually expanding. Therefore, increasing redshift is like looking back in time at an earlier universe.

[4] $D_L^2 \equiv \Lambda/4\pi\Phi$ Since space has expanded by the time we detect the light from a distant object, the expansion of the universe requires the specific "luminosity distance" definition.

Note:

In our attempt to calculate q_o using a "best fit" technique, the values we generated were unpleasant. Further attempts were abandoned and the values from Jason Farris' paper, $q_o = -0.5\pm0.2$, and the High-z Supernova Research Team, $q_o = -1\pm0.4$, were used.

Some Constraints

We used several constraints in our analysis in order to determine which Universes could be probable:

$\Omega_m \geq 0.3$

$\Omega_r \geq 0$

for $\Omega_o = 1$, $\Omega_\Lambda \leq 0.7$

3 Data

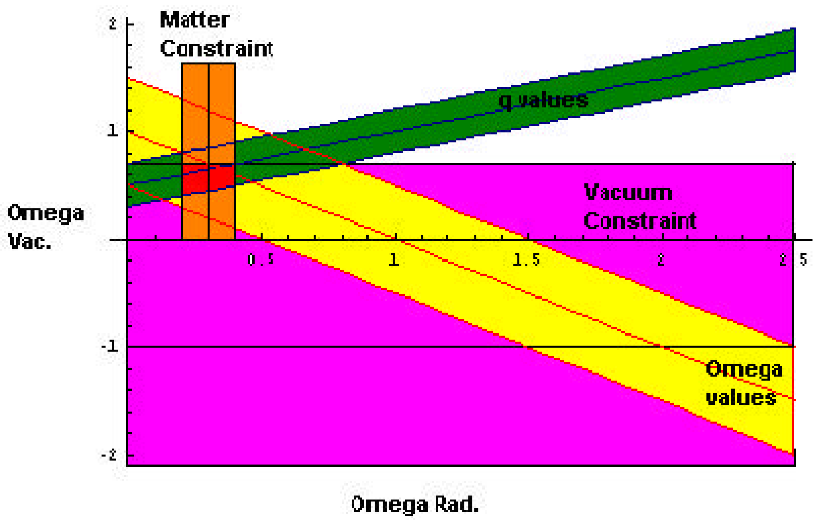

Fig. 1

The projection onto the Ω_m, Ω_r plane. This was done in order to compare the results of the Supernova Cosmology Group with our own.

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[5] H_o is the present expansion rate of the Universe.

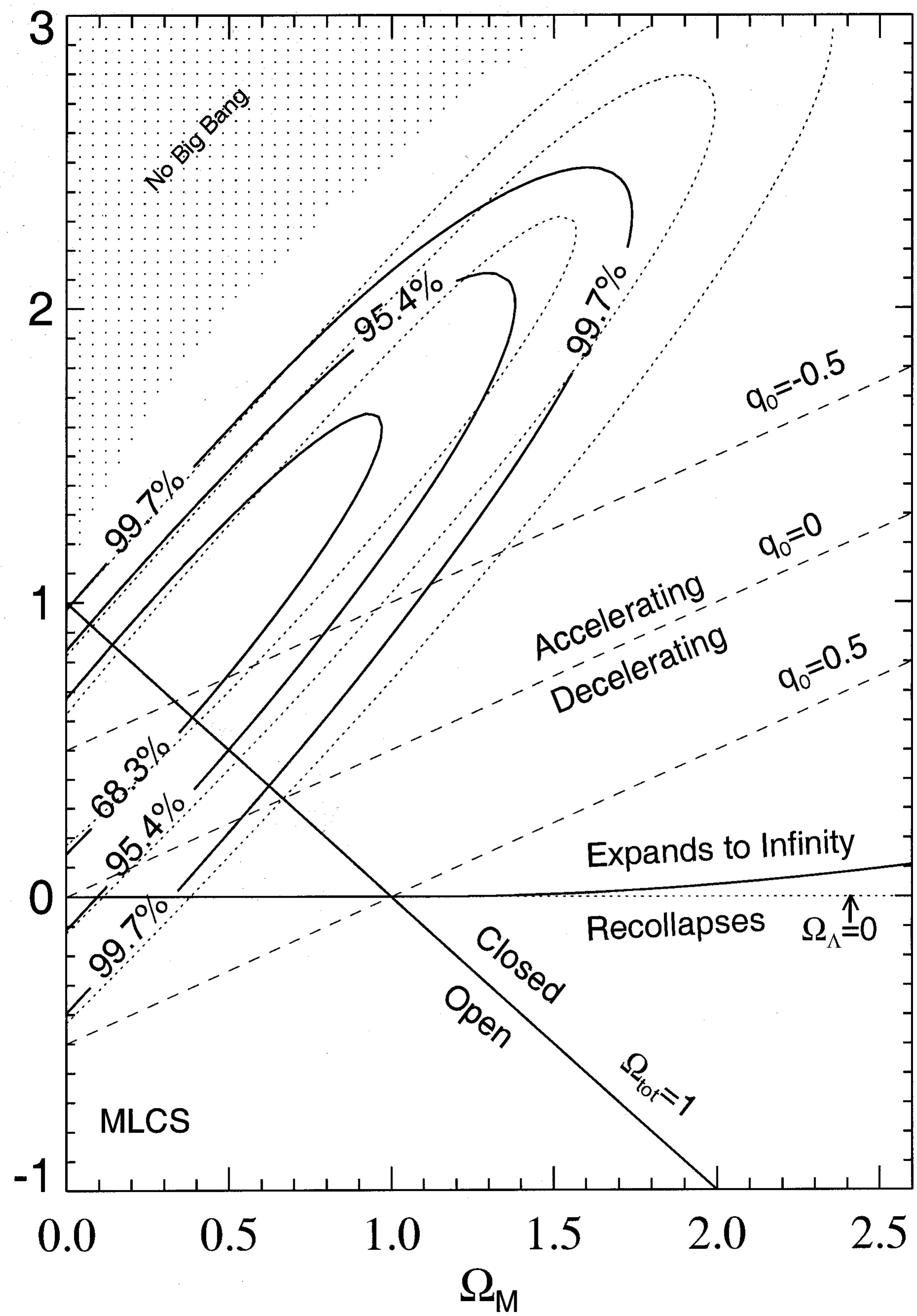


Fig. 2
Shows the results of the Supernova Cosmology Group where $\Omega_r = 0$. As you can see, the best fit for the Universe is a flat Universe ($\Omega_o = 1$) with a deceleration parameter (q_o) = -0.5.

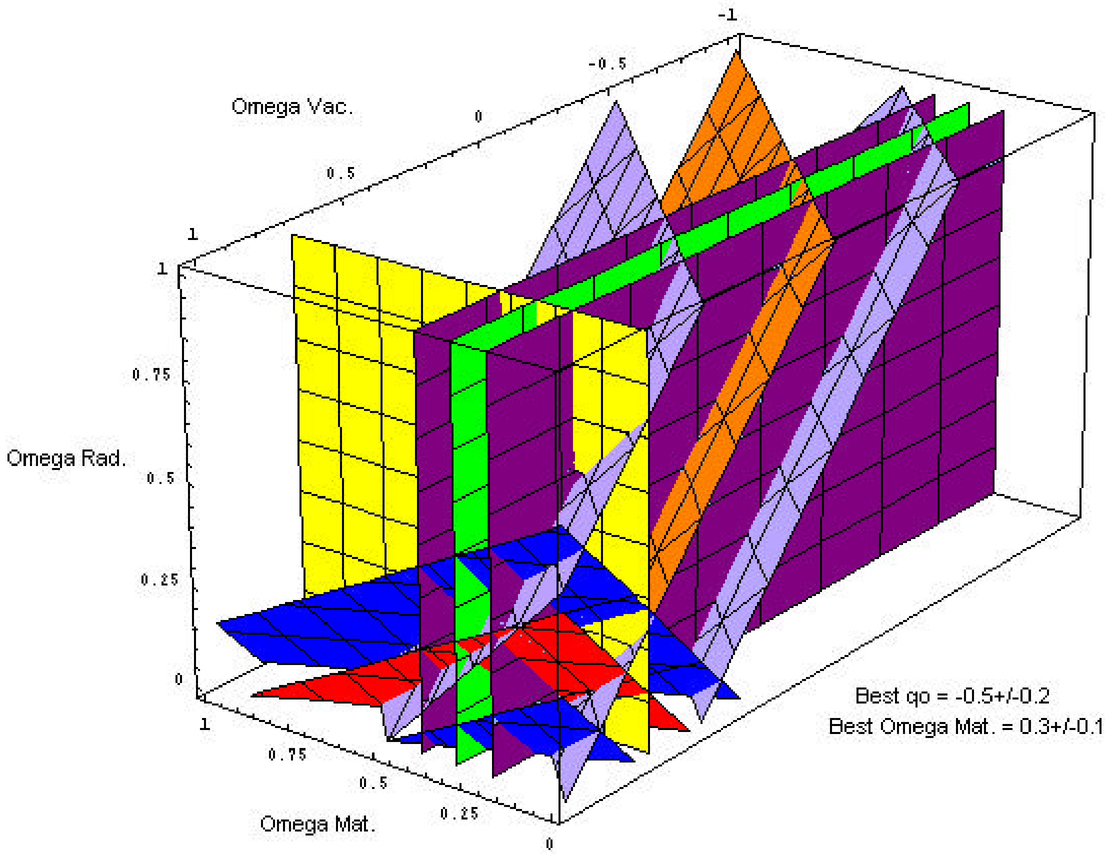
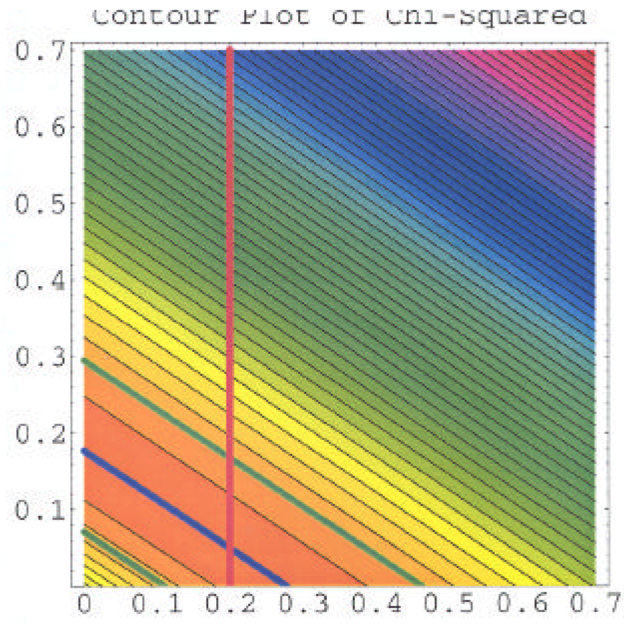
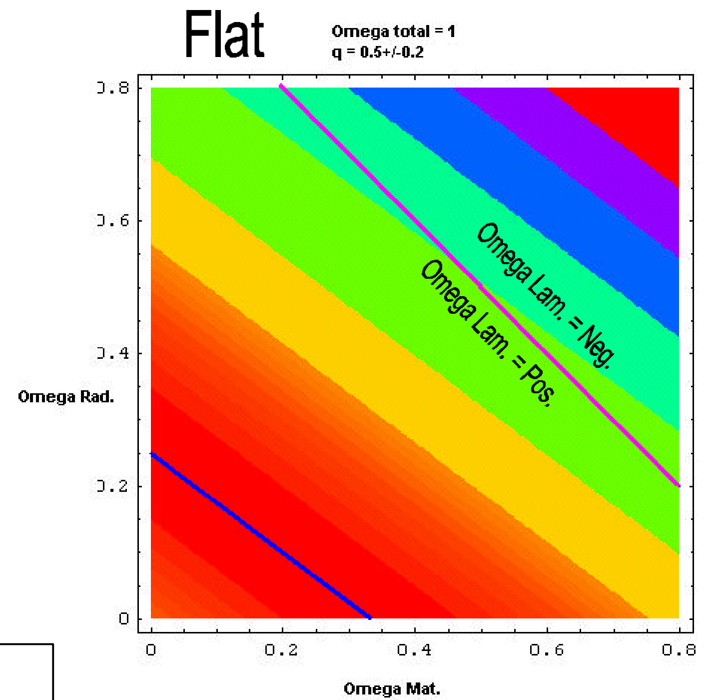


Fig. 3

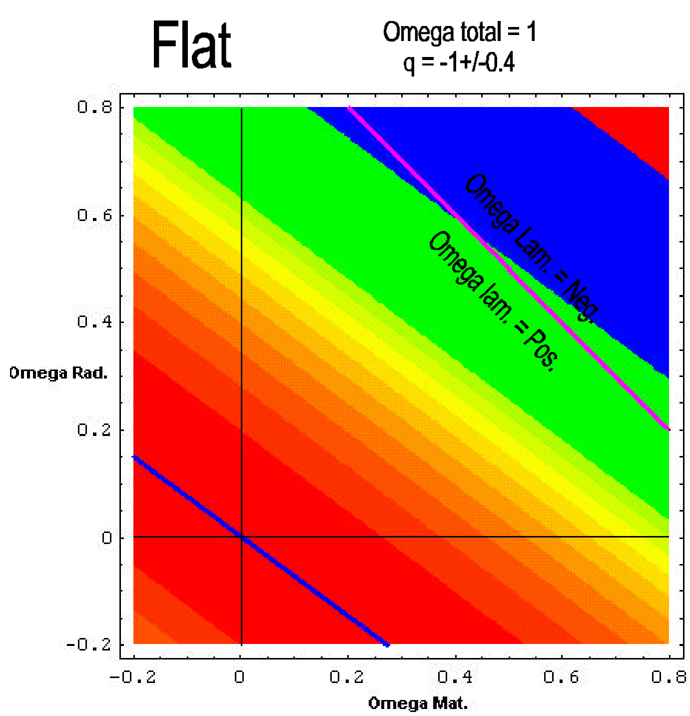
Shows a three dimensional plot of the components of the total energy density of the universe. Here we see the best q_o value of –0.5 in red with 1 sigma planes in blue, the best Ω_m value of 0.3 in green with 1 sigma planes in dark purple, a constraint where $\Omega_\Lambda \leq 0.7$, and an, open, flat, and closed universe in light purple, orange, and light purple respectively moving front to back.

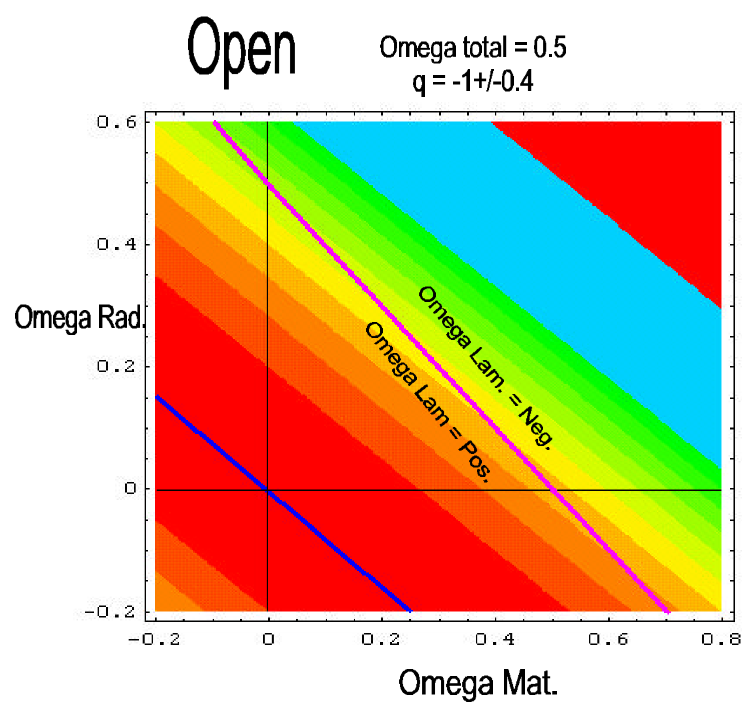




<u>Fig. 4 -</u> <u>(above)</u>
The results of last year's REU student, Jason Farris. The blue line represents a best fit to the data while the green lines are the one sigma level. The red line represents the boundary at which Ωm is allowed: $\Omega_m \geq 0.2$.

<u>Fig. 5</u> <u>– (above)</u>
Here we have a replica of Farris' plot: a flat Universe with a deceleration of –0.5. The best fit line (blue) intersects both axes at slightly different values, but this is mostly due to the different methods used to produce these results. As you can see, this is a probable solution in which it is possible to have $\Omega_m \geq 0.3$ with $\Omega_r \geq 0$ and a positive Ω_Λ component.





<u>Fig. 6 & 7</u><u>– (above)</u>
Here we have a flat Universe and an open Universe where the best fit lines (blue) leads to negative values for Ω_m and Ω_r, hence, not very probable solutions. There is, however, a very small portion in the red zones (the valley area) where Ω_m and Ω_r are positive, but this leads to an Ω_m value of less than 0.3. We already observe $\Omega_m \geq 0.3$, so consequently we can rule out these solutions.

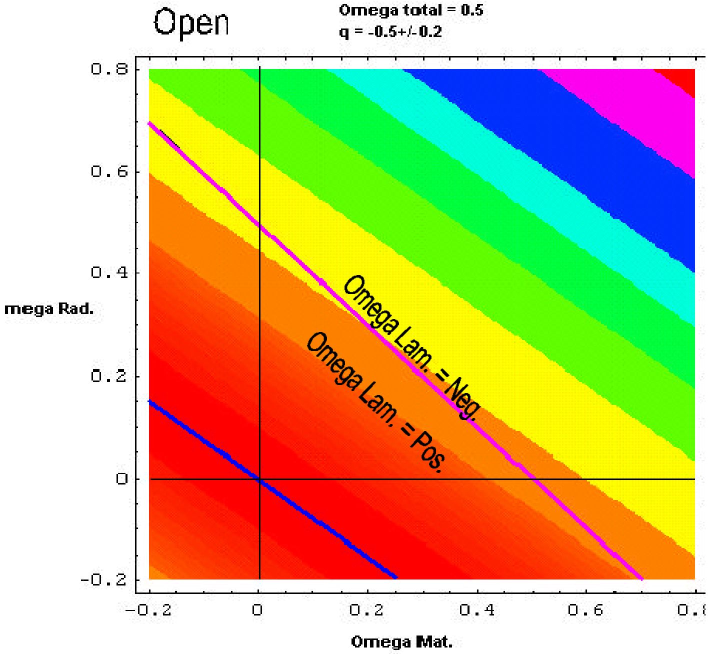


Fig. 8 – (above)
Here we have an open Universe where the best fit line (blue)leads to negative values for Ω_m and Ω_r, hence, not a very probable solution.

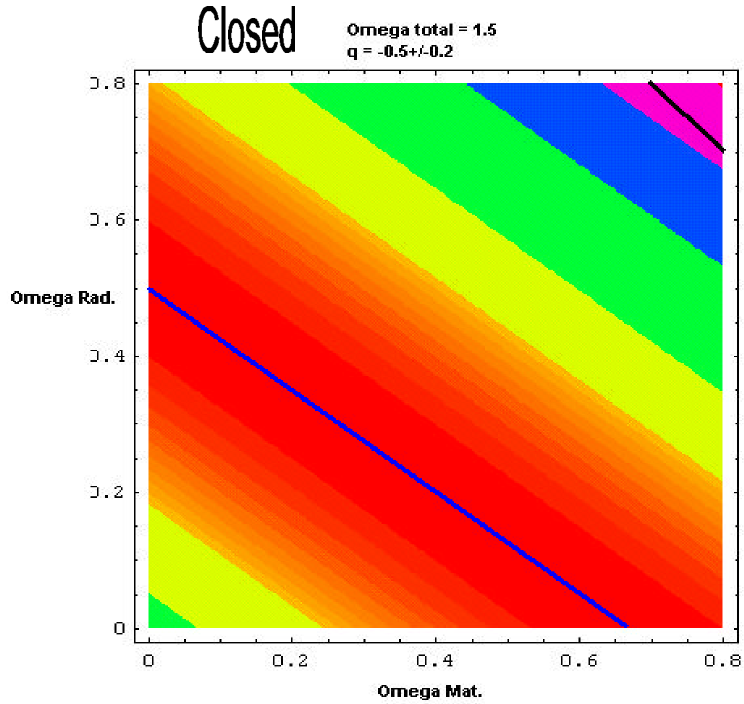


Fig. 9 – (above)
Here is a theoretically probable solution according to the $\Omega_m \geq 0.3$ constraint, however, there could be an upper limit to Ω_m that restricts the graph that we do not know about yet.

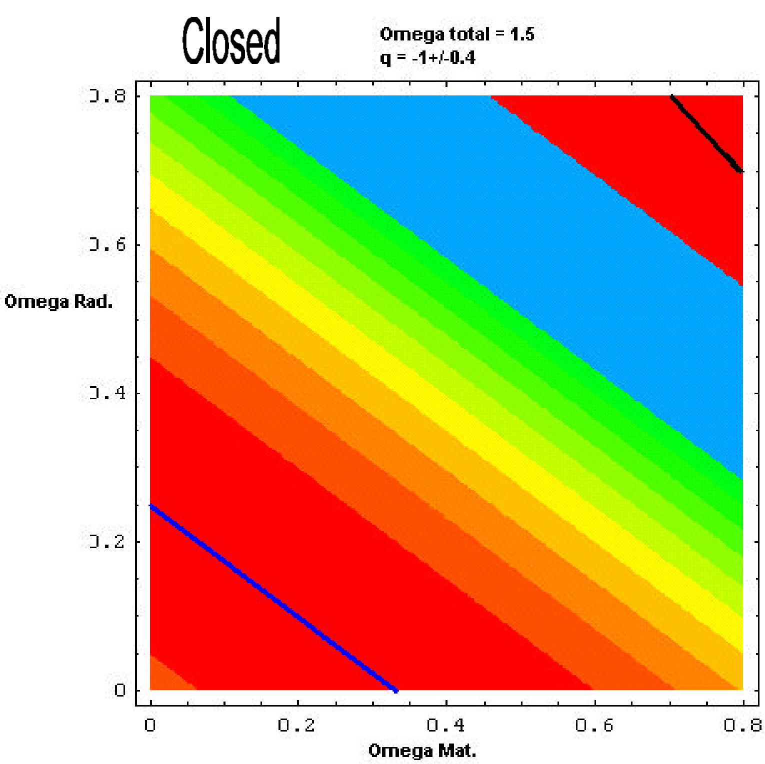


Fig. 10 – (left)
Here is a very probable result for a closed Universe. For $\Omega_m \geq 0.3$, we get a value positive or zero value for Ω_r, and a positive value for Ω_Λ

References

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[5] S. Perlmutter, et. al. *A Supernova at z = 0.458 and Implications for measuring the Cosmological Deceleration*. astro-ph/9505023, 4 May 95.

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