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SEVEN PARADIGMS IN STRUCTURE FORMATION

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Abstract. Have we converged on the definitive model of cosmology? I present a critical assessment of the current paradigms for the evolution of large-scale structure.

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1. INTRODUCTION

The current model for structure formation in the expanding universe has been remarkably successful. Indeed it has recently been argued that we have resolved the principal issues in cosmology. [1] However the lessons of history prescribe caution. There have been more oscillations in the values of the Hubble constant, the deceleration parameter and the cosmological constant over the working life of a cosmologist than one cares to recall. As the quality of the data has improved, one can be reasonably confident that the uncertainties in parameter extraction have decreased. But have we really converged on the definitive model?

I have selected seven of the key paradigms in order to provide a critical assessment. To set the context I will first review the reliability of the fundamental model of cosmology, the Big Bang model, in terms of the time elapsed since the initial singularity, or at least, the Planck epoch, 10^{-43} s.

Galaxies are well studied between the present epoch, ~ 14 x 10^9 yr, and ~ 3 x 10^9 yr ($z \simeq 3$). One can examine the distribution of Lyman alpha clouds, modelling chemical evolution from the gas phase metal abundances, [2] and find large numbers of young, star-forming galaxies back to about 2 x 10^9 yr ($z \simeq 4$). [3] Beyond this are the dark ages where neither gas nor evidence of galaxy formation has yet been detected. Strong circumstantial evidence from the Gunn-Peterson effect, indicating that the universe is highly ionized by $z = 5$, suggests that sources of ionizing photons must have been present at an earlier epoch.

Microwave background fluctuations provide substantial evidence on degree angular scales for an acoustic peak, generated at 3 x 10^5 yr ($z = 1000$), when the radiation underwent its last scatterings with matter. [4] The blackbody spectrum of the cosmic microwave background, with no deviation measured to a fraction of a percent and a limit on the Compton y parameter $\delta y < 3 \times 10^{-6}$ (95% CL) on 7 degree angular scales, [5] could only have been generated in a sufficiently dense phase which occurred during the first year of the expansion. Light element nucleosynthesis is an impressive prediction of the model, and testifies to the Friedmann-like character at an epoch of one second. At this epoch, neutrons first froze out of thermal equilibrium to subsequently become incorporated in ^{2}H, ^{4}He, and ^{7}Li, the primordial distribution of which matches the predicted abundances for a unique value of the baryon density. [6]

Thus back to one second, there is strong observational evidence for the canonical cosmology. At earlier epochs, any observational predictions are increasingly vague or non-existent. One significant epoch is that of the quark-hadron phase transition ($t \sim 10^{-4}$ s, $T \sim 100$ MeV), which while first order cannot have been sufficiently inhomogeneous to amplify density fluctuations to form any primordial black holes. [7] The electro-weak phase transition ($t \sim 10^{-10}$ s, $T \sim 100$ GeV), was even more short-lived but may have triggered baryon genesis. Before then, one has the GUT phase transition ($t \sim 10^{-35}$ s, $T \sim 10^{15}$ GeV), and the Planck epoch ($t \sim 10^{-43}$ s, $T \sim 10^{19}$ GeV), of unification of gravitation and electroweak and strong interactions. Inflation is generally believed to be associated with a strongly first order GUT phase transition, but is a theory that is exceedingly difficult, if not impossible, to verify. [8] A gravitational radiation background at low frequency is one possible direct relic of quantum gravity physics at the Planck epoch, but we are far from being able to detect such a background.

In summary, we could say that our cherished beliefs, not to be abandoned at any price, endorse the Big Bang model back to an epoch of about one second or $T \sim 1$ MeV. One cannot attribute any comparable degree of confidence to descriptions of earlier epochs because any fossils are highly elusive. Bearing this restriction in mind, we can now assess the paradigms of structure formation. The basic framework is provided by the hypothesis that the universe is dominated by cold dark matter, seeded by inflationary curvature fluctuations. This does remarkably well at accounting for many characteristics of large-scale structure in the universe. These include galaxy correlations on scales from 0.1 to 50 Mpc, the mass function and morphologies of galaxy clusters, galaxy rotation curves and dark halos, the properties of the intergalactic medium, and, most recently, the strong clustering found for luminous star-forming galaxies at $z \sim 3$. I will focus on specific paradigms that underly these successes and assess the need for refinement both in data and in theory that may be required before we can be confident that we have found the ultimate model of cosmology.

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2. PARADIGM 1: PRIMORDIAL NUCLEOSYNTHESIS PRESCRIBES THE BARYON DENSITY

Primordial nucleosynthesis predicts the abundances of several light elements, notably ^{2}H, ^{4}He, and ^{7}Li. The principle variable is the baryon density, $\omega_b h^2$. One finds approximate concordance for $\omega_b h^2 \simeq 0.015$, and with the consensus value [9] of H_0 ($h = 0.7 \pm 0.1$) one concludes that $\omega_b \simeq 0.03$. Not all pundits agree on concordance, since the primordial ^{4}He abundance requires a somewhat uncertain extrapolation from the most metal-poor galaxies with He emission lines ($Z \sim 0.02 Z_\odot$) to zero metal abundances. [10] Moreover the ^{2}H abundance is based on intergalactic (and protogalactic) ^{2}H observed in absorption at high redshifts toward two quasars, probing only a very limited region of space. [11] However incorporation of ^{7}Li and allowance for the various uncertainties still leaves relatively impressive agreement with simple model predictions.

Direct measurement of the baryon density at $z \sim 3$ can be accomplished by using the Lyman alpha forest absorption systems toward high redshift quasars. The neutral gas observed is only a small component of the total gas, but the ionizing radiation from quasars is measured. A reasonably robust conclusion finds that $\omega_{gas} \sim 0.04$, implying that the bulk of the baryons are observed and in diffuse gas at high redshift. [12]

At low redshift, the luminous baryon component is well measured, and amounts to $\omega_* \sim 0.003$ in stars. [13] Gas in rich clusters amounts to a significant fraction of cluster mass and far more than the stellar mass, but these clusters only account for about five percent of the stellar component of the universe. Combining both detected gas and stars implies that at $z \sim 0$, we observe no more than $\omega_{gas} \sim 0.005$. Here we have a problem: where are the baryons today?

Most baryons must therefore be relatively dark at present. There are two possibilities, neither one of which is completely satisfactory. The dark baryons could be hot gas at $T \sim 10^6$ K, in the intergalactic medium. [14] This gas cannot populate galaxy halos, where it is not observed, nor objects such as the Local Group, and is not present in rich clusters in a globally significant amount. It remains to be detected: if the temperature differed significantly from 10^6 K the presence of so much gas would already have had observable consequences.

The alternative sink for dark baryons is in the form of compact objects. MACHOs are the obvious candidate, detected by gravitational microlensing by objects in our halo of stars in the LMC, and possibly constituting fifty percent of the dark mass of our halo. However star-star lensing provides a possible alternative explanation of the microlensing events, associated with a previously undetected tidal stream in front of the LMC [15,16] and with the known extension of the SMC along the line of sight. In the LMC case, at least one out of approximately 20 events has a known LMC distance, and for the SMC, there are only two events, both of which are associated with the SMC. [17] The statistics are unconvincing, and since until now one requires binary lenses to obtain a measure of the distance, any distance determinations are likely to be biased towards star-star lensing events.

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3. PARADIGM 2: $\omega = 1$

It is tempting to believe that ω_m is unity. If it is not unity, one has to fine tune the initial curvature to one part in 10^{30}. Moreover inflationary models generally predict that ω is unity. However the evidence in favor of low ω_m, and specifically $\omega_m \approx 0.3$ is mounting. The most direct probe arises from counting rich galaxy clusters, both locally and as a function of redshift. The direct prediction of $\omega_m = 1$ is that there should be a higher-than-observed local density of clusters, and strong evolution in number with redshift that is not seen. [18] However this conclusion has recently been disputed. [19,20]

An indirect argument comes from studies of Type Ia supernovae, which provide strong evidence for acceleration. This is most simply interpreted in terms of a positive cosmological constant. [21,22] The SN Ia data actually measure $\omega\lambda - \omega_m$. Combined with direct measures of ω_m both from galaxy peculiar velocities and from clusters, one infers that $\omega\lambda \approx 0.7$. Hence flatness is likely, and certainly well within observational uncertainties. Further evidence for the universe being spatially flat comes from the measurement of the location of the first acoustic peak in the cosmic microwave background anisotropy spectrum. The location reflects the angular size subtended by the horizon at last scattering, and has Fourier harmonic $l = 220\,\omega^{-1/2}$. Current data requires [23] $\omega \gtrsim 0.4$, where $\omega = \omega_m + \omega\lambda$.

Some possible pitfalls in this conclusion are that unbiased cluster surveys have yet to be completed. Use of wide field weak lensing maps will go a long way towards obtaining a definitive rich cluster sample. There is no accepted theory for Type Ia supernovae, and it is possible that evolutionary effects could conspire to produce a dimming that would mimic the effects of acceleration, at least to $z \sim 1$. Utilization of supernovae at $z > 1$ will eventually help distinguish evolutionary dimming or gray dust, the effects of which should be stronger at earlier epochs and hence with increasing z, from the effect of acceleration, which decreases at earlier epochs, that is with increasing z.

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4. PARADIGM 3: DENSITY FLUCTUATIONS ORIGINATED IN INFLATION

There is an elegant explanation for the origin of the density fluctuations that seeded structure formation by gravitational instability. Quantum fluctuations are imprinted on a macroscopic scale with a nearly scale-invariant spectral distribution of amplitudes, defined by constant amplitude density fluctuations at horizon crossing. This leads to a bottom-up formation sequence as the smallest subhorizon scales acquire larger amplitudes and are the first to go nonlinear. One can compare the predicted linear fluctuations over scales $\gtrsim$ 10 Mpc with observations via microwave background fluctuations and galaxy number count fluctuations. $\delta T/T$ measures $\delta\rho/\rho$ at last scattering over scales from ~ 100 Mpc up to the present horizon. Temperature fluctuations on smaller scales are progressively damped by radiative diffusion, but a signal is detectable to an angular scale of ~ 10', equivalent to ~ 20 Mpc. The conversion from $\delta T/T$ to $\delta\rho/\rho$ is model-dependent, but can be performed once the transfer function is specified. At these high redshifts, one is well within the linear regime, and if the fluctuations are Gaussian, one can reconstruct the density fluctuation power spectrum.

Deep galaxy surveys yield galaxy number count fluctuations, which are subject to an unknown bias between luminous and dark matter. Moreover, all three dimensional surveys necessarily utilize redshift space. Conversion from redshift space to real space is straightforward if the peculiar velocity field is specified. One normally assumes spherical symmetry and radial motions on large scales, and isotropic motions on scales where virialization has occurred, with an appropriate transition between the linear and nonlinear regimes. On the virialization scale, collapse by of order a factor of 2 has occurred in the absence of dissipation, and correction for density compression must also be incorporated via interpolation or preferably via simulations.

Comparison of models with data is satisfactory only if the detailed shape of the power spectrum is ignored. [24] A two parameter fit, via normalisation at 8 h^{-1} Mpc and a single shape parameter $\gamma \equiv \omega h$, is often used. For example, as defined below, $\sigma_8 \equiv (\delta\rho / \rho)_{\rm rms} / (\delta n_g / n_g)_{\rm rms}$, as evaluated at 8 h^{-1} Mpc, equals unity for unbiased dark matter. COBE normalisation of standard cold dark matter requires $\sigma_8 \approx 1$ but the cluster abundance requires $\sigma_8 \approx 0.6$. The shape parameter $\omega h = 1$ for standard cold dark matter, but $\omega h \approx 0.3$ is favoured for an open universe. One can fit a model to the data with $\sigma_8 \approx 0.6$ and $\omega h \approx 0.3$. However detailed comparison of models and observations reveals that there is no satisfactory fit to the power spectrum shape for an acceptable class of models. There is an excess of large-scale power near 100 Mpc. This is mostly manifested in the APM galaxy and cluster surveys, but is also apparent in the Las Campanas redshift survey. [26]

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5. PARADIGM 4: GALAXY ROTATION CURVES ARE EXPLAINED BY HALOS OF COLD DARK MATTER

Galaxy halos of cold dark matter acquire a universal density profile. [29] This yields a flat rotation curve over a substantial range of radius, and gives an excellent fit to observational data on massive galaxy rotation curves. There is a central density cusp ($\propto 1 / r$) which in normal galaxies is embedded in a baryonic disk, the inner galaxy being baryon-dominated.

Low surface brightness dwarf spiral galaxies provide a laboratory where one can study dark matter at all radii: even the central regions are dark matter-dominated. One finds that there is a soft, uniform density dark matter core in these dwarf galaxies. [25] It is still controversial whether the CDM theory can reproduce soft cores in dwarf galaxies: at least one group finds in high resolution simulations that the core profiles are even steeper than r^{-1}, and have not converged.[28]

Disk sizes provide an even more stringent constraint on theoretical models. Indeed disk scale lengths cannot be explained. [29,30] The difficulty lies in the fact that if angular momentum is conserved as the baryons contract within the dark halos, approximately the appropriate amount of angular momentum is acquired by tidal torques between neighbouring density flutuations to yield correct disk sizes However simulations fail to confirm this picture. In practice, cold dark matter and the associated baryons are so clumpy that massive clumps fall into the center via dynamical friction and angular momentum is transferrd outwards. Disk torquing by dark matter clumps also plays a role. The result is that the final baryonic disks are far too small. The resolution presumably lies in gas heating associated with injection of energy into the gas via supernovae once the first massive stars have formed. [31,32]

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6. PARADIGM 5: HIERARCHICAL MERGING ACCOUNTS FOR THE LUMINOSITY FUNCTION AND THE TULLY-FISHER RELATION

Galaxies form by a succession of mergers of cold dark matter halos, the baryons dissipating and forming a dense core. Isolated infall plausibly results in disk formation. Disk merging concentrates the gas into a dense spheroid. The transition from linear theory to formation of self-gravitating clouds occurs at an overdensity of about $\delta_{crit} \approx 200$. A simple *ansatz* due to Press and Schechter yields the mass function of newly nonlinear objects

$$\frac{dN}{dM} \propto M^{-2} \exp\left[-\delta_{\rm cr}^2/\langle(\delta\rho/\rho)^2\,(M,t)\rangle\right] ,$$

where $\delta^2 \equiv \langle(\delta\rho / \rho)^2 \,(M,t)\rangle$ is the variance in the density fluctuations. The variance at 8 h^{-1} Mpc, δ_8, is given by

$$\delta_8 = (R/8h^{-1}\mathrm{Mpc})^{-\frac{n+3}{2}}\,(1+z)^{-1}$$

where $n \approx -1$ on cluster scales but $n \approx -2$ on galaxy scales, and $M = 10^{15}\,\omega\, h^{-1}\,(R / 8h^{-1}\,\mathrm{Mpc})^3\, M_\odot$. Of course the luminosity function rather than the mass function is actually observed. We define $\sigma \equiv \delta / \delta_g$, where δ_g is the variance in the galaxy counts. On cluster scales, one finds that σ_8 $\approx$ 0.6 (± 0.1) yields the observed density of clusters if $\omega = 1$. More generally, σ_8 scales as $\omega^{-0.6}$. A larger σ is required for a given number density of objects in order to account for the reduced growth in δ as ω is decreased below unity.

To match the observed luminosity function and predicted mass function requires specification both of σ_8 and of the mass-to-light ratio. Much of the dark mass is in objects that were the first to go nonlinear, as well as in the objects presently going nonlinear. Hence one crudely expects that $M/L \approx 400\, h$, as measured in rich clusters. The global value of M/L is $M/L \approx 1500\, \omega\, h$, and happens to coincide with the mass-to-luminosity ratio measured for rich clusters if $\omega \approx 0.4$. This suggests that these clusters may provide a fair sample of the universe. Even if most dwarfs do not survive, because of subsequent merging, the relic dwarfs are expected to have high *M/L*. Later generations of galaxies should have undergone segregation of baryons, because of dissipation, and the resulting *M/L* is reduced. Many of the first dwarfs are disrupted to form the halos of massive galaxies. The predicted high *M/L* (of order 100) is consistent with observations, both of galaxy halos and of the lowest mass dwarfs (to within a factor of ~ 2).

However it is the detailed measurement of *M/L* that leads to a possible problem. One has to normalise *M/L* by specifying the mass-to-light ratio of luminous galaxies. The observed luminosity function can be written as

$$\frac{dN}{dL} \propto L^{-\alpha} \exp(-L/L_*)$$

where $\alpha \approx 1 - 1.5$, depending on the selection criterion, and $L_* \approx 10^{10} h^{-2} L_\odot$. Matching to the predicted mass function specifies *M/L* for L_* galaxies, as well as the slope of the luminosity function. One forces a fit to α by invoking star formation-induced feedback and baryonic loss. This preferentially reduces the number of low mass galaxies. A typical prescription is [33] that the retained baryonic fraction is given by

$$f_{\rm B} = (v_c/v_*)^2 \,,$$

where v_c is the disk circular velocity. Dwarfs are preferentially disrupted by winds. In this way one can fit α. There is no longer any freedom in the luminous galaxy parameters.

Potential difficulties arise as follows. Simulations of mass loss from dwarf galaxies suggest that supernova ejecta may contribute to the wind but leave much of the interstellar gas bound to the galaxies. [34] This would be a serious problem as one relies on redistribution of the baryonic reservoir to form massive galaxies. Another problem arises with the Tully-Fisher relation. This is the measured relation, approximately $L \propto V^{\beta}_{\rm rot}$, between galaxy luminosity and maximum rotational velocity. In effect, the Tully-Fisher relation offers the prescription for *M/L* within the luminous part of the galaxy, since the virial theorem requires

$$L \approx V_{\rm rot}^4 \, G^{-2} \, \mu_L^{-1} \, (L/M)^2$$

where μ_L is the surface brightness of the galaxy. Since μ_L has a narrow dispersion for most disk galaxies, the Tully-Fisher relation, where $\beta \approx 3$ is measured in the *I* band and $\beta \approx 4$ is appropriate to the near infrared, effectively constrains *M/L*. The normalization of the Tully-Fisher relation requires $M/L \approx 5h$ for early-type spirals, as is observed directly from their rotation curves within their half-light radii. However simulations of hierarchical clustering, which incorporate baryonic cooling and star formation with a prescription designed to reproduce the luminosity function, give too high a normalization for *M/L* in the predicted Tully-Fisher relation: at a given luminosity the rotational velocity is too high. [35] Moreover the efficient early star formation required in order to fit the luminosity function requires the Tully-Fisher normalisation to change with redshift: galaxies are predicted to be brighter by about a magnitude at a given rotation velocity at $z \sim 1$, and this exceeds the observed offset. [36] Resolution of the Tully-Fisher normalization remains controversial.

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7. PARADIGM 6: THE BULK OF THE STARS FORMED AFTER $z = 2$

Identification of the Lyman break galaxies, by using the 912 Å discontinuity in predicted spectra as a broad band redshift indicator, has revolutionized our knowledge of early star formation. Current samples of high redshift star-forming galaxies, chosen in a relatively unbiased manner, contain ~ 1000 galaxies at z ~ 3 and ~ 100 galaxies at z ~ 4. The volume of the universe involved is known, and one can therefore compute the comoving luminosity density. [37] Since the galaxies are selected in the rest-frame UV, one can convert luminosity density to massive star formation rate. One uncertainty is correction for dust extinction but this is mostly resolved by measurement of the galaxy spectra.

If, say, a Miller-Scalo initial stellar mass function is adopted, one concludes that the star formation rate per unit volume rose rapidly between the present epoch and redshift unity by a factor of about 10. Beyond redshift one, the star formation rate remains approximately constant, to $z > 4$. Moreover the median star formation rate per galaxy is high, around 30 $M_\odot$ per year, the star forming galaxies are mostly compact, and strong clustering is found. [38] One interpretation of the data is that most stars formed late, because of the short cosmic time available at high redshift, and that most of the Lyman-break galaxies are massive, and hence clustered, objects that are probably undergoing spheroid formation. An alternative view is that the clustering is due to merger-induced starbursts of low mass galaxies within massive galaxy halos. [39] Reconcilation of either interpretation with hierarchical clustering theory requires a low ω universe, especially in the former case, and a detailed prescription for galaxy star formation. The rapid rise in the number of star-forming galaxies at low redshift is especially challenging if ω is low, since galaxy clustering reveals little or no evolution at z ~lt 1, as measured by cluster abundances, and both massive disk sizes and the Tully-Fisher relation show little change to $z \sim 1$. One intersting suggestion is that a new population of blue compact, star-forming galaxies is responsible for the evolution in the star formation rate density of the universe. [40]

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8. PARADIGM 7: GALAXY SPHEROIDS FORMED VIA MERGERS

Galaxy mergers are recognized as the triggers of nearby starbursts, especially the ultraluminous far infrared-selected galaxies. These systems are powered in large part by star formation rather than by an embedded AGN, as confirmed by far infrared spectroscopy, and have star formation rates of 100 or even 1,000 $M_{\odot}$ per year. Near infrared mapping reveals de Vaucouleurs profiles and CO mapping reveals a central cold disk or ring with ~ 10^{10} $M_{\odot}$ of molecular gas within a few hundred parsecs. Can one generalize from the rare nearby examples that ellipticals, and more generally spheroids, formed via merger-induced starbursts?

Evidence that gives support to this contention requires a component of star-forming galaxies that is sparse locally to account for three distinct observations of galaxies, or of their emission presumed to be at $z > 1$. Far IR counts by ISO at 175 μm [42] and submillimeter counts by SCUBA [43] at 850 μm require a population of IR-emitting objects that have starburst rather than normal disk infrared spectra. Moreover identification of SCUBA objects demonstrates that typical redshifts are one or larger, but mostly below 2. [44]

A powerful indirect argument has emerged from modelling of the diffuse far infrared background radiation. This amounts to [41] $\nu i \nu \sim 20$ nw/m^{2}sr, and exceeds the diffuse optical background light of about 10 nw/m^{2}sr that is inferred from deep HST counts. The local population of galaxies, evolved backwards in time fails to account for the diffuse infrared light, if one only considers disk galaxies, where the star formation history is known from considerations of their dynamical evolution.

The starburst population invoked to account for the FIR counts can account for the diffuse infrared background radiation. [45] If this is the case, one expects a non-negligible contribution near 1 mm wavelength from ultraluminous FIR galaxies to the diffuse background radiation. For example, the predicted FIR flux peaks at ~ 400 μm if the mergers occur at $z \lesssim 3$. The extrapolation to longer wavelengths tracks the emissivity, or decreases roughly as λ^3. Hence there should be a contribution at 1 mm of order 1 nw/m^{2}sr, which may be compared with the CMB flux of ~ 2000 nw/m^{2}sr. One can measure fluctuations of $\delta T/T \sim 10^{-6}$, and one could therefore be sensitive to a population of ~ 10^6 ultraluminous FIR sources at high z. The inferred surface density (~ 20 per square degree) is comparable to the level of current SCUBA detections. Hence CMB fluctuations on an angular scale of ~ 10' near the CMB peak could be generated by the sources responsible for the diffuse FIR background. Moreover these are rare and massive galaxies, and hence are expected to have a large correlation length that should give an imprint on degree scales.

One can evidently reconcile submillimeter counts, the cosmic star formation history and the far infrared background together with formation of disks and spheroids provided that a substantial part of spheroid formation is dust shrouded. A difficulty that arises is the following: where are the precursors of current epoch ellipticals? A few are seen at $z < 5$ but are too sparse in number to account for the younger counterparts of local ellipticals. [46] Dust shrouding until after the A stars have faded (~ 2×10^9 yr) would help. Other options are that the young ellipticals are indeed present but disguised via ongoing star formation activity, and mostly form at $z > 5$ or else possess an IMF deficient in massive stars.

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9. CONCLUSIONS

Cosmological model-building has made impressive advances in the past year. However much of this rests on supernovae being standard candles. This is a demanding requirement, given that we lack complete models for supernovae. Consider a Type I supernova, for which one popular model consists of a close pair of white dwarfs. We do not know a priori whether a pair of merging white dwarfs will explode or not, or will self destruct or leave a neutron star relic. Other models involve mass transfer onto a white dwarf by an evolving close companion: again, we do not know the outcome, whether the endpoint is violently explosive or mildly quiescent. No doubt some subset of accreting or merging white dwarfs are SNIa, but we do not know how to select this subset, nor how evolution of the parent system would affect the outcome in the early universe.

One of the largest uncertainties in interpreting the SCUBA submillimeter sources is the possible role of AGN and quasars in powering the high infrared luminosities. The absence of a hot dust component in some high redshift ultraluminous infrared galaxies (ULIRGs) with CO detections argues for a star formation interpretation of infrared luminosities as high as 10^{13} $L_\odot$. Observations of far infrared line diagnostics suggest thatup to ~ 20% of ULIRGs may be AGN-powered, [47] but nearby examples such as Arp 220 suggest that even in these cases there may be comparable amounts of star formation-induced infrared luminosity. Interpretation of the hard (~ 30 keV) x-ray background requires the mostly resolved sources responsible for the background to be self-absorbed AGN surrounded by dusty gas that reemits the absorbed AGN power at far infrared wavelenghts and can at most account for ~ 10-20% of the diffuse far infrared background. [48] An independent argument is as follows: the correlation of central black holes in nearby galaxies with spheroids ($M_{bh} \simeq 0.005\, M_*$) suggests that with an accretion efficiency that is expected to be a factor f ~ 10-30 larger than the nuclear burning efficiency for producing infrared emission, the resulting contribution from AGN and quasars to the far infrared background should be ~ 15 (f / 0.03)% of the contribution from star formation.

There are too many unresolved issues in the context of structure formation to be confident that we have converged on the correct prescription for primordial fluctuations in density, nonlinear growth, and cosmological model. And then we must add in the complexities of star formation, poorly understood in the solar neighbourhood, let alone in ultraluminous galaxies at high redshift. One cannot expect the advent of more powerful computers to simply resolve the outstanding problems. Rather it is a matter of coming to grips with improved physical modelling of star-forming galaxies. Phenomenological model building is likely to provide more fruitful returns than brute force simulations, but the data requirements are demanding even on the new generations of very large telescopes. Fluctuation spectra will be measured with various CMB experiments, although disentangling the various parameters of cosmology and structure formation will take time.

However I am optimistic that the anticipated influx of new data, from optical, infrared, x-ray and radio telescopes will go far towards resolving these uncertainties. It is simply that the journey will be long with many detours, before we have deciphered the ultimate model of cosmology.

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