much further than we had any right to expect. We can only marvel at this. Perhaps to conclude, I should add that in view of these demonstrated abilities of humanity, it should be able to take care of spaceship Earth with its crew and passengers, maybe unique or at least quite rare in this marvellous universe. Now I have the honour to hand over to Joe Silk.

Joe Silk:

From Here to Infinity

I will describe our state of knowledge about the contents and evolution of the universe. Observation generally has an advance over theory, but there are some aspects of nature that can be understood by simple physical reasoning. More speculatively, I will briefly describe our origins and future prospects in the context of the Big Bang theory.

Glimpses of the astronomer's universe inspire everybody, child or adult, scientist or poet. My inspiration focuses on cosmology, the science of the entire universe. It seeks to understand the content of the universe, our evolution, our origins, and our future. To keep this presentation within a more practical time-scale, I will describe my work in two areas: the content and the evolution of the universe. I will review our attempts to decipher the nature of the dark matter and to explain how our galaxy and other galaxies formed. I will close with more speculative comments about our origin and our future.

Dark Matter

Dark matter is ubiquitous. Historically, dark matter first surfaced in the Coma cluster of galaxies with the pioneering work of Fritz Zwicky in 1933. After two decades of investigation, evidence accumulated for dark matter in the outer parts of spiral galaxies. Now we find evidence for dark matter in the inner parts of galaxies, including our own Milky Way and its satellites, in elliptical galaxies and throughout the visible universe. Dark matter searches utilise a vast range of telescopes and detectors. These include direct detection experiments located deep underground, conventional telescopes on high mountain peaks and in space, gamma ray telescopes on the ground and in space, under water or under ice neutrino telescopes, and high energy cosmic ray detectors, x-ray and gamma ray telescopes in space.

The guiding precept for these experiments is that the dark matter is weakly interacting and cold, and consists of elementary particles that are potentially detectable in particle accelerators. Dark matter most likely is a weakly interacting massive particle

(WIMP), and a favoured candidate is the LSP found in the theory of supersymmetry. The favoured SUSY candidate is a WIMP in the mass range 0.01-10 TeV, and one of the principal goals of the LHC is to find evidence for SUSY. The motivation for a WIMP arises from the so-called WIMP miracle: the relic abundance of dark matter arises naturally for generic Majorana particle candidates with weak-like interactions if

$$1 \sim < n\sigma v > \sim 3 \text{ x } 10^{-26}\mathrm{cm}^3/\mathrm{s}\ (\Omega_x/0.3).$$

In fact, this conclusion is considerably weakened in more complex particle models, where there are additional degrees of freedom. Of course there are non-WIMP dark matter candidates, ranging from axions to exotic scalar fields. However in this review I will focus on WIMPs as these have become the prime target for a world-wide industry of particle astrophysics experiments. Astrophysical probes complement collider experiments, and astronomy provides a plethora of possible environments to be studied for WIMP signatures.

Direct Detection

Many WIMPs pass through us every second, about 10^6 m^{-2} s^{-1}. Detection techniques involve large masses of some suitable material that is studied for weak signals from the rare WIMP interactions. The detectors are located deep underground or under mountains, to avoid spurious cosmic ray induced events. The nuclear recoil signatures include ionisation, phonons and scintillation, and ideally require all of these effects. Event detections have been reported by several experiments. These include CDMS2 and CoGeNT. However, none of these have sufficient significance to be attributed to dark matter. The one exception is the NaI scintillation experiment, DAMA/LIBRA, now running for 14 years at Gran Sasso. This experiment uses solar modulation to enhance the direct detection signal and reports an 8.9 σ detection. The competing experiments rule out most explanations, including incoherent spin-independent scatterings. One window remaining is via coherent spin-dependent scatterings by light WIMPs on protons. The allowed mass range is experiment- and model-dependent but spans 5-20 GeV.

Indirect Detection

Halo WIMPs occasionally annihilate today into energetic particles: including neutrinos, gamma rays, positrons and antiprotons. They are also trapped by the sun and other stars. All of these lead to possible signals.

Helioseismology

WIMP scattering on protons modifies the solar temperature profile. Low mass WIMPs, of around 5-10 GeV, are trapped, fill the solar core and modify T(r). This leads to a detectable signal from solar physics-motivated experiments. Helioseismology has successfully studied p-modes from the outer regions of the sun. These measurements are sensitive to the temperature profile. The predicted signal probes solar structure. The revised solar opacities have thrown this field into disarray, since the totality of solar data, including solar neutrinos and helioseismology, can no longer be fit by the solar standard model. Addition of low mass WIMPs adds a new degree of freedom, and affects the helioseismology signal because of the (slightly) modified solar temperature profile. The effect is especially strong for 5-10 GeV WIMPs that interact via spin-dependent scatterings. If their abundance is high enough, e.g. if annihilations are partially or totally suppressed, one can even eliminate them as a DM candidate. Annihilation suppression in favour of a built-in asymmetry is reasonably natural for WIMPs in the mass range 5-10 GeV, as this provides an explanation for the observed baryon fraction to be of order the ratio of proton to WIMP masses, admittedly at the price of losing the perhaps less “natural” explanation for the dark matter density.

High energy cosmic rays

Rare particles in cosmic rays, most notably antiprotons and positrons, are a unique signature of dark matter annihilations. The search for high energy antiprotons has led to no surprises so far, although in principle because secondary antiprotons from cosmic ray spallations are Lorentz-boosted, there is a potential signal to be sought below 1 GeV. However, solar modulation effects make this a difficult measurement. Very massive WIMP candidates often overproduce antiprotons. Cosmic ray positrons have provided a far more productive target. Hints of a signal came with the HEAT balloon-borne experiment that detected a rise in the positron fraction above 10 GeV. This has been confirmed by the PAMELA satellite, continues to ~ 200 GeV (Abdo *et al.* 2010), and cannot easily be attributed to a single cosmic ray secondary production source of positrons.

Possible explanations include nearby astrophysical positron sources, dark matter decays or dark matter annihilations. The most likely source is the nearest pulsar, Geminga, detected by EGRET above 1 GeV, and by whatever sources produce the Milagro “hot spots” at a median cosmic ray energy of 10-20 TeV. More distant pulsars will also contribute, but the nearest sources dominate in typical cosmic ray diffusion models. Supernova remnant acceleration models also present a viable option.

The dark matter explanation of the positron excess requires a TeV particle. Antiprotons set a strong constraint on models. In the case of annihilations, a large halo dark matter clumpiness factor of 10^3-10^4 is required in order to boost the signal, since the gamma flux is inversely proportional to the square of the neutralino mass at a specified dark matter density. Theory struggles to generate such large clumpiness factors. One solution is via a Sommerfeld enhancement for ultracold dark matter, as expected for substructure in microscopic clumps (of order earth mass or below) in CDM and for dark matter that has not undergone phase space mixing, as expected to be generically the case following collapse that inevitably generates caustics. For a massive neutralino, one requires a quantum counterpart to gravitational coulomb focussing due to dark matter bound states (Arkani-Hamed *et al*. 2008, Lattanzi and Silk 2009, March-Russell and West 2009). In this case, one achieves a local annihilation cross-section as required with a boost of order 1000. However, this produces excessive gamma rays from the inner galaxy unless tidal destruction of substructure destroys most of the boost in the bulge region. Extragalactic constraints are constraining but await new data before being able to eliminate the annihilation interpretation of the essentially local PAMELA/FERMI/HESS positron/electron fluxes. These include the effects of prolonging the decoupling of the CMB as well as diffuse gamma ray signals (see below). The nearest pulsar wind nebulae are the most promising $e^+ e^-$ pair sources. Such astrophysical solutions will be tested by the predicted anisotropy, which already is close to the FERMI one-year upper limit (Di Bernardo *et al*. 2010).

Gamma rays

Recent data from the Fermi satellite has constrained dark matter models. The FERMI energy range spans 0.02 - 300 GeV, with angular resolution of 5 degrees to 5 arcmin at the highest energies and energy resolution of around 10%. The theory of dark matter annihilations (and decays) predicts several distinct gamma ray signatures. These include a harder spectrum than expected via neutral pion decay channels, spectral bumps and lines, and inverse Compton gammas, as well as radio synchrotron photons from high energy electrons and positrons. The ideal laboratory for dark matter detection via annihilations is to look at dark matter laboratories such as gamma rays from nearby dark matter-dominated dwarf galaxies. Simulations of the Milky Way halo at 1000 solar mass resolution and with the annihilation cross-section weighted by the square of the ratio of density to velocity dispersion approximately give the boost factor required by the positron/electron data (Kuhlen *et al*. 2009). However, hitherto only upper limits have been set on gamma ray emission, with the Fermi satellite setting stronger limits at lower particle masses, and the air Cerenkov array telescopes at higher masses (Sehgal *et al*. 2010).

The WMAP microwave haze

Dark matter annihilations in the galactic bulge lead to a possible radio synchrotron signal. The WMAP quasi-spherical haze residuals in the lowest frequency WMAP channels have been interpreted as such a signal (Finkbeiner 2007), and lead to the prediction that the same high energy electrons would lead to an inverse Compton gamma ray flux, produced by Compton scattering of high energy electrons and positrons on the interstellar radiation field. This leads to an expected Fermi haze, once known templates have been subtracted (Hooper and Zaharias 2007).

Analysis of the Fermi diffuse emission in the inner bulge led to an unexpected discovery. Once known templates were subtracted, the Fermi data reveals the presence of enormous bubble-like features, north and south of the Galactic Center (Su *et al*. 2010). These clearly are not due to dark matter injection but rather arise from an immense explosion some tens of millions of years ago. This interpretation requires local reacceleration over tens of degrees (at least a kpc) in order to account for the short electron lifetimes. In addition to this large-scale diffuse emission, there is an unexplained spectral distortion within the central degree or so. The Fermi haze has recently been revived to account for this spectral feature that is apparently unexplained by known sources or foregrounds. An additional diffuse component may be required in the lower energy channels, with a reasonable spectral fit being attained by addition of a 8 GeV WIMP that annihilates via tau quark production (Hooper and Goodenough 2010). The same electron component reproduces a spectral distortion in the synchrotron component that can also be reinterpreted as the WMAP haze signal (Hooper and Linden 2010), although it remains to be seen if the morphology of the signals are consistent with this interpretation.

Decaying dark matter

The alternative particle physics solution appeals to decaying dark matter, which can account for the PAMELA, FERMI and HESS data on high energy positrons and electrons as being generated by decays of massive neutralinos (Ibarra *et al*. 2009). The morphological differences between annihilating and decaying dark matter provide another distinguishable characteristic (Delahaye *et al.* 2010). However, this interpretation has largely been discounted by FERMI inverse Compton constraints on gamma rays produced by the electron-positron pairs in nearby galaxy clusters. The required decay time is a billion Hubble times.

Decaying dark matter in galaxy clusters turns out to be the best probe since the nearest clusters just fill the Fermi beam, and the gamma ray constraints effectively eliminate decaying dark matter as an option (Dugger *et al.* 2010).

The Future

The Sun

As the sun orbits the galaxy, it traps massive neutralinos that scatter off protons. These accumulate in the solar core where they annihilate, producing energetic neutrinos that may induce signals via muon production in experiments under ice such as IceCube, or under water in experiments such as ANTARES. Future scaled-up experiments should be capable of imaging the sun if neutralinos indeed annihilate at masses up to a TeV. If WIMPs do not self-annihilate, as would be the case for asymmetric or Dirac mass WIMPs, their numbers build up in the sun and lead to another potential signal. At low masses, WIMPs fill the core of the sun and WIMP recoils redistribute the solar temperature profile. This effect is optimised at the lowest masses that do not evaporate from the sun (around 5 GeV) but still gives a potentially detectable helioseismological signal for WIMPs below 20 GeV. This effect will be especially relevant once solar g-modes are detected. There is also a solar neutrino signal (Lopes and Silk 2010) if WIMPs are allowed to accumulate and scatter via spin-dependent couplings where direct detection limits are weak.

Direct detection

How low do we need to go in direct detection in order to eliminate SUSY-motivated WIMPs? Tonne-scale detectors are under construction (Akrami *et al*. 2010) and should be able to go well beyond the LHC benchmark models in terms of sensitivity to dark matter.

Cerenkov telescope arrays

Another technique that allows sensitive determinations of gamma rays measures atmospheric Cerenkov radiation from muon-poor air showers. These are induced by TeV gamma rays and have adequate resolution to resolve out identifiable discrete sources. An ultimate Cerenkov telescope array with 10 square km area can probe down to 10 GeV and achieve SUSY-model sensitivities comparable and complementary to those of tonne-scale direct detection experiments (Bergstrom *et al*. 2010). ACTs provide the most promising avenue for complementing direct detection.

CMB

If the annihilation cross-section is velocity-dependent, one can more easily obtain a boost that can help account for the PAMELA positron flux, at a velocity dispersion typical of cold substructure that may be as low as 10 km/s, or even lower. The price one pays is that annihilations are boosted in the early universe, most notably during matter-radiation decoupling. This leads to a potentially observable CMB damping signal due to extended decoupling, if the cross-section is normalised to that needed for the local positron flux (Galli *et al*. 2009). WIMP masses up to ~ 30 GeV can be eliminated as a thermal cross-section annihilation Source.

Strange stars

A neutron star is a dark matter collector. If neutron matter is metastable, the energy from WIMP annihilations may trigger the conversion of a neutron star to a quark star (Perez-Garcia, Silk and Stone 2010). The rest mass energy of the neutron star is liberated in high energy particles, neutrinos and photons. One might be able to observe such an event, in a region of high dark matter density, as a gamma ray burst of unusual characteristics.

The Galactic Centre

There is a black hole of mass 4 million solar masses identified with the radio source SagA* at the Galactic Centre. Theoretical arguments suggest that when it formed it may have acquired a steep dark matter cusp that would yield an enhanced annihilation signal in gamma rays. The characteristic features of this spectrum are an exponential plus flat power-law, and no variability. HESS data confirms the exponential cut-off above a few TeV and no detectable variability (Aharonian *et al*. 2009), but the power-law seems to be too steep for an annihilating particle with a unique mass. There are two possible interpretations: an astrophysical source, with novel spectral characteristics, or dark matter annihilations of a TeV particle together with a steep power-law contribution from an astrophysical source (or conceivably a lower mass annihilating particle).

LHC

The LHC reach overlaps with indirect dark matter detection experiments. The SUSY benchmark models for direct detection are accessible at the LHC. However the ultimate sensitivity to these models will come from combining direct detection with air Cerenkov array telescopes.

Galaxy Formation

Here are some outstanding questions that pertain to feedback in star and in galaxy formation. Can we predict the initial stellar mass function?

Can we account for the efficiency of star formation? Can we account for the galactic star formation rate? Do we understand supermassive black hole feedback?

The answer to the questions in all cases is no. But we should not despair. The missing link that yields a common thread to these questions is the need for a robust theory of star formation. I will argue that feedback in its diverse manifestations helps to partially resolve these issues. However, much still remains to be done, both observationally and theoretically.

In the beginning...

Star formation theory begins with the founder of the theory of gravitation. Isaac Newton realized in a letter he wrote to clergyman Richard Bentley on December 10, 1692, that fragmentation and subsequent star formation was inevitable in an infinite and initially homogeneous cloud. Gravity operated irreversibly and inevitably in accumulating matter around density fluctuations. “If the matter was evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered at great distances from one to another throughout all that infinite space. And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature”.

Newton’s insight was remarkable. However he could not understand how gravity could differentiate between luminous bodies, or stars, and opaque bodies, or planets. “How the sun alone should be changed into a shining body whilst all the planets continue opaque, or all they be changed into opaque ones whilst he remains unchanged, I do not think explicable by mere natural causes, but am forced to ascribe it to the counsel and contrivance of a voluntary Agent”.

An intensely religious man, Newton gave up in despair at this point and appealed to a higher entity to come to the rescue.

James Jeans was not one to share this opinion, however. He developed fragmentation into quantitative physics. To him, “From the intrinsic evidence of his creation, the Great Architect of the Universe now begins to appear as a pure mathematician”.

In 1902, he developed the theory of gravitational fragmentation which is now central to our understanding of star formation. “We have found that as Newton first conjectured, a chaotic mass of gas of approximately uniform density and of very great extent would be dynamically unstable: nuclei would tend to form in it, around which the whole matter would eventually condense. All celestial bodies originate by a process of fragmentation of nebulae out of chaos, of stars out of nebulae, of planets out of stars and satellites out of planets”.

But Jeans did not solve the challenge posed by Newton of why stars as opposed to planets. The astronomer who faced this challenge was Arthur Eddington, who developed the theory of self-gravitating polytropic spheres in order to model stars. Simple stability considerations led him to realise that stars occupied a relatively narrow mass range. He showed in 1926 that star formation was inevitable. “Imagine a physicist calculating on a cloud-bound planet and ending with the dramatic conclusion: « What ‘happens’ is the stars »”.

Star formation

The Jeans mass sets the scale of fragmentation. It is defined to be the mass within a sphere of diameter the Jeans length, approximately the distance a sound wave crosses in a free fall time, and is proportional to the 3/2 power of the temperature and the inverse square root of density. At low densities, interstellar clouds radiate freely and are isothermal. During the isothermal phase of contraction, the Jeans mass decreases. Eventually the cloud becomes self-shielding, and the ensuing contraction is approximately adiabatic once the optical depth is large. The Jeans mass increases in this phase, which is the precursor to the phase of Kelvin-Helmholtz contraction onto the stellar main sequence. The minimum opacity-limited Jeans mass is the fragmentation scale. It can be shown, quite insensitively to metallicity or dust content, to depend only on the dimensionless quantity $\alpha_g^{-3/2}$, where α_g is the so-called gravitational fine structure constant. This gives a minimum fragment mass of about 0.001 solar mass, a result that is found in essentially all numerical simulations of current epoch star formation. The dependence on temperature is approximately as $T^{1/4}$, and yields 0.01 solar mass for primordial abundances, appropriate to Population III. In general, fragmentation theory applied to a collapsing interstellar cloud implies that the minimum fragment mass is far too small to be a star. Additional physics is needed.

A key addition is the accretion of cold gas. In the case of a singular isothermal sphere, accretion onto the core occurs at a rate v_s^3/G. In nearby cold molecular clouds, at a temperature of $\sim $10 K, the inferred accretion rate is 10^{-6} solar mass per year, and yields solar mass protostars on a time-scale of order the Kelvin-Helmholtz time of 10^6 years or so. However, in the case of the first stars, the presence of trace amounts of molecular hydrogen as a coolant means that the temperature is around 1000 K. Consequently, the accretion rate is 10^{-3} solar mass per year, and one concludes that Population III stars, accreting over 10^5-10^6 years, had characteristic masses of 100 to 1000 solar masses. Again, numerical simulations confirm this result.

However, fragmentation and accretion do not suffice to reproduce the initial mass function of stars. A third process must be added, namely feedback, to halt the accretion, otherwise low mass stars would not form at present. In general, protostellar feedback halts collapse by tapping stellar gravitational energy via releasing magnetic energy. This simultaneously resolves the angular momentum problem, in that there is of the order of two orders of magnitude too much specific angular momentum in cloud cores to form stars directly. The Population III stellar masses are reduced to about 40 solar masses (Hosokawa *et al*. 2011).

Feedback: interstellar clouds

One requires magnetic feedback to account for the turbulence observed in cloud cores. It simultaneously results in inefficient star formation: were cores to collapse on a free fall time, one would have excessive star formation. Protostellar outflows are ubiquitous and provide momentum input by interactions of jets with the magnetized ISM. This suffices to prolong cloud longevity. In the case of massive clouds, OB stars provide feedback that ultimately disrupts the clouds. One observes over a wide range of molecular cloud masses that the star formation efficiency, defined to be star formation rate divided by gas mass and multiplied by cloud free fall time, is approximately 2 percent (Krumholz and Tan 2007). In this way one can arrive at a star formation rate for the Milky Way Galaxy that is comparable to what is observed globally. In fact the Milky Way converts about 2% of its molecular gas content (approximately 3 billion solar masses) into stars over cloud lifetimes of typically 10^7 yr.

Feedback: disk galaxies

It is at first sight rather remarkable that star formation in disk galaxies, both near and far, can be described by a simple law, with Star Formation Efficiency (SFE) being the controlling parameter:

SFE = SFR times (ROTATION TIME) / (GAS MASS) = constant.

The motivation comes from the gravitational instability of cold gas-rich disks, which provides the scaling, although the normalization depends on feedback physics. For the global law, in terms of star formation rate and gas mass per unit area, supernova regulation provides the observed efficiency of about 2%, which fits essentially all local star-forming galaxies. One finds from simple supernova-injected momentum conservation that SFE, defined as the ratio of specific gas momentum to specific momentum injected by supernovae, is about 2%. This comparison is only a crude estimator of the efficiency of supernova momentum input into the interstellar medium but it reproduces the observed global normalization of the star formation law. The fit applies not only globally but to star formation complexes in individual galaxies such as M51 and also to starburst galaxies. This law is known as the Schmidt-Kennicutt law, and its application to galaxies reveals that molecular gas is the controlling gas ingredient. In the outer parts of galaxies, where the molecular fraction is reduced due to the ambient UV radiation field and lower surface density, the star formation rate per unit gas mass declines. In major mergers where the gas specific momentum is high, one expects a correspondingly higher efficiency of star formation.

For disk instabilities to result in cloud formation, followed by cloud agglomeration and consequent star formation, one also needs to maintain a cold disk by accretion of cold gas. There is ample evidence of a supply of cold gas, for example in the M33 group. Other spiral galaxies show extensive reservoirs of HI in their outer regions. Recent data extends the Schmidt-Kennicutt law to a redshift of 2. Remarkably, an efficiency of 2% or so fits low and high redshift star-forming galaxies, with SFE proportional to the product of SFR and galactic rotation rate. Starburst galaxies also lie on this relation (Genzel *et al*. 2010). However, there is a tendency for ultraluminous starbursts, especially at high redshift, to have somewhat higher SFE.

Luminosity function of galaxies

Theory provides the mass function of dark halos. Observation yields the luminosity function of galaxies, usually fit by a Schechter function. Comparison of the two is at first sight disconcerting. One can calculate the mass-to-light ratio for the two functions to overlap at one point, for a mass stellar or luminous mass corresponding to the stellar luminosity.

Define two halo time-scales: the cooling time and the dynamical time-scale for the forming galaxy. For star formation to occur, cooling is essential, and the condition that cooling time be less than or of order of the dynamical time guarantees cooling occurs in an inhomogeneous galactic halo where gas clouds collide at the virial velocity. One finds that there is a characteristic mass scale proportional only to the ratio of these time-scales, and moreover that this ratio is essentially a universal constant over the relevant temperature range for a low metallicity plasma (Gnat and Sternberg 2007). The result is that one finds a characteristic galactic halo mass, in fundamental constants, to be of order a trillion solar masses. The inferred value of the mass-to-light ratio is similar to that observed for typical galaxies. This is a success for theory: dissipation provides a key ingredient in understanding the stellar masses of galaxies, at least for the ‘typical’ galaxy. The characteristic galactic mass is understood by the requirement that cooling within a dynamical time is a necessary condition for efficient star formation. However, the theory greatly overestimates galaxy numbers at low and high masses. Feedback is needed to address this problem.

Feedback in low mass galaxies

Reionization gives an inevitable feedback for the lowest mass dwarfs. An abrupt increase of the sound speed to 10-20 km/s at z~ 10 means that dwarfs of mass 10^6-10^7 solar masses which have not yet collapsed and fragmented into stars will be disrupted. However, more massive dwarfs are unaffected, as are the high density peaks that develop into early collapsing, but rare, low mass dwarfs. The accepted solution for gas disruption and dispersal in intermediate mass and massive dwarfs (10^8-10^{10} solar masses) is by supernova feedback. Most gas is ejected by the first generations of supernovae for systems with escape velocity less than or of order 50 km/s, leaving dim stellar remnants behind. This yields an acceptable fit to the low mass end of the galaxy luminosity function for the classical dwarfs.

One recent issue has emerged, however. The discovery of ultrafaint, low mass dwarfs in the Milky Way halo may be considered as an indication, and even verification, of a prediction of the supernova feedback hypothesis. The only worry is that semi-analytic models tuned to fit the numbers of ultrafaint dwarfs is ineffective on the scale of massive dwarfs such as the Magellanic Clouds (Koposov *et al*. 2009). The problem has been confirmed with high resolution dark matter-only simulations that produce too many massive dwarfs with no observed counterparts (Boylan-Kolchin *et al*. 2012).

Feedback in massive galaxies

Supernovae cannot eject significant amounts of gas from massive galaxies. Baryons continue to be accreted over a Hubble time, and the stellar mass grows. The consequences are that massive galaxies are overproduced in the models, and that the massive galaxies are too blue. Moreover the baryon fraction is typically only of order half of the primordial baryon fraction.

A clue as to a solution for these dilemmas comes from the accepted explanation of the Magorrian relation, which relates supermassive black hole mass to spheroid velocity dispersion. This requires collusion between black hole growth and the initial gas content of the galaxy when the old stellar spheroid formed. One conventionally appeals to outflows from the central black hole that deliver momentum to the protogalactic gas. When the black hole is sufficiently massive, the Eddington luminosity is high enough that residual gas is ejected. An estimate of the available momentum supply come from equating the Eddington momentum with self-gravity on circumgalactic gas shells. Blow-out occurs and star formation terminates when the black hole mass-sigma relation saturates. This occurs for black hole mass proportional to the fourth power of sigma, which also is the observed slope, and gives, at least in order of magnitude, the correct normalisation of the relation.

There is also a role for AGN feedback at late epochs, when the AGN radio mode heats halo gas, inhibits cooling, resolves the galaxy luminosity function bright end problem and accounts for the red colours of massive early-type galaxies. AGN feedback in the radio-quiet mode may also account for the suppression in numbers of intermediate mass and satellite galaxies. Feedback from AGN in the host galaxies preheats the halo gas that otherwise would be captured by satellites.

However, reality may be not quite so simple. A more detailed examination suggests that negative feedback in momentum-driven winds by supermassive black holes falls short of explaining the observed black hole mass-sigma correlation by a factor of a few (Silk and Nusser 2011). Moreover, comparison of baryonic fractions with bulge-to-disk ratios in nearby galaxies demonstrates that AGN alone do not eject significant amounts of baryons (Anderson and Bregman 2010). Something else seems to be needed.

The AGN-star formation connection

The most plausible addition to the physics is inclusion of star formation, induced and enhanced by the SMBH outflows. If AGN-driven outflows trigger star formation, the star formation rate is boosted by a factor of order jet-flow time over dynamical time, and the outflow momentum is amplified by supernovae (Silk and Norman 2009). Consequently, the momentum supplied to the gas is boosted by the combination of AGN and star formation. There is extensive evidence, recently compiled by Netzer (2009), that demonstrates the intimate connection of AGN luminosity and star formation rate over a wide dynamic range. Of course the causal direction is uncertain, and indeed the phenomena could be mutually self-regulating. To go beyond phenomenology, many details need to be refined, the most pressing perhaps being the nature of the black hole growth. However there are examples of jet-induced global star formation, as seen locally in Minkowski’s object, and jet-induced CO formation (and excitation) at high redshift. CO is a prerequisite for star formation, and has been detected in large amounts in the host galaxies of high redshift quasars.

Modes of star formation

Incorporation of a positive role by AGN for star formation in extreme environments leads one to argue that a case can be made for two distinct feedback-regulated modes of star formation: at low redshift via supernovae and without AGN, and at high redshift with triggering by AGN playing a central role. One would expect a transition between these two modes as the AGN duty cycle becomes shorter beyond redshift 1 or 2. Indeed a recent compilation (Gonzalez *et al*. 2010) of the specific star formation rate (SSR, or star formation rate per unit stellar mass) to a redshift of up to 8 in the GOODS field suggests that the star formation time-scale (or 1/SSR) goes from the MWG value of 3 Gyr at low redshift to 0.5 Gyr at z beyond 2.

There are two other transitions in this redshift range that may be relevant. At high redshift, major mergers between galaxies are common. Indeed the high redshift extreme ULIRGs are invariably undergoing major gas-rich mergers. Theory suggests that at low redshift, gas accretion by cold streams is important, and that the cold streams are invariably clumpy and essentially indistinguishable from minor mergers of gas-rich dwarfs. In terms of the cosmic star formation history, normal star-forming galaxies dominate at low redshift whereas ULIRGs dominate at high redshift.

If the disk formation mode is distinct from the spheroid formation mode, then SMBH might be expected to show some reflection of alternative growth histories. So-called pseudobulges form from secular instability of disks and contain smaller SMBH than do the more massive bulges that may have formed via major gas-rich mergers. It is interesting that SMBH in pseudobulges and disks do not correlate with spheroid velocity dispersion (Kormendy, Bender and Cornell 2011), possibly reflecting the different black hole formation histories and the associated distinct star formation modes. Recent data on high redshift quasars suggest that the most massive black holes indeed lie high on the black hole/dynamical mass relation. Much work needs to be done to see whether allowance for two modes of star formation can help resolve some of the outstanding problems in galaxy formation. Perhaps the greatest challenge in any combination of cold stream/minor merger/major merger scenario for gas delivery to drive both star formation and SMBH feeding is that of order 15% of nearby galactic disks are bulgeless. In addition to the many uncertainties in star formation theory (and I have not addressed one of the key issues, that of the initial stellar mass function), there remains the nature of black hole growth. Whether the black holes grow by gas accretion, in which case feedback may play a role in angular momentum transfer (Antonuccio-Deloglu and Silk 2010), or by mergers, or by cold filamentary infall, or by an appropriate combination, remains unresolved.

SUMMARY

Cold gas flows via filaments/minor mergers lead to disk and bulge formation. Supernovae drive turbulence and fountains in star-forming disk galaxies, and are responsible for the low global star formation efficiency. Major mergers along with hot gas infall followed by cooling forms massive spheroids at high efficiency.

However, these solutions create more problems. For example, there are too many small galaxies and too many big galaxies today, and too few big galaxies in the past. Angular momentum loss results in overly massive bulges. Most massive galaxies do not form via major meregers. These problems are all addressed by adding various levels of astrophysical feedback.

Reionization will eject baryons from the smallest clouds to collapse. Supernova-driven winds account for loss of baryons from intermediate mass galaxies before star formation is completed. Tidal disruption kills off many of the satellites that interact with the disk and bulge. These processes enable one to account for the mass function of galaxies.

For massive galaxies, notably the spheroidal galaxies, supermassive black hole-driven outflows occur at early epochs and are responsible both for the quasar phenomenon and quenching of star formation.

The role of SMBH is to quench star formation at early epochs, thereby accounting for the redness of elliptical galaxies, and to heat intracluster gas at late epochs, thereby preventing gas cooling and late star formation. Of course this process cannot be completely efficient, and indeed 30% of nearby ellipticals have modest amounts of ongoing star formation.

More speculatively, SMBH may also play a role in triggering star formation in starbursts, especially in ULIRGs. Positive SMBH feedback can enhance both the star formation efficiency and the specific star formation rate. However, the origin of SMBH remains a mystery, and must certainly play a key role in ascertaining the detailed nature of SMBH feedback. Improved resolution in theory and observation is needed. The great projects of the future, including the ELTs, JWST and LSST, will surely play key roles in this endeavour.

Dark matter is an equally urgent problem. Detection in multiple windows is essential for credibility. If we detect dark matter, there is still much to do in order to achieve consistency with astrophysical constraints. Resurrection is feasible via astrophysics due to the complexity and richness of feedback. The key need is the addition of baryons to make realistic galaxies.

Even the development of the next generation of experiments may barely suffice to probe the constrained minimal SUSY parameter space for dark matter candidates. If these experiments are unsuccessful, one will have to decide whether the optimal strategy is to pursue SUSY candidates emerging from less constrained models, as well as non-SUSY candidates, which are of course numerous, or whether to branch out into more speculative directions, such as scalar fields or higher dimensional relics. At the same time, there is the cosmological challenge: if we fail to plausibly reconcile dark matter with galaxy formation, one might seek resurrection via new fundamental physics. This could include modifying the nature of dark matter or even modifying gravity itself.

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Heinz Gutscher: Thank you very much Joseph Silk. Vincent Desjacques, Professor of Theoretical Physics at the University of Geneva, will now pose some quesitons.