Dark Halos of Spiral Galaxies: ISO photometry *

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ABSTRACT

We exclude hydrogen burning stars, of any mass above the hydrogen-burning limit and any metallicity, as significant contributors to the massive halos deduced from rotation curves to dominate the outer parts of spiral galaxies. We present and analyse images of 4 nearly edge-on bulgeless spiral galaxies (UGC711, NGC2915, UGC12426, UGC1459) obtained with ISOCAM (The CAMera instrument on board the Infrared Space Observatory) at 14.5\(\mu\)m and 6.75\(\mu\)m. Our sensitivity limit for detection of any diffuse infrared emission associated with the dark halos in these galaxies is a few tens of microJy per 6arcsec x 6arcsec pixel, with this limit currently set by remaining difficulties in modelling the non-linear behaviour of the detectors. All four galaxies show zero detected signal from extended non-disk emission, consistent with zero halo-like luminosity density distribution. The 95percent upper limit on any emission, for NGC2915 in particular, allows us to exclude very low mass main sequence stars (M > 0.08 Msun), and young brown dwarfs (\(< \sim 1\) Gyr) as significant contributors to dark matter in galactic halos. Combining our results with those of the Galactic microlensing surveys, which exclude objects with M < 0.01 Msun, excludes almost the entire possible mass range of compact baryonic objects from contributing to galactic dark matter.

* Based on observations with ISO, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, the Netherlands and the United Kingdom) with the participation of ISAS and NASA.
Key words: Dark Matter – galaxies: fundamental parameters – galaxies: stellar content – Galaxy: halo – Galaxy: stellar content –

1 INTRODUCTION

The nature of the dark matter which is required, by conventional dynamical analyses, to dominate the outer parts of galaxies remains unknown. A combination of conservatism and the (very) approximate consistency between the total masses of galactic halos and the total baryonic mass of the Universe, $\Omega_B$, means that baryonic dark matter continues to be of potential interest (cf. Lynden-Bell & Gilmore 1989; Carr 1994). The mass-to-light ratios of galactic (dark) halos are high. Thus compact baryonic candidates are immediately restricted to stellar remnants and low mass stars and sub-stellar mass objects.

In the Galaxy fairly detailed studies are available. Stellar remnants are difficult, and probably impossible, to reconcile with well-understood limits from luminosity and chemical element production in their luminous precursor evolutionary state (eg Hegyi & Olive 1986; Weidemann 1989; Gibson & Mould 1997). Additionally, direct searches, particularly using HDF data, have produced tight limits on their numbers (Elson, Santiago & Gilmore 1996; Kawaler 1998). Low mass stars have also been constrained by direct analysis of local (Kroupa, Tout & Gilmore 1993; Hu et al, 1994; Kirkpatrick et al 1994; Graff & Freese 1996; Fuchs & Jahreiss 1998) and more distant (HST: Santiago, Gilmore & Elson 1996; Gould, Flynn, & Bahcall 1998, and refs therein; cf Mera et al 1998a, 1998b) surveys. Nonetheless, the total number of faint stars seen by HST remains only a few hundred, the area surveyed in any line of sight by HST is tiny, very low mass stars do indeed exist, and the LMC microlensing events remain to be understood (eg Alcock et al 1997). Thus improved limits on low mass compact baryonic objects (stars?) in galactic halos remain of interest.

The obvious observational approach in this context is to complement deep searches for individual stars in the Galaxy halo by surface photometry of the integrated line-of-sight emission from all halo components in external galaxies. The ideal candidate is an edge-on spiral galaxy with no bulge component. Recent efforts here include detection (Sackett, Morrison, Harding & Boroson 1994) and confirmation by several groups (see refs in Lequeux et al 1998) of an extended stellar halo around the edge-on spiral galaxy NGC5907. A plausible explanation in this case is however that the stellar halo is a merger remnant, similar in significance and history to the Galactic thick disk (Gilmore & Wyse 1985), but unrelated to the identification of dark matter (Fuchs 1996, Lequeux et al 1998). Similar halos are sometimes found around other galaxies (Rauscher et al 1996; Abe et al 1998), but always at surface brightnesses such that the stars actually detected are not relevant to the dark matter problem. Dark matter is apparently ubiquitous (eg Casertano & van Albada 1990), and dark.

Extension of the surface photometry to the near infrared substantially increases sensitivity to cool populations (James & Casali 1996; Rudy et al 1997; see also Daly & McLaughlin 1992). It is that approach which we have employed here, using ISO to provide the first deep surface photometry of galaxy halos at $7\mu m$ and $15\mu m$. 

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2 TARGET SELECTION

Suitable candidate galaxies should be known to have dark halos (hence have measured rotation curves), be nearly edge-on to our line of sight (to maximise disk-halo contrast), have minimal bulges (to minimise unrelated stellar contamination), and be isolated (to minimise confusing dynamics). Furthermore, since the observations are to be carried out by ISO (Infrared Space Observatory), we ideally require galaxies with linear dimensions smaller than about 3 arcminutes, so that the whole galaxy fits into a single image field of view. Due to the complexities of processing ISO data, this helps to minimise any possible systematic effects.

The galaxies selected for observation, which satisfy as closely as possible these criteria, are UGC711, NGC2915, UGC12426 and UGC1459. These galaxies range in recession velocity from $\sim 500 \text{ kms}^{-1}$ to $\sim 5500 \text{ kms}^{-1}$, corresponding to distances from about 5 Mpc to about 80 Mpc.

Furthermore, in the event of a detection, a simple way to distinguish between dark matter candidates is to observe in more than one colour. The observations were therefore in the two most sensitive broad band ISO filters LW2 and LW3 (centred at 6.75$\mu$m and 14.5$\mu$m respectively). Recent theoretical advances in cool star, brown dwarf and cool white dwarf spectra have shown that at these wavelengths the spectra do not deviate excessively from black body spectra. Work by Baraffe & Allard (1997) shows that low mass stars and brown dwarfs, in the very dustiest plausible case, show a diminution of flux of only a factor of a few, at most, in the wavelength range of interest. These models are for stars of solar metallicity, and a dark halo is more plausibly an ancient formation, composed of metal-poor stars. In this sense, a blackbody model may be also be suitable. Similarly, work by Chabrier (1997) indicates that cool white dwarfs show little deviation from black body radiation.

The difference in temperature, nevertheless, between low mass stars or brown dwarfs and cool white dwarfs is sufficient to show up in the LW2-LW3 colours, being of order 0.7 dex.

Accurate determination of background levels, set here almost entirely by zodiacal emission, is crucial. Additionally, understanding and quantification of ISO calibrations, and time-dependant changes in flat-fields, etc, is still improving. Thus, for each target field centred on the chosen galaxy, we have an offset field, observed immediately following the target, overlapping in area, and independently processed. To mitigate the effect of current uncertainty, we further choose to adopt a robust method of error estimation. The independently processed overlapping field gives a reliable, processing-independent method of assessing the uncertainties in the results.

2.1 Selection of ISO Filters

Since the aim of this experiment is to extend detection limits to cooler objects than can be studied with ground-based telescopes, we consider the capabilities of the most sensitive ISOCAM filters. Figure 2.1 shows the ISOCAM system sensitivity (i.e. filter transmission $\times$ detector response) superposed on a range of blackbody flux distributions. The ISO LW2 and LW3 filters have particularly strong sensitivities at the relevant wavelengths.
FIGURE 1: The responses for the LW2 and LW3 filters for ISOCAM are shown (linear, right-hand, scale) together with blackbody curves as a function of frequency ($\nu$) for objects of total luminosity $1L_\odot$, at the indicated temperatures.

FIGURE 2: The fraction of incident energy flux transmitted by the labelled filters, as a function of (blackbody) temperature, illustrating the temperature sensitivity range for this experiment.

LW3 filters are centred around 6.75 $\mu$m and 14.5 $\mu$m respectively, and provide the greatest sensitivity to the widest range of temperatures available. The sensitivity of the filters to very cool stellar and sub-stellar objects is shown in figure 2.1. This additionally emphasises the important restriction, that we remain insensitive to extremely cold gas clouds. Detection of very cold baryonic dark matter requires longer wavelength observations than are possible with ISOCAM.

3 THE OBSERVATIONS

3.1 ISOCAM observing mode

The ISO CAM instrument (Cesarsky et al 1996) was used with 6arcsec pixels, in a somewhat non-standard observing mode. An expected detectable signal at a S/N ratio $\gtrsim 10$ is 1-3 mJy in 200s of integration. We need to ensure that this noise level does decrease with increasing integration times, and to ensure maximal reliability of any detection of low surface brightness extended emission. The CAM detector has a special feature, requiring significant time to reach a steady-state response to a stable input flux, and further having a very long decay constant back to a stable state after the flux is removed. Although corrections for these effects are feasible in software (see below) we ensured they were minimised by adopting relatively long stabilisation times after each pointing prior to each integration. That is, we chose the tradeoff between depth and reliability to favour reliability. As the results below illustrate, sufficient sensitivity was also achieved.

We also need to define a local “sky” background, adjacent to each observation, with several criteria. The offset field must be close to the primary pointing in time – to minimise system drift and changing solar elongation – and in direction, to minimise real gradients, especially in zodiacal emission. The offset must however be sufficiently far from the galaxy that any real extended emission associated with the galaxies’ halo does not appear simply as a zero offset. The target choice, noted above, ensured these offset conditions would be met by following each primary exposure with a following (‘concatenated’) exposure of a suitable background field. The adopted field centres are listed in table 1 below.

Thus each long integration for each field consisted of 3360 separate short exposures, with elementary integration time 2.1 seconds, for a total on-target time of two hours per source. The spacecraft was dithered by 2 arcseconds after every 16 images, so that a given source fell at all points on a regular grid covering 30$\times$28 arcseconds. Immediately following each source, an adjacent, partially overlapping where possible, offset ‘sky’ area was observed in exactly the same way. In this way, in final processing, higher resolution can be recovered, while individual bad pixels, and the biasing effects of the row of pixels which is missing from the ISOCAM images, do not severely degrade the quality of the final result.
Table 1. Basic Observational Information

| Field             | $\alpha$ (2000.0) | $\delta$ (2000.0) | Gal. Lat. | Image | Filter | Solar Elongation | Date       |
|-------------------|-------------------|-------------------|-----------|-------|--------|------------------|------------|
| UGC711            | 1 08 37-0         | 1 38 28-0         | -60-9     | 57500601 | LW2    | 66°              | 1997 Jun 13 |
| UGC711-offset     | 1 08 32-2         | 1 36 59-0         | 57500602  | LW2    |         |                  | 1997 Jun 13 |
| UGC711            | 1 08 37-0         | 1 38 23-3         | 21201203  | LW3    | 69°    |                  | 1996 Jun 16 |
| UGC711-offset     | 1 08 32-2         | 1 36 59-4         | 21201206  | LW3    |         |                  | 1996 Jun 16 |
| NGC2915           | 9 26 00-0         | -76 38 30-0       | -18-4     | 62501817 | LW2    | 94°              | 1997 Aug 2  |
| NGC2915-offset    | 9 23 48-0         | -76 38 30-0       | 62501821  | LW2    |         |                  | 1997 Aug 2  |
| NGC2915           | 9 26 00-0         | -76 38 30-0       | 63003409  | LW3    | 93°    |                  | 1997 Aug 7  |
| NGC2915-offset    | 9 23 48-0         | -76 38 30-0       | 63003413  | LW3    |         |                  | 1997 Aug 7  |
| UGC12426          | 23 13 32-3        | 6 34 07-6         | -48-8     | 54700603 | LW2    | 65°              | 1997 May 16 |
| UGC12426-offset   | 23 13 38-3        | 6 34 08-0         | 54700604  | LW2    |         |                  | 1997 May 16 |
| UGC12426          | 23 13 32-3        | 6 34 07-6         | 21600105  | LW3    | 97°    |                  | 1996 Jun 19 |
| UGC12426-offset   | 23 13 38-3        | 6 34 07-7         | 21600108  | LW3    |         |                  | 1996 Jun 19 |
| UGC1459           | 1 59 06-7         | 36 03 47-1        | -24-8     | no-obs | LW2    |                  |            |
| UGC1459-offset    | 1 59 06-7         | 36 02 18-1        | no-obs    | LW2    |         |                  |            |
| UGC1459           | 1 59 06-7         | 36 03 47-1        | 60102102  | LW3    | 69°    |                  | 1997 Jul 9  |
| UGC1459-offset    | 1 59 06-7         | 36 02 18-1        | 60102107  | LW3    |         |                  | 1997 Jul 9  |

3.2 Data Reduction

The standard ISO pipeline reduction of the data uses the best available calibration files at the time of observation and the best available algorithms at the time of reduction. As is the case with other long-term projects, improved calibration files and more experience in data reduction continue to become available, so that the pipeline-processed distributed data products do not correspond to the best possible reductions. In order to benefit from the best available calibrations and algorithms, we have not utilised the standard ISO data products, but have reprocessed the raw data using the CAM Interactive Analysis (CIA) software†. The data, when converted to a usable format, are held as a cube, with the first two dimensions representing the individual images (210 per field in this case), and the third dimension representing the sequence of images taken.

The reduction of the raw data requires the following steps, annotated below:

(i) Dark correction – library darks are subtracted from the image to leave data corrected for dark current.

(ii) Deglitching – cosmic ray effects are quite severe. However, the ‘glitches’ can be reliably identified by a combination of their position in the image and in the time sequence of the data cube. The glitches are removed using the CIA ‘particule’ method, by a thresholding method in position and time.

(iii) Cube reduction – at this point, the 3360 images are condensed into 210 images, one for each dither position, by summing the 16 exposures at each dither position.

(iv) Transient correction – this is the most difficult part of the processing chain to implement successfully. The challenge with the ISOCAM detector is that it is highly non-linear, and has a very strong memory effect. The time for the signal on an illuminated pixel to decay to negligible values is longer than can be implemented into an observing schedule. The corrections

† CIA is a joint development by the ESA Astrophysics Division and the ISOCAM Consortium led by the ISOCAM PI, C. Cesarsky, Direction des Sciences de la Matière, C.E.A., France.
FIGURE 3: Four images of the UGC711 observations. The left column shows the target and control field for the 7\(\mu\)m wavelength filter (LW2), and the right column shows the same fields observed using the 15\(\mu\)m wavelength filter (LW3). The intensity scale is given at the bottom of the image, as is a scale bar of length 1 arcminute. The field size in each case is 3.2 by 3.2 arcmin. Note that the full dynamic range black-white of the intensity scale of these images is less than 10\(\mu\)Jy/arcsec\(^2\) for the LW2 images, and less than 20\(\mu\)Jy/arcsec\(^2\) for the LW3 images. Superimposed on all the images are optical contours derived from the Digitised Sky Survey. The very bright object to the bottom right of the target field is a star of magnitude V=9.3.

FIGURE 4: As for figure 3, but for the galaxy NGC2915.

were thus assigned to software. The method adopted here (the CIA ‘inversion’ method, developed by Abergel & Desert 1997) is based on the empirical observation that the time behaviour of each CAM pixel shows dependence on its complete history. The linear combination of all the previous astrophysical signal, and its decay, falling upon a given pixel can be modelled by an exponential decay. The resulting set of linear combinations produces, at each instant, a matrix relating the observed signal to the expected signal, and can be solved by the inversion of the matrix. This method produces good results for images such as the extended galactic images we have, since it was developed and optimised for processing of images of Galactic cirrus clouds (Abergel et al. 1996).

(v) Flat field correction – a ‘best’ flat field is selected from a library of flat fields, and each image in the reduced data cube is divided by this flat field. ‘Best’ in this sense means close in time, and with the exposure parameters most appropriate to those used in the observations.

(vi) Geometrical distortion correction – The distortion in the image is assumed to be linear about the centre of a CAM image, and is corrected accordingly, using the recent calibration in CIA from Herve Aussel. The severely vignetted edge pixels were removed.

(vii) Raster creation – the default methods supplied in the CIA package at the time of writing do not make best use of the information available in a dithered data set such as this one. In order to use the data as well as possible, we wrote code for a specific implementation of the ‘drizzle’ algorithm of Fruchter & Hook (1996). The ‘drizzle’ algorithm creates an empty output image, and ‘rains’ down onto this empty image the pixels from the input images, cutting the flux into appropriate fractions according to where the input pixel falls when transformed to the same coordinate system as the output image. The pointing information provided in the calibration files for the ISO images was used to specify the position and orientation of these input images. An optimal compromise between noise and resolution can be obtained by shrinking the footprint of input pixels.

3.3 The reduced ISOCAM Images

The processed images are shown in figures 3.3 – 3.3, with optical contours taken from Digitised Sky Survey data superimposed. For each galaxy observed, images were taken centred on the galaxy (target field) and offset from it (a control field), in each of the filters LW2 (∼6.75μm) and LW3 (∼14.5μm).

The following points may be noted concerning the images:

FIGURE 5: As for figure 3.3, but for the galaxy UGC12426.
FIGURE 6: As for figure 3, but for the galaxy UGC1459. In this case there was an observation only at the longer wavelength filter LW3.

Table 2. Average background levels, and distance information. Distances $d_0$, except for NGC2915 (Meurer et al. 1996), are estimated from the recession velocity ($v_0$) using a value of $H_0=70$ kms$^{-1}$Mpc$^{-1}$.

| Galaxy   | $v_0$ | $d_0$ | Ecliptic Latitude | Solar Elongation | Measured (mJy arcsec$^{-2}$) | DIRBE (mJy arcsec$^{-2}$) |
|----------|-------|-------|-------------------|------------------|-------------------------------|----------------------------|
|          | kms$^{-1}$ | Mpc   |                   | LW2 | LW3 | LW2 | LW3 | LW2 | LW3 |
| UGC711   | 1982  | 28    | -5.2              | 66  | 69  | 0.317 | 1.45 | 0.32 | 1.02 |
| NGC2915  | 468   | 5.3   | -71.8             | 94  | 93  | 0.067 | 0.35 | 0.12 | 0.35 |
| UGC12426 | 4720  | 67    | +10.6             | 65  | 97  | 0.279 | 0.75 | 0.29 | 0.92 |
| UGC1459  | 5469  | 78    | +22.4             | –   | 69  | 0.73  | 0.22 | 0.69 |       |

(i) The images have very different mean background levels. The median value of the background for the LW2 images ranges, in mJy arcsec$^{-2}$, from 0.317 (UGC711) to 0.279 (UGC12426) to 0.067 (NGC2915), while the background for the LW3 images varies from 1.45 (UGC711) to 0.75 (UGC12426) to 0.35 (NGC2915). This range is as expected, considering that the ecliptic latitudes of these three galaxies range from $5^\circ \rightarrow 10^\circ \rightarrow 72^\circ$. Further details are presented in table 2. Zodiacal light dominates the background level of these images, but correspondingly then allows an independent check on the ISO flux calibration. To achieve this, we use the DIRBE dataset as a resource for measurements of zodiacal dust. We show in table 2 the value of zodiacal emission averaged over all DIRBE data at that latitude, for a solar elongation of $90^\circ$. The true solar elongations for the observations differ by up to $25^\circ$ from this value, but the functional dependence on angle is small near $\epsilon = 90^\circ$. The values are in agreement, providing an independent check on the flux calibrations adopted here.

(ii) The target galaxies are readily visible in these infrared images. The peak pixels are generally 2-3 $\sigma$ above the background noise. The LW3 image of UGC12426 (figure 3.3) is fairly weak, and shows up only faintly, as a $\sim 1.5\sigma$ perturbation.

(iii) The target image for UGC711 (figure 3.3) in the LW2 band has a bright star (V magnitude 9.3) near the bottom right of the field. In our analysis this part of the image is excised with generous margins (cf figure 3).

(iv) Prior to further analysis, all detected sources were excised from the images. Source removal is complete for all sources detected with integrated flux in excess of 100$\mu$Jy. These sources are discussed in a companion paper (F Ferguson, Gilmore & Unavane 1998).

(v) The data reduction still leaves considerably more noise than the limit set by photon statistics. The patchiness of the background, as well as numerous ‘holes’, or regions of locally correlated noise, are evident. In this experiment our photometric procedure involves the integration of flux in large regions of the images, to maximise sensitivity, so that we are not sensitive to any specific local feature in the background. Given the present state of the flat field calibrations however, we are not yet able to reach the potential sensitivity limit contained in the data. Future re-analyses of these data with improved flat-field calibrations will be valuable, hopefully allowing even tighter limits on brown dwarfs to be drawn.
4 MODELLING PROJECTED GALACTIC ROTATION CURVES AND MASS PROFILES

We require a simple parameterisation of the rotation curves of our target galaxies. Since this is required only to convert our flux limits into mass-to-light ratios, and as we see below, no halo flux was detected, simple spherical models are the most convenient and appropriate.

For present purposes, a galactic rotation curve can be considered to rise from zero at the centre, reaching a constant, at value \( V_\infty \), at large radii, \( R \), exterior to the luminous galaxy. The simplest convenient functional form for a spherical mass halo then has density proportional to \( R^{-2} \) at large radii. An appropriate simple two-parameter mass model which works well is given by:

\[
\rho(R) = \frac{\rho_0}{1 + (R/R_C)^2}
\]

where \( R \) is the spherical coordinate, \( \rho_0 \) the central density, and \( R_C \) denotes a characteristic scale, the ‘core radius’. The corresponding velocity profile in the plane for such a density distribution is given by

\[
v^2 = 4\pi G \rho_0 R_C^2 \left( 1 - \frac{R_C}{R} \tan^{-1} \frac{R}{R_C} \right)
\]

from which \( V_\infty = 4\pi G \rho_0 R_C^2 \). We can therefore parameterise any given actual galactic rotation curve \( V(R) \) by two parameters \( R_C \) and \( \rho_0 \). We emphasise that these are simply parameters, and are not intended, or required, to have any physical significance.

This procedure of course ignores the contribution of the identified baryons in the galaxy to the rotation curve, and so over-estimates the (dark) halo mass. However, for the galaxies here, and at the distances from the centres of relevance here, this effect is unimportant. For NGC2915 for example, the galaxy for which we derive the tightest conclusions on the nature of the dark halo, the rotation curve analysis of Meurer et al (1996) shows the galaxy to be completely dark-matter dominated, with identified baryons contributing only a few percent of the rotation curve amplitude in its very outer parts. We have additionally been conservative in fitting the rotation curves, all of which are still rising at the last measured data point.

4.1 Projected halo mass density

The spherical density distribution adopted above, when viewed from a distance \( d \) sufficiently far away (\( d \gg R_C \)), will be seen to have projected surface density, as a function of the projected distance, \( r \), from the centre of the mass distribution, given by:

\[
\sigma(r) = \int_{-\infty}^{\infty} \rho(\sqrt{x^2 + r^2})dx
\]

For the functional form adopted here, this becomes

\[
\sigma(r) = \frac{\pi \rho_0 R_C^2}{(r^2 + R_C^2)^{\frac{3}{2}}}
\]

Converting to angular measure \( \theta \), which represents the distance from the centre of mass, we have
FIGURE 7: Rotation curves for the four galaxies observed by ISO. Superposed are minimised $\chi^2$ models fitted for the two parameters $R_C$ and $\rho_0$ as defined in equation 5. The scatter in the data for UGC711 are such that its parameters are clearly uncertain.

$$\sigma(\theta) = \frac{\pi \rho_0 R_C^2 d^2}{(d^2 \theta^2 + R_C^2)^{\frac{3}{2}}}$$

where $d$ is the distance to the galaxy, $\theta \ll 1$, and $\sigma$ is measured in $M_\odot \text{sr}^{-1}$. It is this function which must be fit to our observations, given $R_C$ and $\rho_0$ for each galaxy.

4.2 Rotation curves

Rotation curves for the galaxies here are available from the literature for UGC711 (an optical rotation curve from Karachentsev, 1991), and for NGC2915 (HI rotation curve from Meurer et al. 1996). For the two remaining galaxies, UGC12426 and UGC1459, we have obtained new optical rotation curves, in collaboration with J. Lewis. These rotation curves, together with the fits to the two parameters, $R_C$ and $\rho_0$, are presented in figure 4.2.

5 ANALYSIS OF THE ISO IMAGES

The methodology involved in defining the flux, or an upper limit on the flux, associated with the galaxy dark halos, is well defined. By construction, if ‘dark’ matter halos generate the rotation curves observed for these galaxies, then the spatial distribution of any luminosity associated with that dark matter is known. While a variety of halo models can readily be attempted, the firm null results we obtain, together with the complexities in determining the true statistical distribution function of errors in the data, suggest the simplest and most robust approach. The simplest useful experiment is to proceed exactly as is standard for determination of luminous profiles of galaxies, and directly to sum the flux in annuli centred at the centre of the luminous matter distribution.

It is necessary for this experiment to excise bright regions of the surrounding field (e.g. stars, other galaxies) prior to testing for the presence of any remaining extended signal. We have thus excised areas around all sources detectable as such in the images. We then integrate the flux in annuli.

The statistical uncertainty associated with this flux counting exercise is itself very uncertain. The systematic locally-correlated photometric flat-field uncertainties in the reduction remain poorly-defined, and cannot be expected to follow Gaussian distributions to very high precision. We are however able to derive an empirical calibration of this uncertainty using our adjacent, but offset, background fields.

We proceed to quantify both the sky background level, and the associated uncertainty, by defining sets of annuli in the offset field, exactly as in the target field. We measure the background flux level, as a function of radius, in these annuli. Multiple randomly located sets of annuli yield a mean and standard deviation associated with each of the annular sizes in the control field. The data for annuli centred on the target in the target field are then assigned uncertainties equal to the standard
deviations derived in the control field. Since the distribution function is not exactly gaussian, the probability associated with a given ‘standard deviation’ will not be exactly that appropriate to a gaussian. Nonetheless, the error distributions measured on the scales of relevance are close to gaussian, as can be seen in figures [5.1] and [5.1] below. We also adopt very conservative confidence limits. In view of the (null) results below, and the rather short timescale on which ISO data reduction and calibration is evolving, more complex analyses are unjustified. Finally, the photometric measurements, with associated error bars, are tested against a dark halo model by the minimisation of $\chi^2$ in a two-parameter model.

Shown in figure [4] are the galaxy images, with the regions excised indicated, and some example annuli.

5.1 Quantifying flux limits from the dark halos

We analysed above the galaxy rotation curves, to determine the two convenient parameters $\rho_0$ and $R_c$ describing the rotation curve, and hence the dark halo density. We additionally have the redshift distance $d$ for each galaxy. We noted above that the projected luminosity distribution expected from a simple halo model should follow

$$\sigma(\theta) = \frac{\pi \rho_0 R_c^2 d^2}{(d^2 \theta^2 + R_c^2)^{3/2}}$$

where $\rho_0$ can be taken to be an observed luminosity density without loss of generality. Before fitting this functional form to our data, however, we must consider one more practicality.

The offset between the background of the control field and of the target field need not be perfectly zero due to gradients in zodiacal light and galactic emission, and any uncorrected drifts in system sensitivity. Any such offset is unimportant, since it corresponds to a flat zero point offset, and not a gradient centred on the target galaxy. Additionally, most offset fields overlap the galaxy field, providing further independent checks that we are not ignoring dark halos with very flat central luminosity profiles. The standard procedure in IR photometry is to subtract (‘beamswitch’) the offset field from the target field, providing a notionally zero background dataset. However, it is more reliable to fit the relevant background value directly, for each field. Thus, we require an additional parameter, $\sigma_0$, to handle this zero point. That is, we fit a model of the form

$$\sigma(\theta) = \sigma_0 + \frac{\alpha}{(\theta^2 + \theta_0^2)^{3/2}}$$

where $\theta$ is given in arcseconds, and $\theta_0$ is the angular equivalent of the ‘core radius’ $R_C$ (i.e. $\theta_0 = R_C/d$). The essential astrophysics is now quantified in the parameter $\alpha$, which is the normalisation of any luminosity associated with a dark matter-like density profile.

The fits of this model to the data are presented in figures [5.1] and [5.1], while the derived parameters and their uncertainties are presented in table [4]. The zero point flux levels are those presented in table [2] above, where they are seen to be in agreement.
with DIRBE data. Reassuringly, the best fit model parameters, in the minimised $\chi^2$ sense, are given for four out of the seven galaxies by (statistically insignificant) unphysical negative values, and the other half of the time by (statistically insignificant) positive values, in agreement with the expectation for a zero-signal data set and approximately gaussian errors.

A straightforward conversion may be made from a numerical value for the parameter $\alpha$ in equation 7 to the parameter $\rho_0$, which has units of $\text{W Hz}^{-1} \text{pc}^{-3}$ by comparison with equation 3. Note however that this value of ‘central luminosity density’, $\rho_0$, is merely another convenient parameter which will allow us to interpret our limits on ISO emission, quantified through $\alpha$, in terms of real astrophysical sources of radiation. $\rho_0$ represents the extrapolation of a specific model representing the outer parts of the rotation curves of these galaxies, with deliberately no serious consideration of more realistic models of the density law of dark matter inside the optical confines of a galaxy (e.g. Hernandez & Gilmore 1998). $\rho_0$ is not intended to define a physical, observable, central luminosity density, but to quantify the luminosity density associated with the outer rotation curve in convenient units.

The eventual 95 percent confidence upper limits on the parameter $\rho_0$ are presented in the final two columns of table 3. They represent the ISO upper limits on flux from the dark matter which generates the rotation curves in these four galaxies. We now proceed to their interpretation.

6 INTERPRETATION

We now calculate the expected fluxes which would have been measured by ISO, for the range of models of the dark matter for which we are sensitive.

| Galaxy   | $\alpha \pm \Delta\alpha$ ($\mu$Jy arcsec$^{-2}$) | $\rho_0 \pm \Delta\rho_0$ ($10^9 \text{W Hz}^{-1} \text{pc}^{-3}$) | $\rho_0$ (upper) |
|----------|-----------------------------------------------|-------------------------------------------------|-----------------|
|          | $\text{LW2}$ | $\text{LW3}$ | $\text{LW2}$ | $\text{LW3}$ | $\text{LW2}$ | $\text{LW3}$ |
| UGC711   | $-1.0 \pm 8.8$ | $+6.7 \pm 13.3$ | $-0.2 \pm 1.9$ | $+1.5 \pm 2.9$ | $1.74$ | $4.25$ |
| NGC2915  | $+2.5 \pm 10.2$ | $-1.1 \pm 16.6$ | $+0.17 \pm 0.70$ | $-0.1 \pm 1.1$ | $0.88$ | $1.05$ |
| UGC12426 | $+4.3 \pm 7.4$ | $-5.3 \pm 13.8$ | $+0.37 \pm 0.64$ | $-0.5 \pm 1.2$ | $1.03$ | $0.78$ |
| UGC1459  | — | $-13.6 \pm 19.6$ | — | $-1.6 \pm 2.2$ | — | $0.64$ |
6.1 Flux from objects – delta-function masses

We consider initially objects whose masses are distributed as a delta function. Consider objects of mass $m$, with a luminosity given, as a function of frequency, $\nu$, by $L(\nu)$, where $\int_\nu L(\nu)d\nu = L_{\text{tot}}$. If a halo described by the functional form of equation 5 is composed entirely of such objects, the flux per unit frequency reaching the observer is given by

$$\frac{\sigma(\theta)L(\nu)}{4\pi d^2m}$$

(8)

For observations through a photometric filter, where the function $F(\nu)$ quantifies the response as a function of frequency, the observed flux per unit solid angle per frequency interval received at the satellite is given by:

$$\frac{\rho_0 R_e^2}{4m(d^2\theta^2 + R_e^2) \frac{1}{2} \int_\nu F(\nu)L(\nu)d\nu} \int_\nu F(\nu)d\nu$$

(9)

As an example, if the source spectrum is a black body spectrum, then for objects of effective temperature $T_e$ and total luminosity $L_{\text{tot}}$, the function $L(\nu)$ is given by:

$$L(\nu) = 15L_{\text{tot}} \left( \frac{h}{\pi kT_e} \right)^4 \frac{\nu^3}{e^{h\nu/kT_e} - 1}$$

(10)

6.2 Flux from objects – mass functions

If instead the objects are taken to be distributed with a mass function $n(\log m)$, which represents the relative number of sources in the range $\log m \to \log m + d(\log m)$, with lower and upper limits given by $m_1$ and $m_2$, then the normalisation is given by $\int_{m_1}^{m_2} n(\log m)d(\log m)$ Similarly, for a mass function $n(m)$, where $n(m)$ represents the number of stars per unit mass interval per unit volume, the spectrum of a population of this sort is given by the weighted sum of the appropriate library of individual spectra, $f_m(\nu)$.

$$f_{\text{tot}}(\nu) = \int_m n(m)f_m(\nu)dm$$

(11)

6.2.1 Low mass main sequence stars

We have calculated the expected flux assuming all the dark halo mass is in normal main-sequence stars with delta-function mass functions of mass $1.0M_\odot$, $0.5M_\odot$, $0.25M_\odot$, and $0.08M_\odot$. More plausible models will include a mass function. From the delta function calculations, it is clear that only very low mass stars are viable options. Mass functions which rise systematically towards low masses are clearly excluded. In the interests of conservatism, we adopt a mass function which has a maximum near $0.25M_\odot$, and which allows for a rise again near the hydrogen-burning limit, at $0.08M_\odot$. For these purposes, we adopt the observationally-derived local mass function derived by Kirkpatrick et al. (1994).

In each case we adopt a black-body spectrum. We do this following the spectra of Cohen et al (1995). These authors collect high-quality IR spectra of several standard (giant – though the differences from dwarfs at these wavelengths are not important)
Table 4. The Kirkpatrick et al. (1994) mass function for local low mass stars. $\xi$ is given in stars per unit mass interval per cubic parsec. Two sets of luminosities and temperatures are given. The first set represents metal-rich calibrations. The final columns give the luminosity and effective temperature scale for very metal-poor stars, interpolated from Baraffe et al (1997:BCAH).

| Solar Neighbourhood | Metal-Rich | Metal-Poor |
|---------------------|------------|------------|
| Mass                | $\xi$ (stars $M^{-1}pc^{-3}$) | log $(L_{bol}/L_\odot)$ | $T_e$ log $(L_{bol}/L_\odot)$ | $T_e$ (BCAH) |
| 0.4875              | 0.029      | -1.15      | 4070 | -1.10 | 4580 |
| 0.4375              | 0.044      | -1.30      | 3740 | -1.22 | 4420 |
| 0.3875              | 0.029      | -1.50      | 3440 | -1.46 | 4290 |
| 0.3375              | 0.087      | -1.65      | 3190 | -1.56 | 4350 |
| 0.2875              | 0.115      | -1.85      | 3000 | -1.71 | 4150 |
| 0.2375              | 0.245      | -2.10      | 2860 | -1.90 | 4230 |
| 0.1875              | 0.219      | -2.35      | 2770 | -2.08 | 4060 |
| 0.1375              | 0.058      | -2.60      | 2710 | -2.40 | 3800 |
| 0.0875              | 0.129      | -2.95      | 2680 | -3.2  | 3000 |

stars, later used as calibrators for ISO. It is clear from these spectra that the LW3 filter region is an excellent approximation to a black-body (ie, flat in $\lambda^4 F_\lambda$), irrespective of stellar temperature, in all stars which lack a (thermal dust) intrinsic IR excess. In the region of the LW2 filter, water and CO absorption becomes significant in the coolest stars. Nonetheless, this implies a flux loss of only a few percent in the coolest and most metal-rich stars. Metal-poor stars, such as might plausibly make up any baryonic dark matter, should be even better approximations to Rayleigh-Jeans spectra. The adopted mass function is shown in table 4.

Table 4 also lists representative luminosities and effective temperatures, based on a solar neighbourhood calibration. That is, assuming the low mass stars associated with the dark matter are metal-rich. This provides one limit on a reasonable mass – luminosity relation, and is the basis for models M1 to M5 below.

A halo population of exclusively low-mass stars contributing to dark matter might be supposed to be systematically metal-poor. The effective temperature scale is dependant on metallicity, in a manner which is not well calibrated. The general effect is to associate systematically higher temperatures with a given mass than those listed in table 4. Since ISO is sensitive to cool stars, this reduces our sensitivity for this experiment. A conservative calculation of the amplitude of this effect is possible by adoption of the isochrones for stars with $[M/H]=-2$ (approximately $[Fe/H]=-2.35$) and age 10Gyr from Baraffe, Chabrier, Allard & Hauschildt (1997). These isochrones lie systematically hotter than the observations of metal-poor globular cluster and field subdwarf stars at low masses (figures 5, 6, and 8 of Baraffe et al), and so provide an upper limit. These values are also listed in table 4.

The range of calibrations available corresponds to a systematic change in the expected flux in the LW2 band by a factor of about three at a mass of 0.1$M_\odot$, rising to a reduction by a factor of about 10 at a mass of 0.25$M_\odot$, with metal-poor stars being systematically hotter, and hence less luminous for ISO, relative to metal-rich stars. Since the sources are now quite warm, LW3 sensitivity is reduced below useful limits for the hottest mass-temperature calibration at the lowest masses. The conclusions from the LW2 limits are however not strongly dependant on the calibration adopted. The adopted black-body flux approximation should be more accurate for the more metal-poor sources.

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6.2.2 Cool White Dwarfs

Some remarks concerning cool white dwarfs as major contributors to dark halos are noted in the introduction. Chabrier (1997) presents a recent summary of theoretical work on cooling theory. Masses for WDs vary (comparatively) little (from about 0.1M⊙ to 1.4M⊙). For a typical WD of mass (0.6M⊙), at ages of 10 Gyr, we expect the bolometric luminosity to be \( \log(L/L⊙) = -5.0 \), and \( T_{\text{eff}} = 2900 \text{K} \). That is, old white dwarfs have a bolometric mass to light ratio which a factor of approximately 100 higher than that of stars of similar temperature, near the hydrogen burning limit. Correspondingly, they are hard to see.

Given the high gravity, and (probable) low metallicity, the spectra should be adequately approximated by a black-body. As indicated in figure 2.1, objects of this temperature are too warm to allow sensitive direct detections with ISO. We quantify this in model W1 below, which is the power per unit mass in the ISO filters for a \( \delta \)-function mass distribution of white dwarfs, all of mass 0.6M⊙ and age 10Gyr.

6.2.3 Brown Dwarfs

Brown dwarfs are those objects of mass below the minimum mass for hydrogen burning. Considerable progress has been made recently in understanding their properties. Extensive numerical work by Stevenson (1986) led to a set of scaling relations for the luminosity and effective temperature of brown dwarfs of given mass \( m \) and age \( t \) (for an assumed opacity of \( \kappa = 0.01 \)), viz:

\[
L = 1.5 \times 10^{-5} \left( \frac{m}{0.08M⊙} \right)^{1.5} \left( \frac{t}{5\text{Gyr}} \right)^{-1.25} L⊙, \quad T_e = 1420 \left( \frac{m}{0.08M⊙} \right)^{0.79} \left( \frac{t}{5\text{Gyr}} \right)^{-0.31} \text{K} \quad (12)
\]

Analogously to the discussion of low mass hydrogen-burning stars above, we assume that these black-body models are one limiting case, being most appropriate for very metal-poor brown dwarfs.

At higher metallicities, more recent theoretical work on brown dwarf spectra has provided a more detailed view of what the mid-IR spectra of brown dwarfs may look like. Burrows et al. (1998) use detailed opacity models to define a brown dwarf flux model for objects of solar metallicity. They find that, in the wavelength range 6-20 μm, the flux may be diminished by up to a factor of 20 compared to the blackbody value. On the other hand, Baraffe & Allard (1997) provide a set of models covering the ISO filter passbands (their figure 3), and predict deviations from a black-body spectrum which is a strong function of temperature for metal-rich models. For brown dwarfs of 2000K, near the hydrogen-burning limit, their models suggest that the LW2 passband is fainter than the equivalent black-body by a factor of about two, while even at temperatures as cool as 1000K the LW2 flux loss is only a factor of about 3-4. In both cases the LW3 flux is very close to the black-body calculation.

That is, a simple black-body calculation, using the Stevenson scaling relations, is sufficiently accurate, given our complete \textit{a priori} ignorance of the possible brown dwarf mass function.
Table 5. Power per unit frequency per unit mass for different populations in the ISO LW2 and LW3 bands, for the models described in the text.

| Label | Source                 | Value ($10^9$ W Hz$^{-1}$ M$_{\odot}^{-1}$) | LW2 | LW3 | ratio LW2:LW3 |
|-------|------------------------|-------------------------------------------|-----|-----|---------------|
| M1    | Sun                    | 59.9                                      | 14.0| 4.3 |
| M2    | 0.5M$_{\odot}$ MS star | 22.4                                      | 5.5 | 4.1 |
| M3    | 0.25M$_{\odot}$ MS star| 13.7                                      | 3.6 | 3.8 |
| M4    | 0.08M$_{\odot}$ MS star| 5.9                                       | 1.6 | 3.7 |
| M5    | Mass fn as in table 4  | 15.6                                      | 4.1 | 3.9 |
| B1    | 10 Gyr 0.01M$_{\odot}$ BD| 0.03                                        | 0.4 | 0.07 |
| B2    | 10 Gyr 0.08M$_{\odot}$ BD| 0.2                                        | 0.1 | 2.4 |
| B3    | 5 Gyr 0.01M$_{\odot}$ BD| 0.1                                        | 0.9 | 0.2 |
| B4    | 5 Gyr 0.08M$_{\odot}$ BD| 0.4                                        | 0.1 | 2.8 |
| B5    | 1 Gyr 0.01M$_{\odot}$ BD| 2.7                                        | 4.1 | 0.7 |
| B6    | 1 Gyr 0.08M$_{\odot}$ BD| 0.9                                        | 0.3 | 3.5 |
| F1    | Salpeter 10 Gyr fn     | 0.2                                        | 0.3 | 0.6 |
| F2    | Salpeter 5 Gyr fn      | 0.5                                        | 0.6 | 0.8 |
| F3    | Salpeter 1 Gyr fn      | 2.7                                        | 1.9 | 1.5 |
| F4    | Flat 10 Gyr fn         | 0.3                                        | 0.2 | 1.4 |
| F5    | Flat 5 Gyr fn          | 0.5                                        | 0.3 | 1.8 |
| F6    | Flat 1 Gyr fn          | 1.7                                        | 0.7 | 2.5 |
| W1    | 10 Gyr 0.6M$_{\odot}$ WD| 0.07                                      | 0.02| 3.8 |

We have calculated the power per unit mass appropriate to ISO observations for four sets of models; $\delta$-function brown dwarf mass distributions, at both high and low masses and young and old ages, as well as power-law mass functions for both flat, i.e. equal numbers in equal mass bins, and Salpeter-like (index $\alpha=2.35$) mass functions, at young, intermediate and old ages, integrating over the mass range 0.01M$_{\odot}$ to 0.08M$_{\odot}$.

7 ISO LIMITS ON LOW MASS POPULATIONS IN DARK HALOS

We summarise in table 5 the results of the several models considered. The calculation in each case involved evaluation of

$$\int_{\nu} f(\nu)f_{LW}(\nu)d\nu / \int_{\nu} f_{LW}(\nu)d\nu$$

where $f(\nu)$ represents the spectrum of the emission, as discussed above, and $f_{LW}(\nu)$ the filter response from figure 2.1. The result of the calculation, for each mass model described above, is the resulting power output per unit mass of star through the LW2 and LW3 filters (a light-to-mass ratio). Normalisation for the distance and halo mass density for any galaxy then allows direct comparison with observations.

Several features of the results are immediately noticeable. A 0.08M$_{\odot}$ M-dwarf is two orders of magnitude easier to see, relative to the Sun, in the LW2 filter than in bolometric flux. In the brown dwarf models, more power per solar mass is produced by low mass than by higher mass young brown dwarfs, reflecting the fact that their mass to light ratio changes by less than their mass ratio. The reverse is true for older brown dwarfs. The integrated power per unit solar mass for the various brown dwarf mass functions is almost independent of the adopted mass function. This reflects the result above: for...
FIGURE 11: The emissivities of the various dark matter candidates, in both the LW2 and LW3 filters, are indicated vertically, for the models discussed in the text and presented in table 5. Low mass hydrogen-burning star models are indicated with a solid line, brown dwarf models with a dotted line, and the white dwarf model with a dashed line. The 95% confidence limit upper limits imposed by the observations of each of the four galaxies is shown by a labelled thick solid line.

FIGURE 12: The flux per unit mass of various ages (1, 2.5 and 10 Gyr from top to bottom) of brown dwarfs. The solid lines indicate observations with the LW2 filter and the dotted lines indicate the LW3 filter. The present 95% upper limits from our observations of NGC2915 are indicated.

young brown dwarfs, the emissivity is dominated by the lowest masses, for older brown dwarfs it is dominated by the highest masses. Thus, one has minimal sensitivity to the mass spectrum in the range $0.01M_\odot$ to $0.08M_\odot$. Finally, old white dwarfs are not well suited to direct detection by ISO. They are too hot, and have too small a surface area for their mass, for easy detection.

Given these calculated central luminosity densities per unit mass, together with the parameterised central mass densities per unit volume, representing the rotation curve fits in figure 4.2, it is straightforward to compare the models with our observations. The graphical comparison of these results with the observations is given in figure 7. The solid lines indicate the hydrogen-burning star models (M1–M4), dotted lines represent the brown dwarf models, and the dashed line represents the white dwarf model. The bold lines labelled with the galaxy name represents the results from the ISO observations, with in each case the 95 percent upper limits indicated by the lines labelled with the galaxy name.

Models involving significant contributions to dark halos from hydrogen burning stars with a plausible mass function – model M5 – are clearly excluded in both passbands. Even the extreme model, of a $\delta$-function mass function of stars at the hydrogen burning limit is directly excluded. Similarly, models involving a substantial population of young brown dwarfs, with masses near-to, but below, the hydrogen-burning limit, are also directly excluded.

Interestingly, improvements in sensitivity in the longer-wavelength LW3 data by an order or magnitude – which might be feasible with the present observations, given improved calibrations and data reduction algorithms, Though may well require SIRTF, can directly test any model involving brown dwarfs as a significant contribution to galactic dark halos. We illustrate the present situation below, in figure 7. This shows, with better mass resolution, the emissivity as a function of mass of brown dwarfs of a variety of ages, as they would be observed through the ISO LW2 and LW3 filters.

8 CONCLUSIONS

The sensitivity of these ISO observations allows us to limit the baryonic possibilities for halo dark matter, and to exclude hydrogen-burning stars from consideration. The ISO observations are more sensitive and have significantly better spatial resolution than was previously possible with observations at these wavelengths.

For all four galaxies which ISO has observed, the ‘best fit’ models have zero flux contributed by emission from mass distributed like the mass which supports the rotation curve; that is, no significant deviation from background levels is seen.
FIGURE 13: The solid curve shows the halo fraction upper limit (95% level) as deduced by Alcock et al (1998) by combining the results of MACHO and EROS (their model S, for a spherical halo). They place no severe constraints on more massive objects. Our upper limits (dotted line) limit the importance of low mass stars, leaving only the brown-dwarf mass range ($\sim 10^{-3} - 10^{-1} M_\odot$) as even marginally viable.

By testing for the presence of integrated dark halo-like signal, we drive limits on the maximum amount of signal which might be present and yet not be unambiguously detected.

Observation of two galaxies in particular, NGC2915 and UGC1459 allow us to place useful limits on the dark matter content. From the data for these galaxy, we find that the limit imposed by the observation precludes the halo being composed of low mass hydrogen-burning stars; young brown dwarfs ($\lesssim 1$ Gyr) are also weakly ruled out. Improved calibrations should allow a direct test of the remaining possibility that older brown dwarfs and/or cool white dwarfs may constitute a baryonic compact object contribution to dark halos.

We note that the present data do not provide useful new constraints on an extended cD-like stellar halo around these galaxies. Such a halo, with a spatial distribution tracing that of the dark matter, though itself forming an insignificant part of the halo matter, is a natural expectation in standard hierarchical merging models. Loosely bound dwarf ‘galaxies’ dispersing very early will generate free-floating baryonic matter, which being stellar is non-dissipative, and so will trace the dominant non-dissipative dark matter through all later dynamical processes. Such a process is a natural explanation of the faint extended luminous halo around NGC5907, and should in fact be common. Inspection of our ISO images however, shows that a ‘normal’ IMF provides a too-low surface brightness for ISO to detect. Optical data are more sensitive for that experiment.

It is interesting that observations with ISO nicely complement microlensing studies. Extant microlensing studies already severely constrain the mass distribution of objects present in the dark halo of our galaxy which are of too low mass to be reliably detected here. Alcock et al (1998) show, by combining the results of both the EROS and MACHO experiments, that objects between $10^{-7} M_\odot$ and $10^{-3} M_\odot$ make up less than 25 per cent of the halo dark matter, for a variety of halo models. The solid curve in figure 8 shows the 95 per cent upper limit for model S (spherical halo) of Alcock et al. (1998). The constraint is weak for objects lower in mass than $\sim 10^{-7} M_\odot$, and for objects higher in mass than $\sim 10^{-3} - 10^{-2} M_\odot$. It is at this high end that our results allow us to add further constraints. The limits imposed by the observation of NGC2915 in the LW2 wavelength range provide upper limits as shown by the dotted line in the figure. The remaining mass range, where the combination of current ISO observations and microlensing surveys cannot yet place strong limitations, is narrow: effectively the single decade in mass encompassing the brown dwarf regime is the only mass range not yet directly excluded as a significant contributor to baryonic dark matter.

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