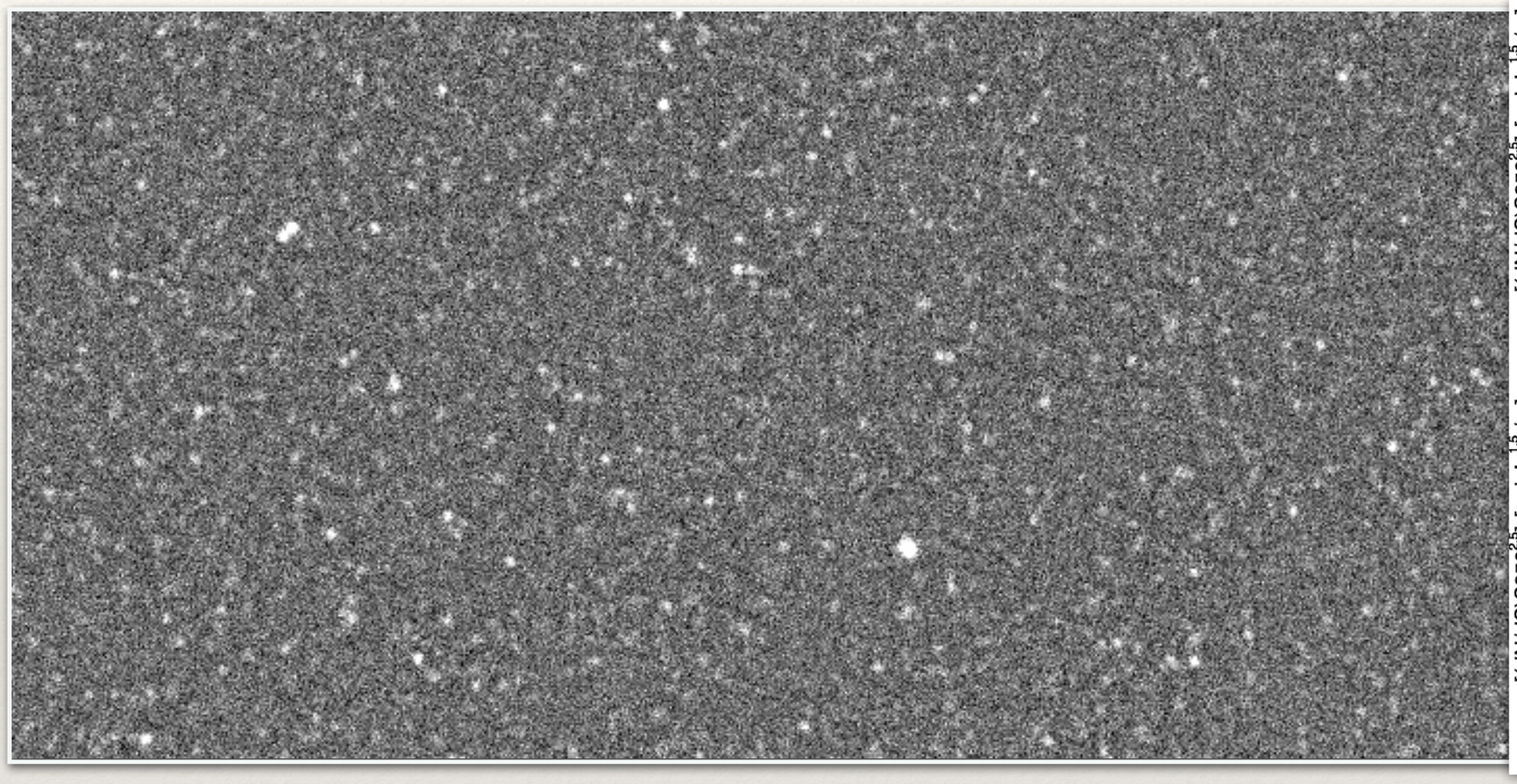
# Identifying SMG counterparts: The effect of sub-mm colour in Herschel-ATLAS

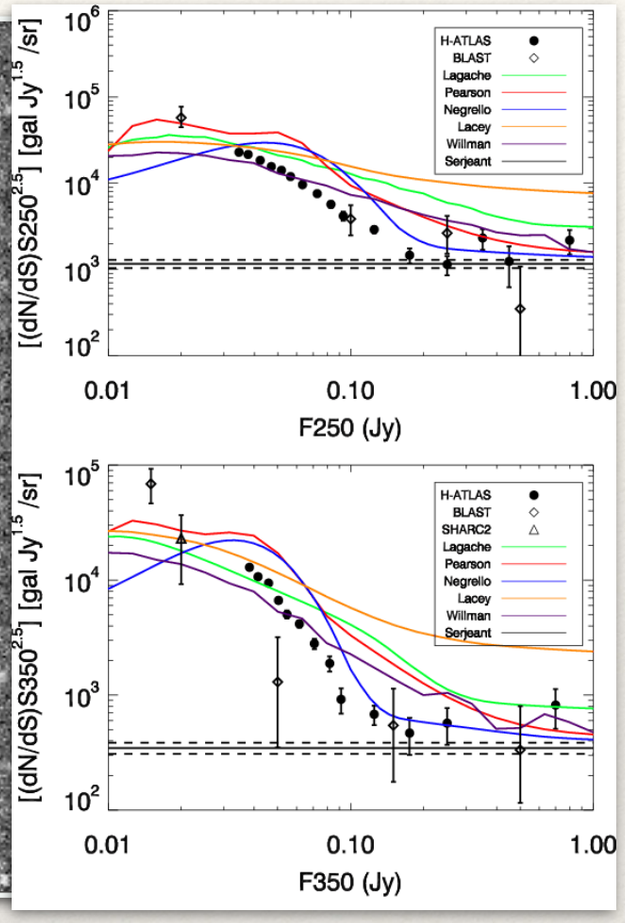
**Nathan Bourne**

—

with Carlos Hoyos, Loretta Dunne, Simon Dye, Steve Eales, Joaquin Gonzalez-Nuevo, Steve Maddox, Dan Smith, Elisabetta Valiante

# SMG IDs: a solved problem?






- A fundamental problem in sub-mm surveys - due to steep source counts and low resolution
  - *P*-statistics
  - Likelihood ratio (LR)

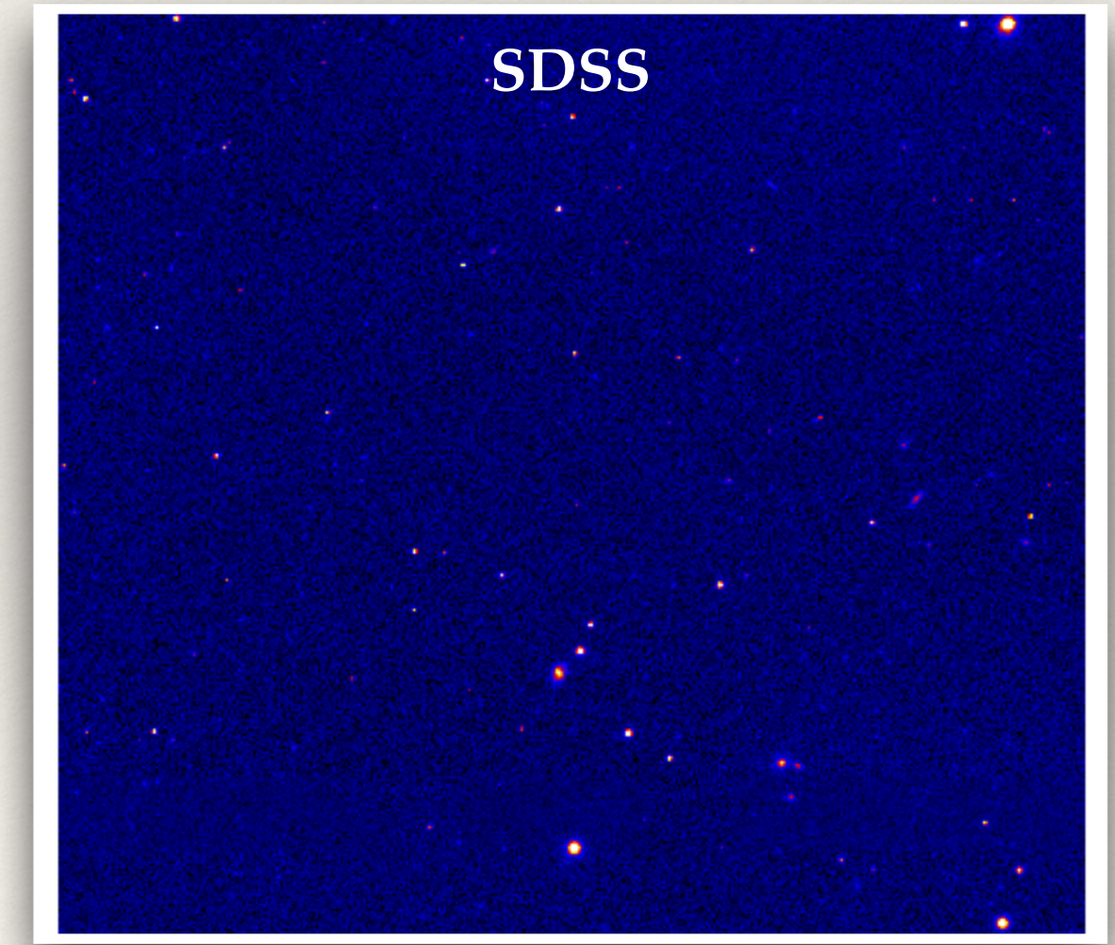
$$p = 1 - \exp(-\mu_r).$$

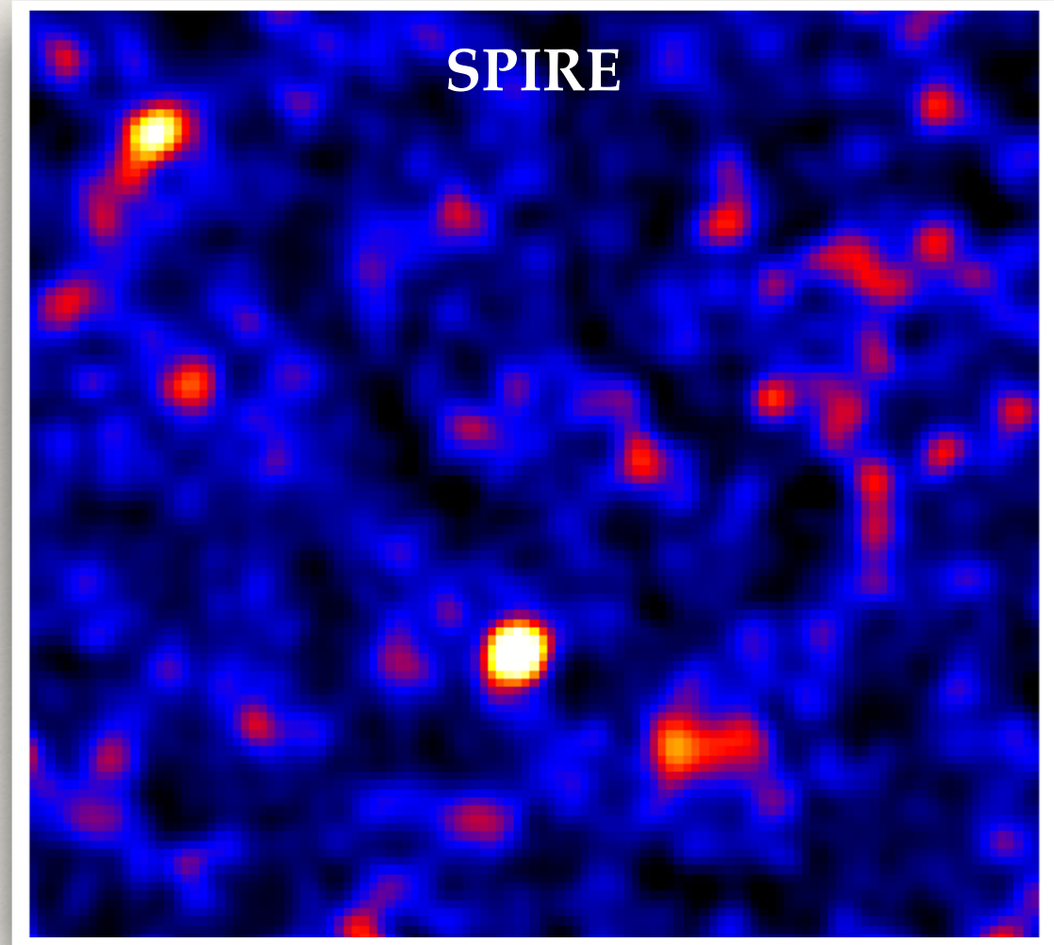
$$L = \frac{P(m, c, x, y, \mathrm{id})}{P(m, c, x, y, \mathrm{chance})} = \frac{q(m, c)\, f(x, y)}{n(m, c)}.$$

e.g. Sutherland & Saunders 92

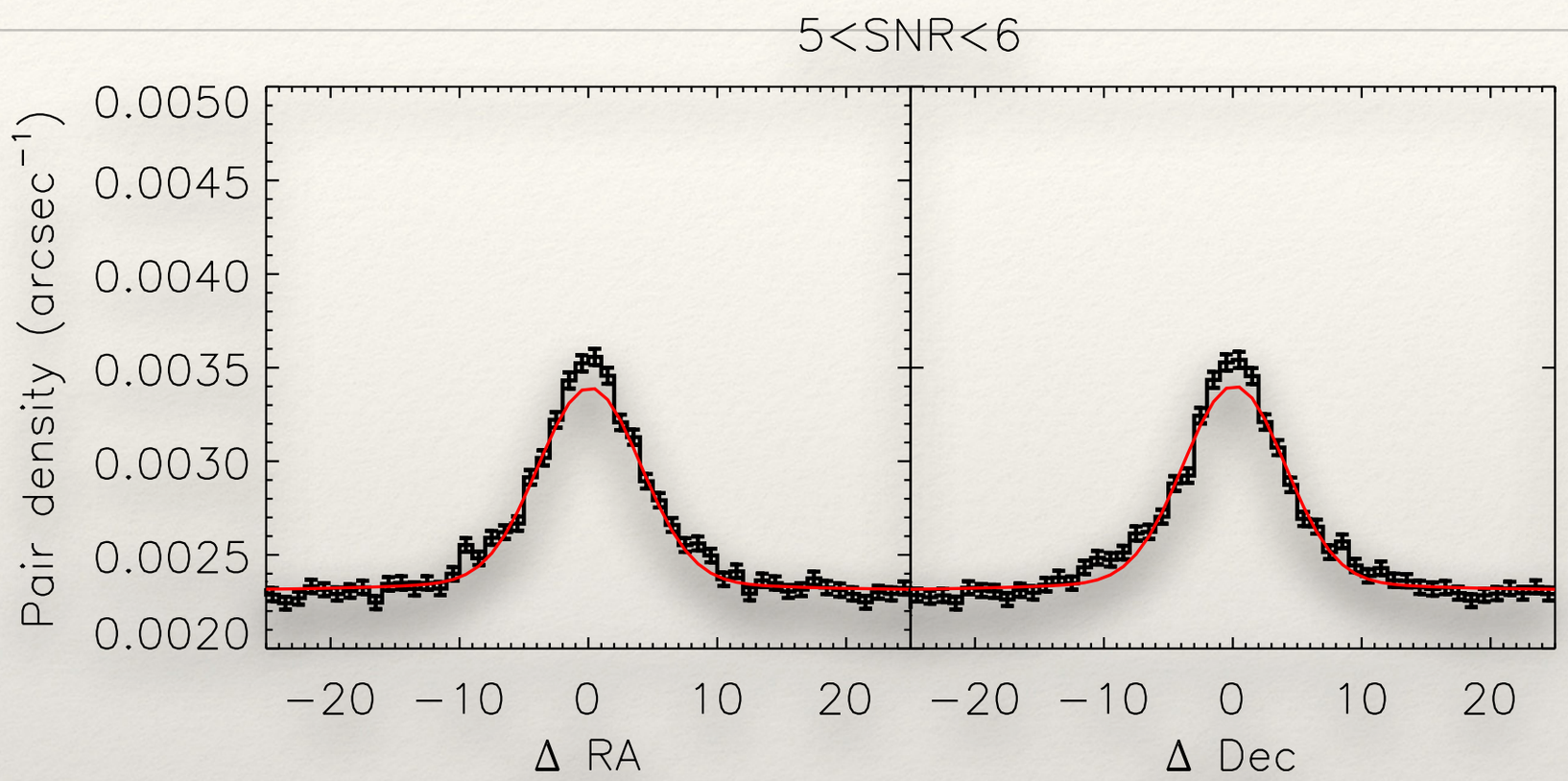
# IDs for Herschel-ATLAS

- ~150 deg$^2$, 5sigma~30 mJy, probing low and high redshifts
- Matching catalogue from SDSS

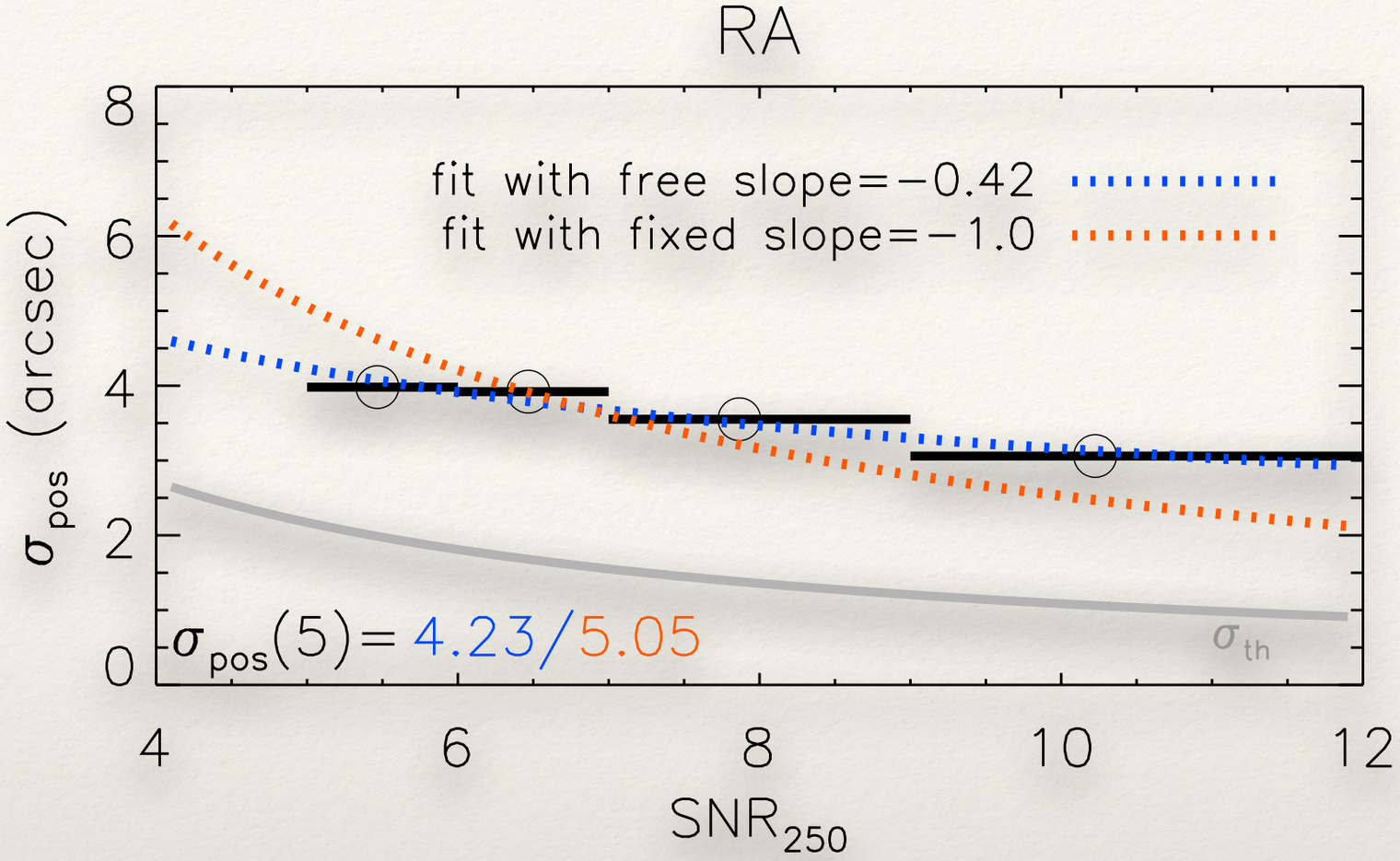


# SPIRE-SDSS positional offsets

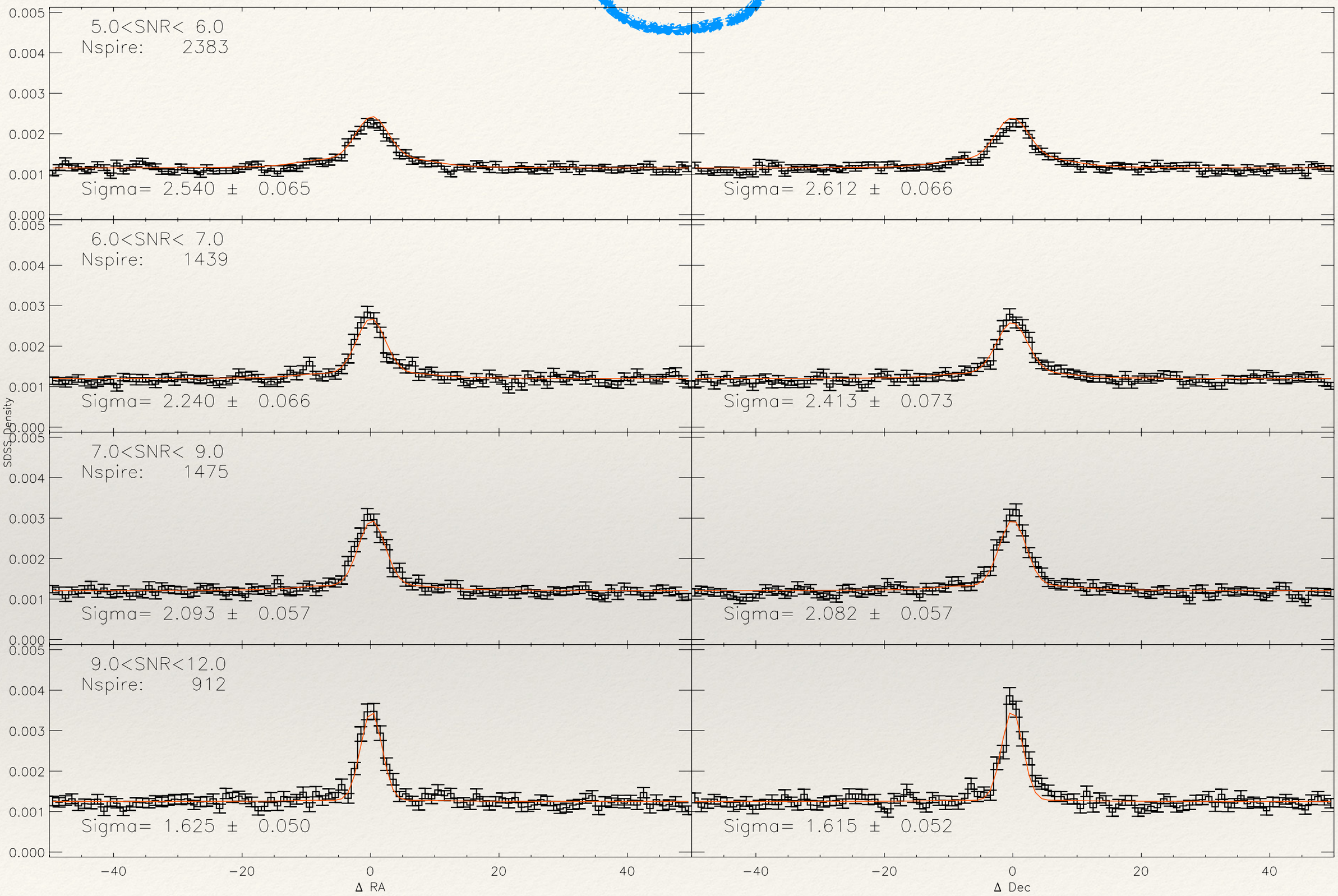



- Offsets to all objects around a SPIRE source:
  - positional errors of true counterparts
  - correlated objects: clustered objects at the same redshift
  - lensing objects in the line of sight

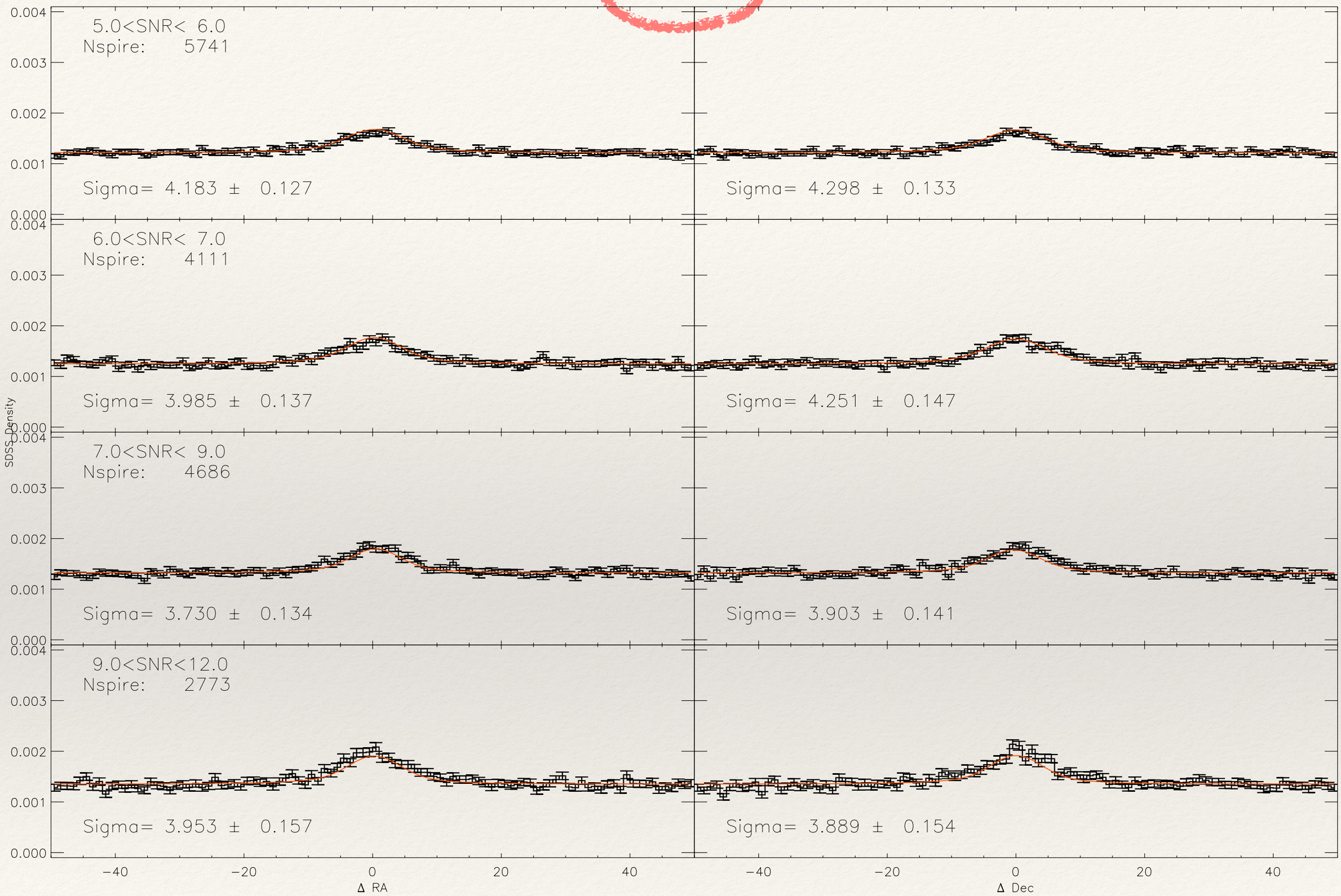


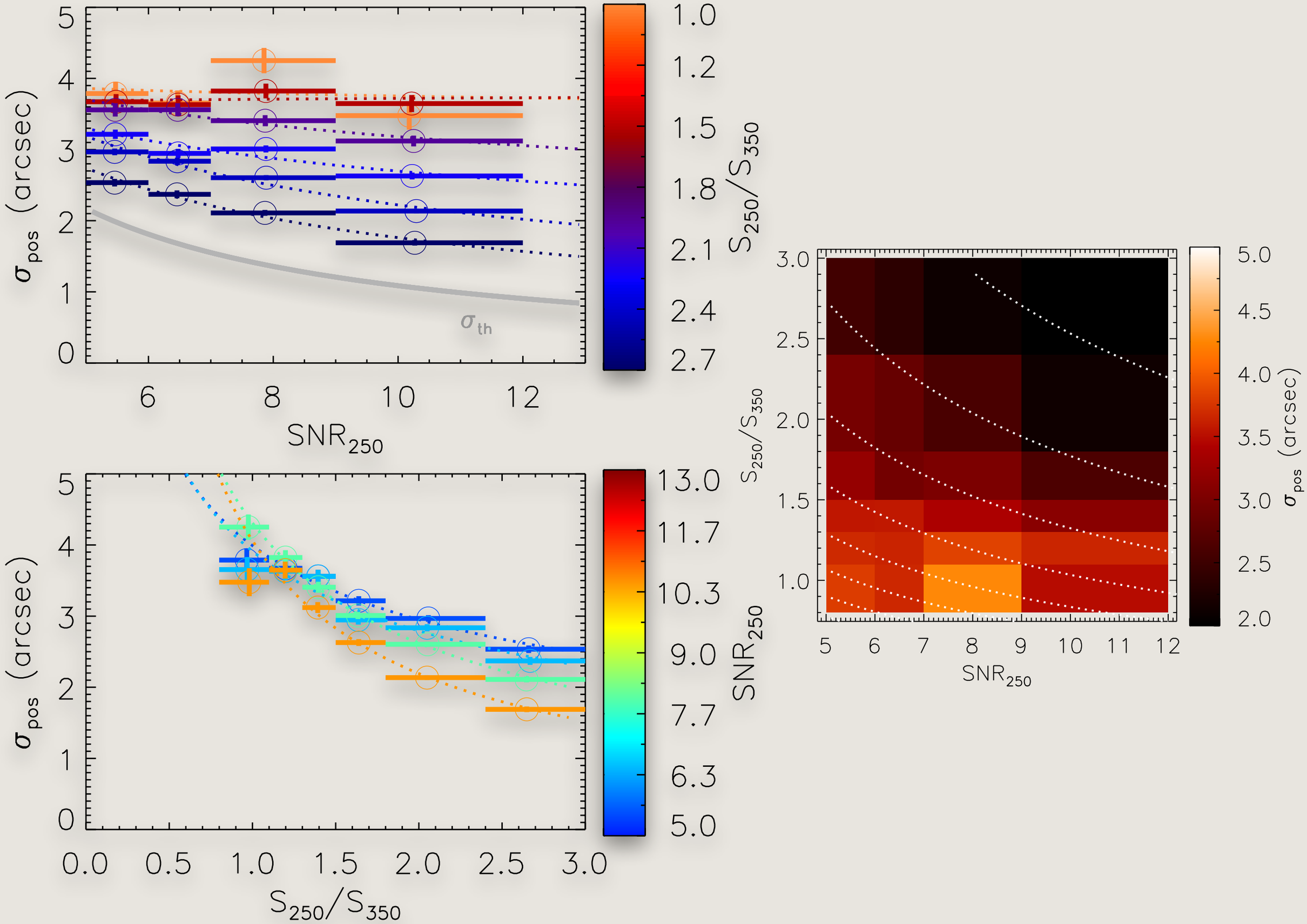

- In theory: $$\sigma_{\rm pos}({\rm SNR}) = 0.6\frac{\rm FWHM}{\rm SNR}$$
- But we see a weaker SNR dependence and apparently much larger positional errors

# Blue (250/350)


5.0<SNR< 6.0
Nspire: 2383
Sigma= 2.540 ± 0.065
Sigma= 2.612 ± 0.066
6.0<SNR< 7.0
Nspire: 1439
Sigma= 2.240 ± 0.066
Sigma= 2.413 ± 0.073
7.0<SNR< 9.0
Nspire: 1475
Sigma= 2.093 ± 0.057
Sigma= 2.082 ± 0.057
9.0<SNR<12.0
Nspire: 912
Sigma= 1.625 ± 0.050
Sigma= 1.615 ± 0.052
SDSS Density
0.005
0.004
0.003
0.002
0.001
0.000
−40
−20
0
20
40
Δ RA
Δ Dec

**Red** (250/350)

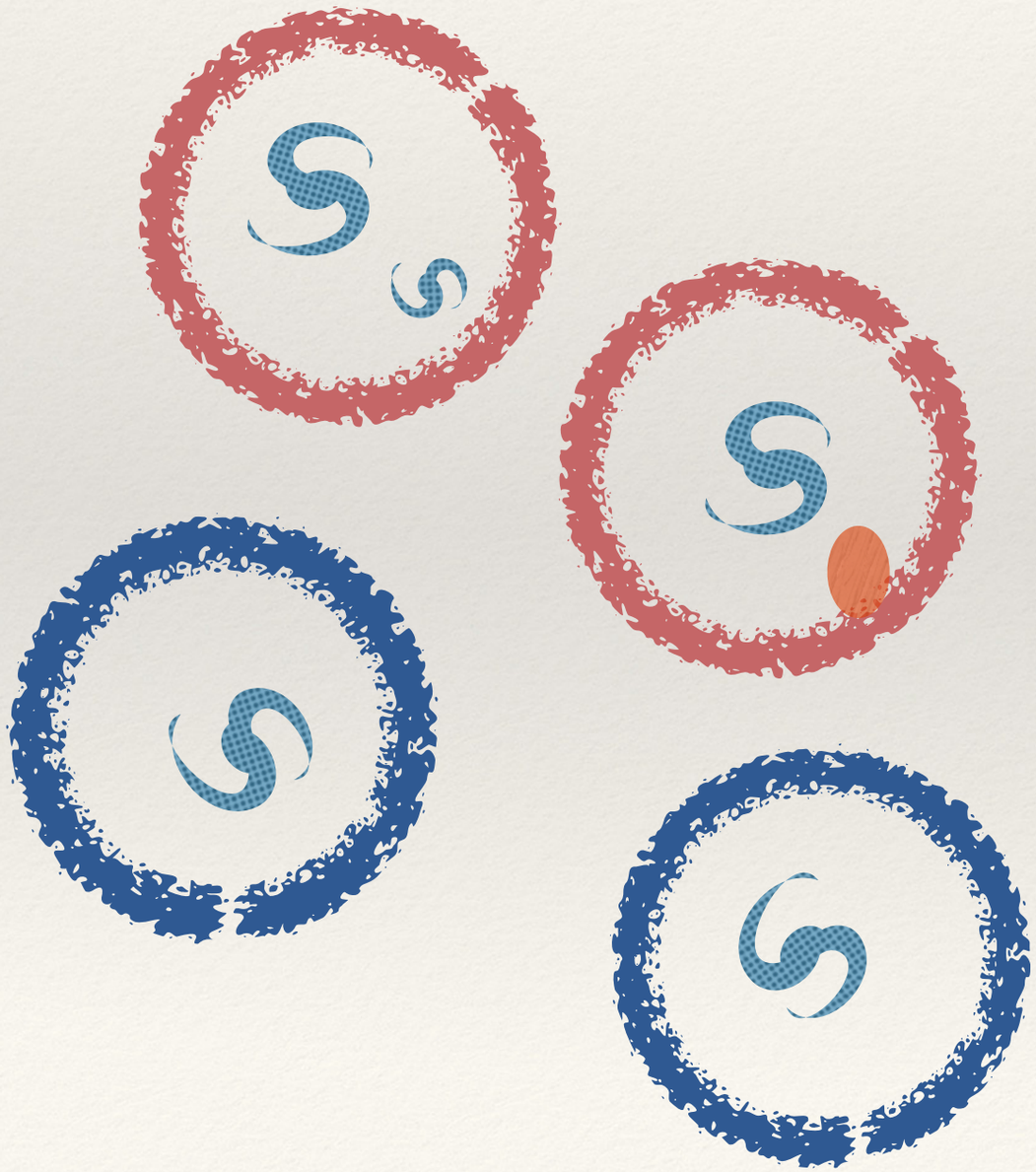

5.0<SNR< 6.0
Nspire: 5741
Sigma= 4.183 ± 0.127
Sigma= 4.298 ± 0.133
6.0<SNR< 7.0
Nspire: 4111
Sigma= 3.985 ± 0.137
Sigma= 4.251 ± 0.147
7.0<SNR< 9.0
Nspire: 4686
Sigma= 3.730 ± 0.134
Sigma= 3.903 ± 0.141
9.0<SNR<12.0
Nspire: 2773
Sigma= 3.953 ± 0.157
Sigma= 3.889 ± 0.154
SDSS_Density
0.000
0.001
0.002
0.003
0.004
−40
−20
0
20
40
Δ RA
Δ Dec


$\sigma_{pos}$ (arcsec)
$\sigma_{th}$
$SNR_{250}$
$S_{250}/S_{350}$
$S_{250}/S_{350}$
$SNR_{250}$
$\sigma_{pos}$ (arcsec)

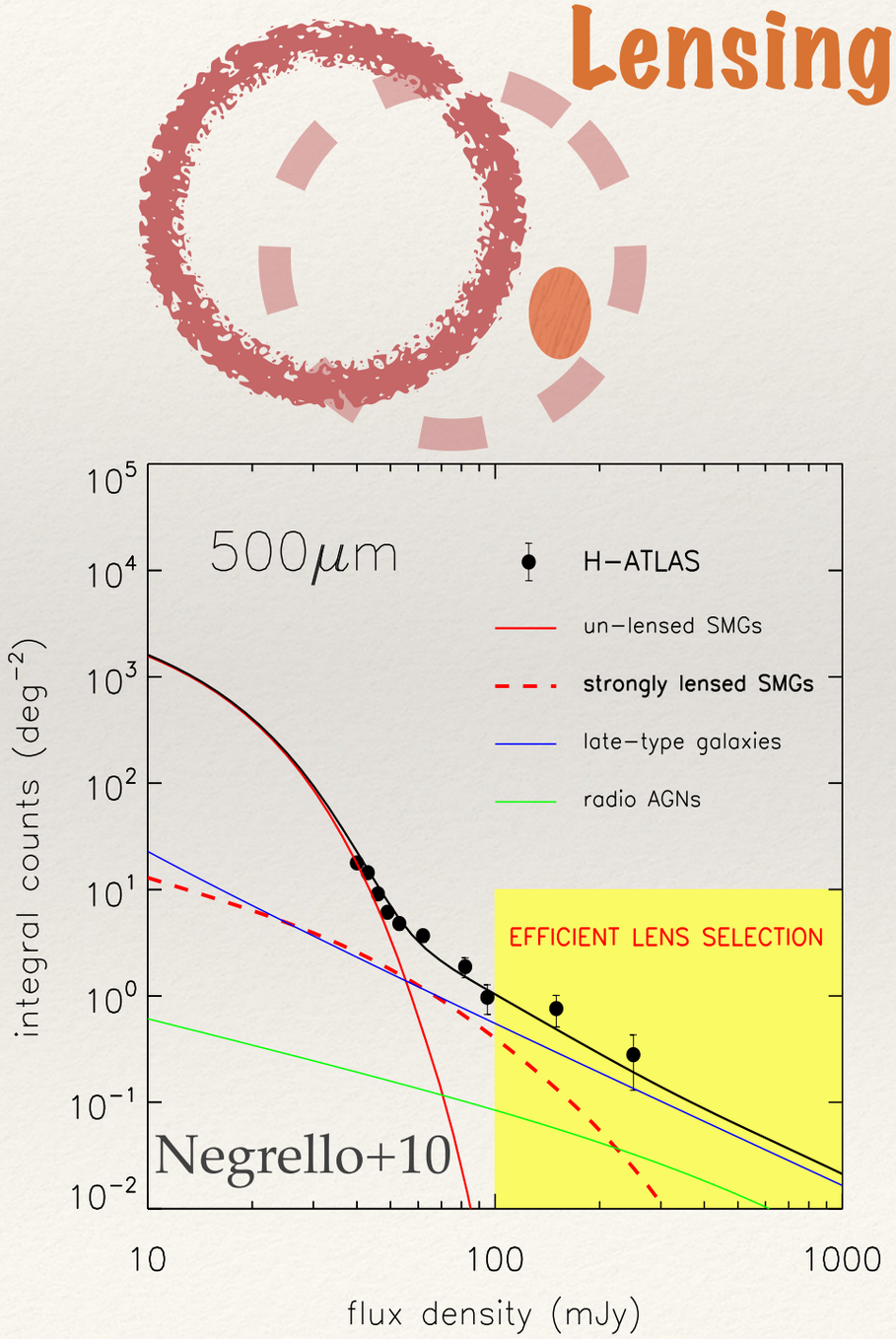
# Brighter, redder SPIRE sources have more SDSS associations at large radii

## Why?

### Clustering



### Lensing



# Brighter, redder SPIRE sources have more SDSS associations at large radii

## Why?

- We know that the brightest red submm galaxies are likely to be lenses
- Could the offsets between the lenses and the submm images be affecting the measured positional errors?

Blue

Faint → Bright

5<SNR<6 | 6<SNR<7 | 7<SNR<9 | 9<SNR<12

Average excess per SPIRE source

1.000
0.100
0.010
0.001

$0.8 < \frac{250}{350} < 1.3$ | $1.3 < \frac{250}{350} < 1.8$ | $1.8 < \frac{250}{350} < 3.0$

0 5 10 15 20

Red

Separation, arcsec

Lens modelling : Gonzalez-Nuevo+ in prep.

# How common is (weak) lensing among SMGs?

- This depends on evolution of the LF at high redshifts
- If strong, then most SMGs are unlensed, but are strongly clustered such that their positional errors are increased
- If it weakens, then lensing is more common, and there is a much greater chance of identifying the lens as the counterpart to a red SMG.

# Summary

- Distributions of positional offsets between sub-mm and optical sources depends on sub-mm signal-to-noise — but not quite as expected
- Also depends on sub-mm colour:
- Redder, brighter sub-mm sources have greater offsets to optical sources than expected (apparently worse positional errors?)
- Could be explained by widespread weak lensing or by correlated optical sources
- Need to explain this otherwise likelihood ratios for SMG counterparts will be inaccurate

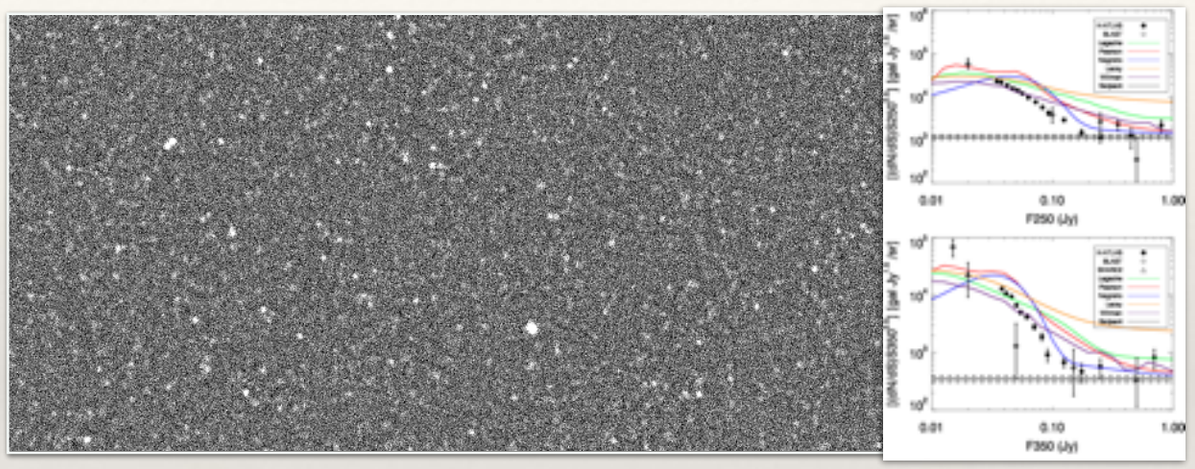
# Identifying SMG counterparts: The effect of sub-mm colour in Herschel-ATLAS

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# SMG IDs: a solved problem?




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$$p = 1 - \exp(-\mu_r).$$

  - Likelihood ratio (LR)

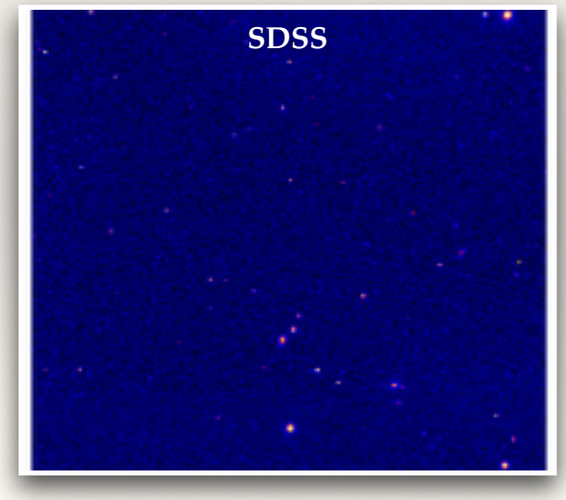
$$L = \frac{P(m, c, x, y, \mathrm{id})}{P(m, c, x, y, \mathrm{chance})} = \frac{q(m, c)\, f(x, y)}{n(m, c)}.$$

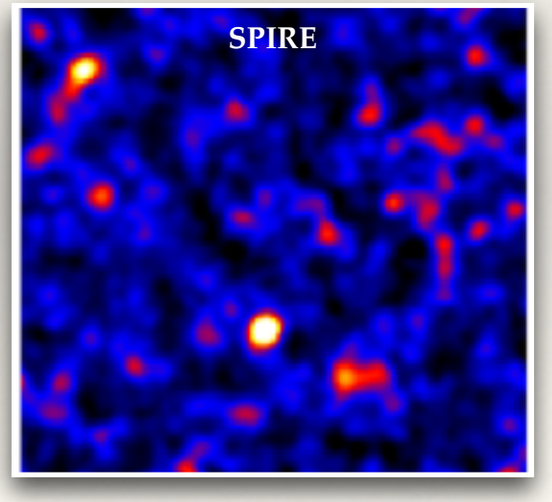
e.g. Sutherland & Saunders 92

Why is this a problem? 1. Steep source counts: many many faint sources on the sky (result of negative k-correction)  2. Poor angular resolution 10-20 arcsec, so that all these sources are blended and confused.
How do we identify the sources of the emission with known objects selected in other wavebands? - optical, 24mum, radio? The objects which are bright in the submm are often not so bright at these wavelengths - differing k-corrections, and dust obscuration.
2 ways to do this: interferometric (sub)mm observations, looking at the same emitting material at high resolution (SMA, ALMA, PdBI…) OR, when you don't have this, use statistical estimates of likelihood.
P-statistics: look for matches within a defined search radius around each source, and calculate the probability of those objects appearing there by chance (mu is expected number of background sources in the search radius)
LR: slightly more sophisticated but requires larger samples to determine the statistics: gives the likelihood that it is a real match relative to the likelihood of a chance alignment. This can also take into account distributions of flux and colour of objects in the matching catalogue as well as positional errors in the sub-mm
But LR does rely on understanding the prior probabilities correctly. Basically it does not allow for the possibility that the matching source is associated in some way with the submm source, without actually being the same object.

# IDs for Herschel-ATLAS

- ~150 deg$^2$, 5sigma~30 mJy, probing low and high redshifts
- Matching catalogue from SDSS

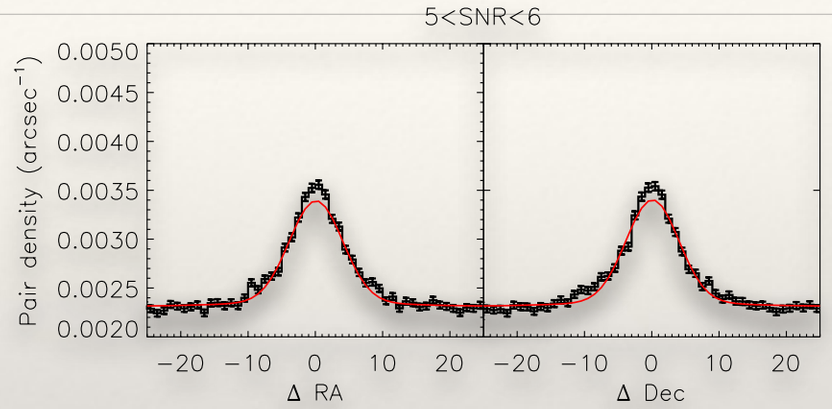



So in H-Atlas we have a large data-set, 10s of thousands of SPIRE 250mum sources, with 100-500mum photometry, and a few million SDSS galaxies in the survey area.
As we know the submm has a very different redshift selection function to most other wavelength regimes, so that sources which are bright in the optical are often faint in the submm, and vice-versa.
So we want to look at the statistics of SDSS counterparts to SPIRE sources, and of the background SDSS population, to calculate those probabilities in the LR for each SDSS source around each SPIRE source.

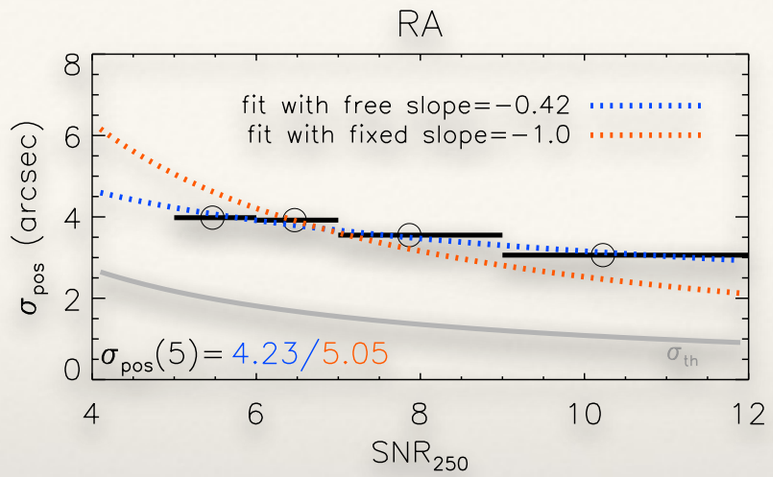
Not going to go into details, but one thing you need to do to understand this is measure the positional accuracy of the SPIRE sources that you extract from the maps.

# SPIRE-SDSS positional offsets




- Offsets to all objects around a SPIRE source:
  - positional errors of true counterparts
  - correlated objects: clustered objects at the same redshift
  - lensing objects in the line of sight

If you count up ALL the nearby SDSS galaxies (not just best matches) as a function of separation from each SPIRE source, as a function of both RA and Dec offset, you expect to see
1 all the actual counterparts which are the same object seen in SDSS, which is offset due the positional error of the SPIRE source
2 anything which is physically clustered with the counterparts, which you can predict from the SPIRE-SDSS cross-correlation
3 additionally anything in the line of sight which has a heightened probability of being associated with the SPIRE source. Eg a lens. But surely lensing is rare, this can't possibly be a large contribution.
4 random background level which is just the surface density of SPIRE sources

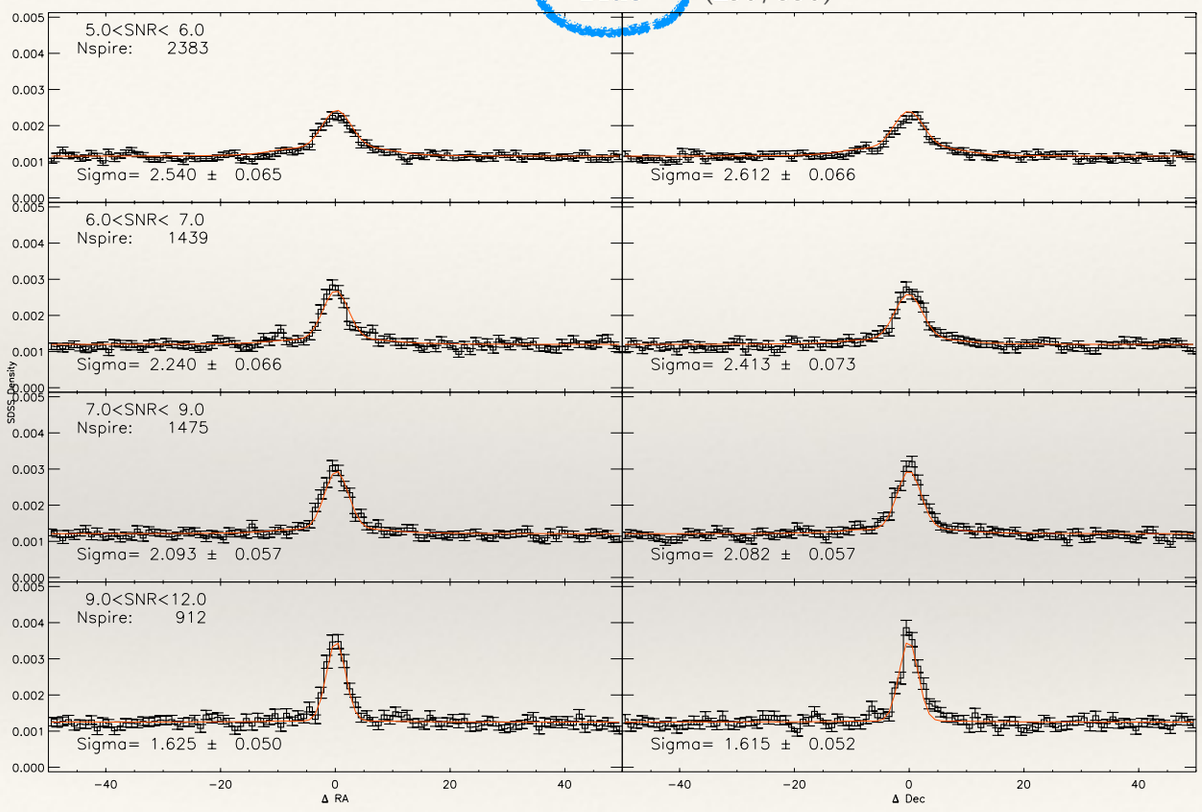



- In theory: $\sigma_{\rm pos}({\rm SNR}) = 0.6\dfrac{\rm FWHM}{\rm SNR}$
- But we see a weaker SNR dependence and apparently much larger positional errors

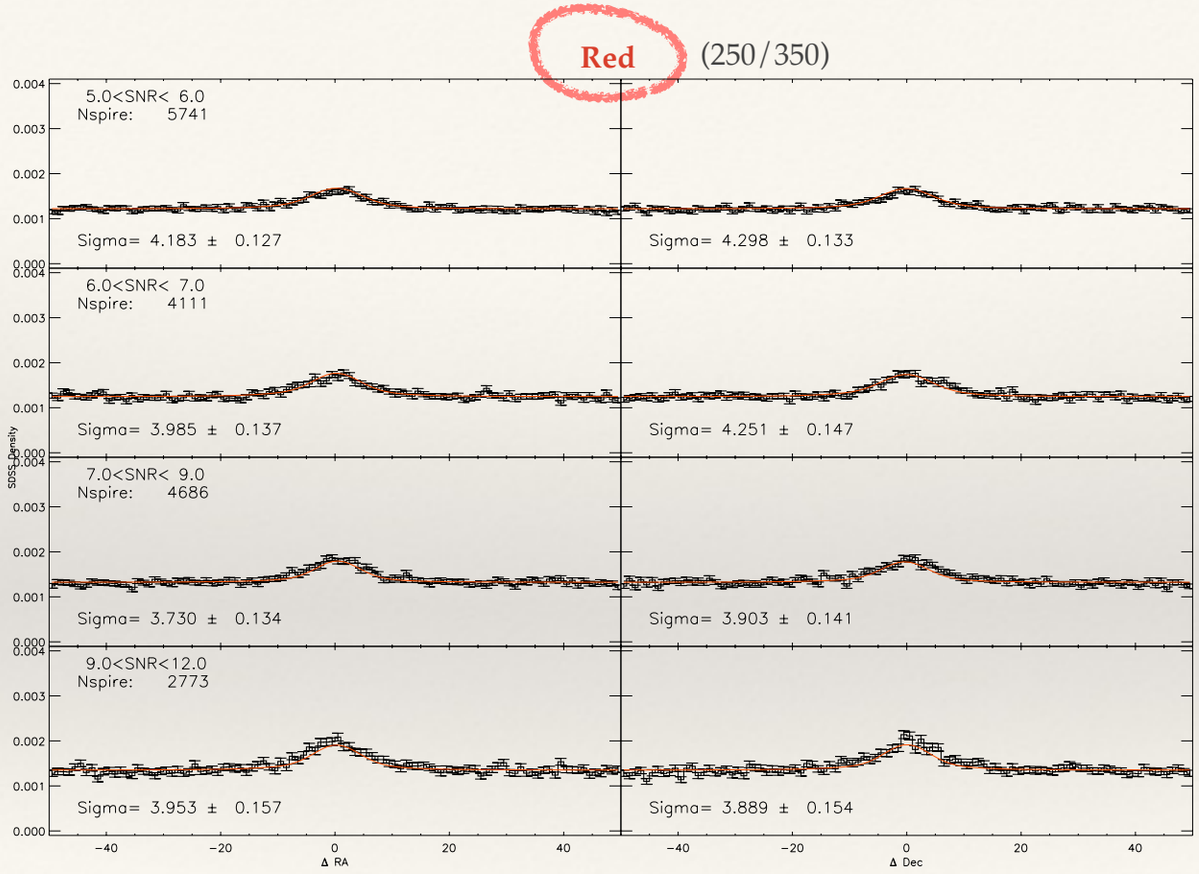
Accounting for the correlation function therefore, you can measure the width of that Gaussian function describing the positional error. If you do this in bins of signal-to-noise you see this. (In RA, you get a similar thing in Dec)
The blue line is the power-law fit to these data.
However, the expected power law slope is given by the orange line.
In fact the theoretical positional error is directly linked to the FHWM of the PSF and the SNR like this - which is given by the grey line.
Now, you can expect that the true errors might be somewhat larger than this due to pointing inaccuracies and so on, but why is this deviation greater for brighter sources, leading to the flatter slope?

So one thing that was noticed in trying to explore this, is that this is significantly different for SPIRE sources of different colours.

**Blue** (250/350)

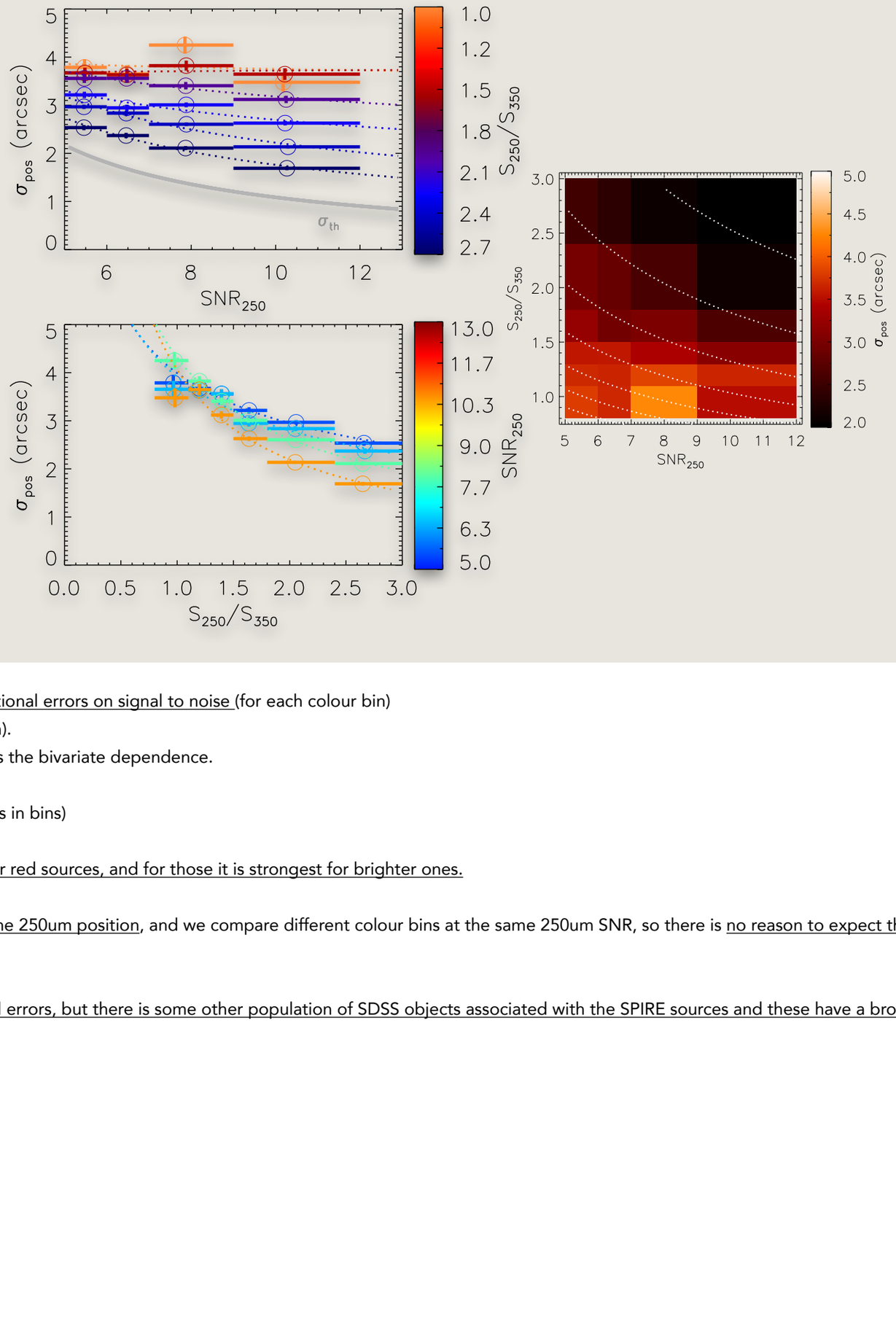



So we build those histograms in delta RA and delta Dec for blue sources (in different signal to noise bins) (top to bottom) - you see more counterparts for brighter sources (top to bottom) and smaller positional errors because the SNR is higher




And we do it for red sources (in 250/350 ratio). So two things are immediately obvious:
these histograms for red sources are much lower, because there are simply fewer actual SDSS counterparts to red SPIRE sources - we expect them to be at higher redshifts.
Secondly, these histograms are much broader.

In fact we do more than these two colour bins, we divide SPIRE sources into several bins of both colour and signal-to-noise




And so we can now plot (top) the dependence of the positional errors on signal to noise (for each colour bin)
And (bottom) the dependence on colour (for each SNR bin).
And to see this more graphically, the right hand plot shows the bivariate dependence.
For blue colours: it declines almost as expected with SNR
For red colours: its much flatter (notice slightly larger errors in bins)

So this increase in the positional errors is much stronger for red sources, and for those it is strongest for brighter ones.

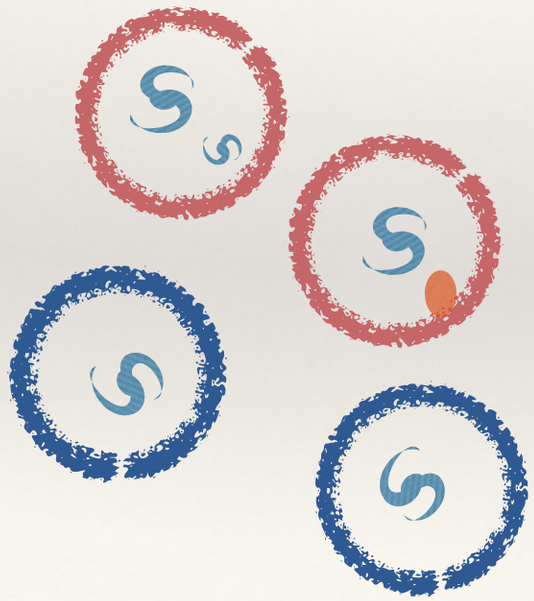
I should point out that all these sources are extracted on the 250um position, and we compare different colour bins at the same 250um SNR, so there is no reason to expect the redder ones to have worse positional errors based on the source extraction.

Therefore, this is not actually a case of increased positional errors, but there is some other population of SDSS objects associated with the SPIRE sources and these have a broad distribution of offsets which makes those positional error histograms look broader.

# Brighter, redder SPIRE sources have more SDSS associations at large radii

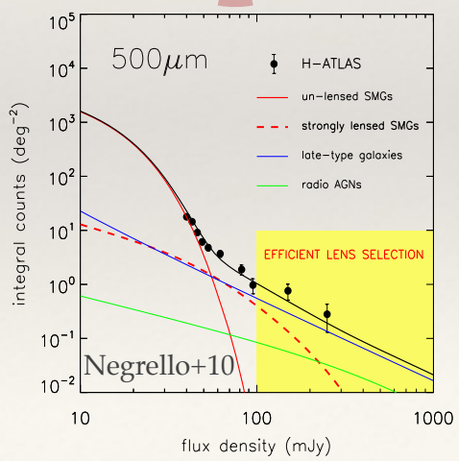
Why?

Clustering



Lensing






why do we see this then?

Maybe we have not properly accounted for the correlation function - we fit those histograms taking account of fits to the cross-correlation on larger scales, but if this behaves differently on small scales (eg less than about 5 arcsec) where we cannot measure it then we could see this unexplained excess
You can imagine a scenario where sources which are say blends of multiple galaxies that are spatially associated (eg in the same halo) tend to have worse positional errors (due to the blending).
They also look redder because the blending is worse at longer wavelengths.
If this is the case then you need to take this increased error into account in your calculation of the likelihoods of matches.
But is this expected to be worst for the brightest red sources, as we saw on the previous slide?

OR
For the brightest sources detected in the submm, we expect a large fraction to be lensed.
This naturally leads to an increased probability of finding an SDSS galaxy at some particular offset from the SPIRE galaxy. Rather than being the counterpart, this galaxy is itself the lens, or is within the halo that is doing the lensing.
But two questions arise: surely lensing is too rare to cause this effect, right?
And do we expect the positional offsets of lenses to be so broadly distributed?

# Brighter, redder SPIRE sources have more SDSS associations at large radii

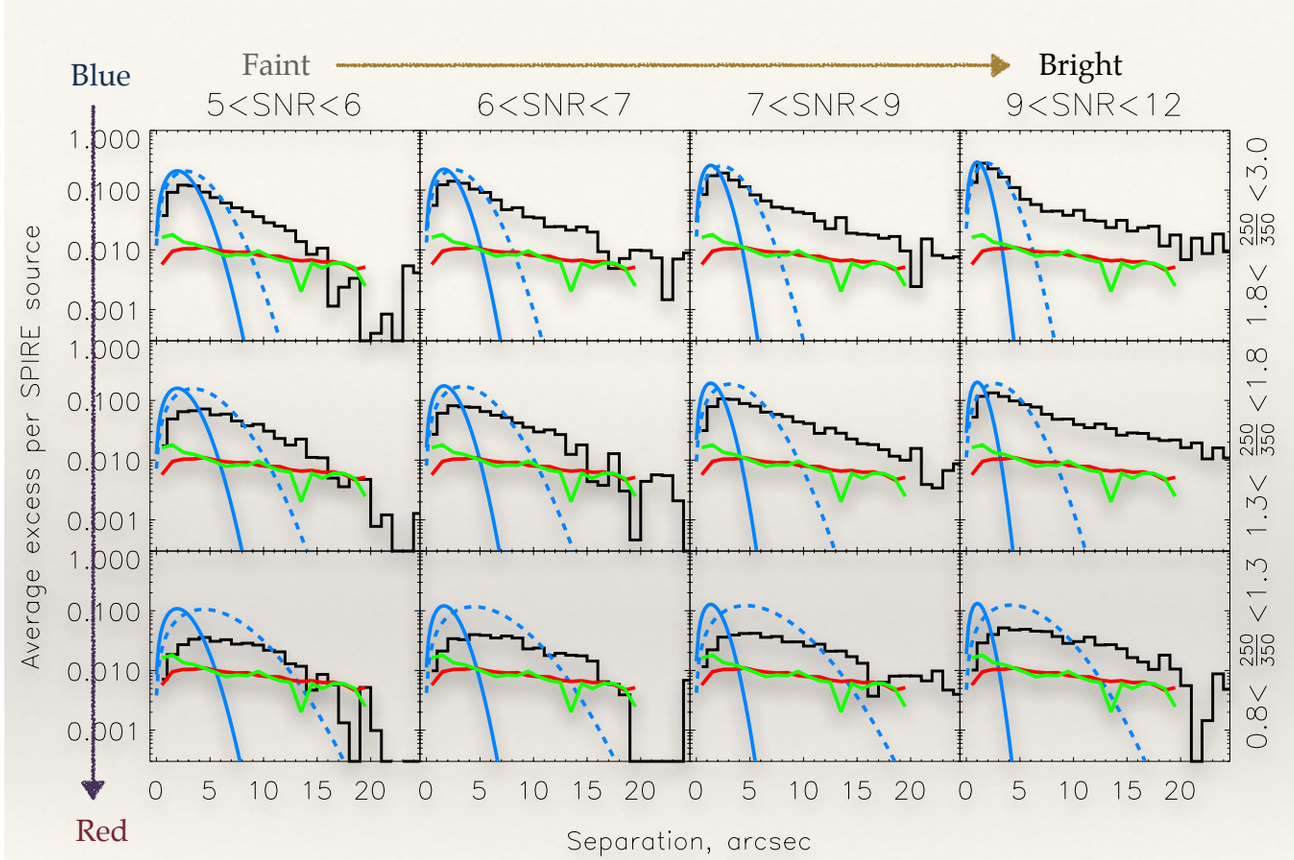
## Why?

- We know that the brightest red submm galaxies are likely to be lenses
- Could the offsets between the lenses and the submm images be affecting the measured positional errors?

For the brightest sources detected in the submm, we expect a large fraction to be lensed.
This naturally leads to an increased probability of finding an SDSS galaxy at some particular offset from the SPIRE galaxy. Rather than being the counterpart, this galaxy is itself the lens, or is within the halo that is doing the lensing.
But two questions arise: surely lensing is too rare to cause this effect, right?
And do we expect the positional offsets of lenses to be so broadly distributed?

For the first question: well it has been shown that most of the brightest 500um sources are strongly lensed. But for 250 and 350um detected sources this is somewhat lower. (source counts…)

And as I said we also need to look at the distribution of offsets that the lensing produces.




Lens modelling : Gonzalez-Nuevo+ in prep.

So here I plot a similar kind of histogram, except that now it is radially binned so the histograms in black are the total SDSS counts in an annulus around the average SPIRE source, in bins from SNR of 5 to 12, and 250/350 colour from blue to red.

Over these I plot the predicted and measured positional error functions in blue.
So that immediately you can see the blue bins are relatively well described by these functions at small radii, but red bins are not.
Over each of these I then plot the predicted offsets between lensing masses and the SPIRE sources, from simulations of weak lensing, either by galaxy sized or cluster sized haloes at the positions of SDSS sources.

So although the form of the green line is reasonably similar to the data (so you can see that sufficiently common lensing would broaden our offset distributions), the normalisation is too low: lensing is too rare to account for the observations.

However, the big caveat is that these lensing predictions rely on our knowledge of the high-redshift evolution in the IR LF.
These simulations assume that this evolution is fairly strong [(1+z)^3] out to z=3.5, but the evolution at z>1 is more uncertain.
A weaker evolution at z>1 would mean that the fraction of lensed sources must be higher to match the source counts.

## How common is (weak) lensing among SMGs?

- This depends on evolution of the LF at high redshifts
- If strong, then most SMGs are unlensed, but are strongly clustered such that their positional errors are increased
- If it weakens, then lensing is more common, and there is a much greater chance of identifying the lens as the counterpart to a red SMG.

In conclusion, it comes down to this question: how common is lensing among SMGs at high redshifts?

If we assume the evolution is as strong as it is at low redshifts, then clustering and confusion must be responsible for the boosting of the reddest Herschel sources. They also increase their positional errors, which we have to account for if we don't want to miss their IDs.

But the flux and colour dependence of these observations suggest that lensing could be responsible for boosting the numbers of low-redshift galaxies correlated with high-redshift SPIRE sources. This may be possible if the LF evolves less strongly at higher redshifts. This would mean that there is a heightened probability of identifying the lens as the counterpart to a red Hesrchel SMG.

This can be solved with high-resolution submm or mm imaging of the sources on an individual basis, but on a larger scale requires that we measure more accurately the IR luminosity function at high redshifts.

# Summary

- Distributions of positional offsets between sub-mm and optical sources depends on sub-mm signal-to-noise — but not quite as expected
- Also depends on sub-mm colour:
- Redder, brighter sub-mm sources have greater offsets to optical sources than expected (apparently worse positional errors?)
- Could be explained by widespread weak lensing or by correlated optical sources
- Need to explain this otherwise likelihood ratios for SMG counterparts will be inaccurate

In order to treat the positional errors correctly and measure accurate likelihoods of matches, we need to understand what causes this increase in measured positional errors.

(e.g. size of the effect on likelihoods? Well it does significantly affect the fraction of red sources with high reliability counterparts - at about the 10% level)