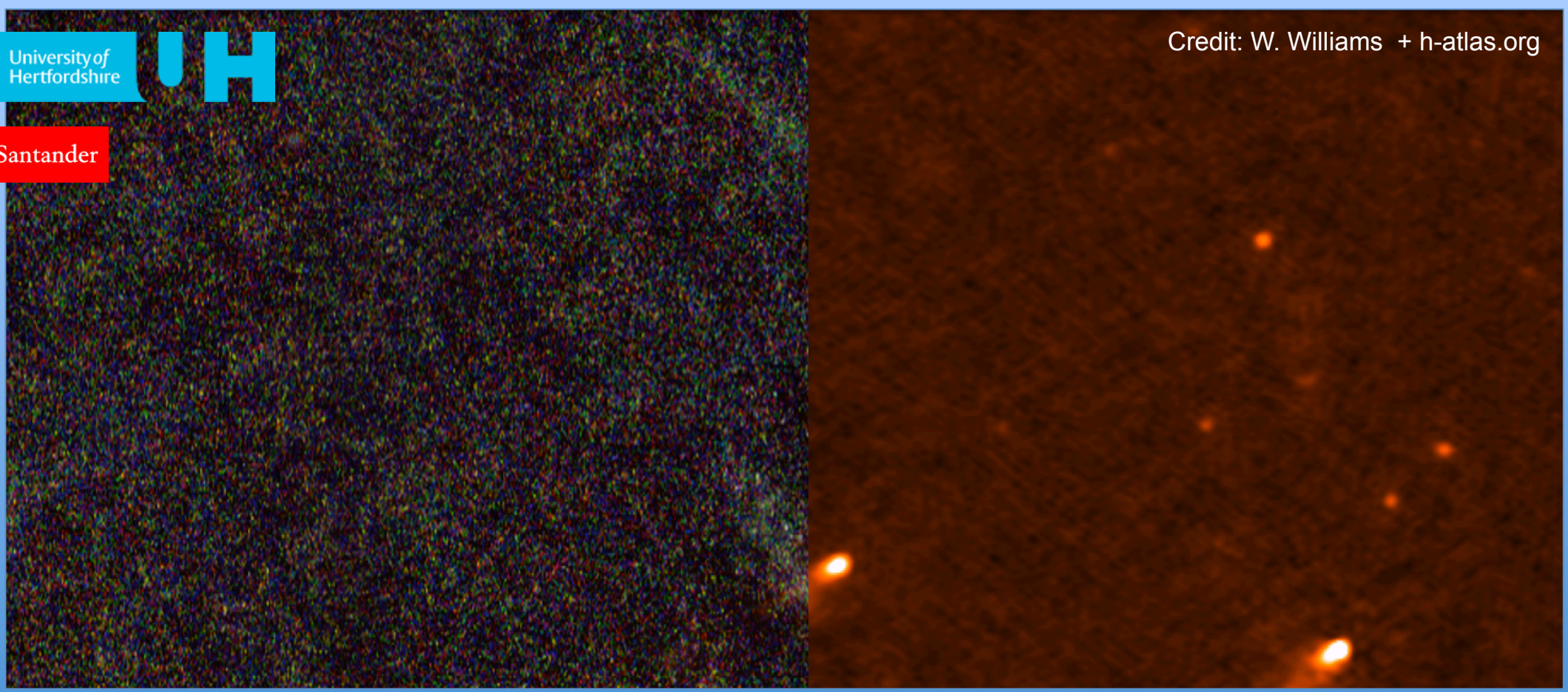


# The temperature dependence of the far-infrared radio correlation in the Herschel ATLAS

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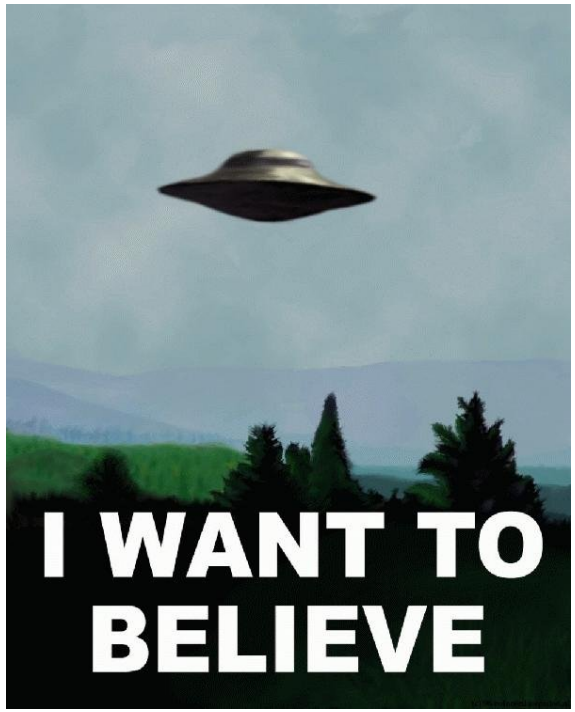
# The temperature dependence of the FIRC in H-ATLAS
## Outline

- Why is the FIRC of interest?
- The H-ATLAS survey & dust temperatures
- The FIRST survey
- k-corrections
- The monochromatic FIRC in H-ATLAS
  - Evolution with redshift?
  - Temperature dependence?
- The future
  - Low-frequency FIRC tests at high-z
  - WEAVE-LOFAR



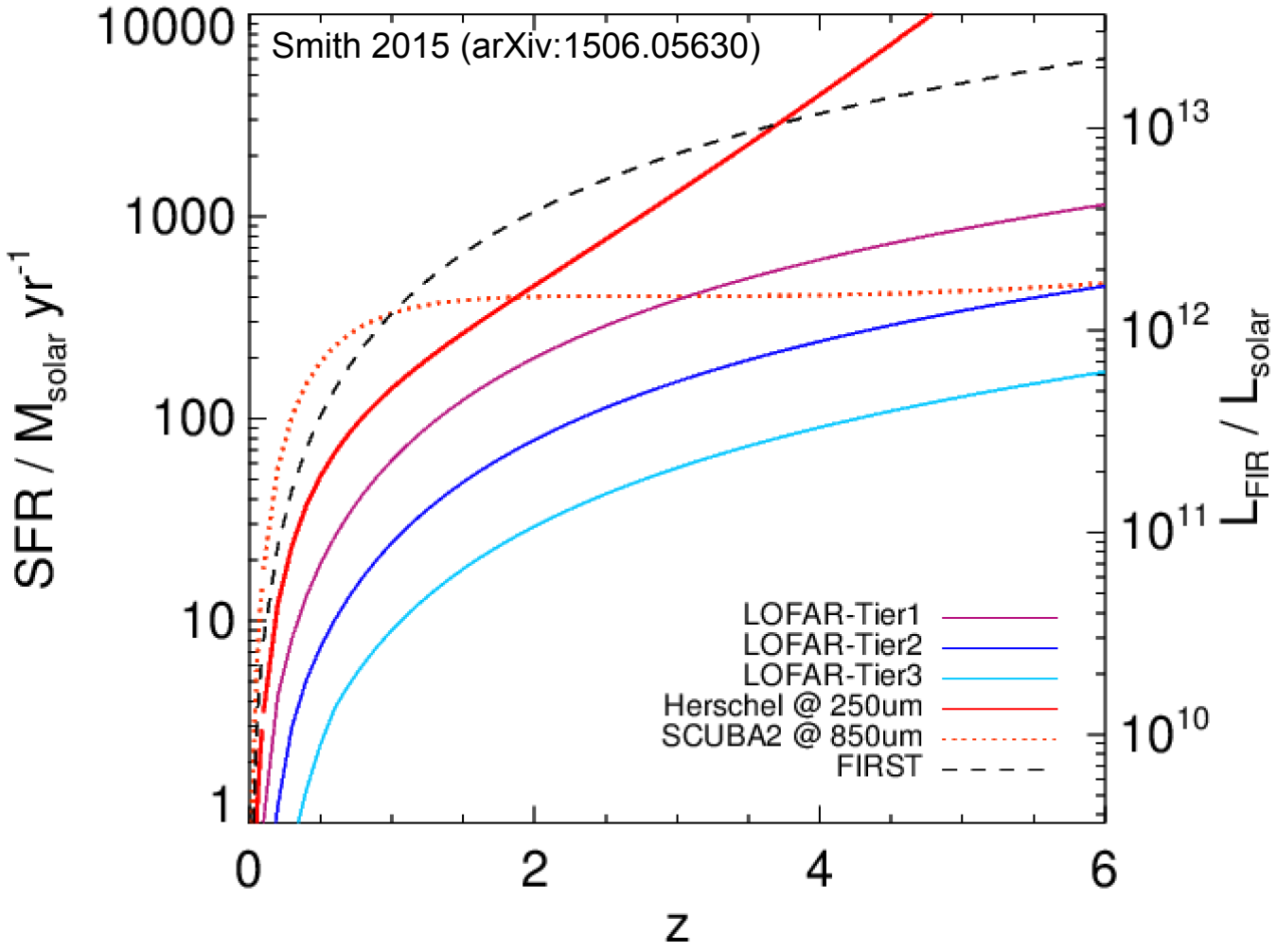
# Why is the FIRC of interest?
## Radio continuum sensitivity is exploding

The FIRC is the source of the radio-continuum SFR calibration (e.g. Yun+ ‘01)

Conspiracies necessary to explain it (e.g. Bell ’03, Lacki+ ’10, Murphy+ ’13 etc)

Radio data are becoming far more SFR-sensitive than far-IR

To exploit this sensitivity we need to know that it works!

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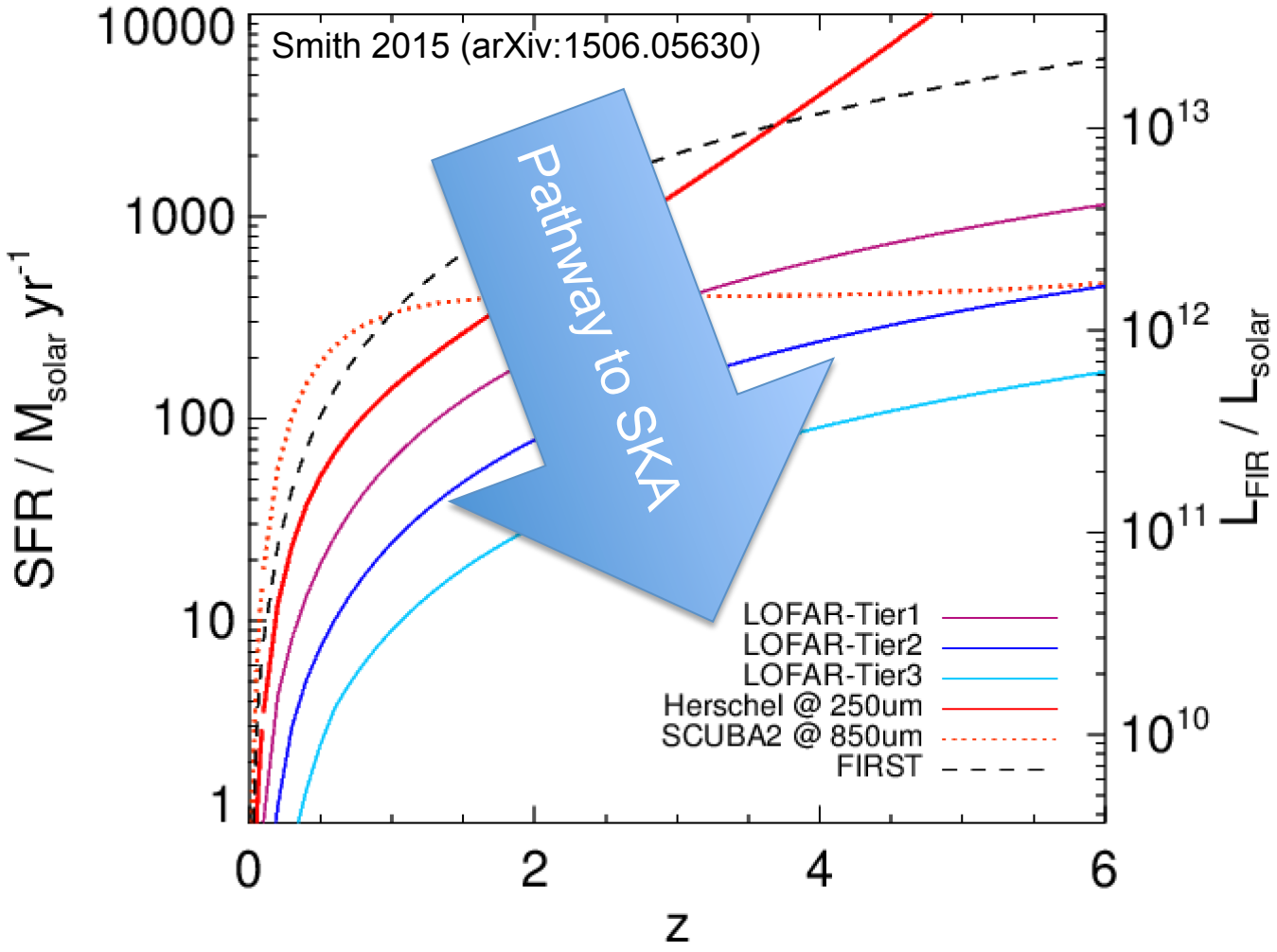


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# Parameterising the FIRC
## Integrated & monochromatic versions

$$q = \log_{10}\left(\frac{L_{dust}/3.75\times10^{12}}{L_{1.4GHz}}\right)$$

e.g. Helou+ 1985

$$q_{\lambda} = \log_{10}\left(\frac{L_{\lambda}}{L_{1.4GHz}}\right)$$

e.g. Appleton+ 2004, Ivison+ 2010, Jarvis+ 2010

- q can be calculated for individual galaxies, or for samples on average, as a function of parameters of possible interest, e.g:
  - redshift,
  - dust temperature
- Dust temperature is of possible interest since e.g. cold galaxies may be dominated by ISM emission not associated with recent SF (e.g. Charlot & Fall ’00, Smith+ 12); FIRC variation expected?
- FIRC also expected to vary with redshift (e.g. Murphy ’13); contrasting previous results due to different selection?

# The temperature dependence of the FIRC in H-ATLAS

## The Herschel ATLAS – phase 1 (Eales et al. 2010)

- 160 deg$^2$ over 9/12/15hr fields
- 100, 160, 250, 350 & 500 μm data
- 5σ limits of 130, 130, 32, 36, 42 mJy
- Reliable counterparts to 14,000 250 μm positions in SDSS, cross-identified using a “Likelihood Ratio” method (Smith et al. 2011, see also Bourne et al. 2014)
- Coverage overlaps with the GAMA survey: spectroscopic redshifts

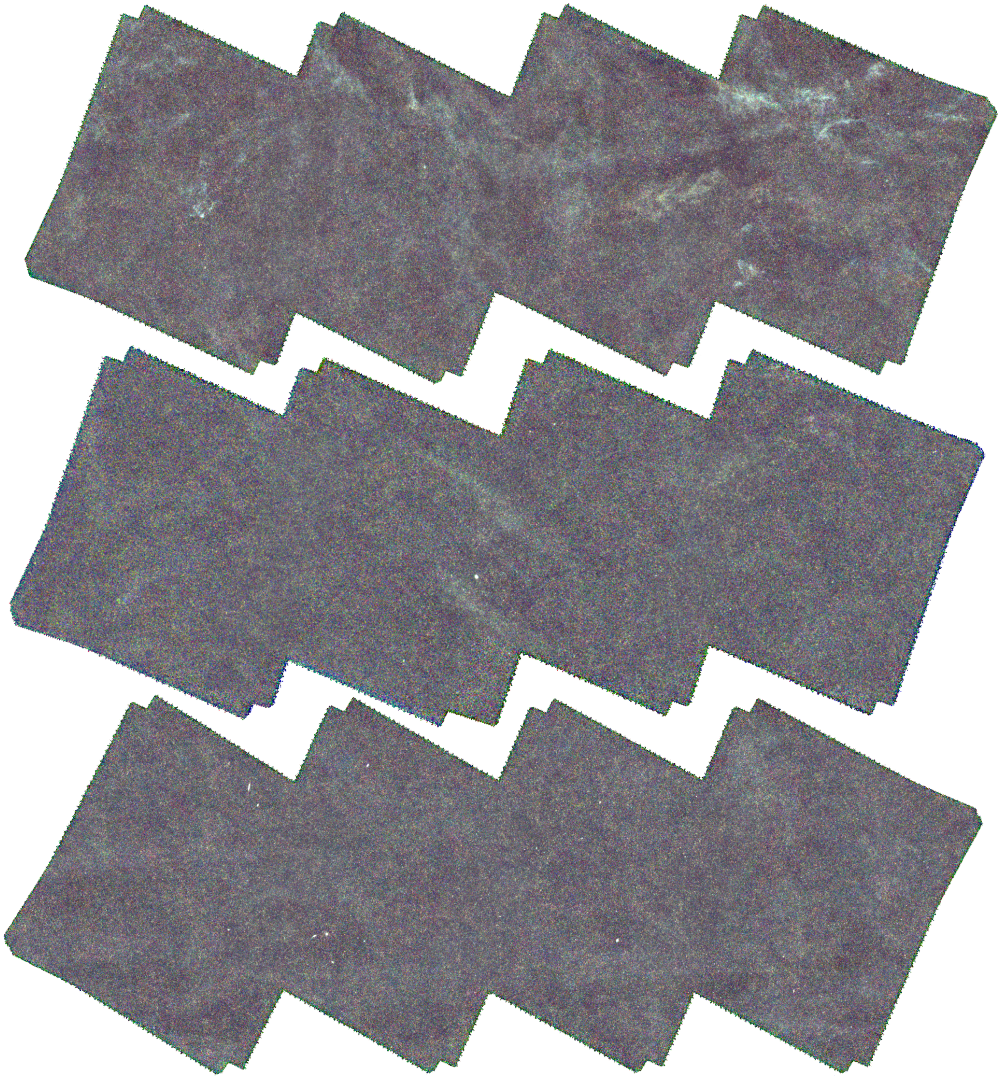

Image: h-atlas.org

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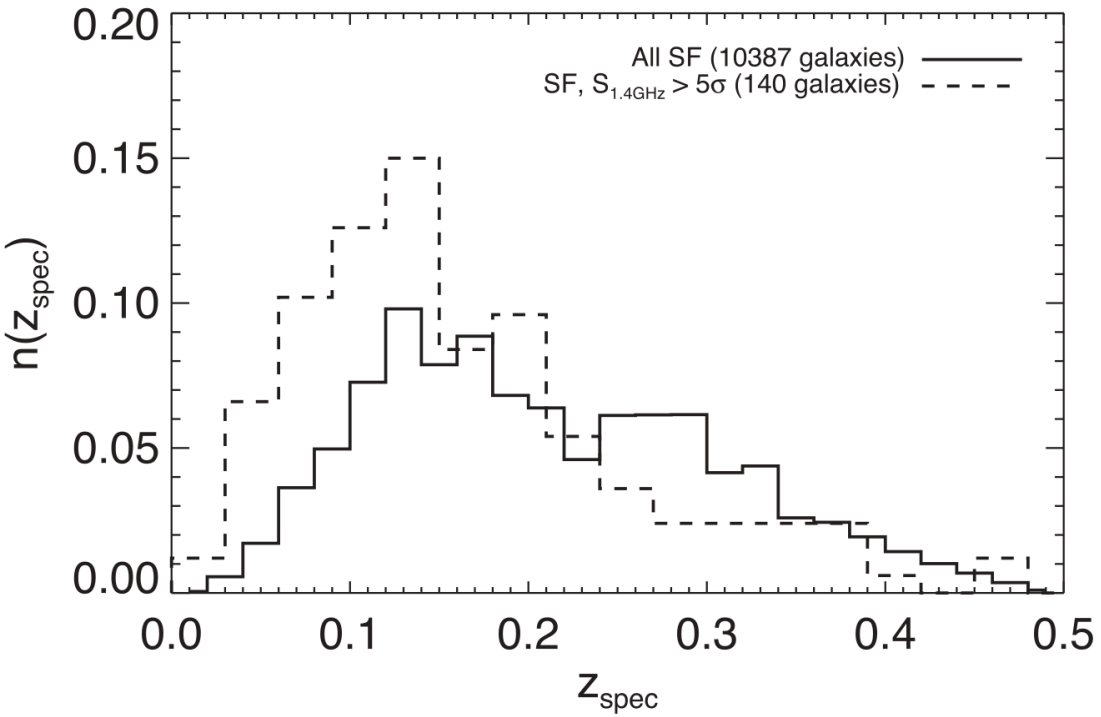
# The temperature dependence of the FIRC in H-ATLAS

## Our sample

- Based on 10,387 galaxies with:
  - 250 μm sources with SNR > 5
  - reliable optical counterparts
  - $0.00 < z_{spec} < 0.50$
  - Smaller than 250 μm beam
  - AGN removed
  - Good $\chi^2$ fits to isothermal model…

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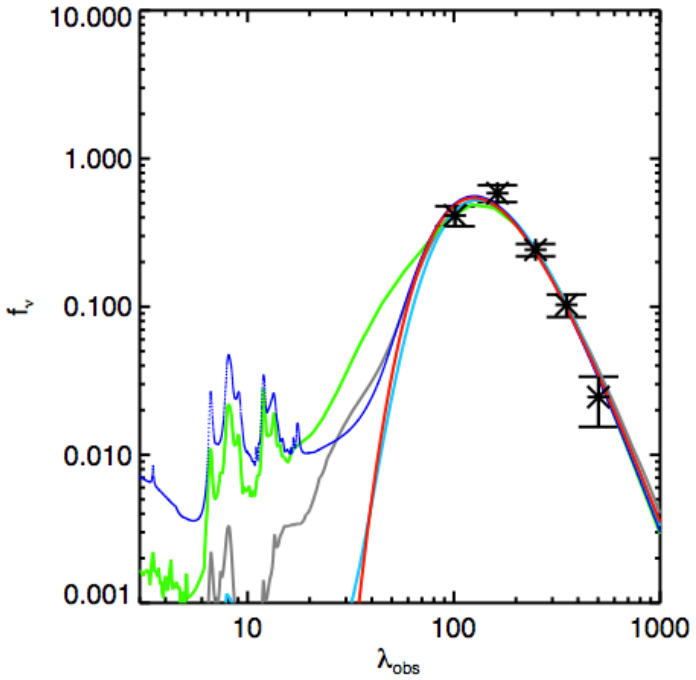
# The temperature dependence of the FIRC in H-ATLAS
## Estimating temperatures from H-ATLAS data

- Assume an isothermal model, convolved with filter curves, to estimate *effective temperatures*
- Smith et al. 2013 showed
  - β = 1.82 for H-ATLAS galaxies
  - PACS data are very important for estimating temperatures
- Allow $5 < T_{eff}(K) < 60$
- WISE detections only for very few sources; Integrated $L_{dust}$ values are model-dependent
- ***Focus on monochromatic luminosities***

$$f_\nu \propto \frac{\nu^{3+\beta}}{\exp\left(\frac{h\nu}{kT}\right) - 1}$$

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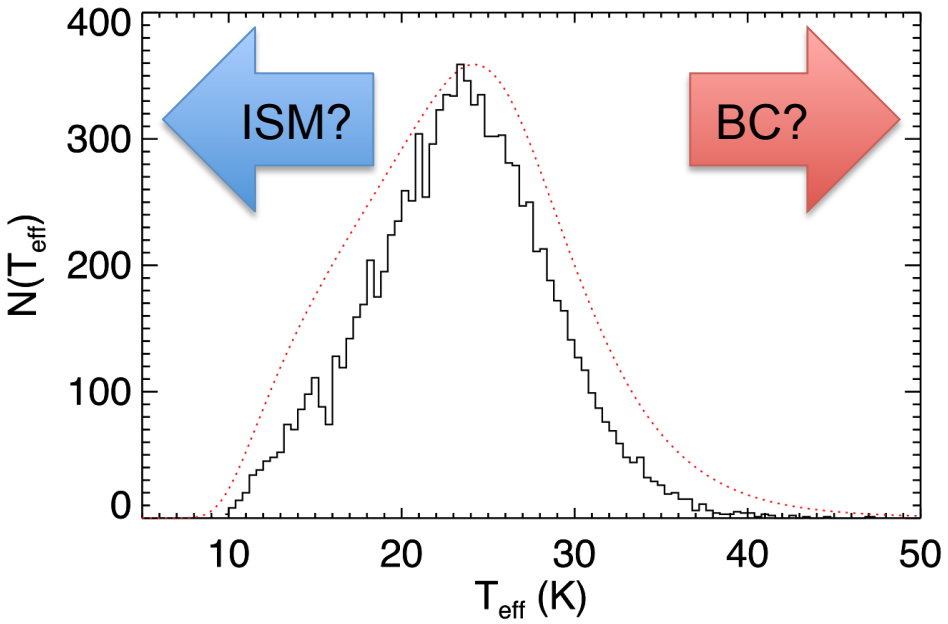
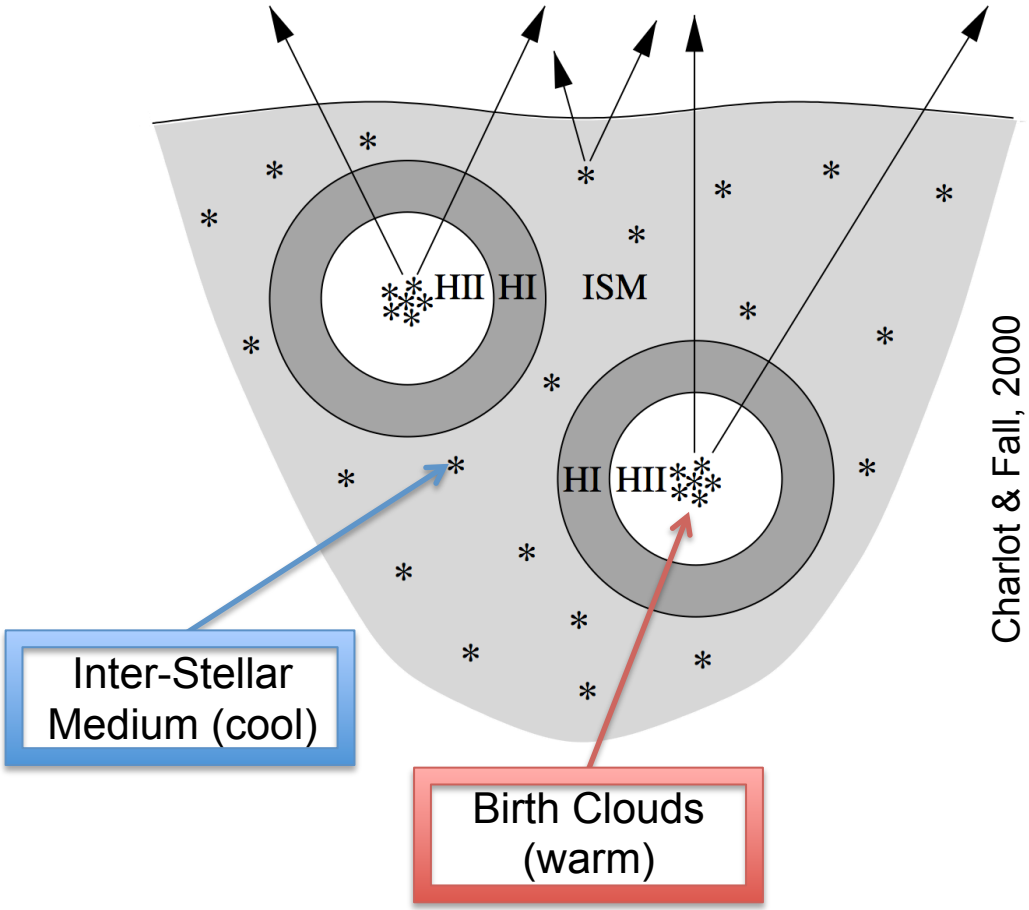
# The temperature dependence of the FIRC in H-ATLAS
## Interpreting effective temperatures

- We don't have the data to derive temperatures/luminosities for two dust components (e.g. Magphys)
- How can we interpret $T_{eff}$?

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# The temperature dependence of the FIRC in H-ATLAS
## Radio data from FIRST

- FIRST (Becker et al. 1995): 10,000 deg$^2$ northern sky; VLA B-configuration gives 5" resolution, 0.15 mJy beam$^{-1}$ RMS
- However, <2% of H-ATLAS sources are detected in FIRST catalogue: biased sample
- BUT: FIRST is very uniform and lends itself to ***stacking***
- We extract flux densities in 5 arcsec apertures directly from the FIRST maps
  - We get excellent agreement with the catalogue fluxes (where they exist)
- Extracted fluxes are much easier to stack than images at varying redshift
  - e.g. "How do you k-correct an image?"

# The temperature dependence of the FIRC in H-ATLAS
## k-corrections: bringing luminosities to rest-frame

### H-ATLAS k-corrections:

- Use the best-fit Siebenmorgen & Krügel (2007) SED template
- Estimate uncertainties by marginalising over different SED libraries:
  - Isothermal
  - SK07
  - Magphys (w and w/o energy balance)
- Uncertainty varies with wavelength; ~14% at 250 μm, 25% at 100 μm

### FIRST k-corrections:

- Assume radio SED of the form:

$$S_\nu \propto \nu^{-\alpha}$$

- α = 0.71 +/- 0.38 (Mauch+ 2013)
- Average uncertainty only ~6%

- K-correction uncertainties are propagated through onto the individual flux densities

- Stacked values are ***median*** stacks, with bootstrap errors from 1000 re-samples with replacement.

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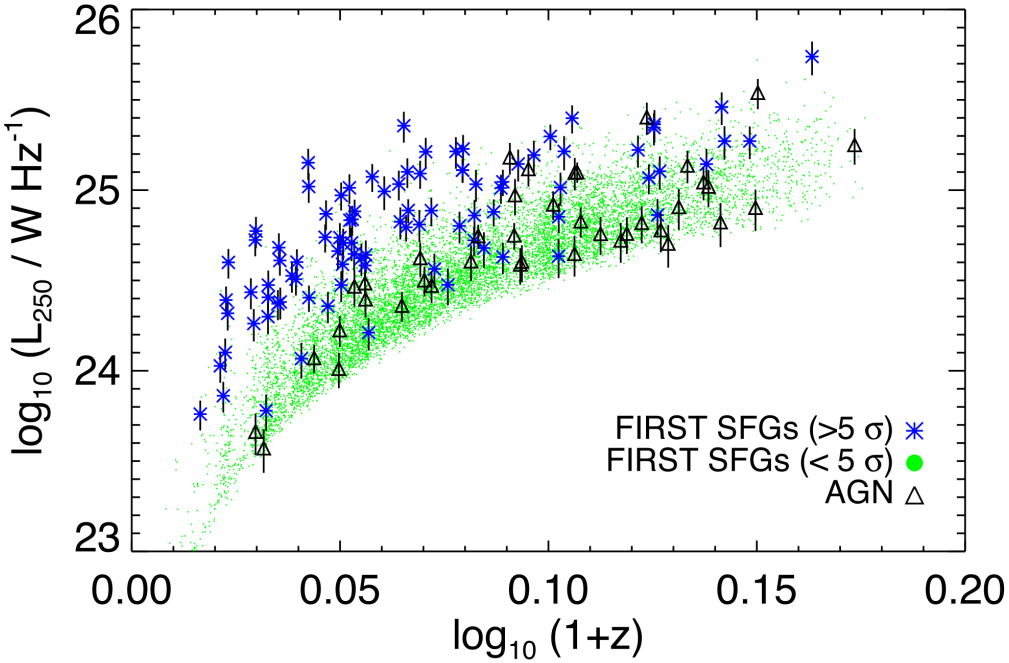
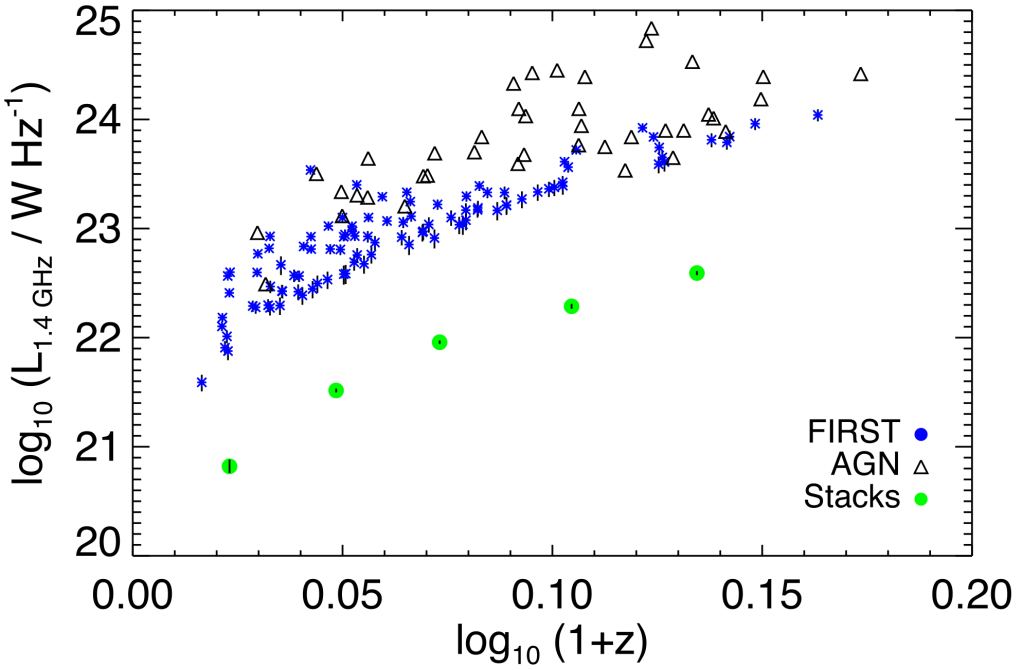
# The temperature dependence of the FIRC in H-ATLAS

## Population demographics

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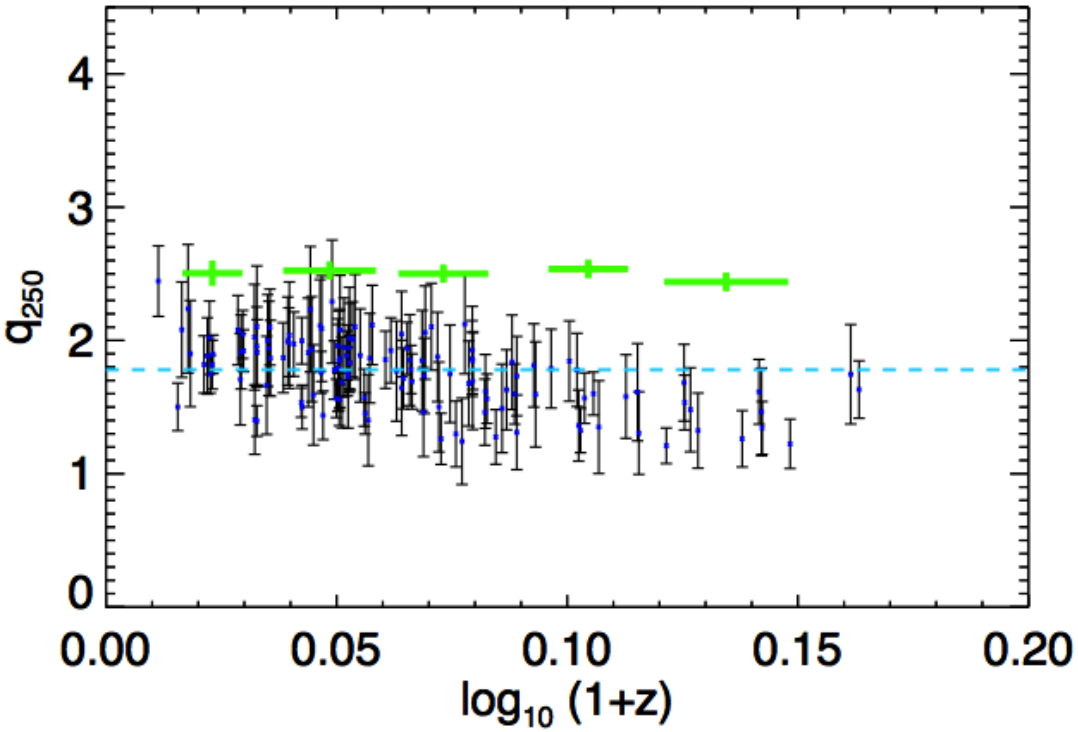
# The FIRC in H-ATLAS
## No evidence redshift evolution at z < 0.5



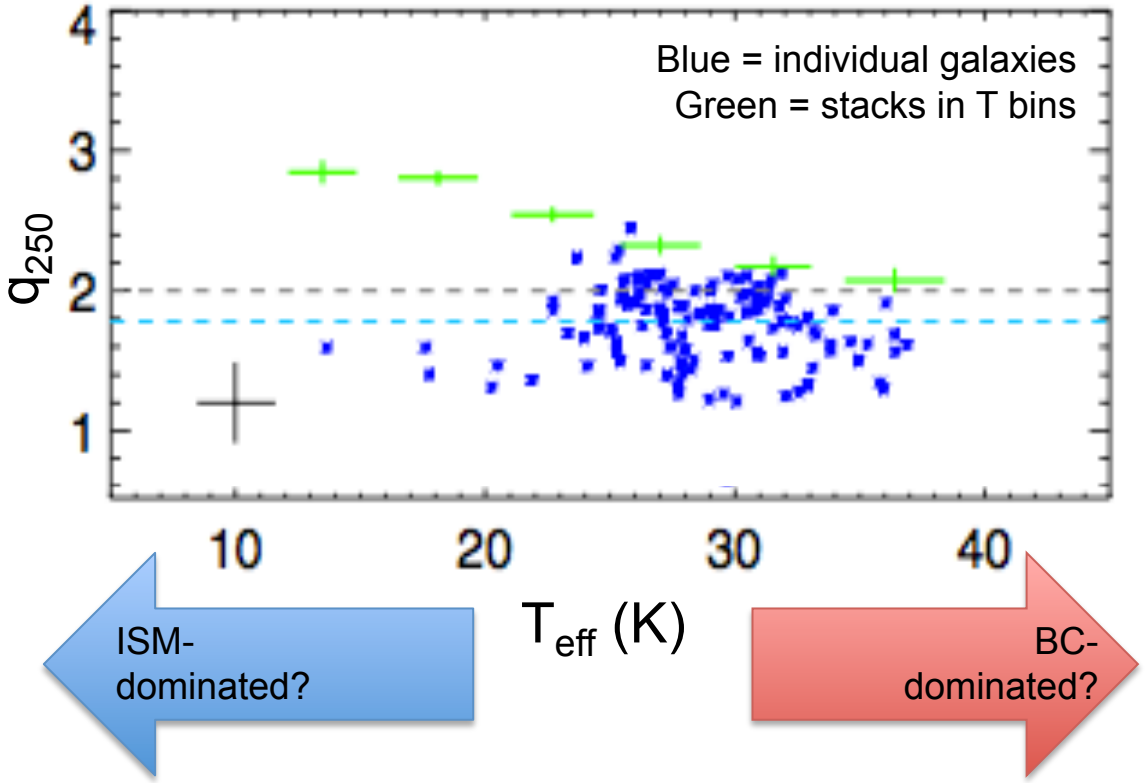

Detections appear to show negative correlation with redshift – evolution?

No! This is just the relative lack of sensitivity in the FIRST data relative to Herschel!

Stacks reveal the true picture – higher q than previously shown

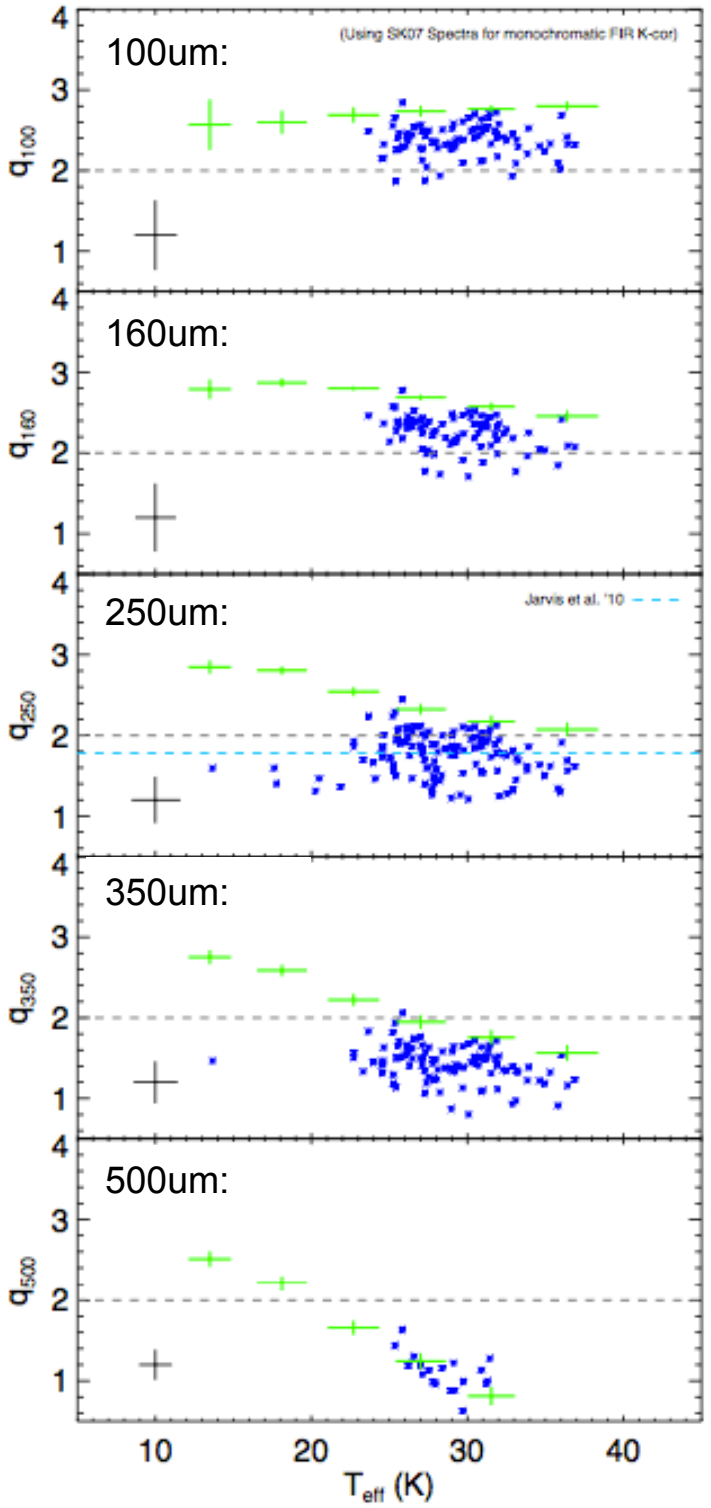
# The FIRC in H-ATLAS
## Temperature dependence

- We can also stack k-corrected luminosities **in bins of temperature**
- Quotients of the stacked luminosities give us monochromatic FIRC $q_\lambda$.
- Clear evidence for lower $q_{250}$ at higher temperatures
- How does this work at other Herschel wavelengths?



# The FIRC in H-ATLAS
## Temperature dependence vs wavelength

- At all wavelengths, the detections give a biased picture of what's going on.
- Stacking is essential to see the true picture
- At 100 μm, the FIRC is approximately flat
- As we go to longer wavelengths, increasingly strong negative correlation with temperature
- This is critical to know about e.g. if using a single far-IR data point to estimate an SFR!

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# Future tests of the FIRC
## Testing the conspiracy theories

Low-frequency observations represent an important test since the FIRC is expected to break down, especially at higher z and lower frequency (Murphy et al. 2013)

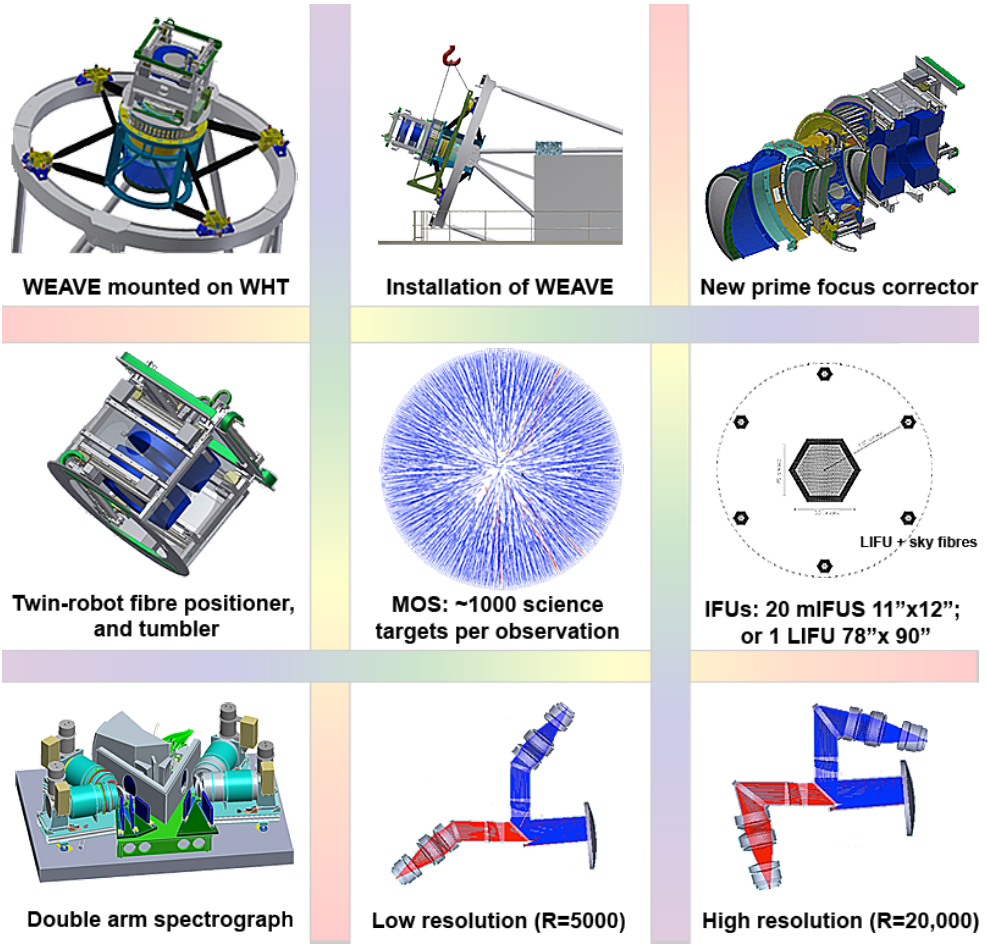
We can do this at some redshifts now (see talks by Gürkan, and Basu?)

Better redshift information (larger samples to higher z) is key!

**WEAVE-LOFAR** will supply it….

# What is WEAVE?
# The WHT Enhanced Area Velocity Explorer

- A multi-object spectrograph, with:
  - 1,000 x 1.3” fibres
  - 2 deg diameter field of view
  - R=5,000 with coverage from 370nm to 1μm
  - R=20,000 with reduced coverage
  - mIFU and LIFU modes
  - See Dalton et al. (2012) for details
- First light in 2017, then five years of survey operations….
- www.ing.iac.es/weave/

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# LOFAR: the Low Frequency Array
## Surveys Key Science Project

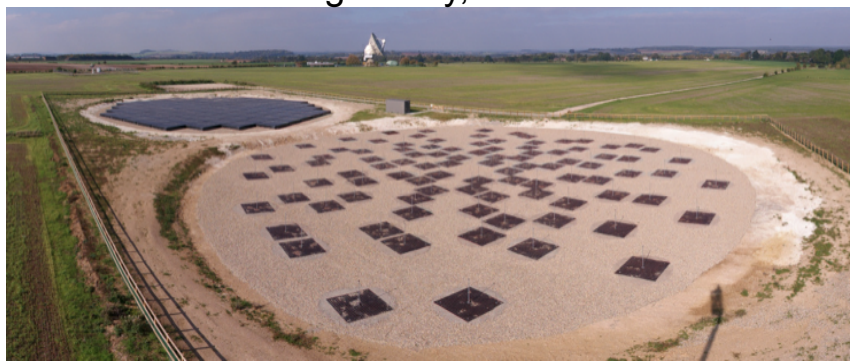
**Tier-1, the "Wide",** will cover whole northern hemisphere, multi-frequency, 0.1 mJy RMS at 120 MHz; SFR sensitivity > Herschel

**Tier-2, the "Deep",** will cover 100s of deg$^2$ to faint flux limits (25 μJy RMS @ 120 MHz)

**Tier-3, the "Ultra-Deep",** will cover 10s of deg$^2$ to sensitivities > the deepest existing imaging (6 μJy @ 150 MHz)

Details: Röttgering et al. 2011

Rawlings Array, Chilbolton



Superterp, NL

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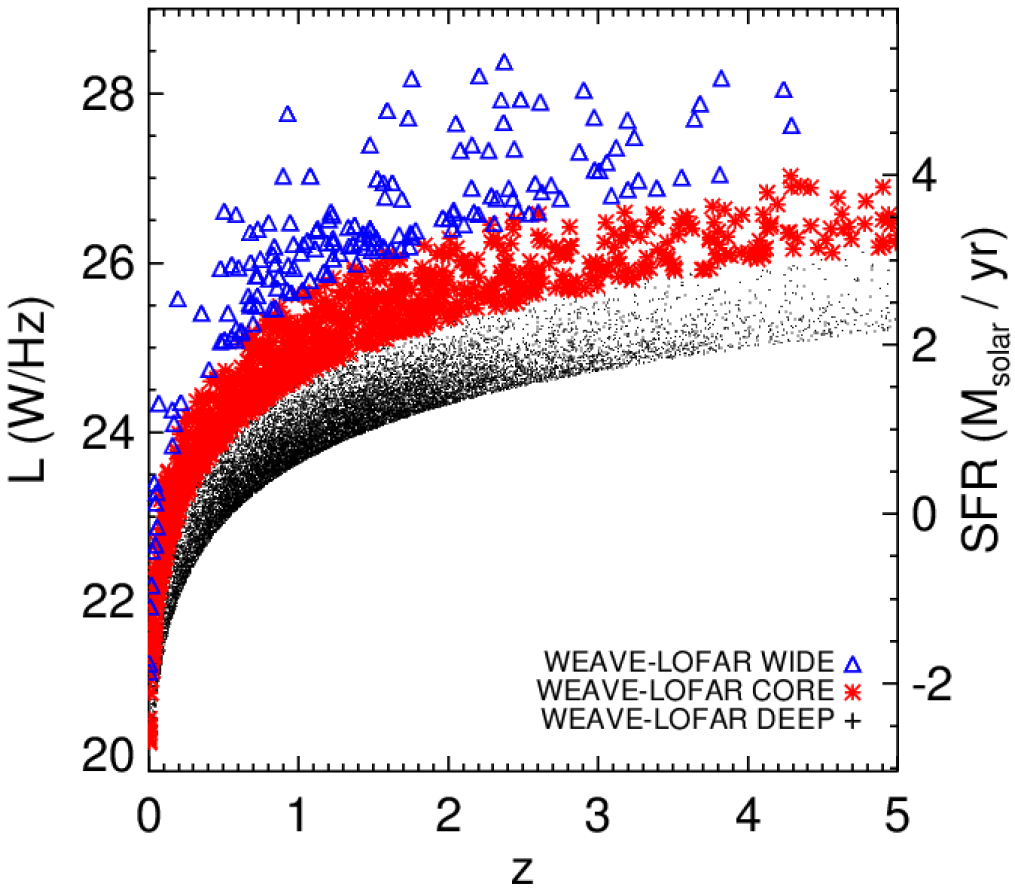
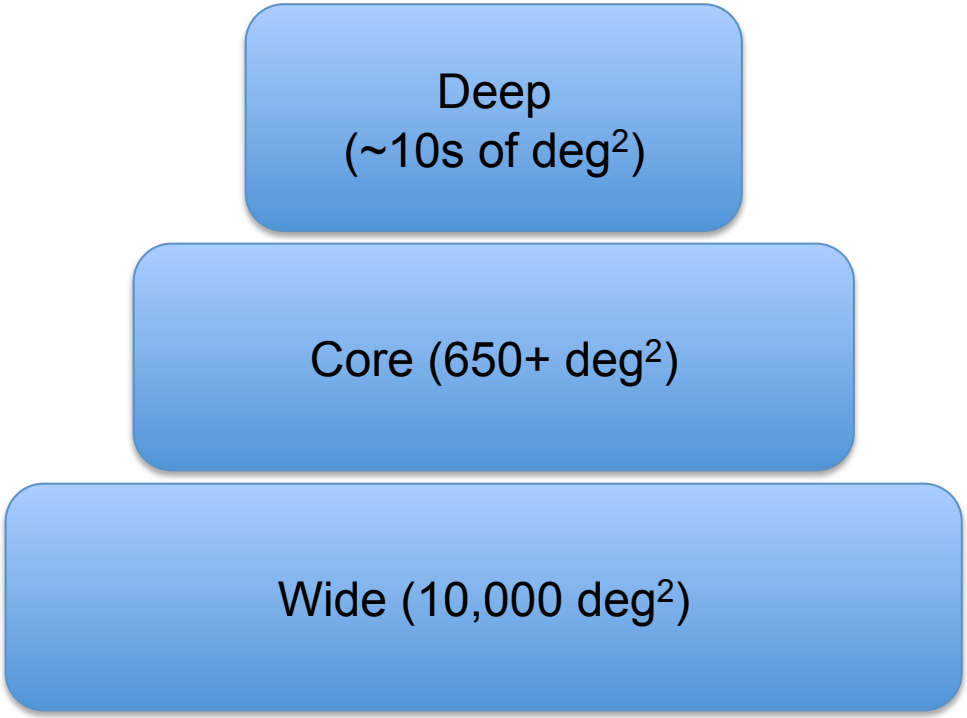
# WEAVE-LOFAR
## Perfect for studying the physics of the FIRC

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**WEAVE-LOFAR Fields chosen to overlap with best ancillary data…**

# Summary
# Temperature dependence of the FIRC in H-ATLAS

- Based on 10,387 galaxies:
  - 250 μm sources with SNR > 5
  - reliable optical counterparts
  - $0.00 < z_{spec} < 0.50$
  - Smaller than 250 μm beam
  - Good $\chi^2$ fits to isothermal model
  - AGN removed

- No redshift evolution in the FIRC
- Clear temperature dependence in the monochromatic FIRC at $\lambda > 100$ μm
- Implications for using single band FIR observations for SFR estimates

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- WEAVE-LOFAR will generate hundreds of thousands of spectroscopic redshifts for low-frequency selected galaxies

- Science goals are many & varied, including understanding the physics of the FIRC as well as e.g. the relationship between star formation and accretion over cosmic history, finding RGs in the EoR, etc

- *If you're interested in WEAVE-LOFAR and in an eligible country, I'd be pleased to hear from you….*

Thanks very much

daniel.j.b.smith@gmail.com