The legacy of Herschel for studies of Galaxy evolution

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Seeing the Stolen Starlight

- Dust grains absorb UV/optical photons
- Heated to 20-80 K and re-radiates in the FIR and sub-mm.
- Use FIR (8-1000 micron) luminosity as a tracer of obscured star formation.
- Dust is also a good tracer of gas mass in galaxies.
- Simple to relate FIR emission to star formation rate and dust mass.

\[
M_d = \frac{S_\lambda \ D^2}{\kappa(\lambda) \ B(\lambda, T_d)}
\]
Herschel – the good, the bad...

- Covers the peak of the FIR SED across a range of redshift (70-500 microns).
- Incredible speed and fidelity of mapping.

- Poor angular resolution (8-36")
- Relative mismatch in sensitivity between PACS and SPIRE so small areas with deep 100/160 data
  Negative K-correction not as strong

Herschel–ATLAS (Eales+10)
Hermes (Oliver+12)
PEP (Berta+11)
HeVICS (Davies+10)
Herschel-GOODS (Elbaz+11)

Pilbratt+10
Griffin+10
Poglitsch+10

Blind – statistical properties
The cosmic evolution of
Evolution of obscured star formation

Evolution of the IR luminosity function from deep Herschel surveys

$N_{\text{galaxies}} \propto SFR$

$L_{\text{IR}}$ proportional to star formation rate

Gruppioni et al. 2013
Cosmic SFRD

Stacking Herschel data
FIR individual detections
Schreiber+ 15

Herschel detections account for ~50% of all stars formed.
Evolution of dust and ISM

Dust evolution in dust mass function over past 4-5 billion years. Galaxies have more dust and gas rich at z=0.5 (Dunne et al. 2011, Berta+ 2013).

Dust Evolution and ISM at z=0 DMF based on H-ATLAS/GAMA (Beeston+ in prep).

Planck and SCUBA observations.
Evolution of dust and ISM

Strong evolution in dust mass function over past 4-5 billion years.

Galaxies more dust and gas rich at $z=0.5$

Dunne et al. 2011, Berta+13
Driver+ submitted, using H-ATLAS, Hermes and MAGPHYS

GAMA/G10 (this work)
Bethermin et al. (2014), scaled using dust-to-stellar mass fraction
Beeston et al. (2017)
Menard & Fukugita (2012)

Dust Mass Density (M_{sol}/Mpc^{3})

Look back time (Gyrs)
Dust as a tracer of gas

Using dust as a gas tracer, there appears to be a fundamental plane in $f_g$-SFR-$M^*$.

Gas fraction increases with redshift (and decreases with stellar mass).

Santini+14  (see also deVis+2017, Rowlands+14, Genzel+15, Scoville+14,16,17)
Dust based: Berta+ 14, Dunne 11, Dunne 2003, Driver 2017

\[ \rho(H_2) [M_\odot \text{ Mpc}^{-3}] \]

\[ 10^7 \quad 10^8 \]

Redshift

Decarli+ 16

ASPECS

Obreschkow et al. (2009a,b)

Keres et al. (2003)

Lagos et al. (2011)

Boselli et al. (2014)

Sargent et al. (2013)

Keating et al. (2016)

Popping et al. (2014)

Walter et al. (2014)
- Deepest Herschel surveys, and mass complete sample > 10.3 Msun

- sSFR continually rises with redshift

- 2/3 of stars formed in galaxies within 0.3 dex of these SFR/M* relations

- Fraction of starbursts does not evolve, even though merger rate predicted to.

- Starbursts are rare, and contribute ~15% to the SFR budget.

Schreiber+ 15, Bethermin+15, Sargent+12, Rodighiero+ 11, Elbaz+ 11
SF-AGN connection

FIR provides uncontaminated view of SF in AGN

<10% of moderate AGN hosted by starbursts

Fuelling of moderate AGN secular and not merger driven

Mullaney+ 12, Santini+ 12, Rosario+12

Now can use multi-wavelength fitting to determine probability of AGN

Delvecchio+14
Evolution of black hole accretion

Delvecchio+14
Herschel sources often found to be multiples at higher angular resolution
Stacking analyses need to take into account clustering (e.g. Bourne+11, Schreiber+ 15)
Clustering also affects P(D) analyses and must be accounted for at 350/500 micron
Number counts are overestimated by as much as x2 at 500 mic for S=5-50mJy.

Bethermin+ 17, Karim+ 13, Hodge+ 13
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Clustering of Herschel galaxies

H-ATLAS angular correlation function for $1.2 < z < 4$. Similar to clustering of faint SMG at $2 < z < 3$.

$M_{\text{min}} = 12.23$, $M_1 = 12.85$, $\alpha = 1.35$

Gonzalez-Nuevo in prep, GN14, Chen+16, Cooray+10, Maddox+10
Cross correlation between high-z Herschel sources and low-z GAMA sources.

Lensing is produced only by the most massive halos in the foreground sample. Such massive halos host massive galaxies, and these produce the strong lensing effect out to 30″.

Has a direct impact on X-ID.

Effects of foreground structure on studies of high-z submm sources.

Gonzalez-Nuevo in prep, GN14, Bourne+14
Zooming in on the highest redshift starbursts
Finding Gravitational Lenses with Herschel

Sub-mm surveys are ideal for finding lenses

- **High redshift**
  - Chapman et al. (2005)
  - High efficiency for lensing

- **Steep counts**
  - Coppin et al. (2006)
  - Strong magnification bias

Diagram:
- Integral counts vs. flux
- Un-lensed distant starbursts
- Strongly lensed distant starbursts
- Nearby galaxies + radio galaxies
- Efficient lens detection
Gravitational Lensing

SDP 81

Herschel

HST + ALMA

Foreground elliptical galaxy lens (optical)  background distant starburst galaxy (FIR)

Negrello+10, Vlahakis (ALMA) 15
Collapsing turbulent disks

This is the same lensed galaxy with ALMA, now at ~200pc resolution at z~3

ALMA consortium+ 2015
Imaging of H-ATLAS ID81

SFR ~ 500 Msun/yr, gas surface density ~ 5000 Msun pc^{-2}
Toomre Q ~ 0.3 -- unstable disk
SFE 60x greater than in local Universe
High pressure ISM (x10^4 MW), SF clouds at high-z more similar to those in Galactic centre

Dye+ 2015, reconstruction of lensed source

also Swinbank+15 Riechers+13, Ivison+13, Rawle+14, Huynh+13, Hezaveh+2013
The birth of the red sequence?

Finding extreme starbursts at $z > 4$ can help pin down the origins of the red sequence which was already in place at $z \sim 2$.

Use colour selection with SPIRE to select ‘ultra-red’ objects (Dowell+14, Asboth +16, Ivison+16) from wide area Herschel surveys (Hermes, HELMS and H-ATLAS).
N(z) for ultra-red Herschel sources

Common SMG SED templates are good predictors for UR

Trend with redshift possibly indicates Td evolution of ~7K from z=2-6

Original Herschel UR selection produces samples with 1/3 at z > 4

Ivison+ 16, Fudamoto+ 17, Zavala in prep.
Extremely luminous, with $L > 10^{13} \, L_{\text{sun}}$ at $z > 4$

Space density $\sim 6 \times 10^{-7} \, \text{Mpc}^{-3}$ with 100 Myr duty cycle. VERY RARE.

10-30x too low to produce observed red sequence at $z \sim 3-4$ (Straatman 2014)

N(z) significantly different to models

Fraction of lensed sources predicted to be high for $S_{500} > 30 \, \text{mJy}$ and $z > 4$.

Ivison+ 16
Nature of the UR Herschel sources

High res imaging with ALMA

~40% lensed

Mix of morphology – merger, isolated disk.

Small size compared to lower z SMG (av. 1.5 kpc)

Many are Eddington limited starbursts and several with SFR > 1000 Msun/yr

Oteo+ in prep, Oteo+ 16
Asboth+16, Ivison+16
The most ‘happening’ place in the Universe:

Proto-cluster at $z=4$ with total inferred SFR of $>8500$ Msun/yr.

Overdensity on several arcmin scales.

Dozens of synchronous starbursts and one flat spectrum radio AGN.

GRH = Great Red Hope
Oteo in prep
Summary

Herschel’s key strengths were in producing huge statistical samples of FIR sources across a wide area and redshift range.

Herschel combined with multi-wavelength data has provided:

• Cosmic evolution of total SFRD.
• Cosmic evolution of dust/gas density
• Evolution of black hole accretion

Herschel also allows study of rare populations through very wide area surveys:

  Strong lenses to study distant SF galaxies in exquisite detail

The most powerful starbursts in the Universe at z > 4

Beware the effects of angular resolution in Herschel studies