DUST EMISSION IN GALAXIES

OBSERVATIONAL BASICS

Intro to dust emission properties to kick off the review.

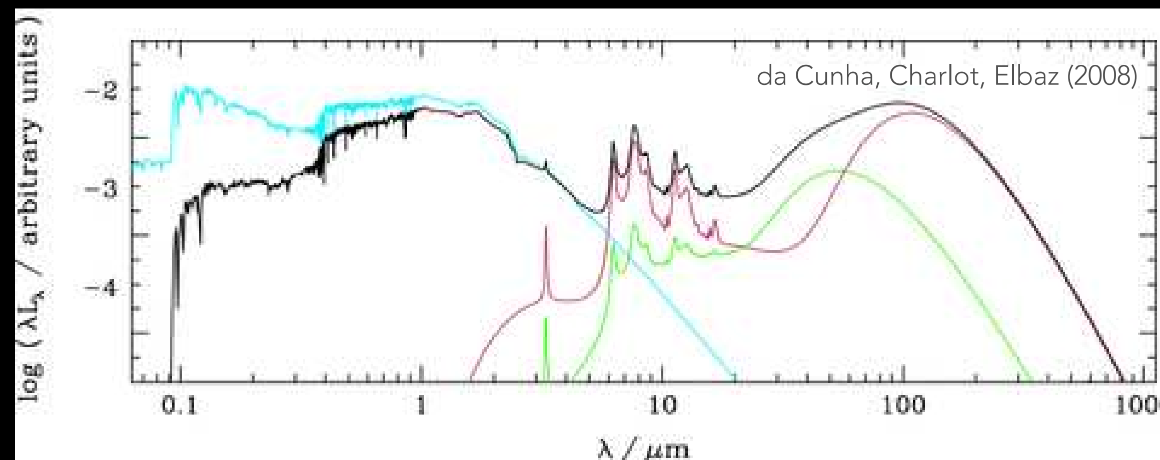
PLAN

- The SED of dust emission
- Calibrating star-formation rates from the infrared
- Tracing gas with dust mass measurements

SPECTRAL ENERGY DISTRIBUTIONS

THE SED OF DUST EMISSION

THE SED OF DUST EMISSION



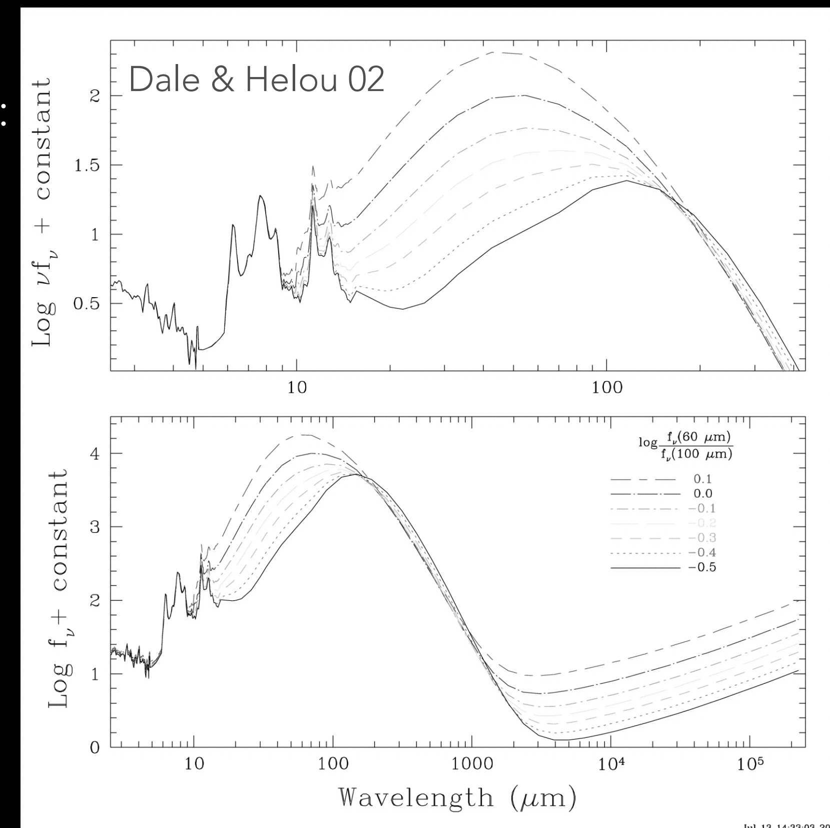
The SED of a full galaxy - in these units, the energy absorbed in the UV-optical is the area between cyan and black lines on the LHS, and this is reradiated by dust in the green and red.

This is the light which is absorbed not scattered. cf extinction curve = abs+scattering

Absorption and scattering will be covered another week.

THE SED OF DUST EMISSION

- Contributions from:
- PAHs (molecules not dust)
- Very small grains (power law)
- Large grains at various temperatures



Various SED modelling papers offer templates for the IR SED of galaxies. Chose this because it shows both nu.f_nu and f_nu. The top one indicates energy emitted, which if you integrate under this curve is about equal to that in the full optical SED from starlight. The bottom one is specific flux in Jy-like units, which is much higher in the FIR than the optical.

Note MIPS spitzer bands, PACS, SPIRE, SCUBA2

Large grains are composed of graphite and silicates up to a micron in size. Small grains are much smaller, down to a few Angstroms (NB atomic size is about 1A).

VSGs have low heat capacity and are stochastically heated by absorption of individual photons because they never attain TE. They oscillate between temperatures of 50-500K on timescales of order minutes and tend to emit a power law in the MIR (non-thermal).

THE SED OF DUST EMISSION

- The modified blackbody

Spectrum of a body with perfect emissivity:

$$B_\nu(T) = 2h\nu^3 \frac{1}{\exp(h\nu/kT) - 1}$$

Emissivity of dust grains: size≪**λ**

$$\kappa_{\rm FIR} \propto \lambda^{-\beta} \propto \nu^{\beta}.$$

Resulting spectrum:

$$S_\nu(T) = \nu^\beta B_\nu(T)$$

Spectral index: **β**=1.8±0.2 (in the Milky Way - Planck collab.)

Some basic properties of the emission SED.

The SED is dominated by the emission from large grains which follows a modified blackbody which of course is a function of temperature.

The modified bit is the additional power-law frequency dependence which represents the changing emissivity (or equivalently opacity) of the grains at different wavelengths, and depends on the grain size distribution. For interstellar dust, grain size << wavelength and the relationship is a simple power law. The value of beta is generally measured at somewhere between 1.5 and 2.0; for the Milky Way it was measured by Planck at 1.8 (with dispersion about 0.2).

THE SED OF DUST EMISSION

- Wien's Law

Wien's displacement law (modified BB):

$$\lambda_{\mathrm{peak}} / \mu\mathrm{m} \approx 3000 \left(\frac{5}{\beta + 5}\right) \frac{1}{\mathrm{T_{dust}/K}}$$

...for a spectrum in S_λ;
For S_ν (Jy) replace the prefactor with 5100, or in νS_ν replace with 3670; hence...

Cold dust: T=25K, $\lambda \approx 108\mu m$ (β=1.8)
Starburst: T=50K, $\lambda \approx 54\mu m$ (β=1.8)
AGN dust: T=500-1500K, $\lambda \approx 5.4$-$1.8\mu m$ (β=1.8)

Wien's law, or Wien's displacement law, shows the relationship between temperature and the peak wavelength of the blackbody.

In general: lambda_max=hc/xkT with x=4.965 (S_lambda spectrum)

or x=2.821 (S_nu spectrum) or x=3.921 (nuS_nu spectrum)

The peak wavelength for an S_lambda spectrum is given by 2898/T

The peak wavelength for an S_nu spectrum is given by 5101/T

The peak wavelength for a nuS_nu spectrum is given by 3670/T

So cold dust in the diffuse ISM at 25K peaks at 110um, and warmer dust surrounding star forming clouds or starburst you might get more like 50K which would peak at 50um.

The dust torus around an AGN will be at around 500-1500K and would peak in the NIR or MIR - but the SED will actually be more of a power-law due to the broad distribution of temperatures.

THE SED OF DUST EMISSION

- The Stefan-Boltzmann Law and Dust Temperatures:

In regions remote from individual stars:

intensity of the ISRF: $U = \frac{4\sigma}{c} T^4$
(interstellar radiation field)

T depends primarily on intensity of ISRF, not colour

In general, dust is in radiative eqm. with the ISRF, NOT in thermal eqm. with interstellar gas

Hence: molecular clouds = cold gas = warm dust
interstellar HI/HII = warm gas = cold dust

This links the energy density of the radiation field with the equilibrium temperature of the dust. The temperature is primarily dependent on the intensity of the ISRF and not the colour.

This holds in ISM regions remote from individual stars (not in HII regions)

So dust around star forming regions absorbs more energy from the strong ISRF originating from a dense population of bright stars, and is therefore warmer than dust in more quiescent regions.

Dust is in radiative equilibrium with the ISRF, not in thermal equilibrium with the gas (TE requires collisions, yet these are rare because the ISM is so diffuse)

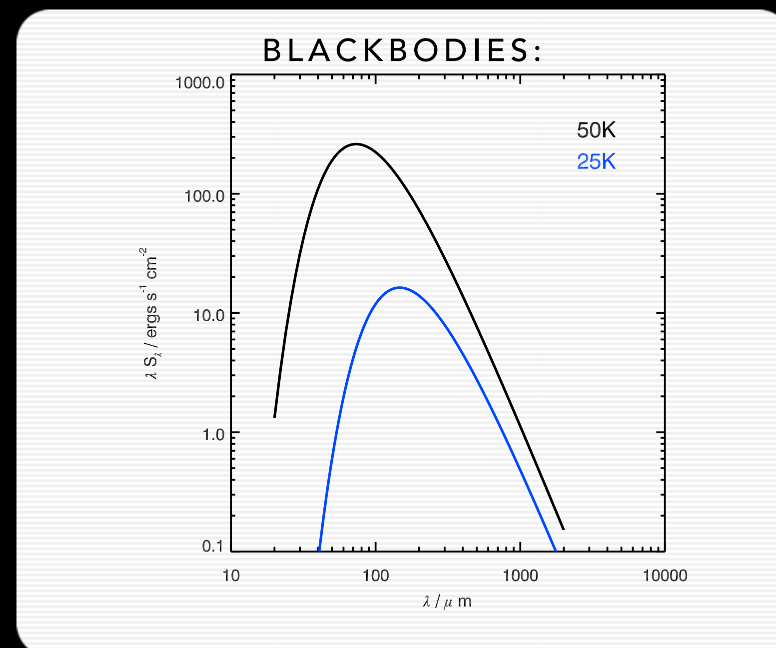
Collisional heating is only important in hot dense plasma such as shock-heated gas in SNRs.

In consequence, dust in the hot gas phase (interstellar HI and HII clouds) is generally cold, and is warm in the cold gas phase (molecular clouds).

On the other hand, the very dust in the centres of the densest clumps and cores in SF regions is shielded from the ISRF by extremely high optical depths and so can get very cold.

THE SED OF DUST EMISSION

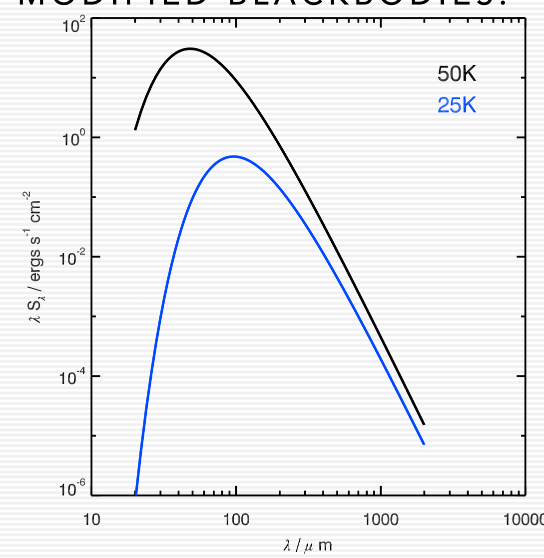
- Some consequences…



If we simply plot the black body SED of a body at 25K and the same body at 50K. The y axis is lambda*Slambda so represents actual energy at a given wavelength, rather than specific energy per unit frequency or per unit wavelength. Notice that although the peak is at a redder wavelength for the cold body, the power emitted is lower at all wavelengths than for the warmer body.

THE SED OF DUST EMISSION

- Some consequences…

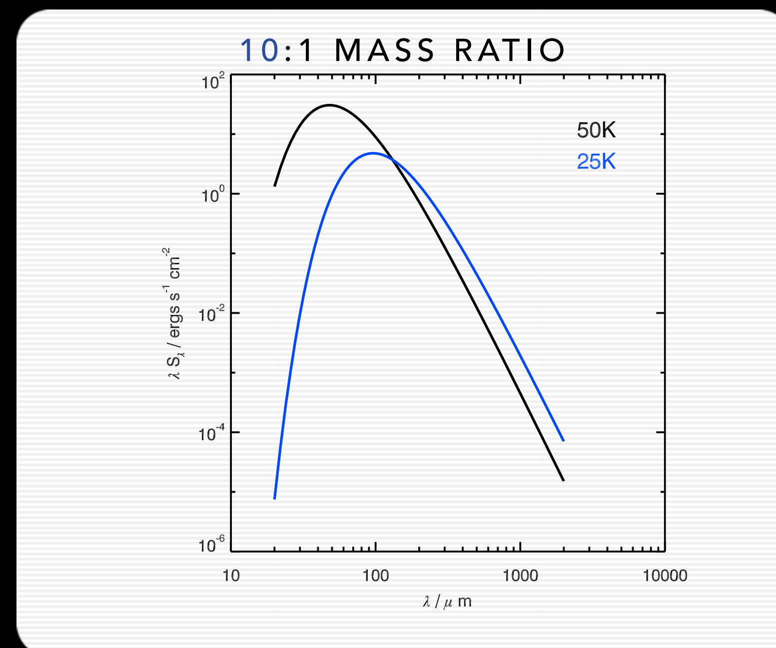


Now we include the nu^beta correction for the emissivity dependence. (beta=2).

note change in shape and movement of the peak, but what I said about the power emitted is still true.

THE SED OF DUST EMISSION

- Some consequences…

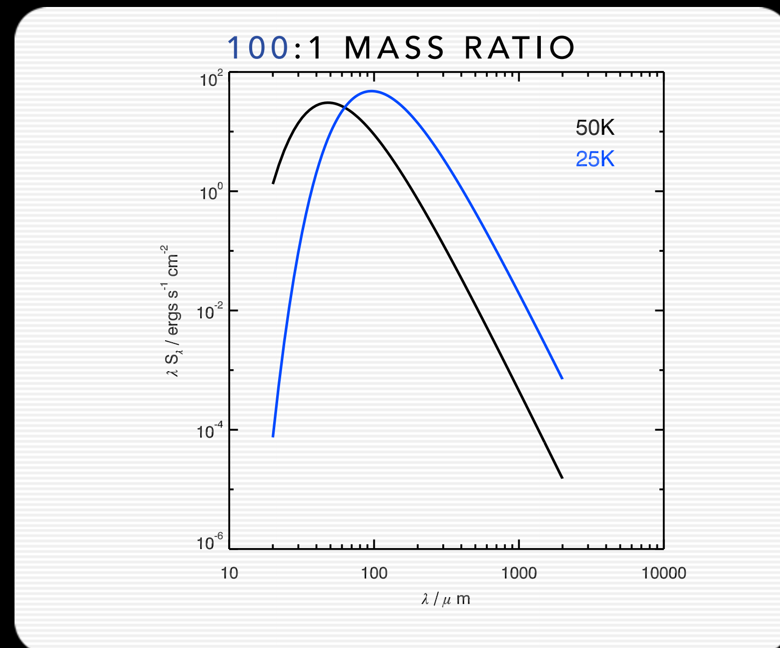


note that if the cold component has most of the mass, its integrated luminosity (area under the curve) is still much lower than that of the warm component (which is 10x less massive)

However, fluxes in the submm are dominated by the cold component: the submm traces cold dust

THE SED OF DUST EMISSION

- Some consequences…



However, when the mass ratio is very large, or in other words when the amount of dust heated to high temperatures is very small, then the colder component eventually begins to dominate the luminosity. So in a galaxy with low star formation rate, the dust luminosity is more dominated by cold dust in the diffuse medium which will be heated by the whole stellar population, not those parts in the molecular clouds.

Now we will see what consequences these things have for our physical measurements…

STAR FORMATION RATES

CALIBRATING SFR FROM THE INFRARED

DUST AND SFR

- Calibrating SFR from the FIR: *we assume…*
    - Total SFR $\propto$ rate of Massive star formation
    - Massive (OB) stars are short-lived and emit large amounts of energy in the UV
    - They remain within birth-clouds which are enshrouded in dust
    - The dust absorbs a fraction of the UV radiation and its emission is therefore correlated with the number of massive stars, hence the SFR
    - Emission from this warm dust is more luminous overall than that from colder dust (even if there is more of the cold dust)

Dust emission is used to trace the rate of star formation in obscured regions because:

massive stars are short-lived and emit a lot of UV light;

They tend to be obscured within dust clouds because they are born in giant molecular clouds and are in general too short-lived to leave them

These stars dominate the radiation field in these regions and heat the dust to temperatures of 40-60K. This warm dust then dominates the FIR output of the galaxy because higher temperature => high luminosity

DUST AND SFR

- Kennicutt 1998 (ARA&A): $\mathrm{SFR}(M_\odot\ \mathrm{year}^{-1}) = 4.5 \times 10^{-44}\ L_{FIR}\ (\mathrm{ergs\ s}^{-1})\ (\mathrm{starbursts})$
  - L_{FIR}=8-1000µm
  - Assuming continuous bursts of 10-100Myr (not applicable where the age is >10^8 yrs)
  - Assuming single power-law Salpeter IMF between 0.1-100$M_\odot$
  - see also Kennicutt et al. (2009) for updated composite tracers
- Kennicutt & Evans 2012 (ARA&A): $\log \dot{M}_*(\mathrm{M}_\odot\ \mathrm{year}^{-1}) = \log L_x - \log C_x.$
  - Kroupa & Weidner (2003) IMF: Salpeter slope (-2.35) @1-100$M_\odot$; flatter (-1.3) @0.1-1$M_\odot$
  - Very similar to Chabrier (2003) IMF

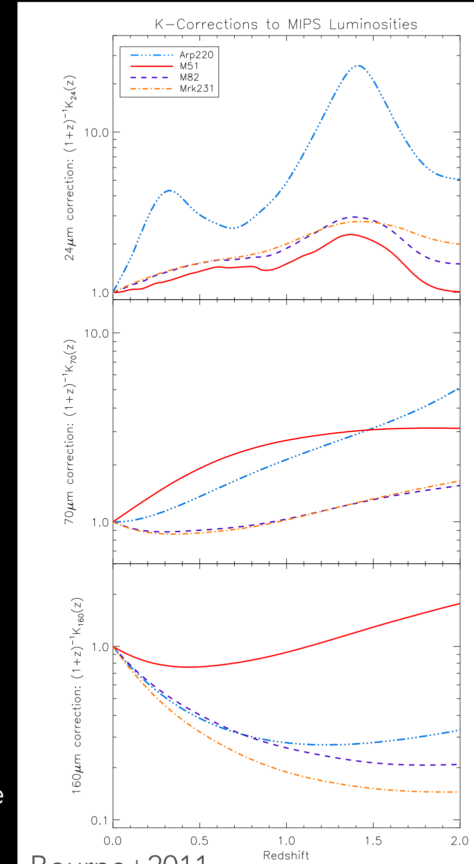
Band	Age range (Myr)[a]	L_x units	log C_x[b]	$\dot{M}_*/\dot{M}_*$(K98)[c]	Reference(s)
TIR	0-5-100[d]	ergs s^{-1} (3–1100 µm)	43.41	0.86	Hao et al. (2011), Murphy et al. (2011)
24 µm	0-5-100[d]	ergs s^{-1} (νL_ν)	42.69		Rieke et al. (2009)
70 µm	0-5-100[d]	ergs s^{-1} (νL_ν)	43.23		Calzetti et al. (2010b)

for example… most commonly used calibrations…

others exist for specific photometric filters but all make similar assumptions.

DUST AND SFR

- Potential problems:
  - Single-band calibrations are subject to the k-correction (especially if sampling the Wiens side)
    - depends on AGN, VSGs and PAHs
  - Measuring only the obscured part of the SFR:
    - really want UV+IR
  - Assuming FIR emission from dust heated by young stellar population with age $<10^8$ yrs
    - older stellar populations can also contribute to dust heating



Bourne+2011

Problems with this picture:

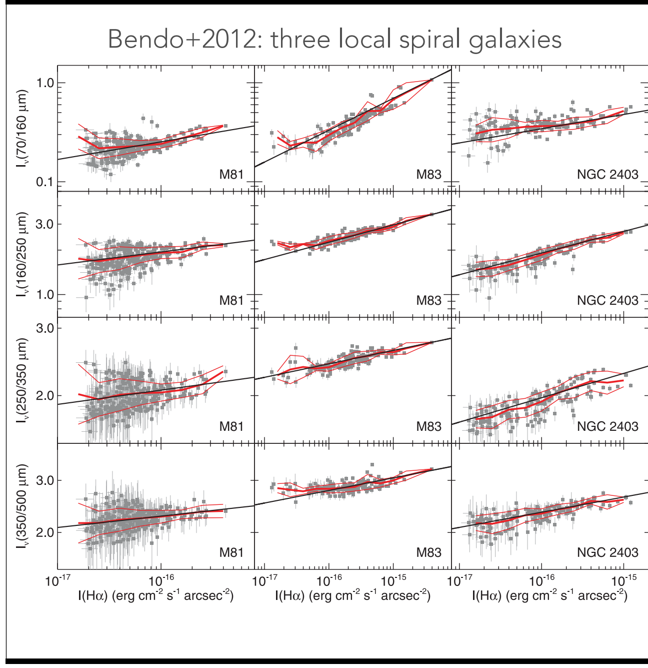
k-corrections: on the Wiens (short-wavelength) side of the peak, the k-correction is very temperature dependent, and is also subject to power law contributions from VSGs, from AGN-heated dust, and from contributions from PAH bands (NB the AGN contribution is a power-law not a thermal shape because of the range of dust temperatures in the torus)

k-correction at longer wavelengths depends on the temperature and on beta (these are degenerate). In RJ tail (power-law) it depends on beta only.

Obscured SFR only: in ULIRGs and LIRGs (for which these calibrations are generally applied, or at least should be, it is reasonable to assume that most of the SFR is obscured - but that is not the case in galaxies with lower SFRs.

DUST AND SFR

- Dust heating by older stellar populations:

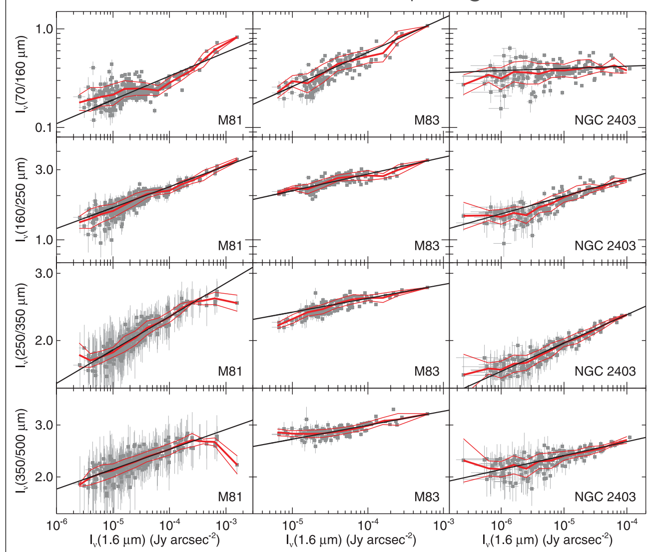


Bendo et al studied 3 local spiral galaxies with resolved Herschel mapping, looking at flux ratios in independent sight lines (beams) within the galaxies. Correlate dust temp with intensity of radiation at different wavelengths: Ha tracing intensity of radiation in star-forming regions, and 1.6um tracing intensity of radiation from old stellar population.

DUST AND SFR

- Dust heating by older stellar populations:

Bendo+2012: three local spiral galaxies



Bendo et al 2012: SPIRE colours are better correlated with 1.6um intensity than with Ha. In the ET-spiral M81 this is also true at shorter wavelengths, but in the LT-spiral NGC2403 the shorter wavelengths are better correlated with Ha.

Modelled SEDs from dust heated by two populations (one traced by I(Ha), one traced by I(1.6um)) and found that much of the dust was heated by older populations.

In the figure Eratio=Esf/Etot=I(Ha)/(I(Ha)+AI(1.6um))

Recall the Stefan-Boltzmann law governs dust heating by the radiation field and links U to T.

(more examples from the literature????)

Lonsdale Persson and Helou 1987

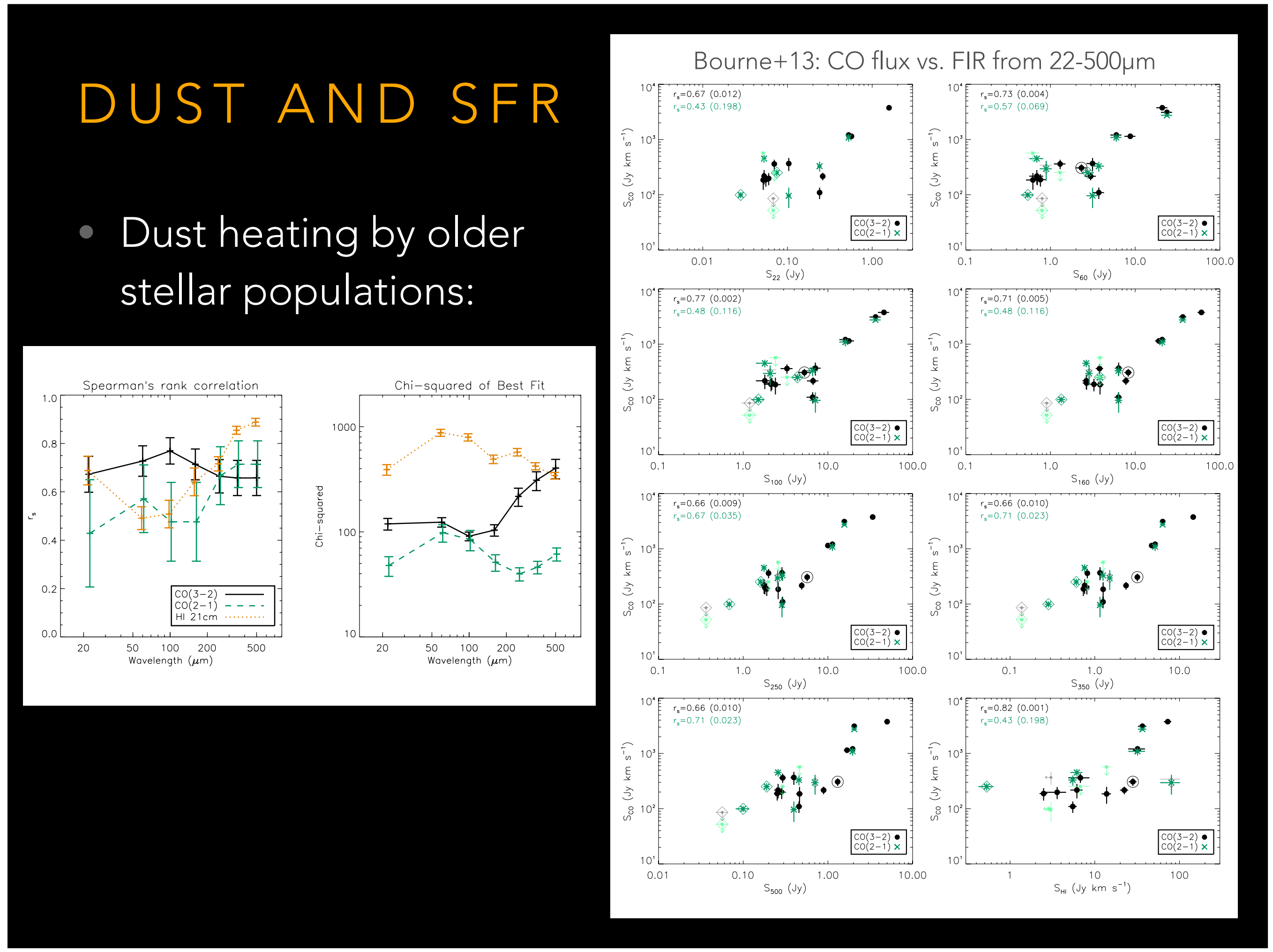
Devereux and Young 1992

Walterbos and Helou 1996

Boselli et al 2010b

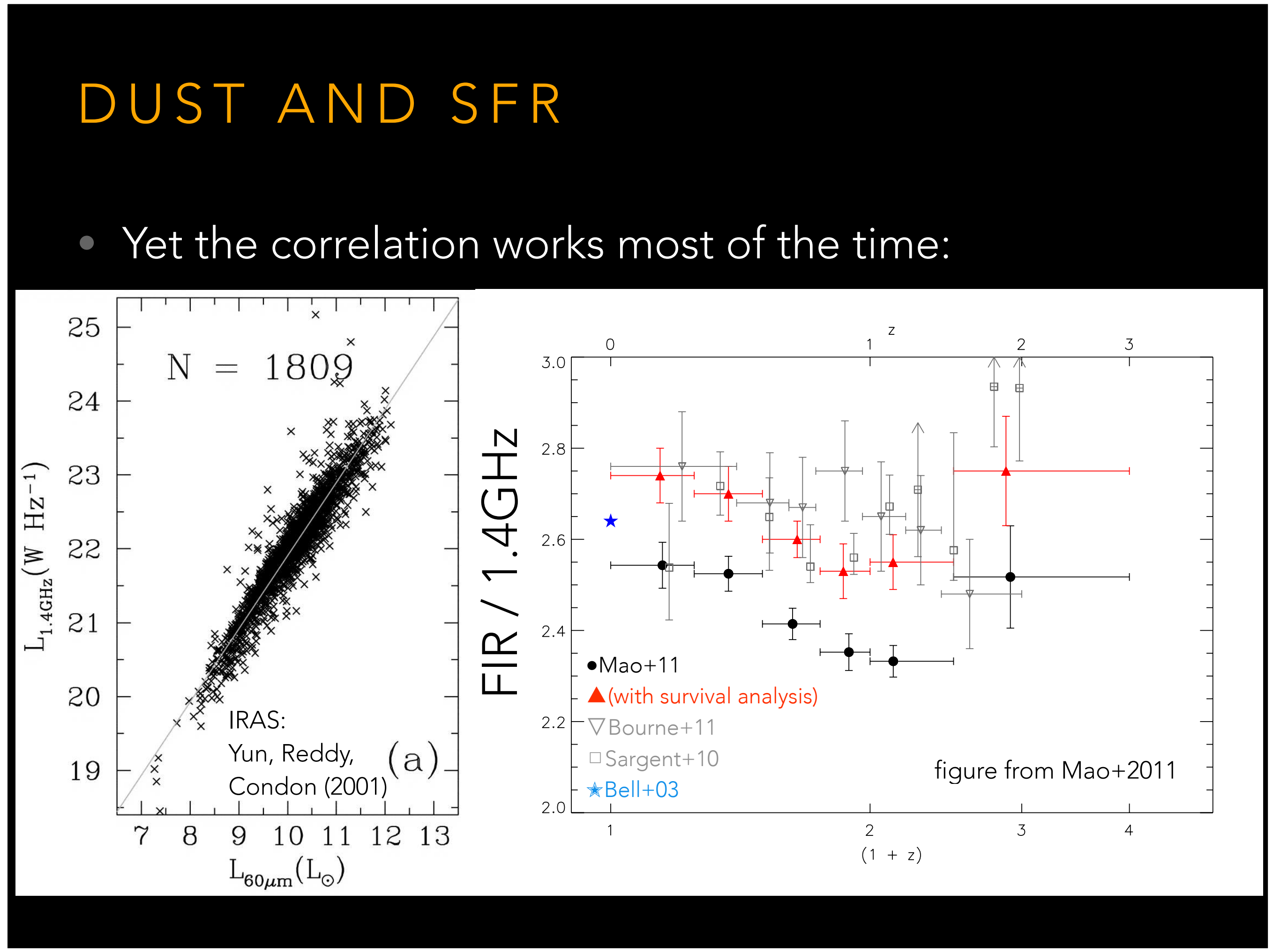
Buat et al 2010

Boquien et al 2011



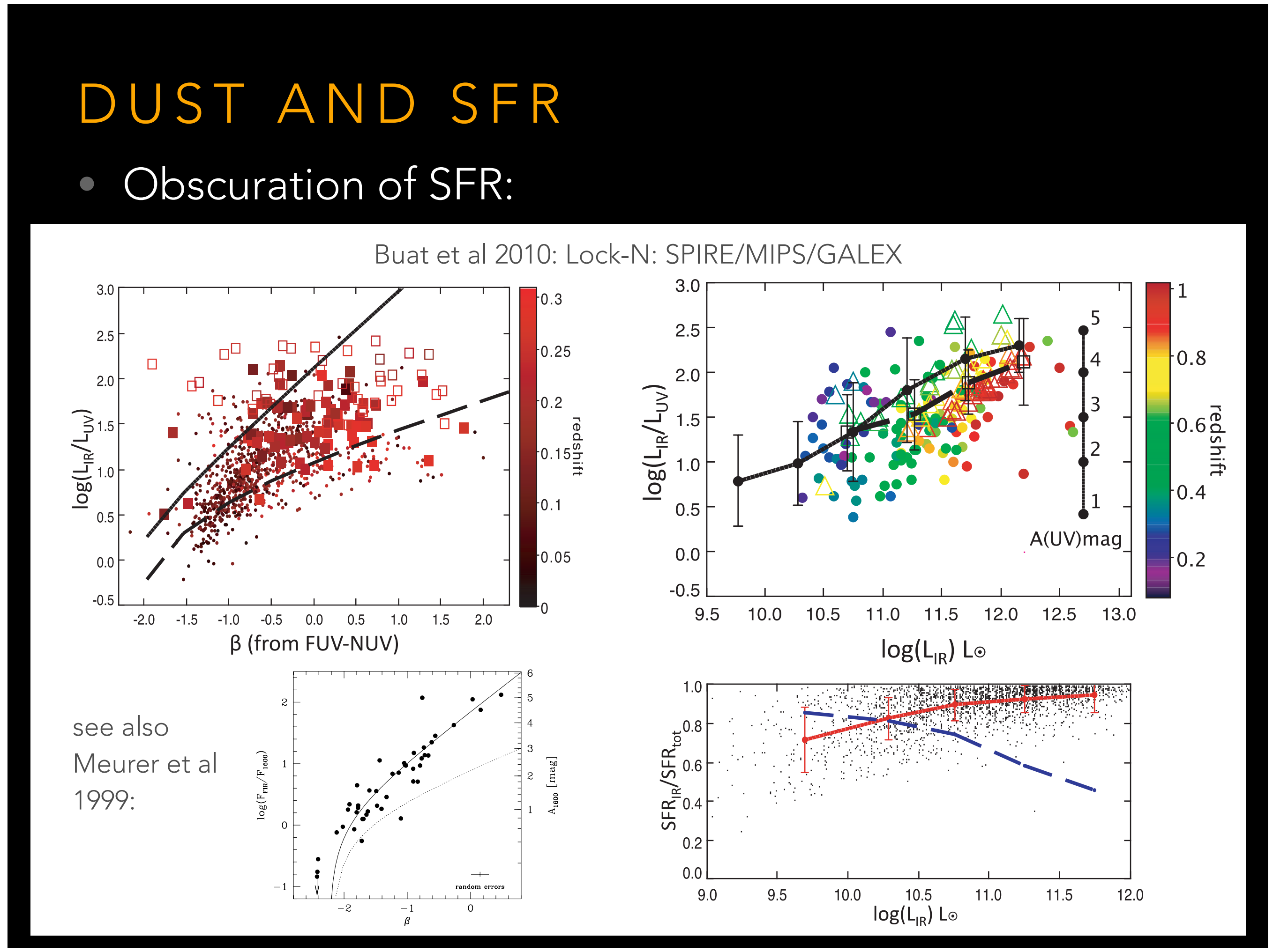
I also found evidence for this in a Herschel ATLAS sample in the local universe: plot CO flux vs FIR flux at different wavelengths from 22 to 500 microns… On the left plot, just looking at the black line you see that the correlation coefficient from these correlations, as a function of wavelength, is slightly lower at long wavelengths indicating poorer correlation between dense gas and submm flux, also lower at 20-60 microns - this is where VSGs can dominate. Opposite trends seen in chi-squared which is a measure of scatter around some fiducial best fit.

These galaxies were selected to be cold, but in this sample we see evidence that other populations may be heating both the cold dust and the VSGs. This means that the conversion from IR luminosity to SFR is not fixed but depends on how much of the IR luminosity results from heating by relatively old stars.



Nevertheless, the assumptions do work well/ or at least they allow us to make useful measurements…

FIR-radio correlation is very tight over many orders of magnitude, and holds in full range of star-forming galaxies as well as star-forming regions within galaxies.



Returning to the problem of only measuring the obscured portion of the SFR: What is the fraction of the SFR that is traced by the FIR, i.e. is obscured?

IRX-beta relationship: the fraction of star formation which is obscured is traced by the IR/UV ratio; and there is a relationship between this and the UV slope, because the UV slope is a measure of the obscuration; it depends on the reddening of the UV spectrum by dust absorption and scattering processes.

Left: filled squares = LIRGS, dots=non-LIRGs, empty squares=LIRGS with less reliable beta measurements; solid line = local SB relation; dashed = local SFG relation

Right: triangles are non-det UV; filled circles = local IR-selected gals; open squares = average from this paper

Shows that dust attention is a function of luminosity or in other words SFR

Bottom right: for most galaxies the IR dominates the SFR: at high LIR it is usually more than 80% of the SFR.

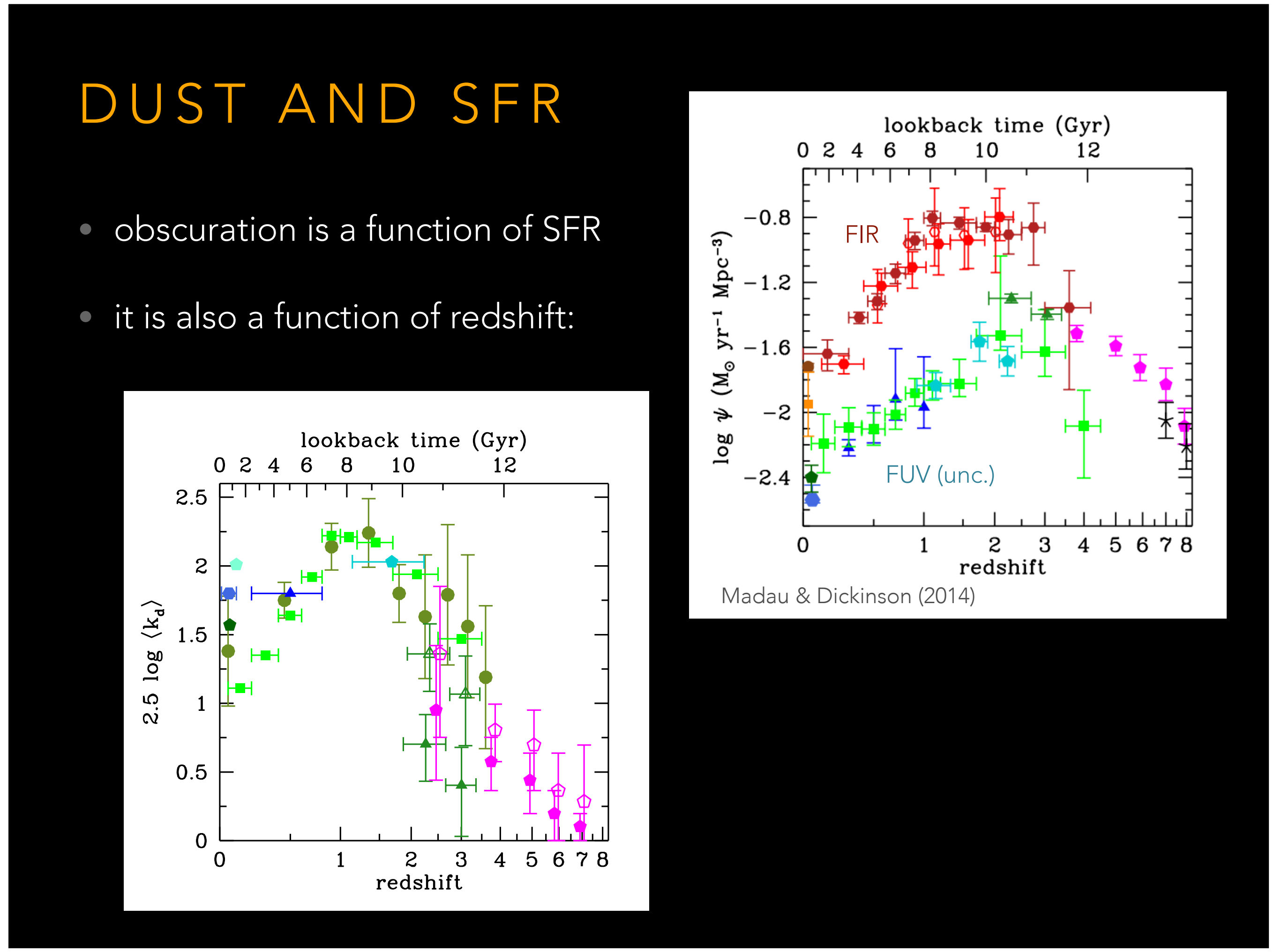
Bottom-right: dashed line = fraction with UV detection. SFR_tot = IR+UV

So the fraction which is obscured is a function of L (therefore SFR)

other refs…

Le Floc'h 2005

Buat et al 2009



We can also see that obscuration of SFR changes with redshift: this is the CSFRD as a function of redshift from Madau and Dickinson's review.

The unobscured SFRD traced by uncorrected FUV falls an order of magnitude below the obscured SFRD traced by FIR.

The obscuration (mean attenuation shown here, on left) as a function of redshift increases towards the peak of the CSFH but seems to decline towards higher z.

DUST AND GAS

TRACING THE RAW MATERIALS FOR STAR FORMATION

DUST AND GAS

- Calibrating gas masses from the dust emission, *we assume…*
  - Dust mass is traced by the dust luminosity, given the temperature
  - Usually this is calibrated in the submm where the emission traces the cold dust component in the diffuse ISM
  - Need the emissivity of the dust: $\kappa_{FIR}(\lambda)$
  - Then assume a dust/gas ratio, which depends on metallicity
  - Generally assume total dust mass traces total gas mass (atomic + molecular phase)

On the one hand we routinely use FIR observations to trace the SFR; but on the other hand they can be used to trace the cold gas mass in a galaxy, which is of course the fuel for SF.
This is because we can assume a constant gas/dust mass ratio, and the dust mass can be calibrated from the FIR.

In general observations on the Wien side (shortward) of the SED peak trace the total luminosity and/or the contribution from warm dust associated with star-formation. On the other hand, observations on the RJ (longward) side and especially in the submm tail are more sensitive to the cold dust which forms the bulk of the dust mass, and are less sensitive to temperature because the RJ law is a power-law. Hence the rest-frame submm at around 300um and longer are best suited for calibrating dust mass.

DUST AND GAS

- Calibrating dust mass from FIR fluxes:

K-correction

Flux measured ideally in the Rayleigh-Jeans tail

$$M_{\rm dust} = \frac{S_{250}\ D_{\rm L}^2\ k(z)}{\kappa_{250}\ B(\nu_{250}, T_{\rm dust})\ (1+z)}.$$

Normalised by the emissivity at the rest-frame wavelength of the observed flux

Blackbody law as a function of the dust temperature

$$\kappa_{\rm FIR} \propto \lambda^{-\beta} \propto \nu^{\beta}.$$

How is this possible?

This equation is written for a 250um flux, but really you want this measurement at as long a wavelength as possible.

Want to have flux measured in RJ tail - this is the long-wavelength limit where the blackbody law approaches a power law.

This means (1) the temperature dependence of the k-correction and the Planck function is minimised, and (2) you are not going to be biased by less massive but hotter components of the dust.

You need to measure or assume a value for the temperature - reasonably simple with two data-points on the RJ tail, although T is degenerate with beta.

The largest uncertainty in the calibration is the value of kappa: recall this is the emissivity which is a function of frequency

DUST AND GAS

- Calibrating dust mass from FIR fluxes:
- Lower κ => higher M/L

$$M_{\rm dust} = \frac{S_{250}\ D_{\rm L}^2\ k(z)}{\kappa_{250}\ B(\nu_{250}, T_{\rm dust})\ (1+z)}.$$

κ/m^{2}kg^{-1}:

κ_{250}=1.6			(Netterfield et al. 2009 - BLAST)
κ_{250}=0.89;	κ_{350}=0.41	κ_{850}=0.077	(Dunne et al. 2000/James et al. 2002 - SCUBA)
κ_{250}=0.58			(Desert et al. 1990 - Theory)
κ_{250}=0.29		κ_{850}=0.025	(Wiebe et al. 2009 - BLAST)
	κ_{350}=0.19		(Li & Draine 2001 - Theory)
κ_{250}=0.24			(Draine & Li 2007 - Spitzer)

Difficult thing to measure…

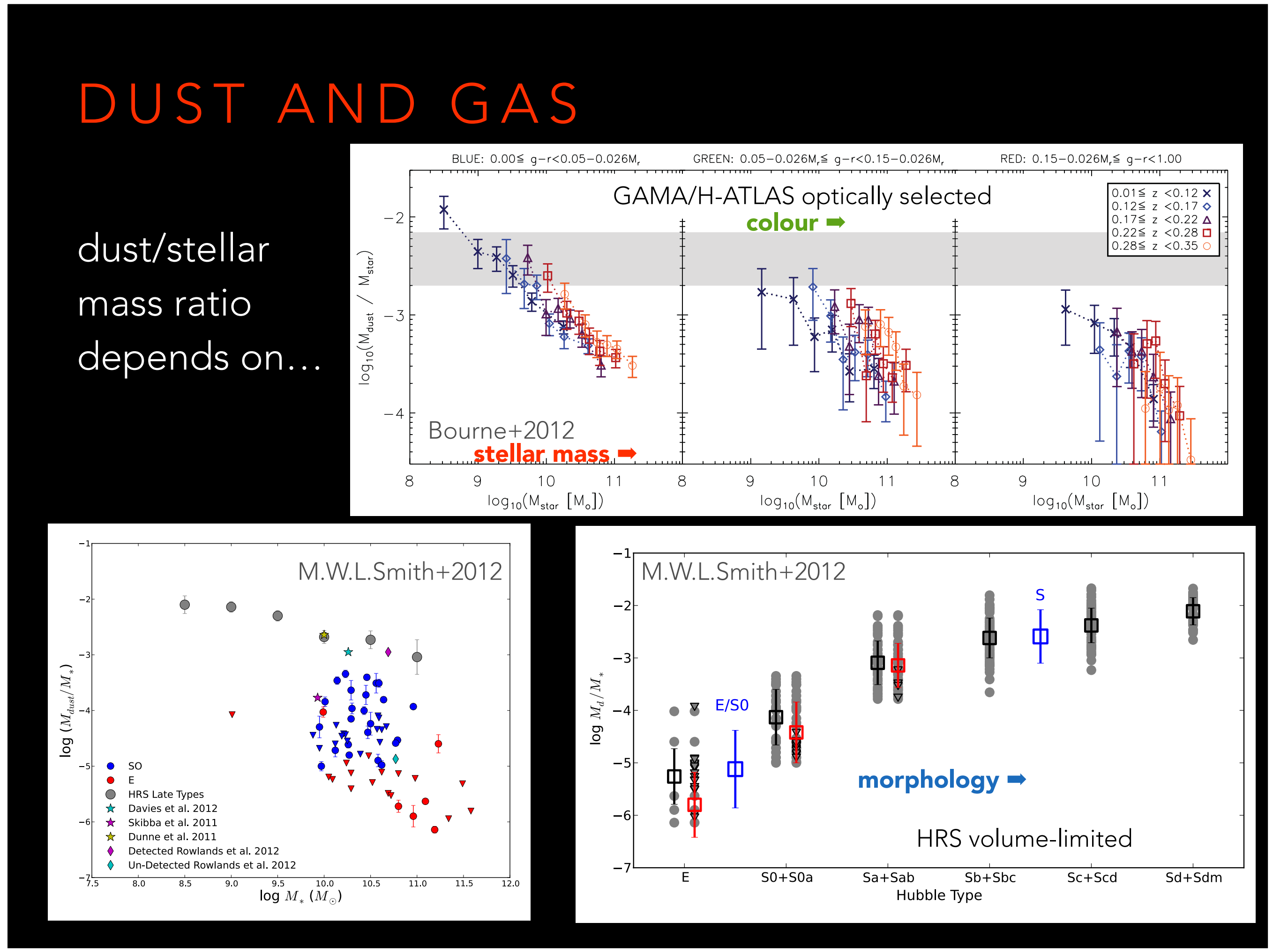
depends on size distribution and composition of grains.

Efficiencies of absorption, scattering and emission are all related.

Can be based on an estimated dust emissivity per H atom (H mass calibrated from 21cm or from CO) and an assumed dust/gas ratio (Netterfield 09)

Or on a measurement of the absorption efficiency in the UV (which should be the same as the emission efficiency in the IR) - so base it on the UV optical depth (Hildebrand 1983)

See also Draine and Li 2007



However, based on these assumptions we can measure the dust masses of galaxies to within a factor of a few (absolute uncertainty), and as a function of various properties.

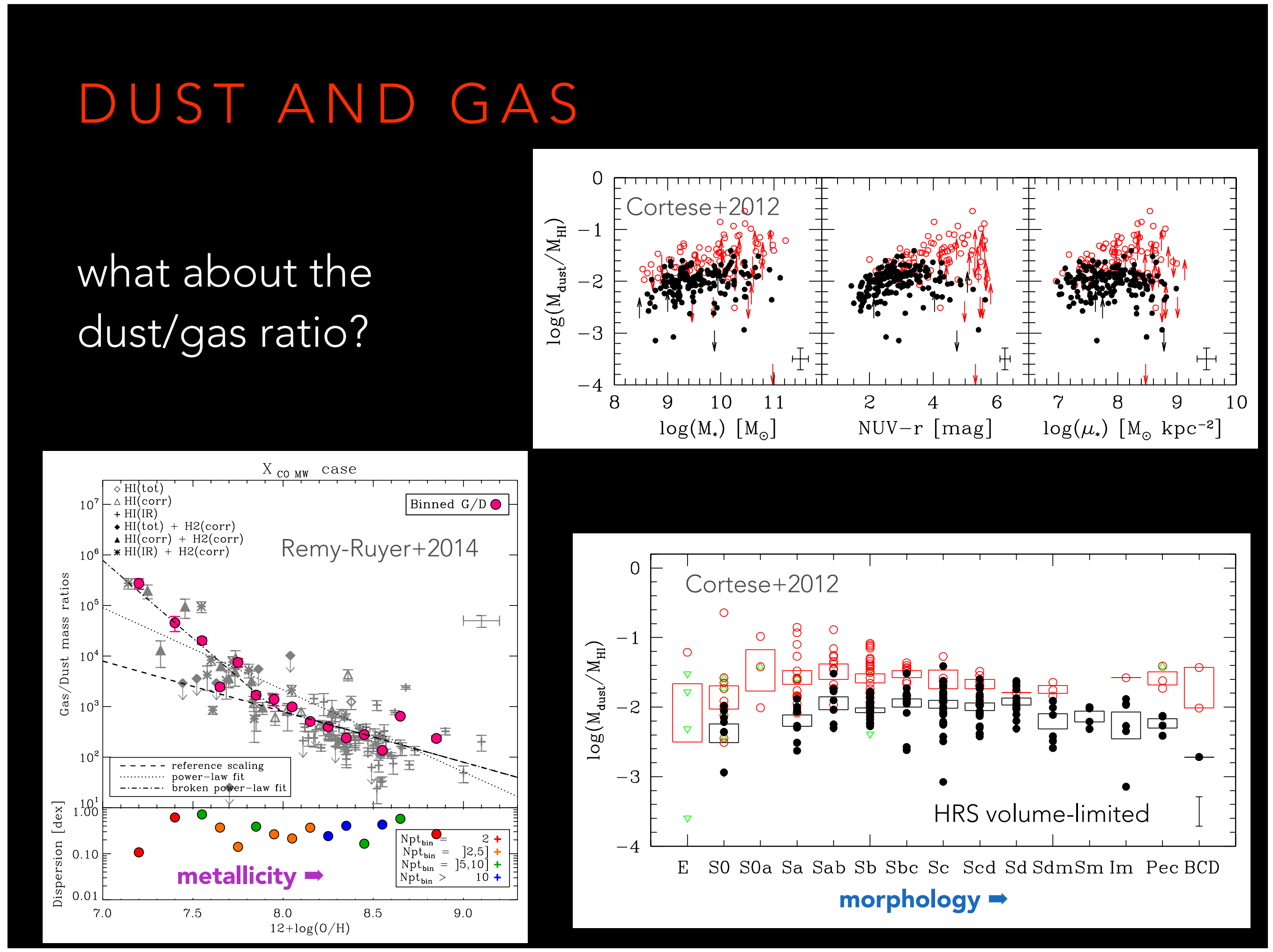
The amount of dust per stellar mass varies as a function of

stellar mass (H-ATLAS optically selected galaxies)

(and HRS volume-limited sample)

and morphology (HRS)

or colour (H-ATLAS)



And the dust/gas ratio, as we'd hope, is more constant at about 1%(for high metallicity at least)…

Cortese:

Squares=average

Black=HI-normal / red=HI-deficient

dust/gas increases with mass and with colour, but about flat with morphology

Remy-Ruyer:

gas/dust (the inverse) decreases with metallicity. More metals=> more dust.

We can go into the dependence of gas/dust on metallicity if people want but that will be a different week.

SUMMARY

- SED of dust emission is a result of re-emission of absorbed starlight
- 40-120μm luminosity dominated by large grains in molecular clouds associated with star-forming regions
    - In most luminous/high-SFR galaxies this dominates the total IR luminosity (8-1000μm)
    - In less active star-forming galaxies, emission at >~200μm often dominated by cooler component of dust associated with the diffuse neutral or ionised medium
- Dust luminosity traces (obscured) SFR but dependent on fraction of dust heating by high-mass stars
- Long-wavelength fluxes trace dust mass but dependent on emissivity coefficient and measurement/assumption of temperature
- Dust mass traces total gas mass, dependent on metallicity-dependent gas/dust ratio

In general observations on the Wien side (shortward) of the SED peak trace the total luminosity and/or the contribution from warm dust associated with star-formation. On the other hand, observations on the RJ (longward) side and especially in the submm tail are more sensitive to the cold dust which forms the bulk of the dust mass, and are less sensitive to temperature because the RJ law is a power-law. Hence the rest-frame submm at around 300um and longer are best suited for calibrating dust mass.