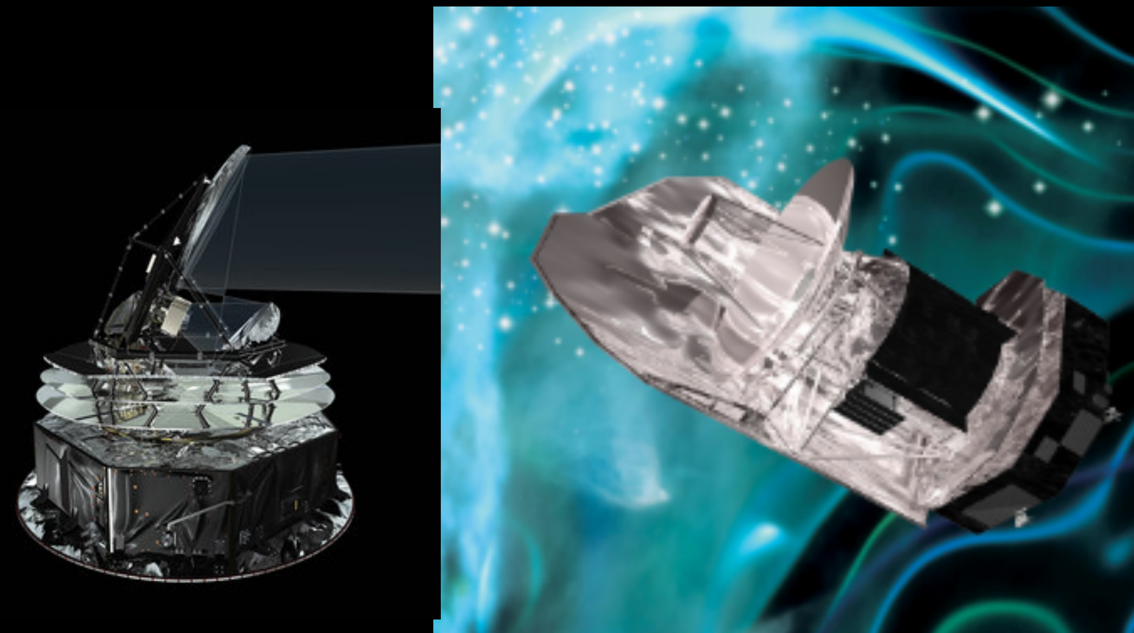
the LOW-ENERGY* view of galaxy evolution

L. Hunt (OA Arcetri)

Two themes here:

- ✓ dust-obscured star formation
- ✓ AGN and stellar feedback



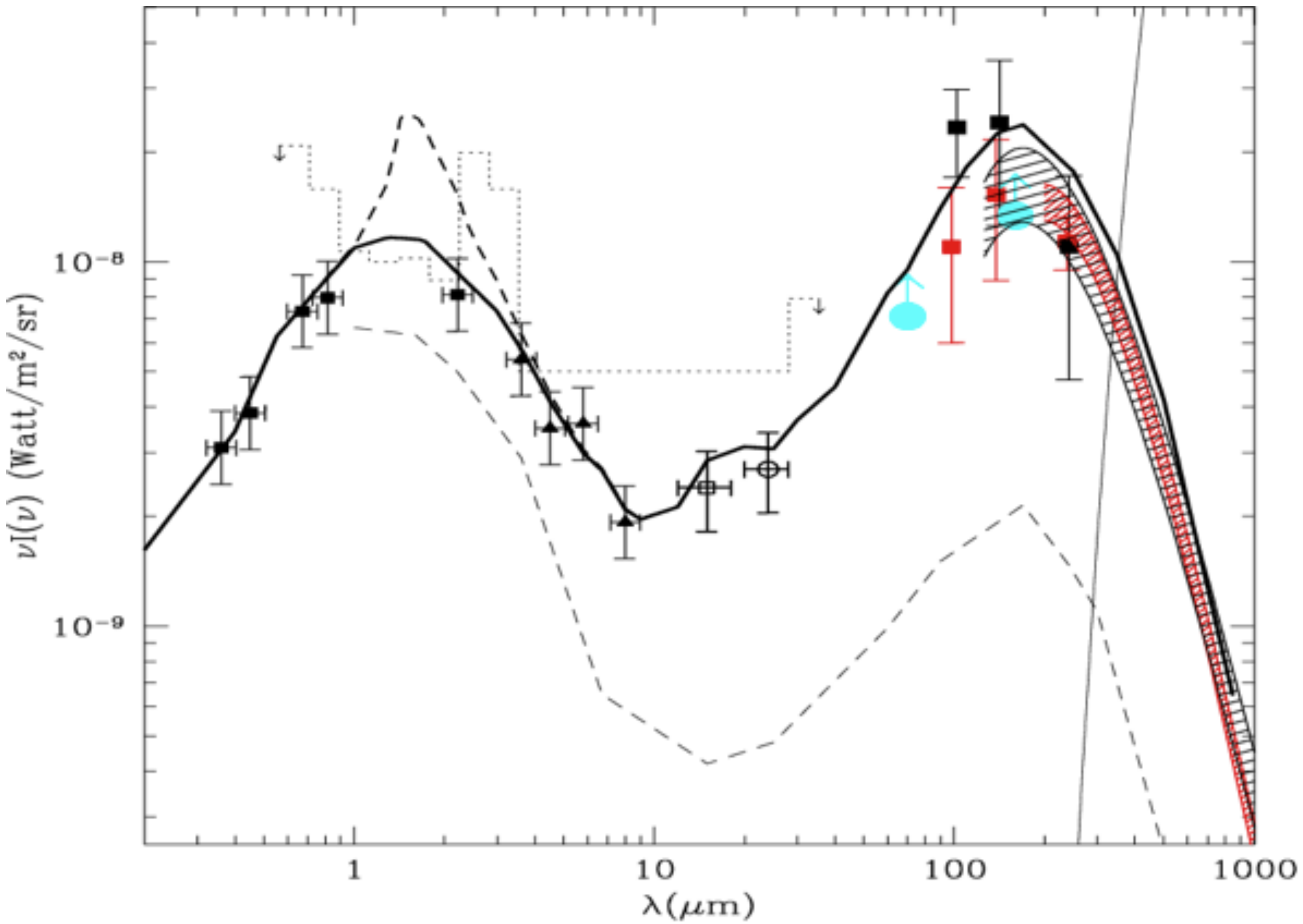
Italy played a fundamental role for *Herschel* and *Planck*, and the "low-energy" INAF community is on the rise

*mid-, far-infrared, (sub) mm: 10-20 μm ≤ λ ≤ 4 mm

NOEMA
IRAM 30m
APEX
ALMA
Planck
Herschel
SOFIA
JWST
Spitzer

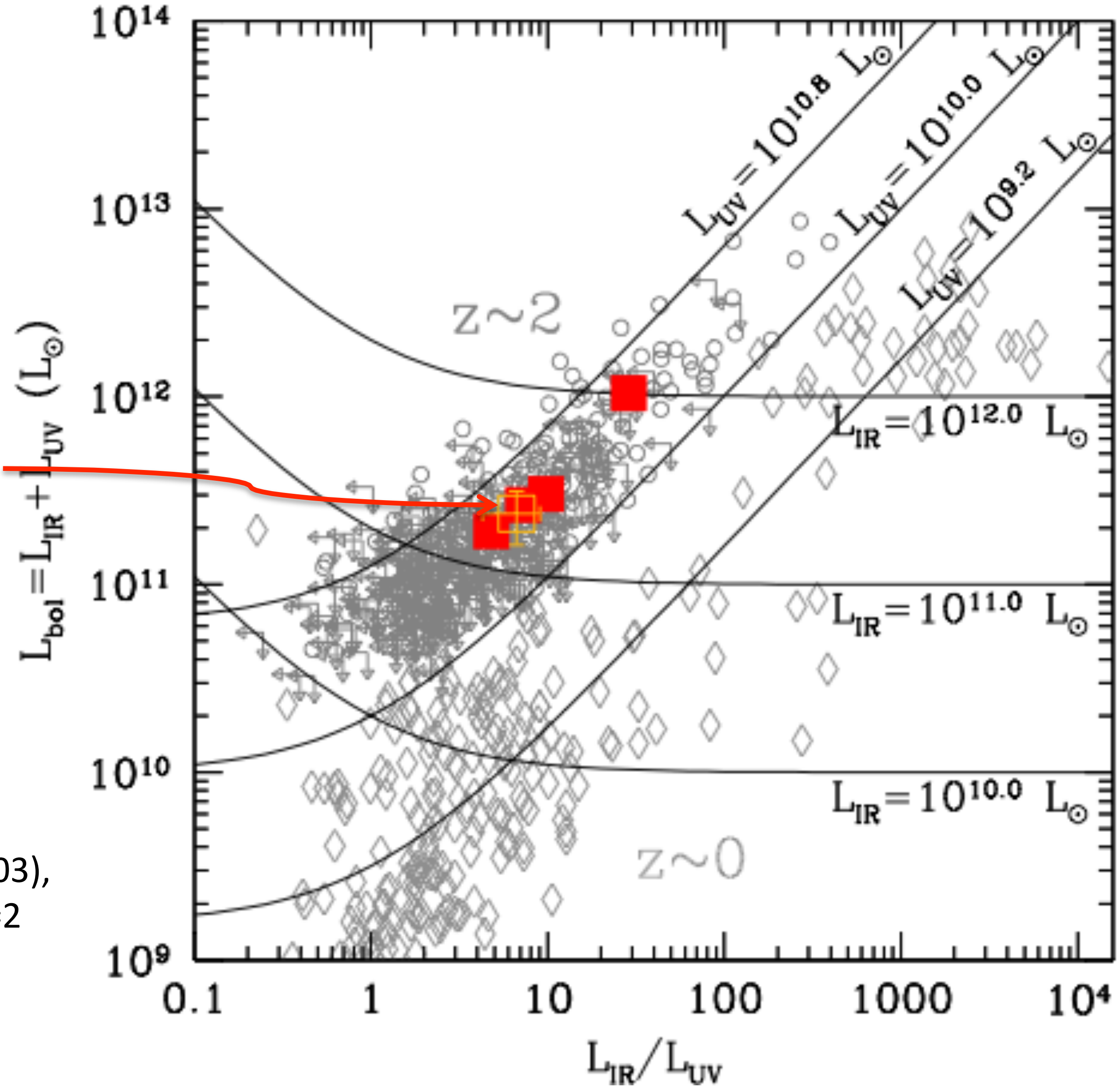
much of the universe is obscured by dust

IRAS, ISO, SCUBA, *COBE, Spitzer, Herschel, Planck* have convincingly shown that half the photons and most of the energy in the universe come from infrared (IR) photons…



Cosmic extragalactic IR background as measured by COBE and optical from ultradeep HST fields, taken from Franceschini + (2008): unresolved infrared-bright galaxies

… and the most luminous galaxies in the universe are also the most obscured. Typical L*galaxies at z ~ 2 have 80% of their SF obscured by dust (Reddy+ 2006, 2012, Casey+ 2014)



z=0 (diamonds) from Bell+ (2003), Huang+ (2009); UV-selected z=2 (circles) from Reddy+ (2010); stacked IR data (squares) from Reddy+ (2012)

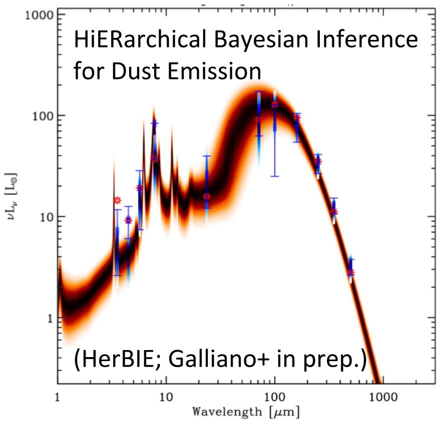
spectral energy distributions (SEDs)
as probes of galaxy evolution

DustPedia - A Definitive Study of Cosmic Dust in the Local Universe (FP7-SPACE proj. 606847, end 6/2018)
PI: Jon Davies (Cardiff University). 6 European nodes. INAF-Arcetri: Bianchi, Casasola, Bocchio

A legacy database of 850 galaxies observed by Herschel (HRS, KINGFISH, HeViCS…).
D_{25} > 1’, v < 3000 km/s, multiwavelength coverage from UV to submm (up to 41 bands/ galaxy)

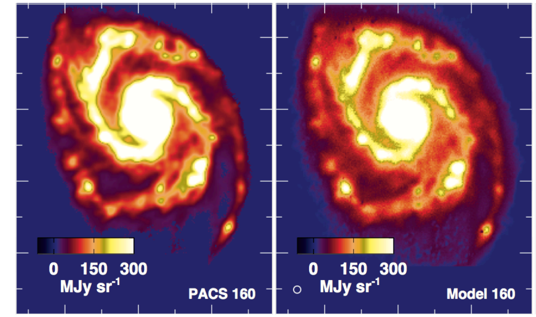
”[…] nearby galaxies offer rich and still far from completely explored clues to a better picture of how galaxies form.” (Peebles & Nusser 2010)

DustPedia

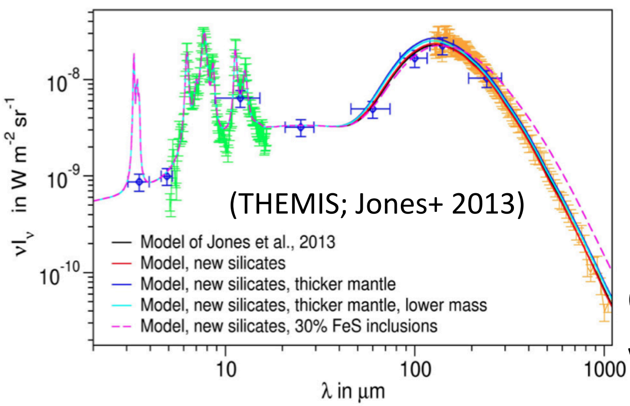


Interpret the galaxy SEDs using full SED and radiative transfer models

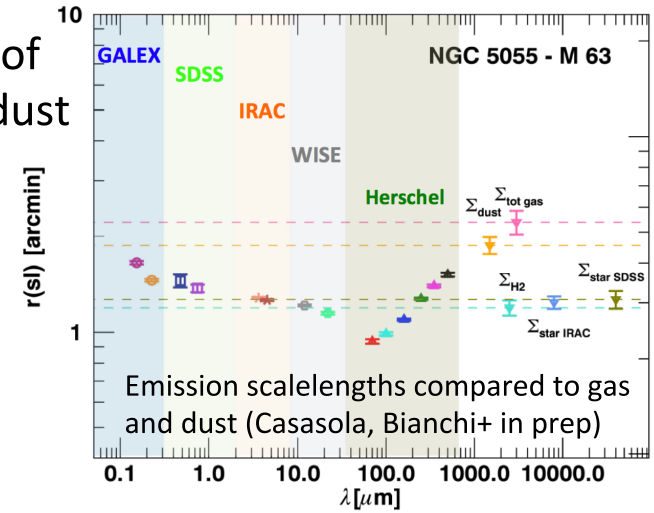
SKIRT model of M51 (de Looze+ 2014)



Study the morphology of stars, gas, metals and dust



Compare MW dust models with DustPedia galaxies.



[A few] DustPedia questions

Can we trace the full dust mass from the SEDs?

Is FIR/submm emission a good tracer of SF?

How dust, gas and metallicity correlate?

Is MW dust the same as in other galaxies?

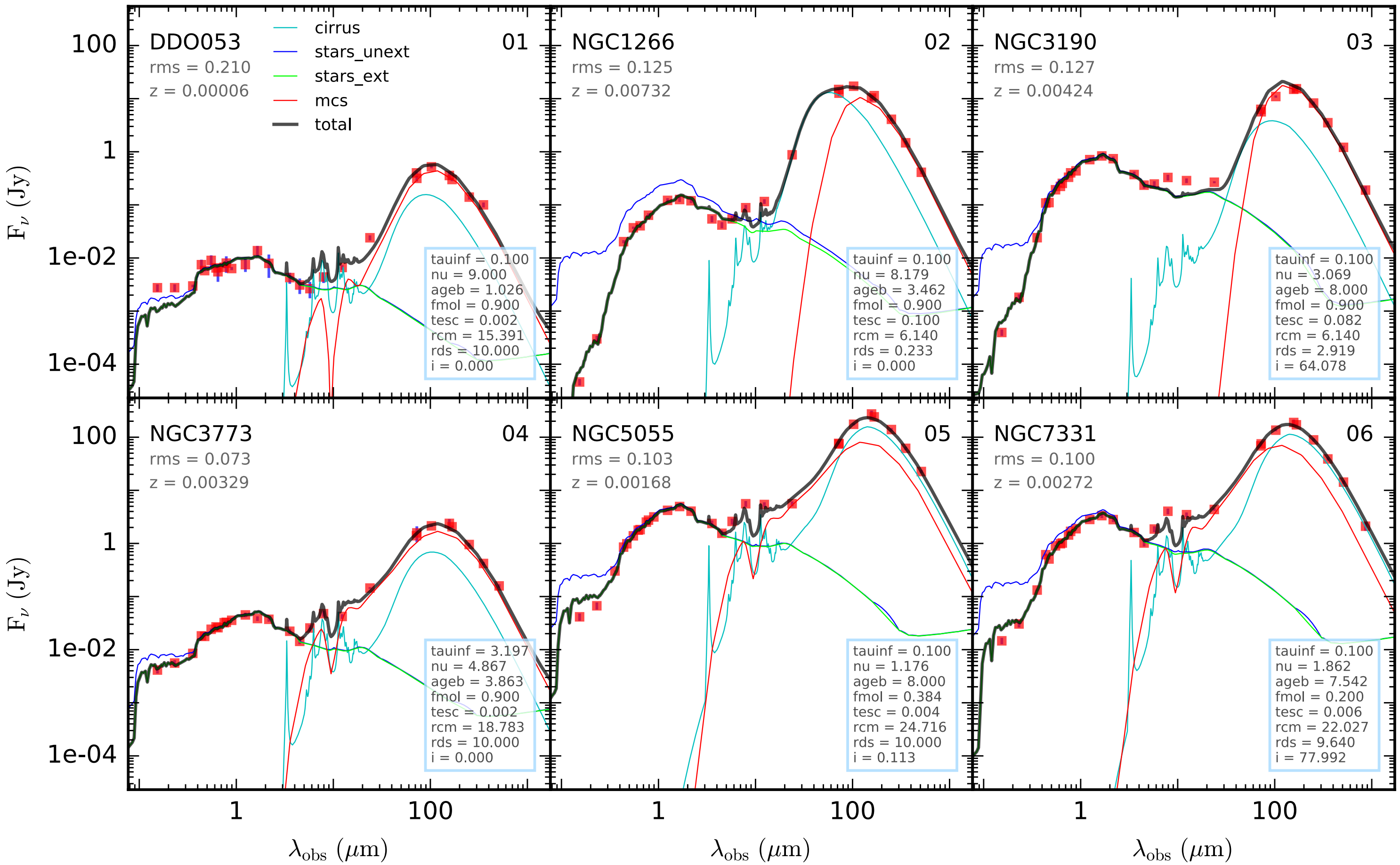
Are evolution models consistent with local dust mass functions and SEDs?

Future needs:

A better MIR coverage to constrain dust heating mechanisms (SPICA)

A more complete molecular (IRAM/NOEMA/ALMA) and atomic (SKA) gas coverage

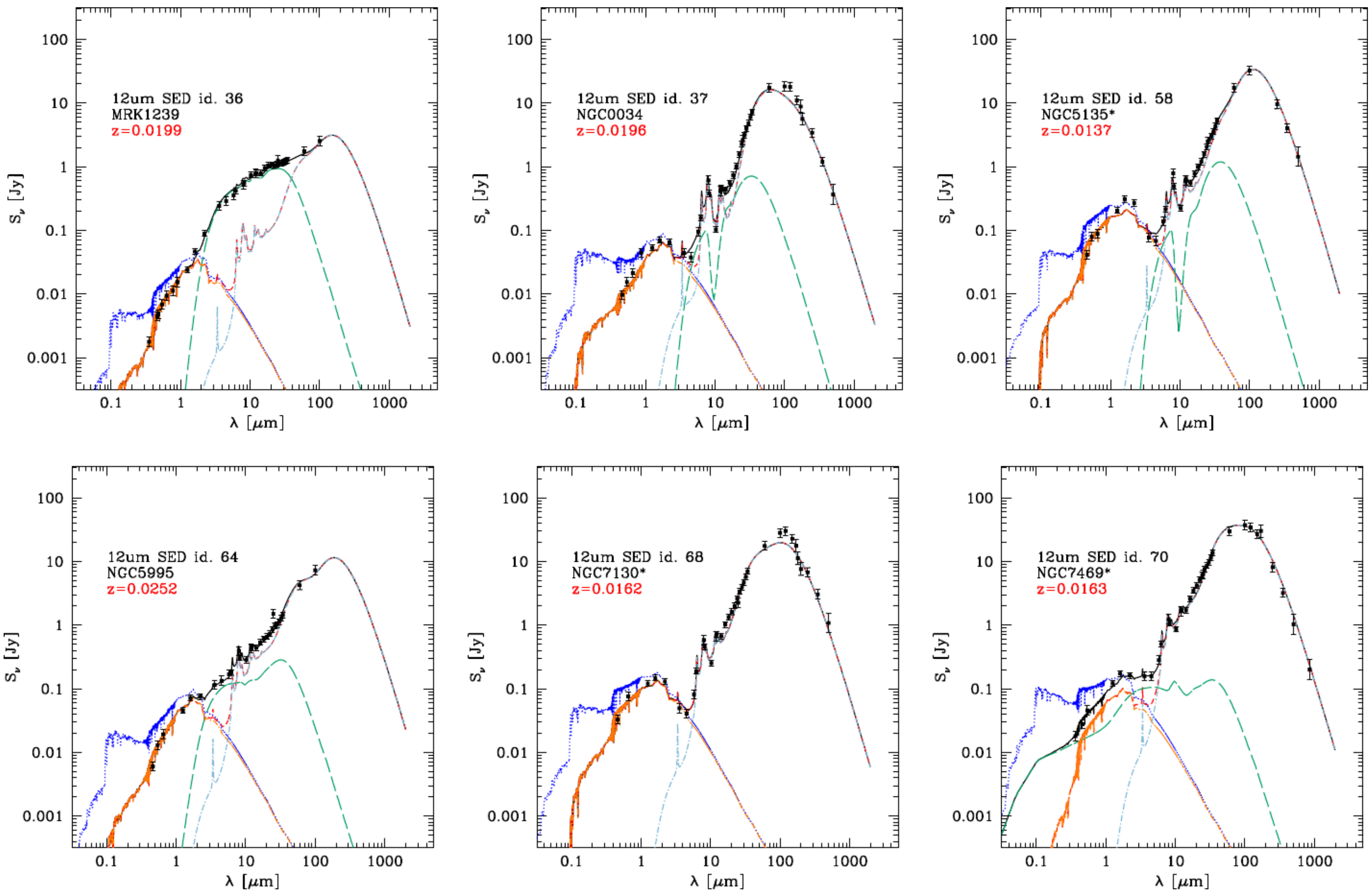
SEDs of nearby galaxies dominated by dust



PRIN INAF 2012 (The role of dust in galaxy evolution: PI Hunt):with OA Trieste, IASF-Bologna, SED fits of KINGFISH galaxies with new library of GRASIL models (Silva+ 1998)

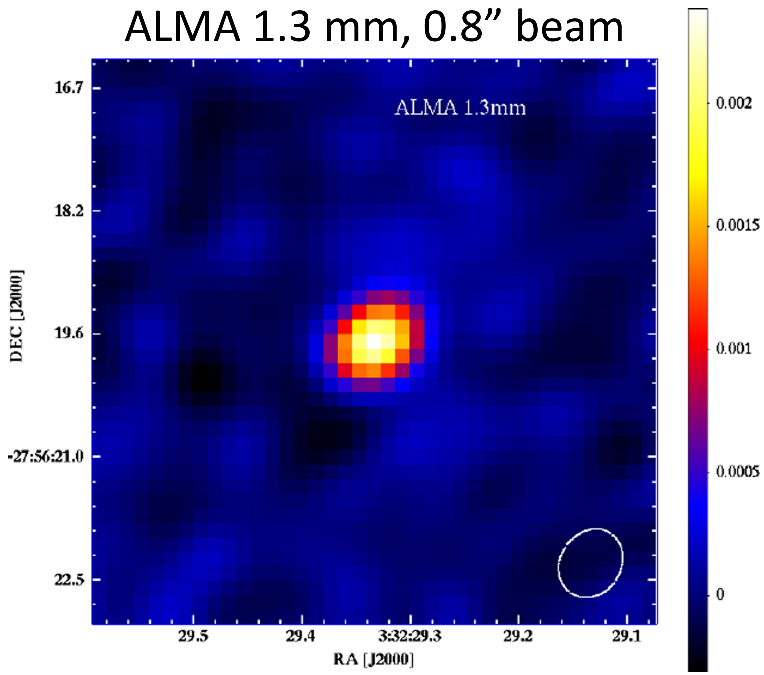
see also PRIN INAF 2012 (Looking into the dust-obscured phase of galaxy formation through cosmic zoom lenses in the Herschel Astrophysical Terahertz Large Area Survey: PI Massardi)

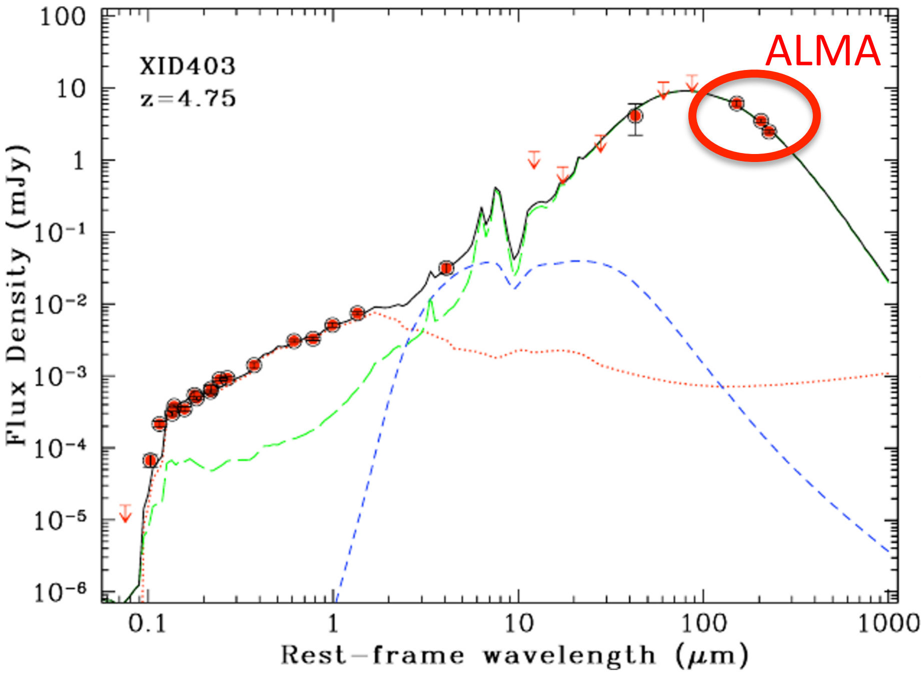
SEDs of local AGN (hosts) also dominated by dust



SED decompositions into stellar, AGN torus, and star-forming components of nearby AGN from the IRAS 12μm sample (taken from Gruppioni+ 2016)

warm, compact starburst + heavily obscured AGN at z=4.75





LESS J033229.4-275619 (XID403), a ULIRG at z=4.75 observed with ALMA in Cycle 0 by Gilli+ 2014.

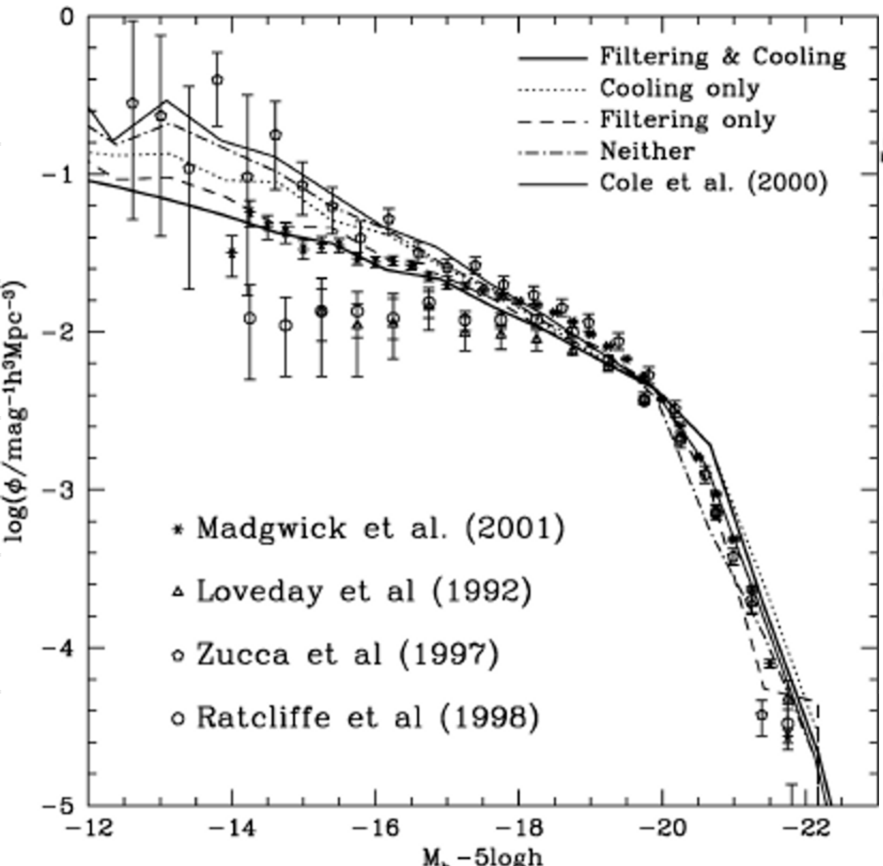
MULTI-WAVELENGTH ANALYSIS: reanalyses of FORS2 spectra and 4Ms Chandra X-ray spectrum show evidence for a possible outflow (redshifted Lyα) and for 6.9 keV Fe line consistent with outflowing thin plasma (Gilli+ 2014)

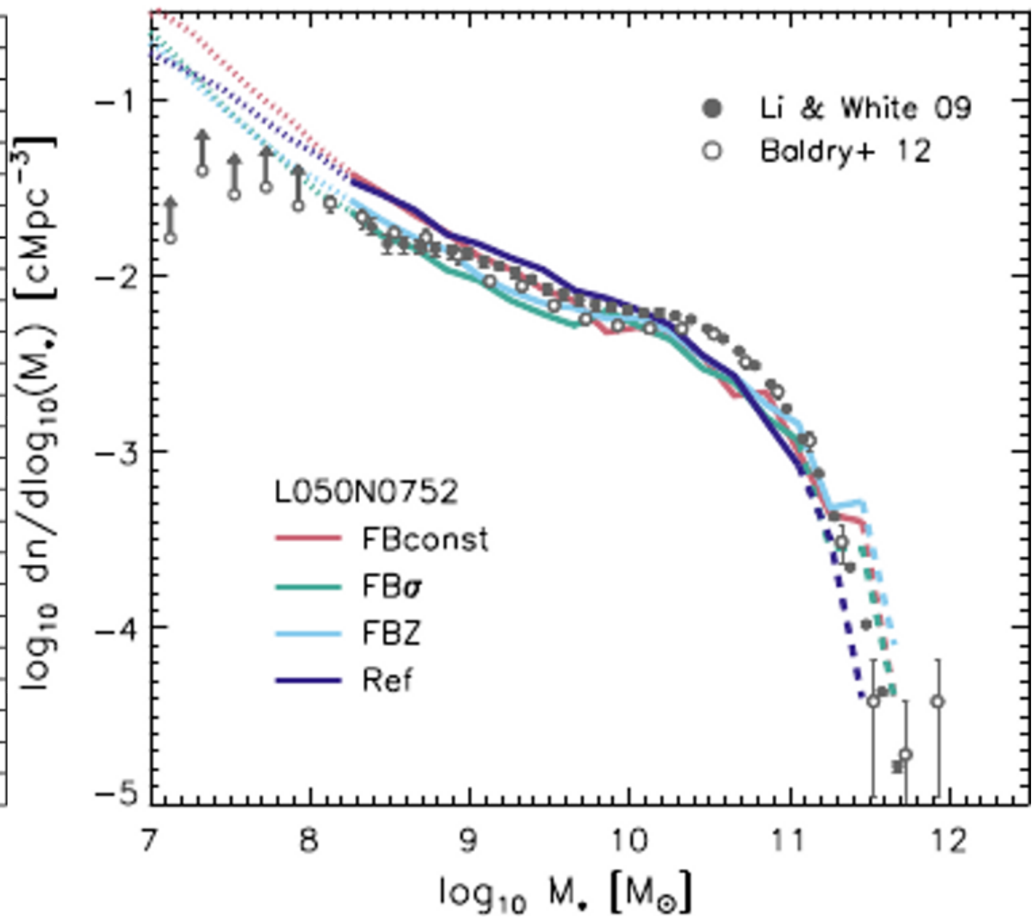
importance of feedback for galaxy evolution

feedback alters galaxy stellar-mass functions

low SFE at low stellar mass translates into flatter galaxy stellar mass functions;

Benson+ 2003 z~0 galaxy luminosity, stellar mass functions Crain+ 2015, EAGLE simulations

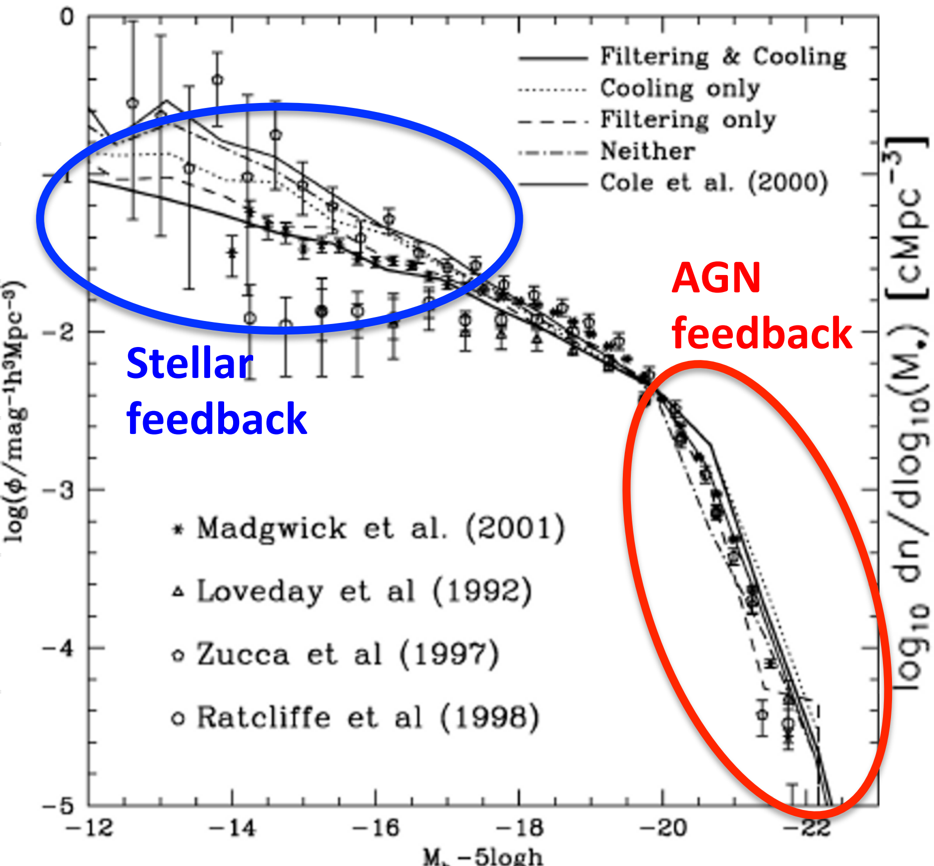


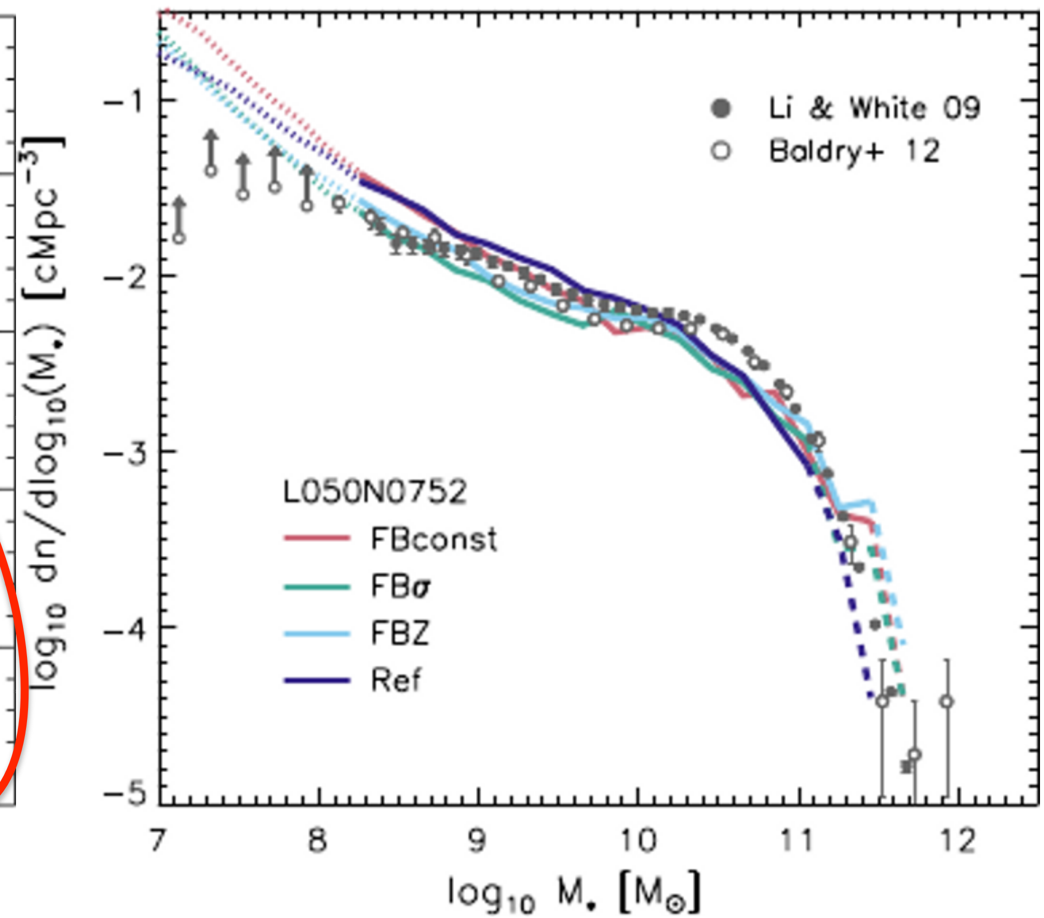


feedback alters galaxy stellar-mass functions

low SFE at low stellar mass translates into flatter galaxy stellar mass functions;
AGN feedback thought to quench star formation at the high-mass end

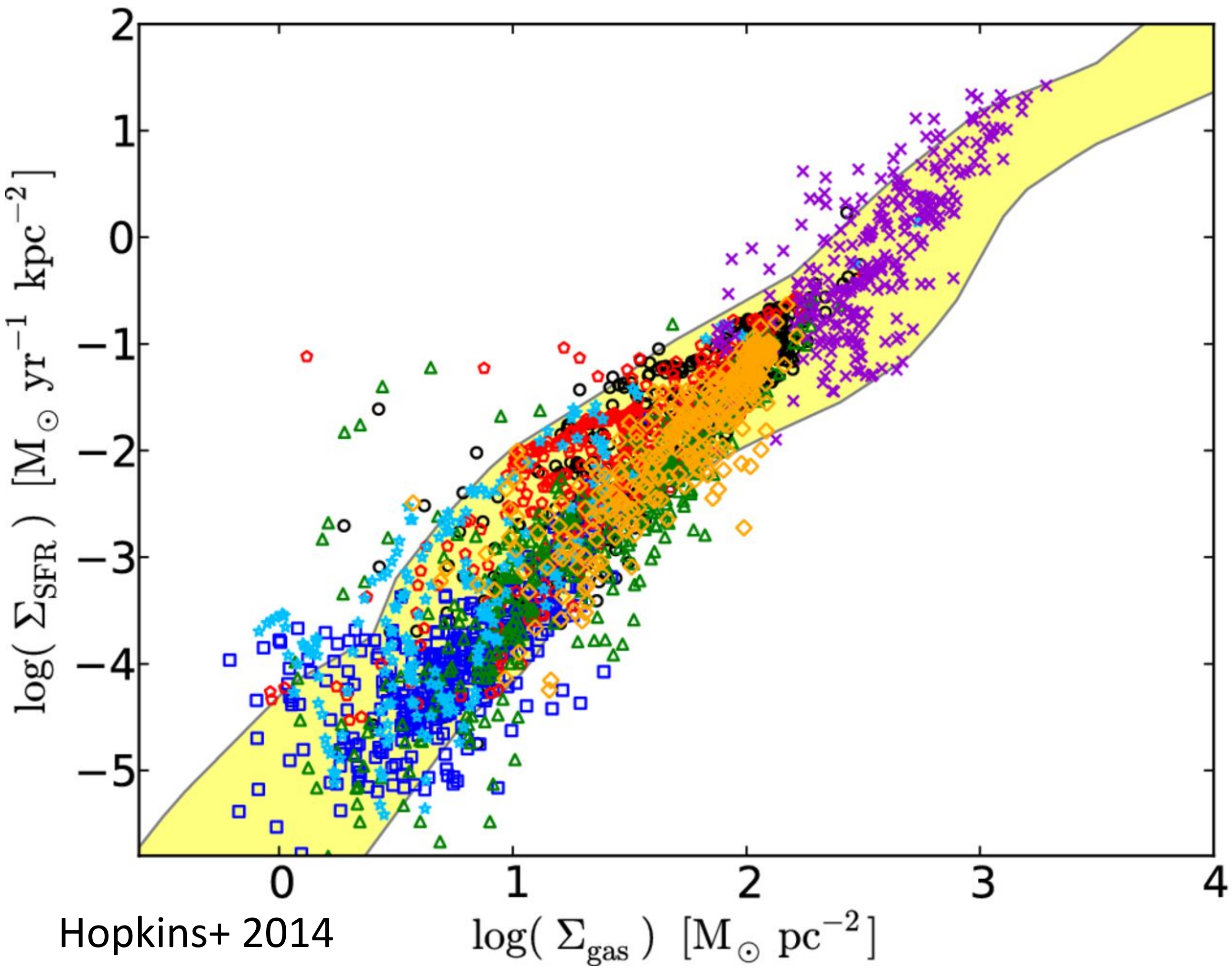
Benson+ 2003 z~0 galaxy luminosity, stellar mass functions Crain+ 2015, EAGLE simulations





stellar feedback governs gas scaling relations ...

stellar feedback injects sufficient momentum to offset dissipation; otherwise too-efficient cooling would cause all gas to collapse and form stars



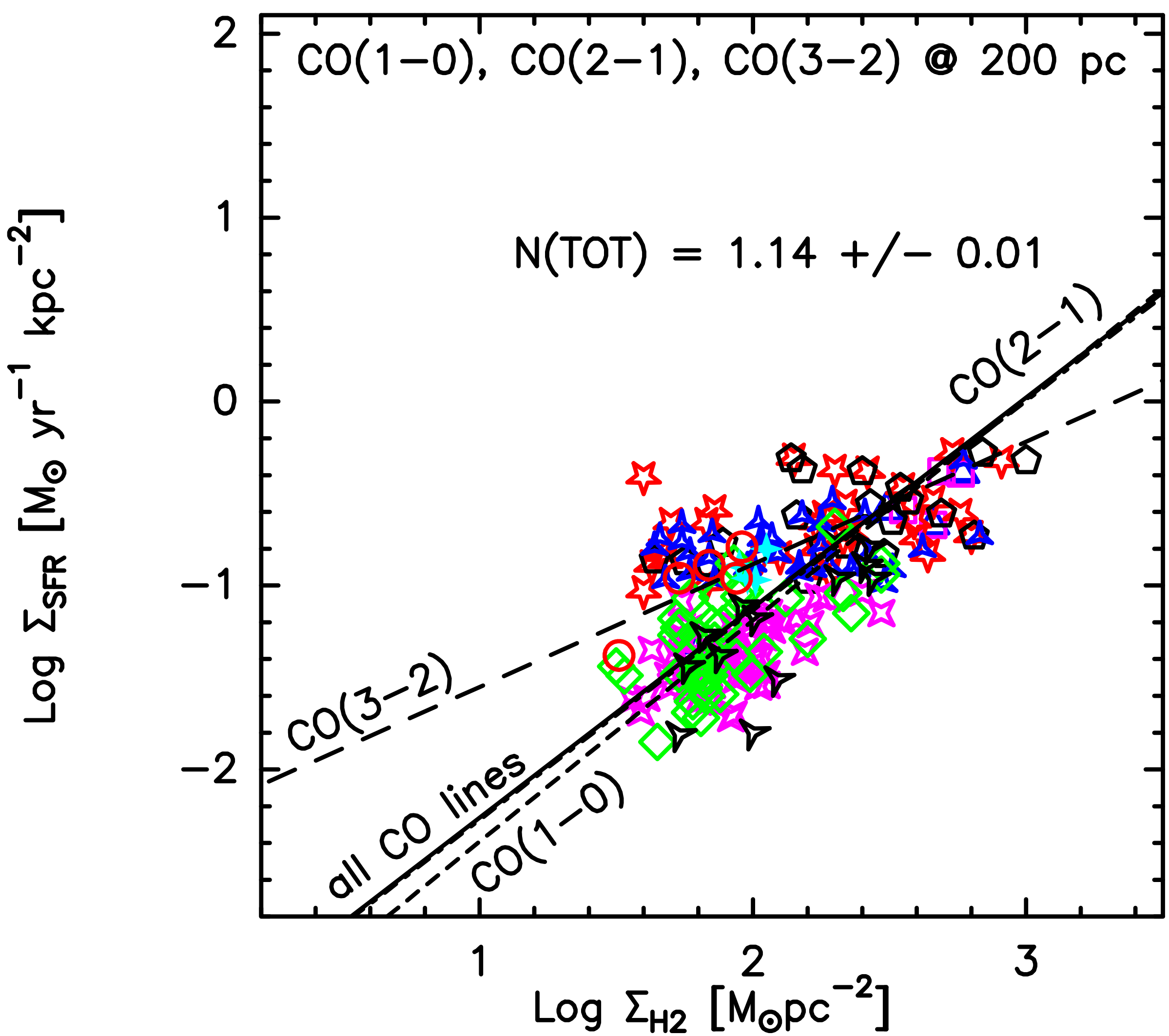
Hopkins+ 2014

Kennicutt-Schmidt (KS) law relating SFR and gas surface densities; observations (Kennicutt 1998; Bigiel+ 2008; Genzel+ 2010; Daddi + 2010) indicated by yellow shaded region.

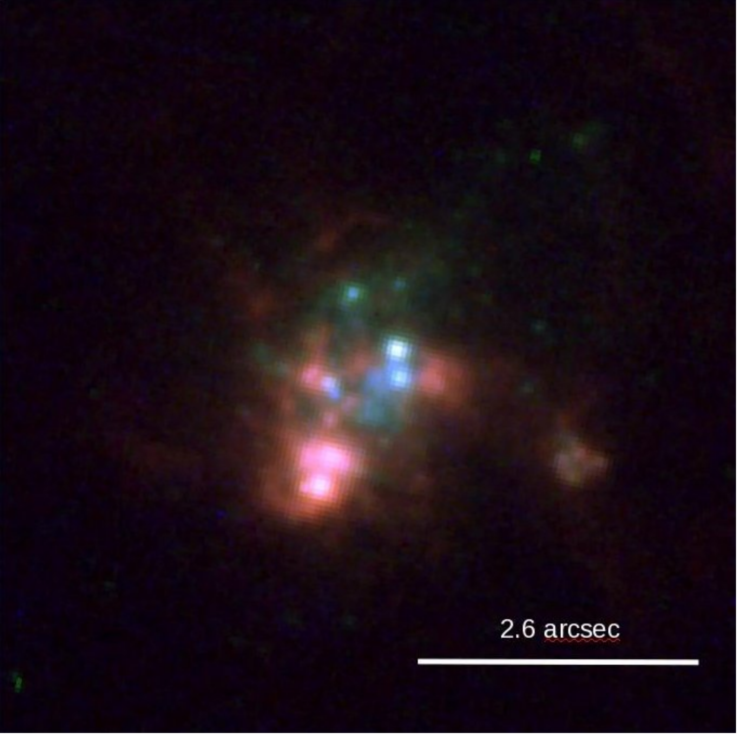
Simulations including various recipes for feedback shown by points. Instantaneous SFE (here SF per dynamical time) in dense gas is 100%, but global SFE is ~2%.

... as observed in nearby AGN

SFR-H_2 surface density scaling relations for 4 low-luminosity AGN in the local universe (from PdBI observations, taken from Casasola+ 2015)



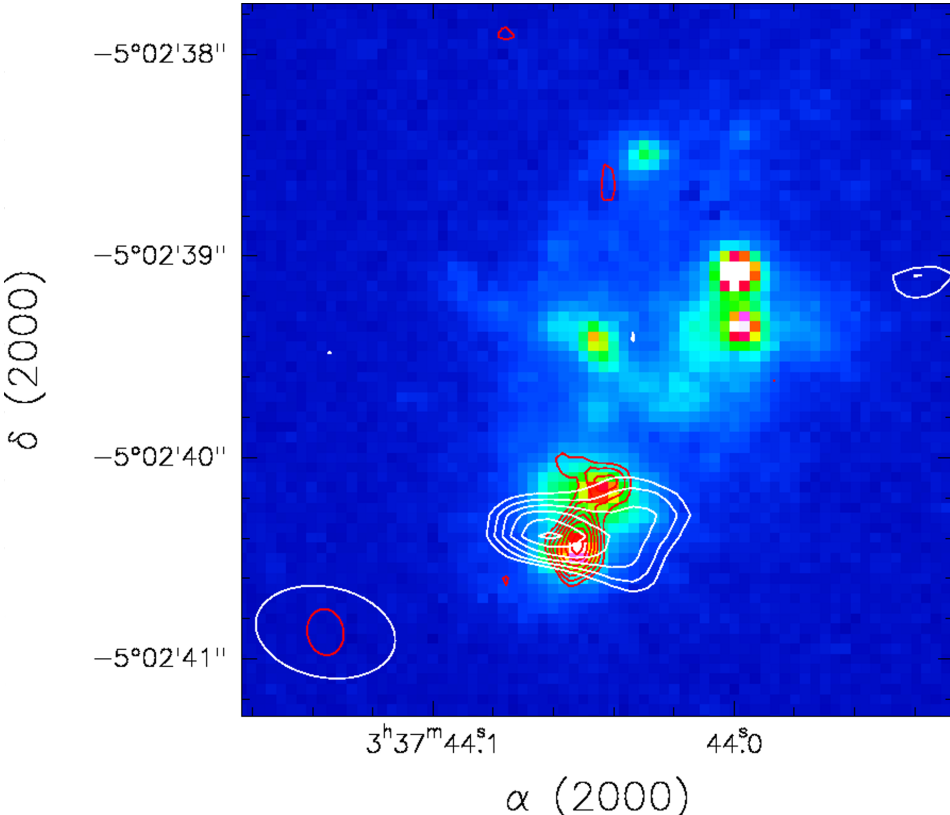
stellar feedback in low-mass (low-metallicity) galaxies



SBS0335-052 hosts six Super Star Clusters (SSCs), distributed over ~700 pc (2.6”). Most of the SF takes place in the two southernmost SSCs, which together host ~10000 O stars. SSCs unresolved at HST/ACS resolution (<~ 30 pc).

12+log(O/H) = 7.23 (0.03 $Z_{\odot}$)

Cycle 0 ALMA Band 7 (345 GHz, 857 µm) in white contours, overlaid on ACS F555M image of SBS0335-052. Red contours show VLA 3.6 cm image (Johnson, Hunt, Reines 2009). Resolution 0.6”, 160 pc.

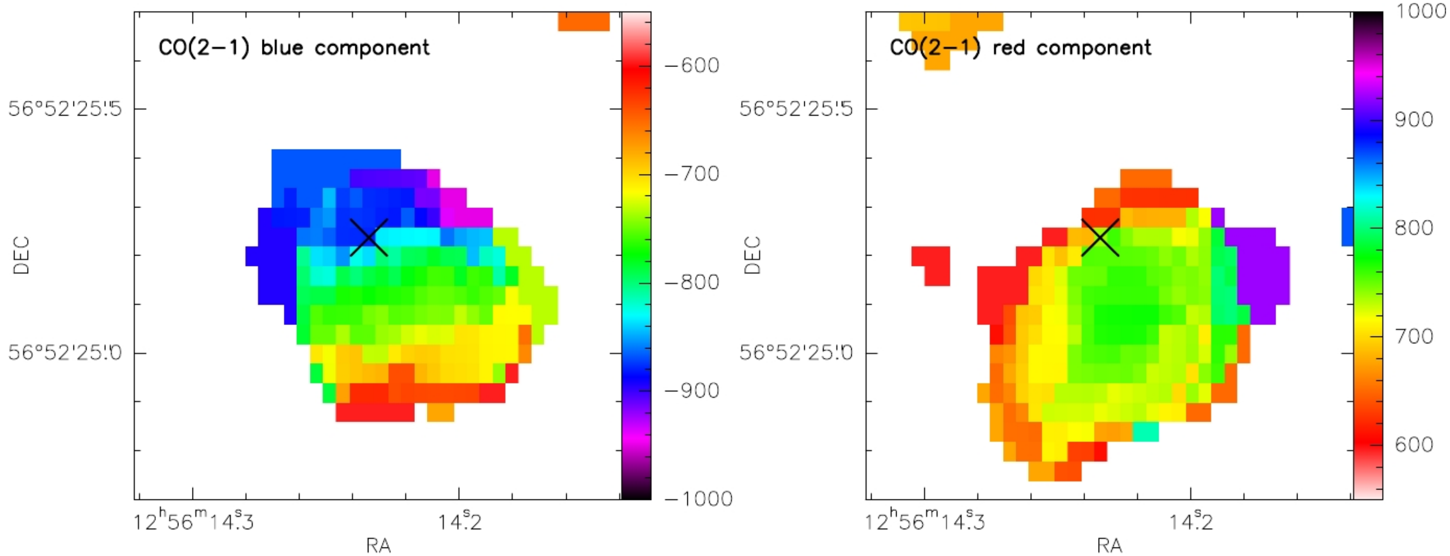


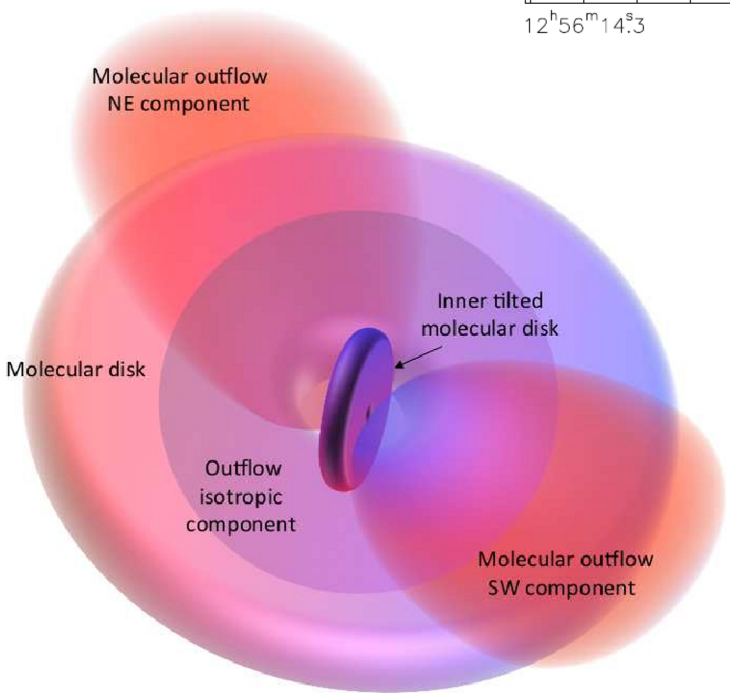
ALMA 870 µm emission is extended, but the elliptical beam shape precludes conclusions about dust+free-free outflow (no CO(3-2) detected to faint limits!)

(taken from Hunt+ 2014)

AGN feedback in massive galaxies at z~0

PdBI CO(2-1) maps of ULIRG Mrk231 show evidence for massive molecular outflow (Feruglio+ 2010, 2015)



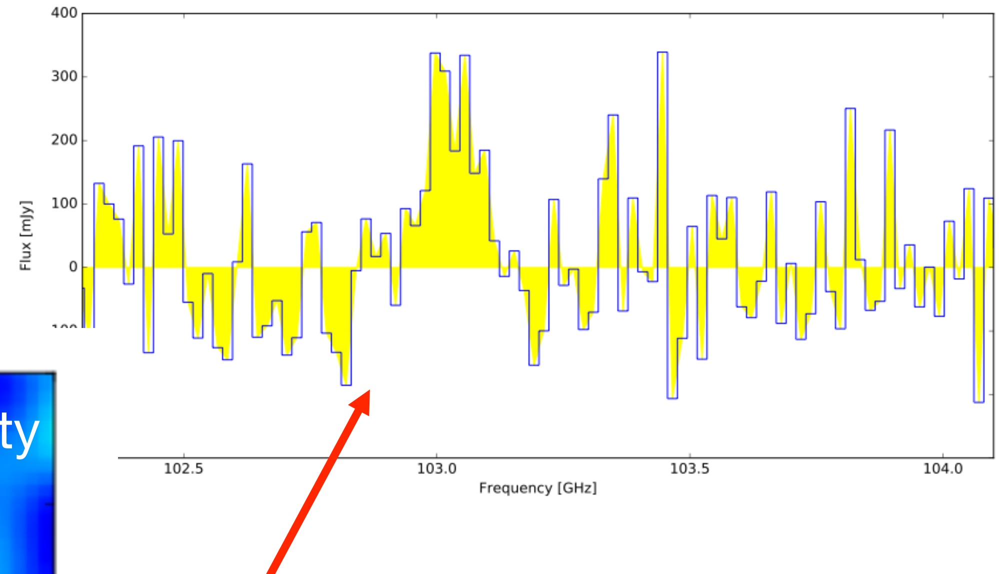


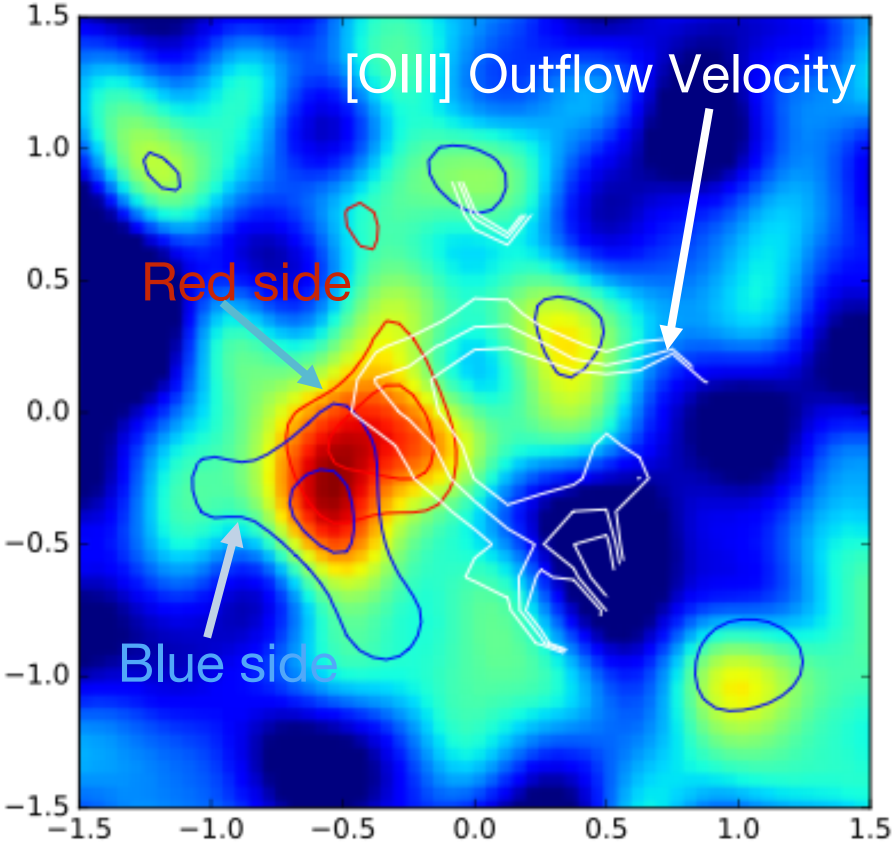
Complex geometry of the outflow constrained by a multi-wavelength approach including Chandra and NuSTAR X-ray observations (ultra-fast outflow)

(taken from Feruglio, Fiore, Carniani+ 2015)

AGN feedback in massive galaxies at z~2

ALMA CO(3-2) image of one of a sample of 6 luminous "normal" quasars at z~2.3-2.5 (Carniani, Marconi, Maiolino, Balmaverde, Brusa, Cano-Diaz, Cicone, Comastri, Cresci, Fiore + 2015)





Expected velocity from narrow Hα

FWHM ~350 km/s

Estimated H_2 mass: ~1.2×10^{10} $M_\odot$

(taken from Marconi+, in prep)

conclusions

- Low-energy (FIR, sub/mm) observations effectively probe dust-obscured star formation both in the local universe and at high redshift
- Low-energy (FIR, sub/mm) observations also trace the massive (cool vs. ionized) gas component in feedback outflows
- Need multi-wavelength approach to effectively study galaxy evolution
- Need coherent strategy to tie low-energy observational constraints to simulations of galaxy formation (e.g., OA Roma, OA+Univ. Trieste, ...): gas scaling relations, AGN feedback, stellar feedback, dust grain formation, molecule formation, ISM cooling, etc.