Galaxy evolution and AGN activity during the cosmic boom years

Mark Dickinson (NOAO)
“The boom years”

- Globally averaged star formation and black hole accretion rates evidently peaked at $1 < z < 3$.
- Dusty, IR-luminous galaxies dominate cosmic star formation at $z > 1$.

Aird et al. 2010
Magnelli et al. 2011
UV to IR: stars and dust

- Unattenuated UV
- Reddened UV
- Quiescent spiral
- Star-forming spiral
- Starburst
- Older stars
- PAHs
- Cold dust + “cirrus”
- Warm dust in star-forming regions

da Cunha et al. 2008
UV to IR: stars and dust

- Unattenuated UV
- Reddened UV
- Quiescent spiral
- Star-forming spiral
- Starburst
- Older stars
- PAHs
- Cold dust + “cirrus”
- Warm dust in star-forming regions

Spitzer @ z≈2

da Cunha et al. 2008
UV to IR: stars and dust

- Unattenuated UV
- Reddened UV
- Older stars
- PAHs
- Cold dust + “cirrus”
- Warm dust in star-forming regions
- Herschel
- Spitzer @ z≈2

da Cunha et al. 2008
Deepest far-infrared images of the sky in the 2 GOODS fields: ~1800 sources down to 1 mJy at 100 \( \mu \)m, 2.6 mJy@160\( \mu \)m, 6 mJy@250\( \mu \)m, 7 mJy@350\( \mu \)m, 9 mJy@500\( \mu \)m

Full data release coming soon!
GOODS-Herschel: Daring to detect the ordinary!

GOODS fields are unique for PACS and SPIRE 250µm data deep enough to detect \( \sim L^*_{\text{IR}} \) galaxies at \( z \approx 2 \)

\[ L^*_{\text{IR}} = 7 \times 10^{11} \, L_\odot \, @ \, z \approx 2 \] (Magnelli et al. 2011)
A “main sequence” for star-forming galaxies

A tight correlation between SFR and stellar mass for star-forming galaxies

Brinchmann et al. 2004, Elbaz et al. 2007

20 July 2012

Gemini Science Meeting
Noeske et al. 2007  0.2 < z < 1.1

Daddi et al. 2007  z ~ 2

Magdis et al. 2010  z ~ 3
Redshift evolution of the specific SFR (SSFR)

Elbaz et al. 2011
Does 24µm data overestimate $L_{\text{IR}}$ at $z \sim 2$? (a.k.a. the mid-IR excess problem)

Pre-Herschel: Papovich et al. 2007, Daddi et al. 2007; Magnelli et al. 2009

Nordon et al. 2010

20 July 2012

Gemini Science Meeting
Focusing consistently on $L(8\mu m)$ vs. $L(\text{IR})$ changes the picture

$IR8 = L(\text{IR}) / \nu L_{\nu}(8\mu m)$

No template extrapolation:
- $z \sim 0$: IRAC 8\mu m
- $z \sim 1$: IRS 16\mu m
- $z \sim 2$: MIPS 24\mu m

Elbaz et al. 2011

CE01 template extrapolation from 24\mu m -> $L(\text{IR})$

20 July 2012

Gemini Science Meeting
Focusing consistently on $L(8\mu m)$ vs. $L($IR$)$ changes the picture

Elbaz et al. 2011

$\text{CE01 template extrapolation from } 24\mu m \rightarrow L($IR$)$

$\text{IR8} = L($IR$) / \nu L_{\nu}(8\mu m)$

No template extrapolation:
- $z \sim 0$: IRAC 8\mu m
- $z \sim 1$: IRS 16\mu m
- $z \sim 2$: MIPS 24\mu m

At all $z$ and $L$, some galaxies have larger $L_{\text{IR}} / L_8$
Starburst galaxies have:

- High specific SFR (SSFR)
- High SFR surface density
- Larger 8μm bolometric correction (IR8)

LIRGs with compact / high surface brightness star formation from GOALS (Díaz-Santos et al. 2010)

20 July 2012
Gemini Science Meeting
New IR templates from GOODS-H

Constructed by shifting normalized GOODS-H photometry to the rest frame

$\nu_{\nu}(L_\odot) \\ 10^{10} \\ 10^{11}$

$\lambda (\mu m)$

Main Sequence

20 July 2012

Gemini Science Meeting
New IR templates from GOODS-H

 Constructed by shifting normalized GOODS-H photometry to the rest frame
New IR templates from GOODS-H

Constructed by shifting normalized GOODS-H photometry to the rest frame

Systematic differences in the far-IR/mid-IR flux ratios for MS vs. SB galaxies make it very difficult to universally estimate $L_{\text{IR}}$ or SFR from Spitzer 24$\mu$m data alone at $z > 1.5$
Improving bolometric corrections for star-forming galaxies

CE01 library:
• 24µm over-predicts $L_{IR}$ at $z > 1.3$ (the “MIR-excess” problem)
• SPIRE over-predicts $L_{IR}$ at $z < 1.3$ (not enough cold dust in CE01 templates)
Improving bolometric corrections for star-forming galaxies

Elbaz+2011 main sequence SED (single template for all galaxies):

- Fixes the “MIR-excess” at high $z$ (although it will underestimate $L_{IR}$ for starbursts)
- More cold dust fixes $L_{IR}$ from SPIRE at low $z$
The contribution of starbursts at $z\approx2$

Herschel far-IR data are essential for measuring SFRs for starbursts.

At $z\approx2$:
- COSMOS Herschel data mainly detect starbursts.
- GOODS-Herschel reaches the main sequence at intermediate stellar masses.
- UV-based SFRs are statistically robust for MS galaxies (e.g., Daddi+2007; Reddy+2010, 2012)

Together these are used to derive the distribution of SSFRs at $z\approx2$
The contribution of starbursts at $z \approx 2$

The star formation rate density is dominated by galaxies on the “main sequence”, with a small contribution from starbursts except at the highest luminosities.

Rodighiero et al. 2011
Locally, ULIRGs are universally interacting and merging galaxies
CANDELS
Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey

Co-PIs: Sandy Faber (UCSC) and Harry Ferguson (STScI)
with a cast of thousands (well, 100+ scientists, 12+ countries)

• HST WFC3-IR J+H imaging of regions within 5 important deep survey fields (GOODS-N+S, COSMOS, UDS, EGS) totaling ~900 arcmin²
• Very deep Y+J+H imaging of two regions (135 arcmin² total) within GOODS-N+S
• Overlapping ACS parallels, mainly in V₆₀₆ + I₈₁₄
• WFC3-UVIS ultraviolet observations in GOODS-N (only)
• Multi-epoch observations to identify SNe Ia out to z ~ 2

• Survey is more than half complete
• 16 public data releases so far via MAST

Follow the CANDELS blog!
http://candels-collaboration.blogspot.com/
What kind of galaxies are the high-z ULIRGs?

HST morphologies for far-IR selected galaxies at high z

1.5 < z < 3:
GOODS-Herschel 100-160 μm + CANDELS HST/WFC3
• ULIRGs: $L_{\text{IR}} > 10^{12} L_\odot$
• Control: $L_{\text{IR}} < 10^{12} L_\odot$

0.8 < z < 1.2:
COSMOS Spitzer 70 μm + HST/ACS imaging
• ULIRGs: $L_{\text{IR}} > 10^{12} L_\odot$
CANDELS imaging (VJH) of Herschel ULIRGs at $1.5 < z < 3$

Kartaltepe et al. 2012
Morphological characteristics of $z \approx 2$ ULIRGs

- $z \approx 2$ ULIRGs show a higher fraction of irregular morphologies and apparent interactions compared to $z \approx 2$ galaxies with lower SFRs.

- Only a small fraction are clearly mergers (contrast with $z \approx 0$).
Morphological characteristics of $z\approx2$ ULIRGs

- At fixed IR luminosity, morphological distributions are similar at $z\approx1$ and $z\approx2$
- $\sim50\%$ appear to be non-interacting disk galaxies
Morphological correlations with specific SFR

- Only weak trends are seen with specific SFR
- More mergers & interactions at higher SSFRs
- More non-interacting disks on the main sequence
- *But:* many exceptions both ways (interactions in the MS; disks among starbursts)
Large gas reservoirs in $z \approx 1.5$ galaxies

Earlier CO observations detected very large molecular gas masses in extremely luminous, high-z submillimeter galaxies ($L_{IR} >> 10^{12} L_\odot$)

Daddi et al. 2010; Tacconi et al. 2010 found comparably large gas masses ($M_{H_2} \approx 0.5-1 \times 10^{11} M_\odot$) for ordinary main sequence galaxies at $z > 1$
Two sequences of star formation efficiency (SFE)
Daddi et al. 2010; Genzel et al. 2010

- Main sequence galaxies at both low and high z have low SFEs
  [This is true even for z≈1.5 galaxies with SFR ≈ 100 M_☉/yr]
- Local ULIRGs and high-z SMGs are starbursts with much higher SFE
Two sequences into one

Daddi et al. 2010; Genzel et al. 2010

Renormalizing the gas surface density by the dynamical time brings the disk galaxies and mergers onto a single sequence.

Very large gas fractions at $z > 1$

Magdis et al. (submitted)

Very steep redshift evolution in the gas fraction for normal main sequence galaxies

- More gas than stars at $z \approx 2$

Some hints of a flattening at higher redshifts

Molecular gas measurements are still difficult & expensive (even w/ALMA, if you could get any ALMA time to do it...)

Uncertainties and systematics in the CO/H$_2$ conversion are a limiting factor for individual sources.
Inferring mean trends in gas and dust at \( z \approx 2 \)

Magdis et al. (submitted)

\( \sim 3600 \) sBzK-selected star-forming galaxies at \( <z> \approx 2 \) in GOODS-N

Divide into bins of stellar mass (\( M^* \)) and SSFR

Stack mid-IR, far-IR and millimeter data (16 to 1100 \( \mu \)m) for these subsamples

Fit Draine & Li (2007) dust emission models to the average SEDs to derive dust masses \( <M_{\text{dust}}> \)

Infer metallicity \( <Z> \) from \( M^*-Z \) relation at \( z \approx 2 \) (Erb et al. 2006)

Use local \( M_{\text{gas}}/M_{\text{dust}} \) vs. \( Z \) relation (Leroy et al. 2011) to infer \( <M_{\text{gas}}> \)
Gas fractions within the main sequence

- Gas fractions systematically increase with SSFR (and decrease with M*) across the MS
- Strongly suggests that varying gas fraction drives variations in SSFR and the “thickness” of the MS

Magdis et al. (submitted)
Stable disks, $z \sim 0.7$

Clumpy disks, $z \sim 0.7$
The spread in the main sequence at $z \approx 1$

Salmi et al. 2012

The offset from the MS average depends on disk color and clumpiness

Clumpiness is a signature of high gas surface density ($\Sigma_{\text{gas}}$)

Higher $\Sigma_{\text{gas}}$ $\leftrightarrow$ higher SSFR $\leftrightarrow$ clumpier/bluer disks

Much of the spread in the MS is due to real, physical effects, not uncertainties in deriving stellar masses or SFRs.
Star formation in AGN host galaxies

2-4 Msec Chandra Deep Field data permits selection of moderately luminous AGN over wide ranges in $L_X$ and $z$.

GOODS-Herschel data measure the FIR luminosities and SFRs of the AGN hosts.

Several studies (including this work) show that the FIR luminosity is usually dominated by star formation, not the AGN. (A few likely AGN-dominated sources are excluded here.)

Mullaney et al. 2011

20 July 2012

Gemini Science Meeting
Accretion luminosity vs. star formation

No correlation between $L_X$ and $L_{IR}$, but a strong trend in $L_{IR}$ vs. $z$ at fixed $L_X$

See also: Mullaney et al. 2010, Lutz et al. 2010, Shao et al. 2010
AGN live in massive host galaxies

Only a weak correlation between M* and $L_X$ and no trend with redshift

Mullaney et al. 2011
AGN live mostly in main sequence galaxies

~80% in MS hosts; 15+/- 7% quiescent; < 10% in starbursts (SSFR > 3x SSFR_{MS})

Suggests that AGN are fuelled by “secular” processes that also fuel SF, and not mainly by mergers

See also morphological arguments: Grogin et al. 2005; Cisternas et al. 2011, Kocevski et al. 2011
A main sequence of SMBH accretion

Individually-detected X-ray AGN show no correlation between $L_X$ and $M^*$

*But:* mean $\langle L_X \rangle$ (from X-ray stacking) shows a correlation parallel to the SFR-$M^*$ main sequence

- Easily understood in terms of accretion duty cycles

SMBHs grow in parallel with stellar mass, perhaps both regulated by gas fuel supply

Mullaney et al. 2012
Summary

- The “main sequence” SFR-M* correlation provides important clues about galaxy and supermassive black hole evolution
- Far-IR data from Herschel have been essential for understanding SFRs at z≈2 and to quantify starburst vs. main sequence activity
- Starbursts contribute only ~10% to the globally averaged SFR density at z≈2
- Mergers and interactions are prominent among high-z starbursts, but morphological trends are surprisingly weak
  - External influences are important but not the only driver for high SFRs and SSFRs
- High-z disk galaxies have very large gas fractions that can fuel high star formation rates over long time scales
- Thickness (in SSFR) of the main sequence is controlled by varying gas mass fractions
- AGN activity (with moderate luminosity) at 0 < z < 2.5 takes place mainly in secularly evolving main sequence galaxies
- Average rates of SMBH growth parallel those of stellar mass growth, demonstrating coeval evolution of SMBHs and their host galaxies
Where is Gemini in all this?

- Gemini’s biggest contributions to high-z galaxy evolution:
  - Galaxy clusters and groups (today’s talks)
  - NIR spectroscopy of massive galaxies (Mariska Kriek’s talk)
  - The Gemini Deep Deep Survey
  - [ Identification of GRBs at extremely high redshifts ]

- Why hasn’t Gemini done more?
  - GMOS field of view, multiplex, throughput
    - Well-suited for high-z clusters, but not competitive for large field galaxy surveys or at very high redshifts (or at $z \approx 2$ without blue throughput)
  - Small field of view for NIR imaging
  - Preponderance of relatively small observing programs
Eagerly anticipating: FLAMINGOS-2

Far too much reliance on photo-z’s for the massive, dusty, star-forming galaxies that dominate the stellar mass, star formation rate, and AGN accretion densities at $z \approx 2$

High-multiplex NIR spectroscopy can revolutionize the field, providing:
- Redshifts
- Excitation diagnostics
- Metal abundances
- Kinematics
Eagerly anticipating: GeMS/GSAOI

HST/WFC3 has opened up survey-scale NIR imaging with high angular resolution to very faint limits
- Optical rest-frame galaxy morphology at \( z > 1 \)
- Spectral energy distributions for very high-z galaxies

But, WFC3 is limited to \( \lambda < 1.7 \) \( \mu \)m
- Optical rest frame only at \( z < 3 \)

GSAOI can provide high angular resolution in K-band over comparatively wide fields
- Optical rest frame to \( z \leq 5 \)
- Angular resolution better than HST/WFC3 – better for compact galaxy sizes, bulge structure, etc.

But: limited sky coverage with adequate guide stars at high Galactic latitudes
Thank you!