Mass and star formation rate evolution of infrared galaxies in the COSMOS field

Helena Domínguez Sánchez

Prof. Andrea Cimatti
Dra. Carlotta Gruppioni
Dra. Francesca Pozzi

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• Galaxy Stellar Mass Function Evolution \((1.4 < z < 3.0)\)
  - Sample
  - SED-fitting: photo-z, mass, SFR, etc
  - Galaxy Classification: star-forming, intermediate, quiescent
  - GSMF evolution & comparison with models

• SFR comparison
  - Sample
  - SFR(H\(\alpha\)) & SFR(LIR)
  - SFR comparison & dependences (z, mass, metallicity...)

• Conclusions
INTRODUCTION

- Mass and SFR are two fundamental and complementary aspects of galaxy formation and evolution theory.
- Bimodality of observed galaxies: Early and Late Type Galaxies.
- ETGs formation theories: Monolitic collapse vs Hierarchical merging.
- Observed evolution of different galaxy types helps putting constrains on theoretical models.
- Need of an accurate SFR estimate.
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Ilbert et al. (2010)
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- Need of an accurate SFR estimate.
1. GSMF of infrared selected galaxies at high z (1.4 < z < 3.0)
Sample

- **IRAC selected** \( \text{mag}_{3.6} < 22 \text{ mag}, 95\% \text{ complete} \)
- **COSMOS** field: multiwavelength coverage, 2deg \(^2\)
- **Multiwavelength catalog with Likelihood Ratio Technique** (Sutherland & Sanders 1992)
  - **IRAC** \( (3.6, 4.5, 5.8, 8.0 \mu \text{m}), \text{ Sanders et al. 2007}) \: 78649 \text{ sources}; 53 \text{ only IRAC (0.5 \%)}
  - **MIPS** 24 \( \mu \text{m} \) \( (\text{mag}_{\text{lim}} = 18.5 \text{ mag}, \text{ Le Floc' h et al. 2009}) \: 11352 \text{ sources}; 14\%\)
  - **Optical** \( (i < 26.5 \text{ mag}; \: u^*, B_j, g^+, v_j, r^+, i^+, z^+, J, K; \text{ Capak et al. 2007}) \: 74742 \text{ sources}; 95\%\)
  - **Ks** \( (B_j, i^+, z^+, J; \text{ 23 mag, McCracken et al. 2010}) \: 3554 \text{ sources}; 4.5\%\)
SED-Fitting

Photometric redshifts

- LePhare code (Ilbert et al. 2006)
- COSMOS SED library (Ilbert et al. 2009)
  - Ellipticals & Spirals (Polletta et al. 2007)
  - Blue galaxies (Bruzual & Charlot 2003)
  - We also included SSP 0.05-3 Gyr (Maraston 2005)

Mass and SFR

- ~ 20,000 high-z sources: 1.4 < z < 3.0
- LePhare code (Ilbert et al. 2006): U-5.8µm
- Maraston (2005) models: better treatment TP-AGB
  \[ \text{SFR} \propto e^{-t/\tau} \]
- Solar metallicity, Chabrier IMF
- 9 values \( \tau \) (0.1, 0.3, 1.0, 2.0, 3.0, 5.0, 10.0, 30.0 Gyr)
- 221 steps in age

z-phoot accuracy

- Comparison with I175 sources with high-confidence epochs (zphoot 3.3, 3.5, 4.3, 4.5)
- Accuracy: \( \Delta z_{\text{phoot}} < 0.05 \)
- Catastrophic errors: \( \approx 5 \% \)
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z-phot accuracy

- **Comparison with 8176** sources with high confidence z-spec (zflags 3.1, 3.5, 4.1, 4.5).
- **Accuracy**: $\sigma_{z/\text{fit}}=0.06$
- **Catastrophic errors**: $\eta=3.3\%$

![Graph showing comparison between z-phot and z-spec values](image-url)
Photometric redshifts

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Galaxy Classification

- **Star-forming:** $\log(\text{SSFR}[\text{Gyr}^{-1}]) > -0.5$
- **Intermediate:** $-2.0 < \log(\text{SSFR}[\text{Gyr}^{-1}]) < -0.5$
- **Quiescent:** $\log(\text{SSFR}[\text{Gyr}^{-1}]) < -2.0$ (no MIPS)

Similar classification as in Pozzetti et al. (2010), Illbert et al. (2010). In agreement with BzK (Daddi et al. 2004)
Galaxy Stellar Mass Function

- \(1/V_{\text{max}}\) Method
- Mass limit (Pozzetti et al. 2010)
- Errors:
  - Poissonian errors
  - Monte Carlo Simulations
  - Cosmic variance (Somerville et al. 2004)
GSMF evolution

**Total**

**Quiescent**

**Star-Forming, Intermediate**

**Mass dependence**

- Agreement with Libori et al. (2016)
- Number of Quiescent & Intermediate galaxies continuously increased with cosmic time.
- Number of Star-forming galaxies decrease at high mass since $z \approx 3.5$
- $z \approx 3.5$ epoch of transition
- Mass dependence: downsizing (Cowie et al. 1996)
Total

1.4<z<1.6

Fontana et al. (2006)
Pérez González ea (2008)
Marchesini et al. (2009)
Ilbert et al. (2010)

1.6<z<2.0

2.0<z<2.5

2.5<z<3.0
Quiescent

\[ \log \frac{dN}{d\log M} \] 

\[ \text{[Mpc}^{-3} \text{dex}^{-1}] \]

-3

1.4 < z < 1.6
1.6 < z < 2.0
2.0 < z < 2.5
2.5 < z < 3.0

\[ \log M \] 

\[ [M_\odot] \]

10.0

10.5

11.0

11.5

12.0
Star-Forming, Intermediate
Mass dependence

- Agreement with Ilbert et al. (2010).
- Number of Quiescent & intermediate galaxies continuously increase with cosmic time.
- Number of Star-forming galaxies decrease at high mass since $z \sim 1.5$
- $z \sim 1.5$ epoch of transition
- Mass dependence: downsizing (Cowie et al. 1996)
**Stellar mass density**

**Comparison with models**

**Theoretical Models**
- N84: Nagamine et al. (2006), hydrodynamical.
- N86: Merson et al. (2006), semi-analytical, AGN feedback.
- NS7: Knapp/Mir/Mort (2007), semi-analytical.
- N95: Bueno et al. (2005), semi-analytical.

**Data**
- N84: Fontana et al. (2001)
- N86: Damen et al. (2005)
Stellar mass density

![Graph showing the relationship between stellar mass density and the age of the Universe.](image)
Comparison with models

Theoretical Models
- N06: Nagamine et al. (2006), hydrodynamical.
- M06: Menci et al. (2006), semi-analytical, AGN feedback.
- K07: Kitzbichler&White (2007), semi-analytical
  Millenium N-body dark matter simulation.

Data
- F09: Fontanot et al. (2009)
- D10: Damen et al. (2010)
CONCLUSIONS

- **IRAC selected sample important** to study the mass function evolution at high $z$.
- The **quiescent GSMF continously increases with time**.
- **$z \sim 1.5$ epoch of transition**: At higher $z$ the mass function is dominated by star-forming galaxies at all masses. At lower redshifts the intermediate and quiescent galaxies become more important.
- **Mass dependence: Downsizing**, i.e. more massive galaxies become quiescent first.
- **Significant number of quiescent galaxies** already in place at $z > 2.5$ ($\rho \sim 6.0 M_\odot/Mpc^3$).
- Models predict an increase in the fraction of quiescent galaxies with cosmic time.

The **K07 Milleniumm based model** is the one which better **reproduces the shape of the data**.
2. Comparison of star formation rates from Halpha and infrared luminosity as seen by Herschel
SFR Indicators

SFR from Infrared Luminosity

- Dust absorbs light emitted by young stars and re-emits in the IR.
- Commonly used Kennicutt (1998)
- Valid only for young ($10^8$ yr) starbursts.

SFR ($M_\odot$ yr$^{-1}$) = $4.5 \times 10^{-44} L_{FIR}$ (ergs s$^{-1}$)

SFR from Hα luminosity

- Young (< 20 Myr) massive (> 10 $M_\odot$) OB stars ionize the molecular gas
- Commonly used Kennicutt et al. (1994), Madau et al. (1998)
- Direct probe of the young population
- Must correct for dust extinction

SFR ($M_\odot$ yr$^{-1}$) = $7.9 \times 10^{-43} L(H\alpha)$ (ergs s$^{-1}$)

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\text{SFR (}\text{M}_\odot \text{ yr}^{-1}) = 7.9 \times 10^{-42} \text{ } L(H\alpha) \text{ (ergs s}^{-1})
\]
The importance of PEP data

- PACS Evolutionary Probe
- Herschel Space Telescope
- P.I. Dieter Lutz
- Data at 100 and 160 μm in some of the most widely studied fields (COSMOS).
- Very important to constrain the peak of the IR emission

PEP Selected Sample

- **PEP selected**: 100, 160 μm (~7000 sources, blind catalog, 3σ limit 5 and 10.2 mJy)
- **COSMOS field**: multiwavelength coverage, 2deg 2
- **MIPS 24 μm** ($S_{24}=80$ μJy, Le Floc’h + 3.6 μm selected) multiwavelength catalog ($S_{24}=1$ μJy, NUV-8.0 μm Ilbert et al. 2010)
- **zCOSMOS 20k** spectroscopic information: **23% of the PEP sample**
- $z < 0.46$ to observe Hα (6562.8 Å)
- -High zflag (> 2.1), Hα emission line $S/N=3$
- **No AGN emission**:
  - Diagnostic Diagrams Bongiorno et al. 2009
  - SED-fitting with Polletta et al. 2007 templates
  - X-Ray detection (Chandra or XMM-Newton)

474 galaxies
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474 galaxies
SFR(LIR)

- *LePhare* code
- IR libraries:
  - Dale et al. (2001)
  - Chary & Elbaz (2001)
  - Lagache et al. (2004)
- Integrated from 8-1000 μm
SFR(\(\text{H} \alpha\))

Dust Extinction correction

- From \(\text{H} \alpha/\text{H} \beta\) observed ratio.
- Quality of spectra not enough to measure \(\text{H} \beta\) for each source.
- Construct average spectra in 6 LIR bins.
- Subtract continuum emission and measure the \(\text{H} \alpha/\text{H} \beta\) observed ratio.
- Derive average \(E(B-V)\) values.
- Find strong correlation between \(\log \text{LIR}\) and \(E(B-V)\)
$E(B-V) = 0.289 \times \log L_{IR} - 2.54$
Effect of using median spectra

- Selected 31 galaxies with high S/N in the continuum near the Hα, Hβ emission lines.
- Constructed average spectra for these 31 sources.
- Compared the average extinction value and the single value.
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SFR comparison

\[ \log[\text{SFR}(L_{\text{IR}})](M_\odot \text{ yr}^{-1}) \]

\[ \log[\text{SFR}(H_\alpha)](M_\odot \text{ yr}^{-1}) \]

\[ m = 1.01 \pm 0.03 \]
\[ \sigma = 0.28 \]

Very good agreement between SFR indicators over the whole SFR range.
SFR Comparison dependences

Redshift

Mass

Metallicity

SSFR

Morphology

Comparison with model for dust evolution in spiral galaxies (Chini et al. 2009; Schinner et al. 2009)
Redshift
Metallicity

Comparison with model for dust evolution in spiral galaxies (Calura et al. 2009, Schurer et al. 2009)
Morphology

\[\log[\text{SFR}(L_{\text{IR}})] \quad (\text{M}_\odot \text{ yr}^{-1})\]

\[\log[\text{SFR}(H_\alpha)] \quad (\text{M}_\odot \text{ yr}^{-1})\]

- \(\sigma = 0.31\), \(m = 0.91\), \(\sigma_m = 0.07\), \(N = 71\) (Sa)
- \(\sigma = 0.27\), \(m = 0.95\), \(\sigma_m = 0.05\), \(N = 202\) (Sb)
- \(\sigma = 0.26\), \(m = 1.04\), \(\sigma_m = 0.06\), \(N = 130\) (Sc)
- \(\sigma = 0.32\), \(m = 1.62\), \(\sigma_m = 0.43\), \(N = 17\) (Sd)
Conclusions

- **PEP data** important to **constrain the IR peak** to derive $L_{\text{IR}}$.

- **SFR($L_{\text{IR}}$) and SFR(H\alpha)** very good agreement for the bulk of galaxies ($m=1.01\pm0.03$, $a=-0.08\pm0.03$)

- **No z dependence** in the SFR indicators comparison (up to $z=0.46$).

- **Mass dependence**: slight dependence at low masses ($M<9.3\ M_\odot$), mainly driven by metallicity.

- **Metallicity dependence**: average values of log $[\text{SFR}(L_{\text{IR}})/\text{SFR}(H\alpha)]$ differ by ~ 0.6 dex from metal-poor to metal-rich galaxies. Metal rich galaxies are more efficient in absorbing and re-emitting light from young stars in the IR. The observed behaviour can be explained with a theoretical model for dust evolution in spiral galaxies.

- **SSFR dependence**: low SSFR, log $[\text{SFR}(L_{\text{IR}})/\text{SFR}(H\alpha)]>0$, maybe due to old stellar population. High SSFR, log $[\text{SFR}(L_{\text{IR}})/\text{SFR}(H\alpha)]<0$ due to intense bursts of star formation.

- **Morphological type**: 3σ agreement for all morphological types. Indication of an increment of the slope when moving from early to late type galaxies although no significant enough statistical sample.
Future work:

Carefully study the ~ 300 "only IRAC" sources from Domínguez Sánchez et al. 2011

- **new COSMOS data** (ultraVISTA, CANDELS, PACS, SPIRE).
- **SEDs**: fundamental galaxy properties (photo-z, stellar masses, ages, SFR, etc)
- **Morphologies**

Highly obscured starburst or very high-z massive galaxies?

References:

Thank you for your attention!

Questions?