Integral Field Spectroscopy in the Near IR

The study of local LIRGs and ULIRGs

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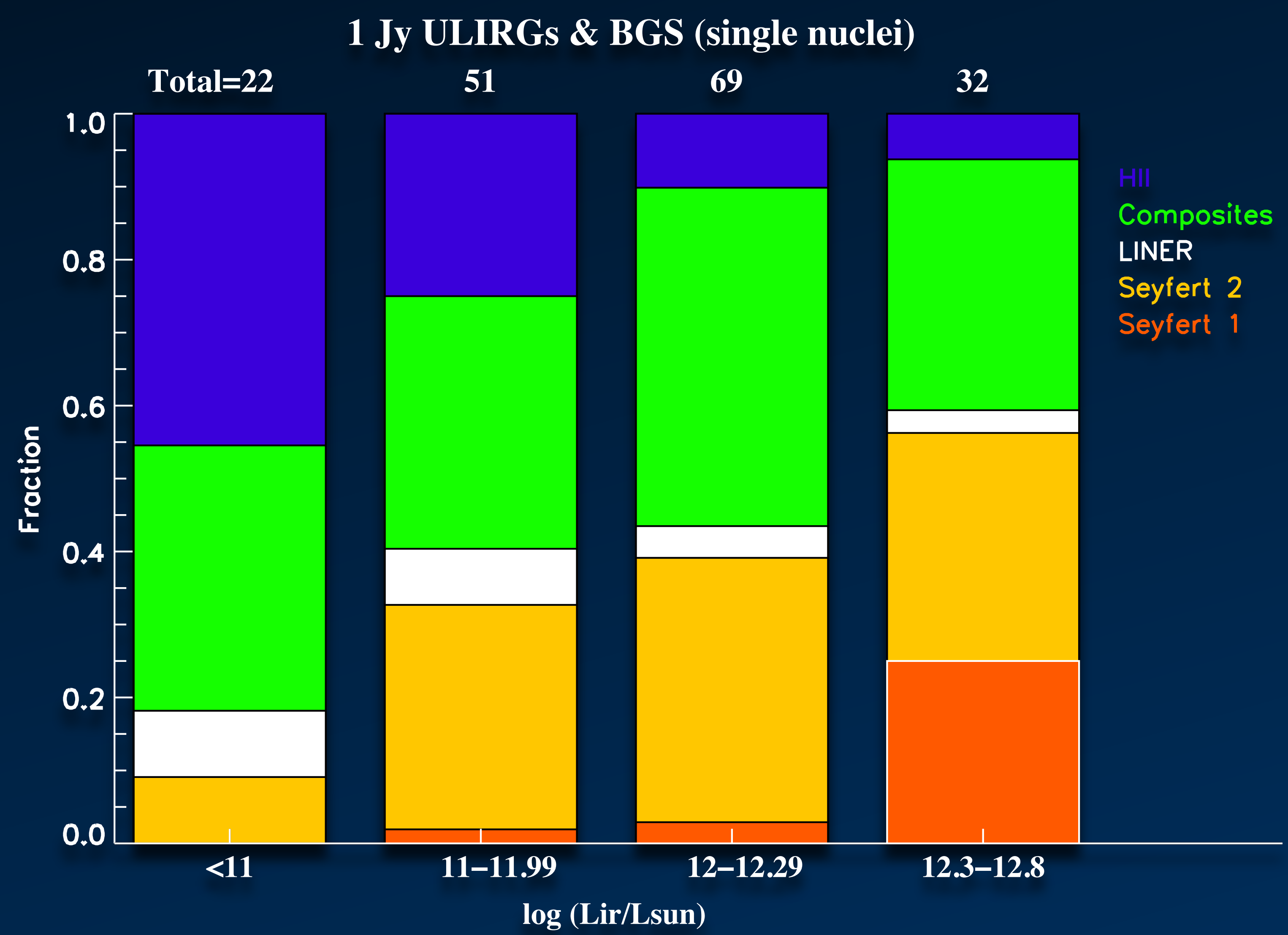
Overview of the talk

- Introduction:
  - LIRGs and ULIRGs: a general perspective
  - SINFONI: the near-IR IFS at VLT
- Data analysis and calibration
- Near-IR integral field spectroscopy of local LIRGs and ULIRGs:
  - The sample
  - 2D morphology and gas kinematics
  - Dust extinction
  - Sub-kpc analysis of the SFR
- Detailed kinematics
- Summary

LIRGs and ULIRGs: a general perspective

- Definition:
  - LIRGs: $10^{11}L_\odot \leq L_{IR} < 10^{12}L_\odot$
  - ULIRGs: $10^{12}L_\odot \leq L_{IR} < 10^{13}L_\odot$
- IR luminosity explained as the output from reprocessed radiation from dust.
- Power source: Extreme star-formation activity and AGN.
- Increasing contribution of AGN at high L_{IR} (e.g. *Yuan et al. 2010, Alonso-Herrero et al. 2012*)
- Large fraction of LIRGs and almost all the ULIRGs show signatures of recent interactions: triggering mechanisms (e.g. *Borne et al. 2000, Veilleux et al. 2002, Kartaltepe et al. 2010, Haan et al. 2011*)



Yuan et al. 2010

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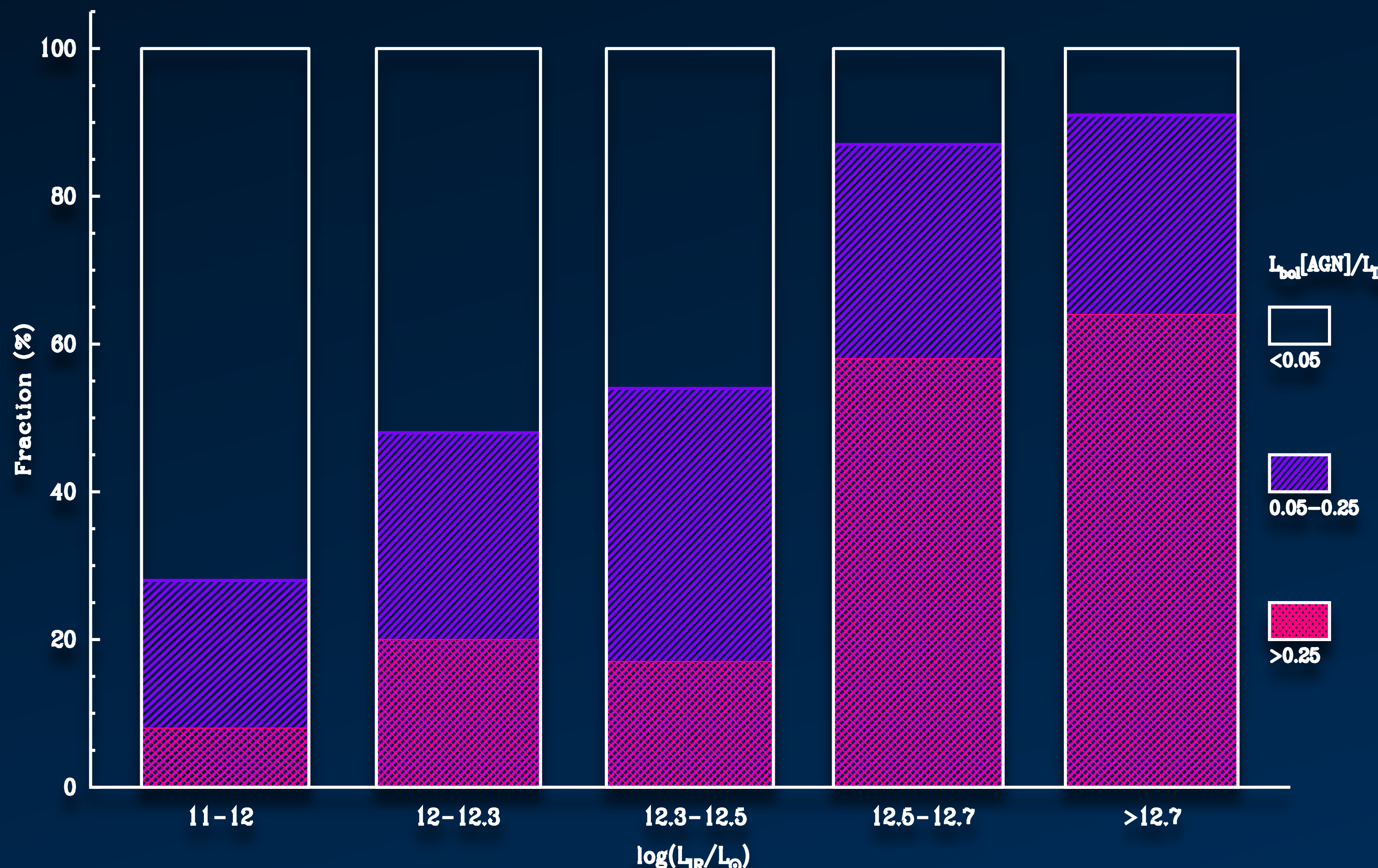

Alonso-Herrero et al. 2012

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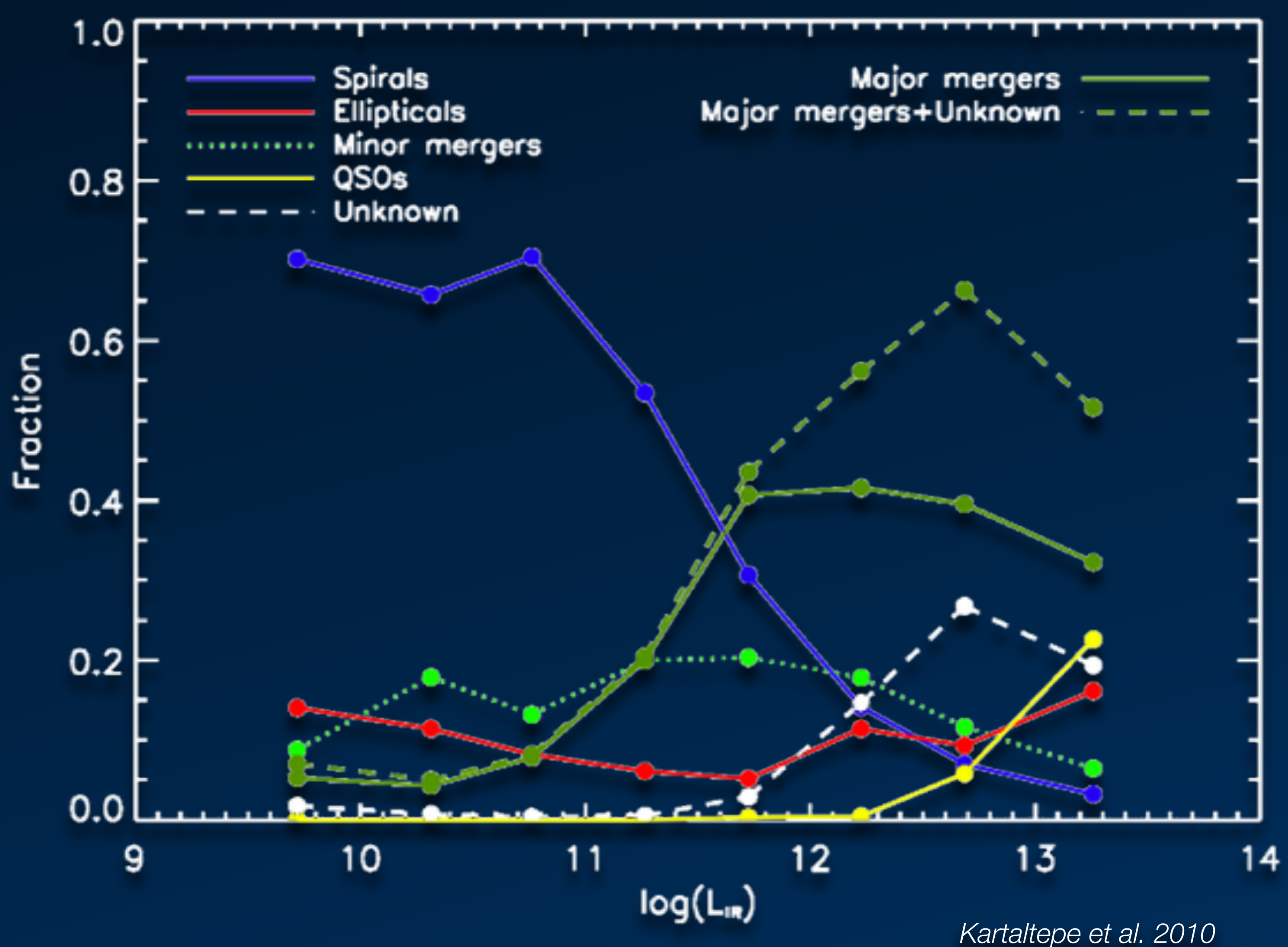
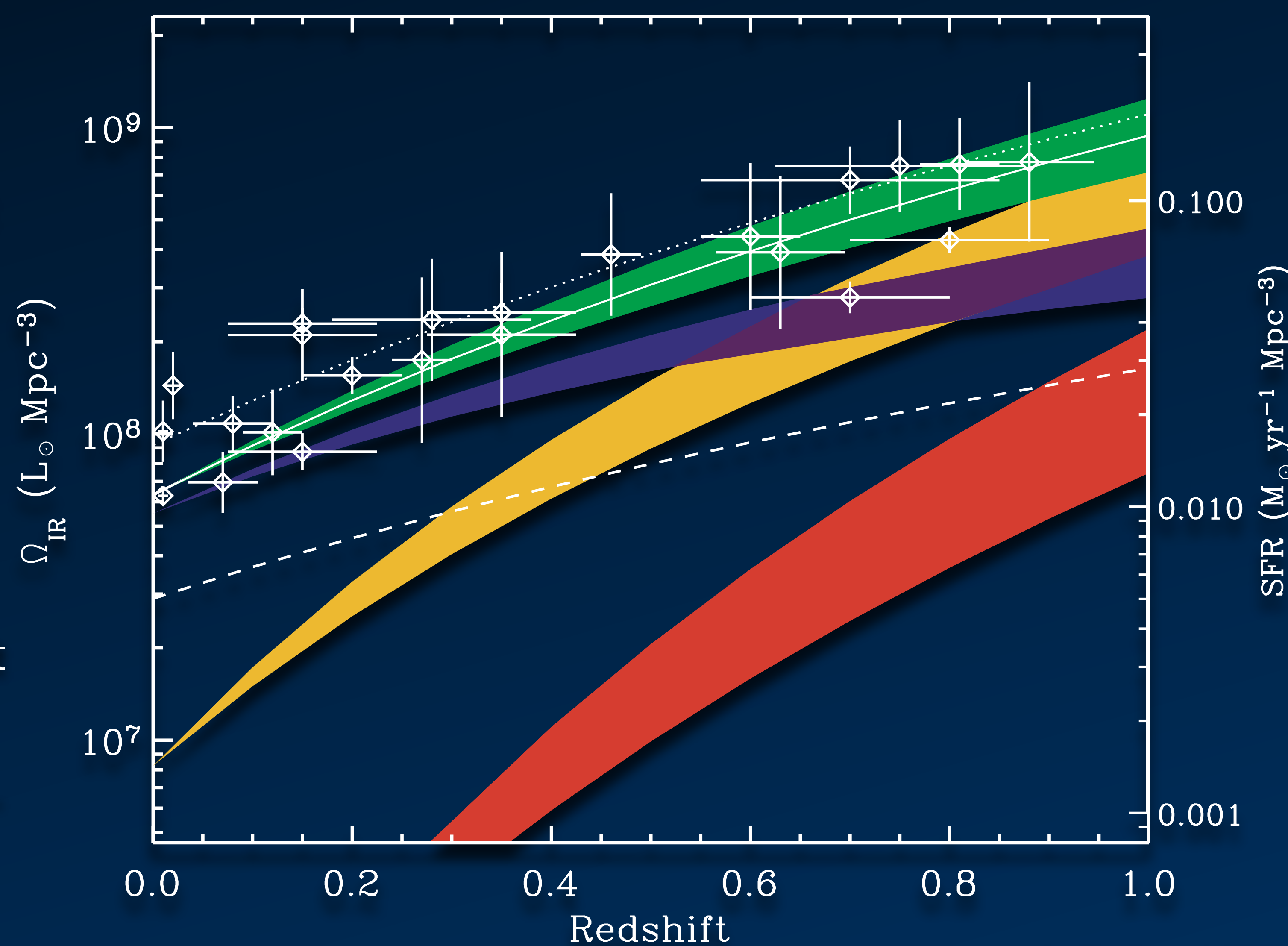


Kartaltepe et al. 2010

LIRGs and ULIRGs: a general perspective

- (U)LIRGs play a key role in galaxy evolution
  - Detected in large quantities at high-z (z>1) with *Spitzer* and *Herschel* (e.g. *Le Floc'h et al. 2005, Nardini et al. 2008, Magnelli et al. 2013*)
  - ULIRG contribution may be the dominant component to the SFR at z>2 (*Pérez-González et al. 2005, Magnelli et al. 2011, 2013*)
  - However, they are not very common in the local Universe…
- Then, why local (U)LIRGs?
  - Study of extreme environments with great amount of detail.
  - Compact star-formation and coeval AGN.
  - Feedback processes: outflows, quenching of the SF.
  - Link to high-z: main sequence of star-forming and normal galaxies.

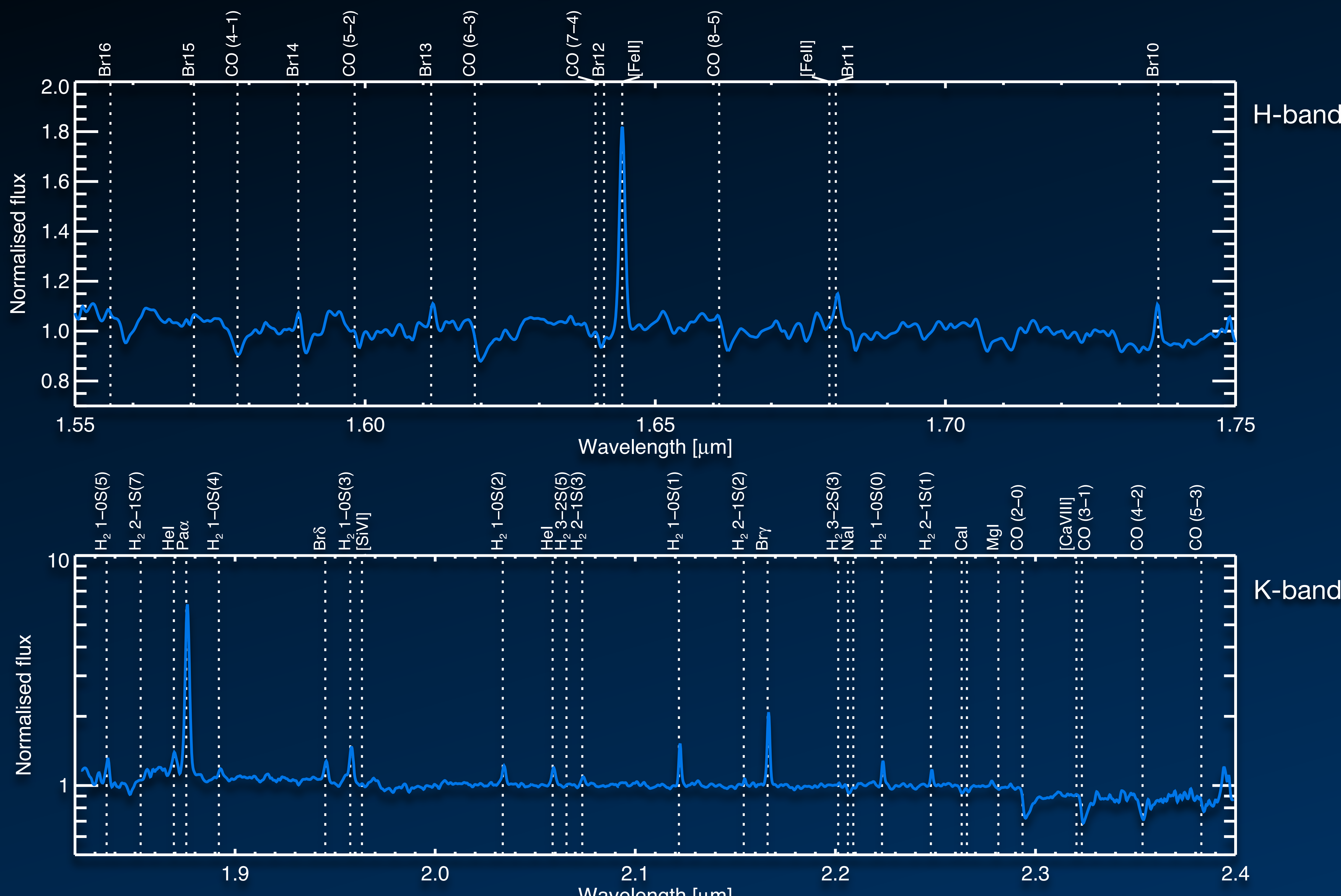


Le Floc'h et al. 2005

SINFONI: the NIR IFU at VLT

- Near-IR (1.1-2.45) integral field spectrograph at the Cassegrain focus of VLT-UT4 (*Eisenhauer et al. 2003, Bonnet et al 2004*)
- Seeing-limited and AO-assisted observations
- Four gratings: J, H, K and H+K
- Intermediate spectral resolution: R~2000- 4000 (J, H and K), R~1500 (H+K)
- Three plate scales: 0.025, 0.100 and 0.250 arcsec per spaxel yield FoV's of ~0.8"×0.8", 3"×3" and 8"×8"
- ~4000 individual spectra per data cube

Physics in the near-IR



Piqueras López et al. 2012

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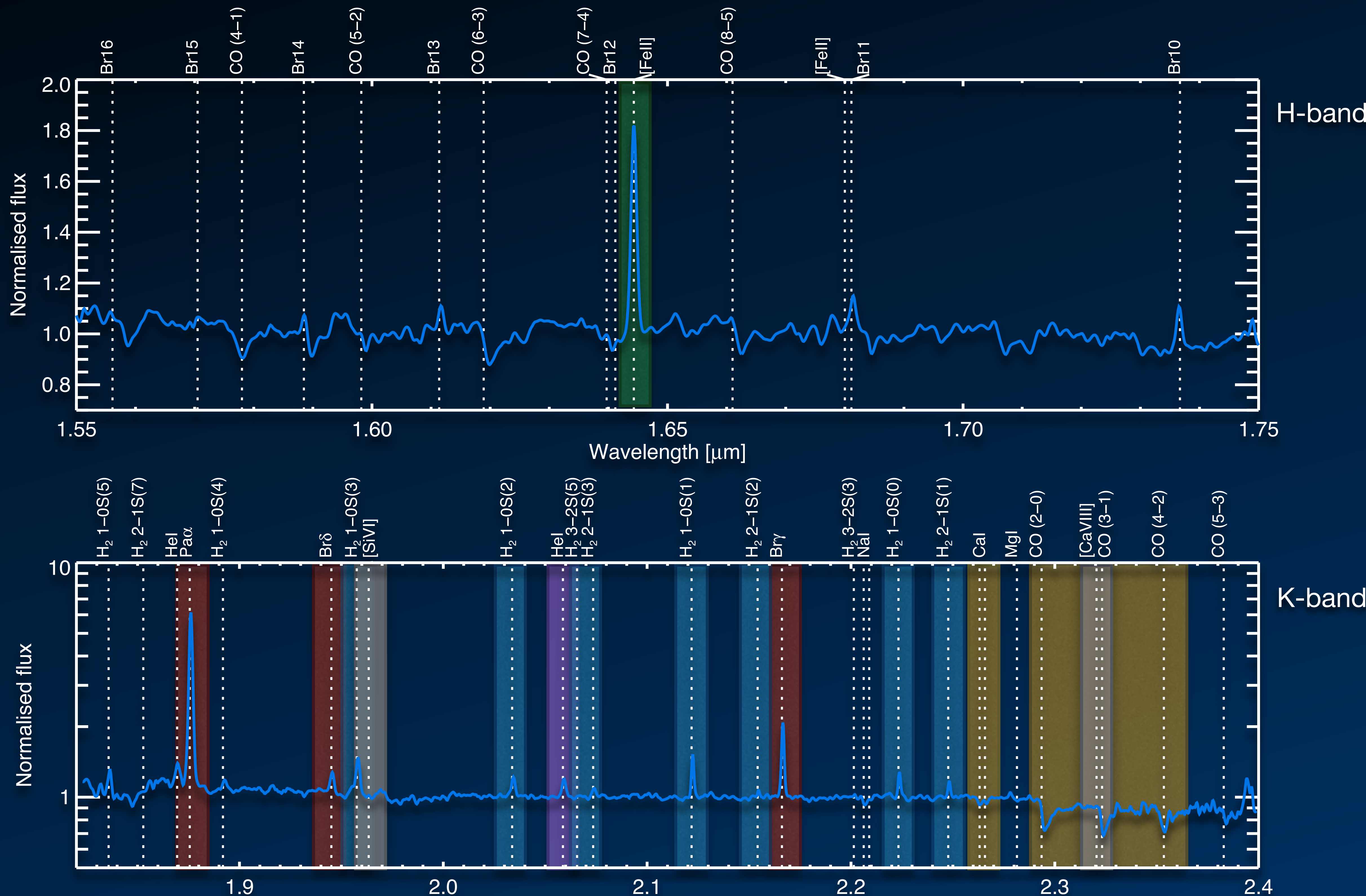


Piqueras López et al. 2012

IFS study of local LIRGs and ULIRGs

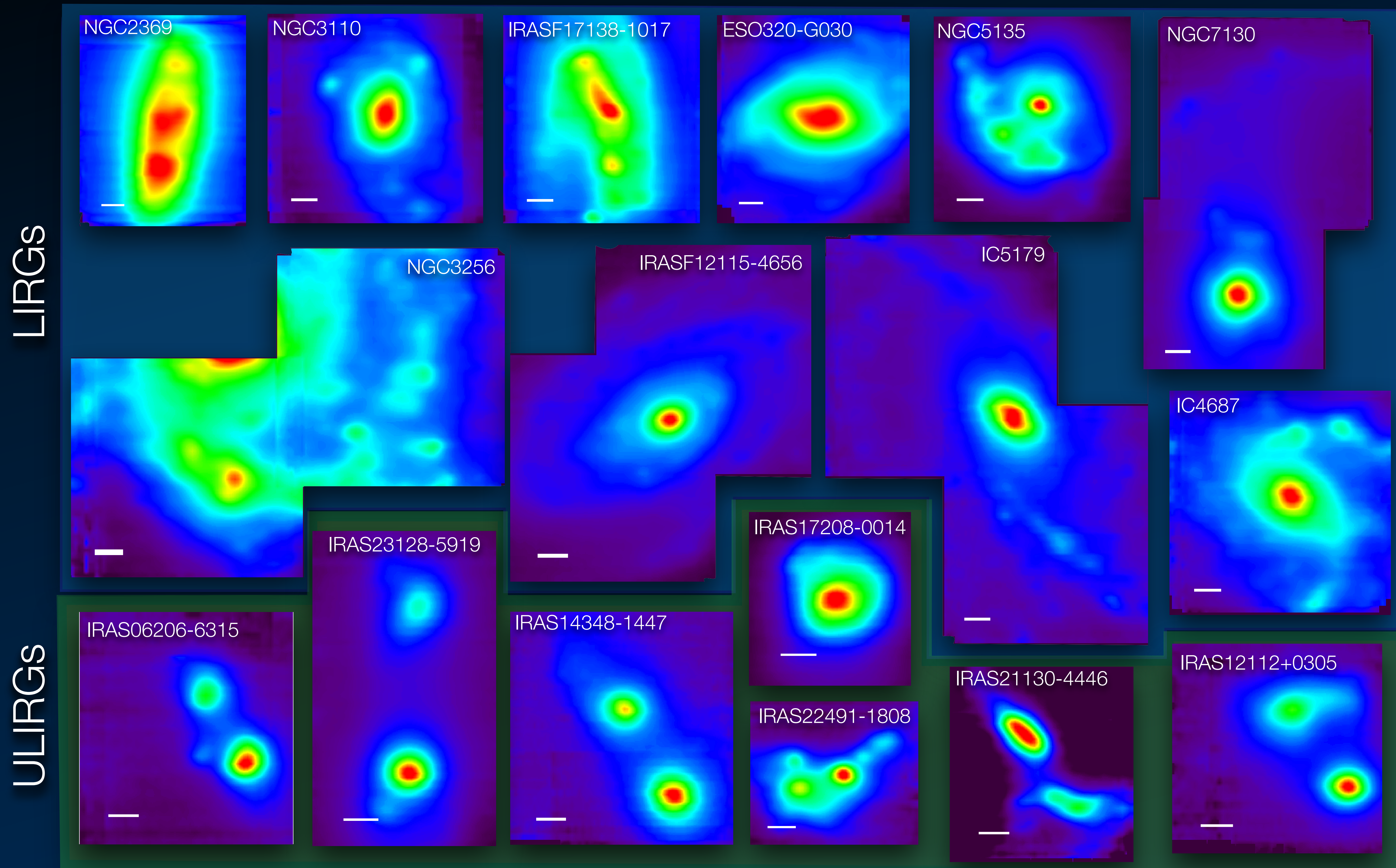
- First comprehensive NIR IFS study of a sample of local LIRGs and ULIRGs
  - Representative sample of 10 LIRGs and 7 ULIRGs @ $z<0.1$
  - $\log(L_{IR}/L_{\odot}) \sim 11.1 - 12.4$
  - Different morphological types, objects with intense star formation, AGN activity, isolated galaxies, strongly interacting systems, mergers
  - Part of a larger sample of local LIRGs and ULIRGs observed with different IFS facilities (*Arribas et al. 2008*)
- Observations:
  - Seeing limited, ~0.6 arcsec (FWHM)
  - FoV ~8”x8”, spatial resolution ~0.125 arcsec/spaxel
  - LIRGs
    - H- and K-band, R~3000-4000
    - FoV ~3x3 kpc, spatial resolution ~0.2 kpc (FWHM)
  - ULIRGs
    - K-band, R~4000
    - FoV ~12x12 kpc, spatial resolution ~0.9 kpc (FWHM)

Data analysis and calibration

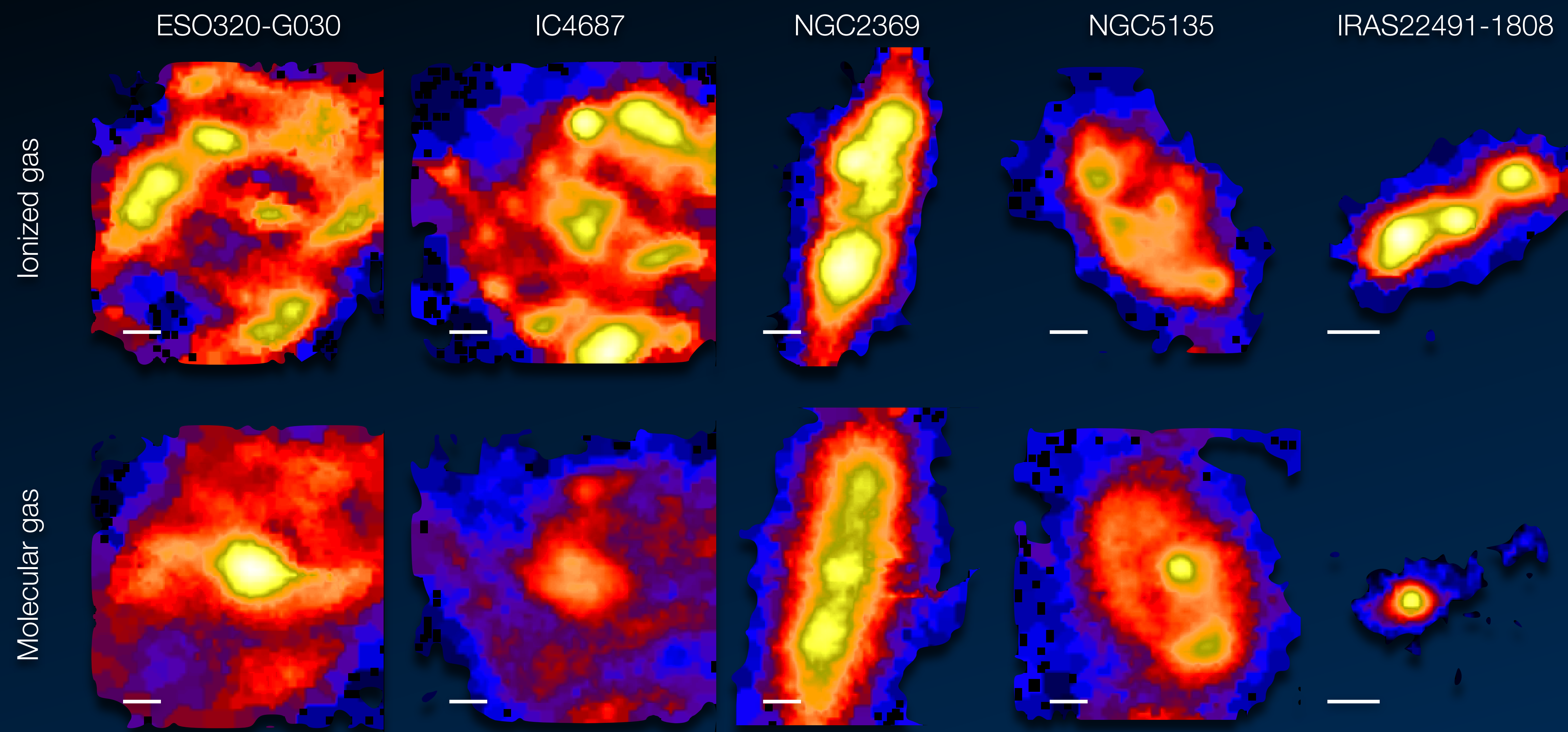
- Data reduction and calibration
  - ESO standard pipeline: EsoRex.
  - Flux calibration: substraction of the sky emission, atmospheric absorption, and absolute flux calibration.
  - Own IDL routines to improve the final data cubes: La3D and background-match method.
- Emission and kinematic maps:
  - Emission lines: single Gaussian fitting on an spaxel-by-spaxel basis.
  - Voronoi tesselation (*Cappellari & Copin 2003*): maximise the mean S/N of the maps.
  - Stellar kinematics: pPXF (*Cappellari & Emsellem 2004*) to fit a library of stellar templates.

Morphology and gas kinematics

LIRGs and ULIRGs K-band continuum



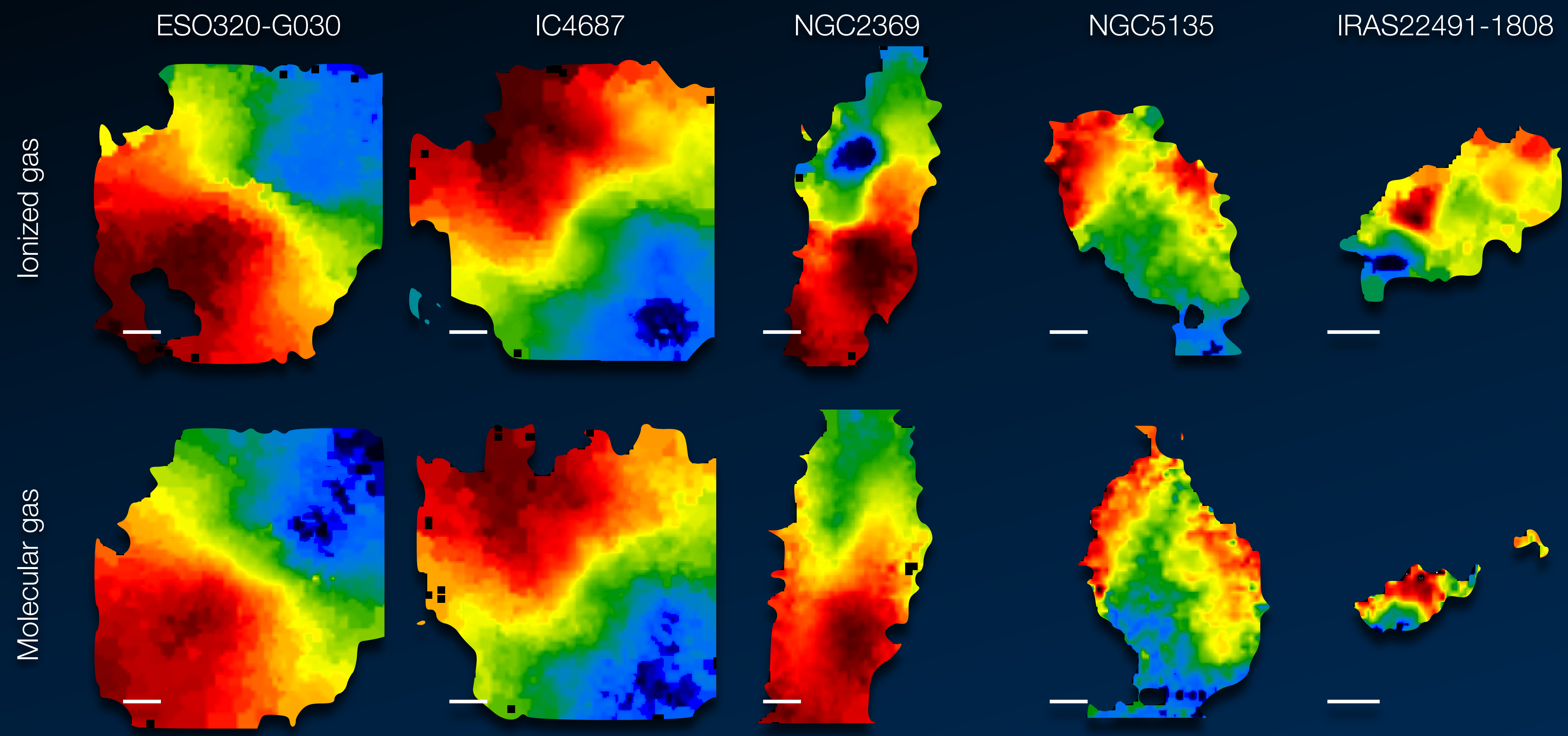
Gas morphology and kinematics



Piqueras López et al. 2012

- Star-forming regions are concentrated on structures like rings or spiral arms.
- These structures dominate the emission of ionised gas.
- Regions with intense star formation (~30 $M_{\odot} yr^{-1}$) at distances ~2-4 kpc from the nuclei.
- Warm molecular gas is mainly concentrated at the nuclei of the galaxies.
- H_2 1-0S(1) and Brγ lines show similar luminosities.

Gas morphology and kinematics



Piqueras López et al. 2012

- Both ionized and molecular phases show very similar global kinematics.
- Velocity fields in LIRGs show typical rotational patterns.
- ULIRGs show complex kinematics, with different velocity gradients due to their interacting nature.

Dust extinction and star formation

Extinction and SF in (U)LIRGs

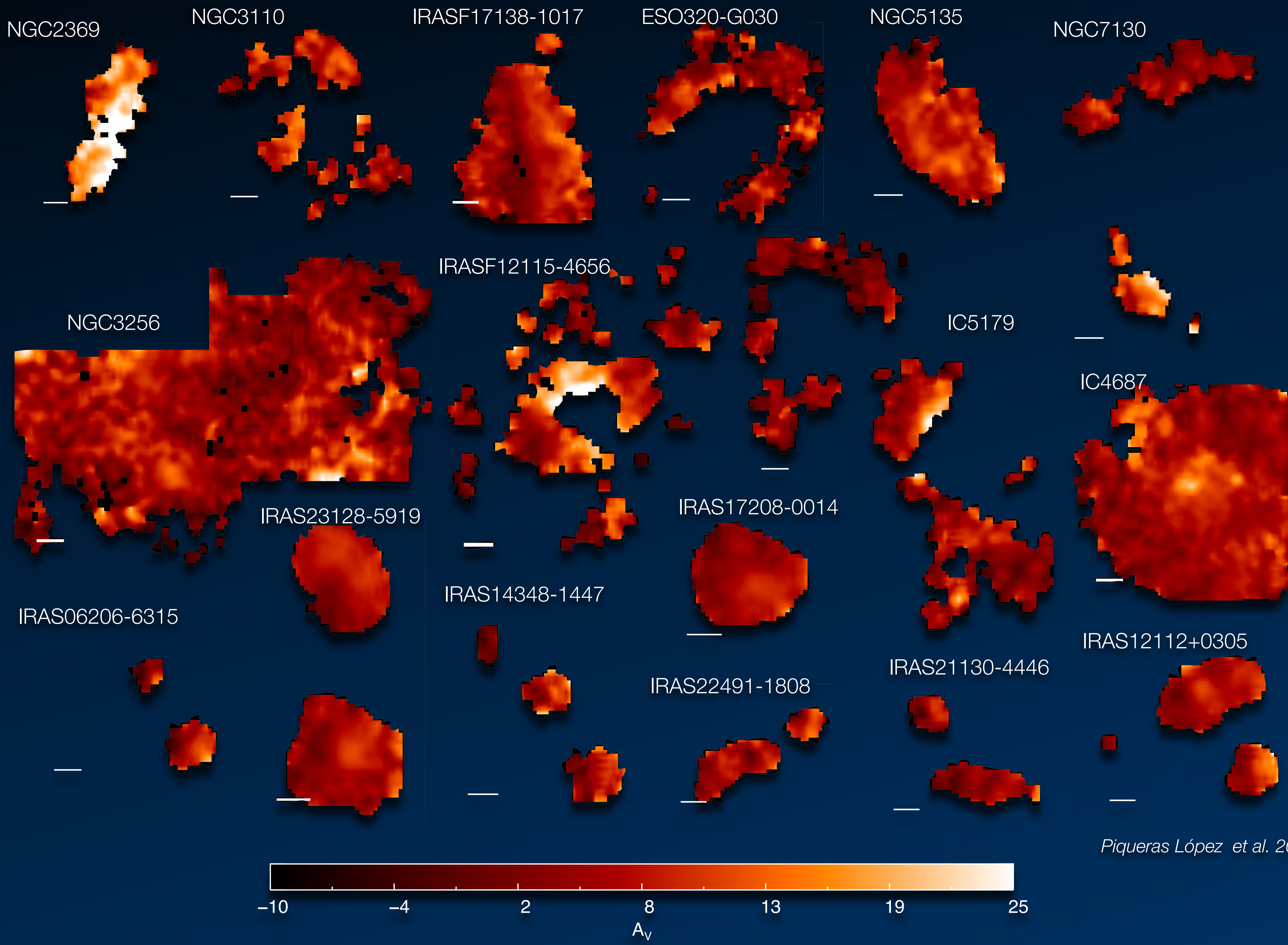
- Analysis of the dust extinction:

$$A_{\lambda_1} - A_{\lambda_2} = -2.5 \cdot \log \frac{(F_{\lambda_1}/F_{\lambda_2})_O}{(F_{\lambda_1}/F_{\lambda_2})_T}$$

$$A_{Br\gamma} = 0.096\,A_V,\; A_{Br\delta} = 0.132\,A_V \text{ and } A_{Pa\alpha} = 0.145\,A_V$$

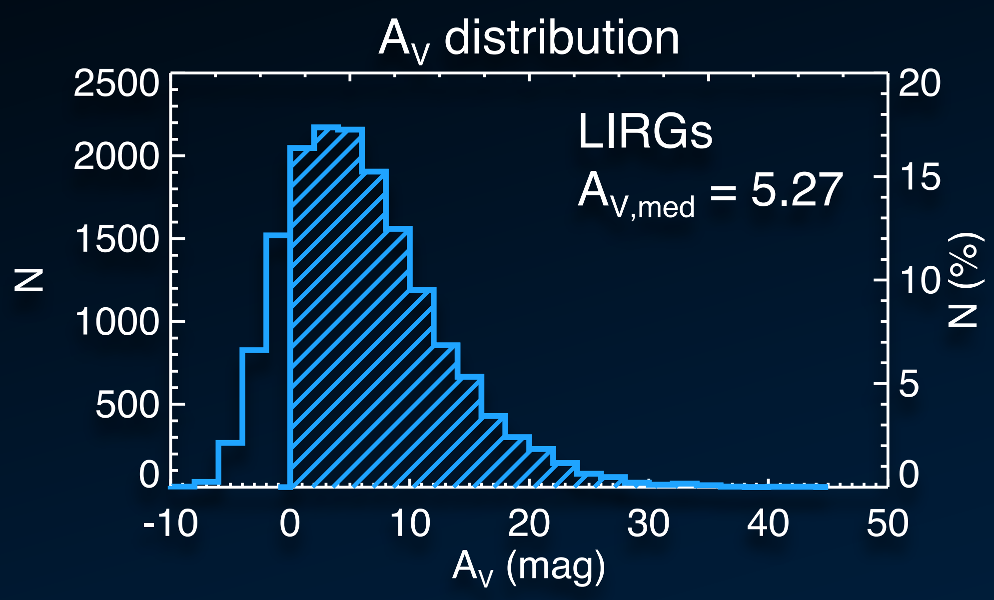
- Star-formation rate (see *Calzetti, 2012; Kennicutt & Evans 2012*):
  - Ionized gas: Brγ (LIRGs) and Paα (ULIRGs)
  - Monochromatic mid-IR (24 μm)
  - Integrated far-IR (8-1000 μm)

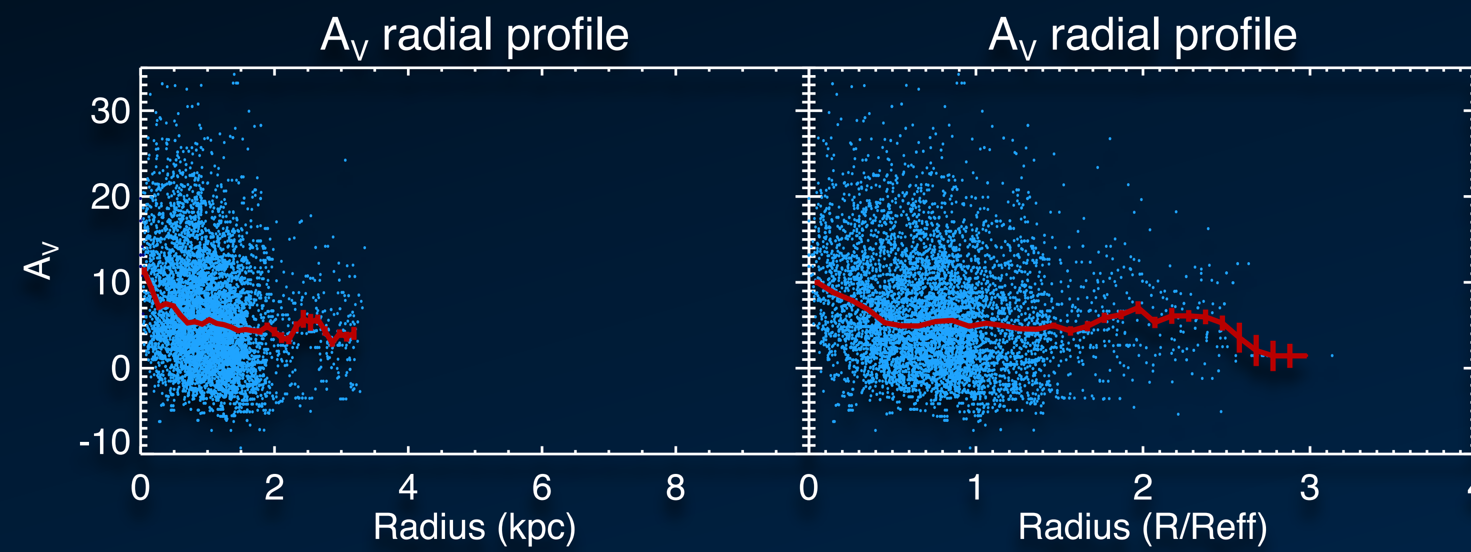
2D extinction structure



Piqueras López et al. 2013

Av distributions and radial profiles





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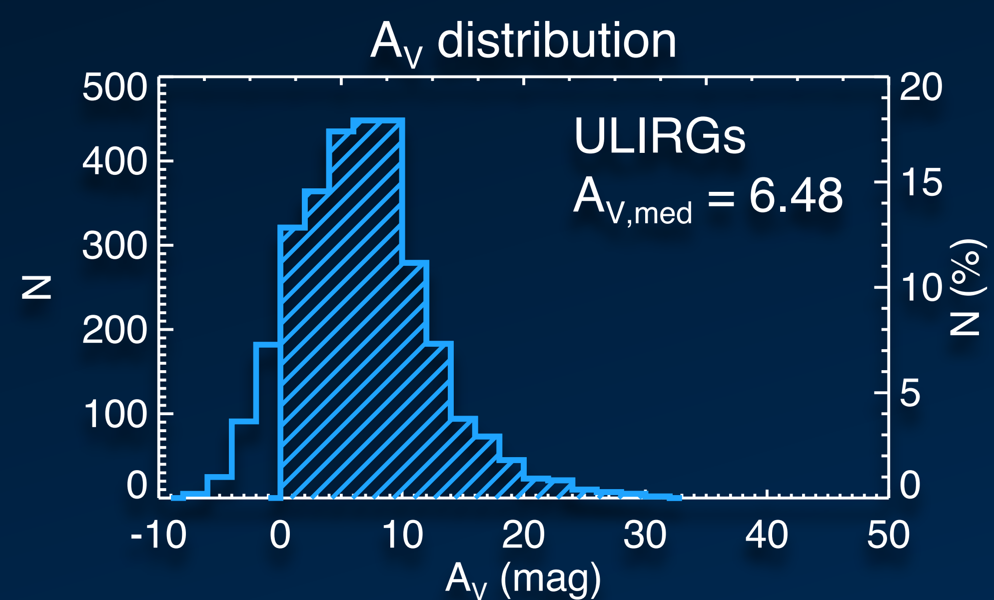
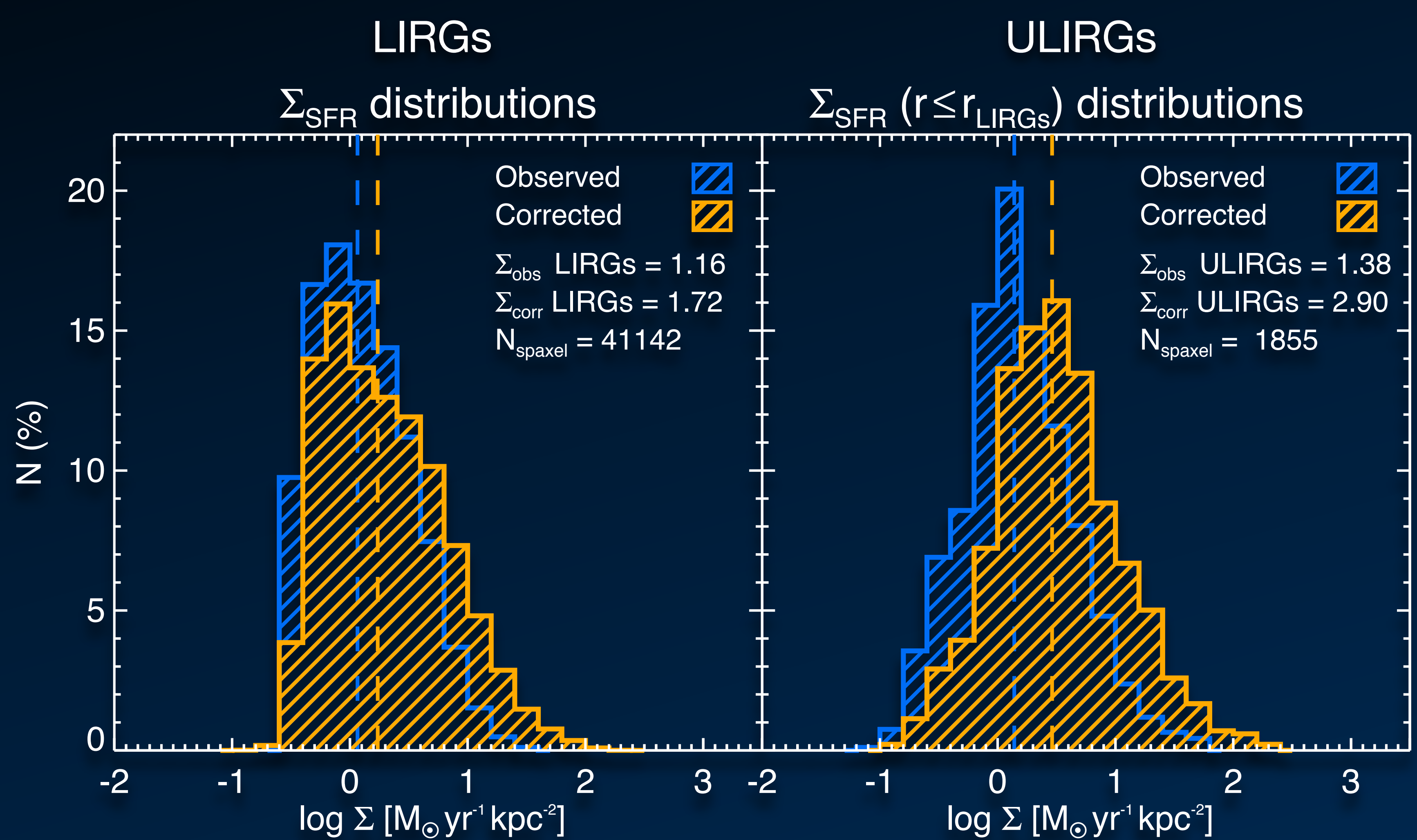


- Typical spaxel-by-spaxel values: Av ~ 1 - 30 mag
- Individually, there is no dependence on luminosity.
- Global distributions:

  Av (ULIRGs) ~ Av (LIRGs) +1.2 mag

- Radial profiles:
  - Mild dependence on galactocentric distance up to ~1 kpc.
  - Visual extinction decreases ~2-3 mag within the first kpc.

Σ_{SFR} distributions



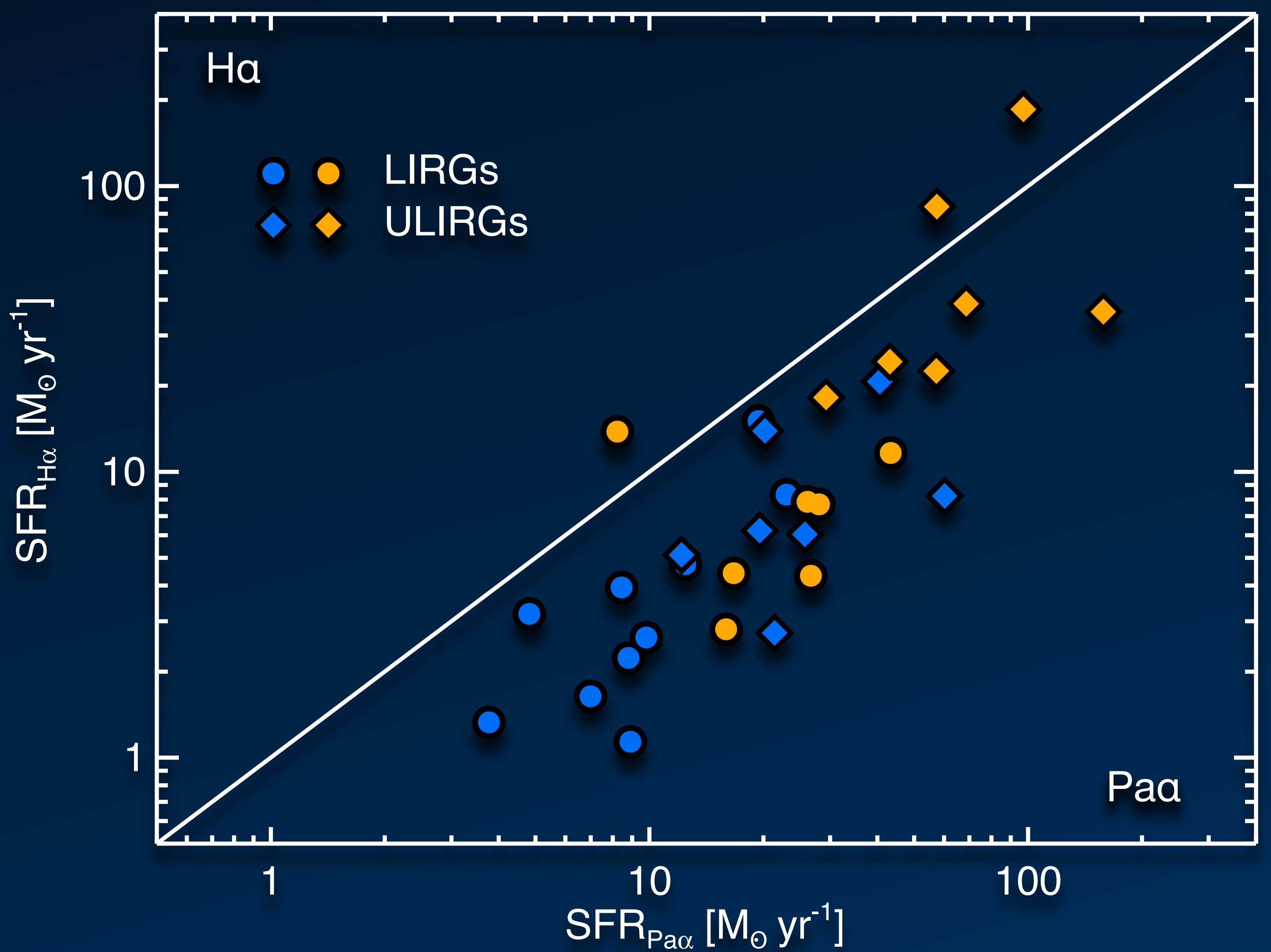
Piqueras López et al. 2014, in prep.

- Spaxel-by-spaxel distributions of the Σ_{SFR} of LIRGs and ULIRGs (observed and extinction corrected) in regions with similar physical scales (r < 1.4 kpc)
- Median values: Σ_{SFR} (LIRGs) = 1.72 $M_\odot yr^{-1} kpc^{-2}$; Σ_{SFR} (ULIRGs) = 2.90 $M_\odot yr^{-1} kpc^{-2}$

Σ_{SFR} (ULIRGs) ~ 1.7 x Σ_{SFR} (LIRGs)

Comparison with other SFR tracers

- Optical (Hα):
  - Observed and extinction-corrected values.
  - Deeply obscured regions: optical measurements underestimate the extinction.
  - SFR(Paα) ~ 3 x SFR(Hα)
- Mid-infrared (24 μm):
  - Strong correspondence with SFR(Paα) measurements
  - Some discrepancies at the high luminosity range.
- Far-infrared (L_{IR}):
  - SFR(Paα) measurements are systematically lower than SFR(L_{IR})
  - Extinction effects.
  - Contribution from underlaying old stellar populations.



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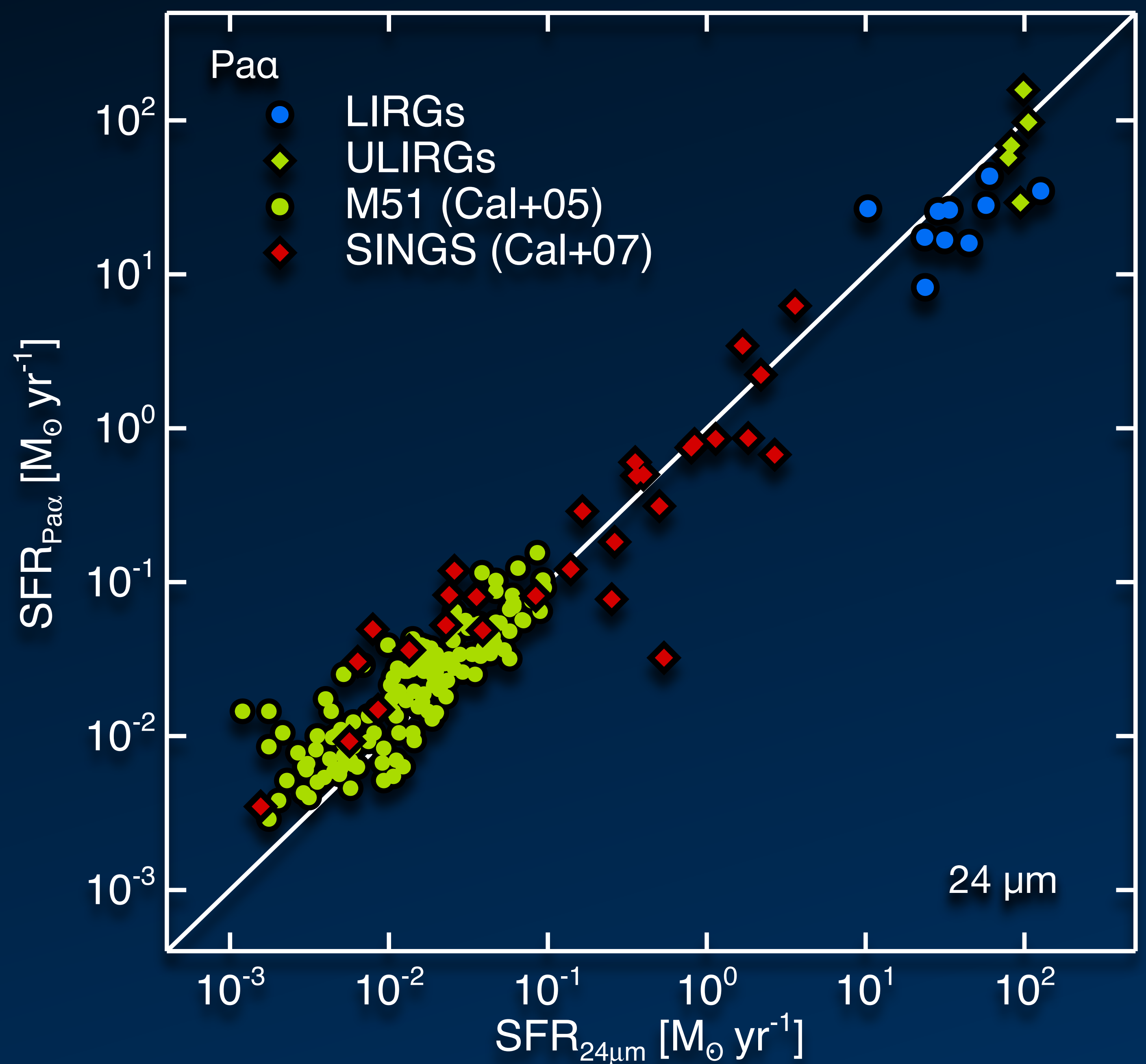

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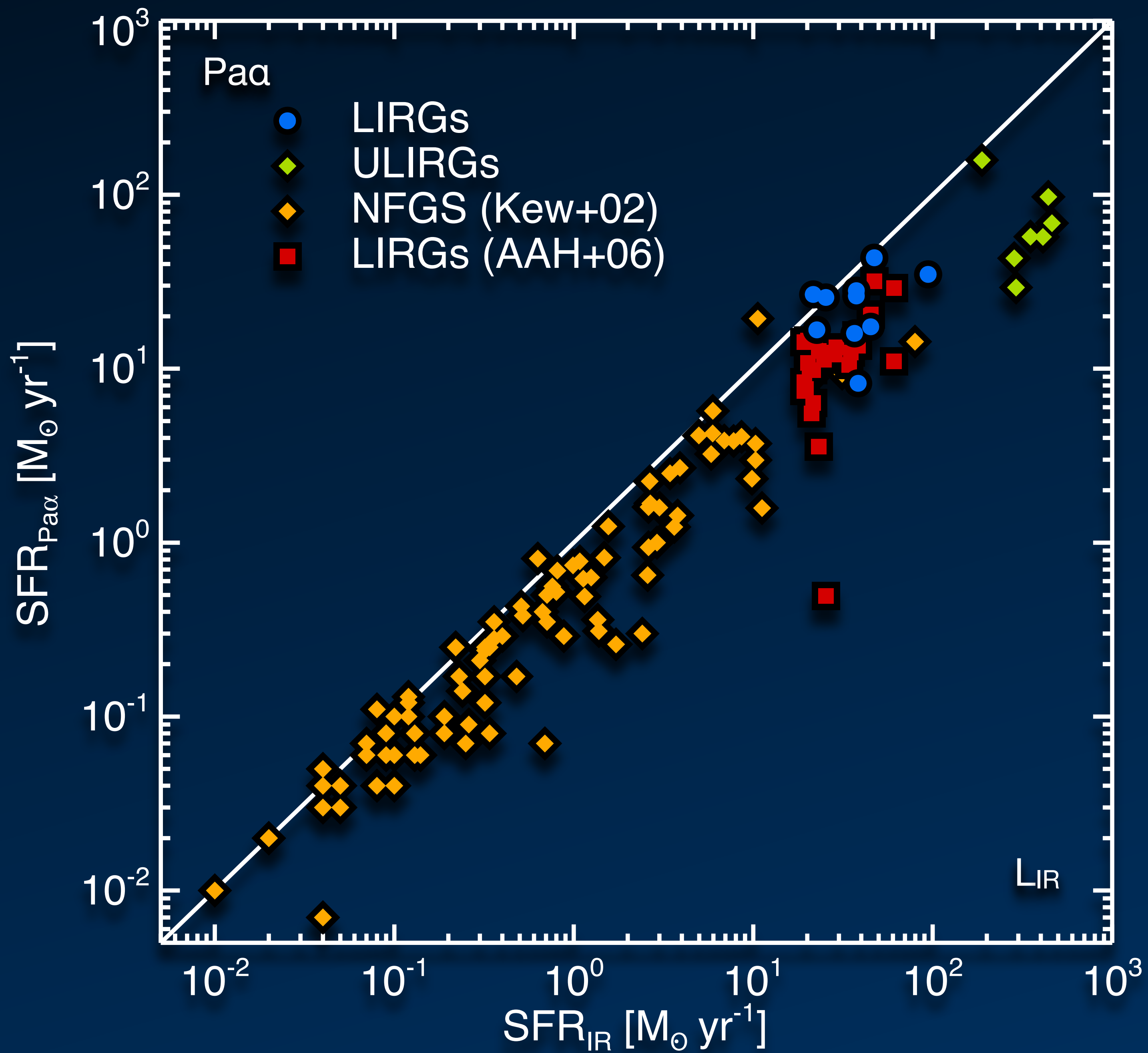
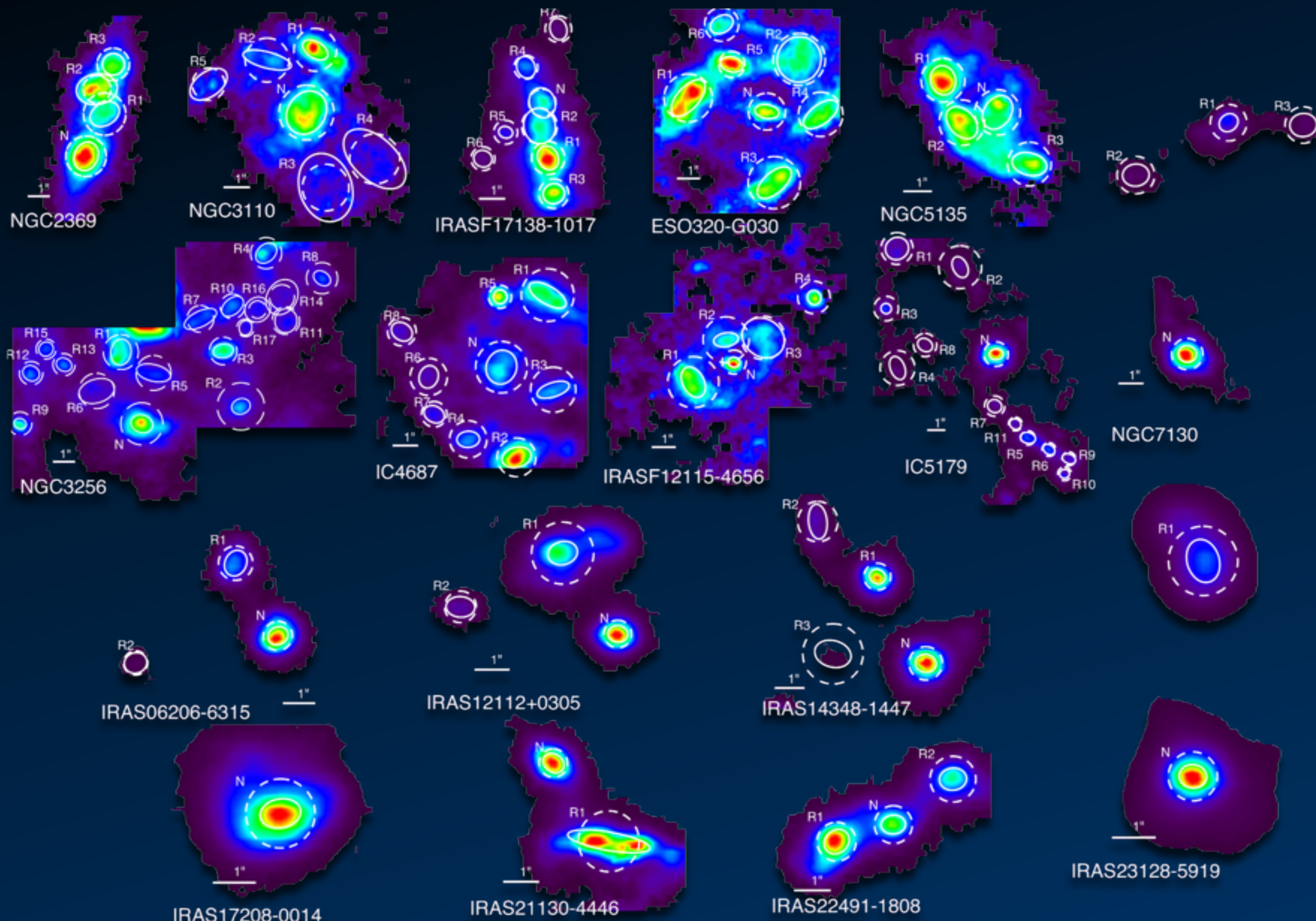


Piqueras López et al. 2014, in prep.

Characterisation of star-forming regions



Characterisation of star-forming regions

- Two methods (effective and core radius) yield similar results.
- Size:
  - LIRGs: r~60-400 pc
  - ULIRGs: r~300-1500 pc
- Luminosity:
  - LIRGs: $L_{Pa\alpha}$~10^5-10^7 $L_\odot$
  - ULIRGs: $L_{Pa\alpha}$~10^6-10^8 $L_\odot$
- SFR surface density:
  - LIRGs: Σ_{SFR}~1-90 $M_\odot yr^{-1} kpc^{-2}$
  - ULIRGs: Σ_{SFR}~0.1-100 $M_\odot yr^{-1} kpc^{-2}$
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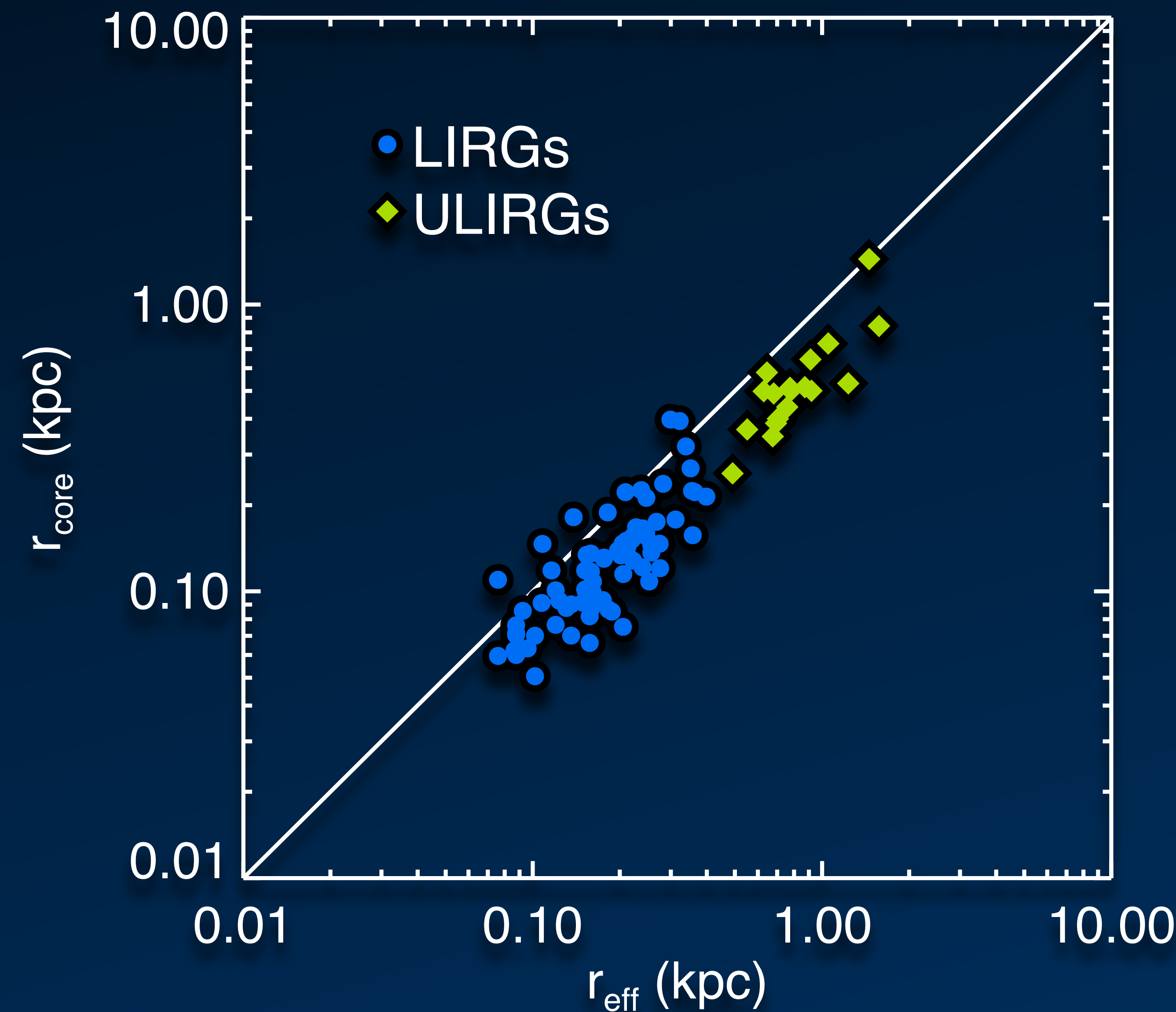

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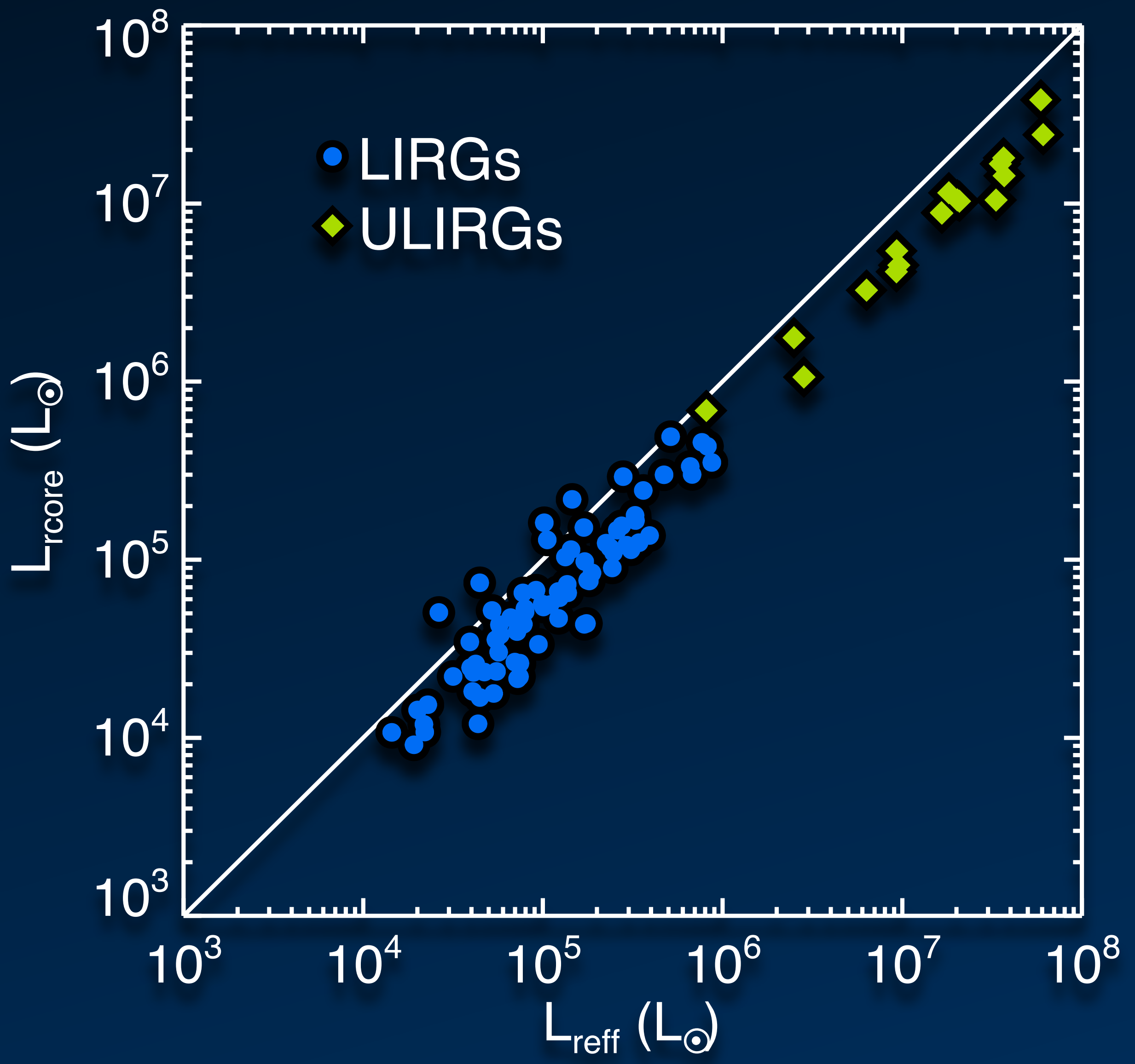

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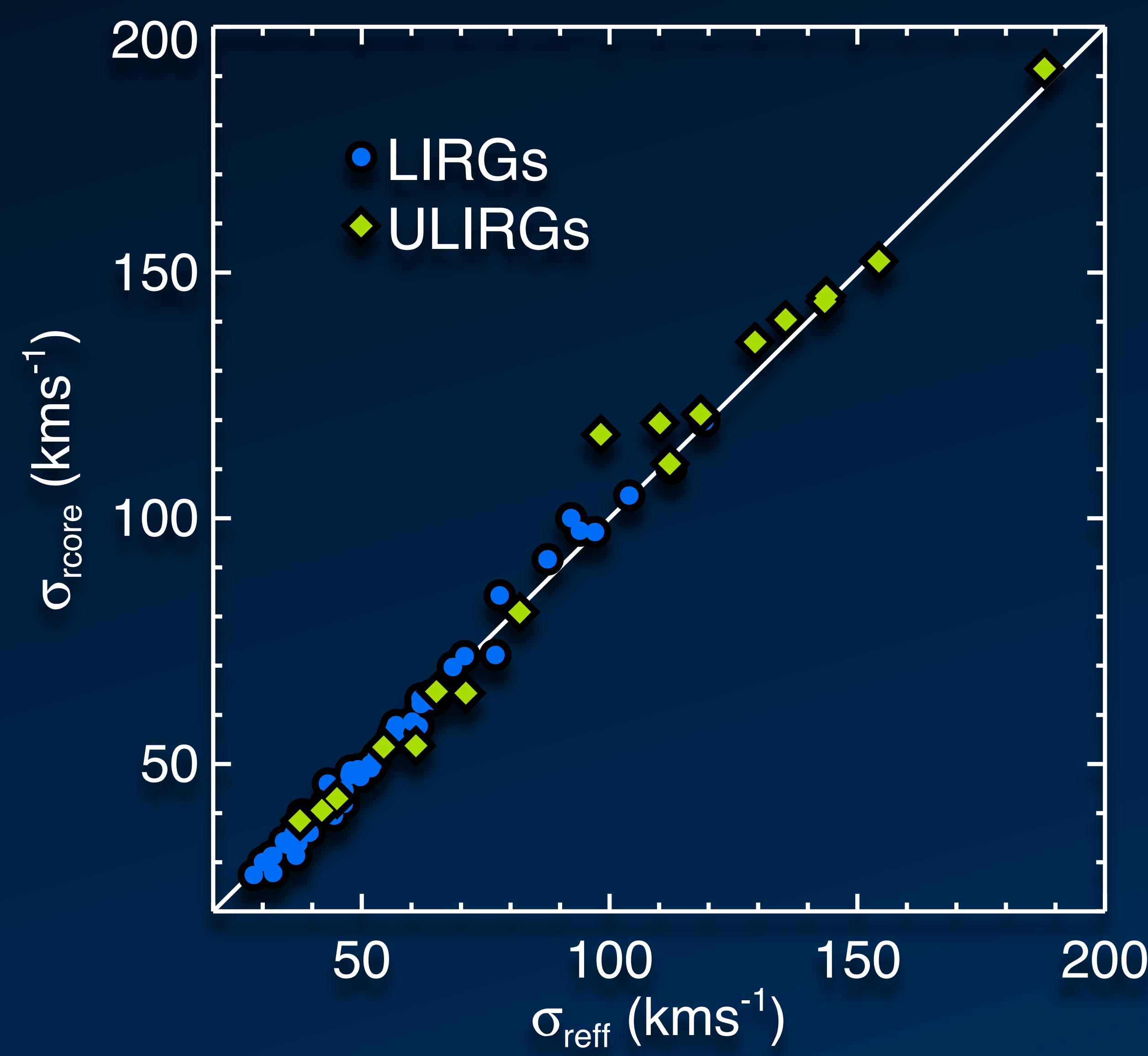
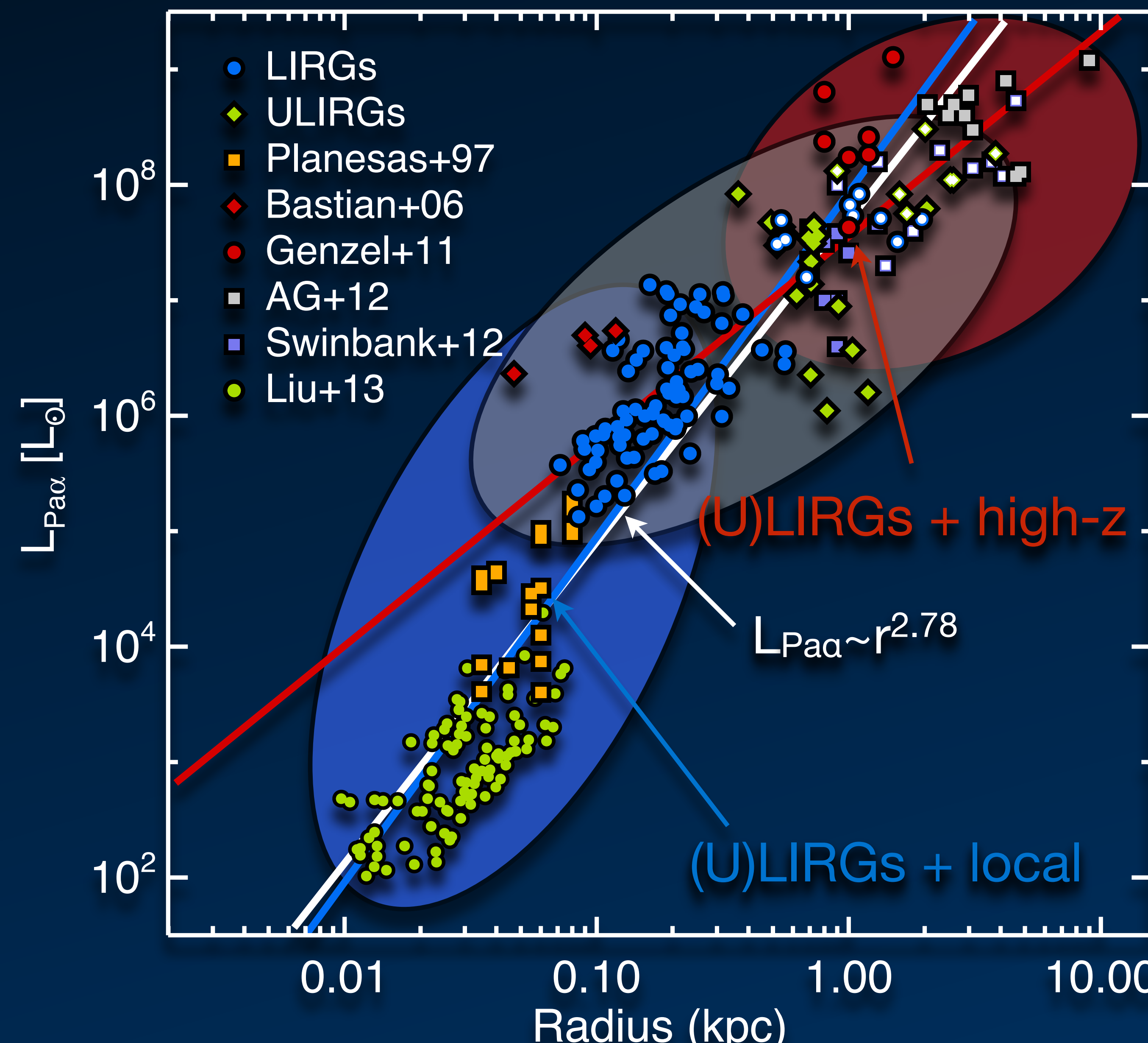


Piqueras López et al. 2014, in prep.

Comparison with local and high-z samples

- Comparison with other samples:
  - Locally: star-forming regions from 'normal' and starbursts galaxies, and Antenae.
  - High-z: star-forming regions and global measurements within z~0.8-2.7.
- $L_{Pa\alpha}$ - r relation, possible transition:
  - Ionized-bounded regions (Strömgren spheres): n = 3
  - Density-bounded regions: n < 3
  - Frontier at $L_{Pa\alpha} \sim 10^5\ L_\odot$ (*Beckman et al. 2000*)
- Linear fitting to different samples:
  - (U)LIRGs + local: n = 2.98
  - (U)LIRGs + high-z: n = 1.77
  - All samples: n = 2.78
- Possible resolution effects, blending, S/N (*Liu et al. 2013*)

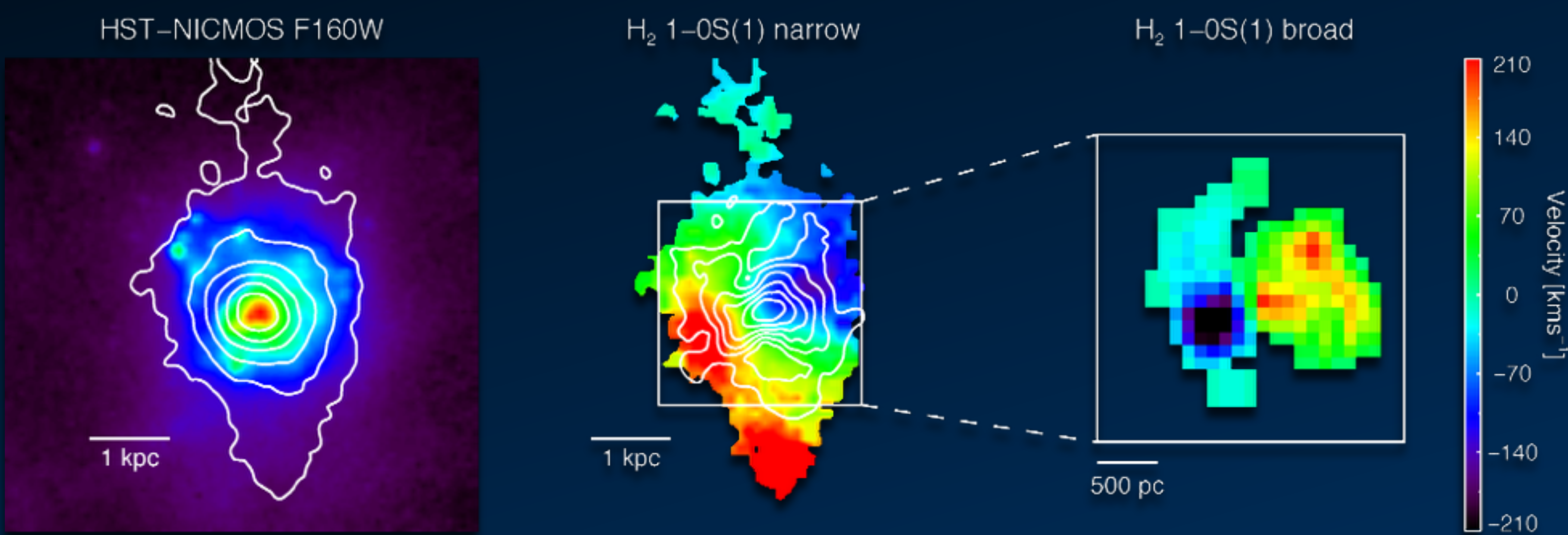


Piqueras López et al. 2014, in prep.

Detailed kinematics

Multi-component gas kinematics

IRAS17208-0014



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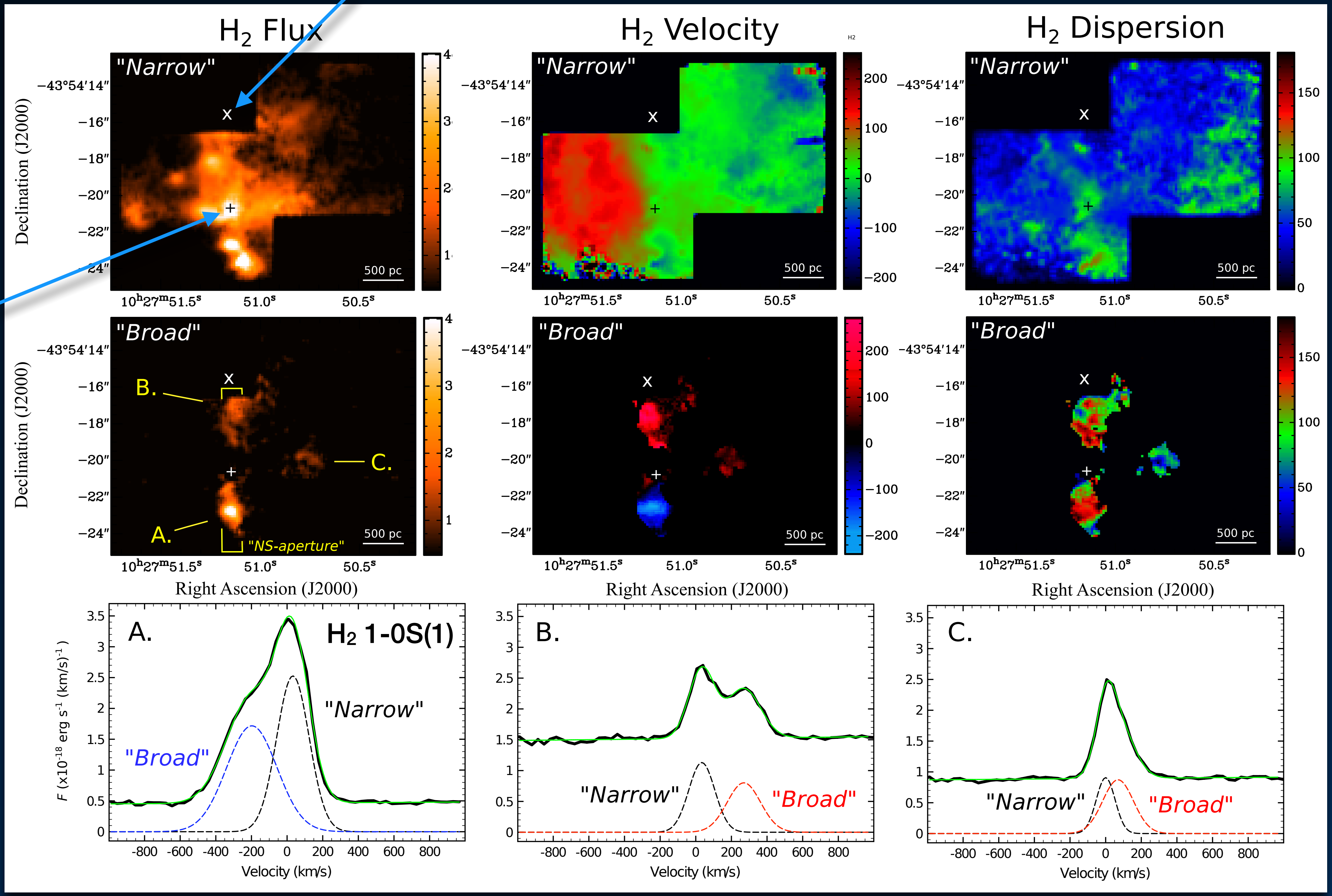
Multi-phase outflows: AGNs

NGC3256

Main nucleus

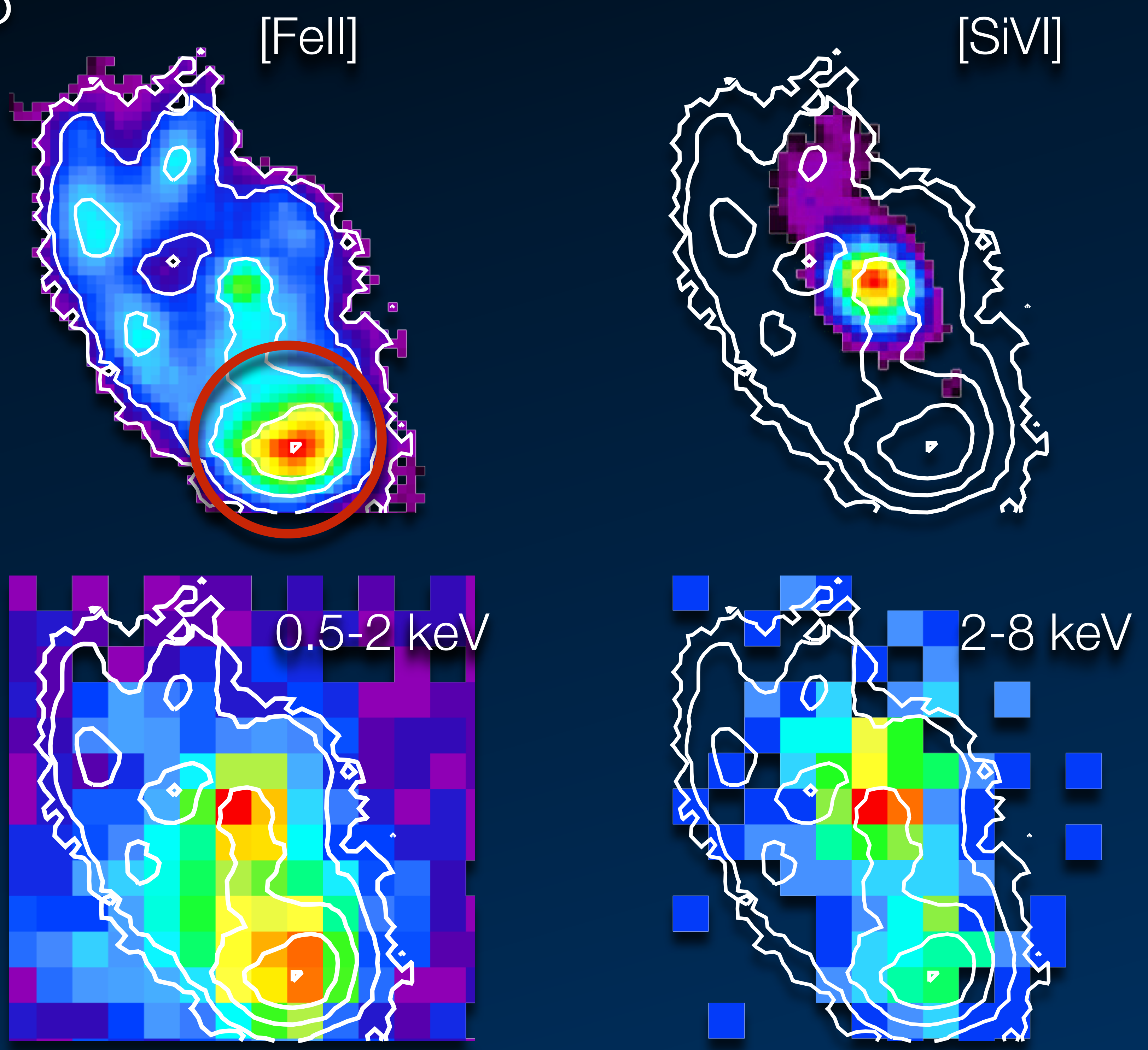
Secondary nucleus



Emonts et al. 2014 (accepted, A&A)

Multi-phase outflows: SNs

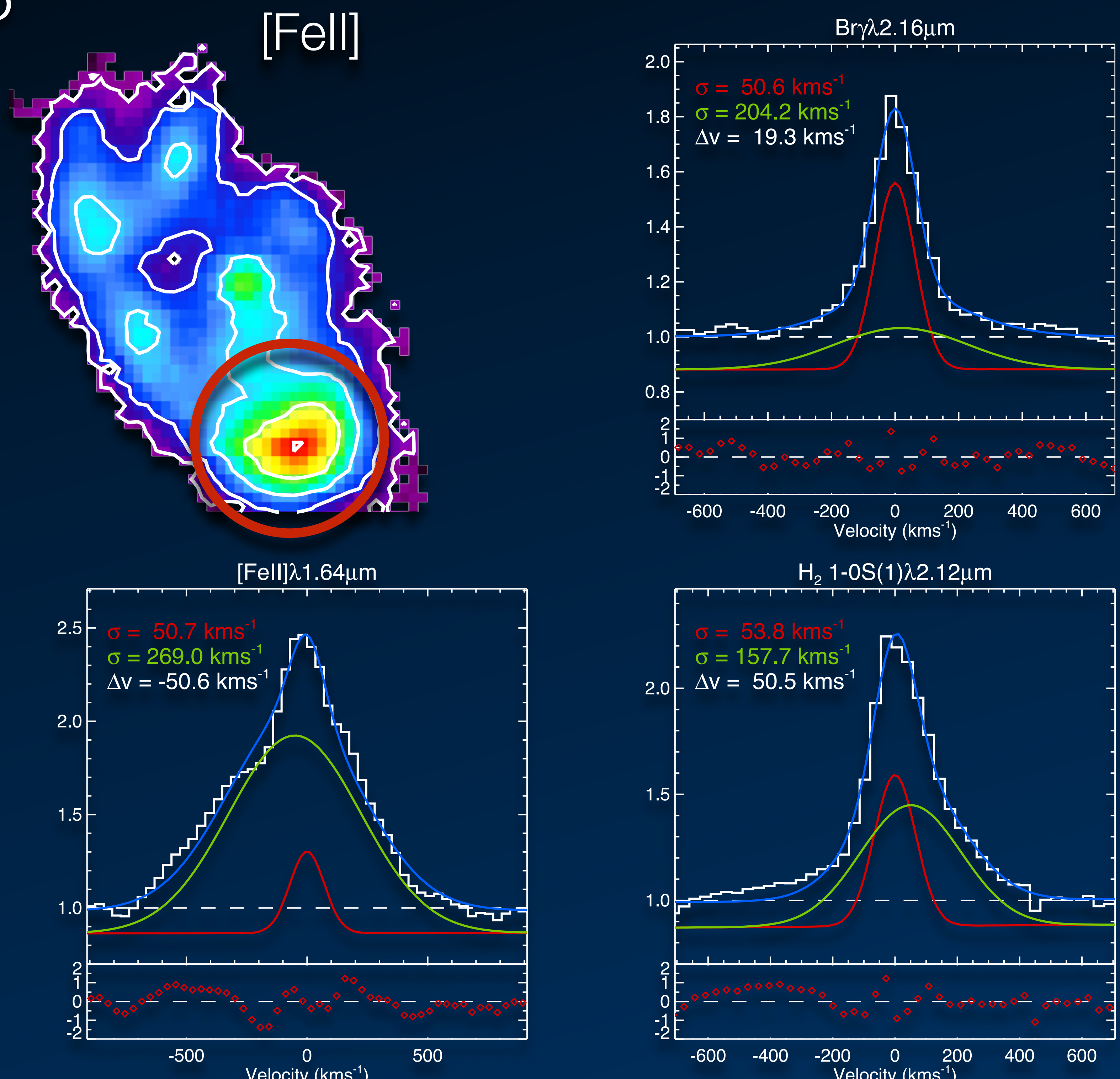
NGC5135



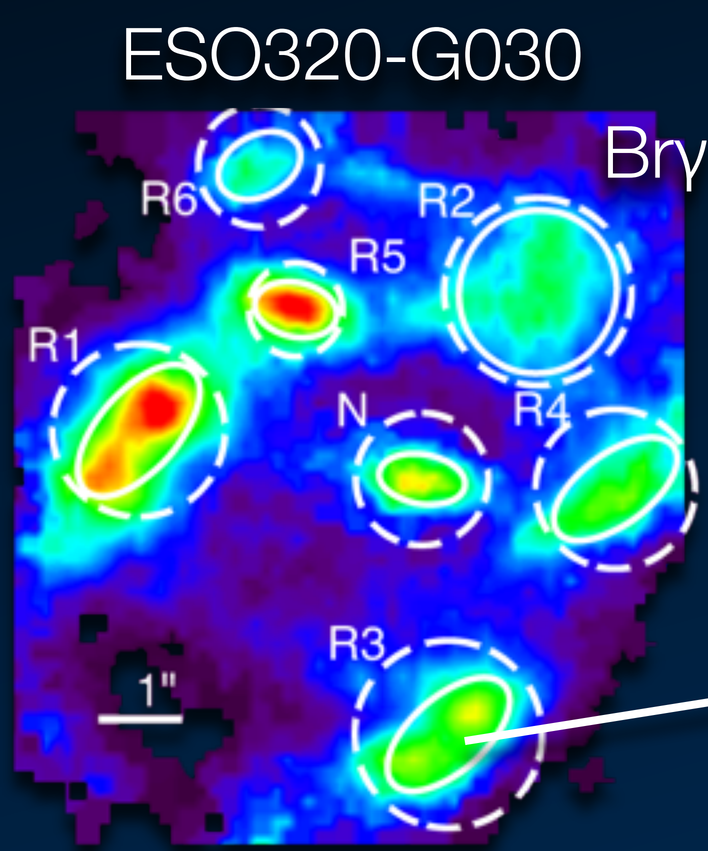
Bedregal et al. (2009), Colina et al. (2012)

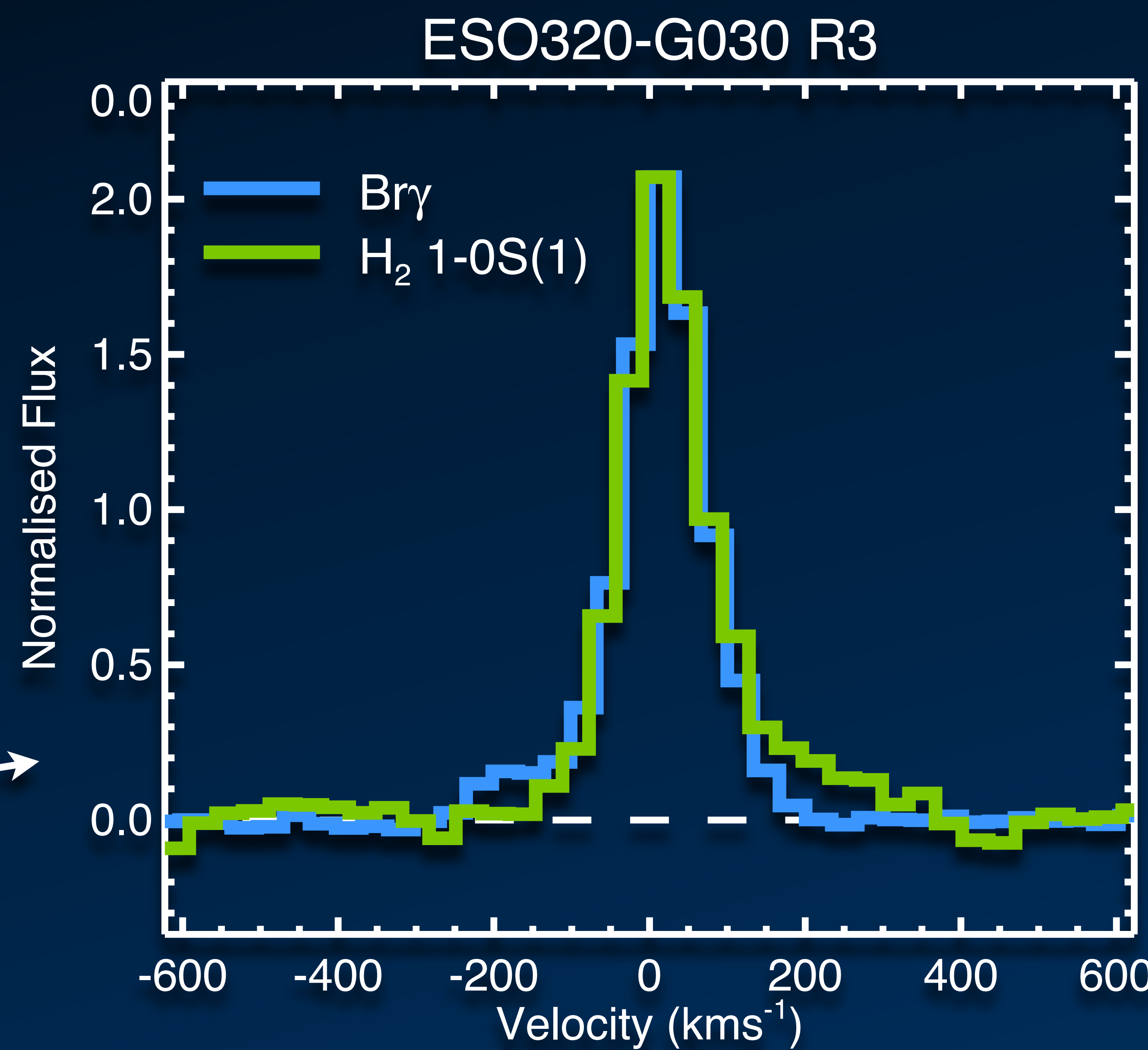
Multi-phase outflows: SNs

NGC5135



Multi-phase outflows: Star formation





Piqueras López, J., 2014, PhD Thesis

Summary

- Near-IR IFS:
  - Allows us to perform comprehensive analysis of a wide variety of physical processes.
  - And trace the kinematics of different phases of the ISM simultaneously using a single, self-contained data set.
- SINFONI study of local (U)LIRGs
  - Different phases of the gas present different morphologies and small-scale kinematics.
  - Ionized gas associated with SF regions in rings and spiral arms, molecular gas concentrated towards the stellar nuclei of the sources.
  - Wide range of Av values on a spaxel-by-spaxel basis, from regions almost transparent to Av~25-30 mag.
  - Star formation:
    - Σ_{SFR} ~ 0.3-50 $M_{\odot} yr^{-1} kpc^{-2}$ in LIRGs and ~ 0.05-15 $M_{\odot} yr^{-1} kpc^{-2}$ in ULIRGs
    - Σ_{SFR} (ULIRGs) ~ 1.7 x Σ_{SFR} (LIRGs) within the same physical scales.
  - Star-forming regions:
    - Analysis of 95 individual regions: SFR ~ 0.03 - 30 $M_{\odot} yr^{-1}$, r~60-400 pc in LIRGs and r~300-1500 pc in ULIRGs.
    - Star-forming regions, especially in ULIRGs, present similar properties than those observed at high-z.
  - Multi-phase outflows: ubiquitous, with independence of their driving mechanism.