The HST GOALS Survey:
Probing the Morphology and Evolution of U/LIRGs

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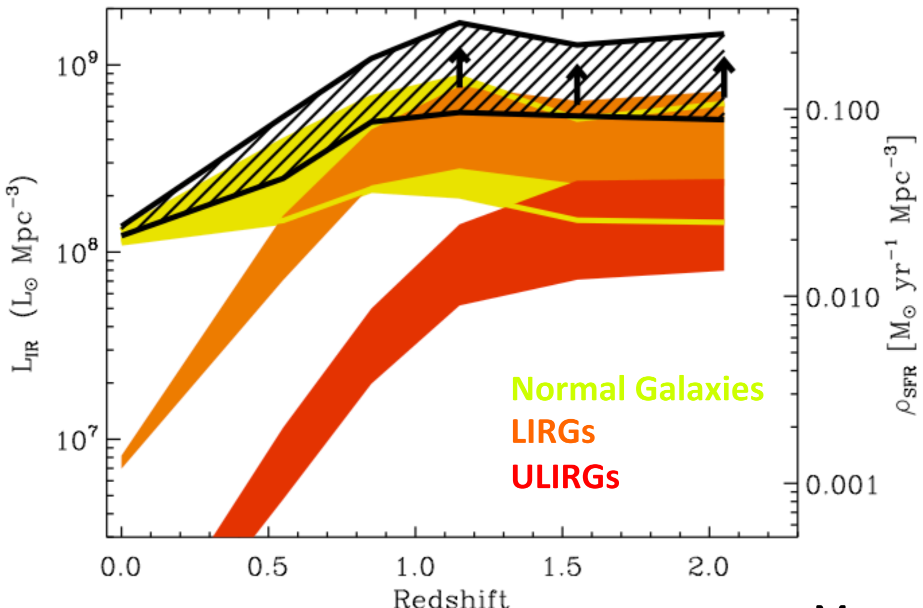
26 Sep 2013, Sydney

Luminous Infra-Red Galaxies

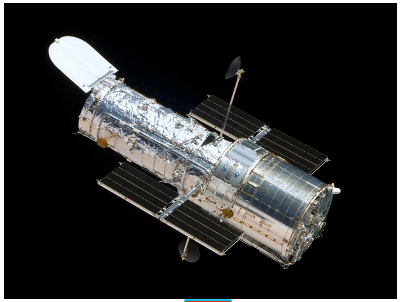
- Enhanced IR luminosity (LIRGs $L_{IR} > 10^{11}\ L_\odot$; ULIRGs: $L_{IR} > 10^{12}\ L_\odot$)
- Very gas- and dust-rich, 10 to 500x larger SFR than normal galaxies
- Comprise >50% of cosmic IR background and dominate SF activity at z > 1
  (Caputi+07, Magnelli+11, Berta+11)
- Represent a critical phase in the evolution of galaxies where most of the stellar galaxies mass is building up



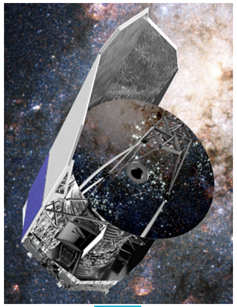
Magnelli+11

Spitzer

HST

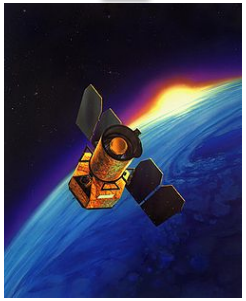


Herschel



GOALS Great Observatory All-sky LIRG Survey

Chandra

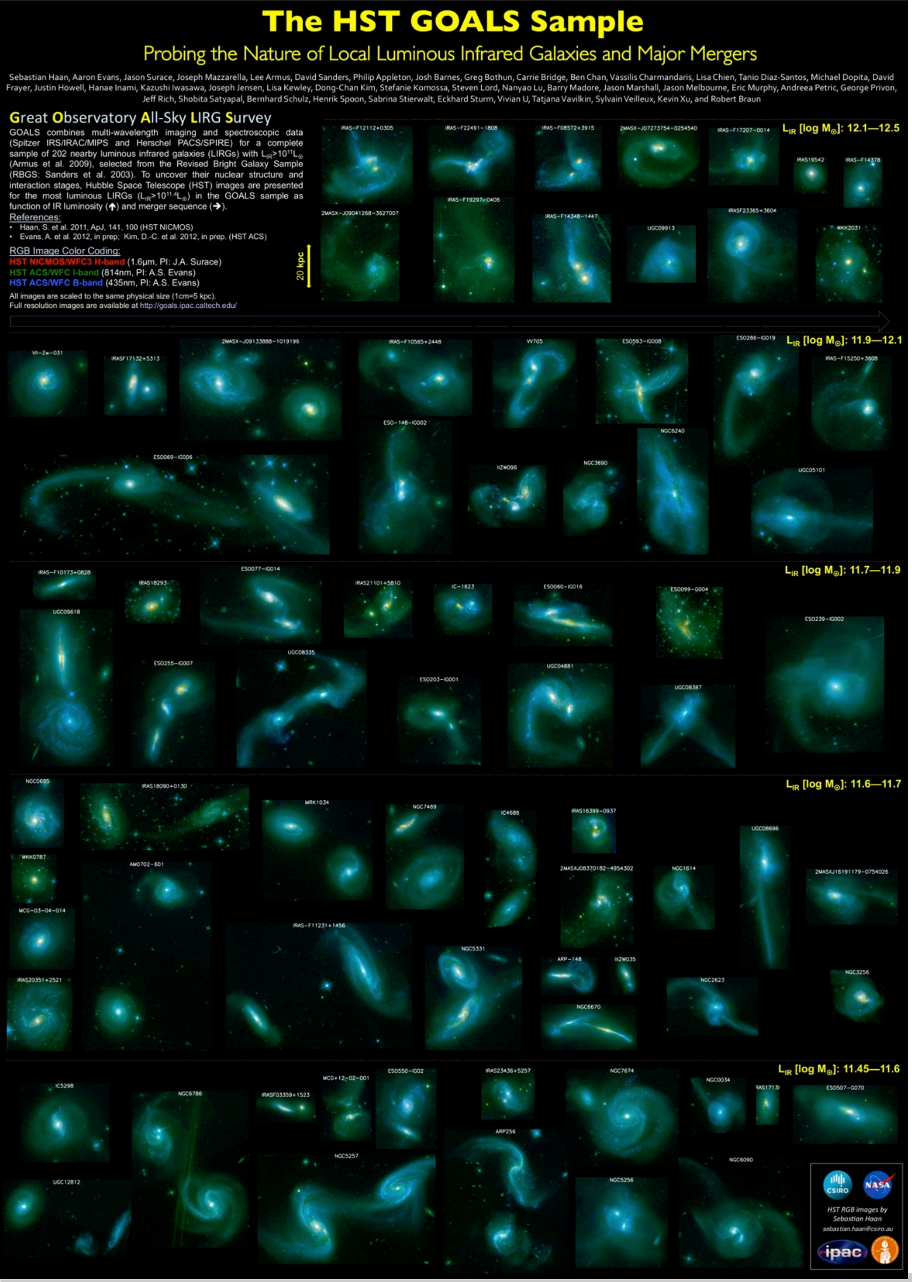


GALEX

Groundbased:

- **JVLA**
- **Palomar**
- **CSO**
- **ALMA**

Lee Armus, Aaron Evans, David Sanders, Philip Appleton, Josh Barnes, Greg Bothun, Carrie Bridge, Ben Chan, Vassilis Charmandaris, Lisa Chien, Tanio Diaz-Santos, Michael Dopita, David Frayer, Justin Howell, Sebastian Haan, Hanae Inami, Kazushi Iwasawa, Joseph Jensen, Lisa Kewley, Dong-Chan Kim, Stefanie Komossa, Steven Lord, Nanyao Lu, Barry Madore, Jason Marshall, Jason Melbourne, Joseph Mazzarella, Eric Murphy, Andreea Petric, George Privon, Jeff Rich, Shobita Satyapal, Bernhard Schulz, Henrik Spoon, Sabrina Stierwalt, Eckhard Sturm, Jason Surace, Vivian U, Tatjana Vavilkin, Sylvain Veilleux, Kevin Xu



The GOALS Sample

- Complete subset of the IRAS Revised Bright Galaxy Sample (RBGS) with 202 LIRGS and ULIRGs
- Combination of imaging and spectroscopic data from Spitzer (IRAC, IRS), HST (ACS, NICMOS, WFC3), Chandra, GALEX, and Herschel.

HST:

- 88 most IR luminous systems ($\log[L_{IR}/L_{\odot}] > 11.4$)
- H-, I-, and B-band (1.6µm, 814nm, 435nm)

  → 50% of nuclei are dust-obscured in B-band!
- Predominantly mergers and interacting galaxies
- Resolution: 0.15 arcs (~106pc), redshift $z < 0.05$

Probing the dust-unobscured nuclear stellar structure!

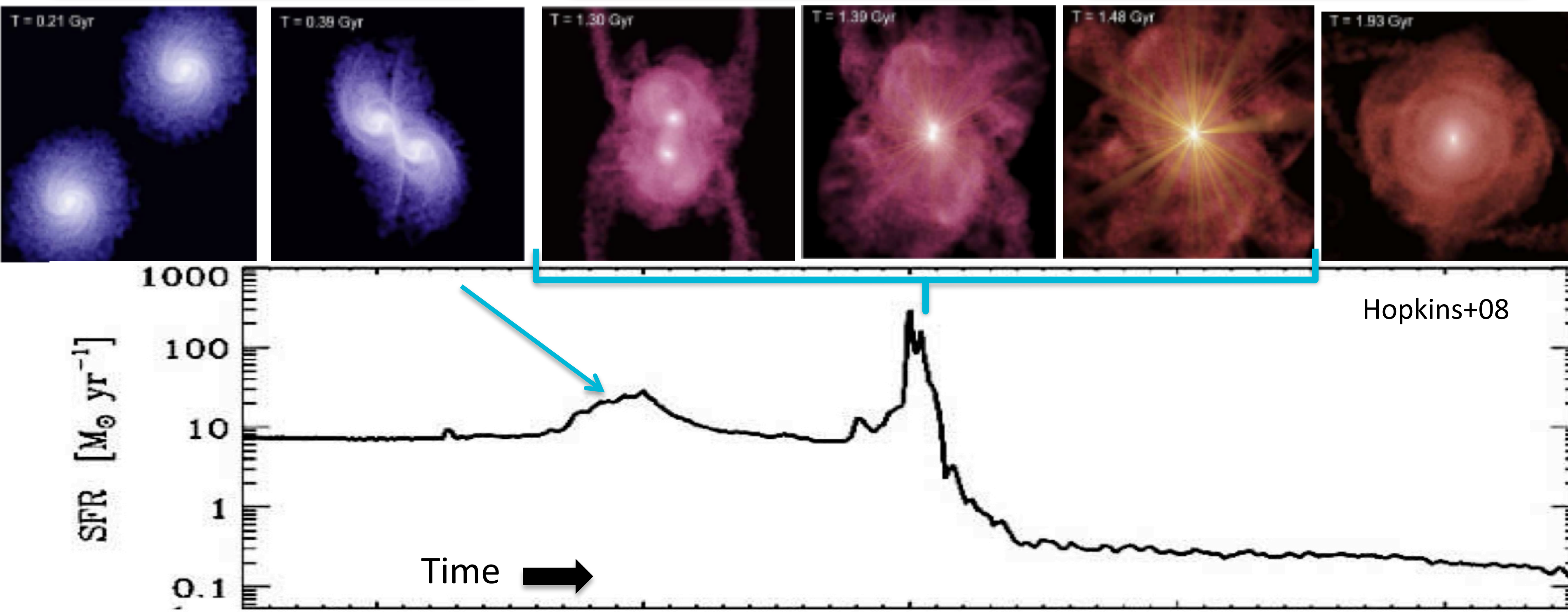
Probing the Formation of Nuclear Stellar Cusps

Interaction and tidal forces:
→ Gas Inflow

Final coalescence of nuclei:
Dense gas in center
→ extreme Starburst
(10—1000 $M_\odot$/yr)
→ Stellar Cusp is build up

Gas evtl. expelled from center
→ Shutdown of star formation
Nuclear stellar cusp remains

Progenitor stars form spheroid

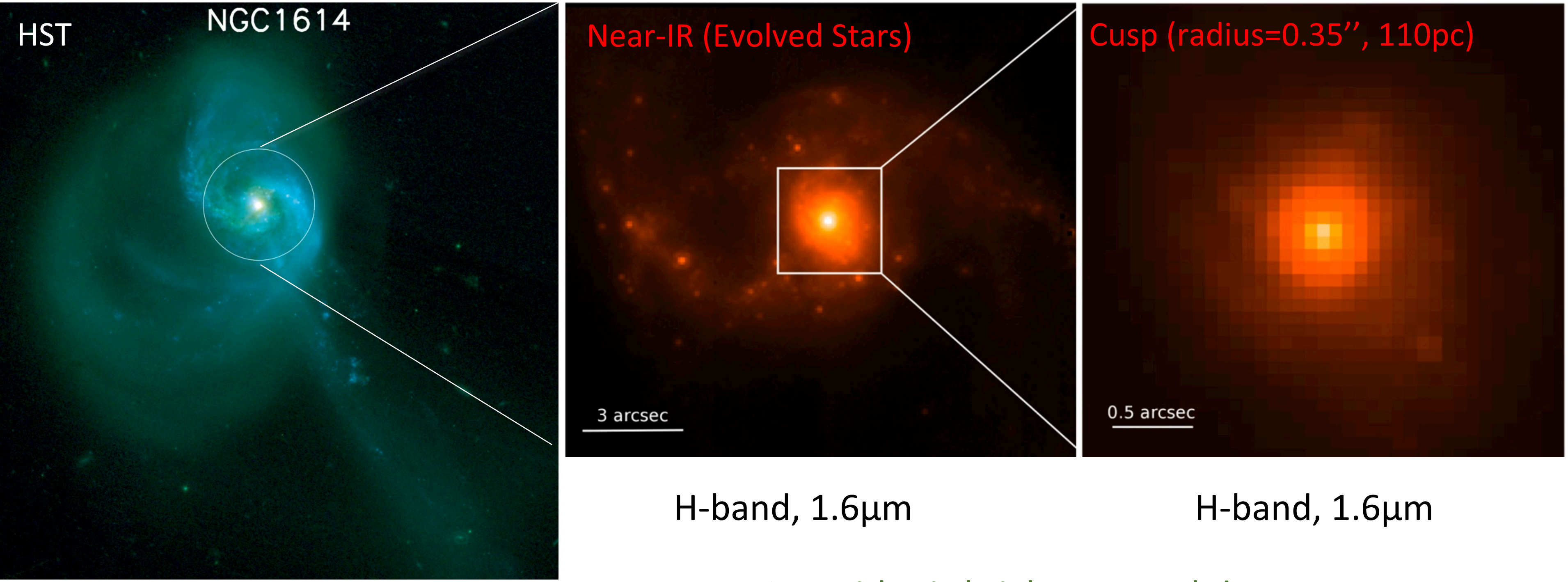


Observational evidence: Some elliptical galaxies show excess light in their radial light profiles.

Open questions:

- Can we see cusp formation during the actual starburst phase and how does it link to the nuclear properties of elliptical galaxies?
- How much stellar mass is typically built up in nuclear cusps and what are the critical time-scales for cusp formation?
- Is there a link between the strength of cusps in LIRGs and the current rate of star formation in these galaxies?
- Do we see the same fraction of cusps in LIRGs as in elliptical galaxies?

An Example of a Nuclear Stellar Cusps

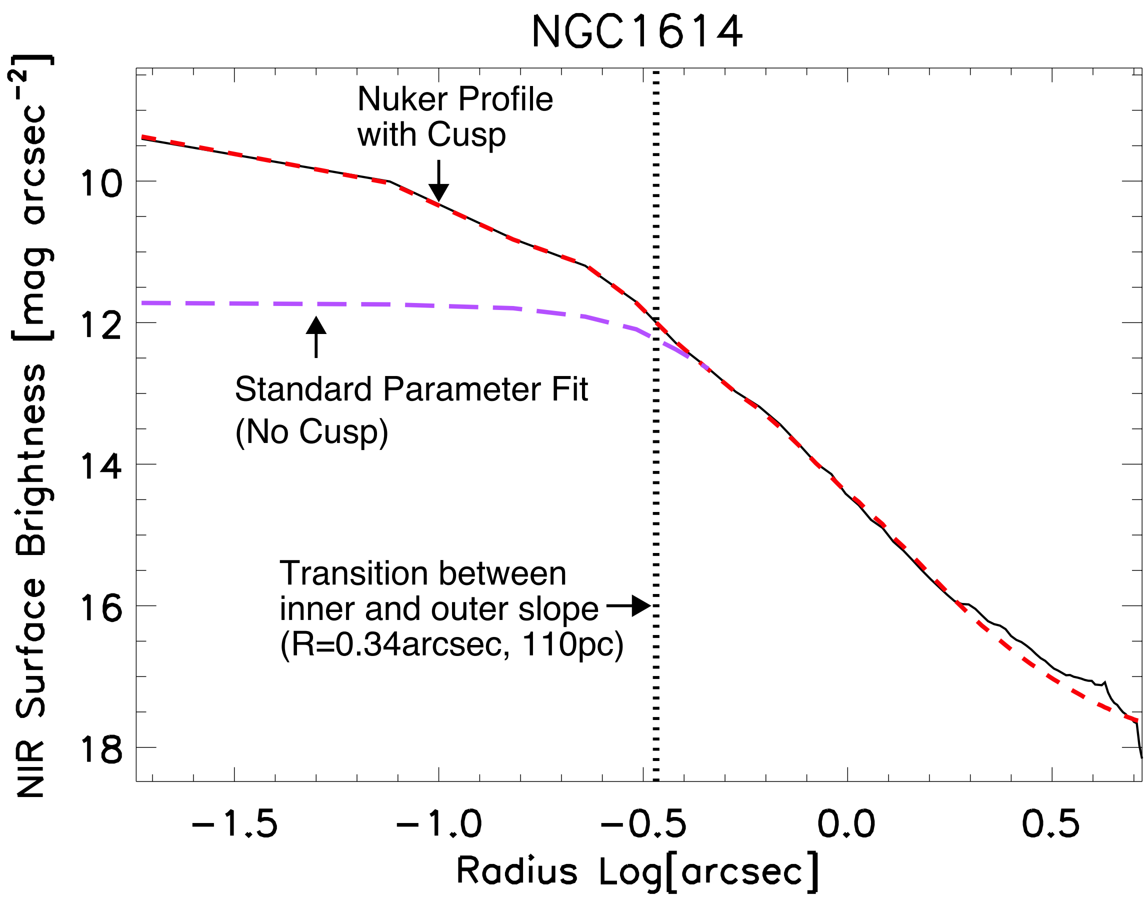


H-band, 1.6µm

H-band, 1.6µm

Logarithmic brightness scale!

RGB Image (H-, I-, B-band)

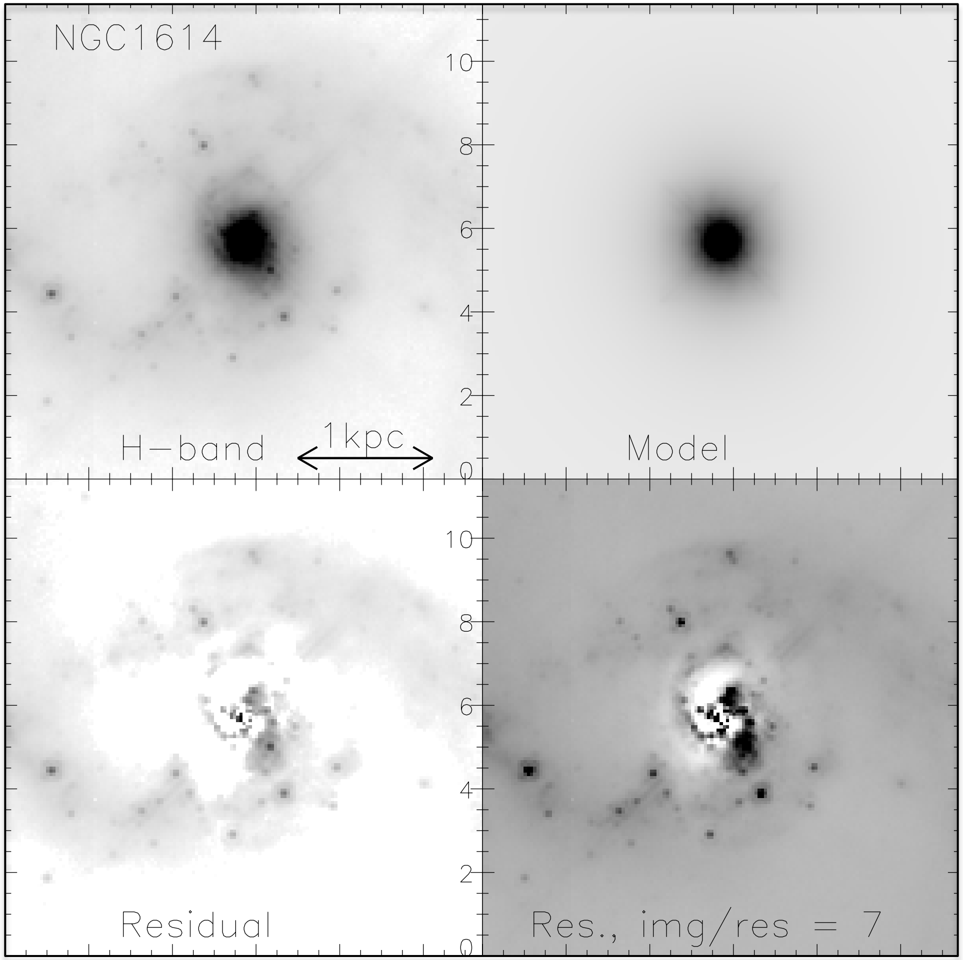


The Nuker Profile (Lauer et al. 1995):

- Double power law
- **γ** is the inner (cusp) slope

$$I(r) = 2^{(\beta-\gamma)/\alpha} I_b \left(\frac{r_b}{r}\right)^{\gamma} \left[1 + \left(\frac{r}{r_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

Fitting of the nuclear stellar light and cusp



In practice:

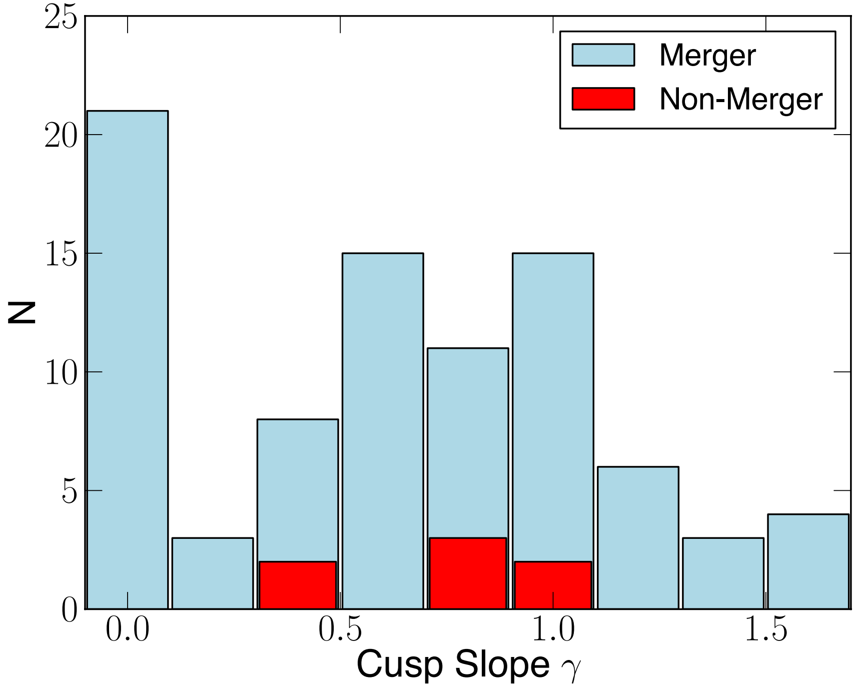
2-dimensional fit with GALFIT

(Peng et al. 2010)

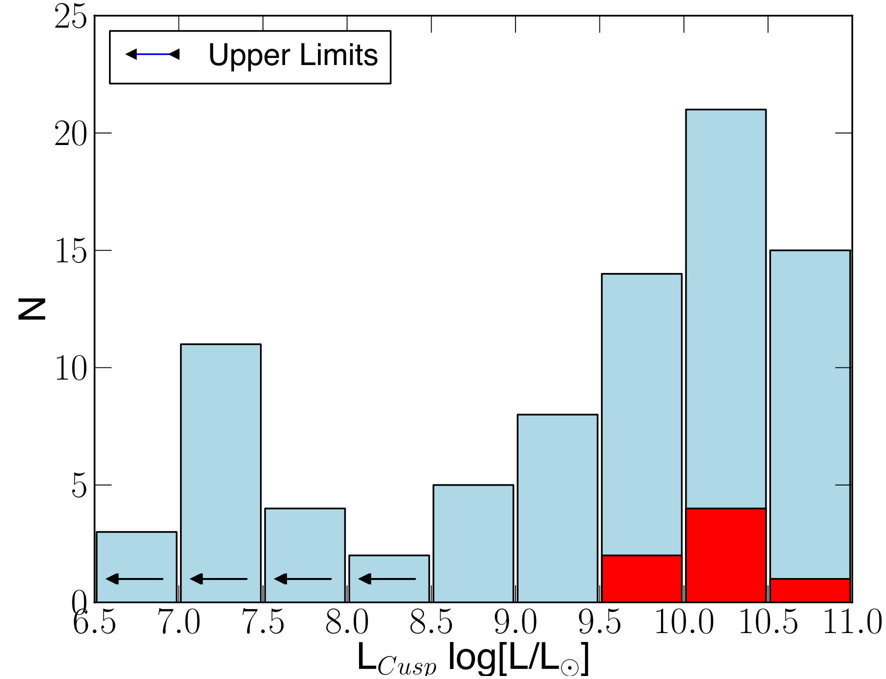
- Simultaneous fitting of several components
- Fitting and subtracting of central unresolved light component

Cusp Slope and Luminosity Distribution

Nuclear Slope

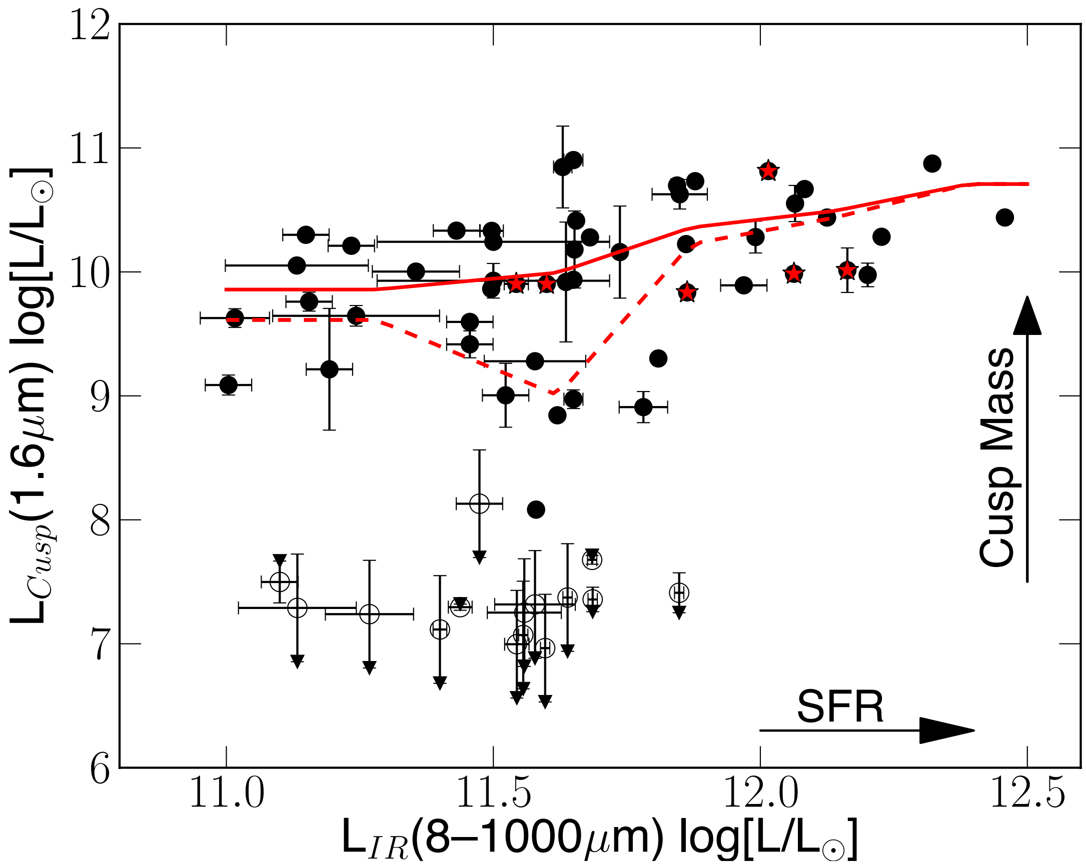


H-band Cusp Luminosity



Resolve nuclear cusps in 76% of LIRGs

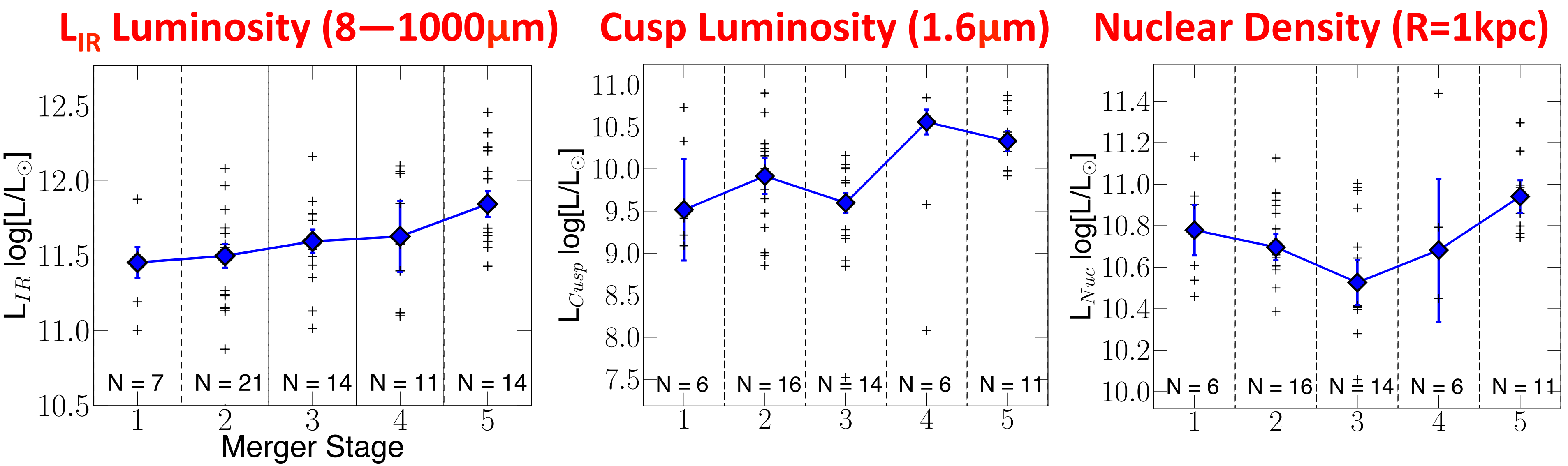
Relationship between Current Star-formation and Cusp Strength



Haan+13

Increase in Cusp Mass:
Above log[L_{IR}/$L_\odot$]=11.9:
all galaxies have large cusp NIR luminosities.
On average, five times larger than for lower luminosity LIRGs (log[L_{IR} /$L_\odot$ ~ 11.5]).

Cusp Properties as Function of Merger Stage



Current starburst activity is associated with the build-up of cusps due to merger process.

Stellar Masses and Timescales for Build-up of Cusps

- Increase in stellar cusp mass towards late merger stages:

$$\Delta M_{cusp} = (7 \pm 3.5) \times 10^9 M_\odot$$

(Y_H = 0.3 ± 0.15, from STARBURST99 and dynamical mass measurements)

- Typical merger timescale from mid-stage to late stage: ≈500 Myrs

- Timescale to build-up stellar cusp mass:

$$\Delta t = (60 \pm 30) \text{ Myrs}$$

(based on current SFR, ≈220 $M_\odot$ /yr, and 50% of L_{IR} from cusp region)

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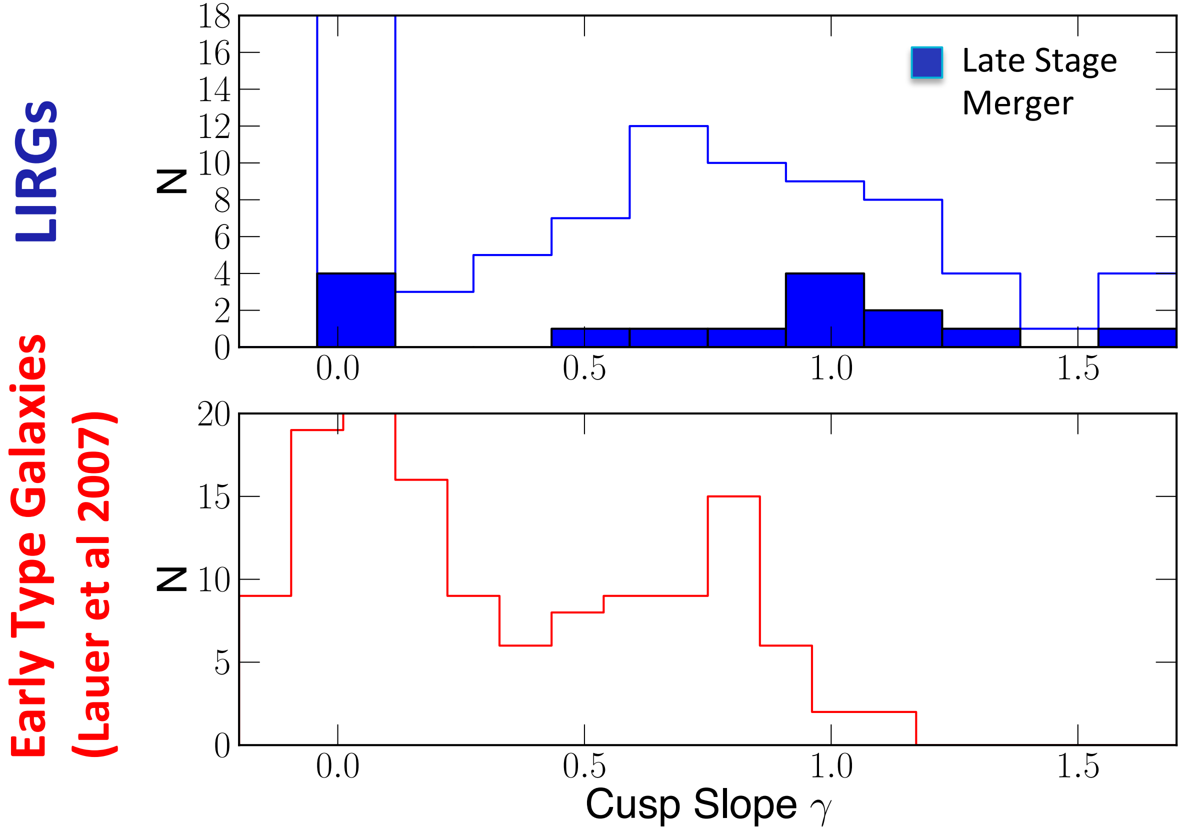
Comparison of Cusp Distribution to Ellipticals

Statistics for same range in host galaxy mass:

$-23 < M_H < -25.5$ [mag] (98% of the LIRGs in our sample)



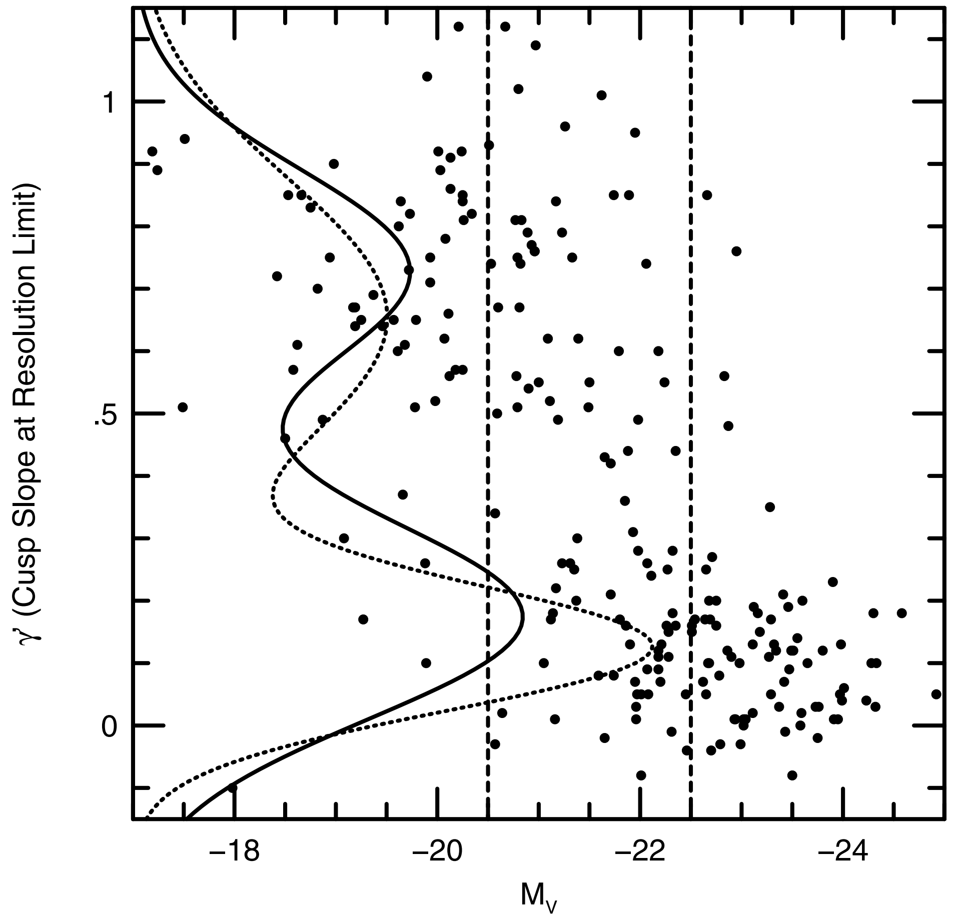
cusp/core > 3.2:1

cusp/core = 0.7:1

Cusp-Core Dichotomy in Early Type Galaxies

Cusp

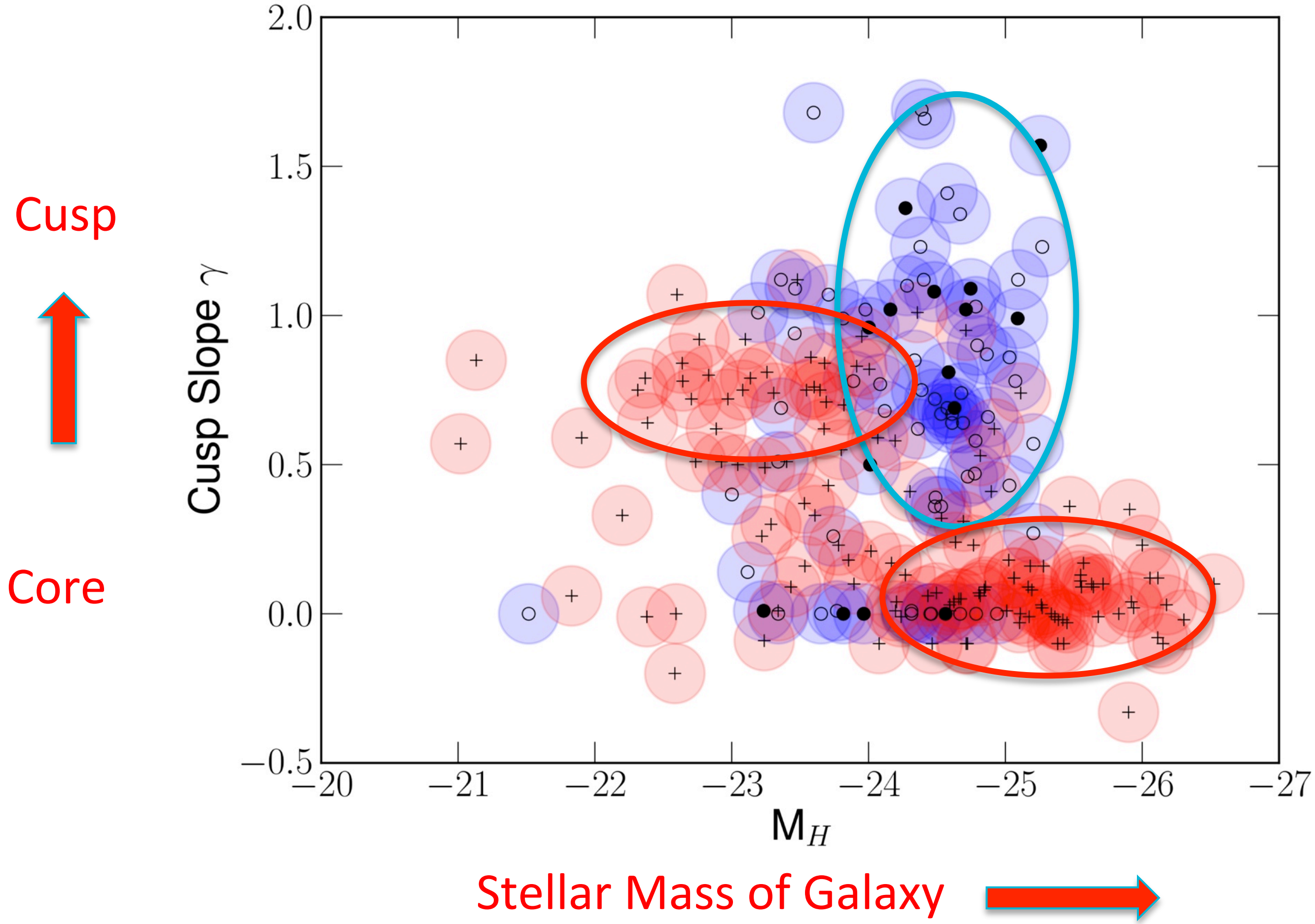
Core



Lauer+07

Stellar Mass of Galaxy

Early Type Galaxies vs LIRGs

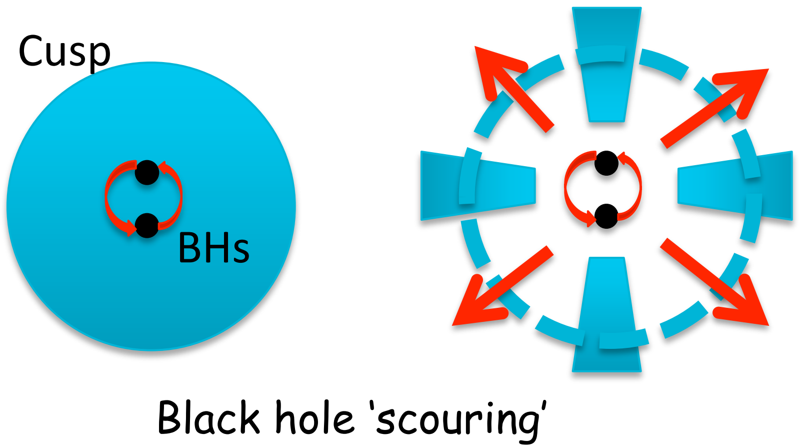


Haan+13

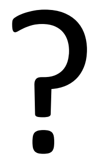
What's going on?

Different environment during formation and evolution: a) gas fraction, b) mass of progenitor galaxies, c) merger density/history

Cusp Destruction:
via BH binary in a subsequent dry merger (no gas)
→ Formation of massive **core ellipticals**



Different Cusp-Galaxy Formation Scenario
E.g. most **cusp ellipticals** formed at an early phase of the universe when most galaxies were smaller and had larger gas fractions than in today's LIRGs.



Summary & Conclusions

- Measurement of the nuclear structure provides important insight into merger and starburst history of galaxies.

- Nuclear stellar cusps are found in at least 76% of (U)LIRGs.

- Cusp strength and luminosity increase with merger stage and total IR luminosity (excluding AGN), confirming models that recent starburst activity is associated with the build-up of cusps.

- Nuclear stellar structure becomes more compact towards late merger stages.

- Comparison to local early-type galaxies:
  a) Local (U)LIRGs have a significantly larger cusp fraction
  b) Most LIRGs have host galaxy luminosities (H-band) similar to core ellipticals which is roughly one order in magnitude larger than for cusp ellipticals.

CSIRO

Thank you

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