Gas Inflow and Shocked Outflows in Major Mergers of Gas Rich Galaxies

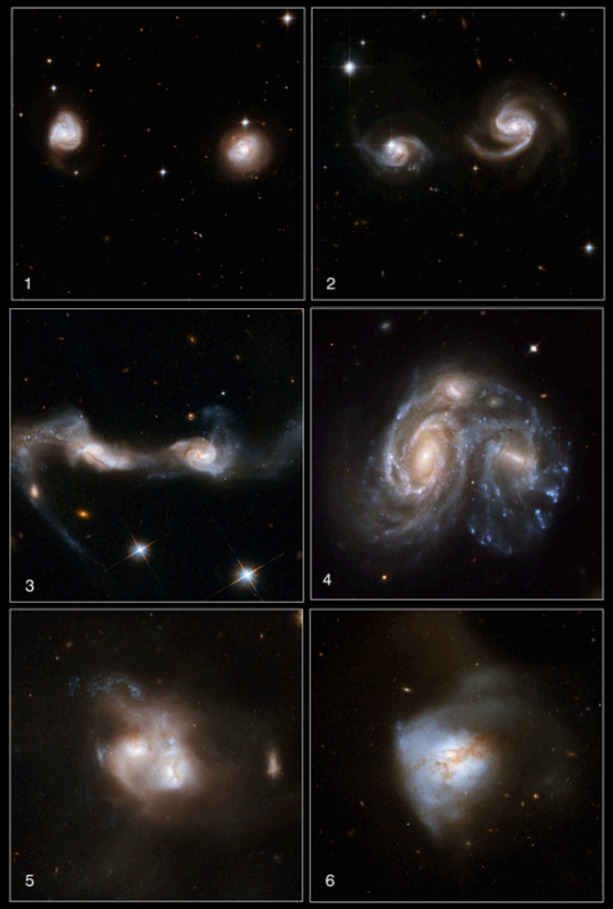

Image Credit: NASA, ESA, Hubble Heritage Team, A. Evans, K. Noll, and J. Westphal

Galaxy merger
- ➔ increase in gas surface density
  - ➔ increase in star formation

What is the timescale for gas to flow in?
- Models assume a dynamical timescale, but could be a longer viscous timescale (Hopkins+ 2009)

Does the increase in gas density produce outflows?
- Na I absorption winds are seen in the cold gas (Rupke 02, Martin 05,06)
- What kinematics appear for the warm-hot phase?

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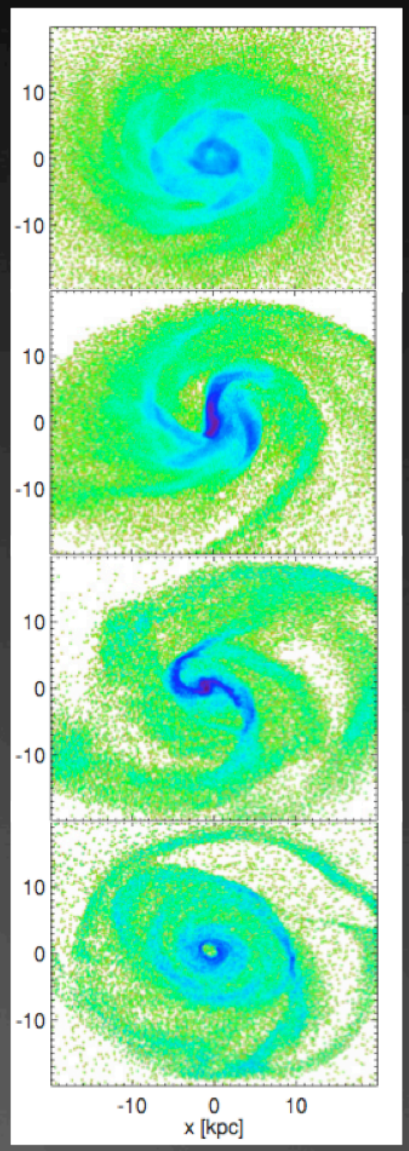
ULIRGs as Local Laboratories

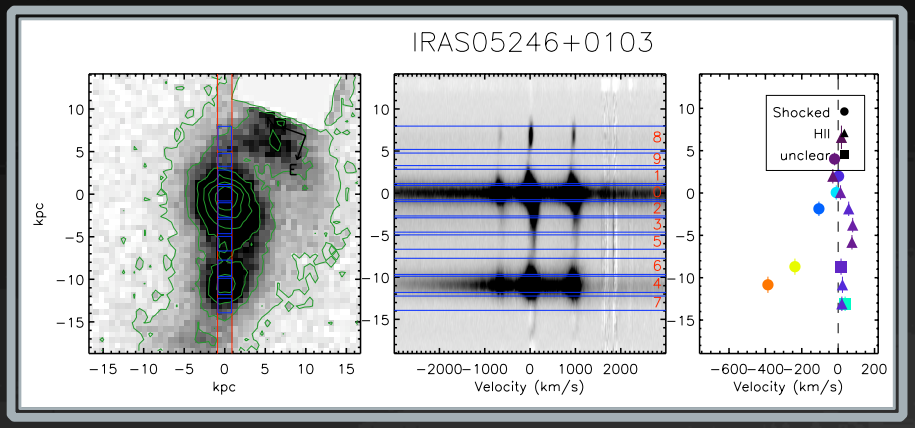
- Gas-rich mergers
  - Proceed on a dynamical timescale (Hopkins+ 2009; Mihos+1994; Lotz+ 2008)
  - Dilute the metallicity (Kewley+ 2010)
  - Predict truncation of star formation in outer disk (Roskar et al. 2008)
- Become more common towards z~1

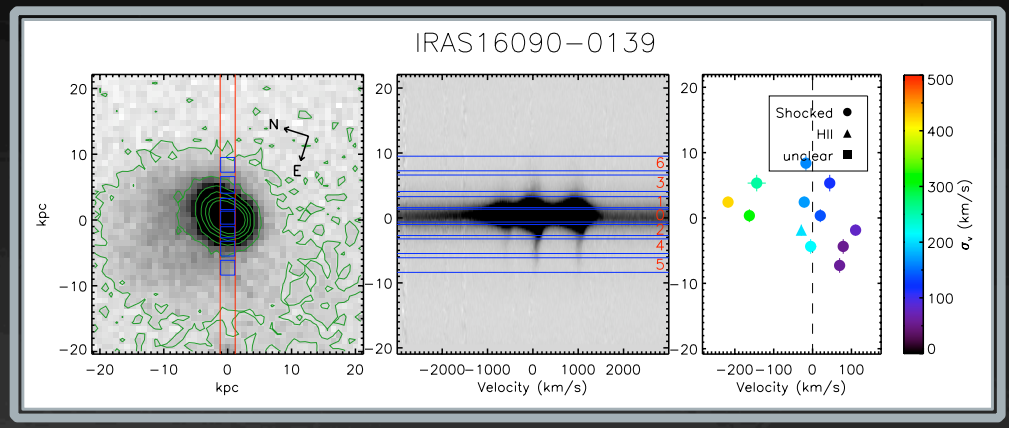
  (Le Floc'h 2005)
- Select the highest star formation rate galaxies at z < 0.1
- Offer the closest **analogy to conditions** at high z
- Can provide insight into feedback processes at high SFR at any redshift
- Can provide **empirical calibration** of feedback process (e.g., Heckman + 1990)

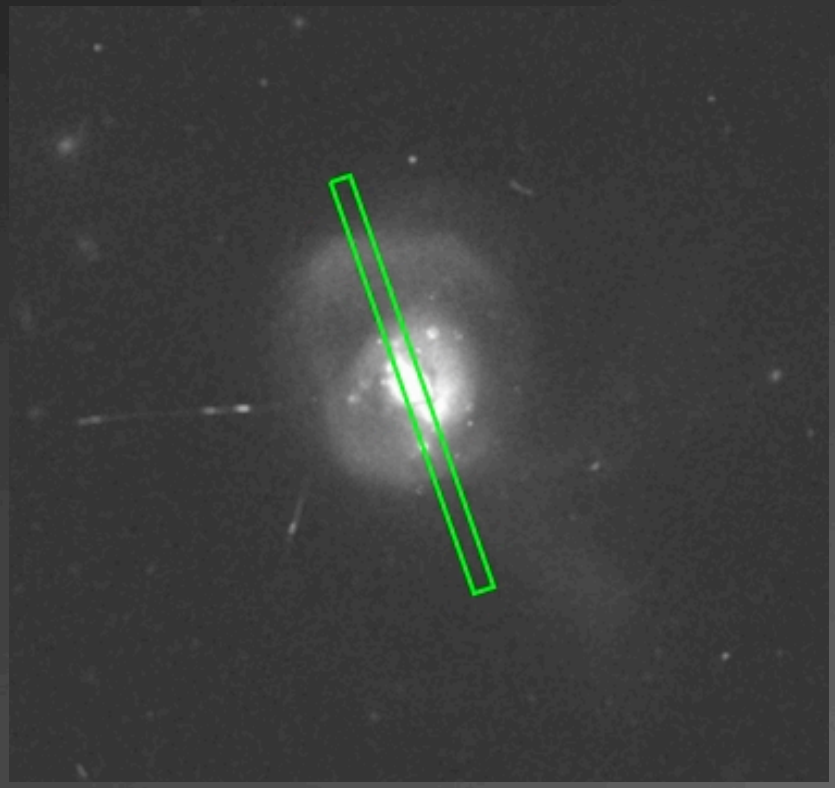


Hopkins + 2009

ULIRGs – Gas Rich Mergers in progress







Keck ESI

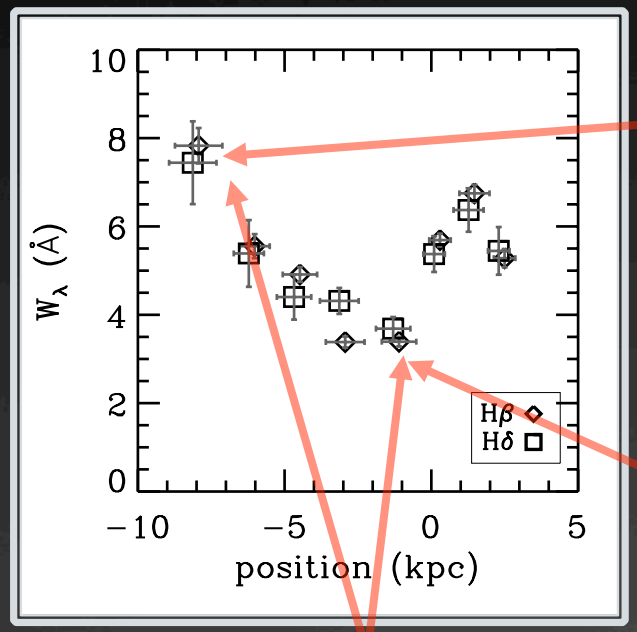
- Longslit Spectroscopy 1" x 20"
- median 0.8" seeing provides spatial resolution on kpc scale
- R ~ 5000 provides velocity resolution ~60 km/s
- Spectral coverage includes Hα, [N II], [S II], [OI], Hβ, [OIII] for emission line diagnostics

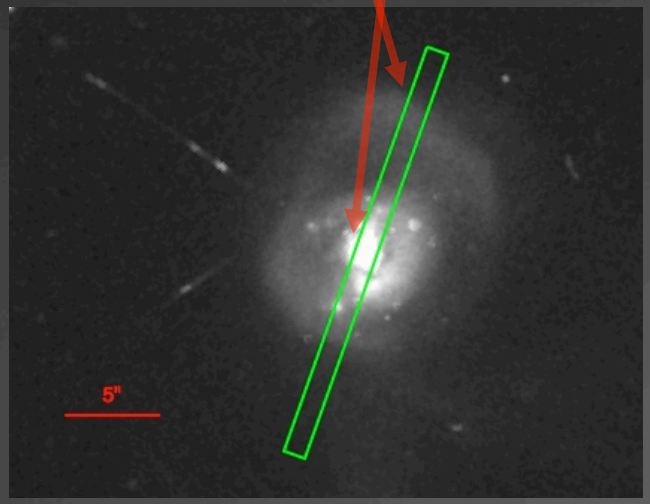
Sample

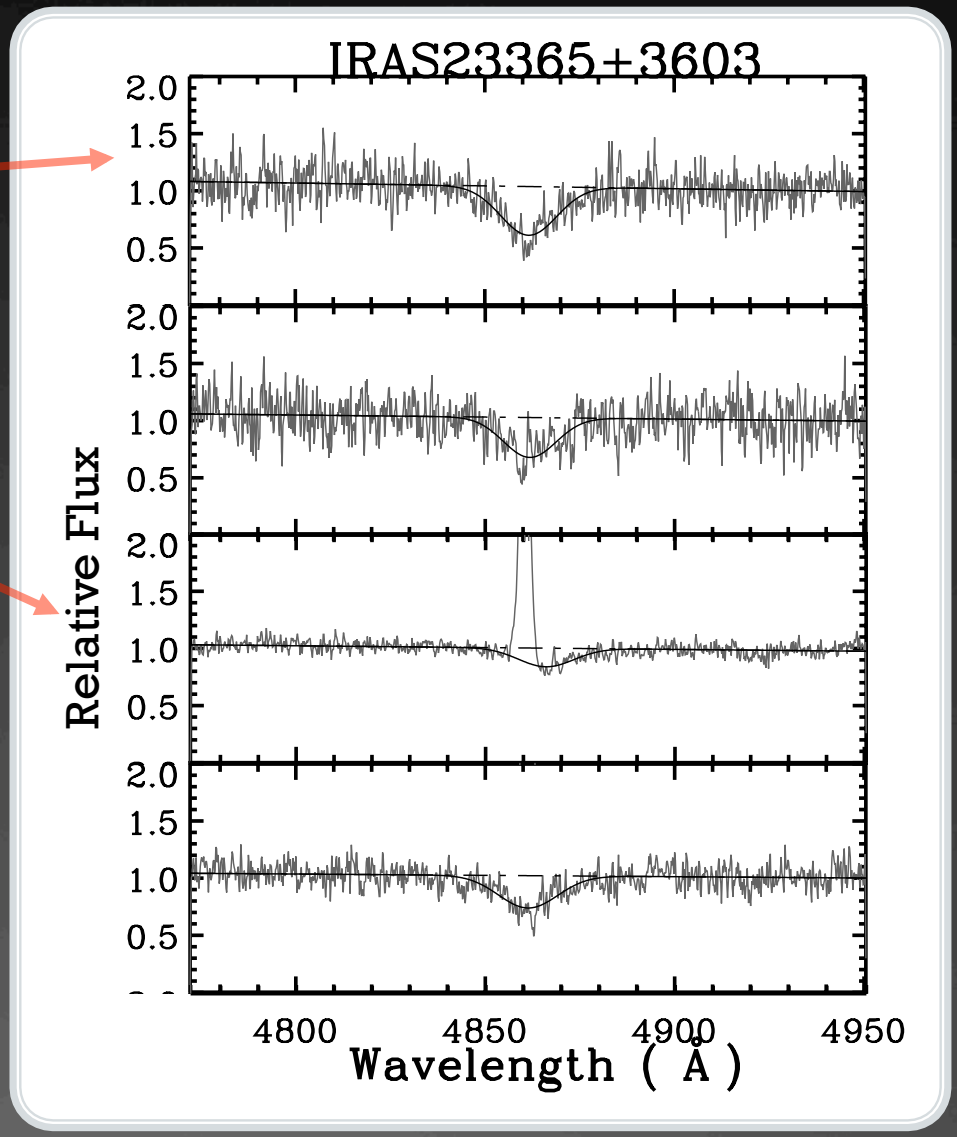
- 39 ULIRGs at various stages of Merging
- z = 0.046 – 0.15

H β absorption Equivalent width increases with radius indicating changes in stellar population

Soto & Martin 2010 ApJ...716..332







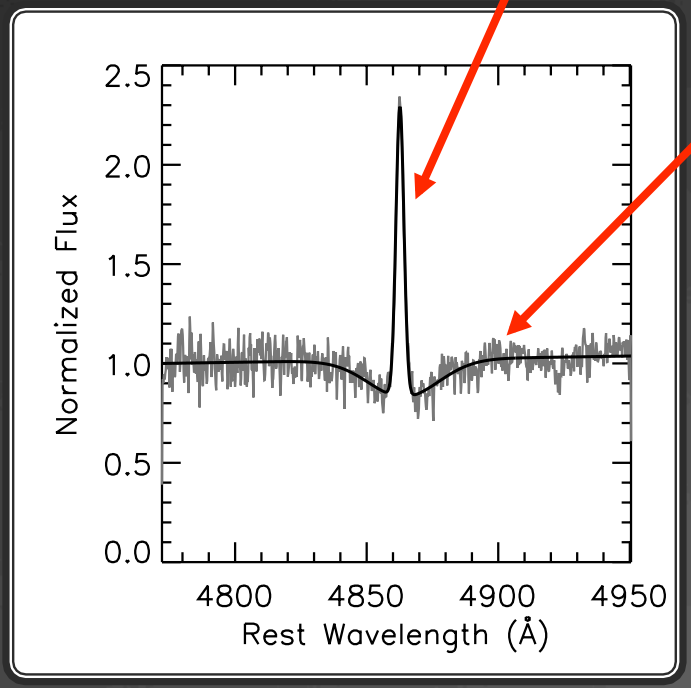
Evidence for Post Starburst Population

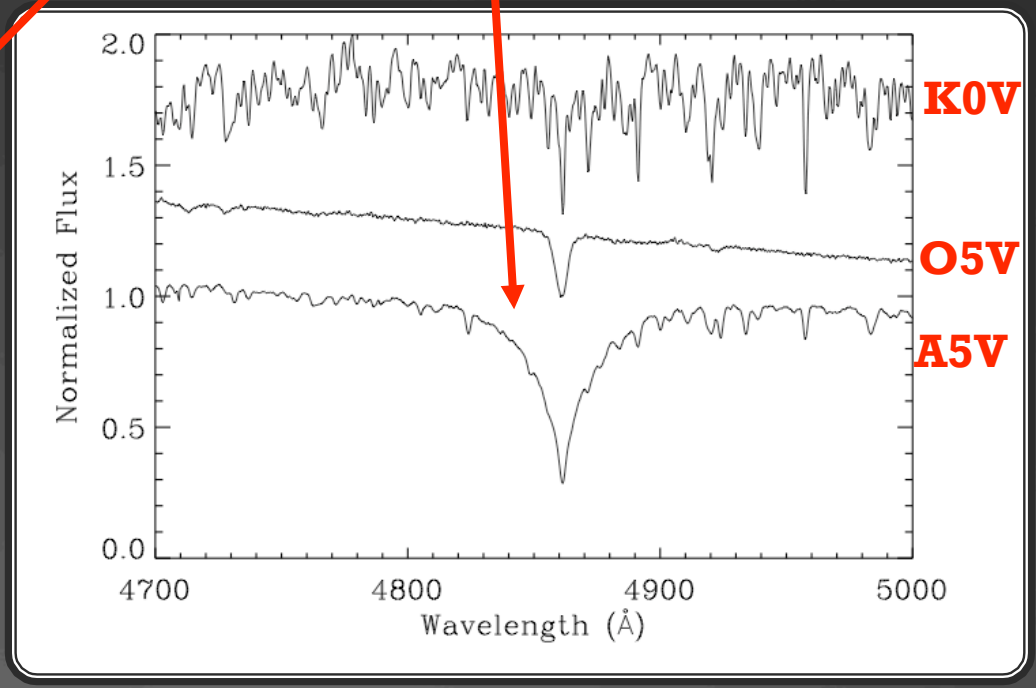
A stars provide strongest absorption

Balmer Emission

Stellar Continuum with Balmer absorption

Soto & Martin 2010

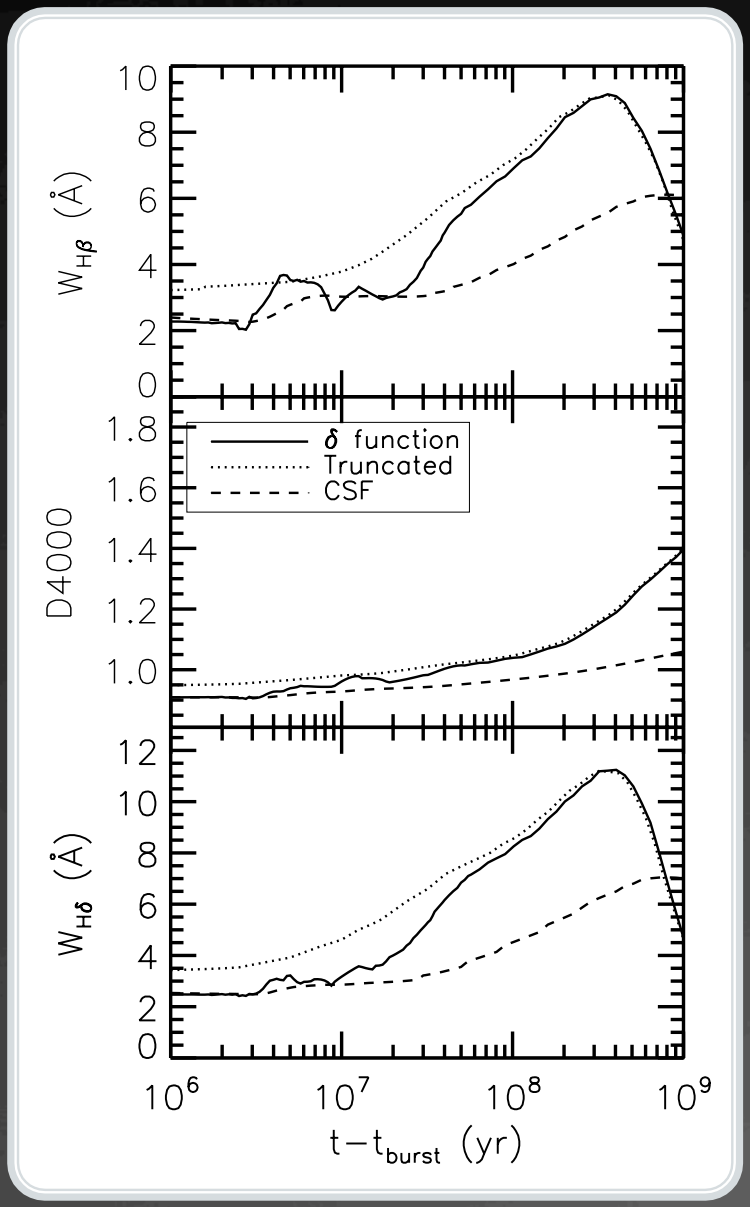




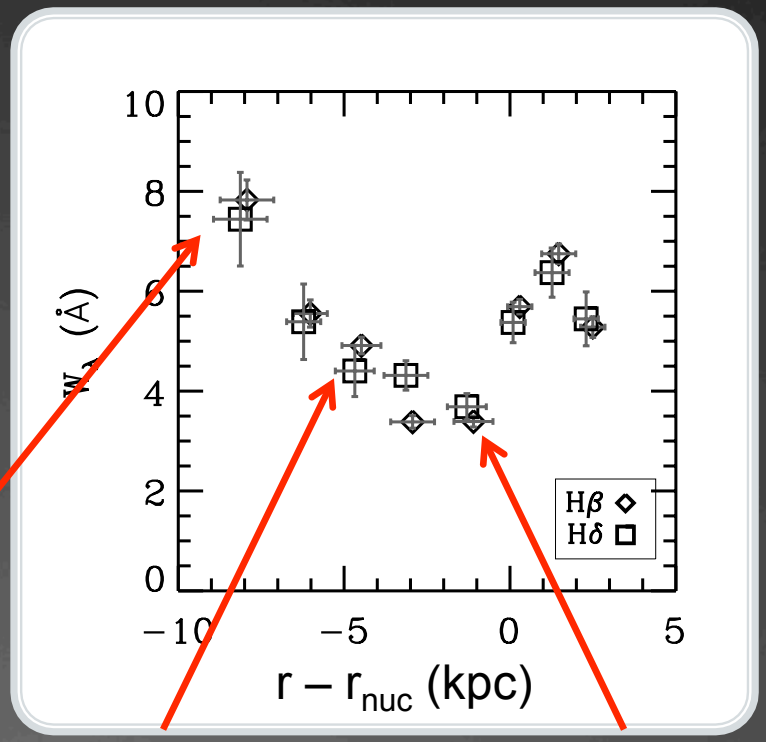
Soto & Martin 2010 ApJ...716..332

Position Dependence of Star Formation Histories Reveals Previous Gas Inflow

- Star formation stopped abruptly to create observed equivalent widths
- Star formation stopped from the outside inward
- Implies gas inflow in the merger process
- Inflow feeds the current star formation



BC03

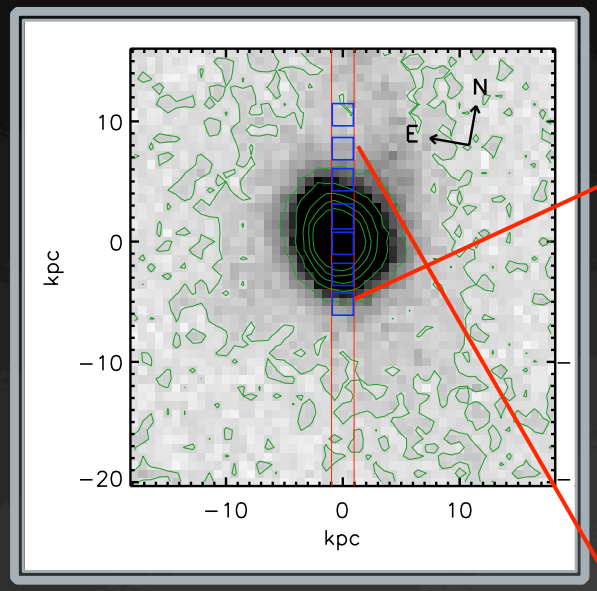


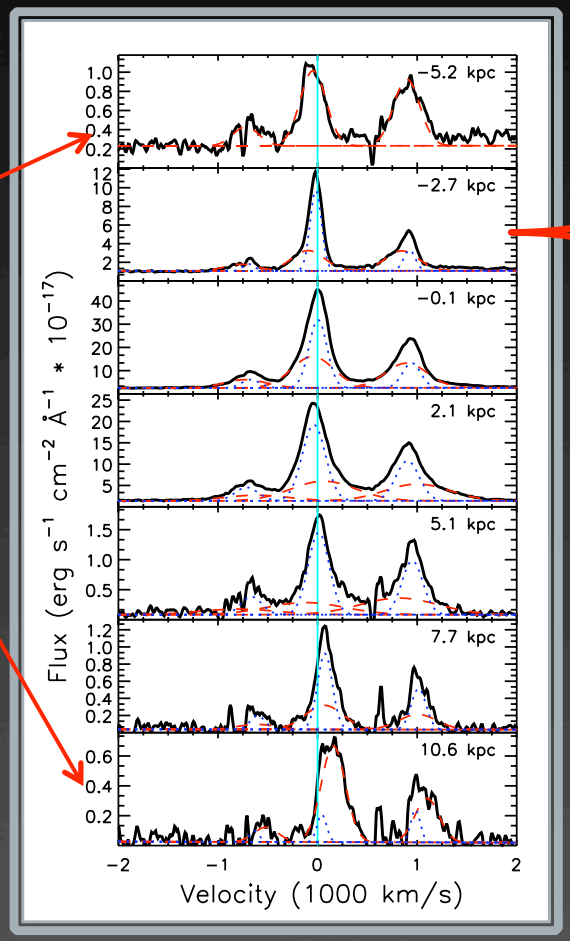
140 Myr

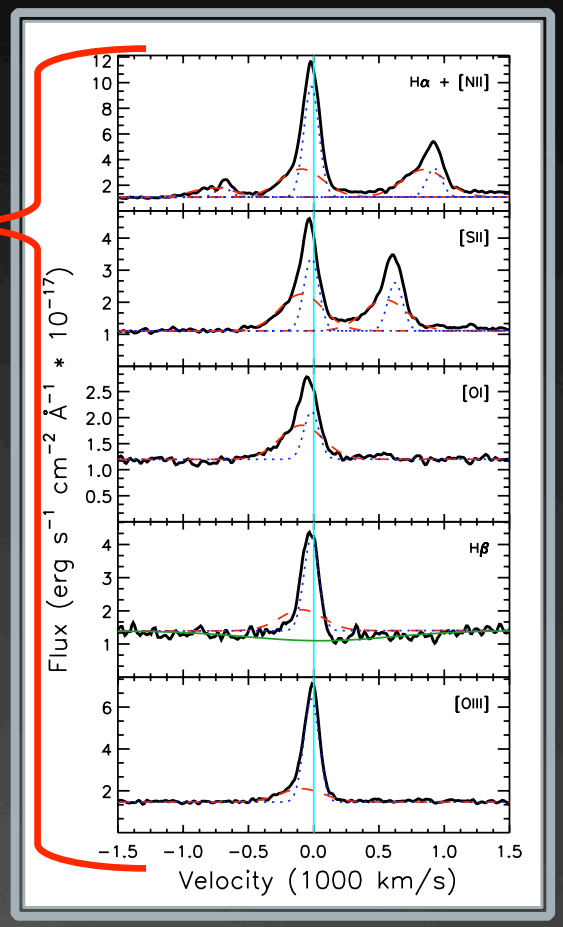
80 Myr

20 Myr

Component-wise Excitation Measurements





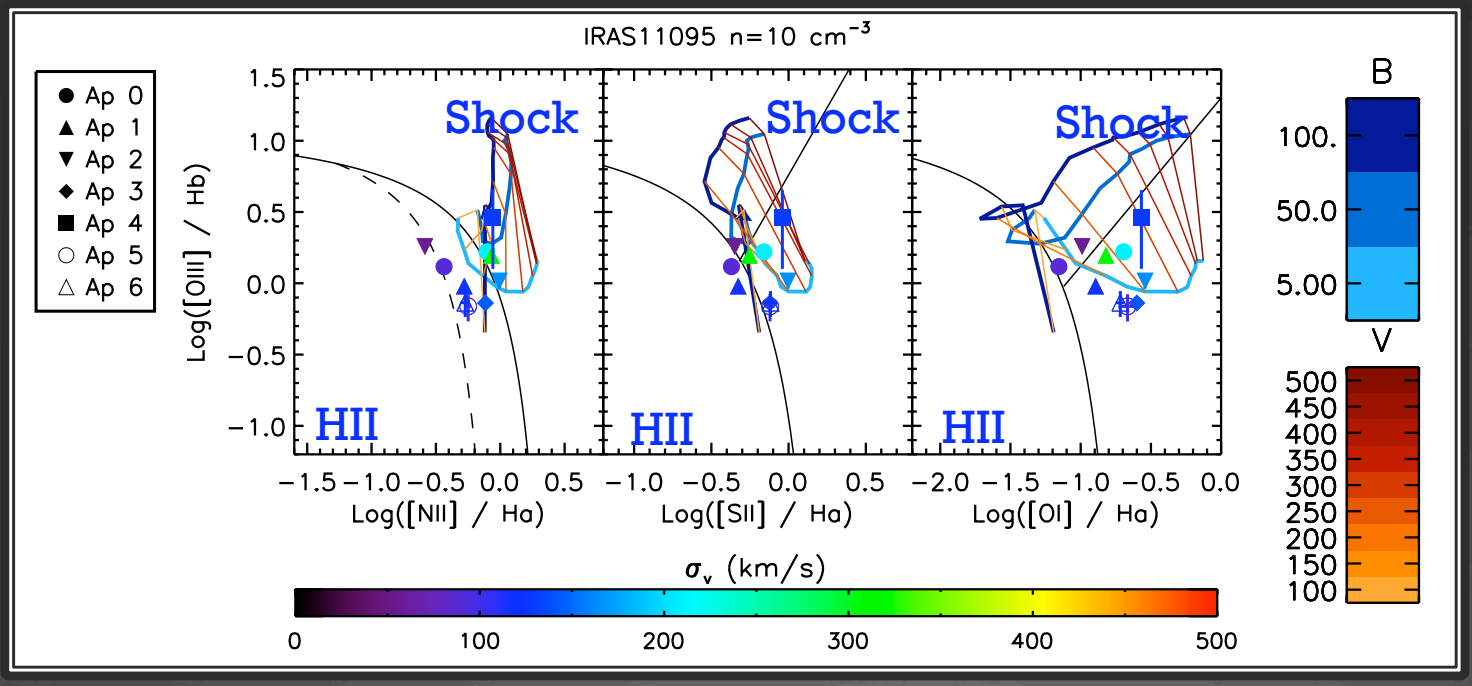


Soto+ 2012
(ArXiv:1205.0083)
Soto & Martin 2012
(ArXiv:1205.0082)

- line profiles are asymmetric
- line profiles vary differently across the slit
- We describe the profile with multiple emission components with the same kinematics in each transition
- Measure the flux ratios of the component individually to examine excitation

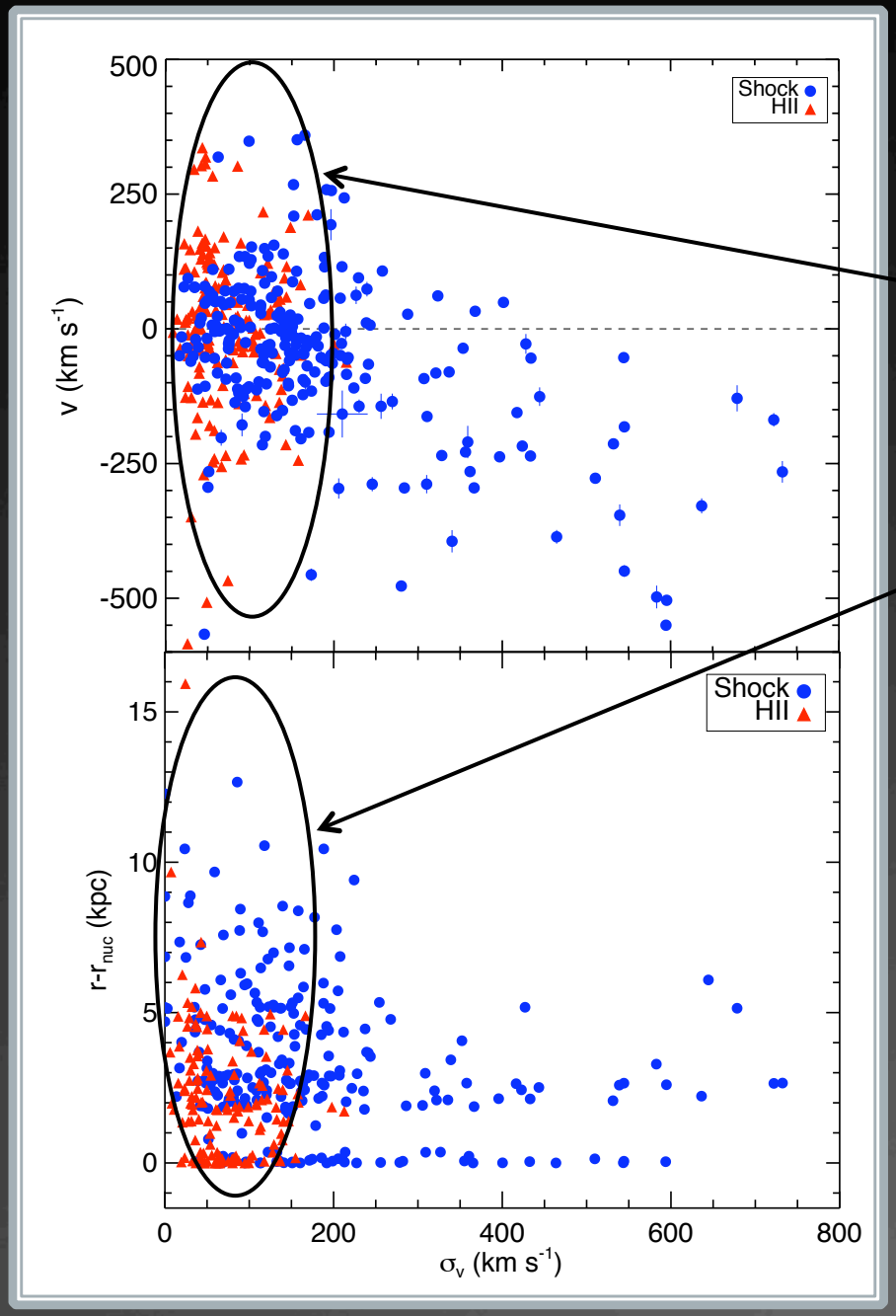
Emission Line Components Identify Shock

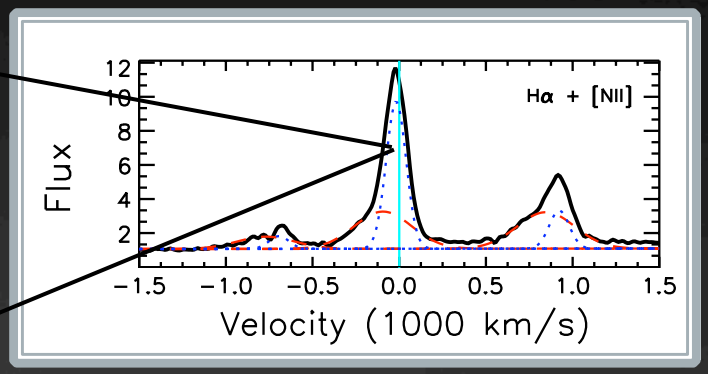
- Selected shock-like components above maximum star formation line
- Measured the shock velocities for the line ratios
  - typically 150 – 400 km/s
- [O I]/Hα is the most sensitive to shock, decision is heavily weighted by this measurement



Soto & Martin 2012 (ArXiv:1205.0082)

Narrow components suggest disks



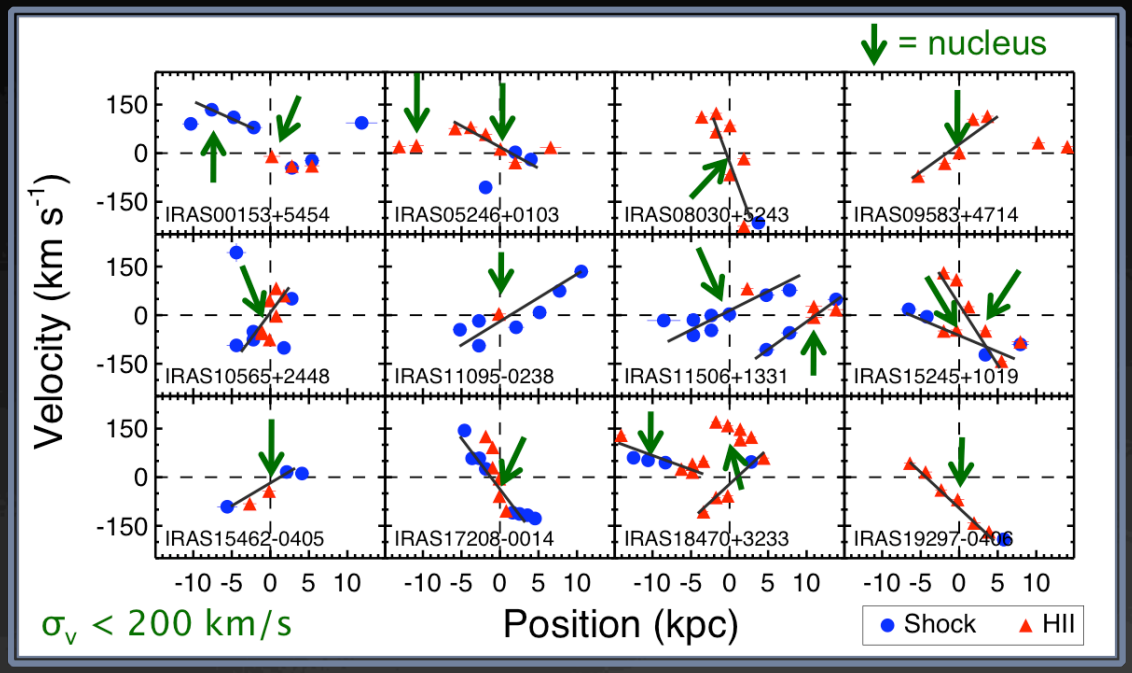


Narrow components

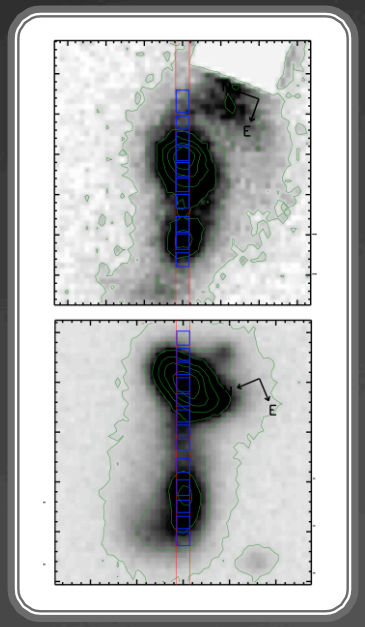
- Kinematics within ~ ± 250 km/s
- Shock-like gas @ R ~ 12 kpc
- Possible Disk – examine individually

Soto & Martin 2012 (ArXiv:1205.0082)

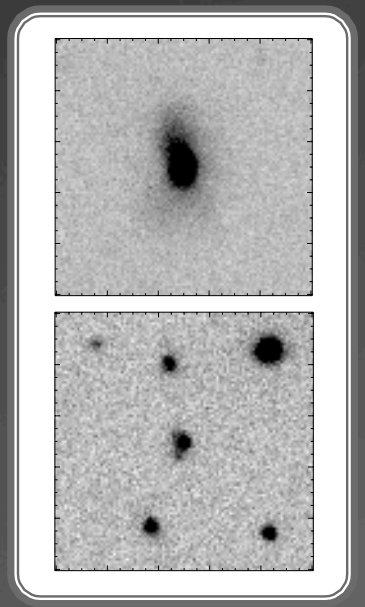
Rotation Profiles Reveal Shocked Gas Disks



Disk



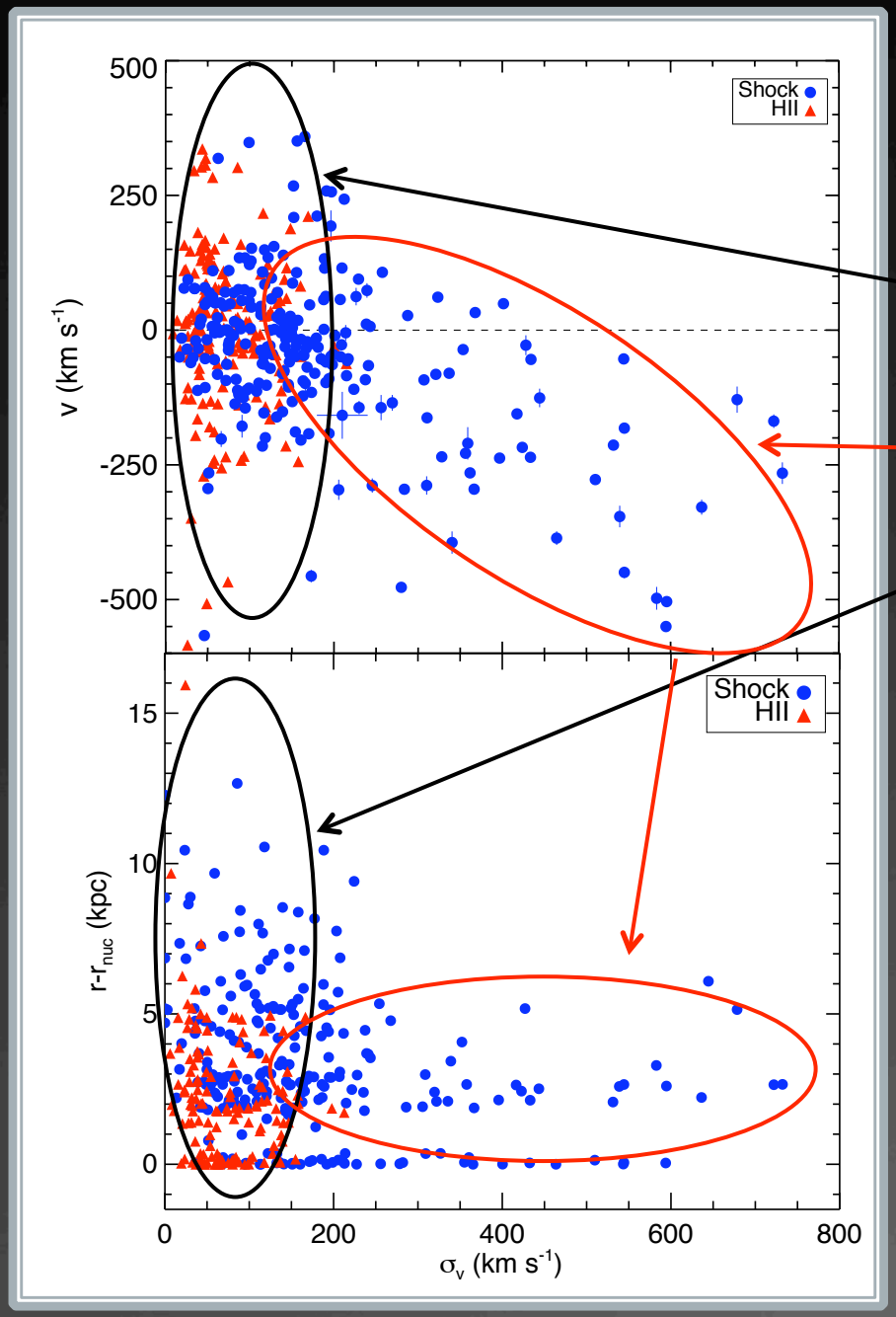
No Disk

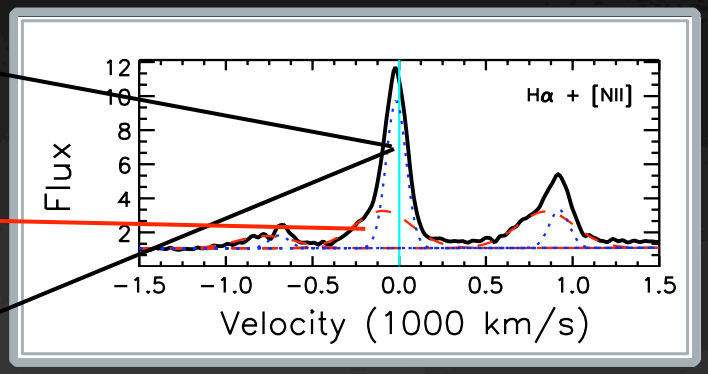


- Obvious disks most often found in wide binary stage of merger.
- Later stages disks are not as evident
- Early stage disks consistent with the star forming disk to elliptical evolution scenario
- Energy from the merger is a possible source of highly extended shock
- Gas disk is less frequent at later stages - is consumed or blown out in winds

Soto & Martin 2012 (ArXiv:1205.0082)

On large scale Identified inflows, outflows, and disks





Narrow components

- Kinematics within ~ ± 250 km/s
- Shock-like gas @ R ~ 12 kpc
- Possible Disk – examine individually

Broad shock-like components

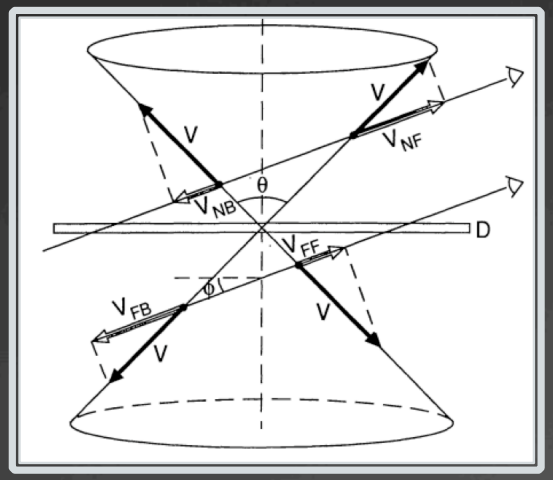
- up to 5 kpc from the nuclei
- primarily blueshifted
- High dust content

➔ emitting gas is on the nearside

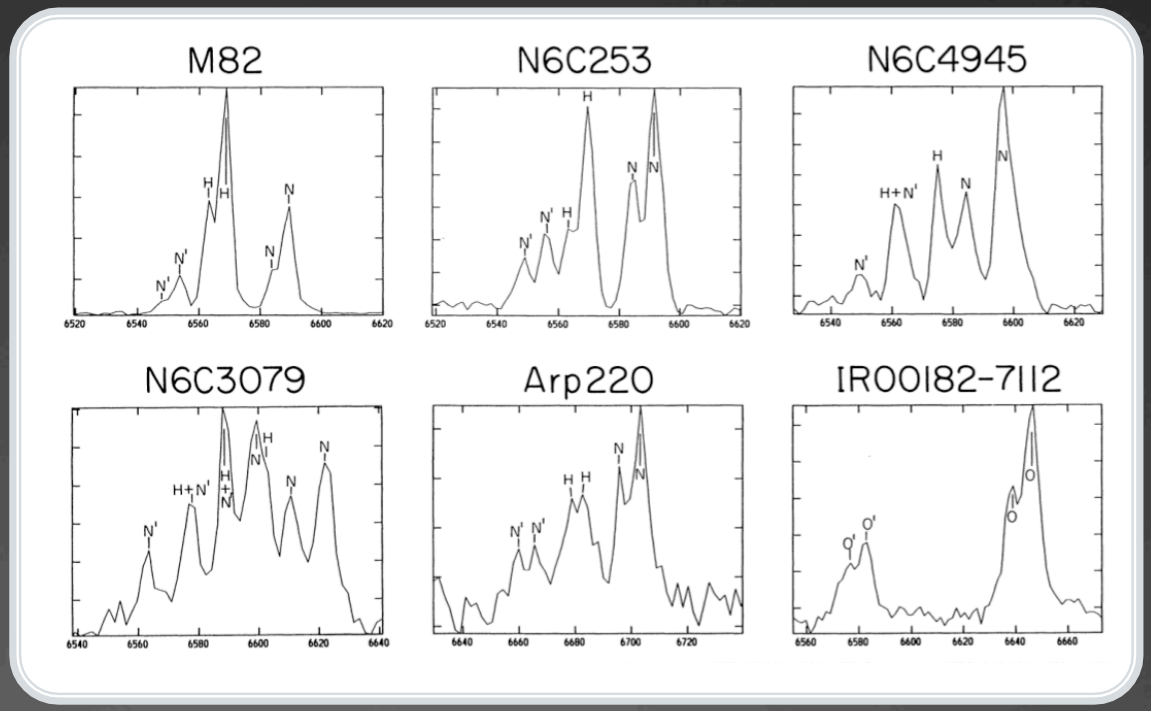
➔ Blueshift means an outflow

Observed Outflows are Unlike those from LIRGs

- Typical outflow structure is a hollow bicone in lower star formation rate galaxies
- This structure leads to double peaked emission line profiles
- The line profiles in the ULIRGs consist of a narrow emission component and a broad blueshifted component.

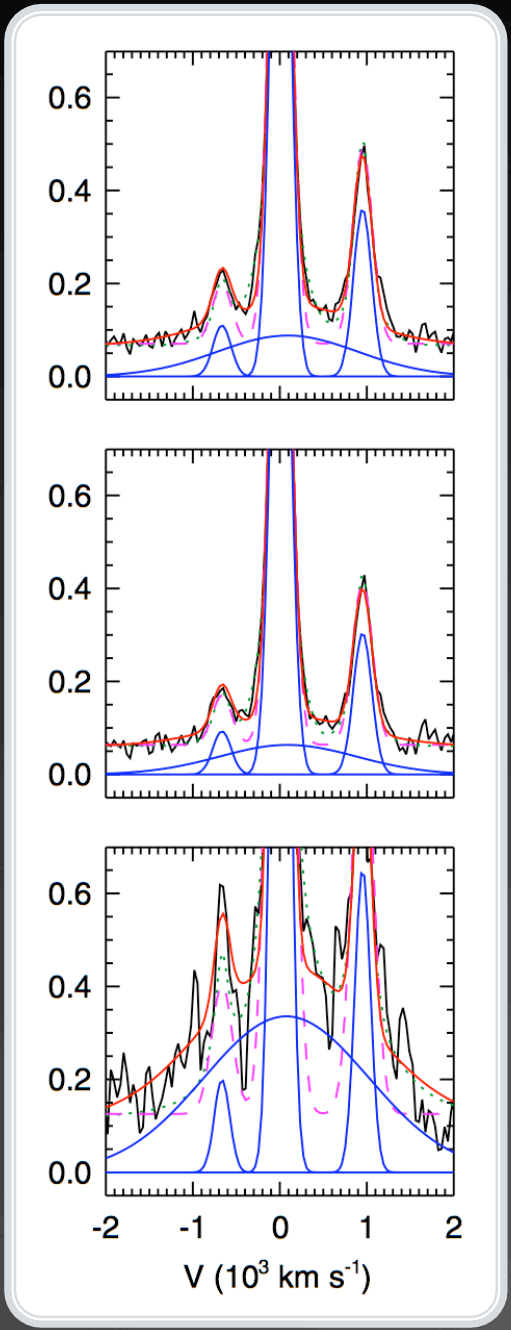


Heckman + 1990

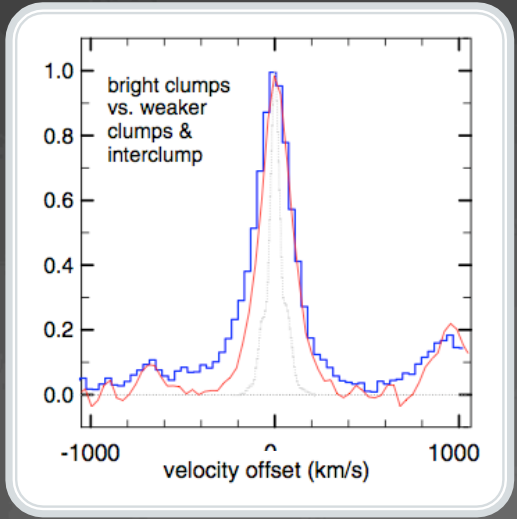


Local Major Mergers have Similar Line Profiles to z~2 SINS Galaxies

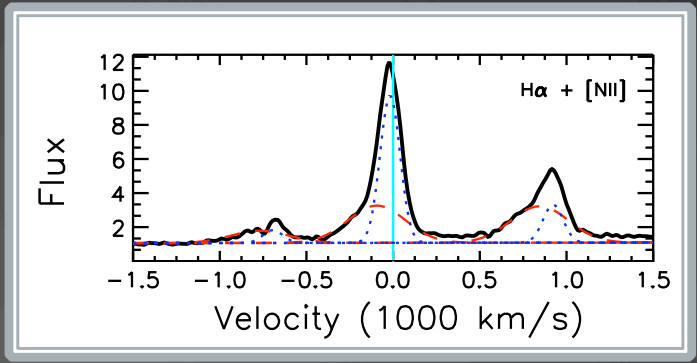
- High star formation rate galaxies at High redshift present broad emission line wings
- Star formation distributed in clumps
  - SFR ~ 70 $M_\odot$/yr, 10-40 per clump –
  - ULIRGs 70 – 200 $M_\odot$/yr
- Similar outflow mass
  - M = 1-2 x 10^8 $M_\odot$
- dM/dt
  - total 100 - 300 $M_\odot$/yr
  - ULIRGs 1-50 $M_\odot$/yr
  - ULIRGs hiding another factor of 2



Shapiro+ 2009



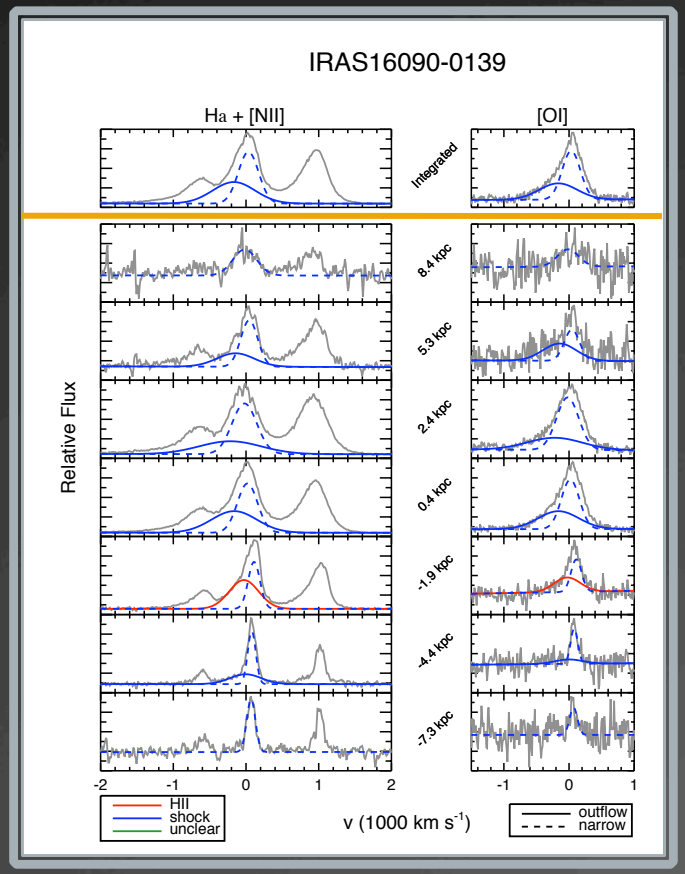
Genzel+ 2011

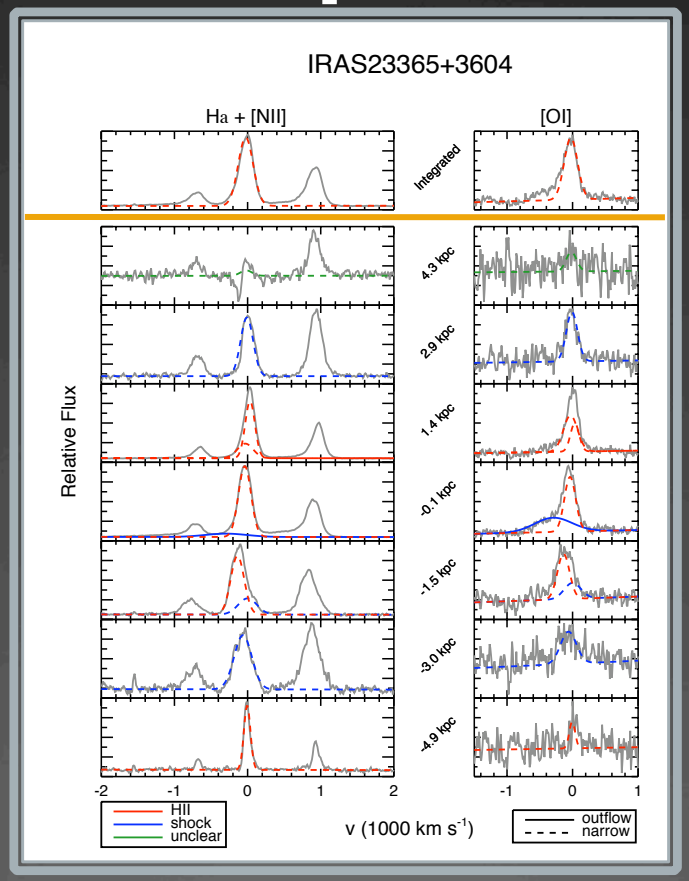


Soto+ 2012 (ArXiv:1205.0083)
Soto & Martin 2012 (ArXiv:1205.0082)

Large samples of integrated spectra may hide outflows detectable in emission

- Outflow is evident in some integrated spectra.
- Need spectral resolution of R~5000
- Need [OI] to deblend Hα + [NII]
- Depends on brightness of narrow component and its kinematics





Soto+ 2012
(ArXiv:1205.0083)

Summary: Gas Kinematics and Gas Excitation in Nearby Major Mergers of Gas-Rich Galaxies

Consistent with the galaxy merger evolution picture

Merger ➔ Starburst ➔ AGN ➔ Elliptical

Galaxies accrete new fuel for star formation several ways.

- Major / Minor Merging (We measure dynamical time scale inflows)
- Cold Mode Accretion
- Condensation of Cold Clouds in a Hot Halo

Regardless of the mechanism, accretion of cold gas enhances star formation

- At z~2, cold flows may trigger star formation
- In the nearby universe, Major mergers fuel the most luminous starburst.
- Do they drive outflows? (Yes, we find outflows in Balmer and forbidden line emission)

Ultraluminous Infrared Galaxies (ULIRGs) offer the closest analogy to high star formation rate conditions at high z.

Our technique (fitting multiple lines in high resolution spectra) has important applications in the next generation of spectroscopic galaxy surveys

- Outflow census can be obtained from moderate resolution, infrared spectra
- Coverage of rest-frame, optical lines from [O I] to Hα + [NII] at R~5000 required
- JWST will provide these spectra over the entire era of galaxy formation and growth, and MOSFIRE at Keck and MUSE at VLT will start providing results soon.