The SINS Survey: SINFONI Integral Field Spectroscopy of $z \sim 2$ Star-forming Galaxies

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Galaxy Physics Class
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Results Overview

- Largest survey of spatially resolved **gas kinematics**, **morphologies** and **physical properties** of star forming galaxies at $z \sim 1-3$
- **SINS Hα sample**: 62 objects were detected in rest-frame UV: Hα(656.28nm) & NII (double line emission: 654.8nm and 658.3nm).
- Reasonable representation of Massive $M_\star \geq 10^{10} M_\odot$ galaxies.
- Population analysis:
  - 1/3 Rotation dominated turbulent disks
  - 1/3 Compact and Velocity dispersion dominated objects
  - 1/3 Interacting/Merging systems
- Massive galaxies tend to be more "rotation dominated".
- Hα Luminosities and equivalent widths:
  - Twice higher dust attenuation towards the HII regions.
  - Comparable current and past-averaged star formation rates.

Background

- The global population properties of the galaxy are generally understood:
  - Rapid evolution in $z \sim 1-4$
  - Downsizing
  - Color bimodality and Hubble sequence originate from $z \sim 1-2$.
- Current (before this paper) dependencies:
  - SED fitting and color analysis
  - Global properties such as: Stellar mass, age, SFR, interstellar extinction and sizes.
  - Limited integrated spectroscopy in the NIR. More direct and detailed constraints needed
- **Important question**: How massive galaxies assemble their mass?
  - Major mergers
  - Cold flows and Minor mergers

Previous work

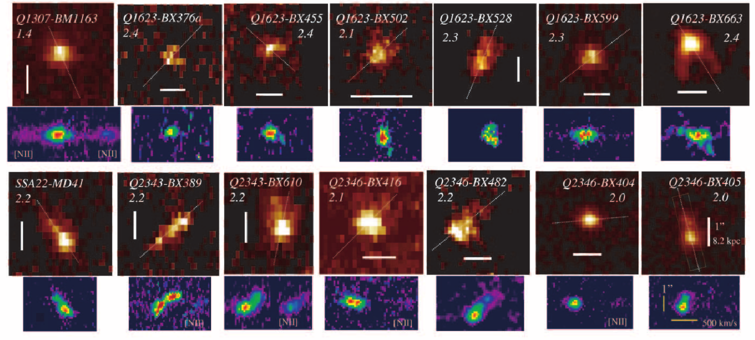
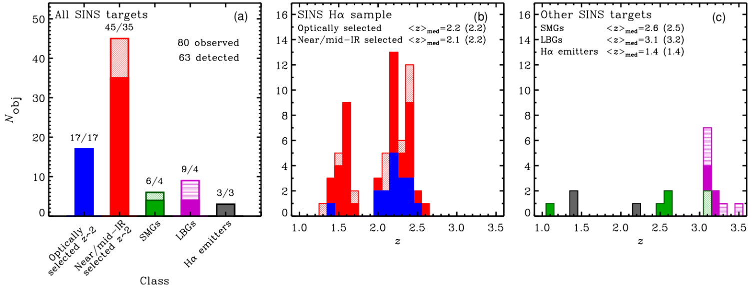


Figure: Förster Schreiber et al. 2006.

- Diversity in Kinematics and Morphologies of Hα sources.
- Large fraction having disk like rotation.

General properties

- Full sample: 80 spectroscopically confirmed galaxies with 63 observed in one emission line.
- Selectrion criteria:
  - Target visibility
  - Night sky line avoidance for Hα or [OIII]:5007Å
  - Emission line flux of $\geq 5 \times 10^{-17} ergs^{-1} cm^{-2}$. (Estimated with SED fitting for 2/3 of the final samples)
- AGNs were avoided, but present: line emission could be spatially or spectrally separated.



Separate class selection

- **Optical**: BM/BX: Actively star-forming with moderate extinction in $z \sim 1.5 - 2.0$(BM) and $z \sim 2.0 - 2.5$(BX). Selected by spectroscopy with the NIRSPEC at Keck II.
- **Near Infra-Red**
  sBzK: More specifically evolved and/or dust-obscured populations of star-forming (sBzK) that may be under-represented in optical surveys.
  - K20 survey (5): Previously observed Hα and [NII].
  - Deep-3a survey (7): bright at 24μm with flux $\geq$ 100μJ, AO.
  - GMASS survey (19): 4.5μm selected. Hα flux estimated and non-elliptical morphologies.
  - zCOSMOS-deep survey (4): sBzK with $1.4 < z_{sp} < 2.5$; morphology was also a criterion
  - GDDS survey (8): redshift range and on going star formation.
- **Lymann Break Galaxies**: Mainly taken from Steidel et al. 1999.
- **Submillimeter Bright Galaxies**: Accurate positional and spectroscopic information.
- **Line emitters**: In the vicinity of radio source MRC1138-262 and NIC J1143-8036a/b.

General Analysis

Bias

- The variety lowers bias compared to separate samples
- Optical z_{spec}: UV-brighter galaxies
- Minimum Hα flux: younger galaxies

Reference Population:

- Chandra Deep Field South (CDFS) catalog used for comparison
- Sources with $K_{s,vega} < 22$ and z_{photo} in the same range

SED construction (Appendix A)

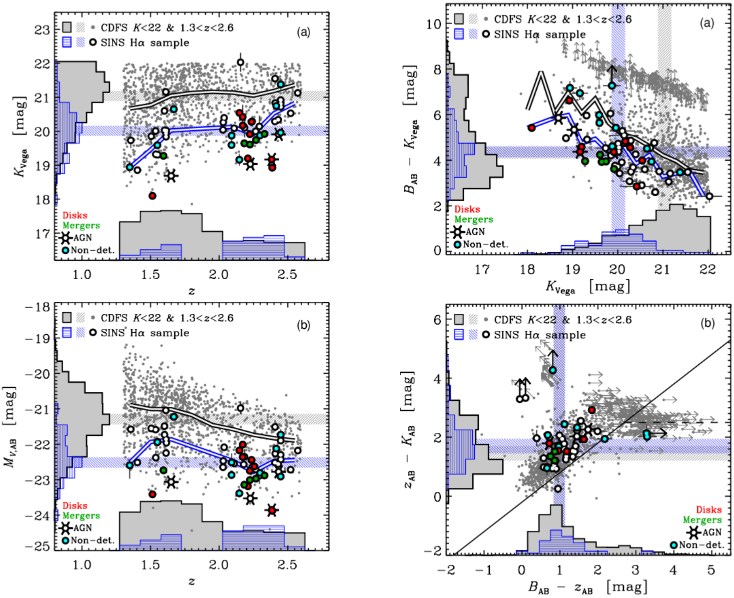
Characteristics (e.g. Mass, Age and etc.) could not be used from the catalogs because each used different assumptions in modeling.

- All galaxies were remodelled: newer results (compared to the base catalogs) were used in this process.
- Total photometric uncertainties were either given or found from the original images. Galactic extinction towards various fields were also considered.
- Bruzual & Charlot (2003) synthesis code was used:
  - Fixed solar metallicity, Chabrier (2003) IMF, Calzetti (2000) redenning and Madau (1995) intergalactic H opacity, $\lambda_{rest} \leq 912$Å was set to zero.
  - Star Formation History + Dust models considered:
    - Constant Star Formation + dust
    - Instantaneus Star Formation + No dust
    - Exponentially declining SFR ($\tau = 300$Myr) + dust
- Synthetic spectra were convolved with a filter curve
- $H\alpha$ redshift (optical when not applicable) taken as base redshift

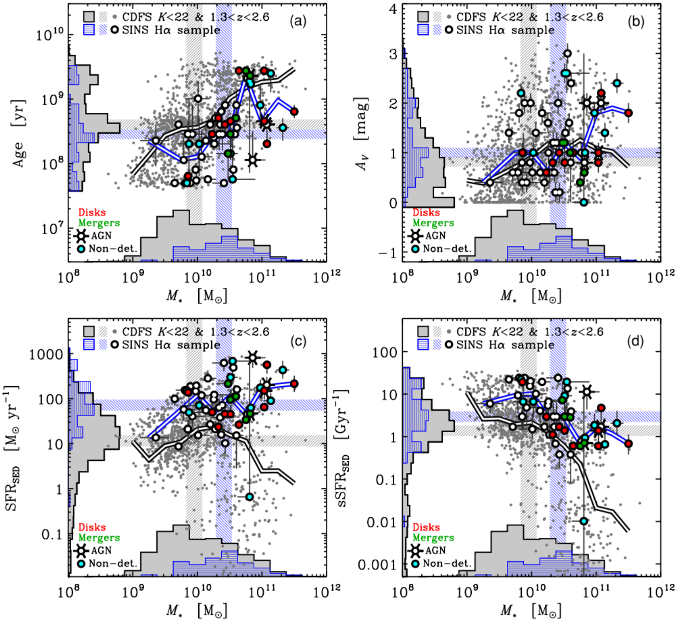
SED FITTING (APPENDIX A)

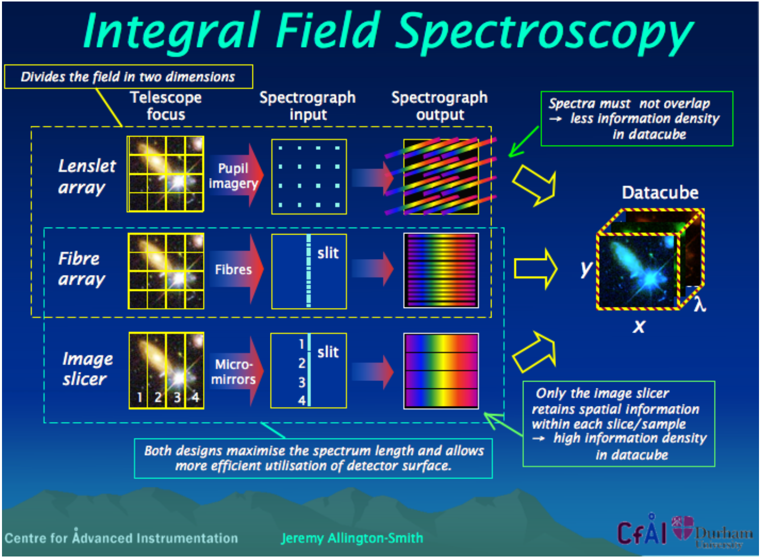
- Age, Extinction & luminosity scaling were taken as free parameters in the fitting and found through χ^2 minimization
- Acceptable age: $50Myrs < Age < Age\_of\_universe$.
- Best of three SFHs, was taken as true SFH.
- Errors in free parameters from 200 Monte-carlo simulations on observed SEDs.
- Emission line contribution was not corrected for:
  - All emission lines could not be accounted for in all galaxies.
  - Hα was on average only 10% of all emission lines.
  - Since trends are necessary here, the effect is very low.
- Errors (Monte Carlo simulations) not considered: Metallicity, Reddening, IMF, Synthesis code & SFH.
  - Poorly understood for z$\sim$ 2 universe
  - Not too significant in trends
  - Same effect on the CDFS galaxies

Population Comparison



Population Comparison

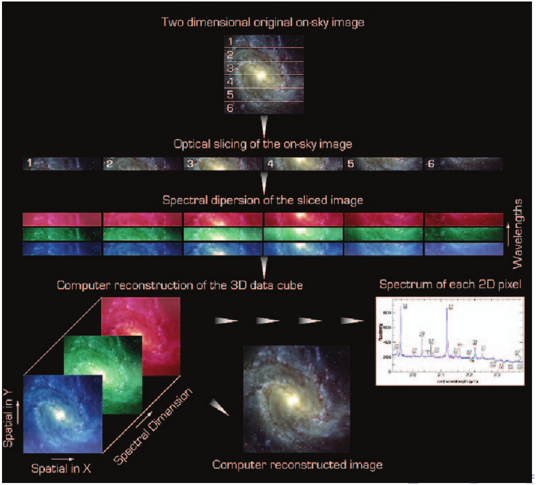



Integral Field Spectroscopy
Divides the field in two dimensions
Telescope focus
Spectrograph input
Spectrograph output
Spectra must not overlap → less information density in datacube
Lenslet array
Pupil imagery
Datacube
Fibre array
Fibres
slit
y
λ
x
Image slicer
Micro-mirrors
1 2 3 4
slit
Only the image slicer retains spatial information within each slice/sample → high information density in datacube
Both designs maximise the spectrum length and allows more efficient utilisation of detector surface.
Centre for Advanced Instrumentation
Jeremy Allington-Smith
CfAI
Durham University

SINFONI:

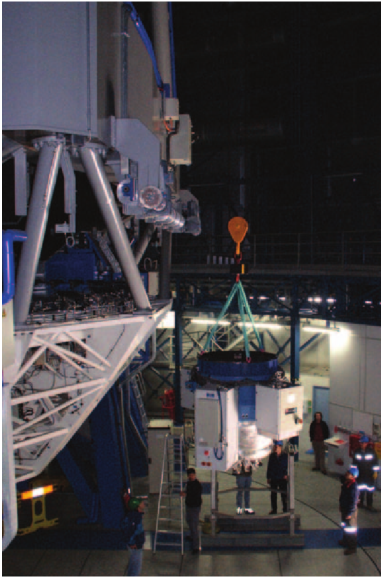
- Adaptive Optics (MACAO)
- Integral Field Spectrometer (SPIFFI)

The final Image of SINFONI is a 2D spatial array of 64×32 pixels and the spectral dimention is: 2048 pixels



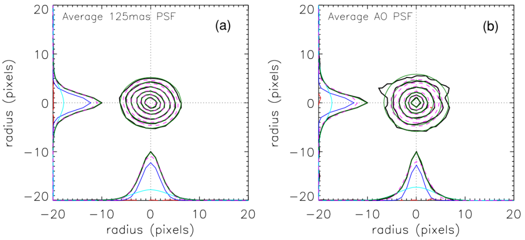
Data collection

- 24 observing campaigns: 03/2003 to 07/2008.
- Based on redshift H or K gratings were used for Hα
- 8 objects observed with AO
- Sky subtraction:
  - Onsource dithering (majority)
  - Offsets-to-sky
- Individual exposures: 300s, 600s & 900s
- Total integration times: 20min to 10h
- Observation did not continue if Hα emission was not visible after 1-2hrs.
- Data reduction procedures are omitted here



PSF characteristics(Appendix B)

- The PSF for each object was obtained from nearby stars
- All adequate were averaged to achieve higher S/N, normalized to unity and 5σ clipped.



- Narrow core and broad component: elliptical Gaussian
- Model galaxies (in spectroscopy and photometery) were constructed and convolved with various PSFs to find that uncertainties in PSF size have a small impact on the kinematic properties derived.

Noise characteristics (Appendix C)

- $\sigma_{real} \neq C \times N \times \sigma_{pix}$:
  - slitlet projection.
  - special data reduction method.
- σ_{real} was calculated by the dispersion in the dispersion of apertures of N pixels taken from empty regions of each wavelength's 2D image.
- σ_{real} shows this behavior:

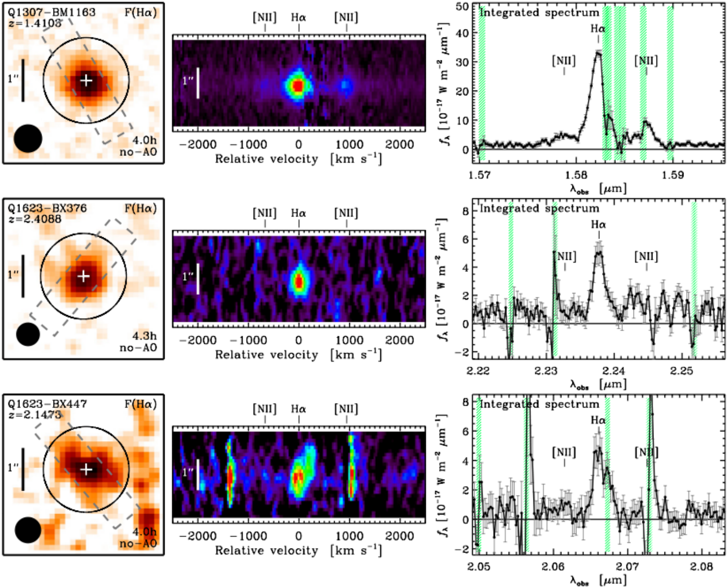
$$\sigma_{real}(N, \lambda)/[N \times \sigma_{pix}(\lambda)] = a(\lambda) + b(\lambda) \log N$$

- It is found that a and b are independent of λ, so the median value of each was taken.
- Finally, to find the noise for each measurement this relation was used:

$$\sigma_{real}(N, \lambda) = [N \times \sigma_{pix}(\lambda)] \times (a_{med} + b_{med} \log N)$$

- The noise from this method is on average $\times 2$ the Gaussian noise assumption.

Hα Maps, Position velocity diagrams & Integrated Spectra (Appendix D)



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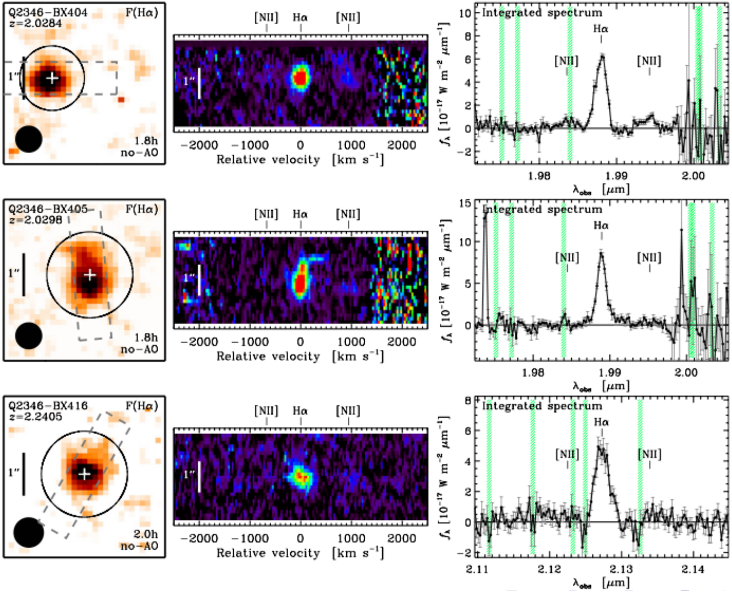
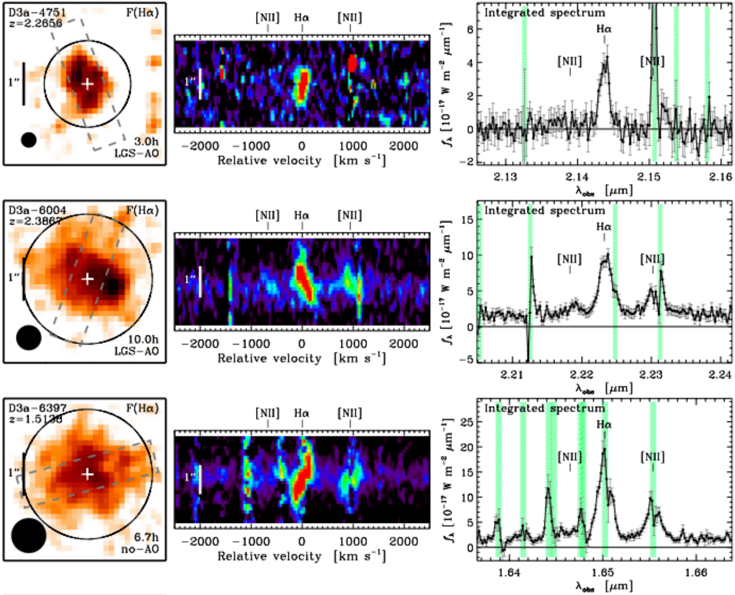


Hα Maps, Position velocity diagrams & Integrated Spectra (Appendix D)



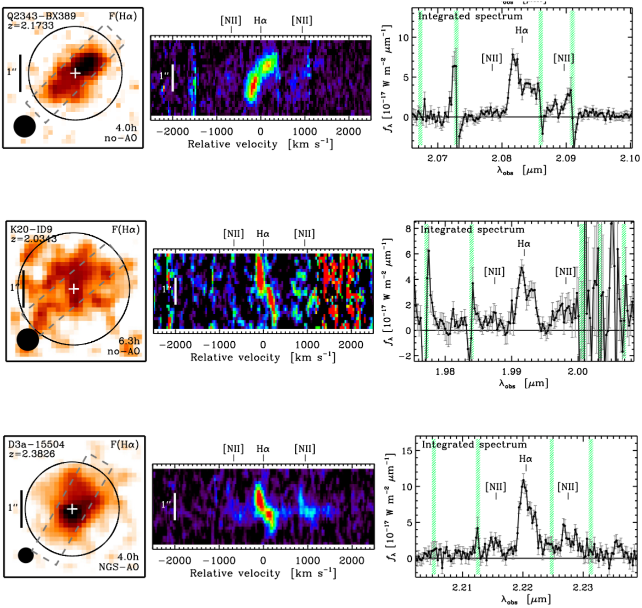
Line fitting

Velocity integrated line fluxes, Relative velocities and Velocity dispersion were calculated using LINEFIT.

- Data cubes median filtered (2 or 3 pixel wide filter)
- Instrumental resolution through sky lines
- *Uniform*, *Gaussian* or *Poisson* weighted fits are preformed.
- Continuum component subtracted
- Fitting uncertainties are computed from 100 monte carlo simulations.
- Asymmetries observed: Double peak profiles, Faint-blue/redshifted tails and multiple components.

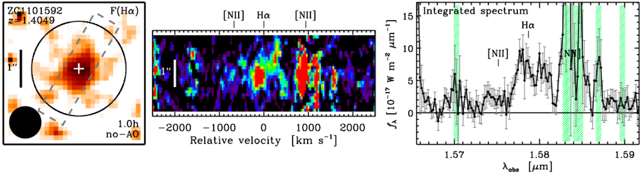
Spectral points were obtained from 90% circular apertures of the Hα image of each cube.
Integrated velocity dispersion ($\sigma_{int}(H\alpha)$) was calculated without shifting of the spectra

Double Peaked:

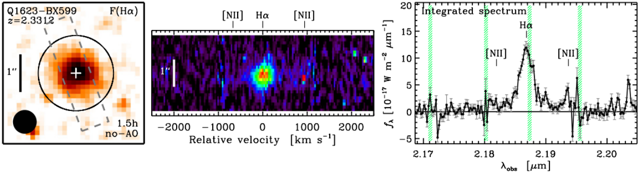


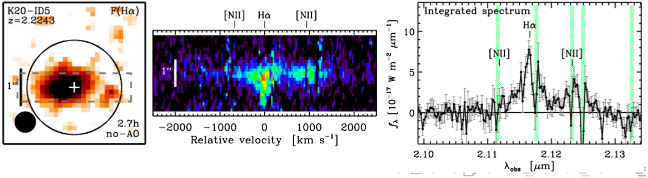
OTHER:

Faint-blue/redshifted:



Narrow and broad components:

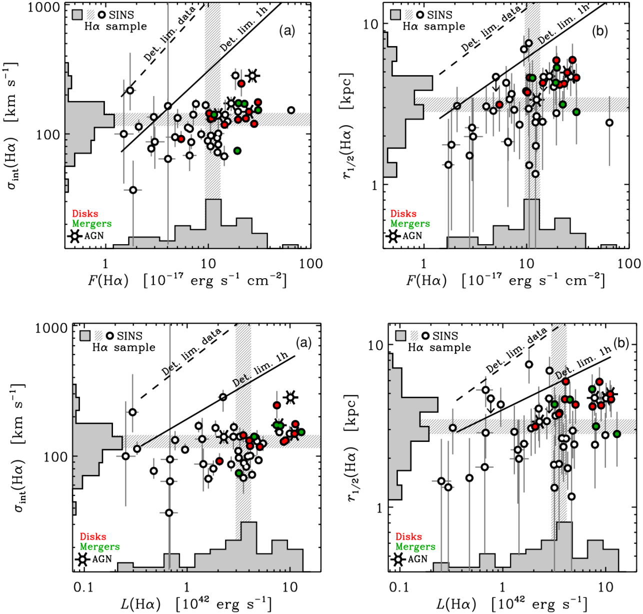




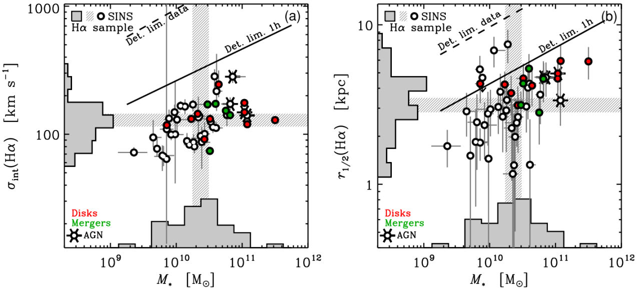
Morphological properties

- Morphological major axis was usually within 20° of the kinematic major axis: direction of maximum $H\alpha$ gradient.
- The kinematic P.A. was taken as the major axis.
- Gaussian profile is assumed for the $H\alpha$ sources
- $r_{1/2}(H\alpha)$ from $H\alpha$ curve-of-growth analysis and corrected for seeing
- PSF variations are of order 20%; size uncertainties in the order of $\approx 30\% - 35\%$
- Typical detection limit, not straightforward:
  - Sensitivity varies with wavelength.
  - Wide range of integration times.

Distributions relative to Hα flux & Luminosity



Distributions relative to mass

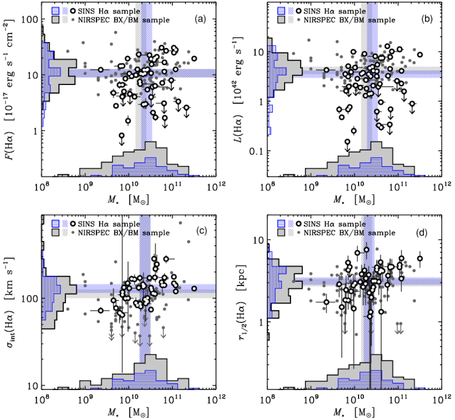


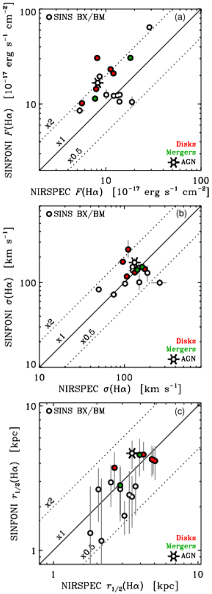
- Similar trends seen in all three cases
- Those identified as Disks and Mergers tend to higher horizontal values.
- AGNs are not outliers.
- Sensitivity limits:
  - Dashed line: Sensitivity limit
  - Bold line: Exposure time limit (1h); Observation strategy.

Comparison with Erb et al. 2006 $z \sim 2$ samples

With NIRSPEC Long-slit spectroscopy

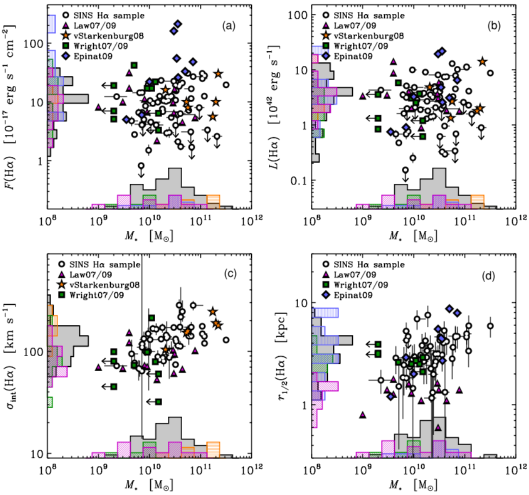
- Higher fluxes with SINFONI by $\times 1.6$; Slit loss & Slit miss-alignment.
- Over all, Slit Spectroscopy seems to be highly reliable.





With other IFS:

- SINS has a larger mass range
- Little difference in $F(H\alpha)$ and $L(H\alpha)$



AGN & $H\alpha$

Is $H\alpha$ from Star forming regions or AGNs or shock-ionized material?

From Star forming regions:

- Rest-frame optical line ratios (e.g. $[NII]/H\alpha$)
- Rest-frame UV spectra
- In one of four AGNs, $H\alpha$ is dominated by star-forming regions.

From AGNs:

- Shapiro et al. 2009 show a broad underlying $H\alpha$ component in all SINS samples
  Could be due to lower level or obscured AGN
- AGNs would also affect the SED results

L($H\alpha$), Equivalent width & SFR

$H\alpha$ **Luminosity**:

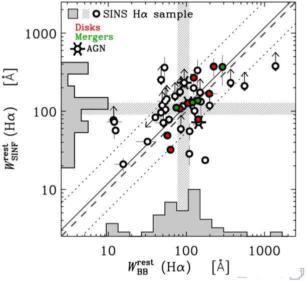
- SED fitting extinction: $A_{V,SED}$: $L^{0}(H\alpha)$
- Extinction due to dust: $A_{V,Neb} = A_{V,SED}/0.44$: $L^{00}(H\alpha)$
- Calzetti et al. 2000 redenning: $A_{H\alpha} = 0.82 \times A_V$
- Balmer absorption and Galactic extinction neglected.

$H\alpha$ **Equivalent width**:

- Ratio of $H\alpha$line flux to Broad band flux densities: $W^{rest}_{BB}(H\alpha)$
- Measurements of line-free continuum of the integrated spectra: $W^{rest}_{SINF}(H\alpha)$

SFR found by Kennicut(1998) paper:

$$\log\left(SFR(H\alpha)[M_{\odot}/yr]\right) = \log\left(L(H\alpha)[erg/s]\right) - 41.33$$

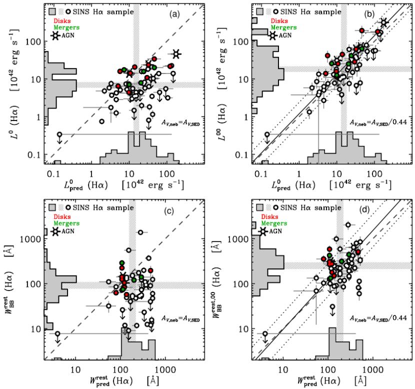


Dust distribution

- Only $H\alpha$ is suitable for constraining dust distribution.
- The right column (with differential attenuation: DA) has a better fit.
- (a), (b) & (d) are not independent.

Even with DA, the observed values are $\sim$ 30% larger

- AGNs?.
- Metallicity?
- Density bounded HII regions?
- IMF biased towards more massive stars? YES



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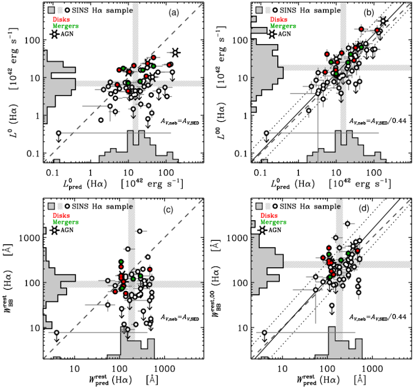

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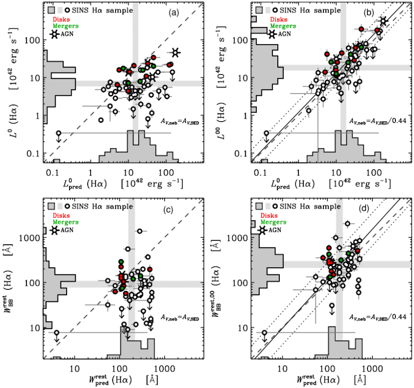

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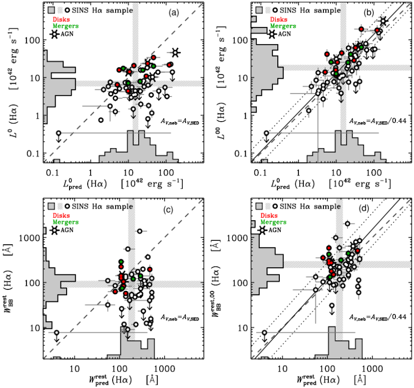

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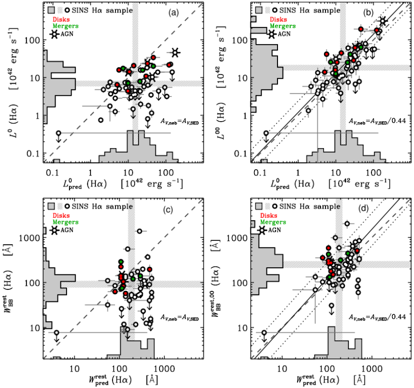
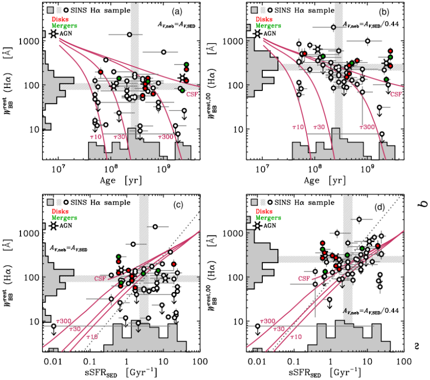
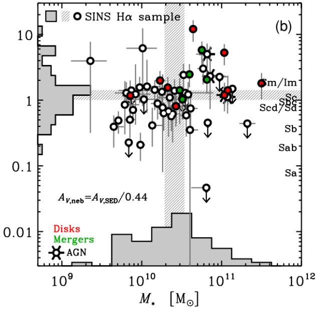


Star Formation Histories

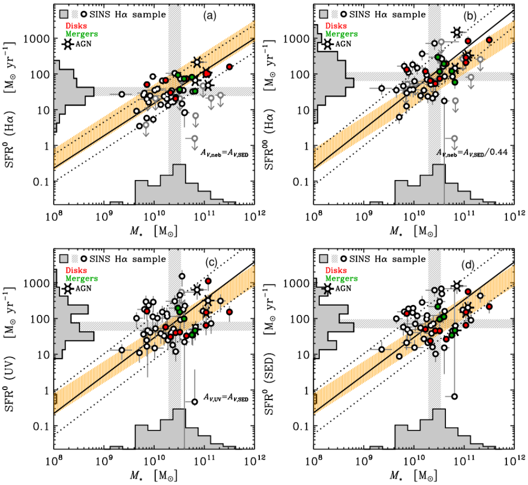
- Left column: No DA, Right column: DA.
- Right column is less dispersed and the best SFH is Constant Star Formation (CSF)
- b=(current SFR)/(past-averaged SFR)





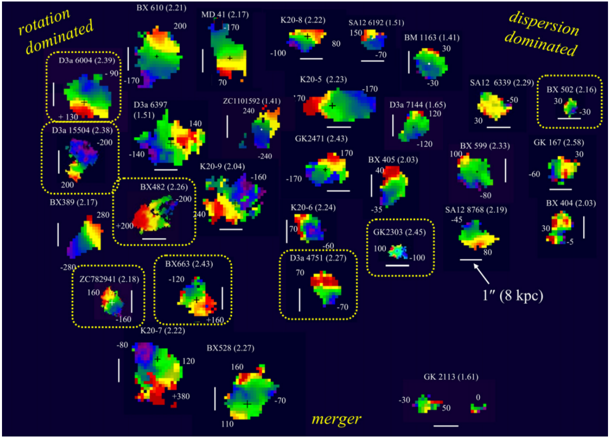
Star Formation Rates

- Good Agreement between (b), (c) & (D)
- The SINS SFRs cannot help in resolving the theoretical-observational discrepancy in SFR evolution.



Kinematic Diversity

- All on the same angular scale
- Gas kinematics ($H\alpha$ emitting) are used for galaxy kinematics



Kinematic Classification

Disk or Merger:

- *Quantitative*: Degree of asymmetry; 10 Disks, 5 Mergers
- *Qualitative*: Similar fraction of disks and mergers

Rotaion/Dispersion Dominated:

- *Reliable*: $v_{rot}/\sigma_0 = 1$; 13 rotation & 1 dispersion dominated.
- *Simulations*: The above boundary can be translated to: $v_{obs}/(2\sigma_{int}) \sim 0.4$: $\sim 1/3$ of sources are dispersion dominated.

So:
1/3 Disks,
1/3 Mergers,
1/3 velocity dispersion dominated (mainly compact and low mass)

Rotation Dominated Galaxies

- $v_{rot}/\sigma_0 \sim 1 - 7$; for local galaxies: $10 - 20$
- So the variations in rotational velocity are very high; Thick disks and high turbulence.
  Has been confirmed directly and indirectly by other studies
- Possible origins for this turbulence:
  - Intense star formation Feedback.
  - Heating due to Gas accretion.
  - Stirring due to Internal dynamical processes.
- On AO observed sources, deviations from pure rotation on kpc scale have been noticed.

Dispersion Dominated Galaxies

- Tend to be more compact
- Very low values of velocity gradients are observed
- What can they be?
  - Small disks with unresolved rotation.
  - Nearly Face on disks.
  - Systems with random/non-circular kinematics; e.g. late stage mergers or very young systems.
- Law et al. (2009), studying less massive galaxies found a larger fraction of such sources.

MERGERS/INTERACTING SYSTEMS

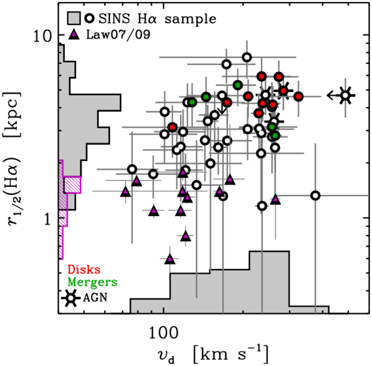
- Consisting of rotation or dispersion dominated components.
- Cannot be classified by integrated $H\alpha$ or stellar properties.
- Selection Criterion:
  - Projected separations $\leq 15 - 20kpc$.
  - Elevated Star Formation.
  - Perturbed and asymmetric gas kinematics on 1-5kpc scales.
- Such phases occur on a very short time scale ($\sim 100Myr$).
- Morphological analysis of mergers is necessary for a complete analysis.

Velocity-Size relation

The Law et al. 2009 sample was also included.

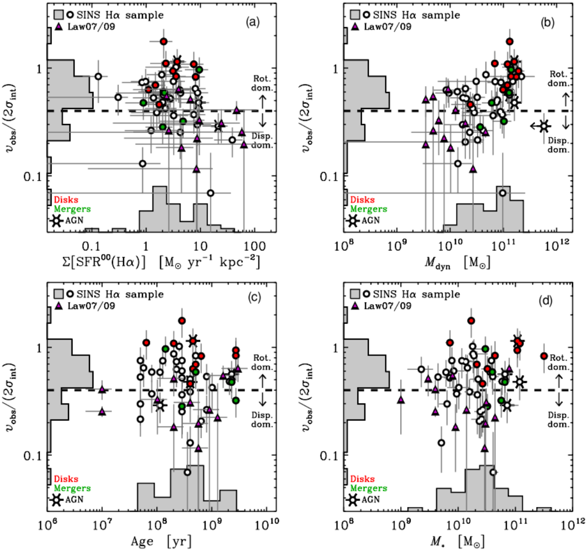
v_d is the circular velocity:

- **Kinematic modelling**
- **Velocity Gradient + width**: Rotation dominated, average of: $v_d^{vgrad} \sin(i) = 1.3 v_{obs}(H\alpha)$ and $v_d^{width} \sin(i) = 0.99 \sigma_{int}(H\alpha)$
- **Velocity Width**: dispersion dominated, virial relation: $v_d = \sqrt{3}\sigma_{int}(H\alpha)$



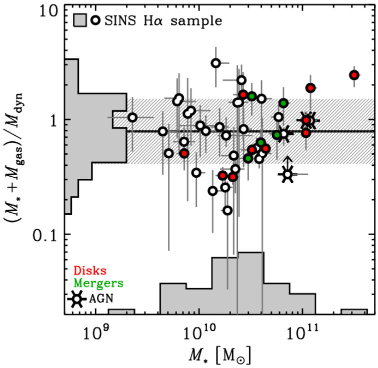
Velocity-Size relation

Test of Feedback processes due to star formation



MASS FRACTIONS AND DARK MATTER CONTRIBUTION

- Baryonic Mass fraction: $f_{baryons} = (M_{gas} - M_{\star})/M_{dyn}$.
- SED modelling errors (for M_{gas} & $M_{\star}$) aren't significant
- Gas mass fraction is $\sim 15 - 30\%$.
- Dark matter contributions in central 10kpc is $\sim 20 - 30\%$.



Summary

- Reasonable sample of Massive, actively star-forming galaxies at $z \sim 2$
- Differential Extinction between HII regions and stars is seen.
- SINS galaxies have undergone a roughly Constant SFR.
- They have Large velocity dispersion: $\sim 30 - 90 km/s$
- Gas kinematics is often surprisingly ordered.
- *Rotation dominated, Velocity dispersion dominated* and *Mergers/Interactions* are equally distributed.
- The rotation dominated galaxies follow a velocity-size relation and tend to be more massive.
- The dispersion dominated galaxies have lower mass and lower angular momentum; have a wide range of ages.