STUDYING GALAXIES AT LOW AND HIGH REDSHIFT WITH WIDE FIELD IFUs

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Carnegie Fellow
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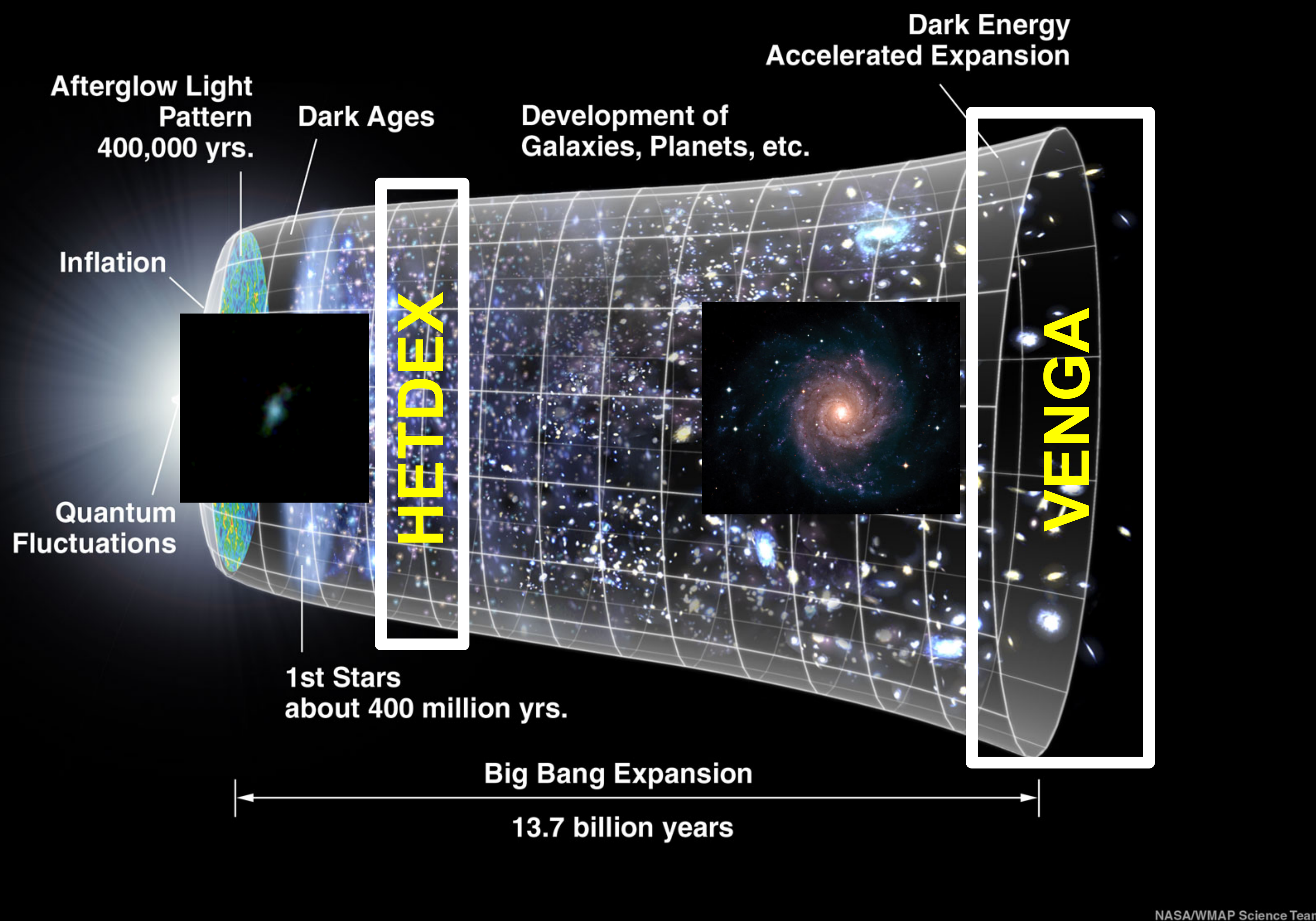
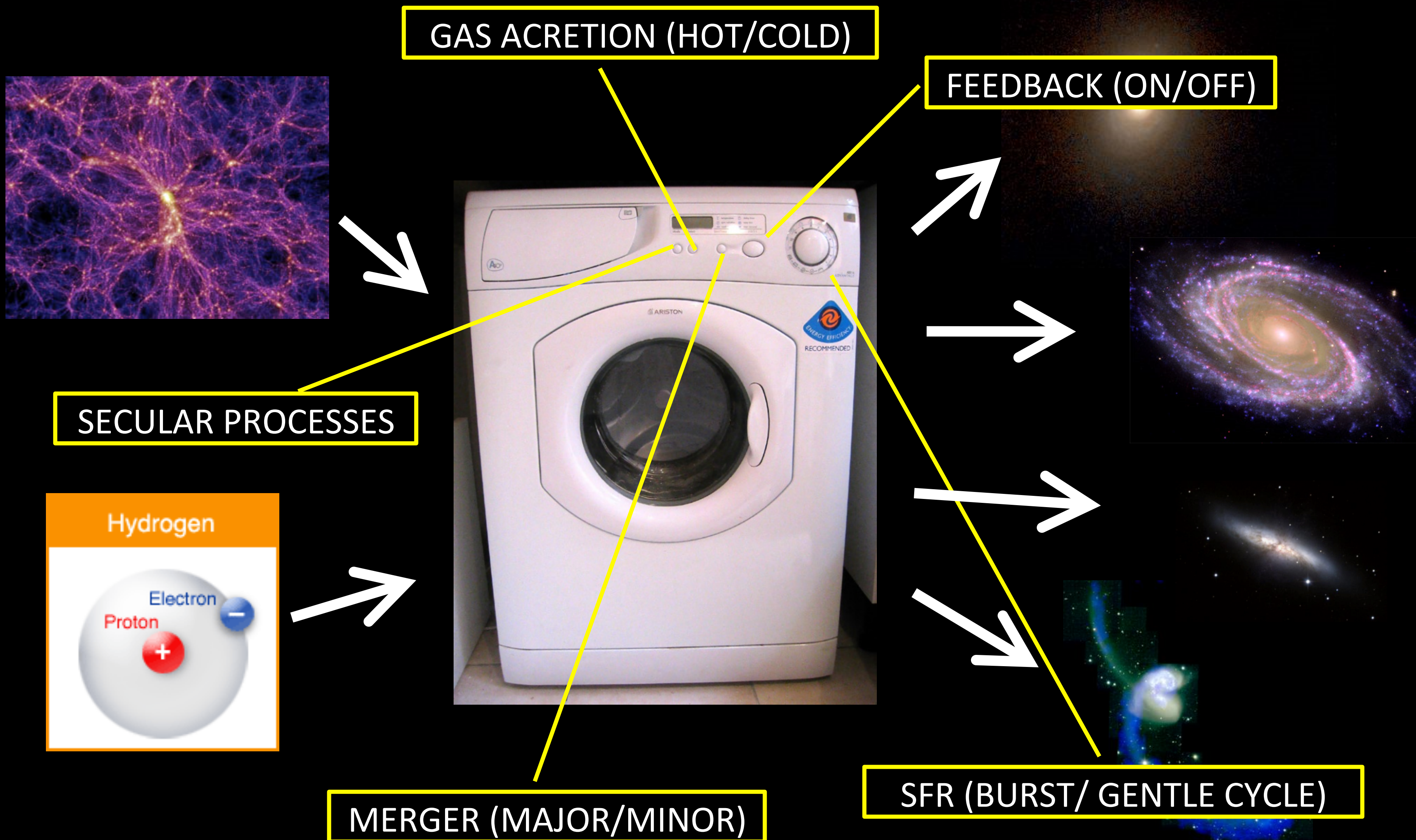


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
HETDEX
VENGA
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

- HOW DO GALAXIES FORM AND EVOVLE?



- HOW DO GALAXIES FORM AND EVOVLE?

Distributions and correlations of galaxy properties over large samples:

COSMOLOGICAL PARAMETERS, CLUSTERING, POWER SPECTRUM
LUMINOSITY FUNCTION, MASS FUNCTION,
SCALING RELATIONS, SFR HISTORY, REDSHIFT EVOLUTION, ETC.

Internal structure of individual galaxies:

MORPHOLOGY (STARS, GAS, DM), STELLAR KINEMATICS, GAS KINEMATICS,
METALLICITY DISTRIBUTION, STELLAR POPULATION DISTRIBUTION,
STAR FORMATION ACTIVITY, ETC.

OUTLINE

- Part I: HETDEX
  - Dark Energy and Lyman Alpha Emitters (LAEs)
  - VIRUS and VIRUS-P spectrographs
  - HETDEX Pilot Survey:
    - The Lyα Photon Escape Fraction across cosmic time

- Part II: VENGA
  - Survey design and Motivation
  - The Star Formation Law in M51a (NGC 5194)
  - The X_{CO} Factor across M74 (NGC 628)

HETDEX

The Hobby-Eberly Telescope

Dark Energy Experiment

HETDEX

Hobby-Eberly Telescope Dark Energy Experiment

Illuminating the Darkness

University of Texas:

Josh Adams

Guillermo Blanc

Barabara Castanheira

Taylor Chonis

Mark Cornell

Taylor Chonis

Karl Gebhardt (PS)

Gary Hill (PI)

Eiichiro Komatsu

Hanshin Lee

Phillip MacQueen

Jeremy Murphy

Marc Rafal (PM)

Matt Shethrone

Masatoshi Shoji

Mimi Song

Sarah Tuttle

MPE/USM:

Ralf Bender

Max Fabricius

Ulrich Hopp

Martin Landriau

Helena Relke

Jan Snigula

Jochen Weller

Houri Ziaeepour

Penn State University:

Robin Ciardullo

Caryl Gronwall

Larry Ramsey

Don Schneider

Ana Matkovic

AIP:

Andreas Kelz

Volker Mueller

Martin Roth

Mathias Steinmetz

Lutz Wisotzki

Texas A&M:

Darren DePoy

Steven Finkelstein

Jennifer Marshall

Nicolas Suntzeff

Niv Drory (UNAM)

Donghui Joeng (Caltech)

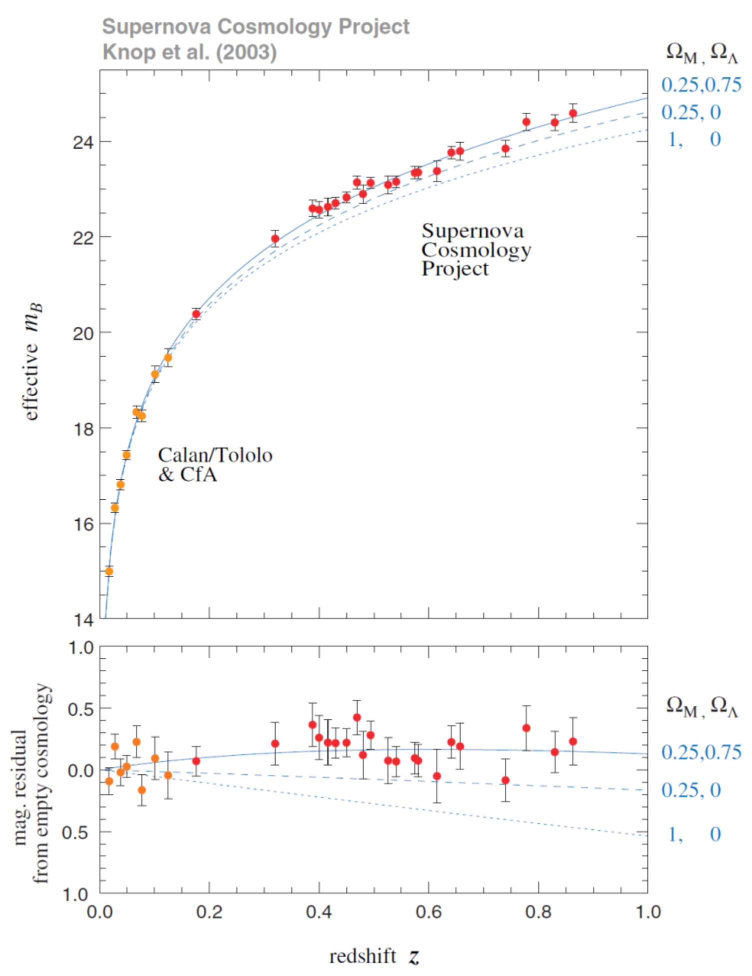
Eric Gawiser (Rutgers)

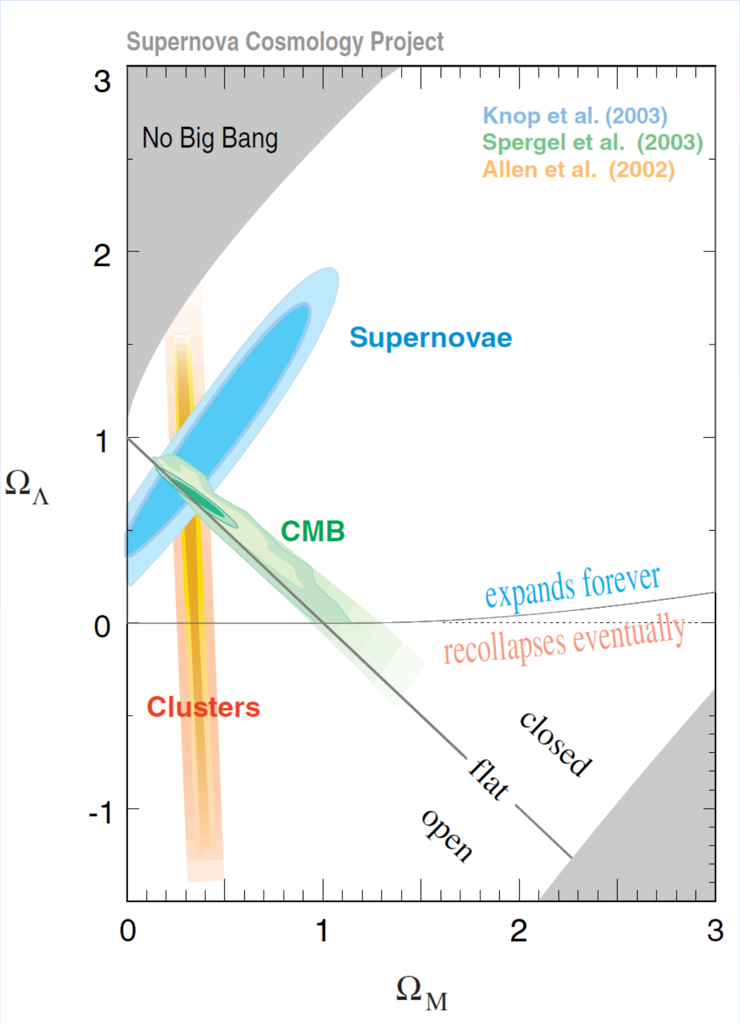
Povilas Palunas (LCO)

Lei Hao (Shanghai Observatory)

What is Dark Energy?

$$(d^2a/dt^2)_{z=\{0-1\}} > 0 \quad = \quad \text{DARK ENERGY}$$





What is Dark Energy?

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right) + \frac{\Lambda}{3}$$

We observe $\ddot{a}>0$ which can happen in 3 ways:

- Non-zero cosmological constant: $\Lambda>0$
- Universe is dominated by some particle or field with: $\rho+3P<0$

  $w=(P/\rho)<-(1/3)$

- The equation is not a proper model:
  - Either GR or the Standard Cosmological Model or both are incorrect or incomplete.

The Hobby-Eberly Telescope Dark Energy Experiment

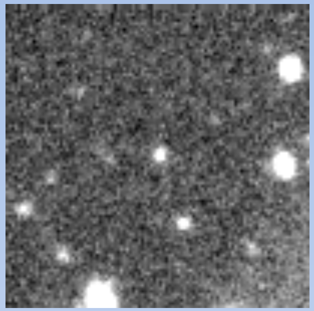
- HETDEX will measure the power spectrum for 700,000 Lyman Alpha emitting galaxies (LAEs) at $1.8 < z < 3.5$ over a volume of 3 Gpc^3.

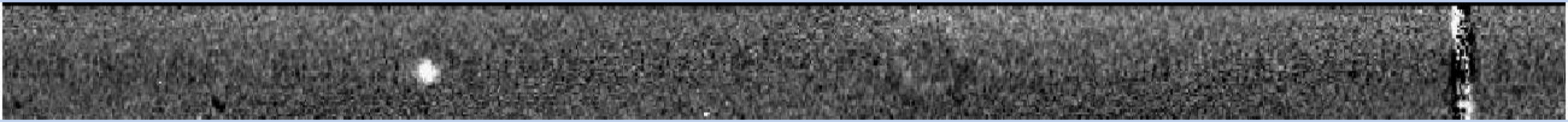
- From the power spectrum HETDEX will measure $w(z)=p_{DE}(z)/\rho_{DE}(z)$ with a 1% accuracy and the curvature "k" with a 0.1% accuracy at z=2-3

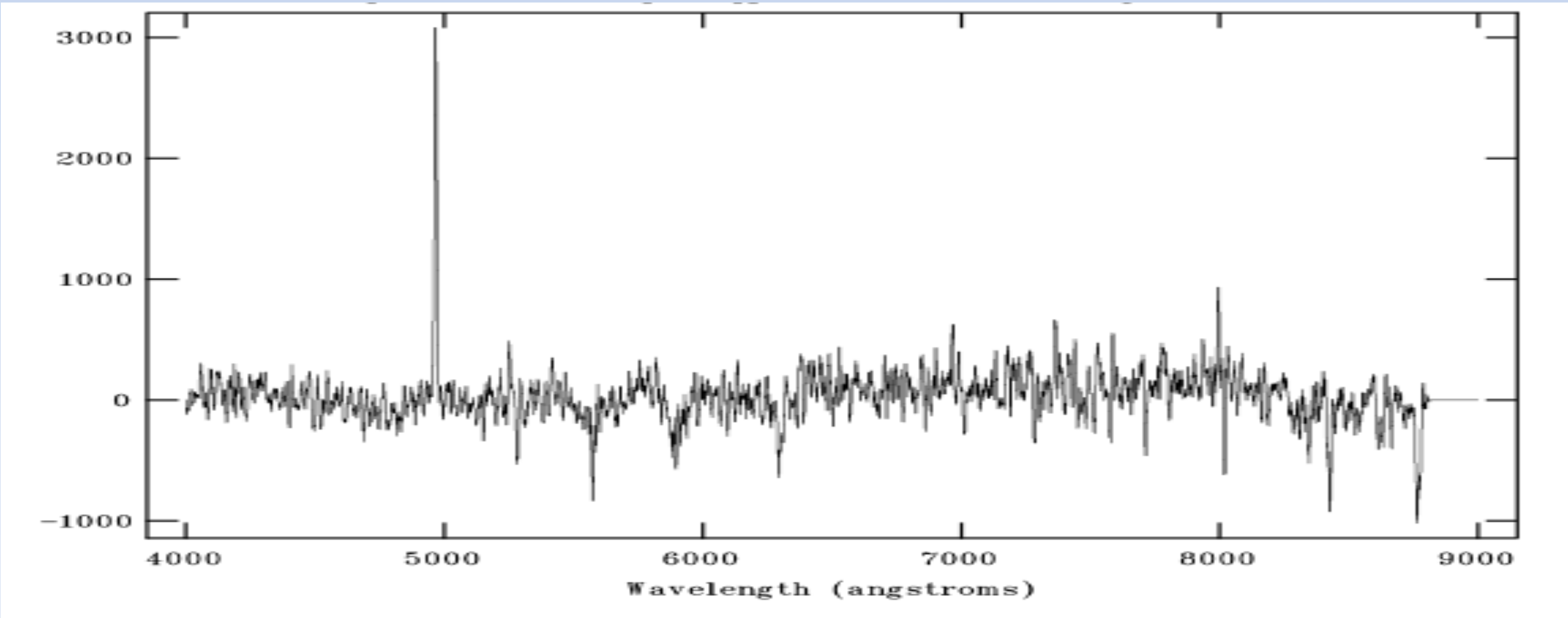
- High-z measurements are complementary to low-z measurements and allow to study evolution.

MUSYC LAE in E-CDFS, R=25.7, z=3.085

Lyα EW=200Å, (6 hr IMACS exposure)

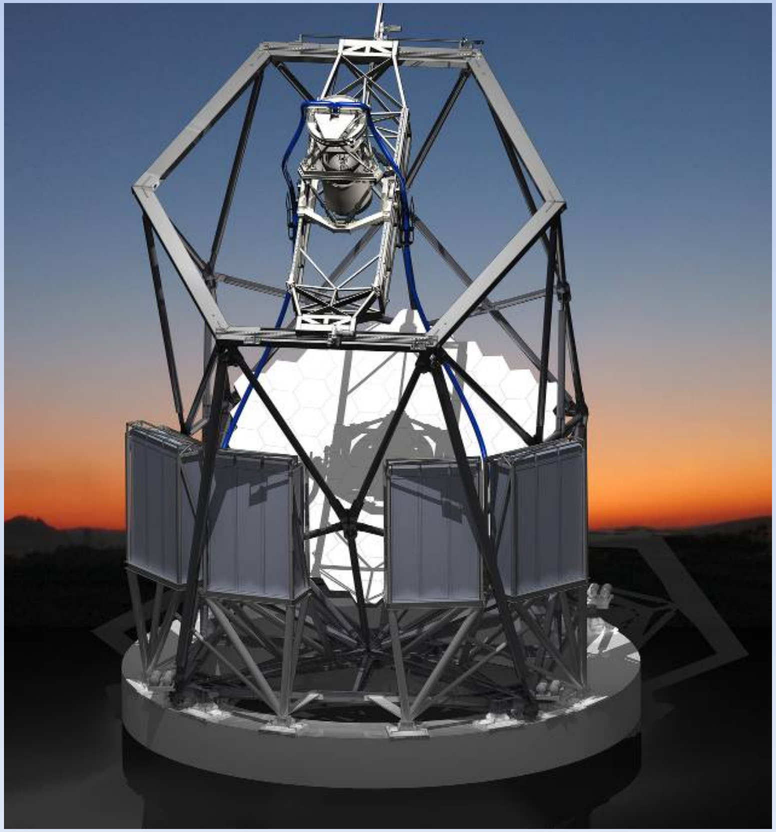






- How do you find 700,000 LAEs?

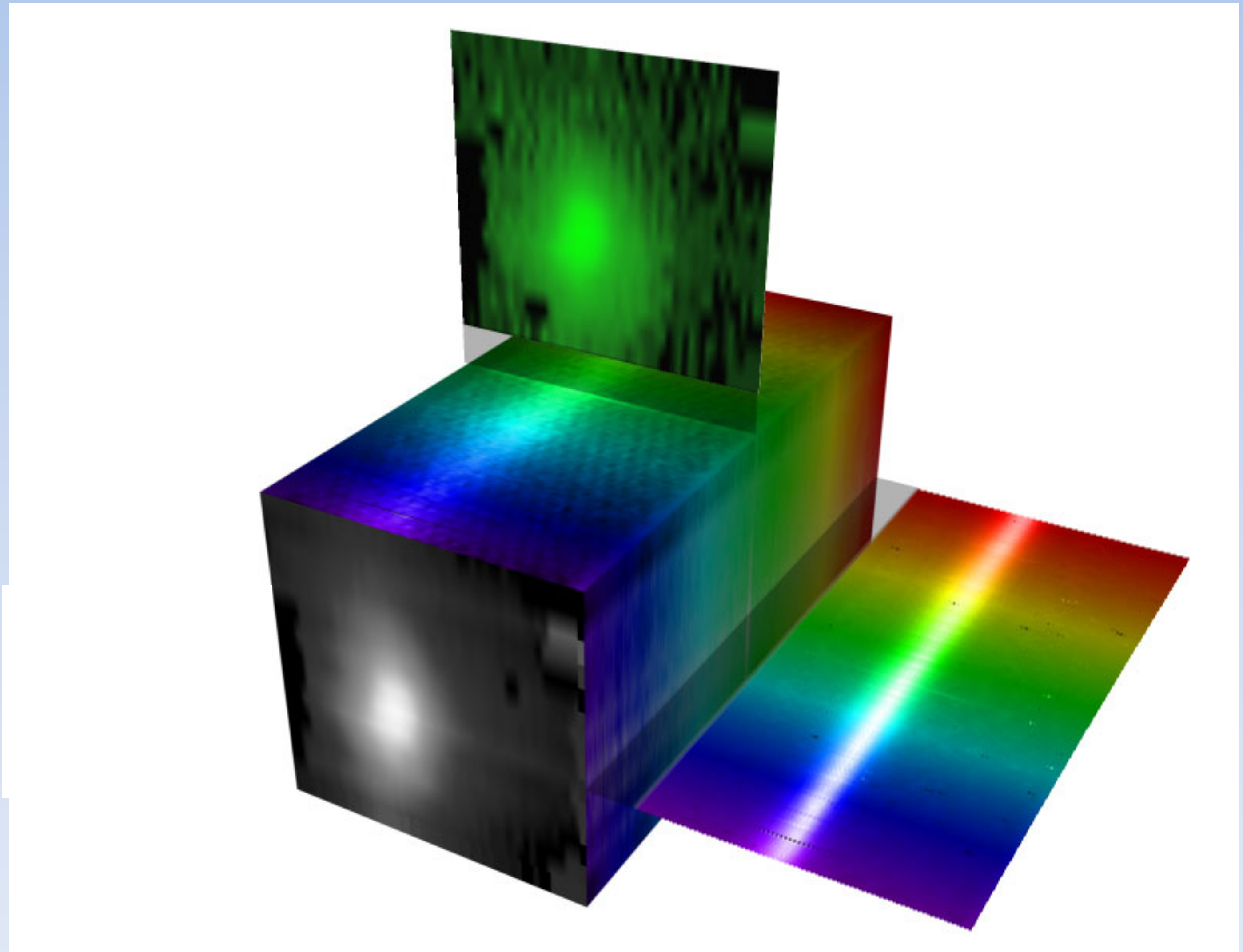
You use a **VIRUS**



Visible **I**ntegral-field **R**eplicable **U**nit **S**pectrograph

150 replicable Integral Field Unit Spectrographs (IFU)

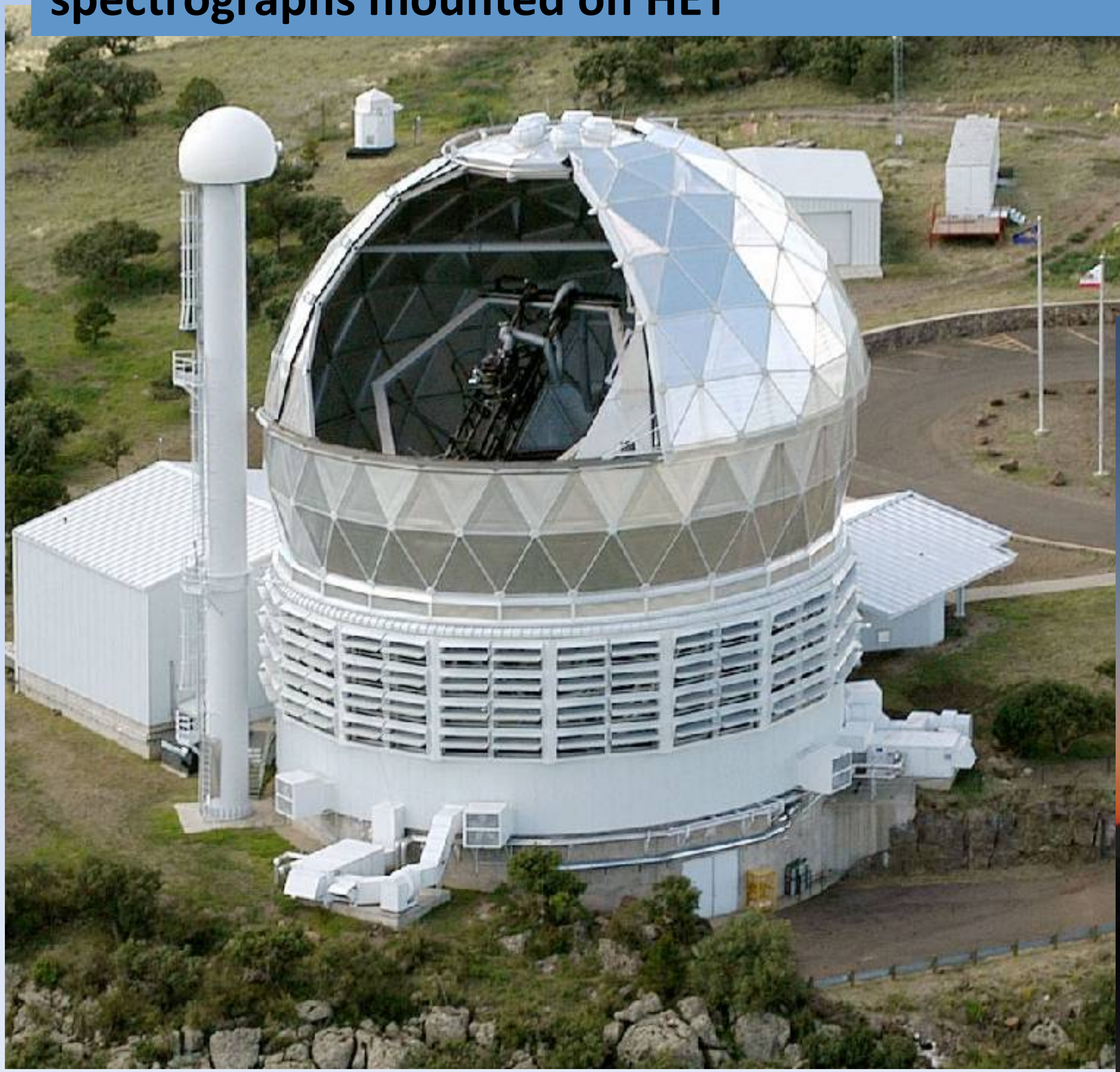
INTEGRAL FIELD SPECTROSCOPY



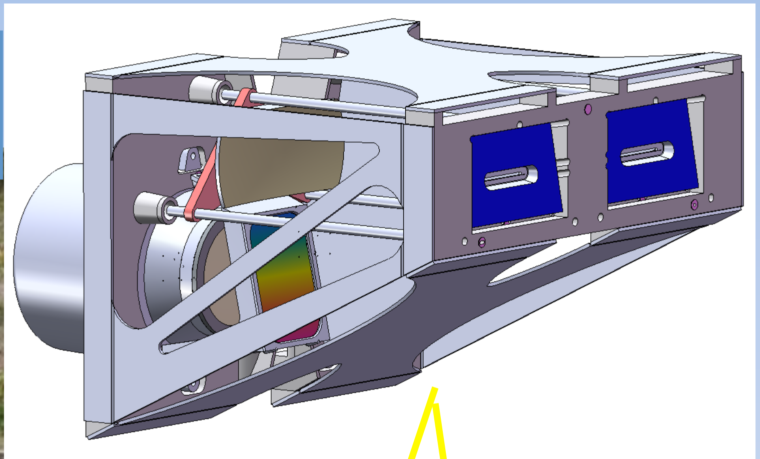
The active galaxy NGC1068, imaged using an Integral Field Unit

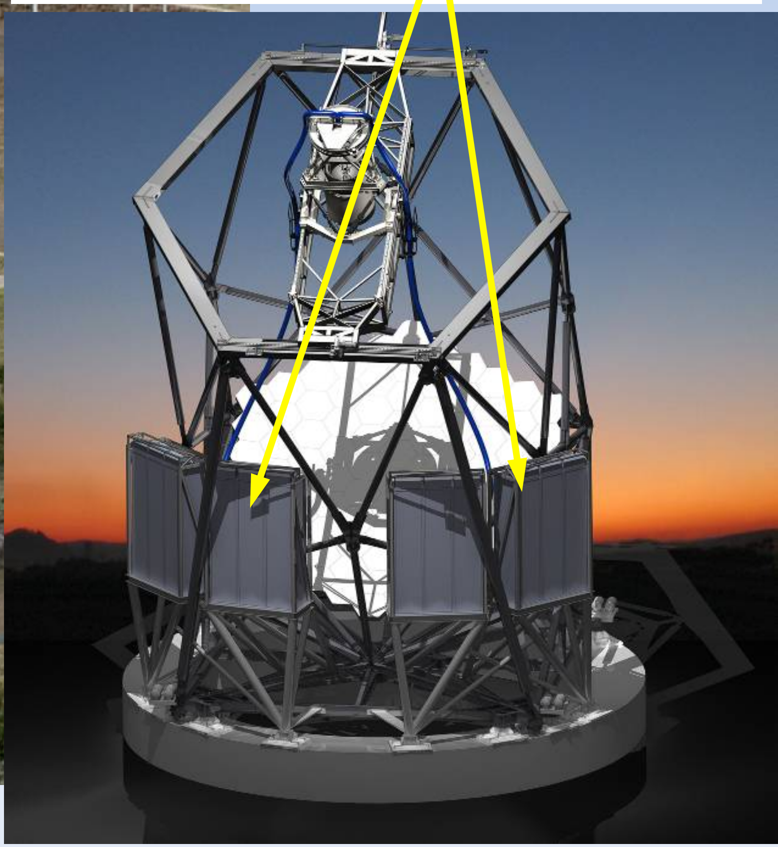
Image: Stephen Todd, ROE and Douglas Pierce-Price, JAC.

VIRUS consists of 75 IFUs feeding 150 spectrographs mounted on HET



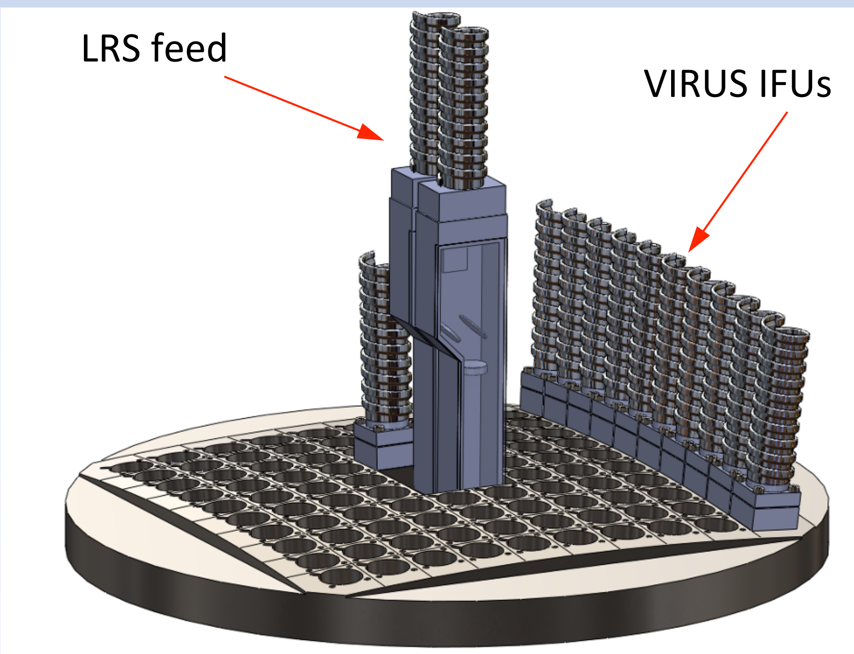
HET 9.2m at McDonald Observatory, Mt. Fowlkes west Texas

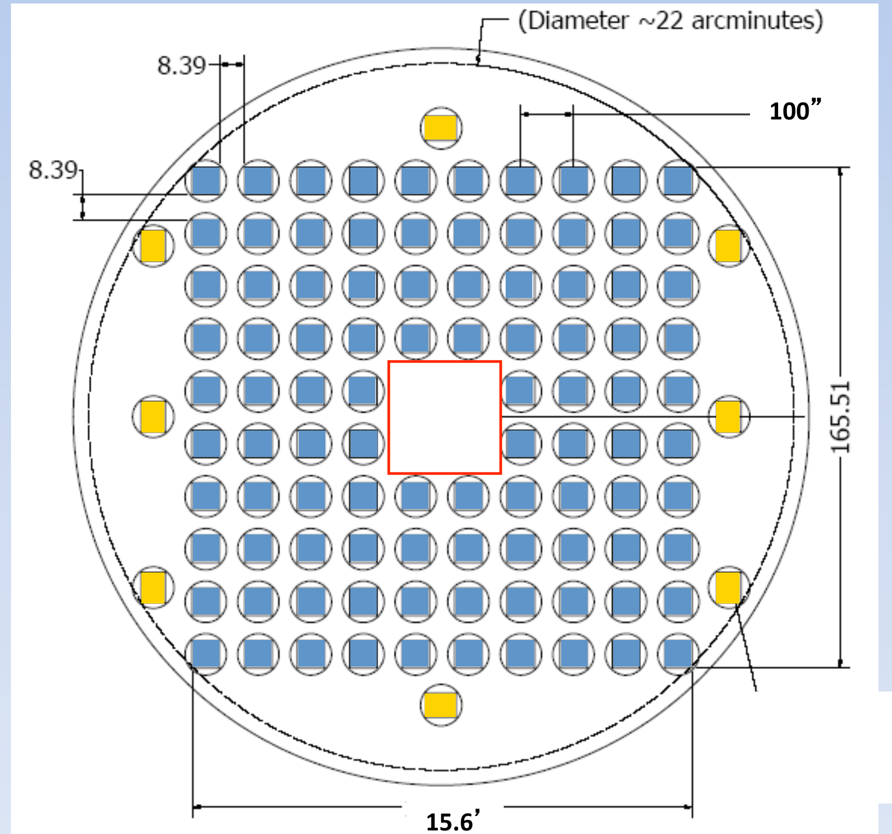




VIRUS field layout

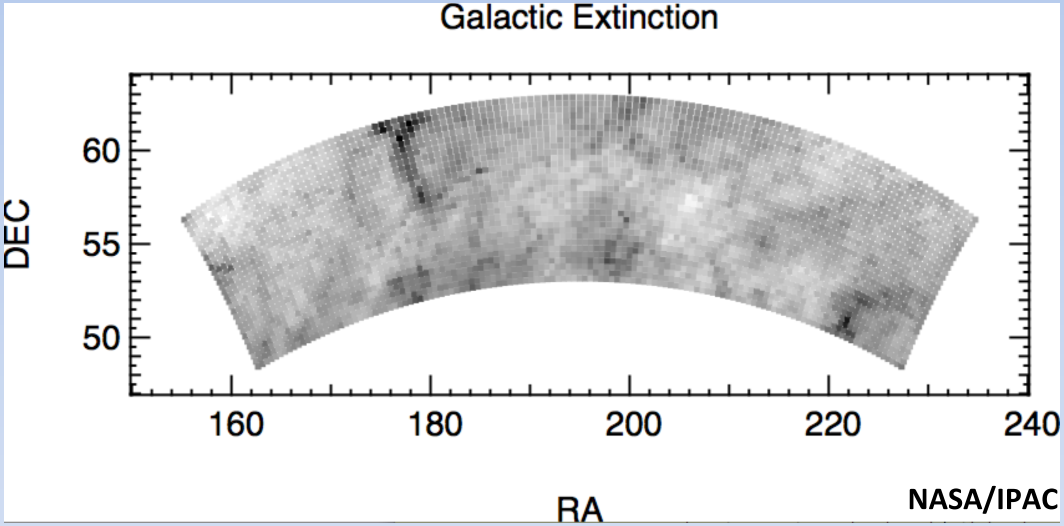
- Grid layout of IFUs with ¼ fill factor
  - feeds for other instruments at the middle of the field
- Allows parallel observations with VIRUS
- Baseline 75 IFUs will leave some gaps, but goal is to fill the matrix



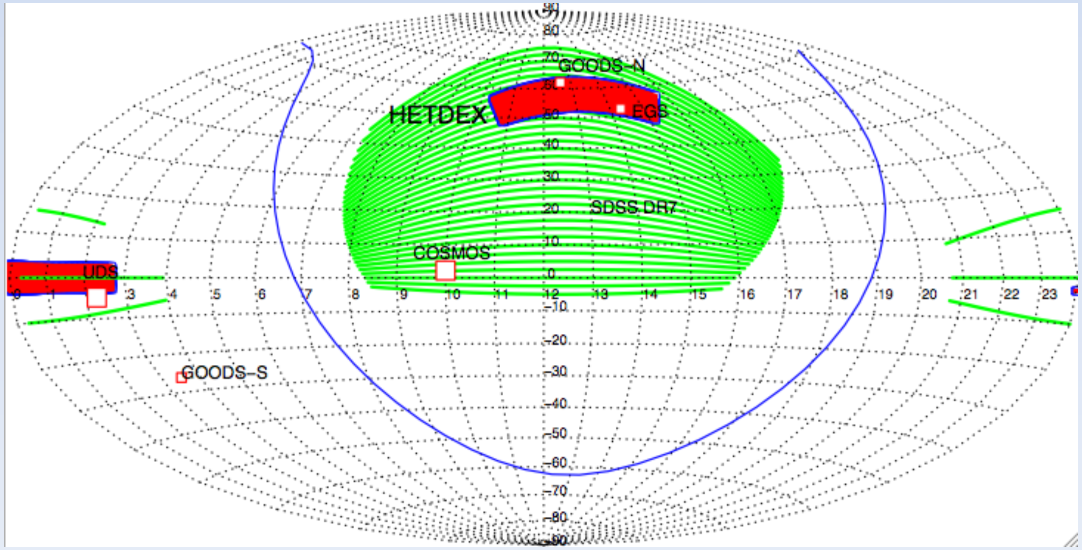


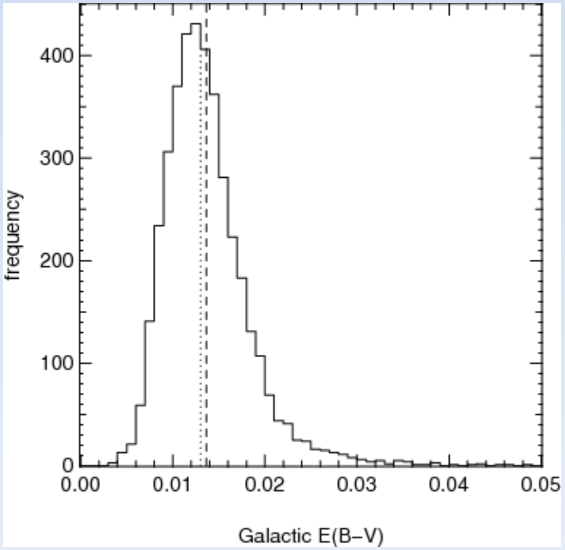
HETDEX Survey on Sky

- Dec δ = 53-63^{O} optimal for HET
- 420 sq. degrees covered
  - 60 sq. deg observed
  - 20 minutes per observation
- 4000 observations in 3 years
- Plus Fall and Deep Fields (COSMOS, UDS, EGS, GOODS-N)

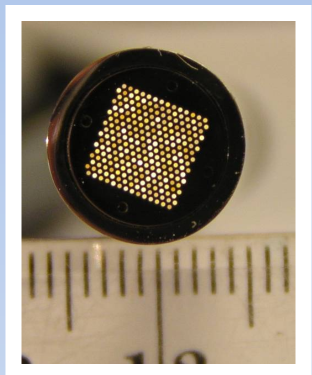


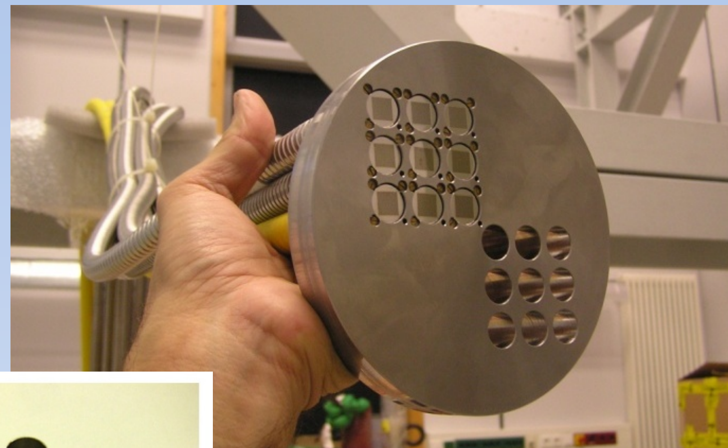
NASA/IPAC

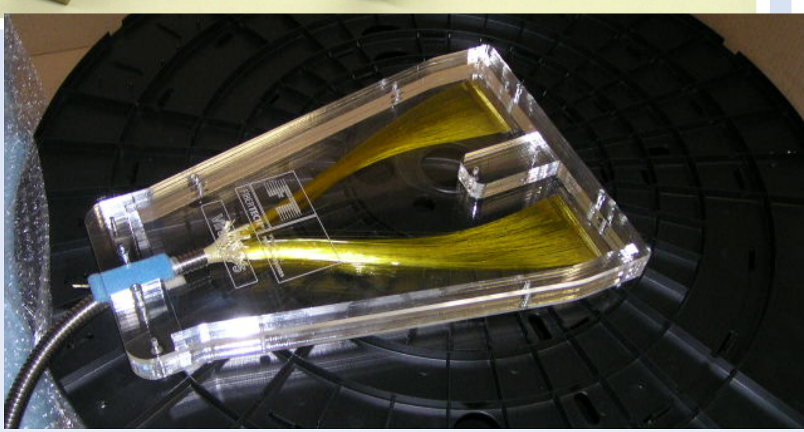




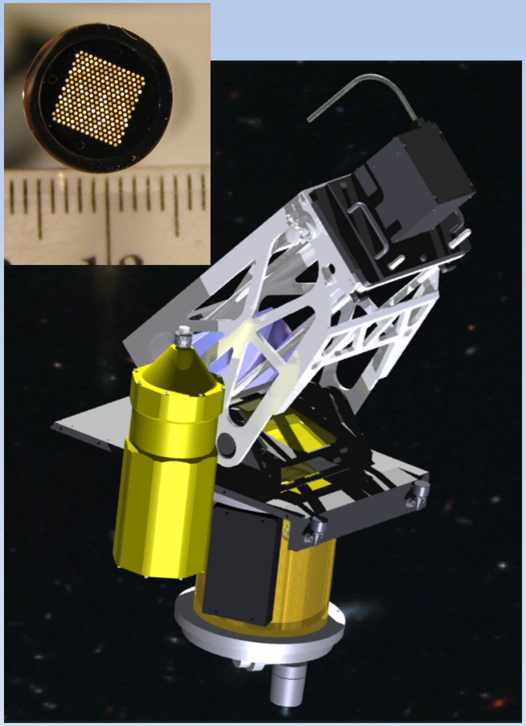
VIRUS will be commissioned on late 2013







VIRUS-P: The Prototype

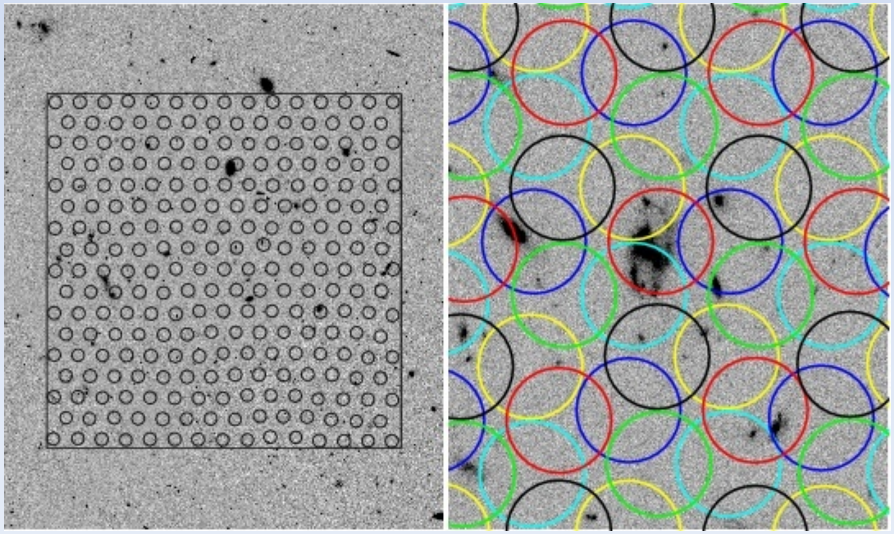


- VIRUS Prototype IFU
- 1.7’x1.7’ FOV at HJST 2.7m
- 1/3 filling factor
- Largest FOV of any existent IFU
- 4.3’’ diameter fibers on sky
- 3500-6800 Å / $\Delta\lambda$=2200 Å
- Blue DEX Setup: 3600-5800 Å
- Ly-Alpha @ $1.9 < z < 3.8$
- R=1000 @ 5000Å

The HETDEX Pilot Survey

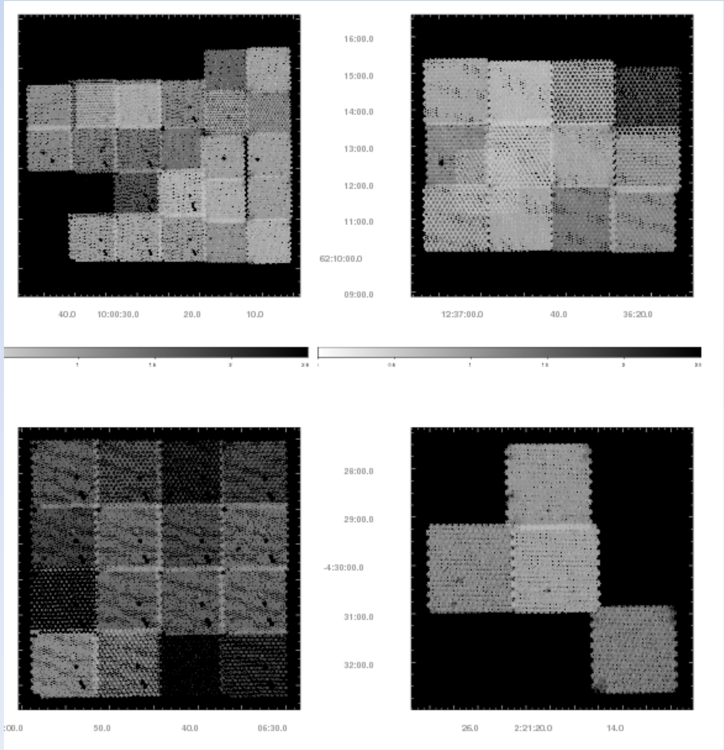
SURVEY DESIGN:

- 169 arcmin^2 surveyed on COSMOS, GOODS-N, MUNICS-S2, and XMM-LSS fields
- Fields selected to have deep multi-wavelength broad-band imaging
- 6 position dither pattern ensures good field coverage
- Three 20 min exposures at each position
- 2 hr of effective exposure time
- 5σ flux limit of ~6x10^{-17} erg/s/cm^2 for a point-source emitting and unresolved line
- Adams et al. 2010; Blanc et al. 2010, Finkelstein et al. 2010

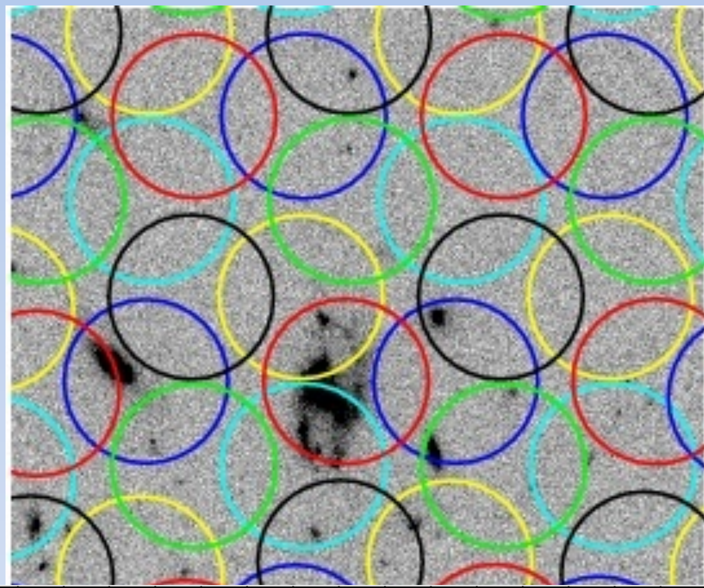


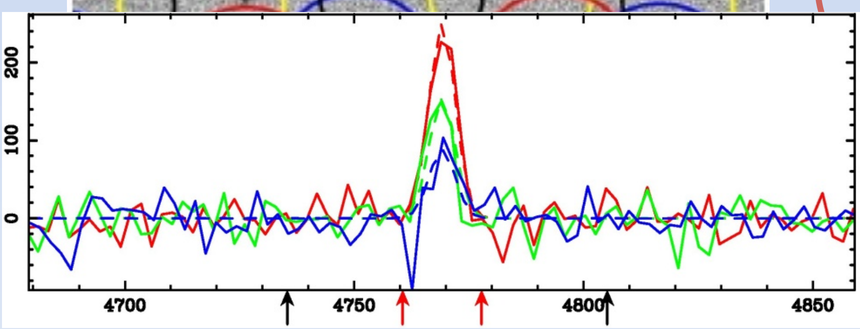
GOALS:

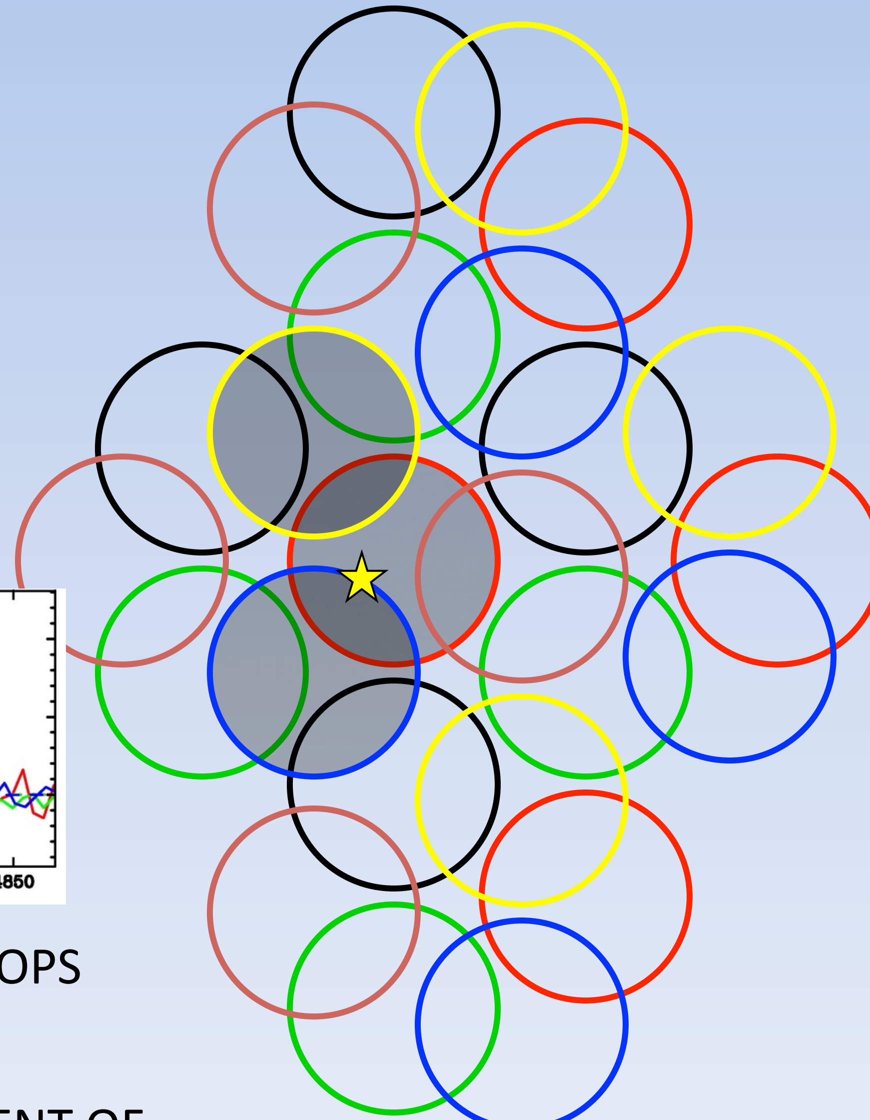
1. HETDEX and VIRUS proof of concept
2. Create an LAE sample spanning a large redshift range, to study the properties of LAEs and the escape fraction of Lyα photons from galaxies, and their evolution with redshift.



DETECTION OF EMISSION LINES



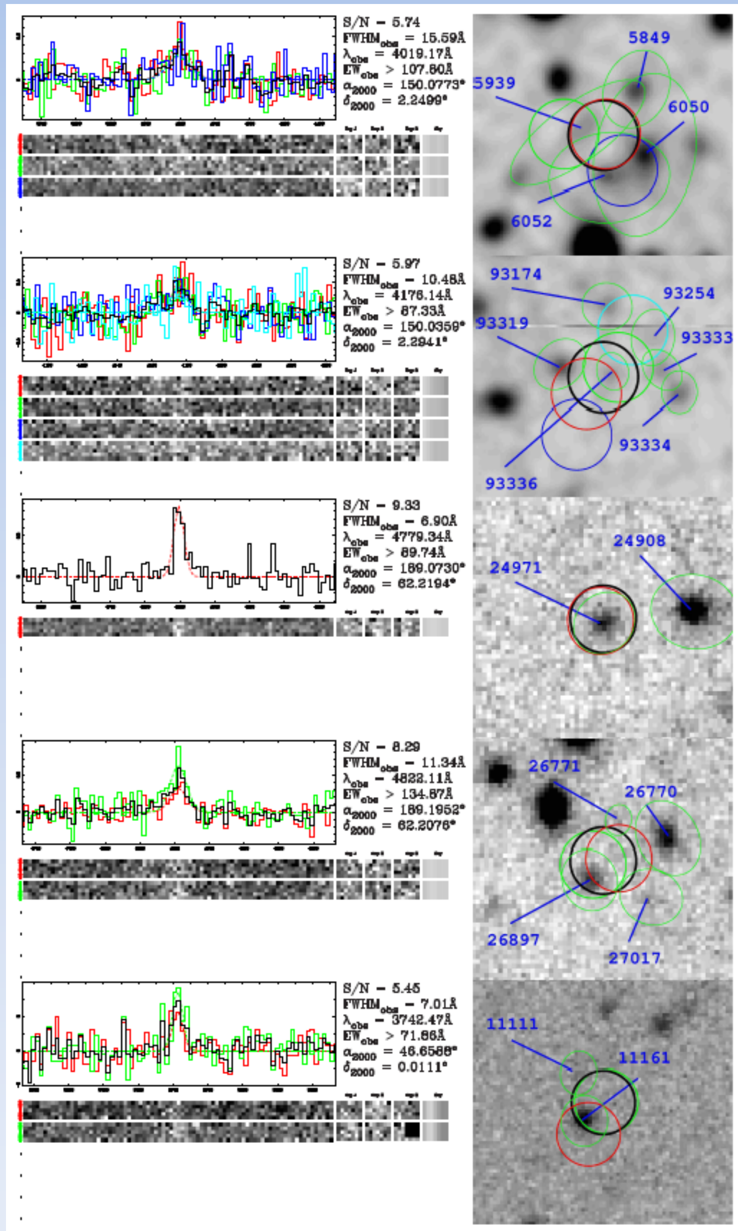


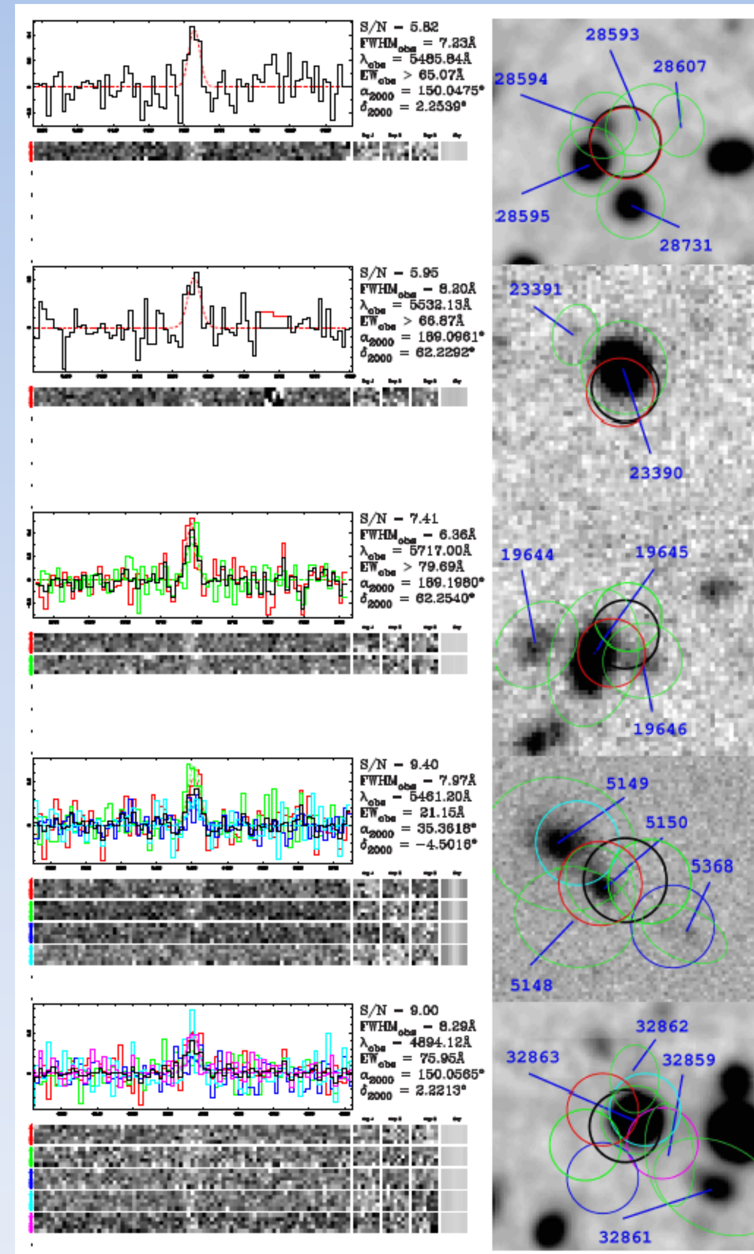


- GROW DETECTION UNTIL S/N STOPS INCREASING
- POSITION GIVEN BY FIRST MOMENT OF LIGHT DISTRIBUTION

LYMAN ALPHA EMITTERS

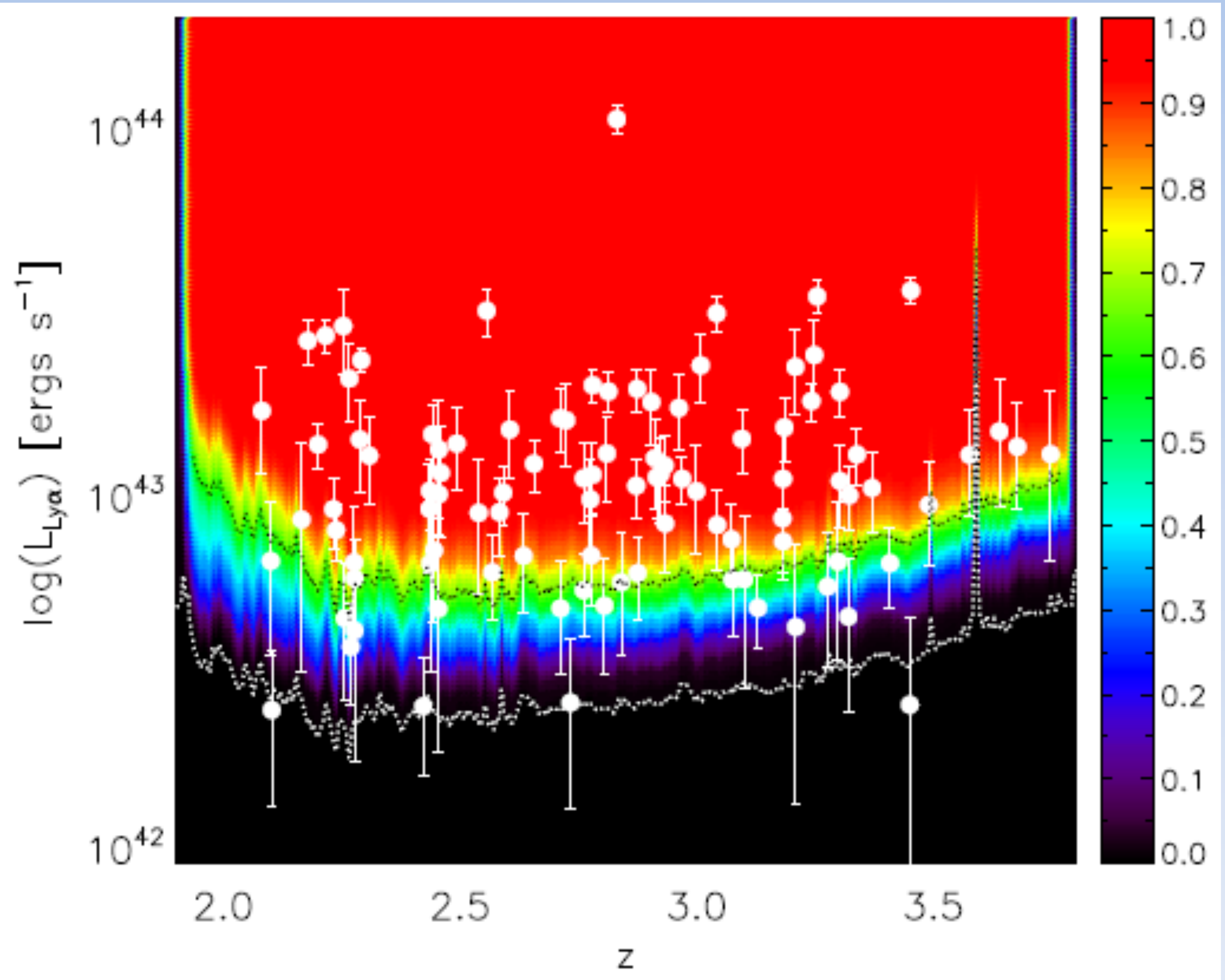
Low-z GALAXIES





Adams et al. 2010

98 LAEs at 2<z<4 !!!



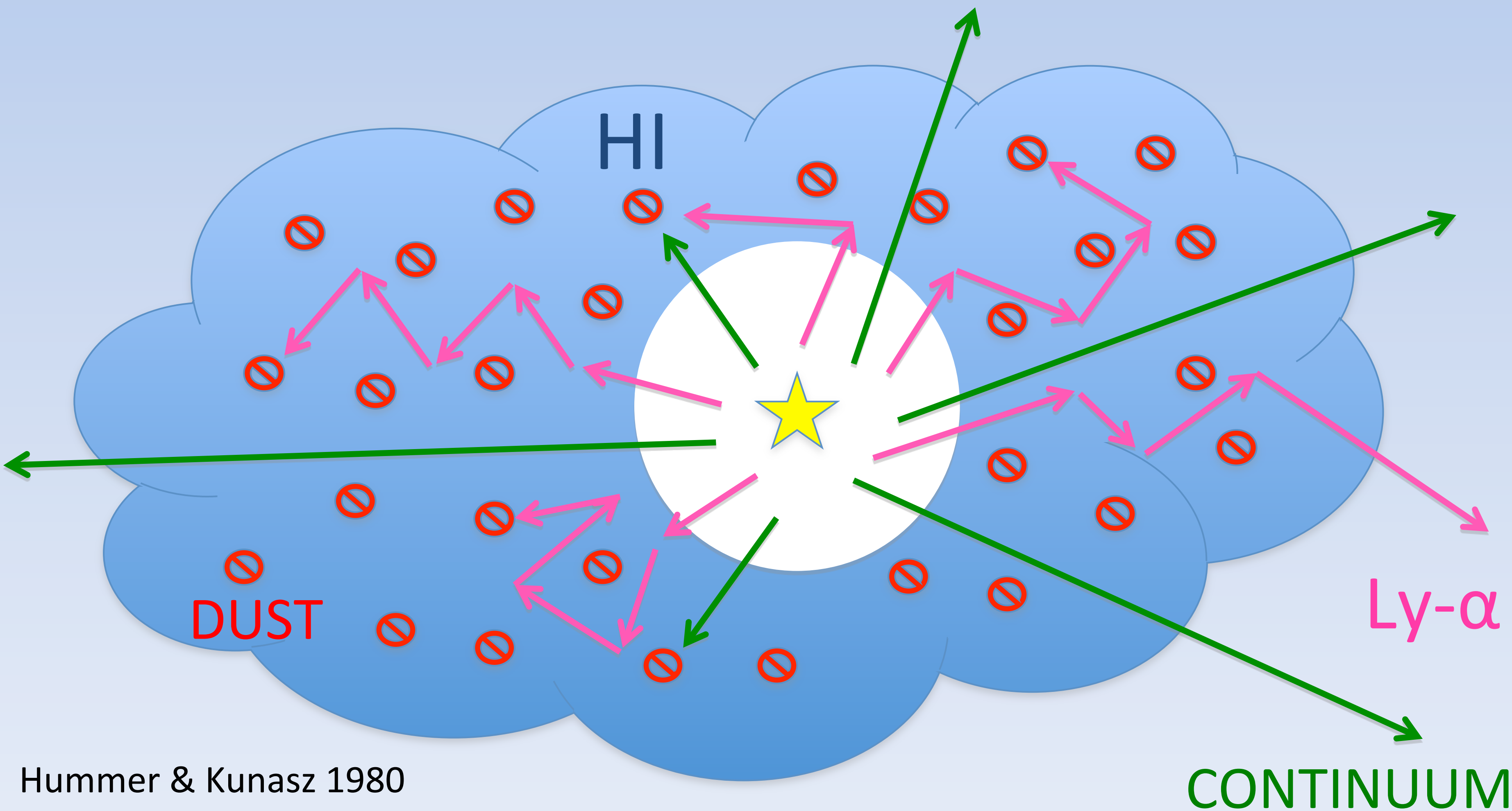
and ~300 low-z galaxies and AGN

THE ESCAPE OF Lyα PHOTONS

- IMPORTANCE:
  - ISM Structure and Kinematics
  - IGM Structure and Kinematics
  - LAEs are young galaxies (~100 Myr)
  - Constraint Epoch of Reionization

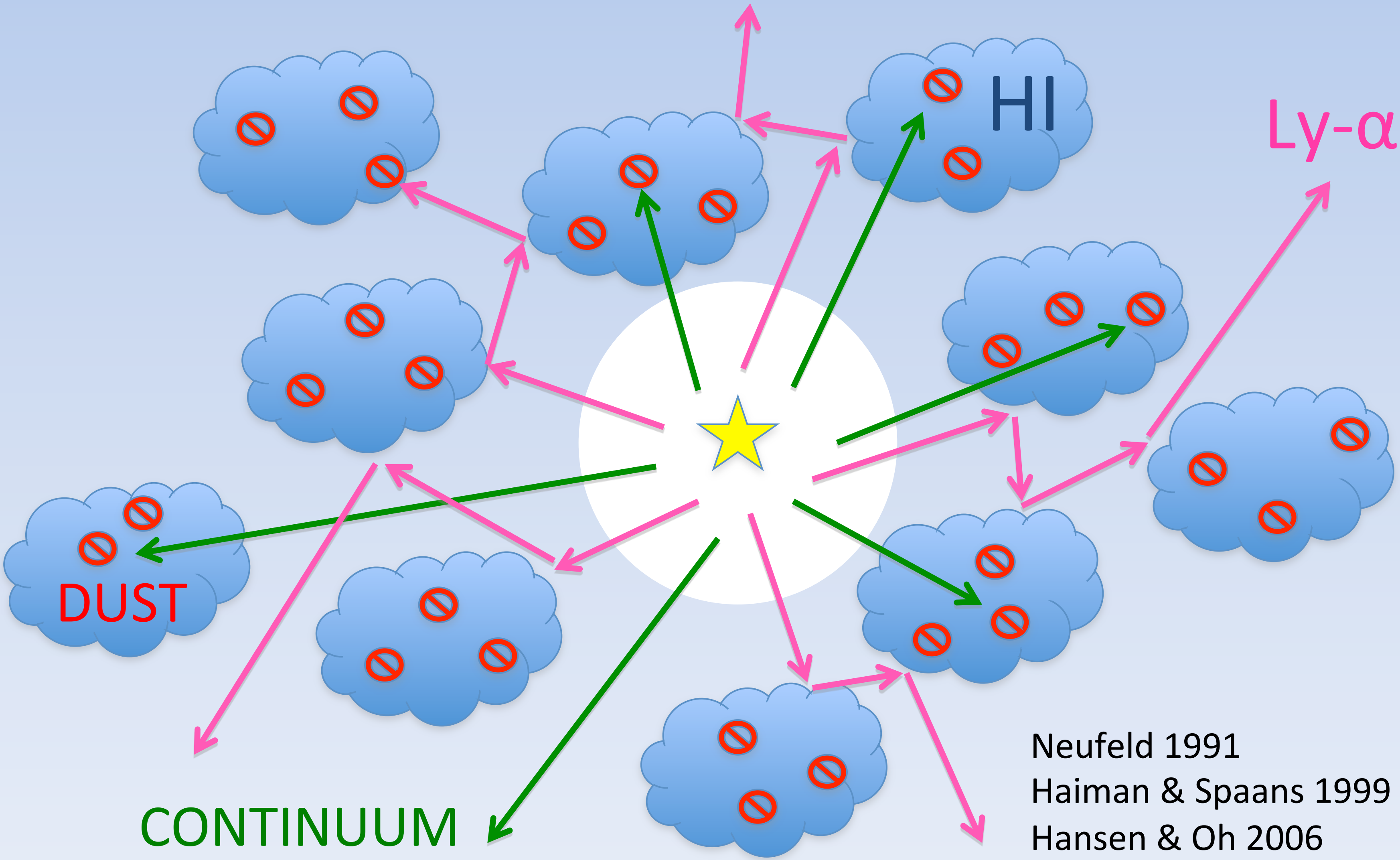
TWO EXTREMES

1) HOMOGENEOUS ISM: $\tau_{Ly\alpha} > \tau_{UV}$



Hummer & Kunasz 1980
Charlot & Fall 1993

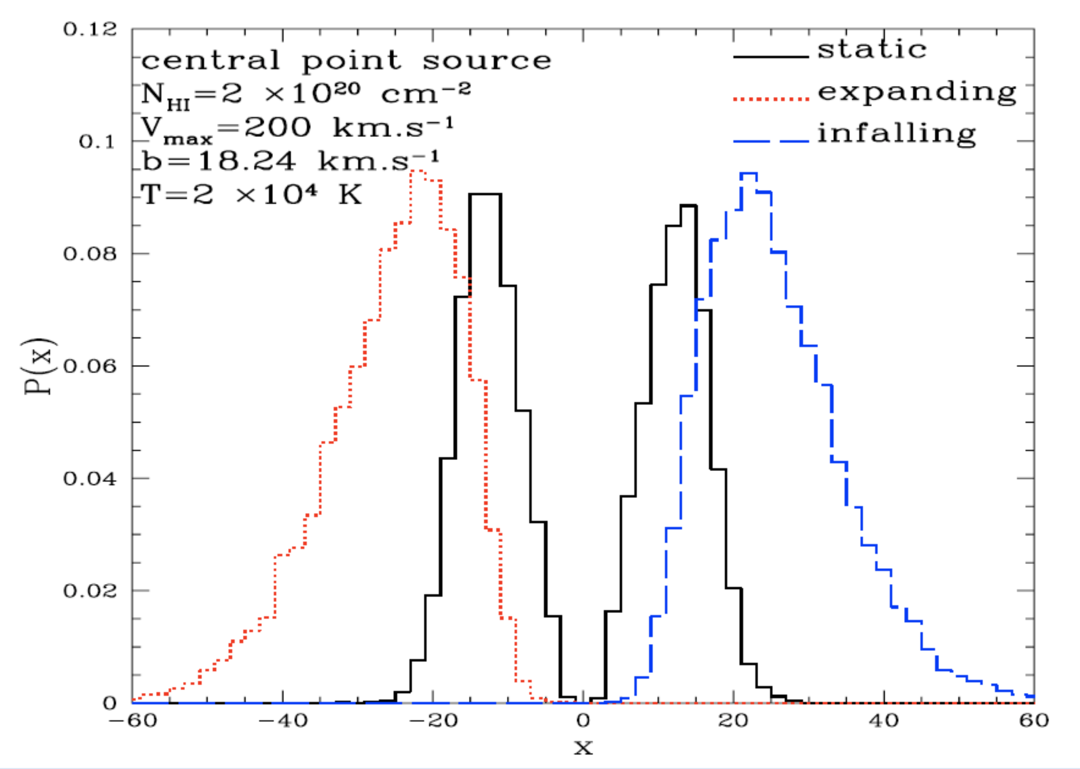
TWO EXTREMES:
2) CLUMPY ISM: $\tau_{Ly\alpha} < \tau_{UV}$



Neufeld 1991
Haiman & Spaans 1999
Hansen & Oh 2006

KINEMATICS

HI kinematics shift photon frequency with respect to resonance frequency



Verhamme et al. 2006

See also: Dijkstra et al. 2006, 2007, Verhamme et al. 2008, Adams et al. 2009. Laursen et al. 2010, Zheng et al. 2010

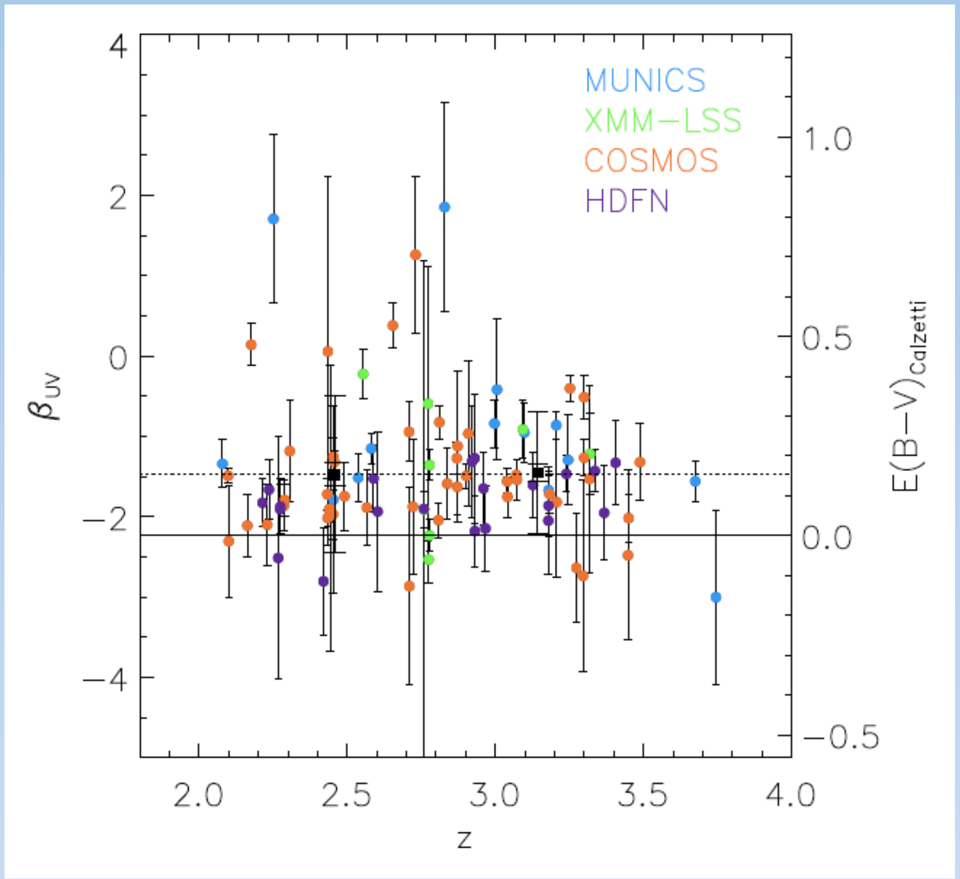
Relation between DUST and Lyα ESCAPE FRACTION

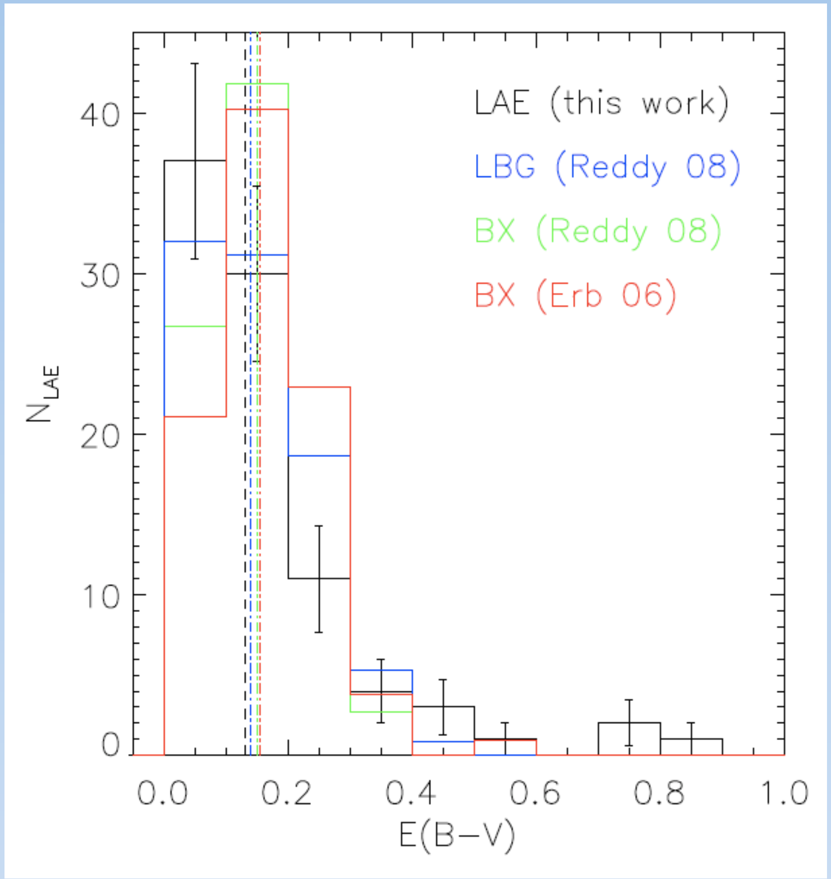
↕

ISM structure and kinematics

- For our sample of LAEs measure:
  - Dust Content (UV slope)
  - Lyα Escape Fraction (Lyα and UV Luminosities)
  - See how they relate
  - Study how they evolve

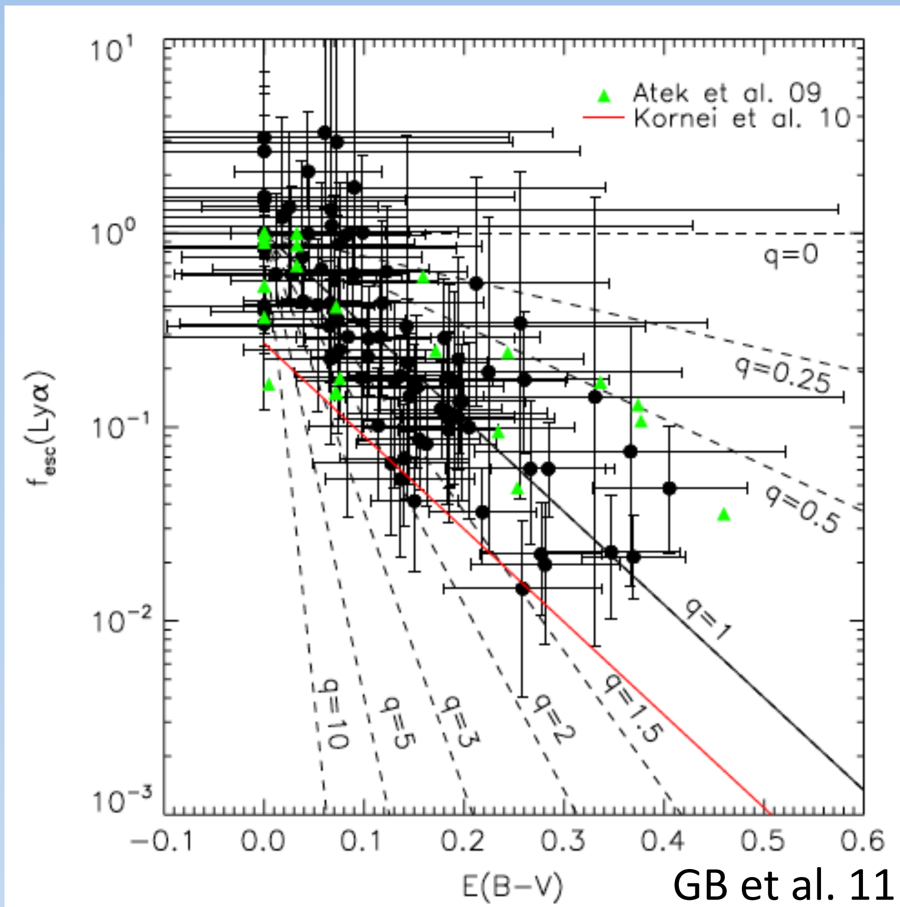
DUST EXTINCTION





GB et al. 11

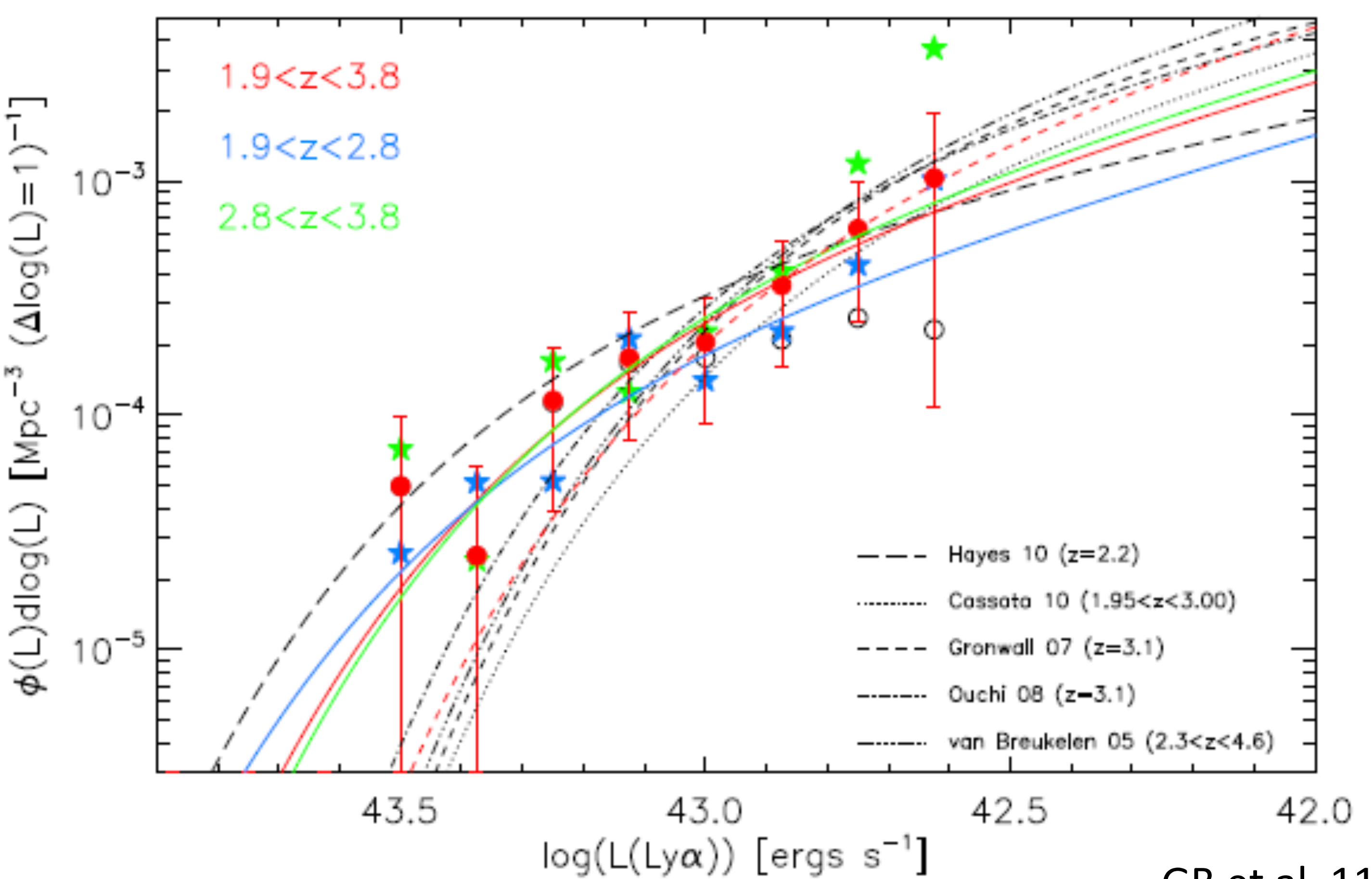
Dust and the Escape of Lyα



$$q = (\tau_{Ly\alpha} / \tau_{\lambda=1216})$$

- LAEs have favorable ISM configuration (structure + kinematics)
- BUT!! Only up to $\tau_{Ly\alpha} = \tau_{UV}$. No EW enhancement.
- LAEs are an upper envelope for the overall galaxy population
- No evolution from z=3 to z=0.3.

Lyα Luminosity Function



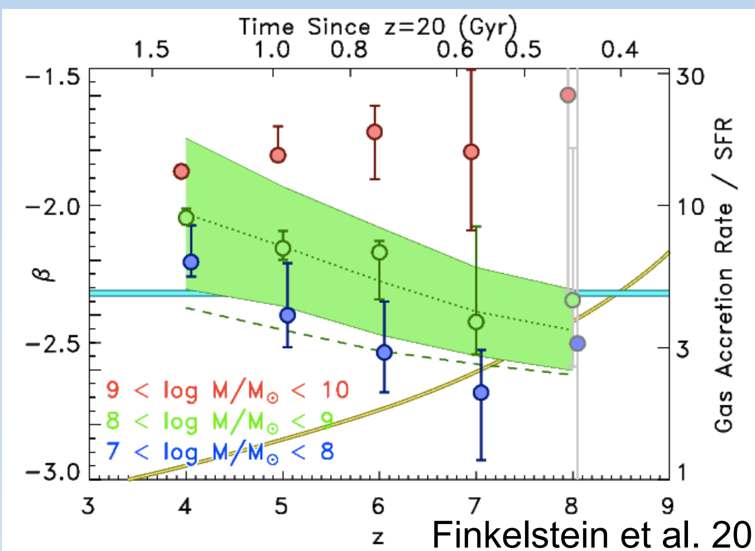
GB et al. 11

THE OVERALL GALAXY POPULATION
Lyα ESCAPE FRACTION

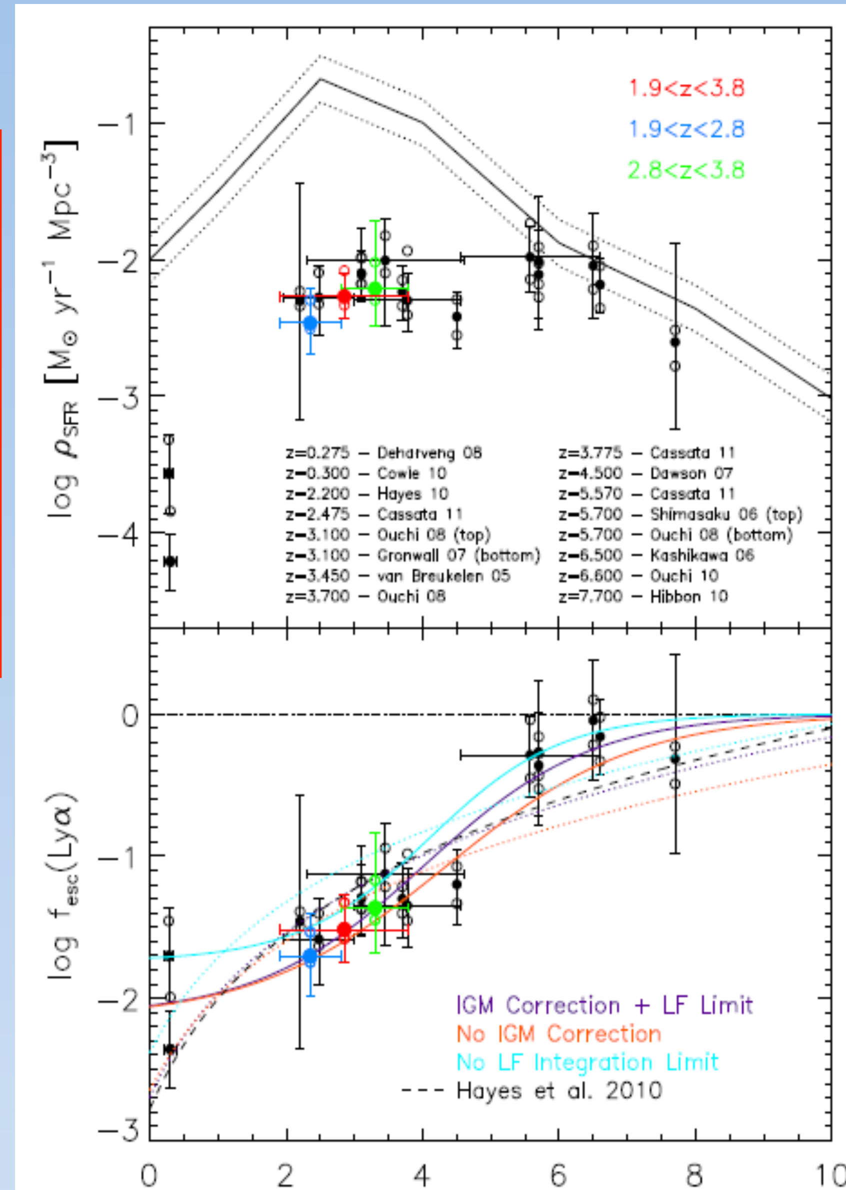
- Estimated by predicting Lyα luminosity expected given the SFR density history of the universe, and comparing to the integral of the Lyα Luminosity Function.

- Sharp transition from ~80% down to 5% between z=6 and z=3.

- $F_{Ly\alpha}$ traces dust build-up in galaxies.

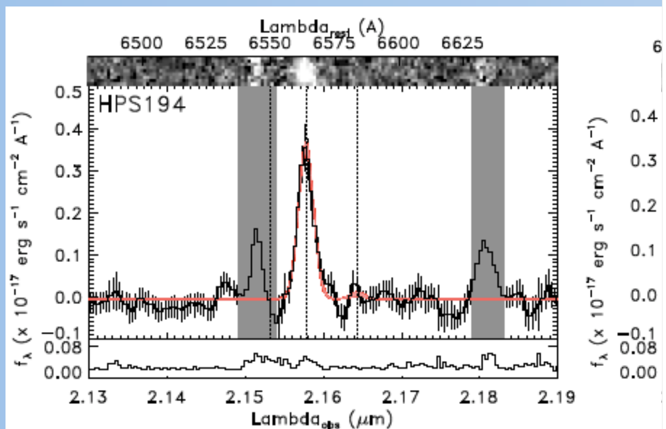


Finkelstein et al. 2011

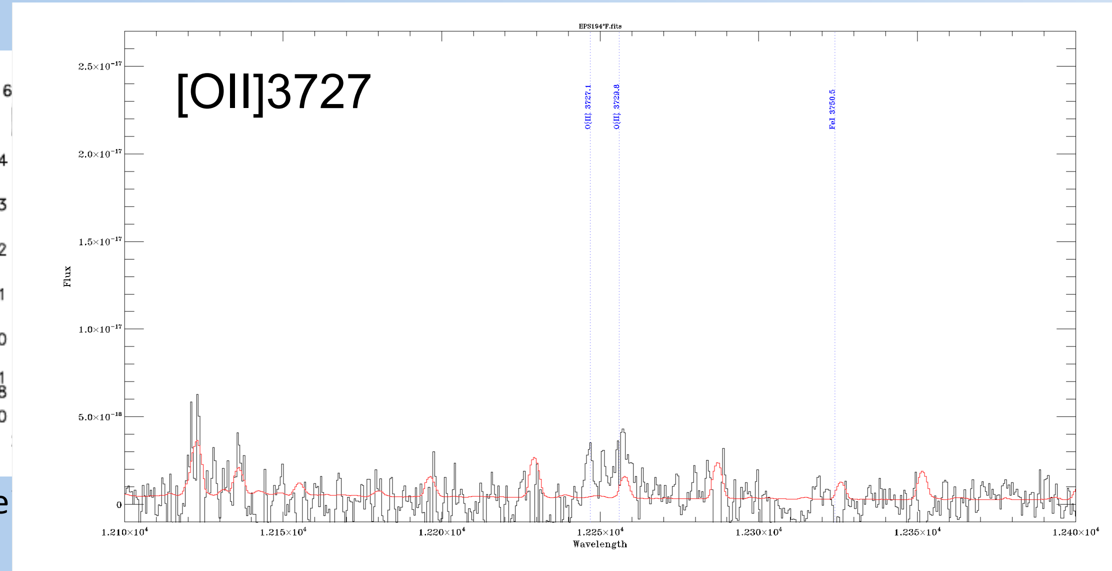


GB et al. 11

CHEMICAL ABUNDANCES AT z=2

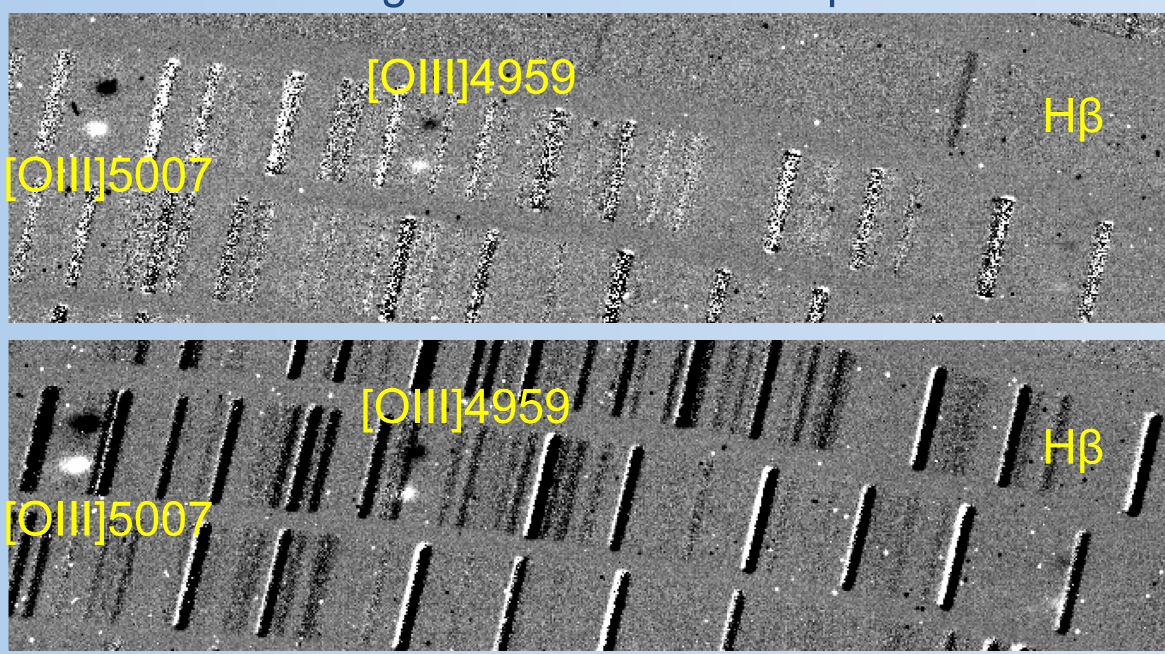


NIRSPEC Finkelste



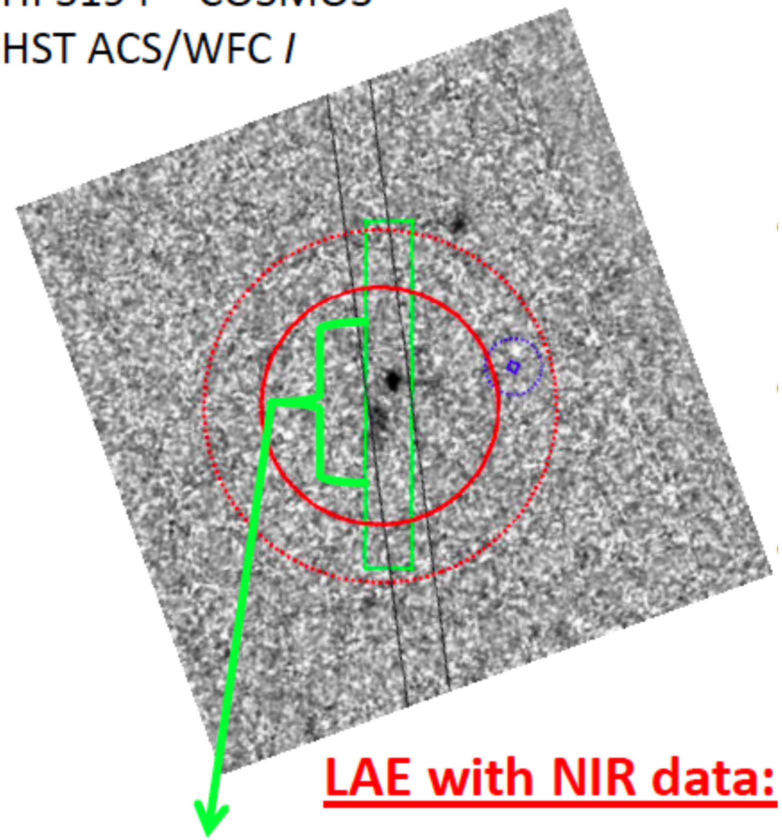
- Near-IR Follow-up:
  - NIRSPEC (Finkelstein)
  - SINFONI (Song)
  - FIRE (Blanc)
- Upper Limits in Z from N2Ha
- FIRE:
  - Multiple Lines
  - 3 bands in 1 exposure
  - R23, N2O2, N2HA
  - Decouple Z from q

Magellan FIRE Follow-up

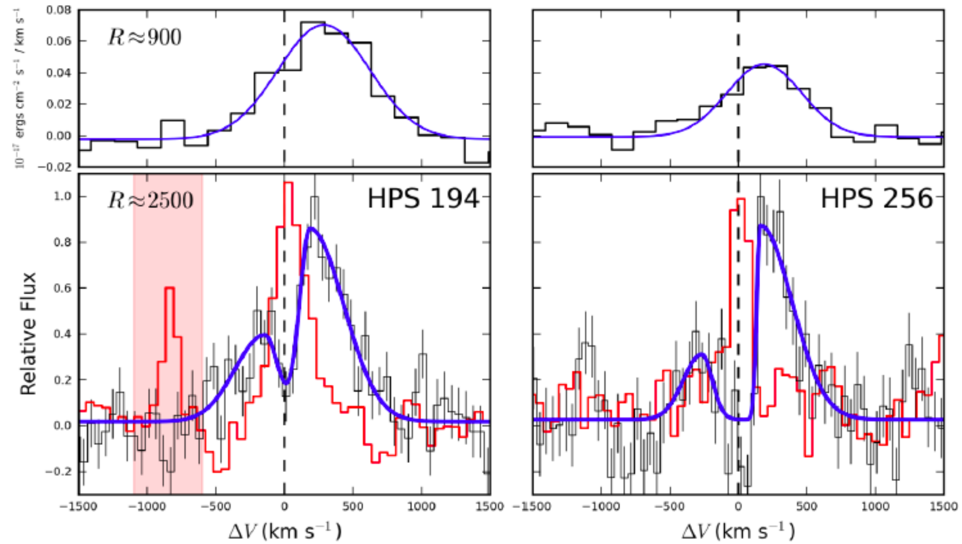


Circum Galactic Gas Kinematics

HPS194 – COSMOS
HST ACS/WFC *I*



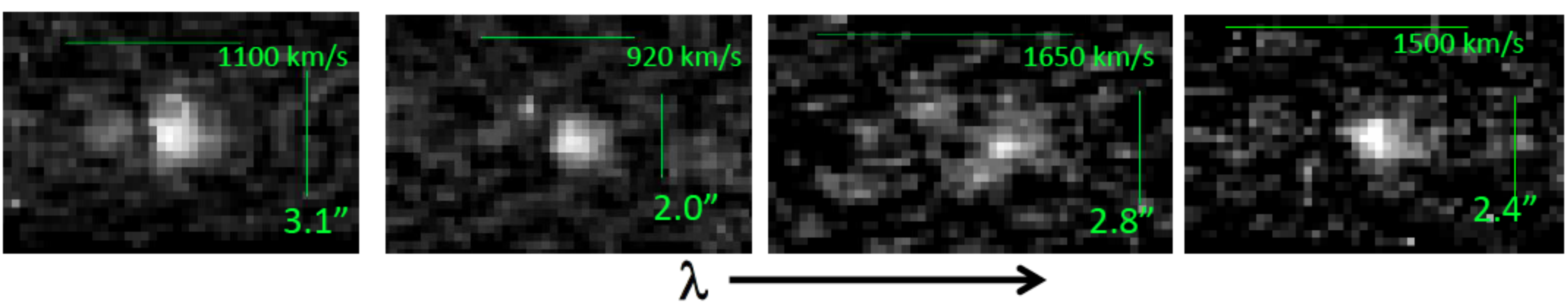
High Resolution Lyα Profiles from VIRUS-P



IMACS R=1500 Follow-up of 33 LAEs
Chonis, Blanc et al. (in prep.)

LAE with NIR data:

HPS194 **HPS256** **HPS251** **HPS306**



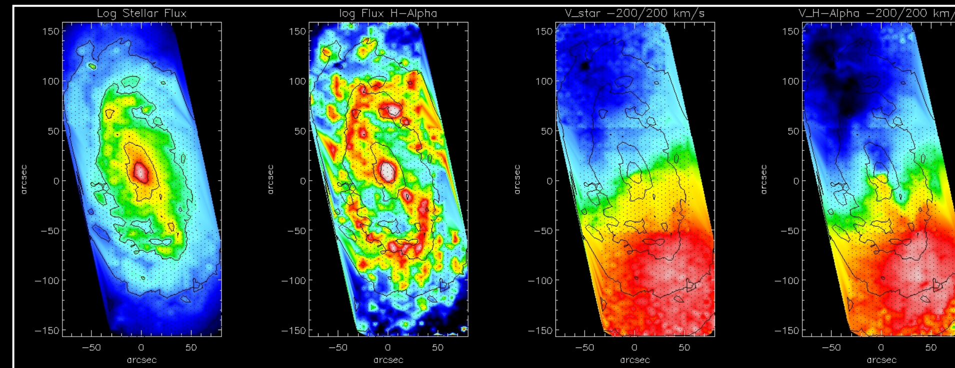
Part I CONCLUSIONS

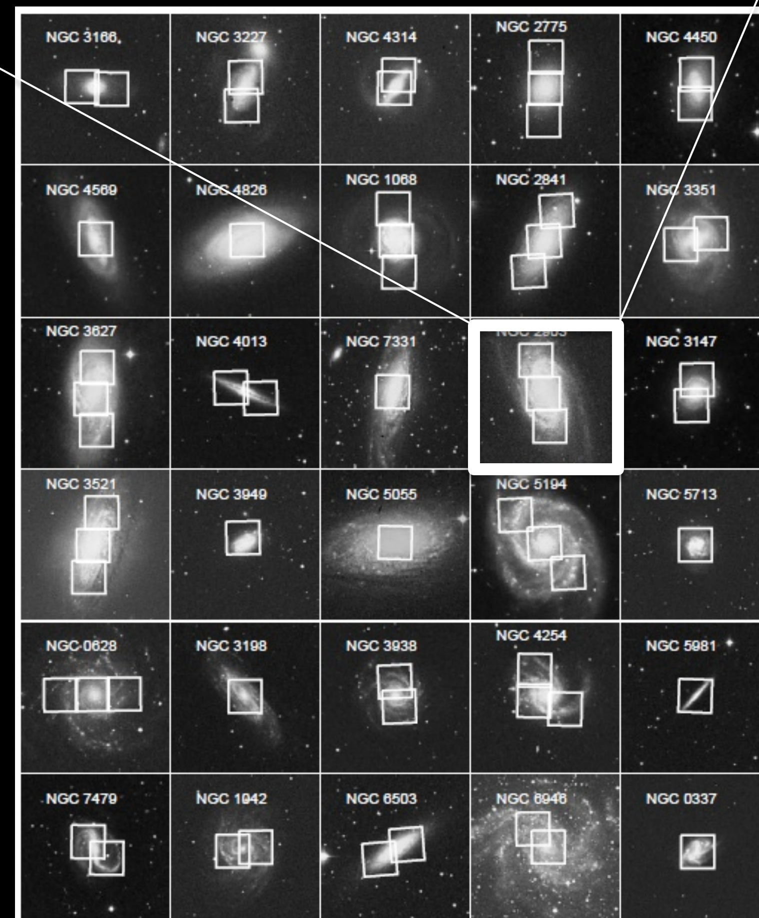
- HETDEX Pilot Survey provides proof of concept for HETDEX.
- Wide-field IFUs are ideal to detect emission line galaxies over large volumes (e.g. VIRUS, MUSE)
- Some combination of ISM geometry and kinematics makes Lyα and continuum photons to suffer similar amounts of dust extinction.
- The overall galaxy population f_{esc}(Lyα) falls from 80% to 5% from z=6 to z=3, tracing the build-up of dust in the ISM of galaxies.
- Ongoing HPS Follow-up Programs with Magellan:
  - FIRE: Chemical Abundances
  - IMACS: Kinematics of the Circum-Galactic Medium

VENGA

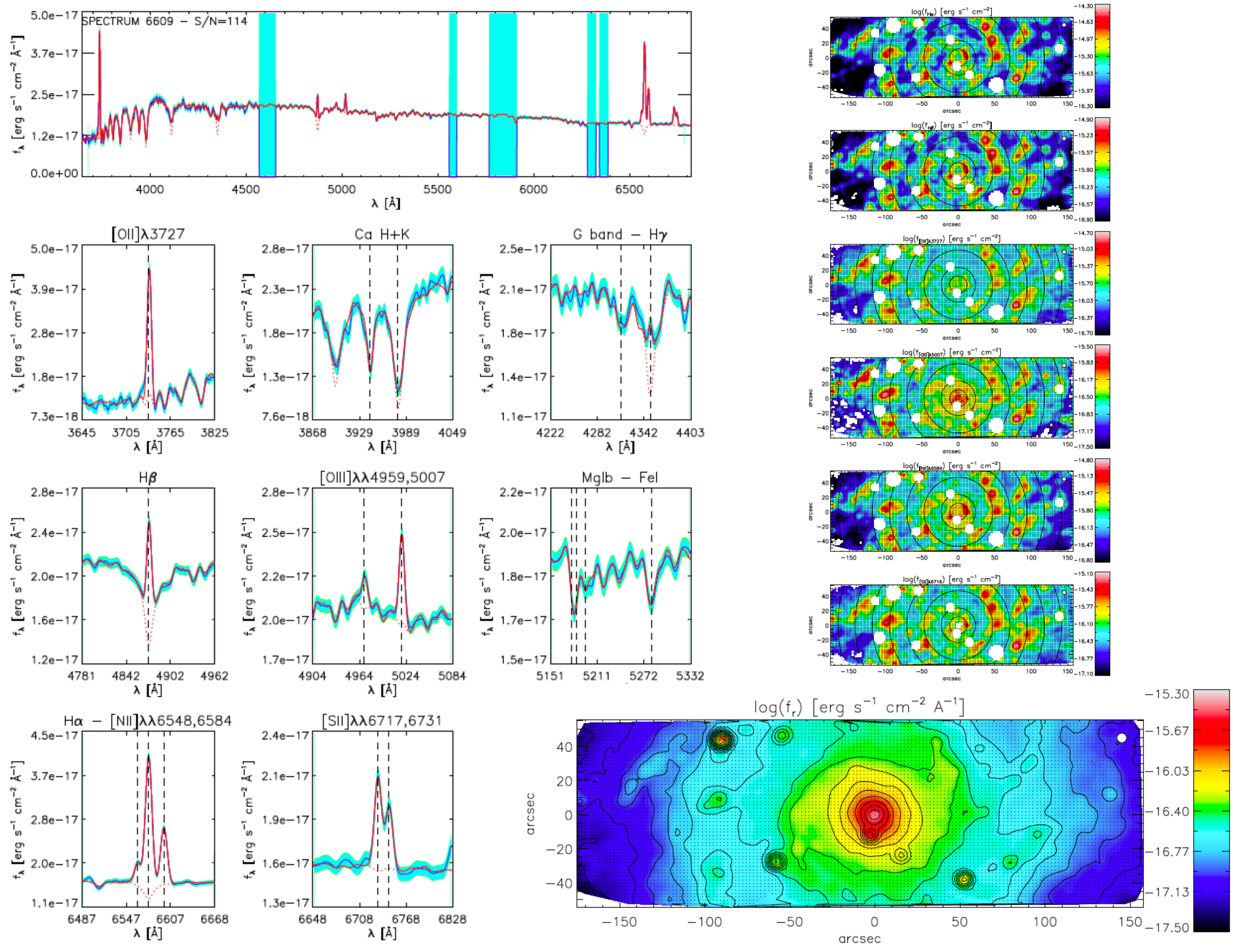
VIRUS-P EXPLORATION OF NEARBY GALAXIES

NGC 2903





- 30 Nearby Spiral Galaxies
- Wealth of Multi-wavelength Data
- 60 1.7’x1.7’ VIRUS-P Pointings
- ~ 44,000 spectra: 3600 Å – 6850 Å
- Spectral Resolution: 5 Å (120 km/s)
- Coverage ~ 0.7 R_{25}
- Median S/N=40 per fiber
- High Resolution VIRUS-W (25 km/s)


SPECTRUM 6609 – S/N=114
f_λ [erg s^{-1} cm^{-2} Å^{-1}]
λ [Å]
[OII]λ3727
Ca H+K
G band – Hγ
Hβ
[OIII]λλ4959,5007
MgIb – FeI
Hα – [NII]λλ6548,6584
[SII]λλ6717,6731
log($f_{H\alpha}$) [erg s^{-1} cm^{-2}]
log($f_{H\beta}$) [erg s^{-1} cm^{-2}]
log($f_{[OII]\lambda3727}$) [erg s^{-1} cm^{-2}]
log($f_{[OIII]\lambda5007}$) [erg s^{-1} cm^{-2}]
log($f_{[NII]\lambda6584}$) [erg s^{-1} cm^{-2}]
log($f_{[SII]\lambda6716}$) [erg s^{-1} cm^{-2}]
log(f_r) [erg s^{-1} cm^{-2} A^{-1}]
arcsec

The Spatially Resolved SFL

What sets the SFR across disks?

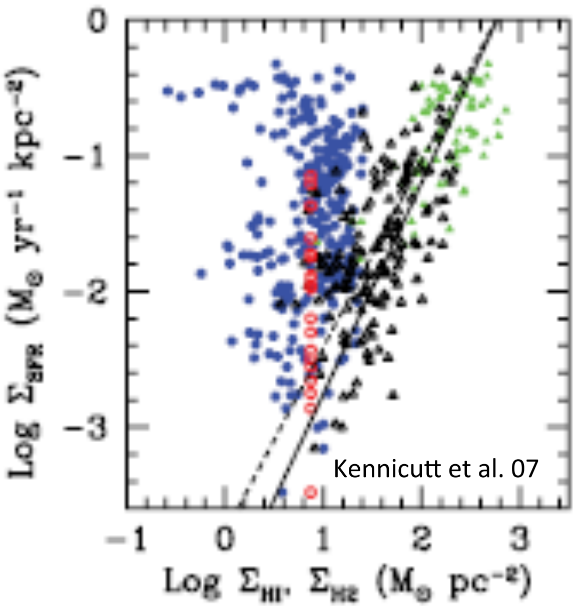
– Molecular gas availability: Star Formation “Law”

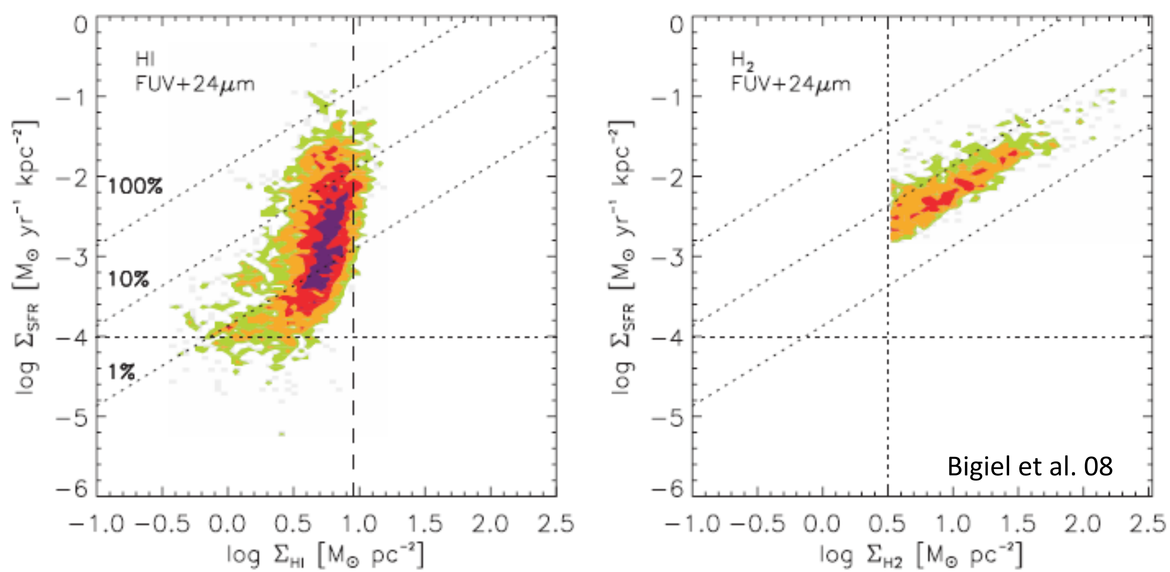
$$\frac{\Sigma_{\rm SFR}}{1\ M_\odot\ {\rm yr}^{-1}\ {\rm kpc}^{-2}} = A\left(\frac{\Sigma_{\rm gas}}{100\ M_\odot\ {\rm pc}^{-2}}\right)^N \boxed{\times\ 10^{\mathcal{N}(0,\epsilon)}}$$

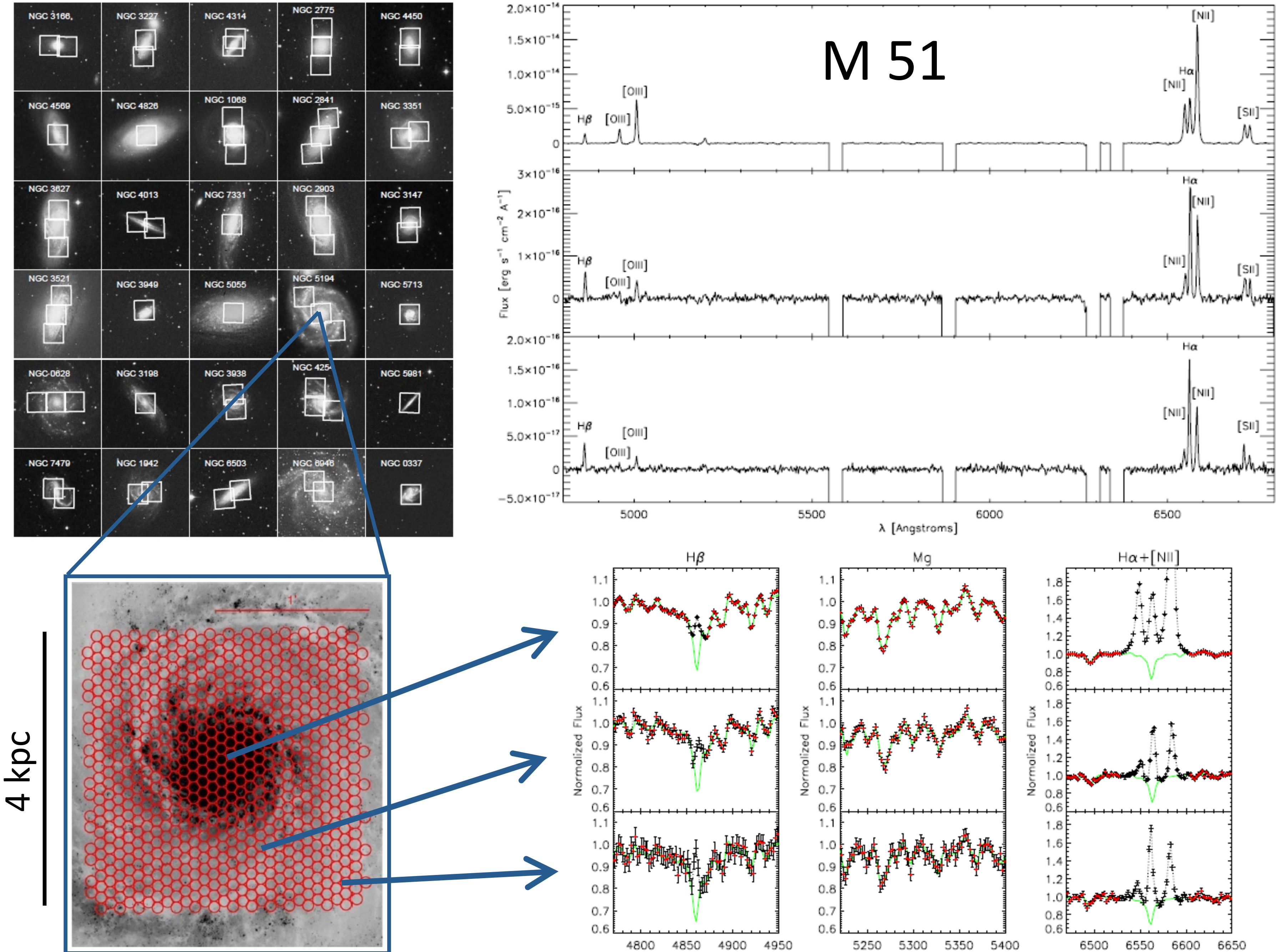
– Constraint slope in the typical spiral galaxy ISM regime.

– Quantify intrinsic scatter in SFL, and its origin.

Measure robust SFRs using IFU spectroscopy.

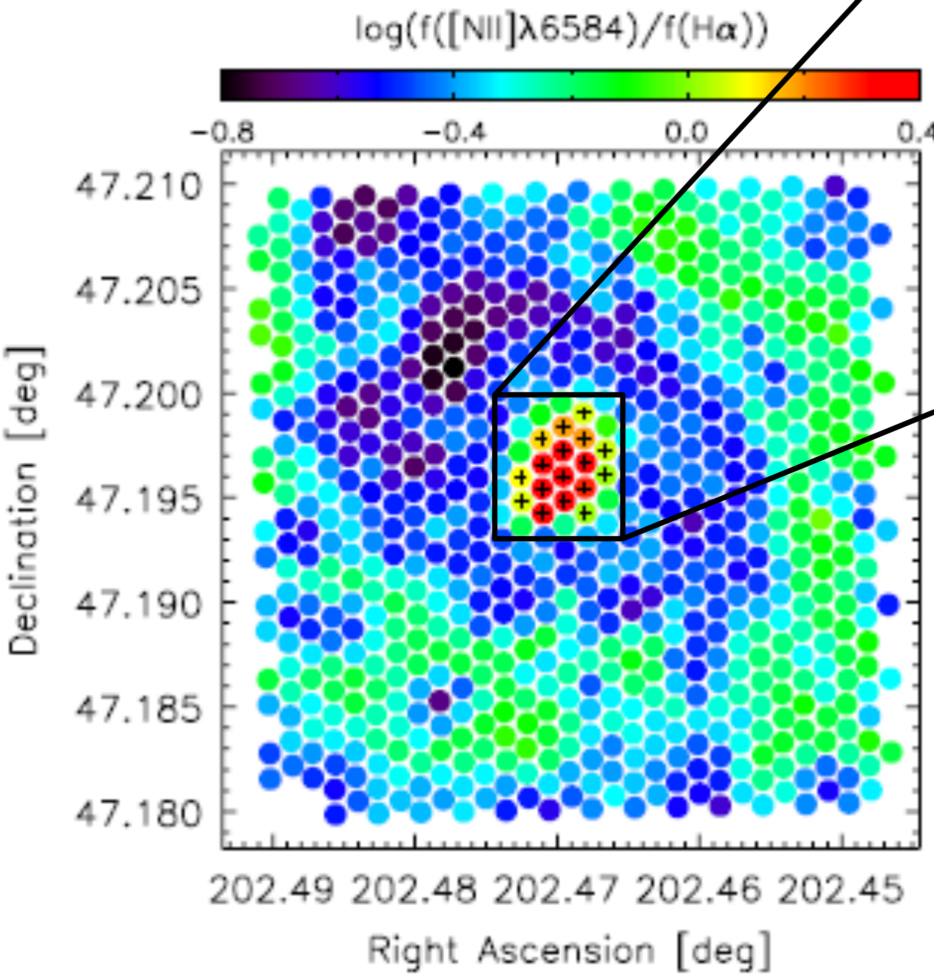


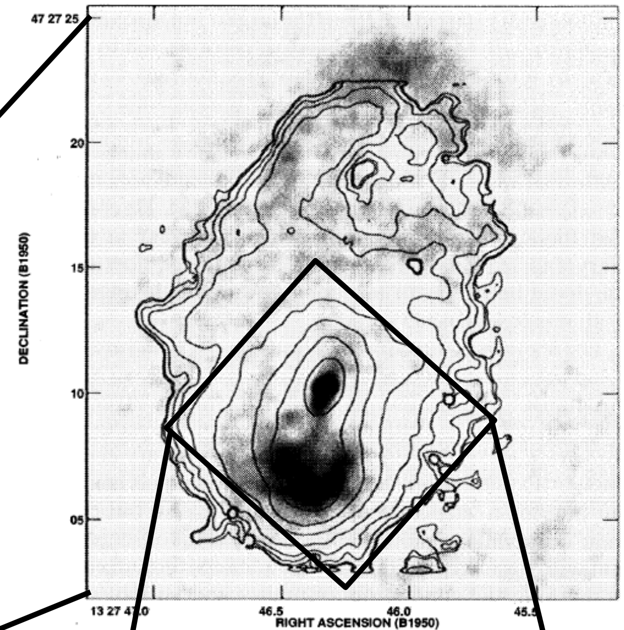




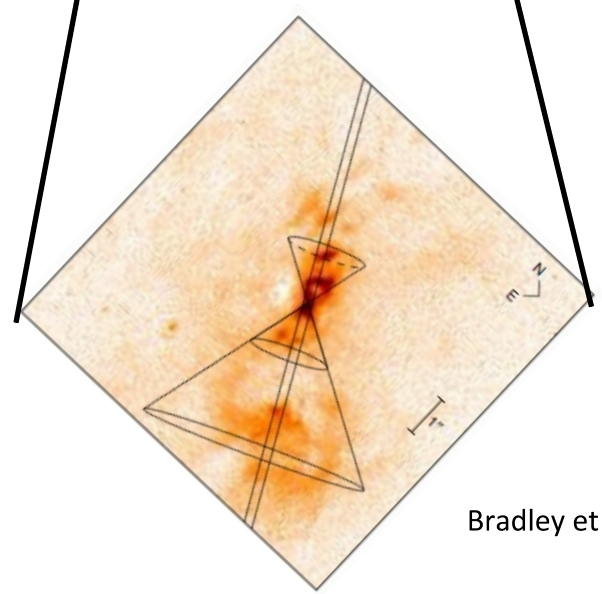
NGC 3166
NGC 3227
NGC 4314
NGC 2775
NGC 4450
NGC 4569
NGC 4826
NGC 1068
NGC 2841
NGC 3351
NGC 3627
NGC 4013
NGC 7331
NGC 2903
NGC 3147
NGC 3521
NGC 3949
NGC 5055
NGC 5194
NGC 5713
NGC 0628
NGC 3198
NGC 3938
NGC 5981
NGC 7479
NGC 1042
NGC 6503
NGC 6946
NGC 0337
M 51
Hβ
[OIII]
Hα
[NII]
[SII]
Flux [erg s^{-1} cm^{-2} A^{-1}]
λ [Angstroms]
4 kpc
1'
Hβ
Mg
Hα+[NII]
Normalized Flux

CENTRAL AGN



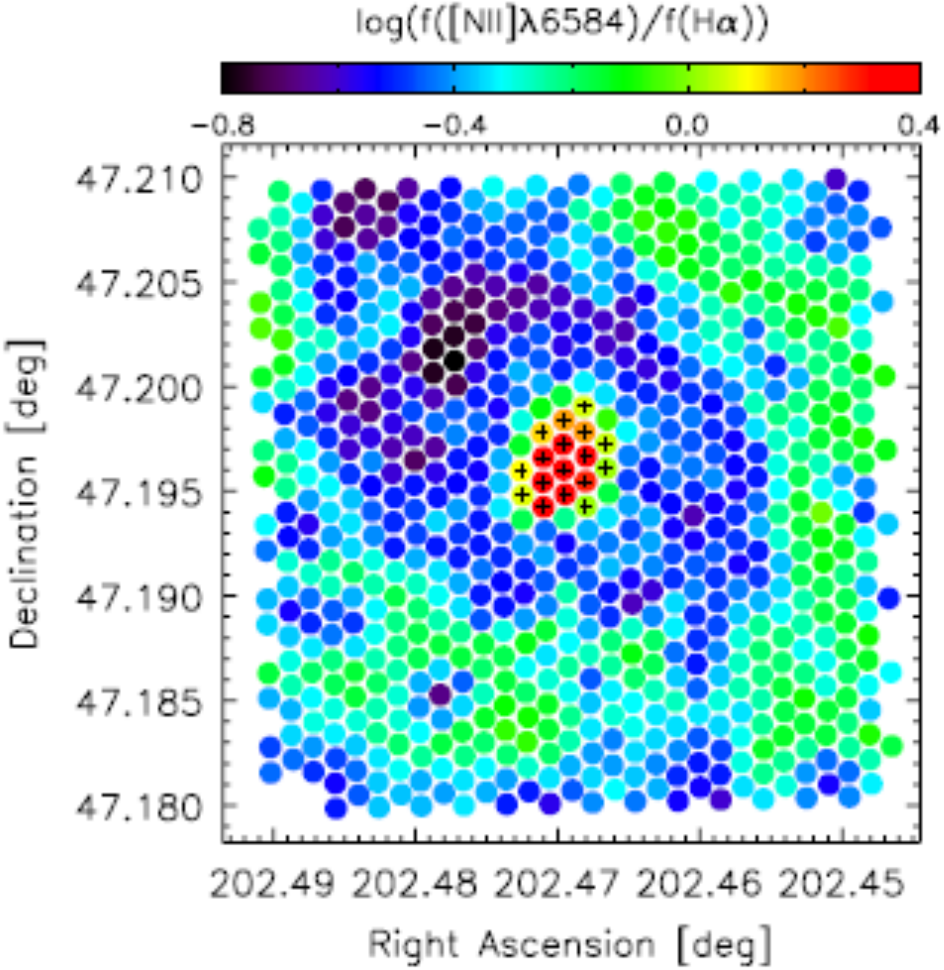


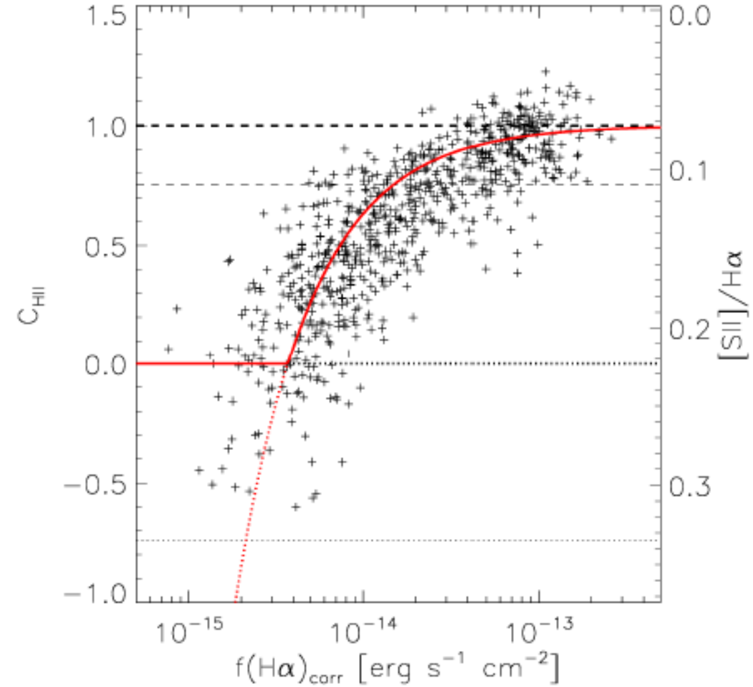
Crane et al. 1992

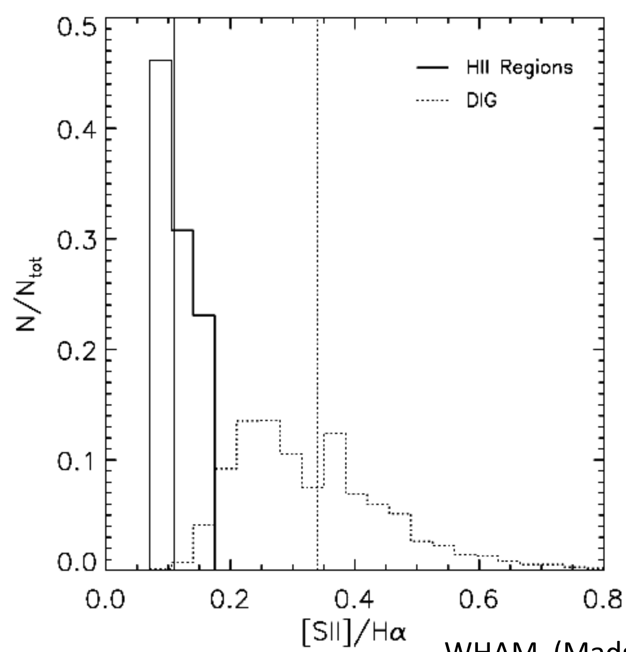


Bradley et al. 2004

DIFFUSE IONIZED GAS



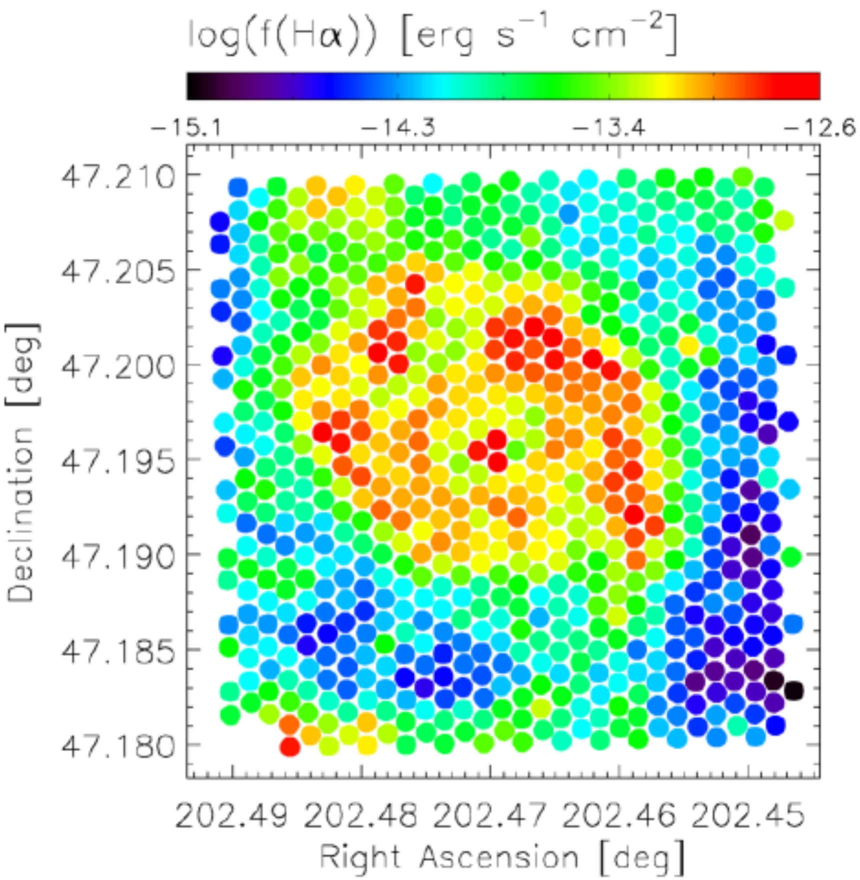




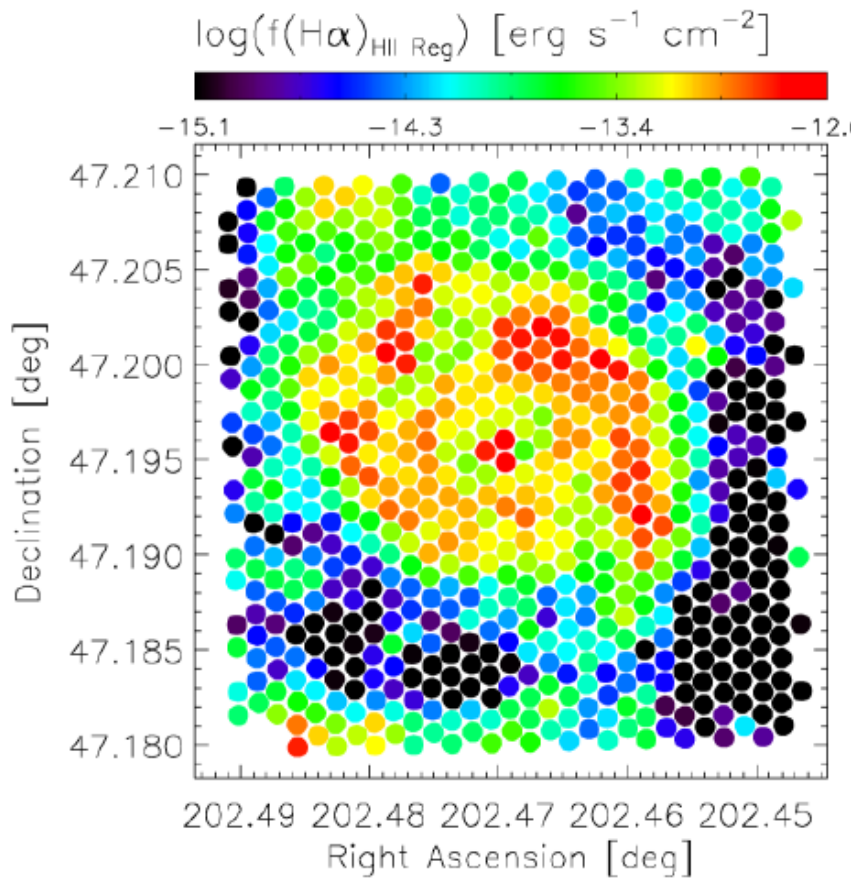
WHAM (Madsen et al. 2006)

- DIG accounts for 11% of total Hα luminosity

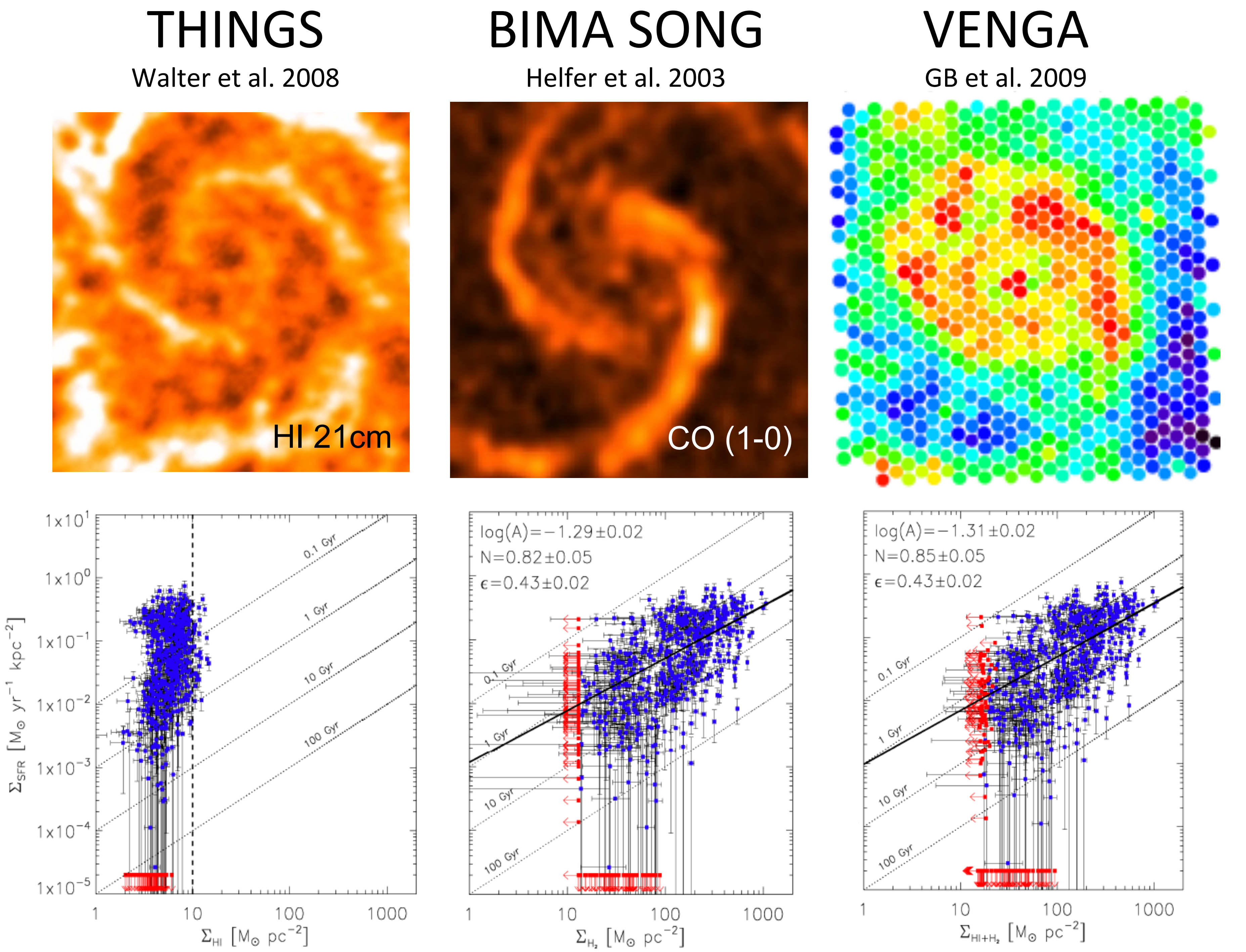
LOCALIZED STAR FORMATION Hα



HII Regions + DIG



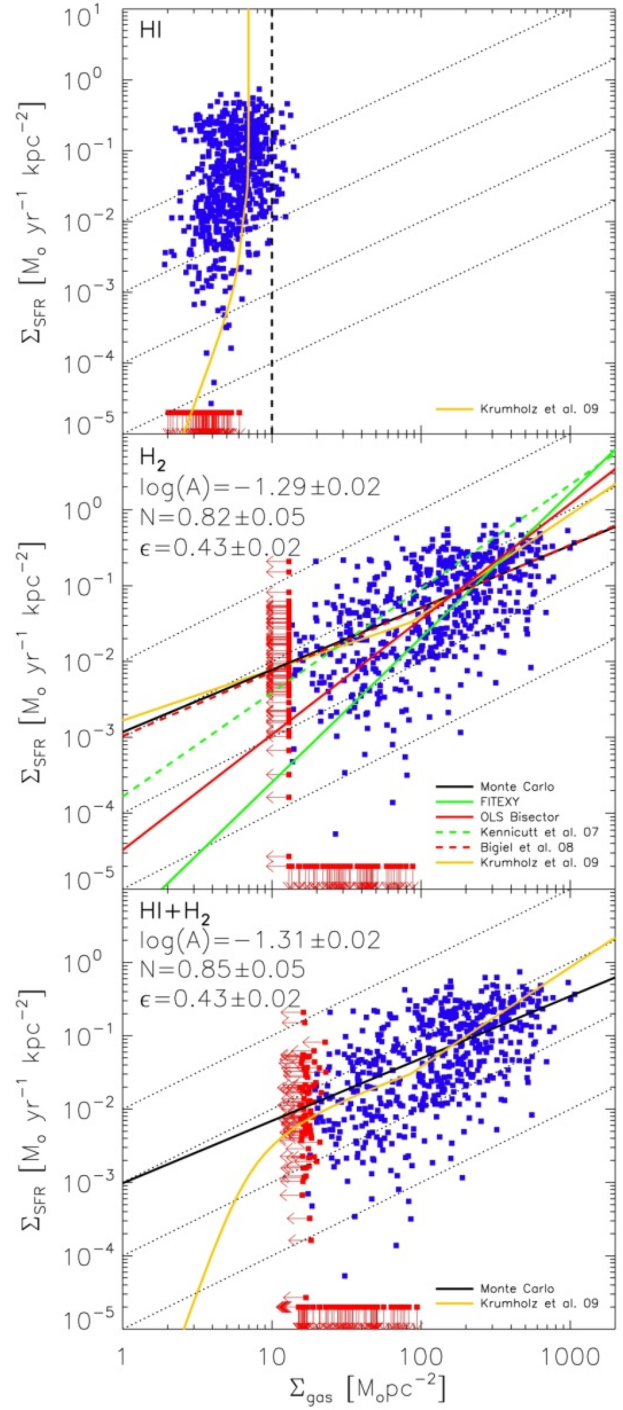
HII Regions Only



THINGS
Walter et al. 2008
BIMA SONG
Helfer et al. 2003
VENGA
GB et al. 2009
HI 21cm
CO (1-0)
log(A)=−1.29±0.02
N=0.82±0.05
ϵ=0.43±0.02
log(A)=−1.31±0.02
N=0.85±0.05
ϵ=0.43±0.02
0.1 Gyr
1 Gyr
10 Gyr
100 Gyr
Σ_{SFR} [$M_\odot$ yr^{-1} kpc^{-2}]
Σ_{HI} [$M_\odot$ pc^{-2}]
Σ_{H_2} [$M_\odot$ pc^{-2}]
Σ_{HI+H_2} [$M_\odot$ pc^{-2}]

RESULTS

- 735 regions (D=170 pc) in the central 4.1 × 4.1 kpc^2
- Lack of correlation with the atomic gas surface density, which saturates around 10 $M_\odot pc^{-2}$.
- Clear correlation with the molecular gas surface density, which drives the total gas SFL
- Monte Carlo Fitting of total gas SFL parameters:
  - N = 0.85 ± 0.05
  - A = $10^{-1.31\pm0.02}$ = Depletion timescales of 2 Gyr
  - ε = 0.43 ± 0.02 dex.
- Consistent with a roughly constant SFE in GMCs, which is almost independent of the molecular gas surface density. NOT consistent with a N~1.5 slope.
- Good agreement with the theoretical SFL model of Krumholz et al. (2009).



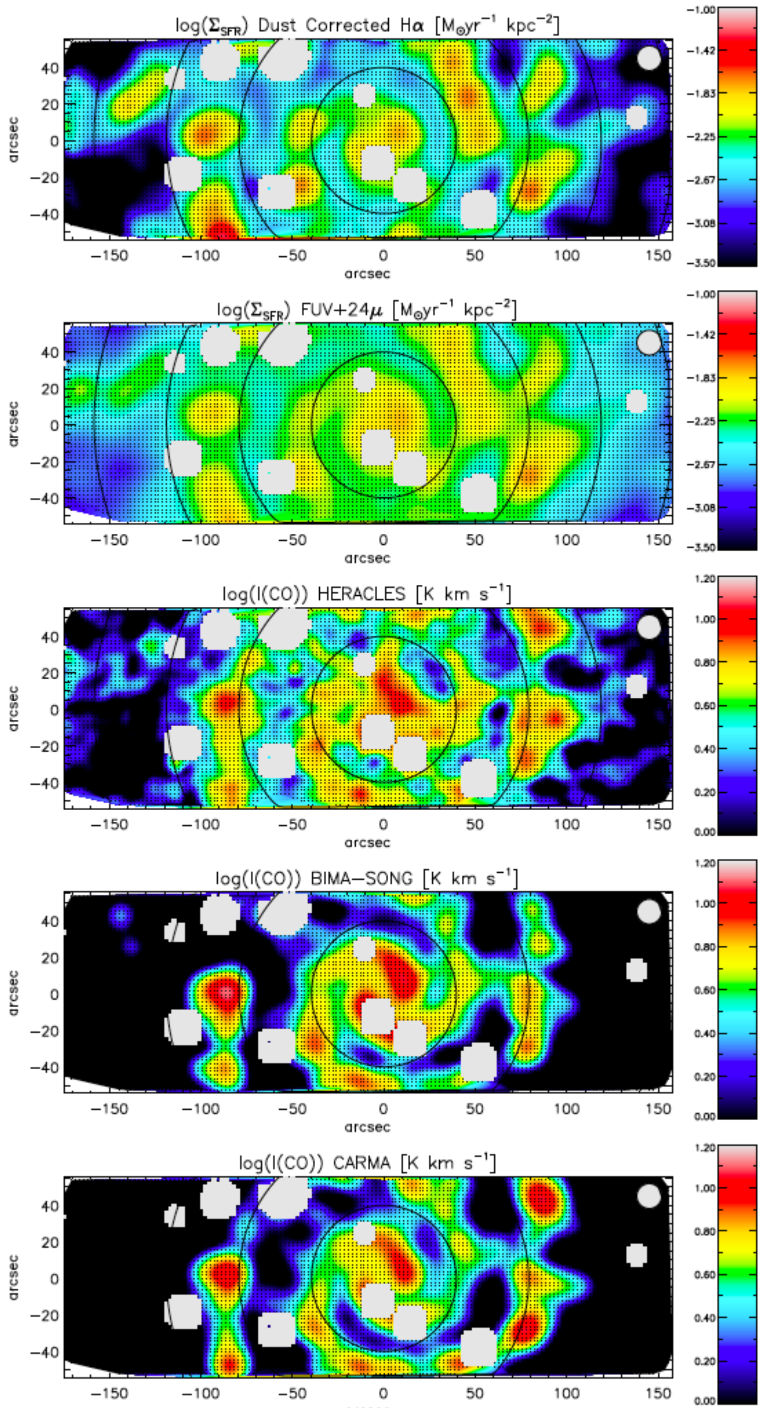
The X_{CO} Factor in NGC 628

- H_2 transitions do not get excited in cold gas in GMCs
- Typically use CO to trace molecular gas
- X_{co} well measured in the solar neighborhood

$$X_{co}=(2\text{-}4)\times10^{20}\ \text{cm}^{-1}\ (\text{K km s}^{-1})^{-1}$$

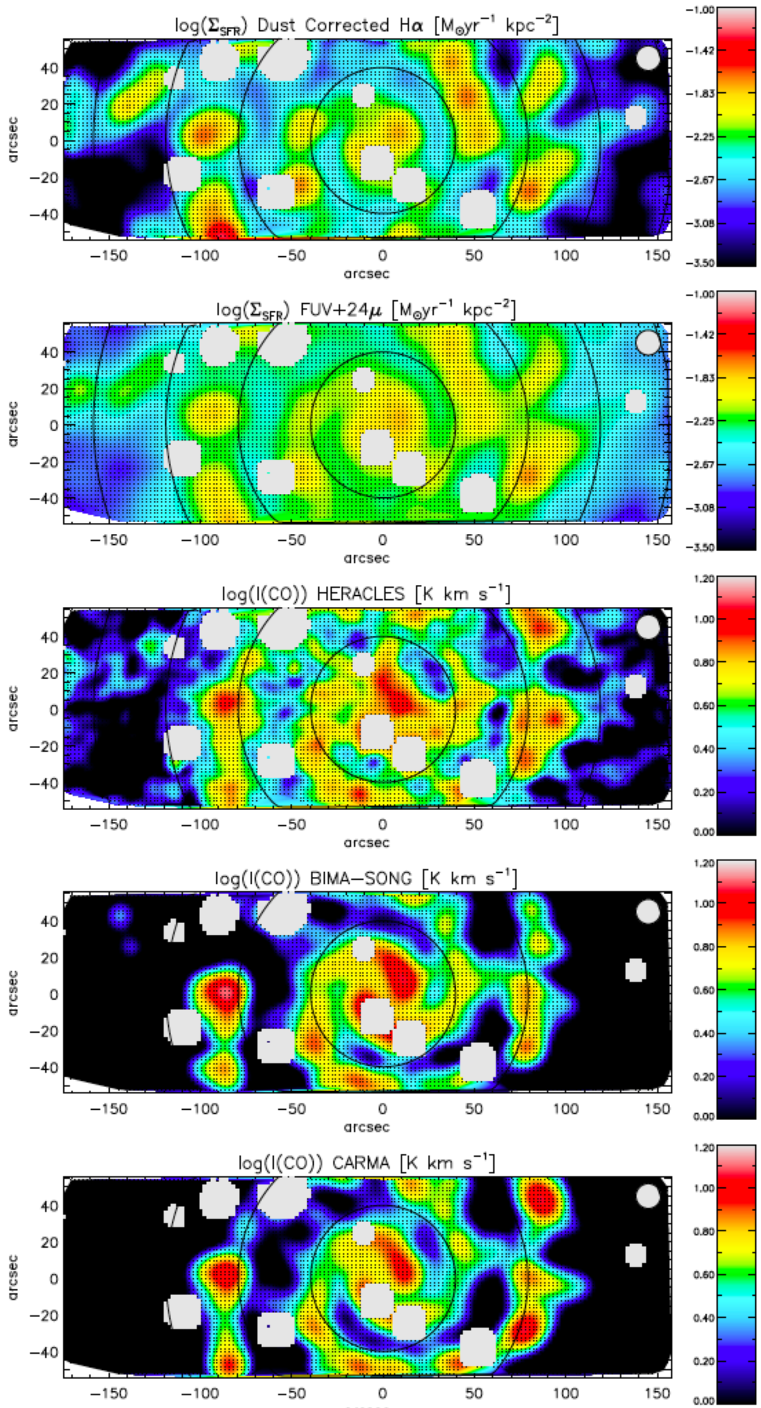
- Can we simply apply this value everywhere?

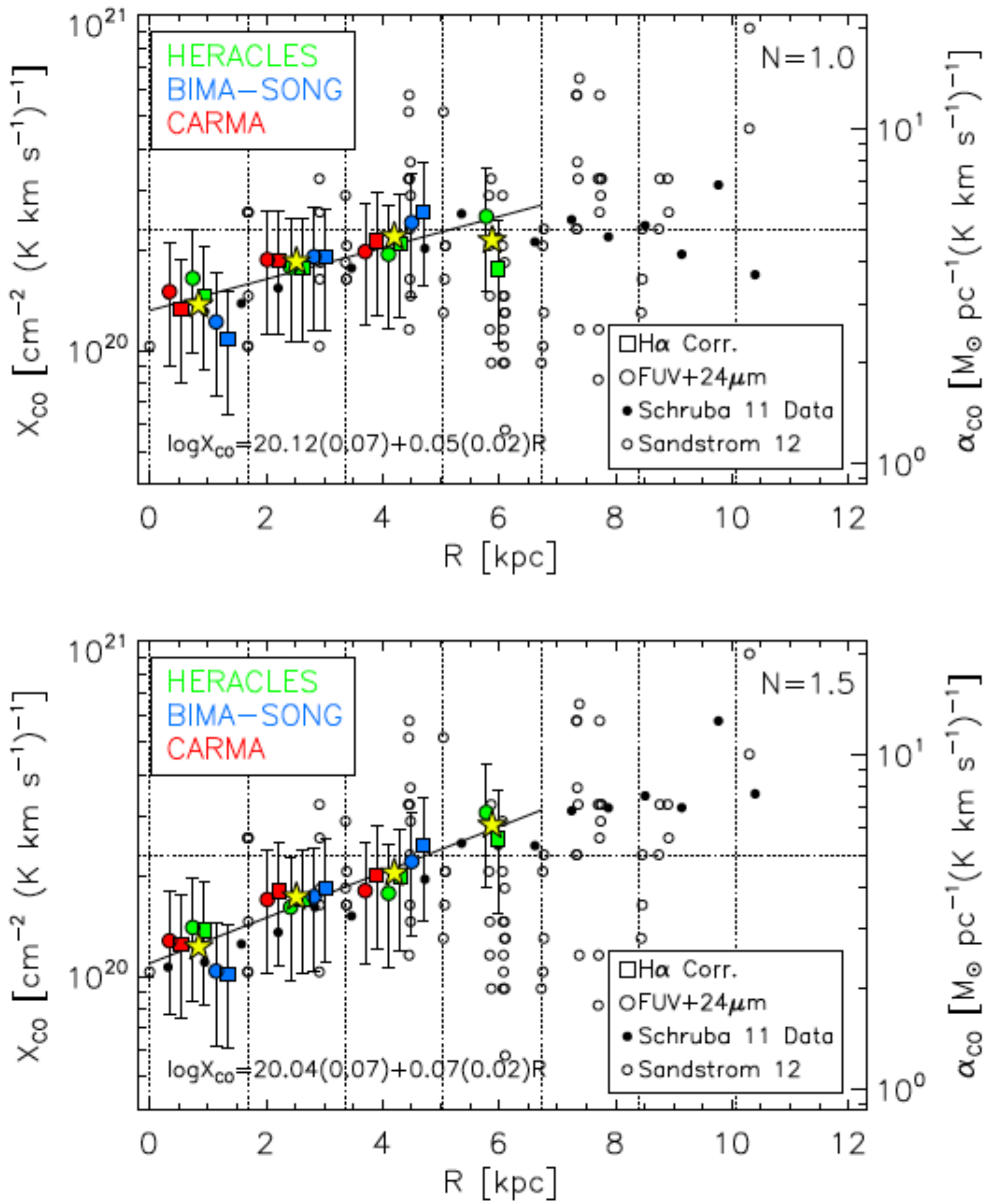
  - Metallicity, Temperature, and Turbulence change X_{co}
  - X_{CO} measured to be 4 times lower in mergers, starbursts and MW center (e.g. Downes & Solomon 1998, Oka et al. 1998.)
  - X_{CO} measured to be 10-100 times higher in low-Z dwarf galaxies (e.g. Bolatto et al. 2008, Leroy et al. 2011, Schruba et al. 2012)



$$\frac{\Sigma_{SFR}}{1 \mathrm{M}_\odot \mathrm{yr}^{-1} \mathrm{kpc}^{-2}} = A \left(\frac{\Sigma_{H2}}{10 \mathrm{M}_\odot \mathrm{pc}^{-2}} \right)^N$$

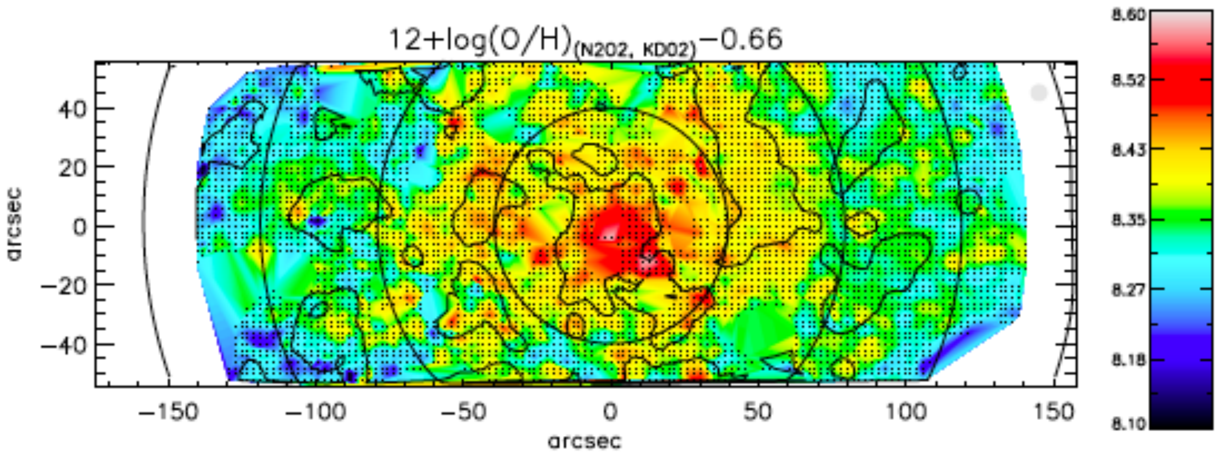
- Invert SFL to get independent measurement of H_2
- Compare to I(CO) to measure X_{CO}
- Study systematic uncertainties:
  - SFR tracers
  - CO(1-0), CO(2-1)
  - Single Dish vs. Interferometry
  - Assumed SFL

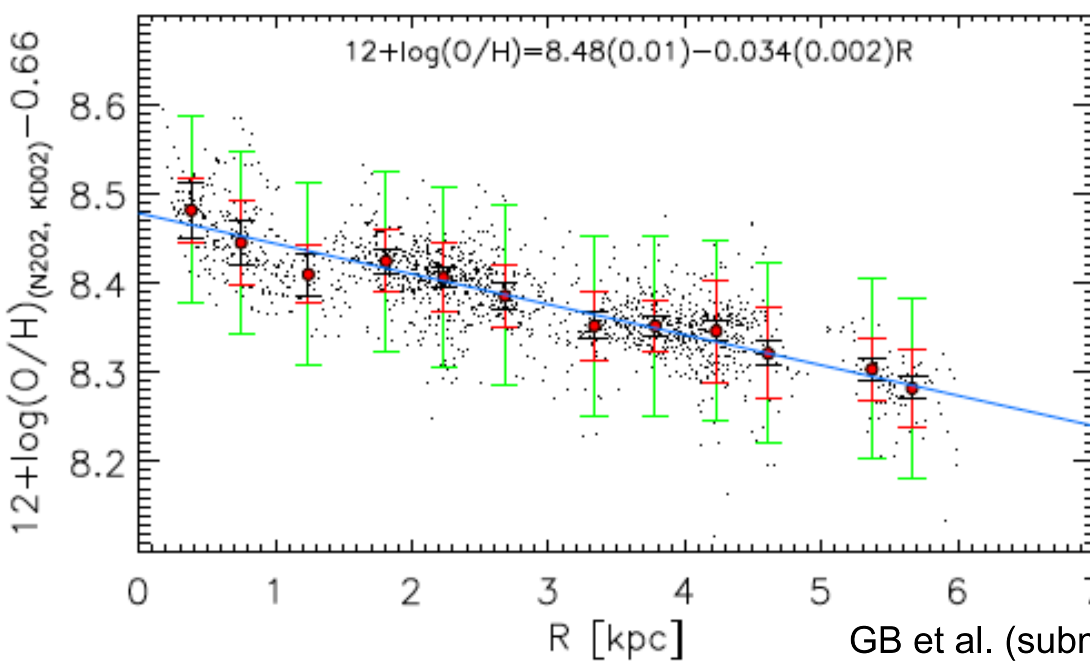




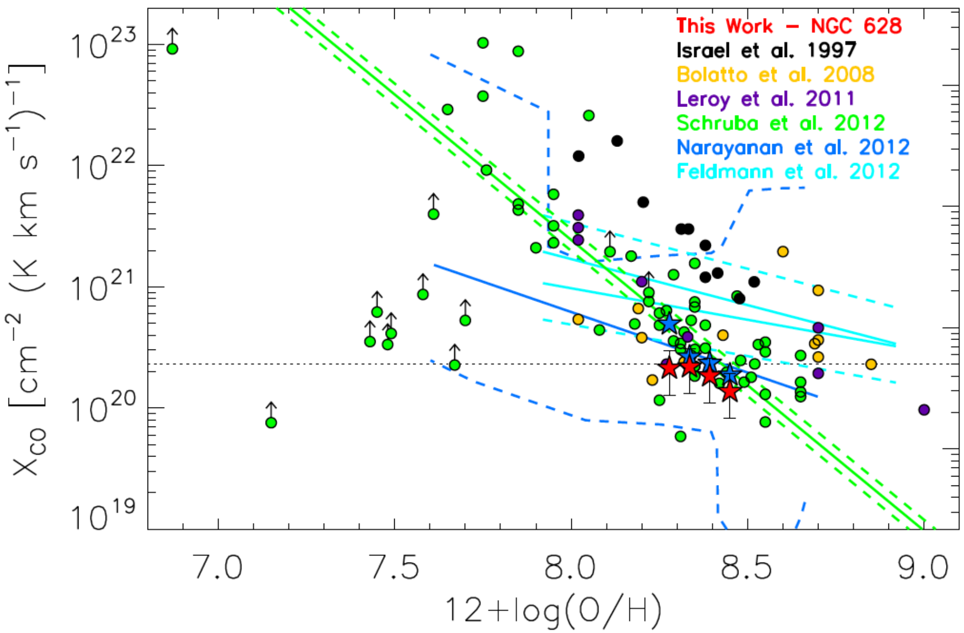
GB et al. (submitted)

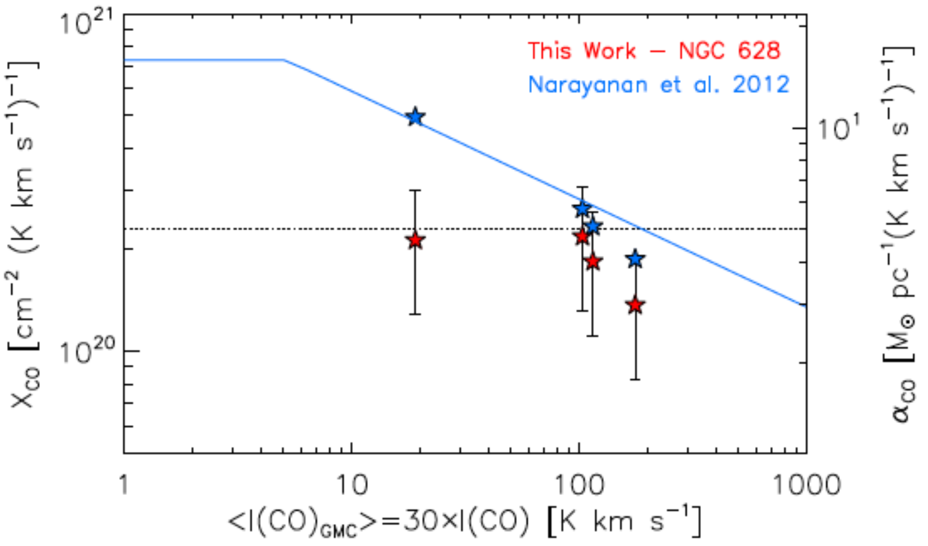
Metallicity Gradient





GB et al. (submitted)





GB et al. (submitted)

- There is an X_{CO} Gradient across the disk of NGC 628
- Metallicity and Surface Density dependence agrees with simulations, but not everywhere.
  - Comparison is difficult:
    - 3D vs 2D
    - Physical parameters vs observables.

- Do NOT use a single X_{CO} value everywhere in a galaxy!!

Part II CONCLUSIONS

- VENGA:
  - Wide IFU maps for 30 nearby spirals
  - Structure, dynamics, and chemistry of both stars and the ISM in disks out to > 0.75 R_{25}
- Measured the spatially resolved SFL in M51a:
  - E(B-V) : Hα, Hβ
  - AGN shocked and photo-ionized regions: [OIII], [SII], Hα, Hβ
  - Separate DIG from HII regions: [SII], Hα
  - Balmer Absorption from stellar continuum fitting
  - No [NII] contamination in Hα fluxes
  - Reliable SFR from spectrocopically measured Hα
- Detected X_{CO} radial gradient across M74

CONCLUSIONS

- Wide field IFUs are great tools to study galaxies, both at high redshift and in the nearby universe.

- Exciting instruments coming: VIRUS, MUSE, MANGA

- Wide field IFUs are powerful general use instruments for small telescopes (e.g. VIRUS-P, VIRUS-W, SED-Machine, PMASS-PPAK, MANGA).

EXTRA SLIDES – Part I

How do we measure DE?

$$H^2(a) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_X a^{-3(1+w)}\right]$$

- CMB constraints $H_0^2\Omega_m$ and $H_0^2\Omega_r$ very well.
- We can constrain DE by measuring very accurately the expansion history of the universe: $H(a)=(\dot{a}/a)$
- a is easy to measure: $a=1/(1+z)$
- $\dot{a}$ is almost impossible to measure
- We must use indirect observables for H(a)!!!!

How do we measure DE?

- 2 indirect observables:
  - Distance-redshift relation:

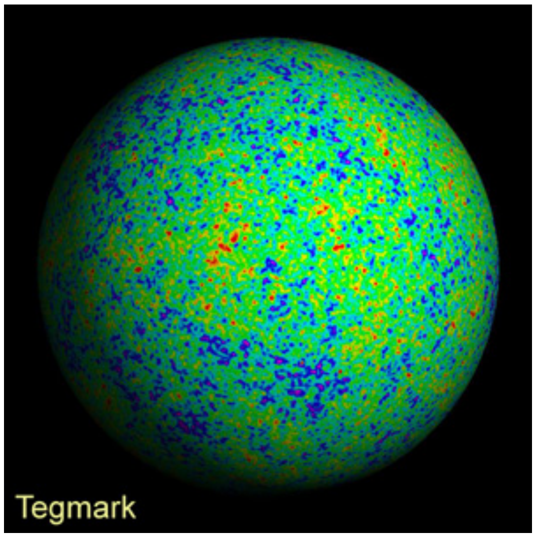
$$D(z) = \int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = \int_t^{t_0} \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')}.$$

    - Luminosity Distance: "standard candles"
    - Angular Diameter Distance: "standard rulers"
  - Growth of structure:
    - Gravitational collapse competes with expansion
    - Parametrized as a function of redshift by a "growth factor", the mass function of clusters, amplitude of PS, etc
- Both should agree!!

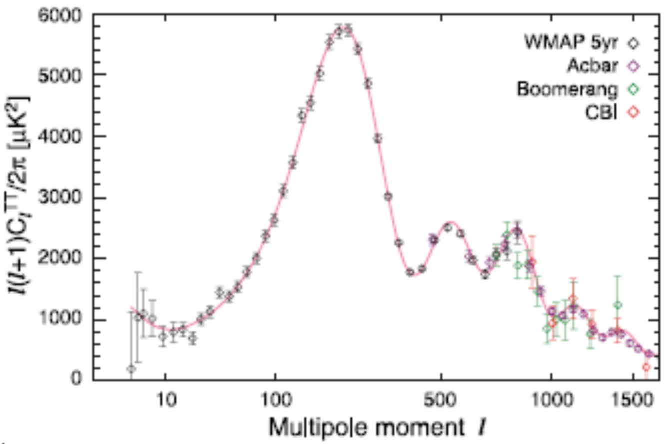
How do we measure DE?

- Supernovae:
  - use SN as "standard candles".
- BAO:
  - use the size of the sound horizon of pre-recombination acoustic waves in the CMB as a "standard ruler".
- CLUSTERS
  - Use the "cluster mass function" as a function of redshift to measure the growth of structure.
- WEAK LENSING
  - Use the "shear field" as a measure of both the expansion history and the growth history.
- FULL POWER SPECTRUM MODELLING

BARYONIC ACOUSTIC OSCILLATIONS

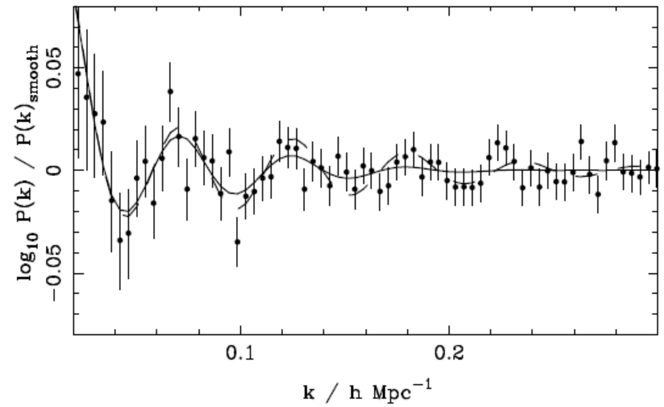


WMAP

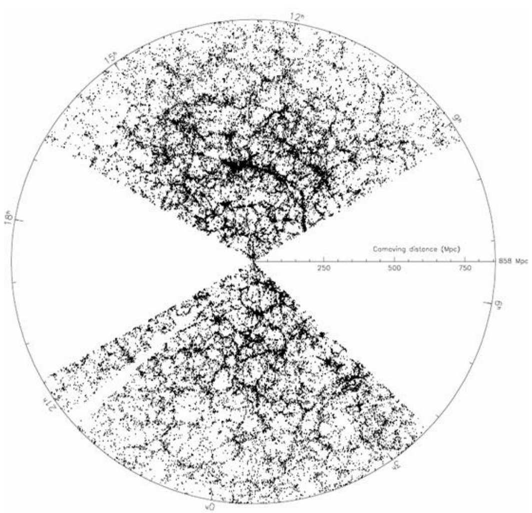


Nolta et al. 2009

SDSS-DR5

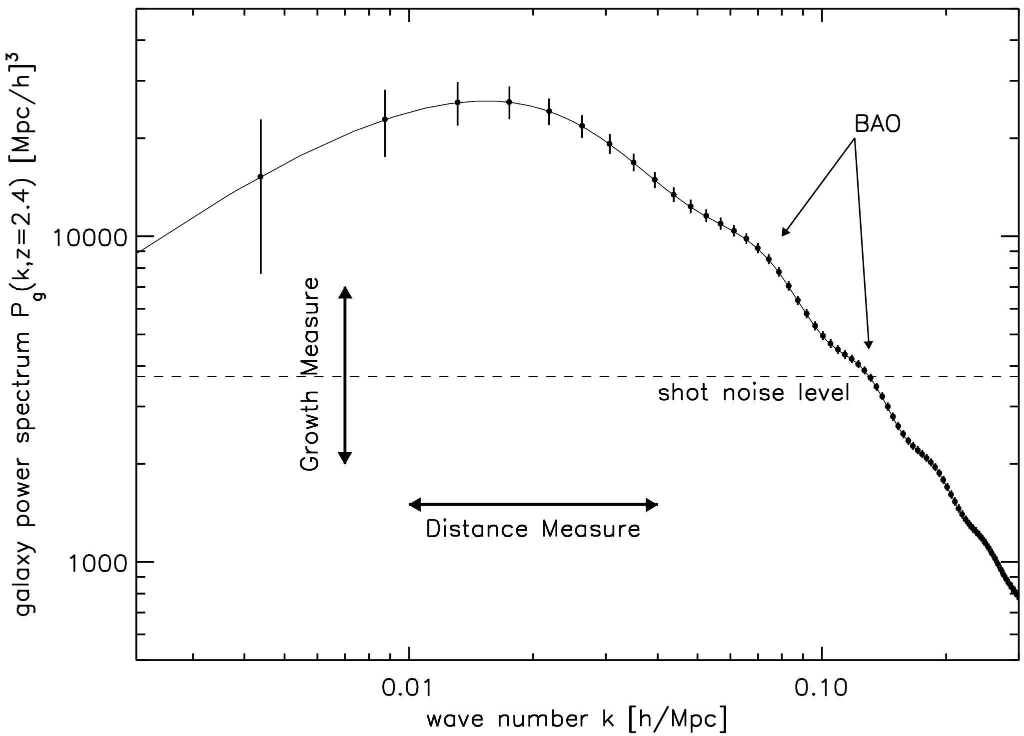


Percival et al. 2007



$$H(z) = h\sqrt{\Omega_m(1+z)^3 + \Omega_X exp[3\int \frac{1+w(z)}{1+z}dz]}$$

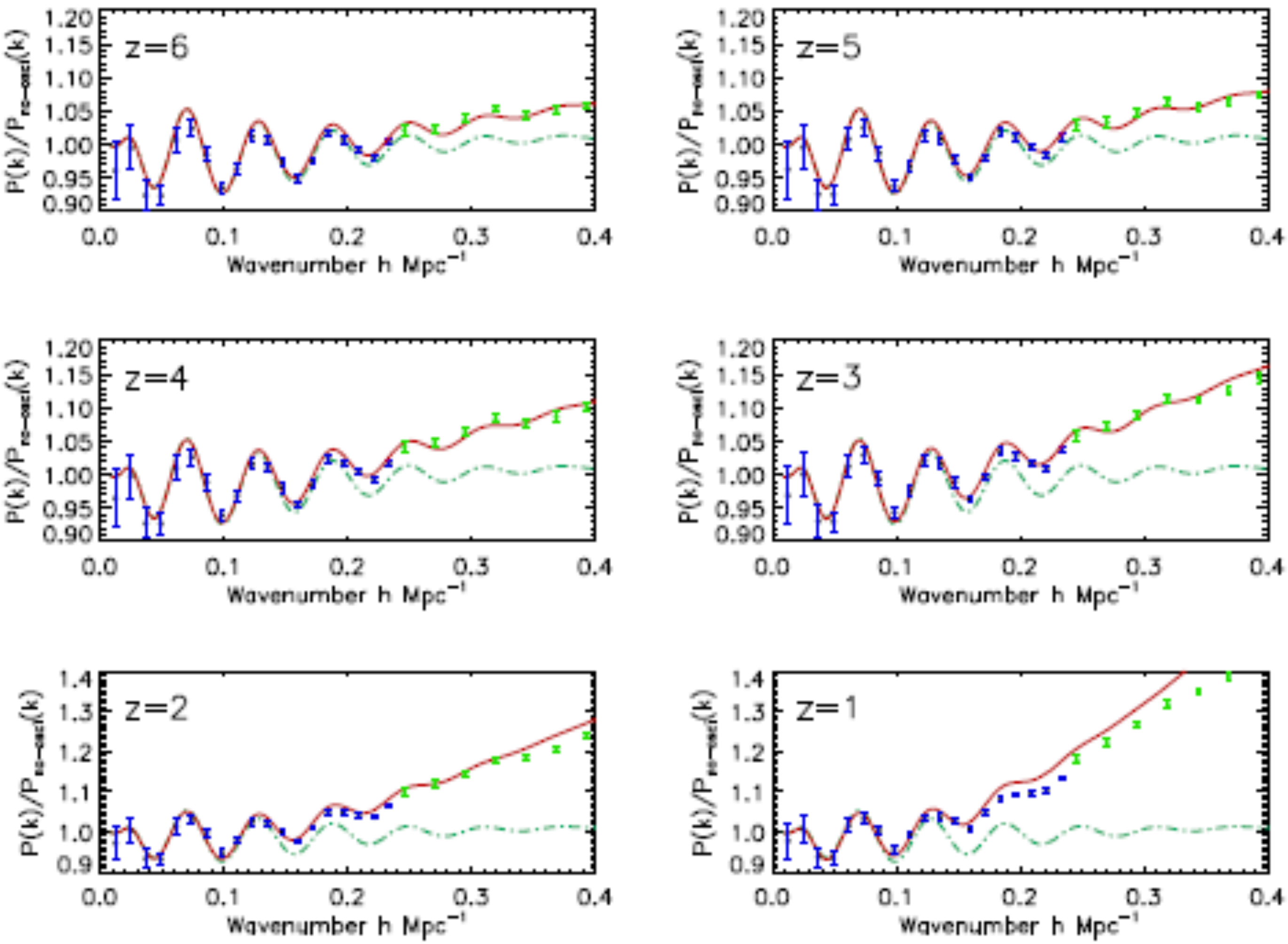
$$D_A(z) = \frac{c}{1+z}\int \frac{dz}{H(z)}$$



P(k) has 5 measures to exploit:

1. **Phase of the oscillations: geometric**
2. **Amplitude of oscillations: structure growth**
3. **Amplitude of P(k): structure growth**
4. **Linear/non-linear transition: geometric**
5. **General shape (e.g., turn-over): geometric**

BAO vs FULL PS MODELLING



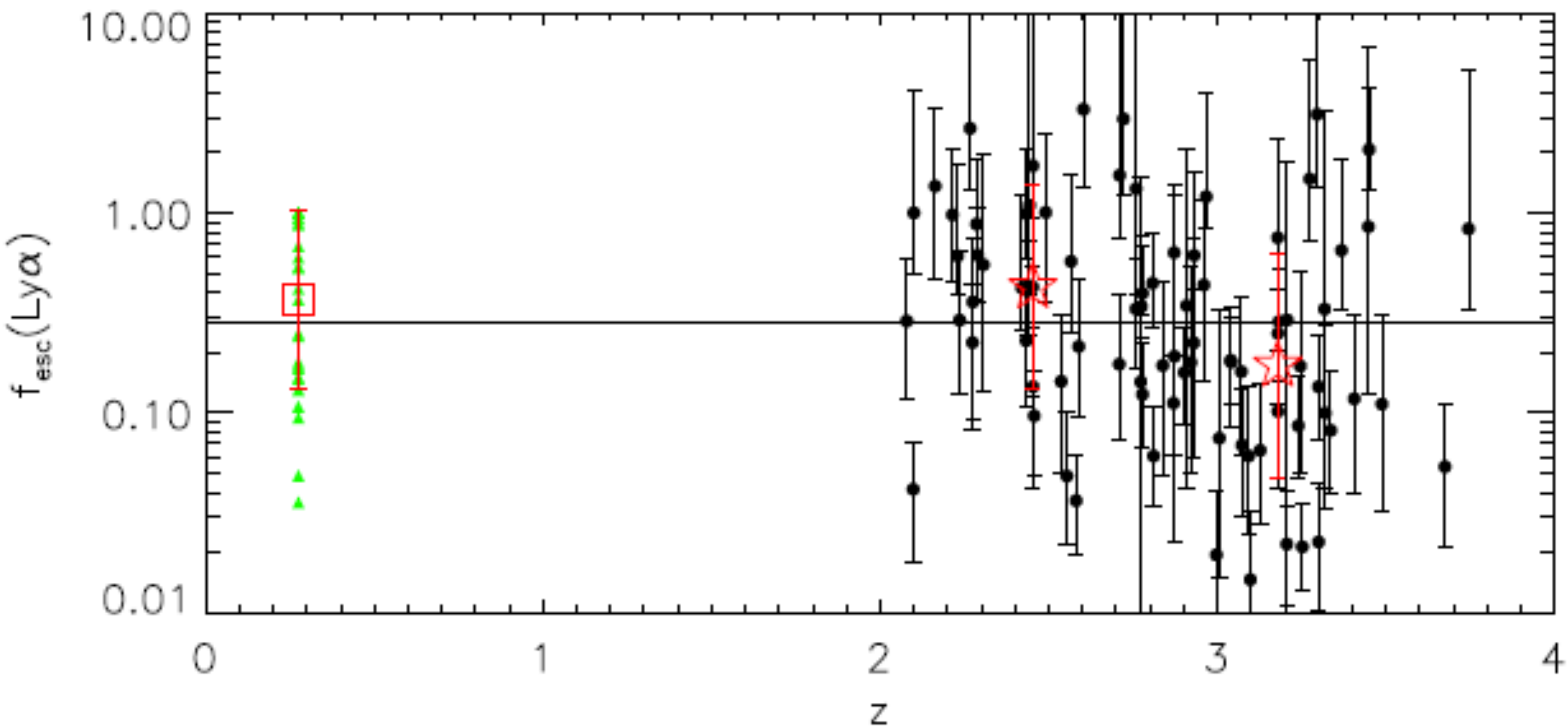
3rd Order Perturbation Theory: Jeong & Komatsu 2006

CONCLUSIONS

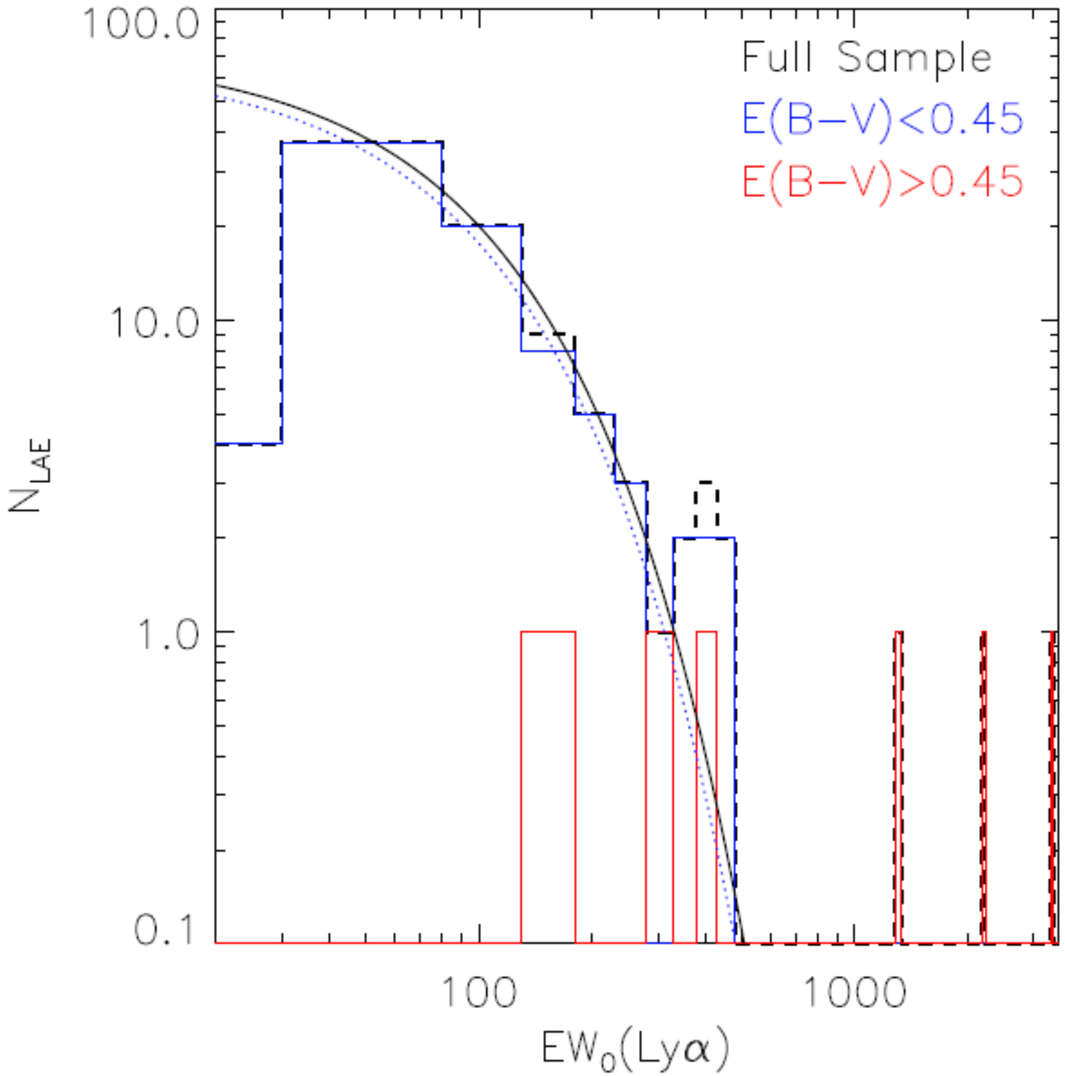
Wavelength (nm)	350	425	485	550
Redshift (for Ly-α)	1.9	2.5	3.0	3.5
Line Sensitivity (10^{-17} erg/cm^2/s)	9.5	3.9	3.4	3.5
Continuum Sensitivity (AB mag)	21.5	22.0	21.9	21.6

- HETDEX is a blind spectroscopic survey of 50 deg^2.
  - 800,000 LAEs at $1.8<z<3.5$
  - 1,000,000 [OII] Emitters at $z<0.5$
  - 400,000 other galaxies
  - 250,000 MW stars with spectra
  - 2,000 galaxy clusters
  - 10,000 – 50,000 AGN at $z<3.5$
  - 10,000 LABs
- And whatever it is we are not looking for!!!!!!

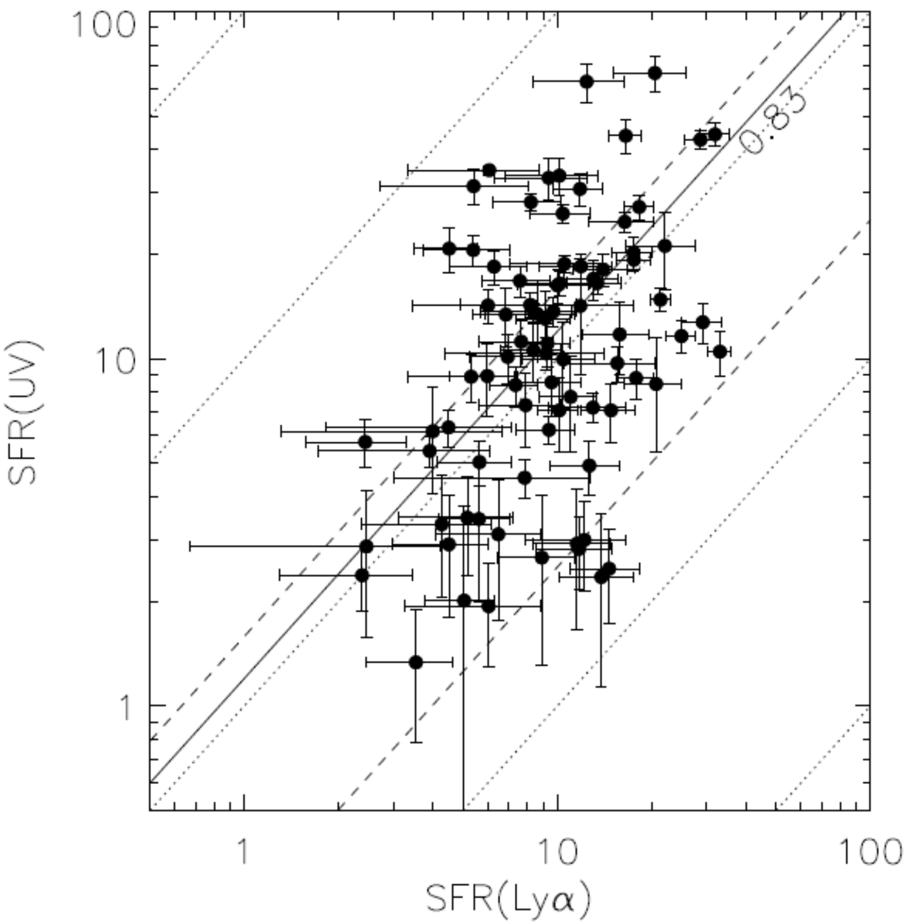
LAE Fesc Evolution



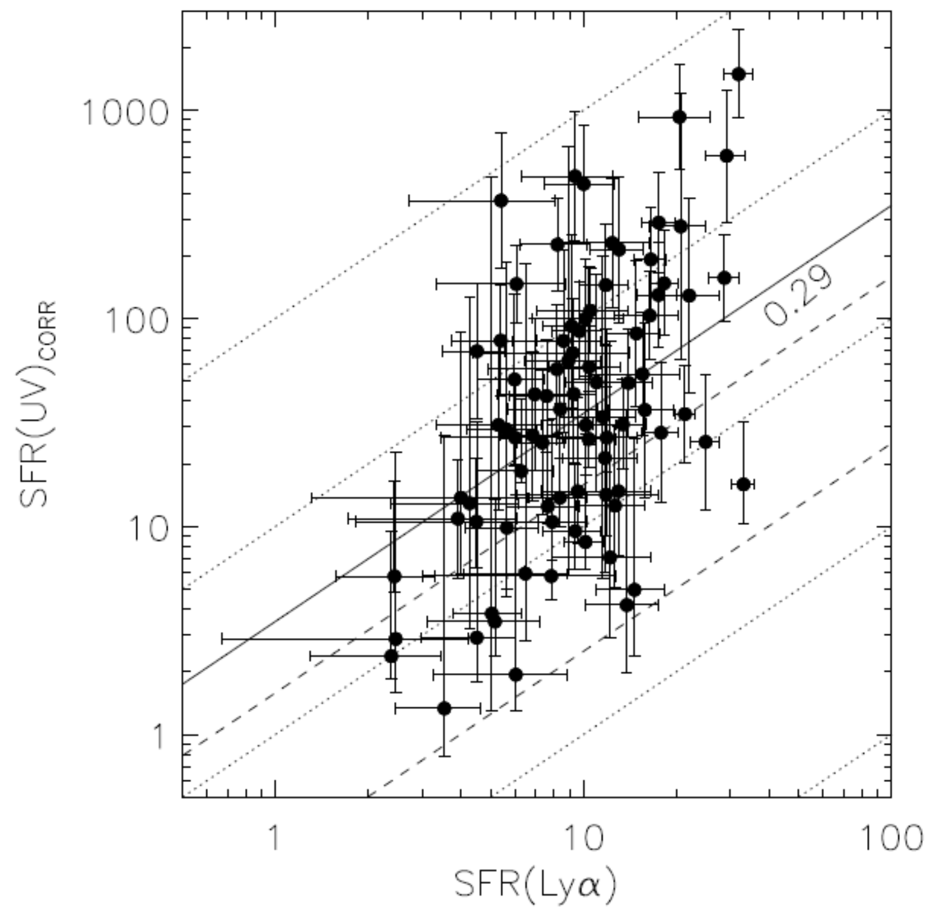
EW Distribution



UV vs Lyα SFR

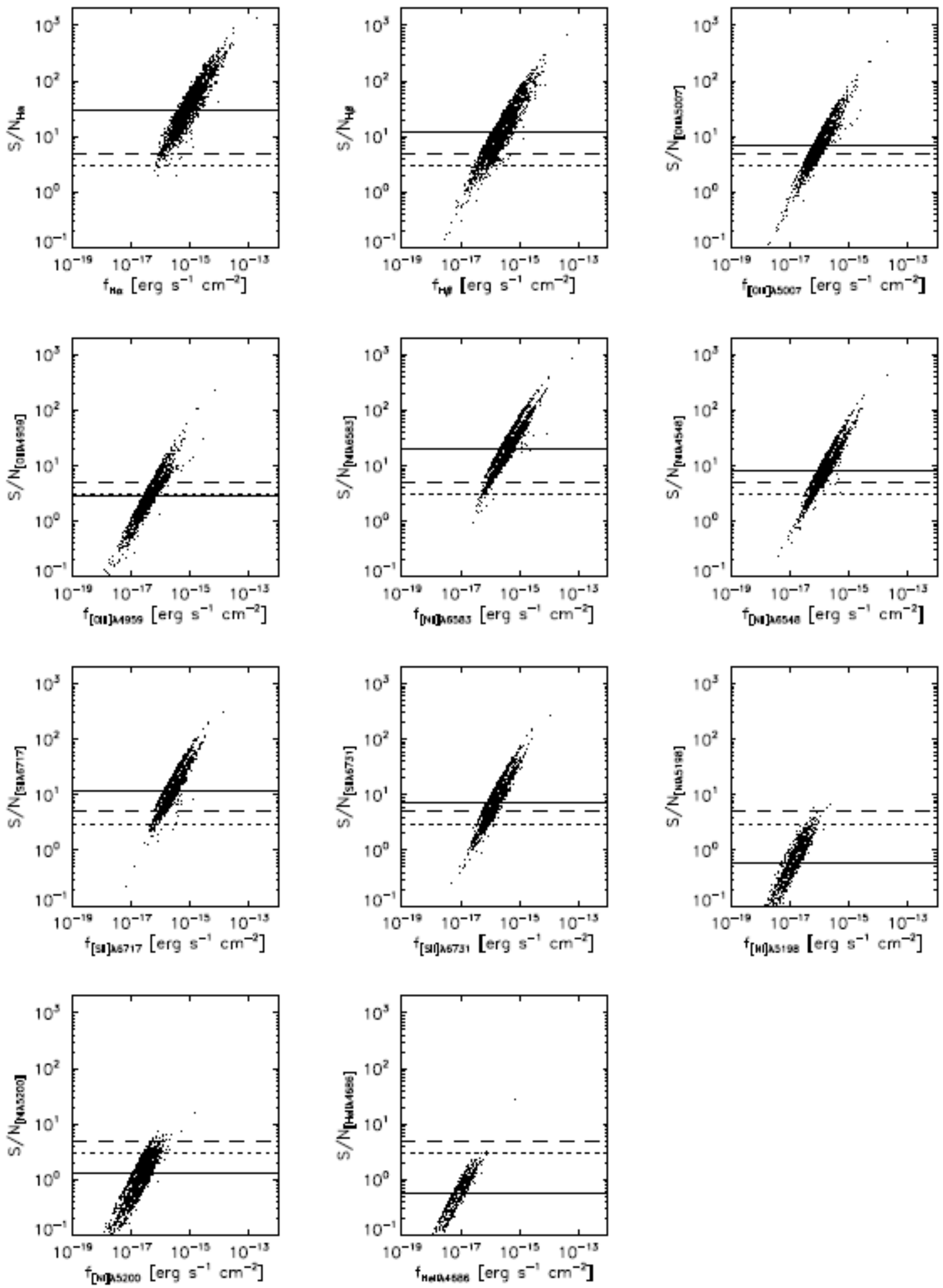


100
10
1
SFR(UV)
1
10
100
SFR(Lyα)
0.83



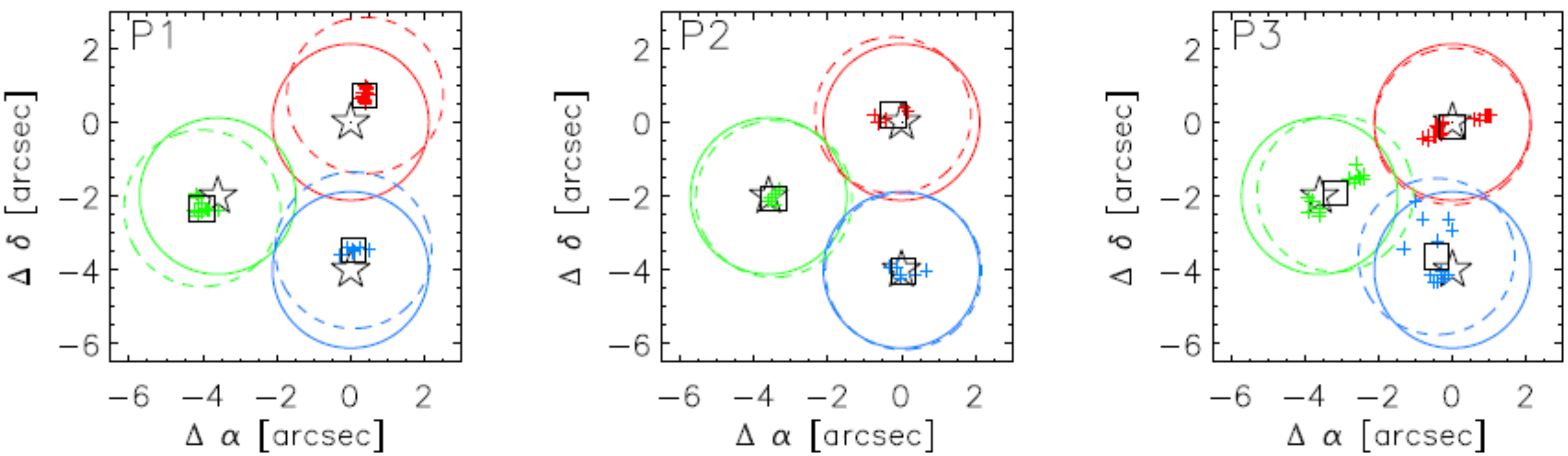
1000
100
10
1
SFR(UV)CORR
1
10
100
SFR(Lyα)
0.29

EXTRA SLIDES – Part II

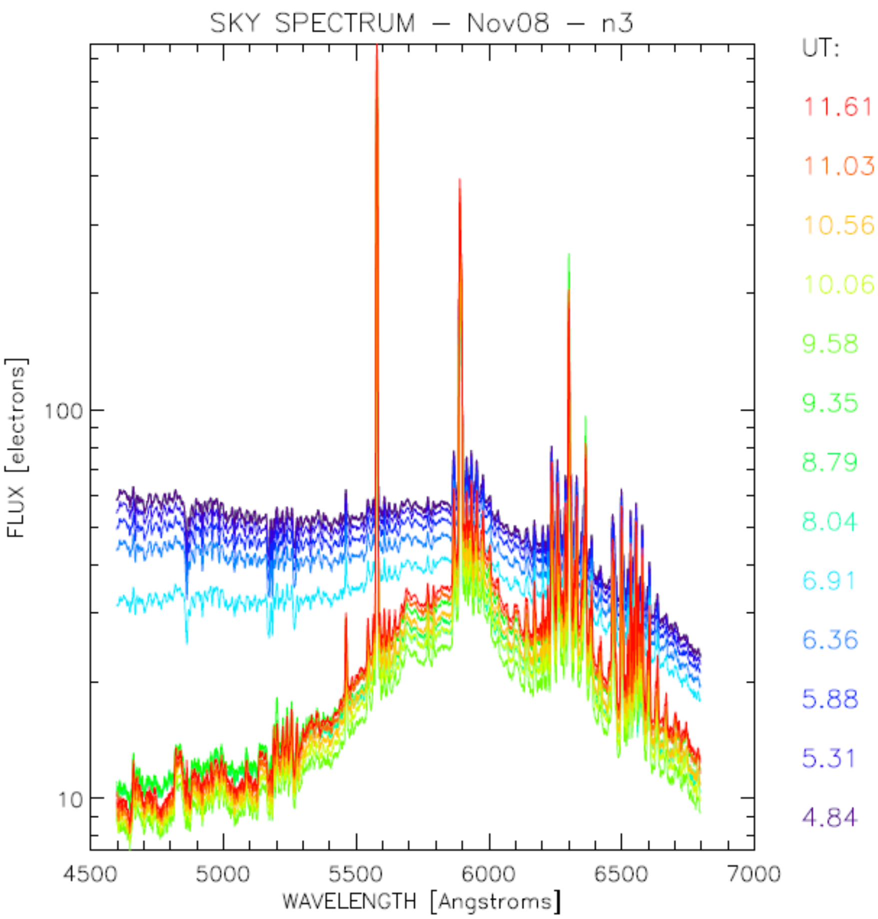


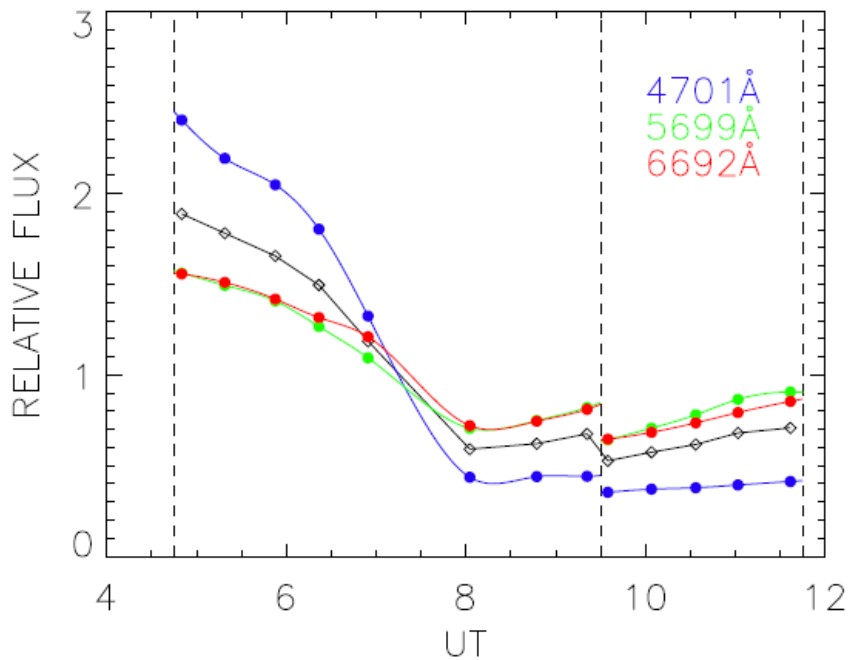
S/N_Hα
f_Hα [erg s^-1 cm^-2]
S/N_Hβ
f_Hβ [erg s^-1 cm^-2]
S/N_[OIII]λ5007
f_[OIII]λ5007 [erg s^-1 cm^-2]
S/N_[OIII]λ4959
f_[OIII]λ4959 [erg s^-1 cm^-2]
S/N_[NII]λ6583
f_[NII]λ6583 [erg s^-1 cm^-2]
S/N_[NII]λ6548
f_[NII]λ6548 [erg s^-1 cm^-2]
S/N_[SII]λ6717
f_[SII]λ6717 [erg s^-1 cm^-2]
S/N_[SII]λ6731
f_[SII]λ6731 [erg s^-1 cm^-2]
S/N_[NI]λ5198
f_[NI]λ5198 [erg s^-1 cm^-2]
S/N_[NI]λ5200
f_[NI]λ5200 [erg s^-1 cm^-2]
S/N_HeIIλ4686
f_HeIIλ4686 [erg s^-1 cm^-2]

DITHERING ACCURACY

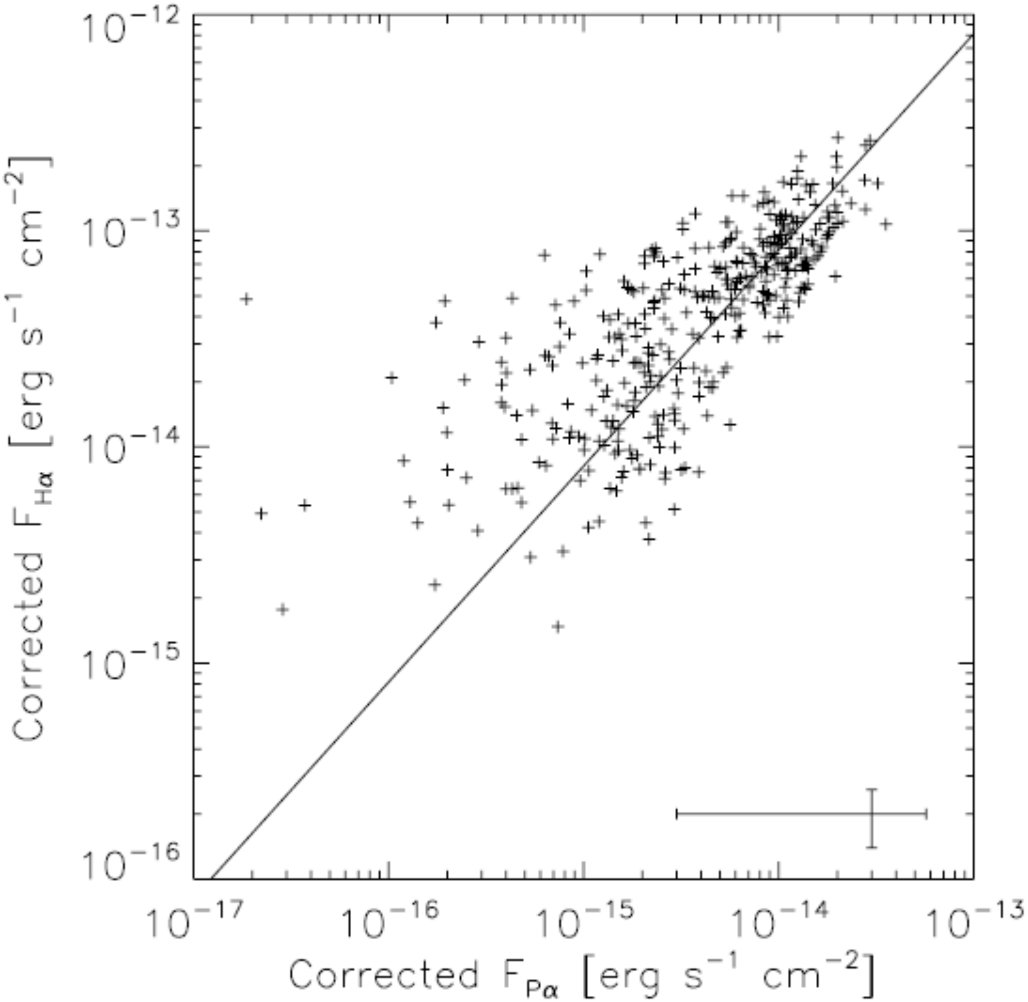


SKY SUBTRACTION

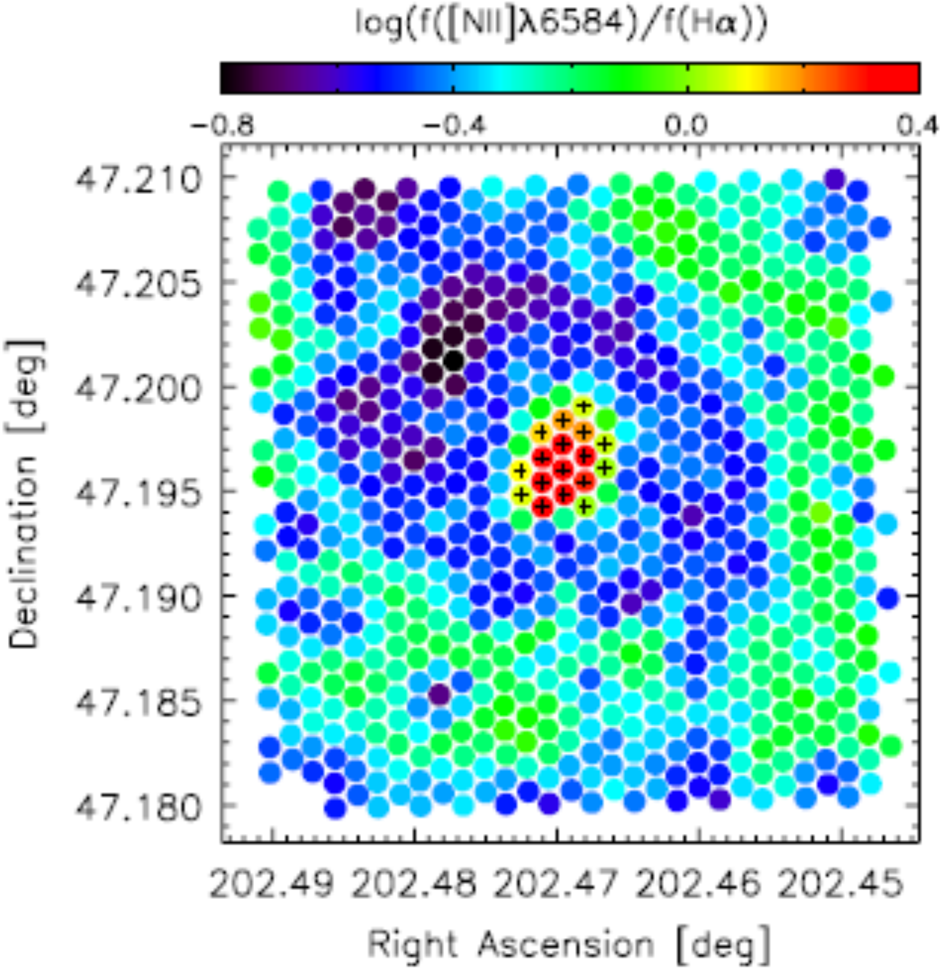


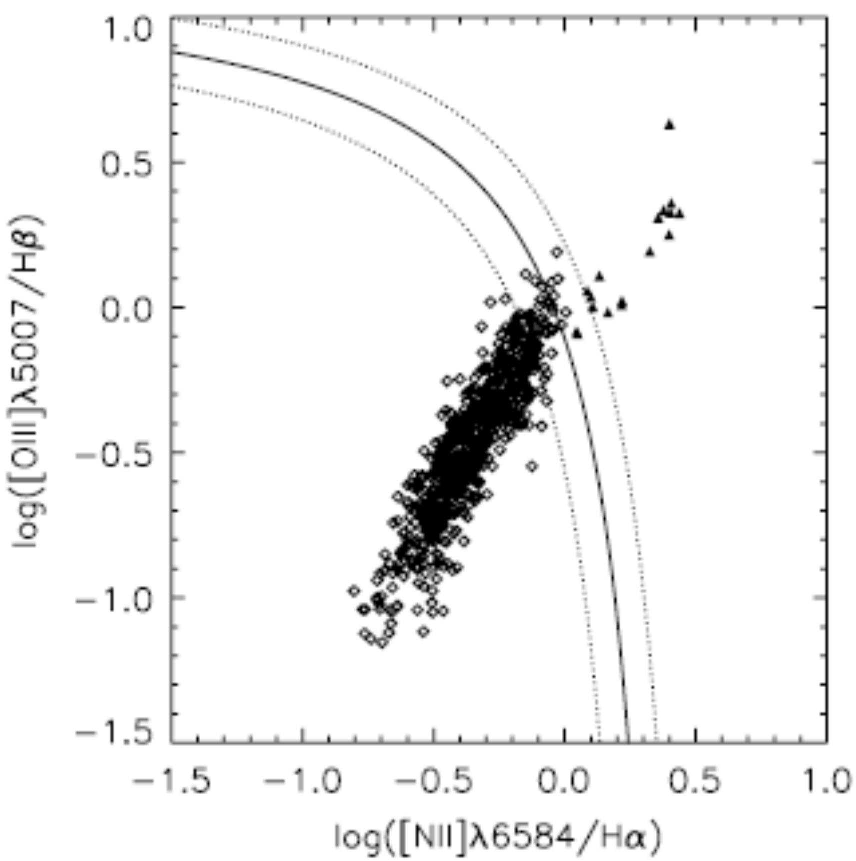


M51a DUST EXTINCTION CORRECTION

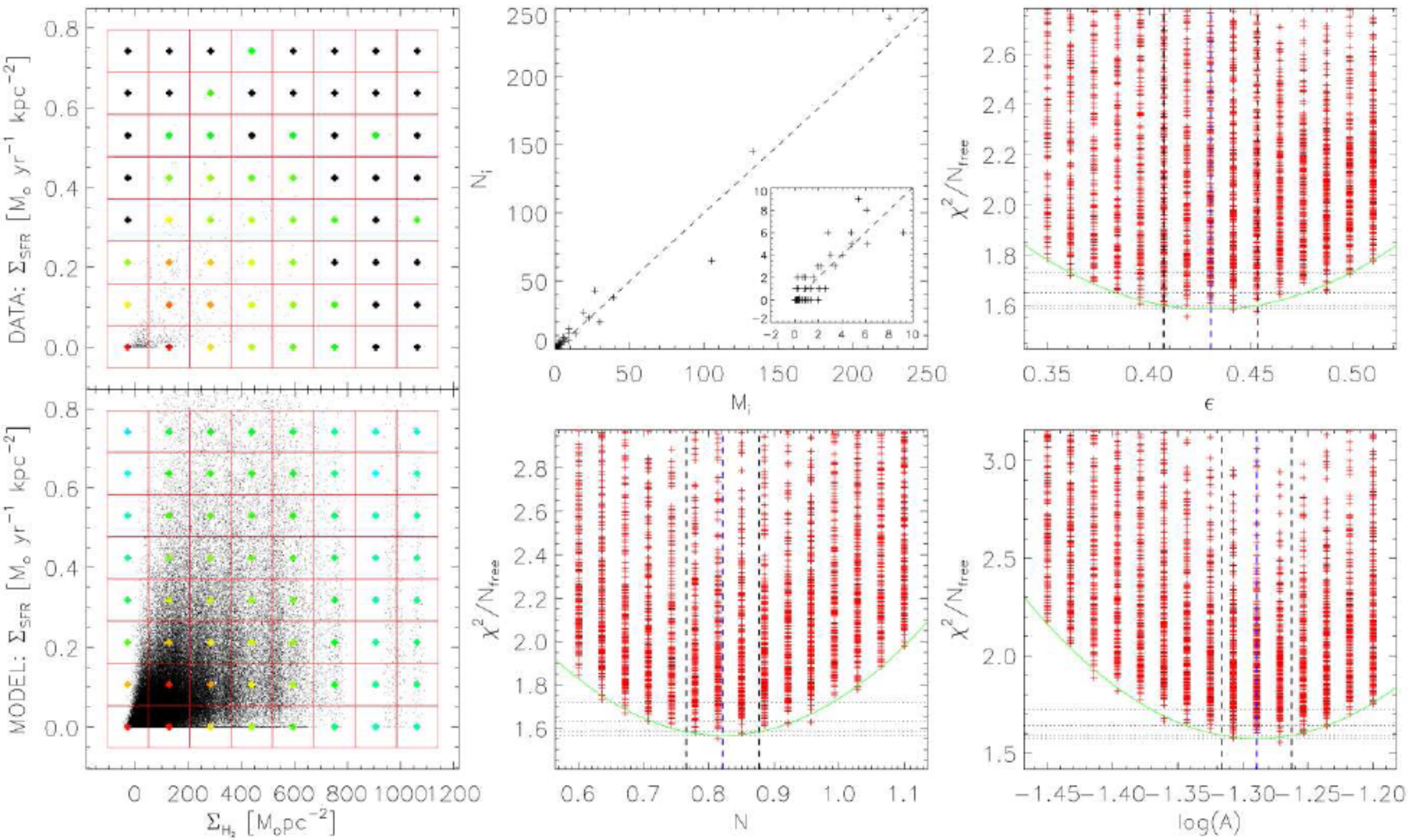


M51a CENTRAL AGN





MC FITTING METHOD



IMPLICATION FOR NARROW-BAND IMAGING