Planning and Analyzing WFIRST Grism Observations

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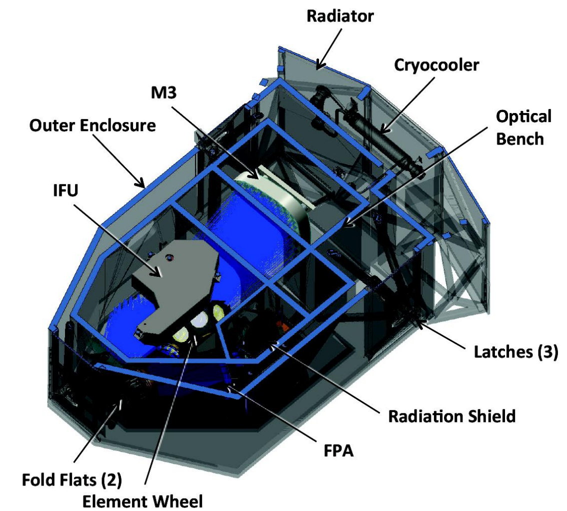
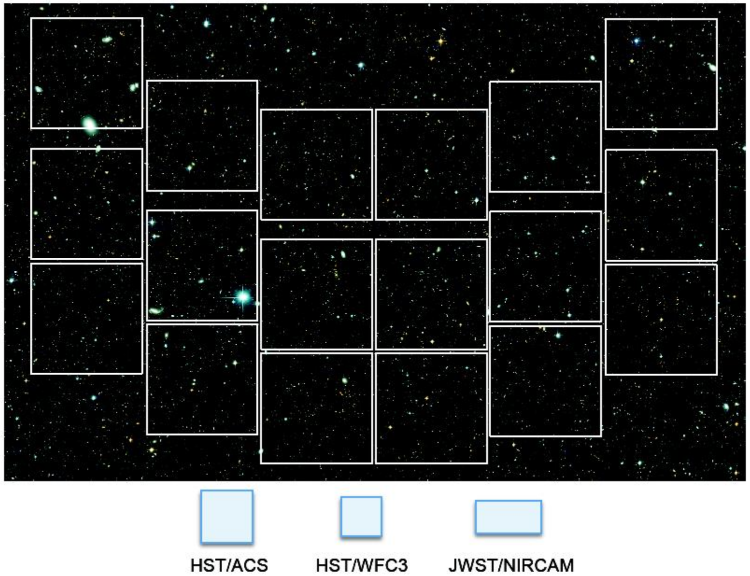
WFI Grism Observations in the WFIRST Mission

- Slitless Spectroscopy observations with the WFI Grism constitute a large part of WFIRST's mission
  - High-Latitude Spectroscopic Survey will take 0.7 years of observations
  - One of three key cosmology measurements (Baryonic Acoustic Oscillations, measuring the scale of the Universe at z = 1-3)
  - Very desirable for high-visibility Guest Investigator and Guest Observer science
    - Several one-page science ideas in the SDT Report involve Grism observations
    - Grism observations constitute as much as 25% of HST observations in recent years
- Scale, complexity, and required precision of grism observations present several challenges:
  - Calibration quality and complexity
  - Source overlap
  - Pointing stability and reconstruction
  - Operating mode – separation of direct and dispersed images
  - Data Analysis scale and complexity
  - Wavelength accuracy
  - Additional observing modes
- This presentation summarizes the contents of two Technical Reports (found at http://www.stsci.edu/wfirst/technicalreports) and additional work in progress
  - WFIRST-STScI-TR1502: Planning for the Analysis of WFIRST-AFTA Grism Data: A Review of Current and Future Slitless Spectroscopy Software and Data Analysis Approaches (MacKenty et al.)
  - WFIRST-STScI-TR1506: Slitless Grism Spectroscopy with WFIRST: Observing Modes and Strategies (Casertano et al.)

The Wide Field Imager and the Grism element

- The wide-field channel of the Wide Field Imager is the WFIRST workhorse for wide-area imaging and spectroscopy
  - Field of view ~ 0.27 square degrees (>100x ACS, NIRCAM)
  - 18 4k x 4k IR detectors (110mas pixels) with throughput 0.76-2.5 μm
  - Imaging: 5 normal filters (Z087, Y106, J129, H158, and F184) plus a very wide filter (W149, 0.927-2.00 μm)
  - Spectroscopy: GRS grism, 1.35-1.89 μm, R ~ 500
- Grism manufacture challenging (wide field of view, large dispersion, require 90% of light in first order)
  - Three-element design with two dispersing surfaces
  - Zero order suppressed, light spread over large area
  - Engineering unit being manufactured to test design
- Readout every 5.4s except for guide windows (one 64x64 pixel per detector)
- Detector requirements achieved in lab devices
  - Dark current < 0.1 e/s/pixel
  - Read noise < 20 e (CDS)
  - QE > 60%
  - Pixel-to-pixel capacitance < 12%



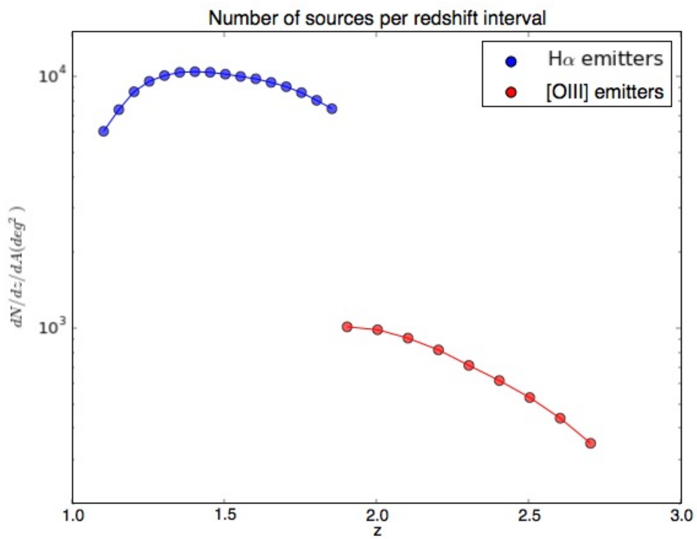


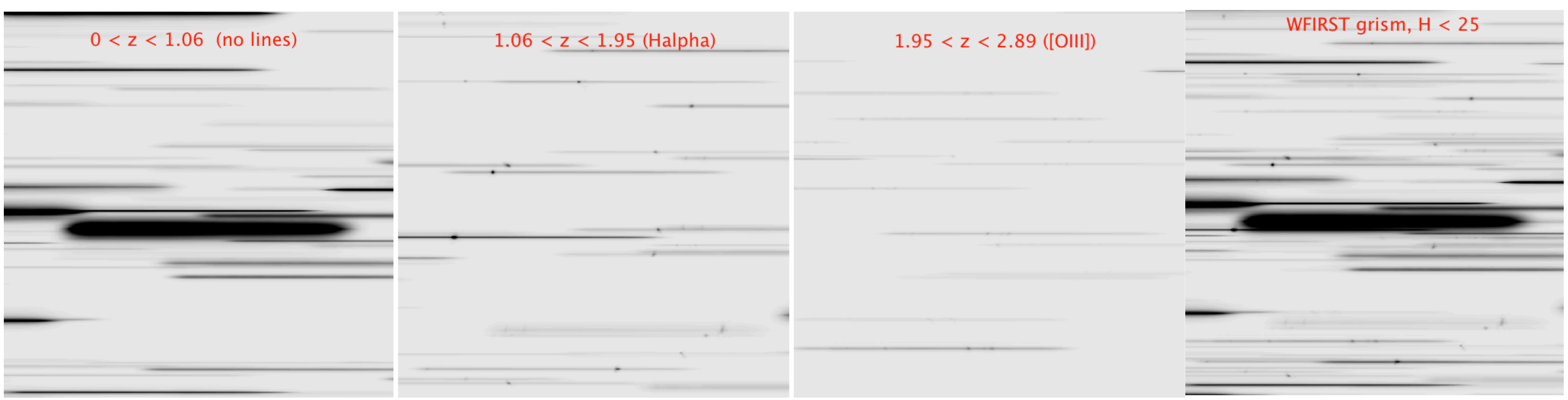
The High-Latitude Spectroscopic Survey

- Covers > 2200 square degrees
  - Direct imaging in 4 filters (Y106, J129, H158, and F184), > 1000s total integration per filter, 2 orientations, 3-5 exposures each
    - Dithers to cover gaps between detectors at each orientation
    - Expected point source sensitivity 25.7 to 26.7 AB (5-σ)
  - Slitless spectroscopy with grism over same area
    - Current design has two passes ~six months apart, with two slightly different rolls in each pass (+/- 15 deg), resulting in dispersion angles differing by 15, 180, 195 degrees
    - Two exposures at each roll; median exposure time ~2500s
    - Line flux sensitivity 1.2 10^{-16} erg/s/cm^2 (7-σ, for sources with 0.3" effective radius)
  - Survey constitutes 40% of mission time: 1.3 years for imaging, 0.7 years for spectroscopy
  - Direct and dispersed images may not be taken at the same time
- Spectroscopic survey critical for Baryonic Acoustic Oscillations
  - Redshift survey with > 15 million galaxies at z = 1-3, primarily measured through Hα and [OIII] emission
  - Find angular scale of Acoustic Peak in galaxy correlation function vs. redshift
  - Expect measuring the scale of the BAO feature to 0.3%
    - Systematics expected to be below 0.1%
  - Requires accurate redshift measurement with rms error < 0.001 (systematic and statistical)
- Other science returns include:
  - Early structure formation (> 10,000 galaxies at z > 8)
  - Characterization of high-redshift QSO (~2000 at z>7)
  - Identifying the highest starforming galaxies at z~2 (covering 5% of the sky)
  - Improving census of ionizing radiation at z~2 by extending the faint end of the luminosity function

Performance needed to achieve BAO goals (1)

- Source density and distribution
  - Expect ≈10^4 sources per square degree per redshift interval in Hα, ≈10^3 in [OIII]
  - Assumes typical 70% completeness above sensitivity threshold
  - Line identification helped by photo-z constraints
  - Confusion, incompleteness at high S/N not fully discussed
    - Low-redshift sources have similar density, spectra will overlap
    - Bright sources can create avoidance regions (including zero order flux)
    - Multiple dispersion angles can help both overlap and avoidance; quantitative analysis on realistic simulations needed
  - Image quality degradation may affect sensitivity to line emission if pointing stability worse than 0.5 pixels (current requirement set at 0.2 pixels, under evaluation)

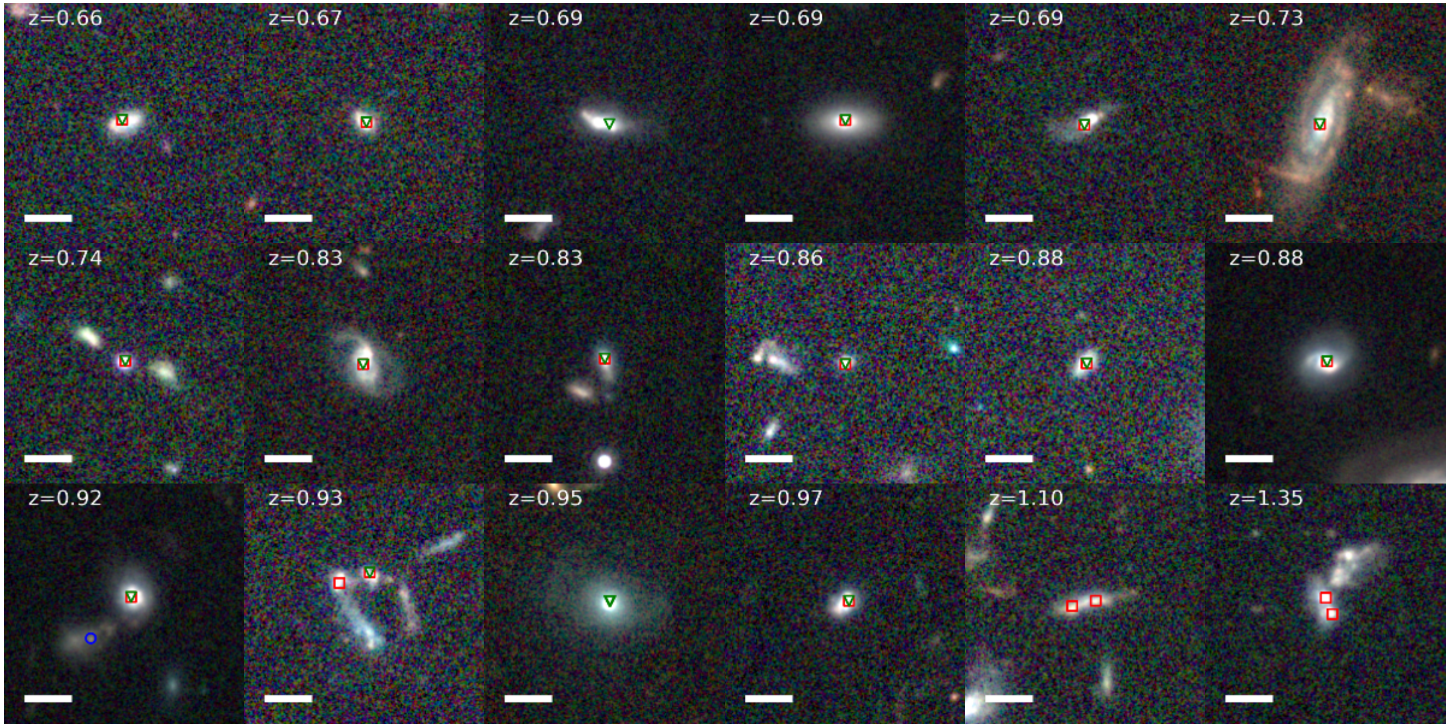




Performance needed to achieve BAO goals (2)

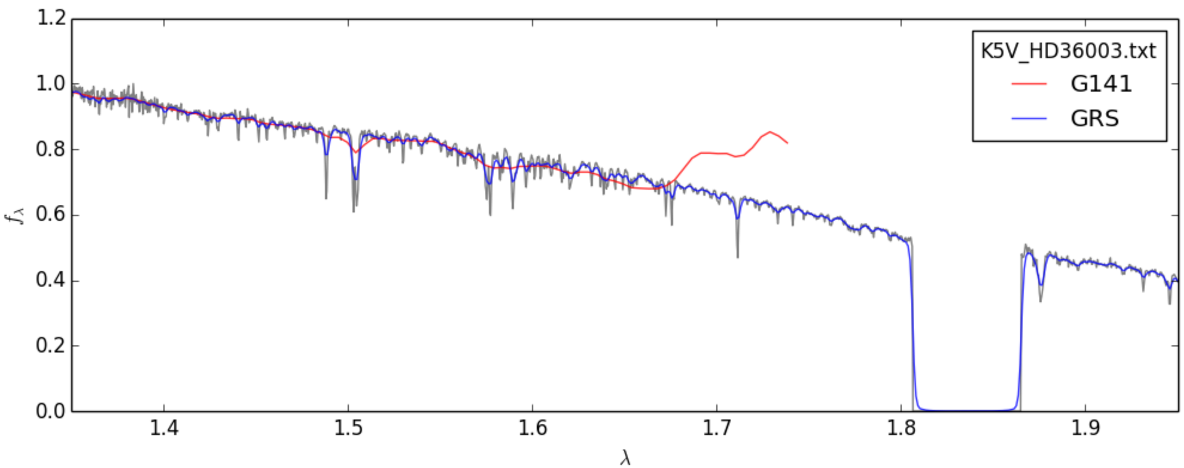
- Redshift accuracy $\sigma_z \sim 0.001\,(1+z)$
  - Requires total uncertainty < 15 Å, ≈ 1.4 pixels at 1.5 μm
  - Contributing elements include:
    - Wavelength calibration
    - Geometric calibration
    - Pointing reconstruction
    - Knowledge of source position
    - Measurement accuracy (limited by S/N, spatial extent of emission region)
- Source structure is a significant source of uncertainty
  - Line emission distributed differently from continuum
  - Need to identify position of line emission for proper wavelength determination
  - May be able to use colors to define line emission regions
  - Angle diversity (180 degree flip or triangulation) can also help reduce uncertainty
  - Not included in current simulations and analysis
    - Critical upgrade needed for simulations
    - Triangulation methods, multi-angle software under development for analysis
- Pointing reconstruction also under investigation
  - Use of filter edges on bright stars (spectral ramp up/ramp down) subject to uncertainties on underlying stellar SED
  - Accuracy sufficient if edges sharper than 1%

Continuum geometry vs. line position at ACS resolution.
White bar = 1".
Line emission is typically unresolved.
From Pirzkal et al (2013)



Calibrating WFI Grism

- Includes geometric distortion, trace, and wavelength calibration
  - Experience with HST instruments provides starting point
  - WFC3 used bright line sources (compact PNe) and continuum sources (WD) at 9 locations to establish the basic wavelength and trace calibration
  - Trace calibration refined from rich stellar fields
  - All calibrations based on the match between direct and dispersed image
- Challenges for WFI Grism:
  - Same density of calibration would require over 1000 observations
  - Larger field, dispersion might entail larger local deviations -> interpolation may not be viable (to be reviewed on the basis of current design)
  - Lack of zero order image, direct image limits precision of calibration to on-board blind small angle manoeuver precision
  - Wavelength calibration requirements more stringent
- Calibration program will require careful design and analysis
  - Could benefit from rich fields for trace *and* wavelength calibration (e.g., open clusters with tens of viable stars per detector)
    - Higher dispersion enables use of stellar features for wavelength zero point solution and basic calibration
    - Greatly reduce pointing-related errors, data volume required
    - If single-target needed, consider partial field readout to limit data volume
  - Wavelength calibration using well-studied galaxy fields is also under consideration



Stars can serve as wavelength calibrators at WFI Grism spectral resolution (blue), not at WFC3/IR resolution (red)

Pointing reconstruction

- HLS direct and dispersed images may not be obtained at the same time
- Wavelength calibration requires precise relative astrometry (error budget 0.2 pixel)
- Registration can be achieved using bright stars and the edges of the grism transmission curve
- The quality of the registration depends strongly on the sharpness of the edges of the transmission curve:
  - For a transition width originally assumed at 3% (from 0.1 to 0.9 over 0.03 of the midpoint wavelength), uncertainties induced by SED variation on individual stars exceed the desired budget
    - e.g., difference between K0III and K0V corresponds to 0.3 pixels
    - Systematic differences exceed noise for $H < 19$
    - Would require multiple stars and/or detailed SED modeling for each star
  - If the transition width < 1% (suggested by current filter samples), stars with $H < 19$ will typically provide the needed accuracy
- Pointing reconstruction is feasible with no special tools if the transmission edges are 1% or sharper
- A Technical Report (Dixon, 2016) is currently in draft form

Items to consider for future simulations and studies

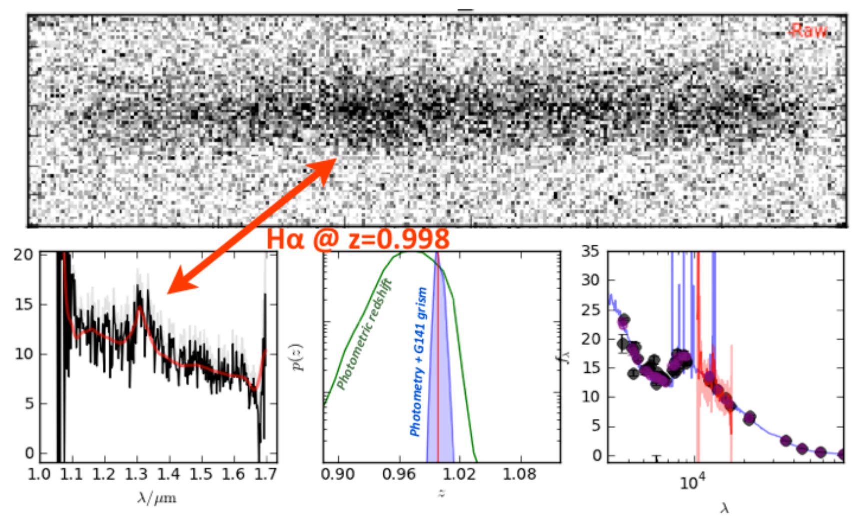
- Realistic number density and brightness of continuum and line sources
  - Low-redshift continuum sources outnumber the desired line sources
  - Confusion from overlapping spectra can be addressed with roll diversity; quantitative estimates needed
- Estimate completeness under expected survey parameters
  - Consider image quality degradation and its impact on sensitivity
  - Effect of bright stars, including widely spread zero order light
- Reexamine wavelength error budget
  - Develop estimates of calibration accuracy (wavelength, trace, distortion) based on complete plan
  - Include effects of spectral diversity of targets (emission line region different from continuum)
  - Quantify astrometric match between direct and dispersed images
- Set limits for line misidentification (redshift outliers)
- Fully account for focal plane geometry (including chip gaps) and possible instrumental and detector artifacts
- Also consider the possibility of special observing modes:
  - Limited field/chip readout (single chip, subarray)
    - Can reduce data rates for programs with many short, single-target observations (e.g., possible calibration programs)
  - Faster reads (may need subarrays)
    - Ability to observe brighter targets without saturation
  - Scanning mode
    - Enables higher precision photometry, astrometry as for WFC3
    - Very high precision time-resolved spectrophotometry for extremely bright targets (e.g., exoplanet hosts during transits)

Current Analysis Software: aXe

- Several current HST projects use variants of the aXe package (originally ST-ECF, now maintained and expanded at STScI)
  - Identify sources (and their light profile) in direct image
  - Follow the spectral trace and apply wavelength calibration for each source based on calibration/configuration files
  - Extract 2-d spectra via aXeDrizzle
  - Obtain optimally-weighted 1-d spectrum
- aXe can extract hundreds of spectra quickly
- Various groups (GRAPES, PEARS, WISPS) have adapted aXe to their needs by adding processing steps or using custom wrappers for the aXe package
- A companion package (aXeSIM) can be used to generate simulated data (see presentation by James Colbert)
- Potential limitations of the aXe approach:
  - Current design expects direct image aligned with dispersed image
  - Cannot readily incorporate information from multiple rolls at the pixel level; overlapping sources cannot be separated
  - Some special observations (very bright sources, observations obtained in scanning mode) are not well suited to the aXe approach
  - Ability to scale and run unsupervised over thousands of square degrees is untested

Alternatives for the future: Forward Modeling

- Motivated by 3D-HST program (van Dokkum; Brammer, Momcheva, et al)
  - Large area coverage (two-thirds of CANDELS fields, 625 sq arcmin)
  - Aim to provide uniform, unbiased redshift measurements for CANDELS galaxies
  - Rich photometric data available
  - Has extracted spectra and determined redshifts for 20,000 galaxies to H ~ 24 (AB); redshift precision ~ 0.3%
  - Mostly automated, with visual inspection to clear out 5% of objects with poor data quality
  - Current implementation performs template fit (using galaxy templates + line emission) directly to the 2-d extracted spectra
    - Automatically accounts for source shape and light distribution
    - Corrects for features such as edges in the transmission curves
- Future implementation will generalize to multiple sources/rolls
  - Sources that overlap in one orientation can be separated in another
  - Spectra for each source characterized by a number of parameters (e.g., stellar synthesis models, combination of empirical libraries, etc)
  - Optimize to determine the best description for all the available data (including photometry and morphology)
- Models can be iteratively improved using the wealth of data obtained from WFIRST
- Self-calibration concepts can also be included

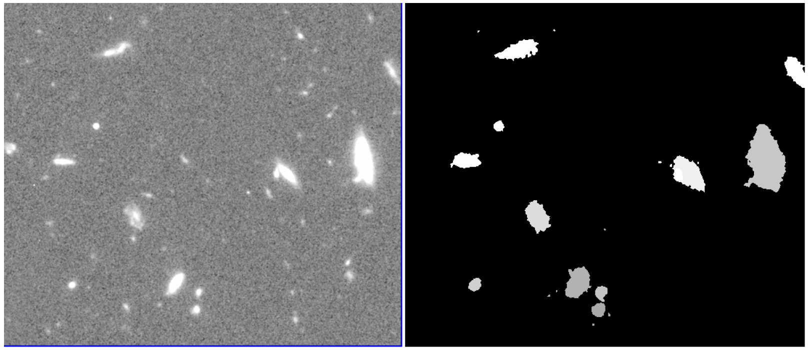


2-d extraction and template fit (red curve) and joint redshift measurement (blue shaded area) for a galaxy with Ha at z=0.998 in 3D-HST data. The fit is carried out on the full 2-d spectrum.

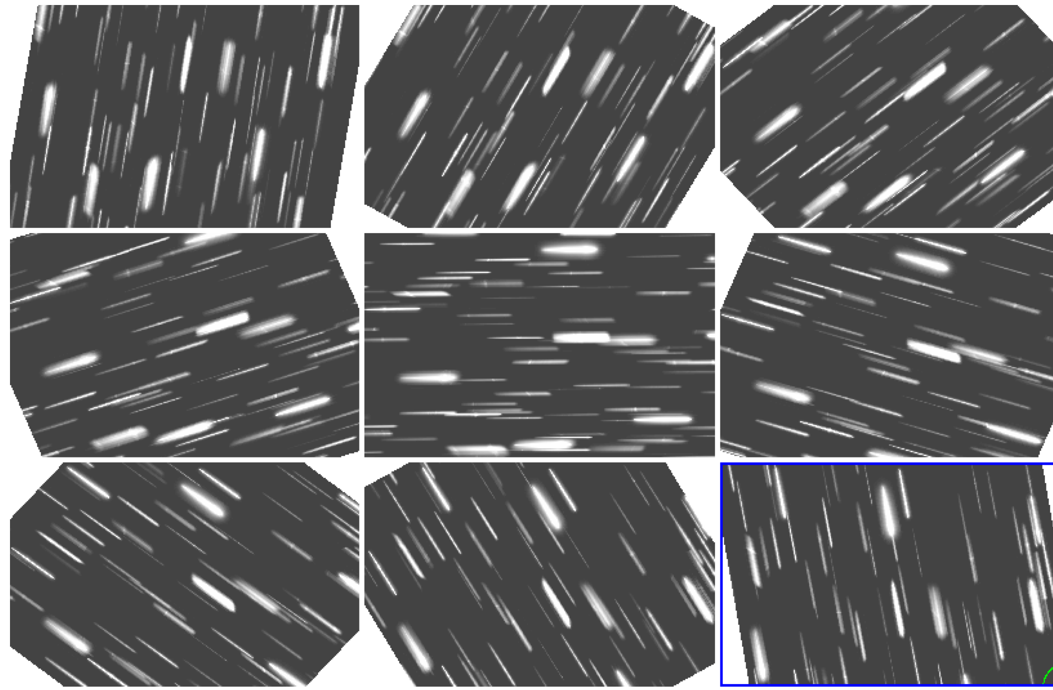
Alternatives for the future: Linear Reconstruction

- New method for the analysis of multiple-roll data directly in observed pixel space
  - Designed to handle sources with overlapping spectra
  - Use linear least squares solution to solve simultaneously for the spectra of all sources in the field
  - Computationally very demanding
    - Need to store separately the coefficients of the signal produced by each wavelength element in each dispersed image
    - A typical dataset may require storage of 10^8 coefficients and the solution of an extremely sparse 10^6 x 10^5 system for WFC3/IR
    - Requirements scale by an order of magnitude or more for WFIRST
  - Pilot software under development uses the LSQR algorithm (Paige and Saunders 1982) for the least-squares matrix solution
  - Test cases carried out with WFC3/IR parameters
    - Total run time 10 hours for 9 images
    - Demonstrate very good extraction in the low-noise regime
    - Currently investigating noise properties; expect quantitative estimates in < 6 months

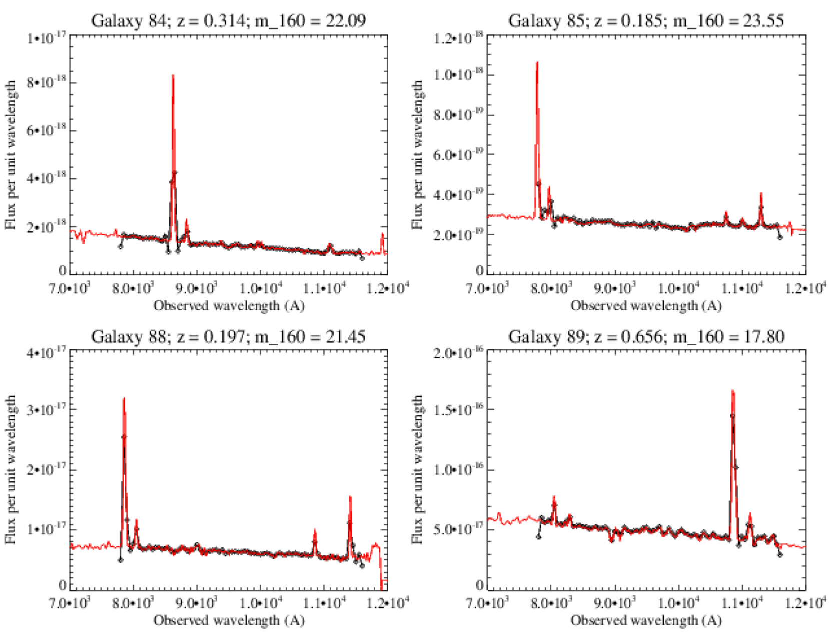
Linear Reconstruction test



Input direct image and segmentation map
(130 sources selected; not all visible on this scale)



Simulated dispersed images (9 roll angles)



Subset of extracted spectra (noiseless): Red (model), black (extracted)

Concluding Thoughts

- Slitless observations with WFIRST will present substantial challenges in scale, complexity, and accuracy
  – Extremely large field of view (1 exposure > a Large HST program…)
  – Tight calibration and error requirements
  – Higher dispersion than current HST grisms increases source overlaps
  – Data volume and processing requirements will require rethinking of current paradigms
- Experience with current missions and observatories provides insight on how to meet these challenges
  – Existing data and tools can be used to guide necessary studies
  – Careful models and simulations are needed to verify that the goals can be achieved to the desired level
    - Realistic parameters and analysis needed
    - Account for spectral diversity in sources, spectral overlaps
- New tools are being developed that might be better suited to WFIRST goals

Let's figure out the right questions to ask – and work together to answer them!