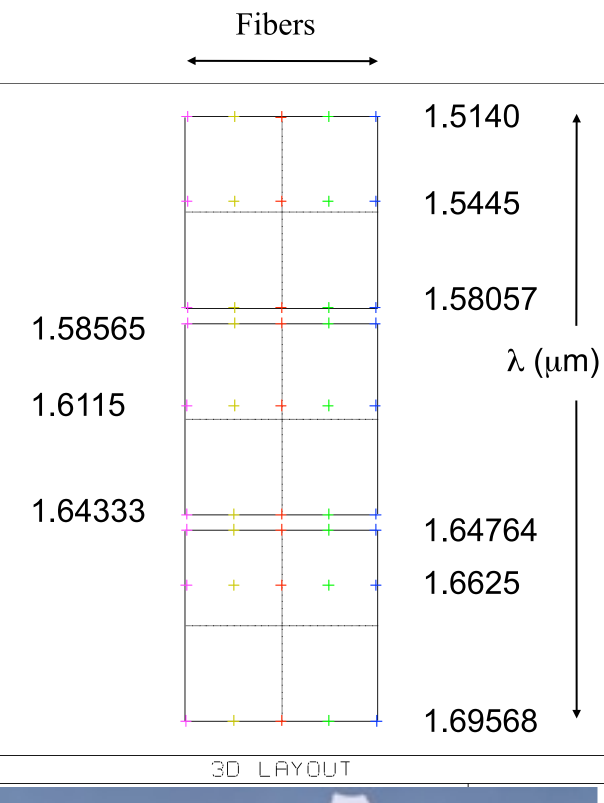
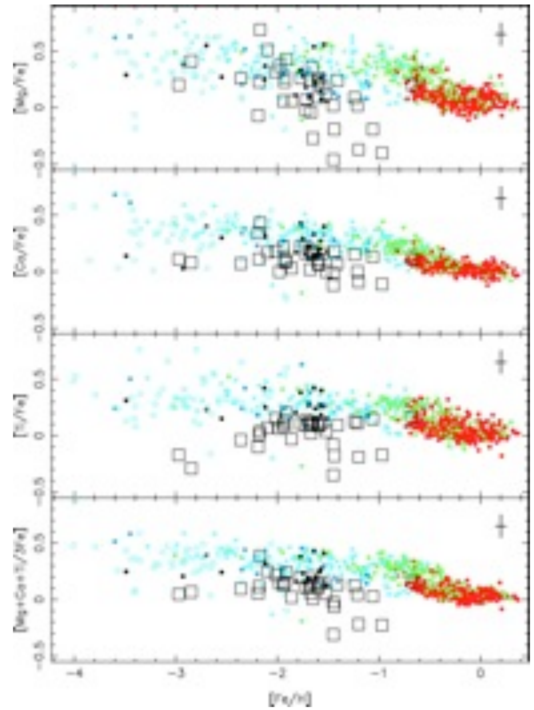
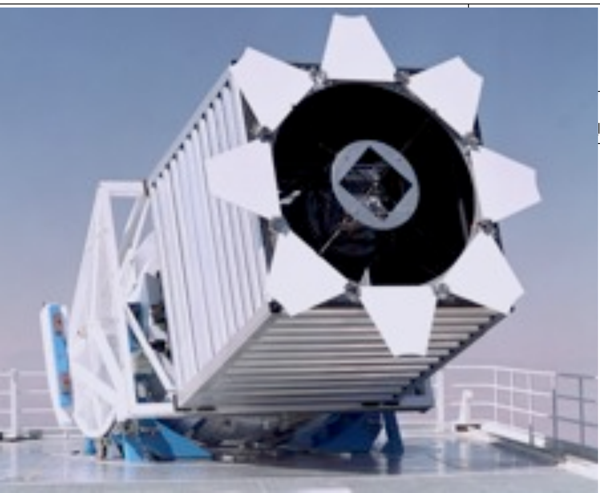


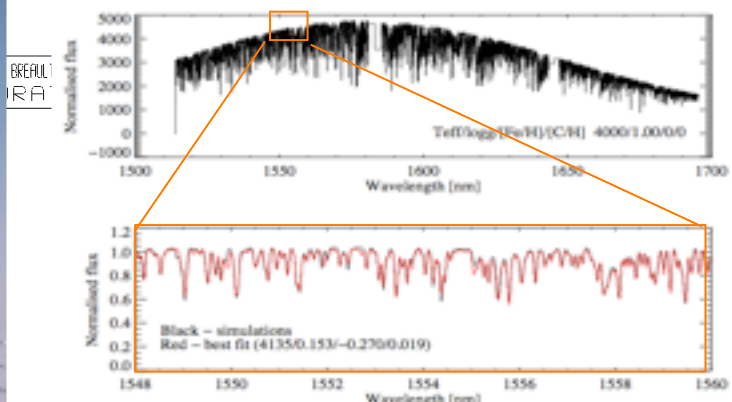
The APOGEE Survey

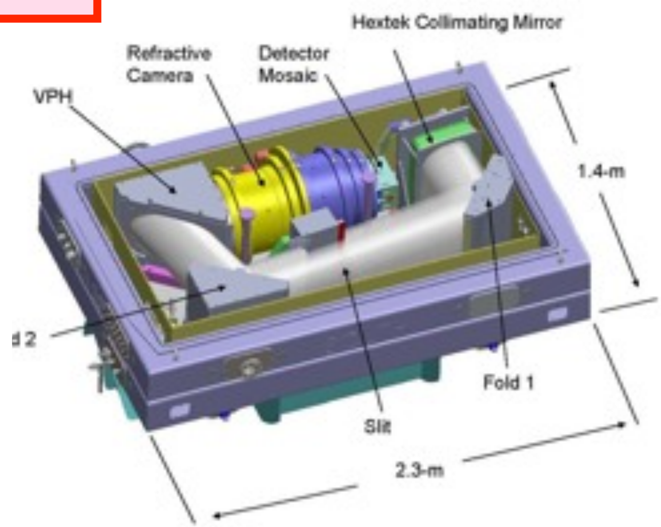
Steven Majewski
University of Virginia

September 16, 2010
SDSS-III Collaboration Meeting
Paris





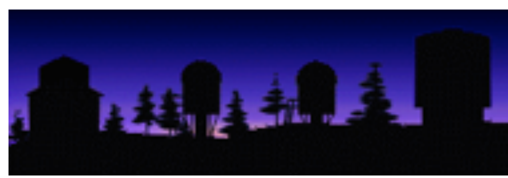




APOGEE at a Glance

- Bright time 2011.Q2 - 2014.Q2
- 300 fiber, $R \sim 30{,}000$, cryogenic spectrograph
- H-band: 1.51-1.68μ($A_H/A_V \sim 1/8$
- Goal: S/N = 100/pixel @ H=12.5 for 3-hr total integration
- Typical RV uncertainty < 0.5 km/s
- 0.1 dex precision abundances for ~15 chemical elements

  (including Fe, C, N, O, α-elements, odd-Z elements, iron peak elements, possibly even neutron capture)
- 10^5 2MASS-selected giant stars across all Galactic populations.



Top Level Science Requirements

First large scale, systematic, uniform spectroscopic study of *all* Galactic stellar populations to understand:

- chemical evolution at precision, multi-element level
  (especially for preferred, most common metals CNO)
  -- sensitivity to SFR, IMF

- tightly constrain GCE and dynamical models (bulge, disk, halo)

- access typically ignored, dust-obscured populations

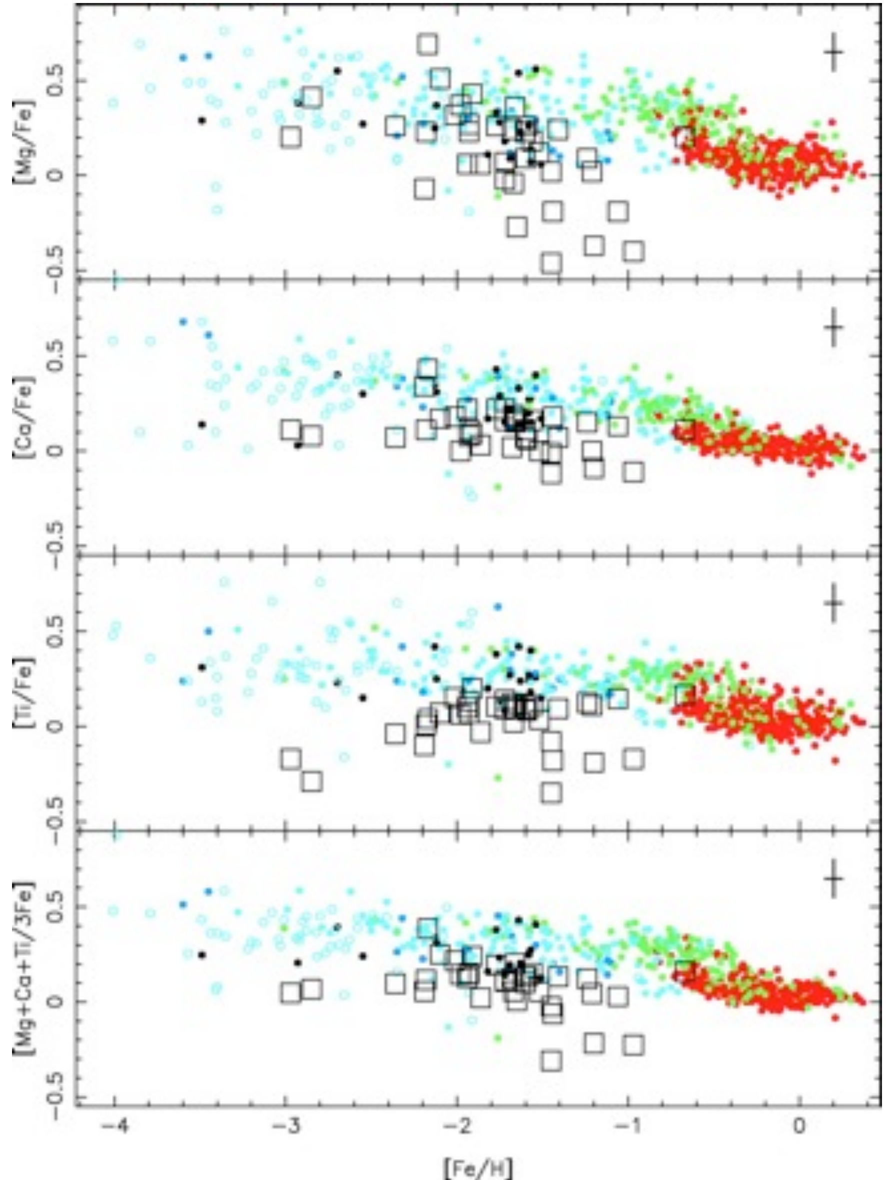
- Galactic dynamics/substructure with very precise velocities

- order of magnitude leaps:
  ~1-2 orders more high *S/N*, high *R* spectra *ever taken*
  ~2-3 orders larger than any other high *R*, GCE survey

Top Level Science Requirements

- <u>reliable statistics</u> (= solar neighborhood) in many (R, θ, Z) zones

(E.g., Venn et al. 2004 *compiled* solar neighborhood sample of 781 thin disk, thick disk and halo stars [colored dots] + several dozen dSph stars [boxes])



With 10^5 stars, APOGEE seeks to measure similar distributions for many elements and for many other discrete Galactic zones.

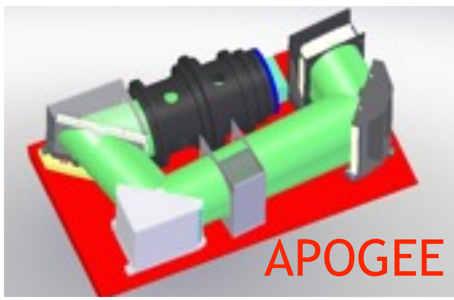
APOGEE in Context

Current and Future Spectroscopic Surveys of the Galaxy:

Now or "imminent"

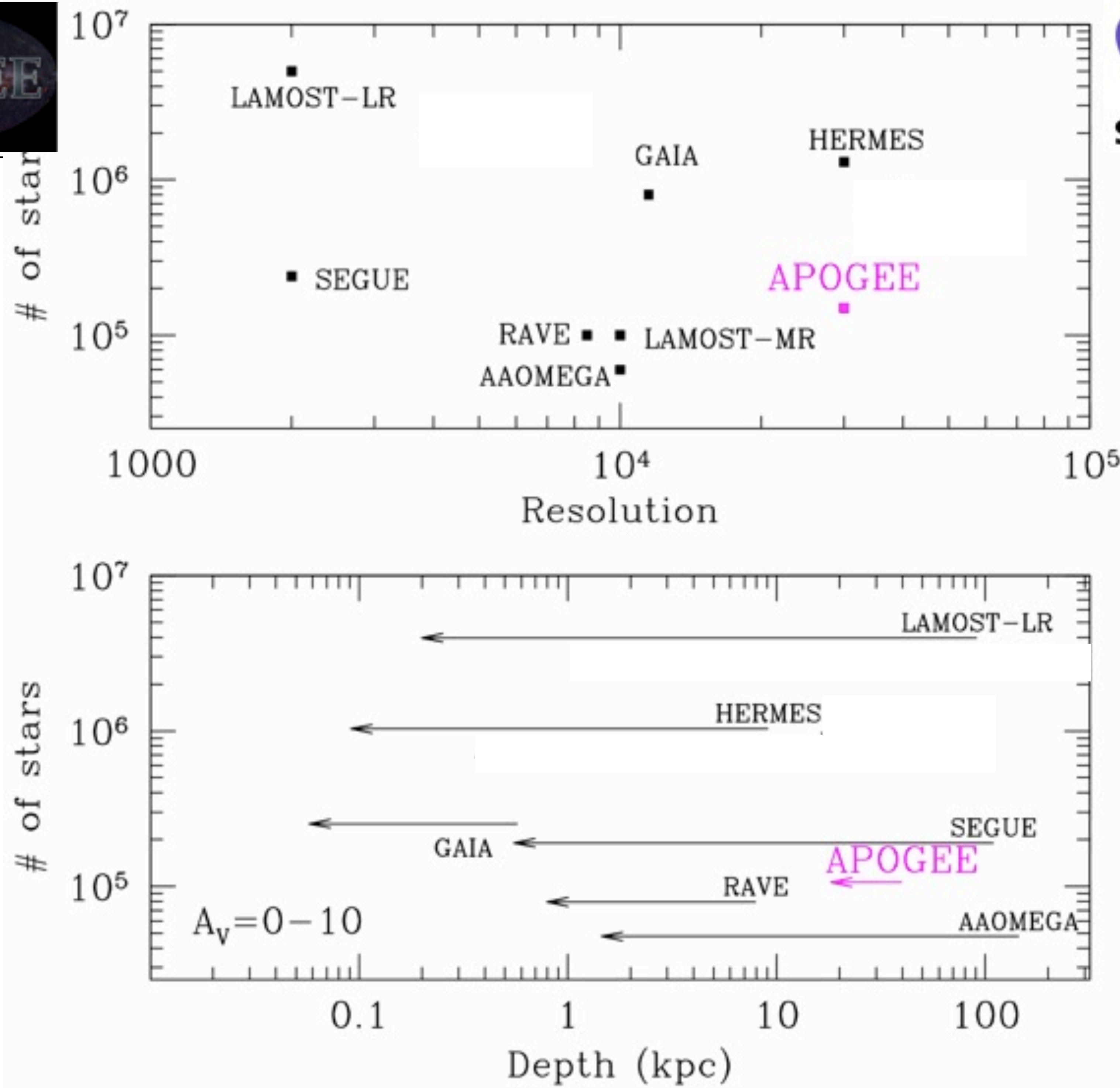
RAVE — SEGUE: Mapping the Galaxy — LAMOST

2011-2012



2015

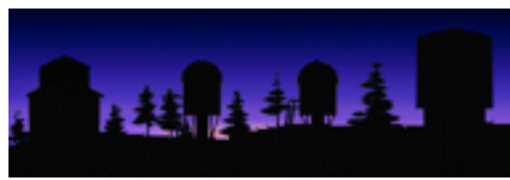
GAIA RVS



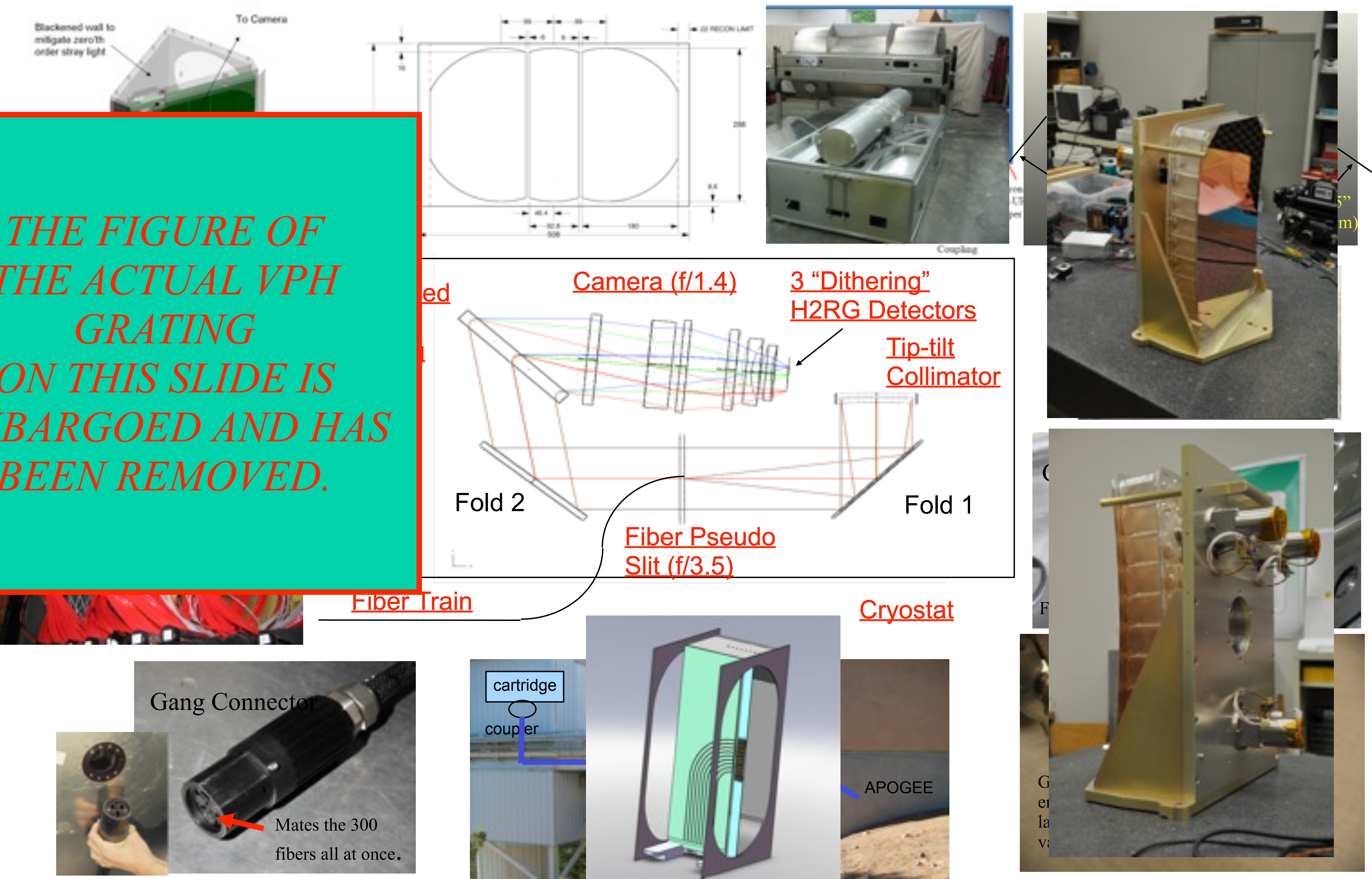
LAMOST−LR
GAIA
HERMES
SEGUE
APOGEE
RAVE
LAMOST−MR
AAOMEGA
# of stars
Resolution
LAMOST−LR
HERMES
SEGUE
GAIA
APOGEE
RAVE
AAOMEGA
A_V=0−10
# of stars
Depth (kpc)

APOGEE Ancillary Science Programs

- Just released call for ancillary APOGEE science proposals:
  - Compelling science that takes advantage of unique instrument.
  - Up to 5% of survey (15,000 fiber hours) allotted for ancillary science.
  - Variety of possibilities:
    - Specific objects landing in already existing APOGEE pointings.
    - Random objects selected from among a class (defined, e.g., by color & mag) in already existing APOGEE pointings.
    - Small numbers of new, special field pointings possible.
  - Proposals due November 1.
  - *Please ask the APOGEE team if you have any questions.*
  - APOGEE parallel sessions on topics relevant to APOGEE main survey objectives.

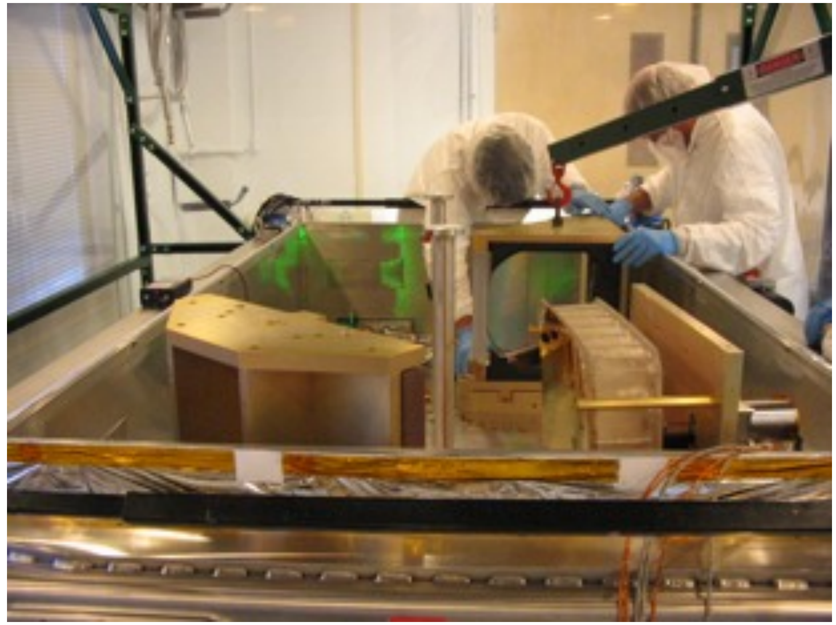


The APOGEE Instrument



APOGEE Instrument Status

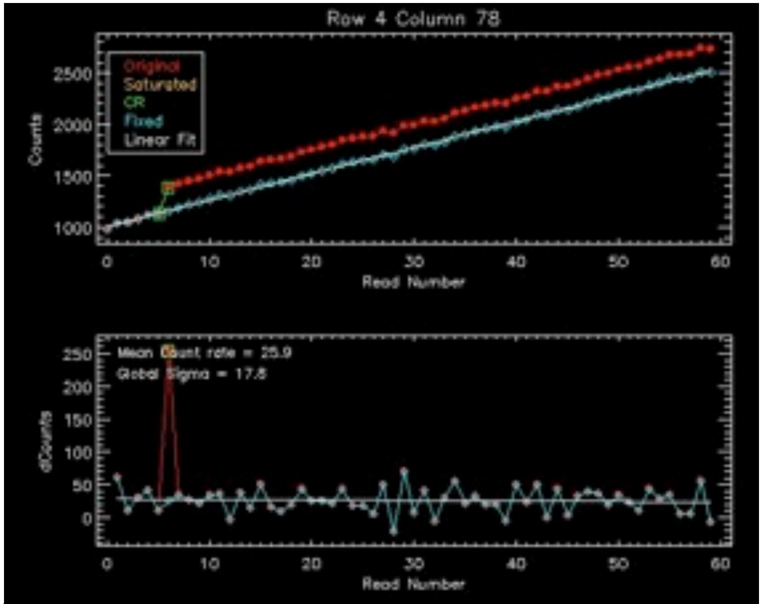
- Anticipate meeting all SRD specifications.
- All spectrograph optics delivered, assembly underway at UVa.

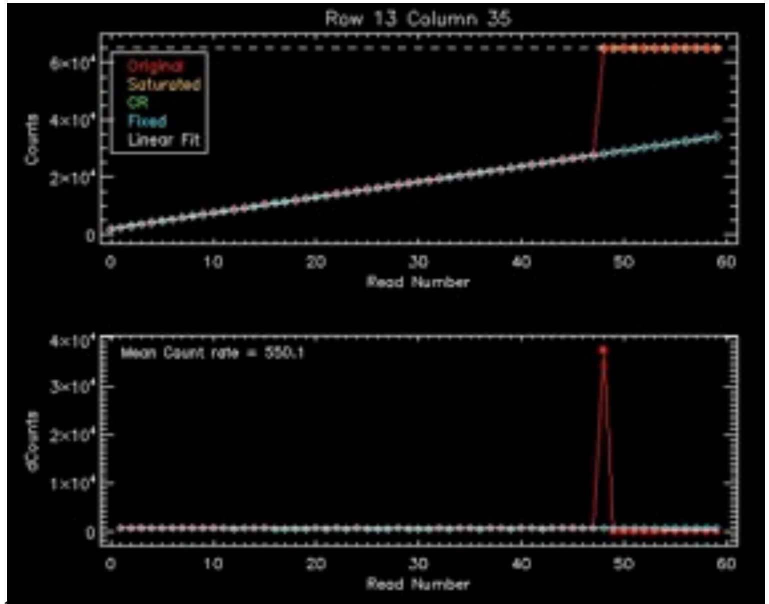


- Expect first lab spectra in October.
- Delivery to mountain by end of this year.
- Sky commissioning January-April 2011.
- Currently APOGEE more or less on schedule!

How APOGEE Data Are Taken

- Multiple non-destructive reads for each exposure.
  - Can monitor build up of exposure, adjust exposure length to achieve needed S/N.
  - "Up the ramp" sampling improves noise, can remove exposure defects (CRs, saturation).



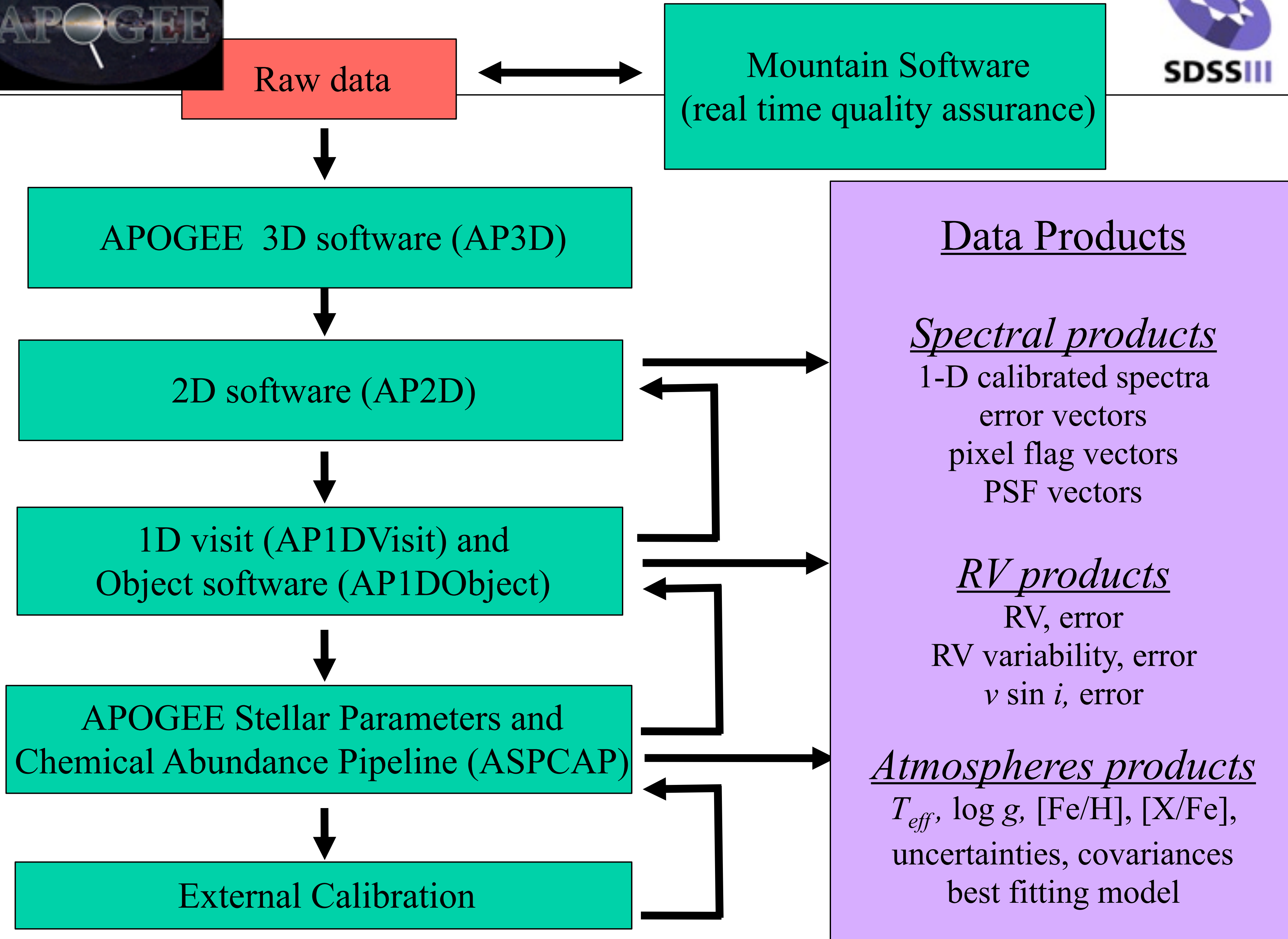


- Multiple exposures are taken for each visit to a field (w/ pixel dithering).

- Multiple visits are combined for each object (w/ RV corrections).

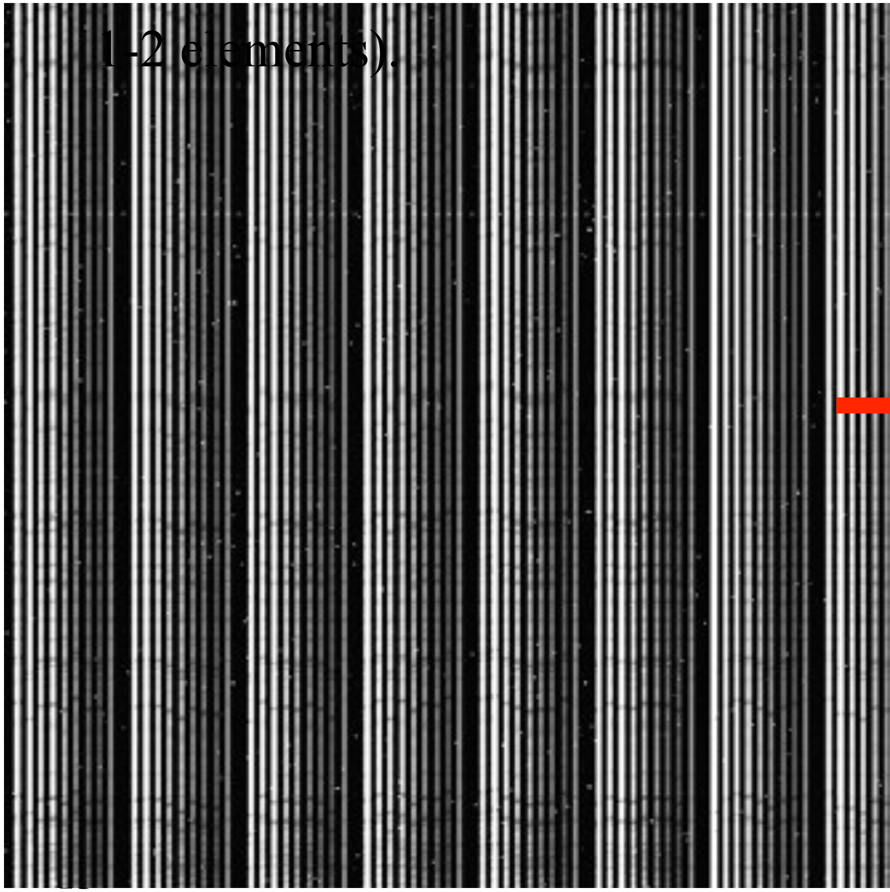
Software Overview

- Three Primary Software Modules
  - Target selection and plate design
    - I.e. making input catalogs, dereddening, target selection, plate design files.
  - Data reduction and quick look
    - From pixels to calibrated spectra.
    - Slim-downed version for real time, quick look mountain QA software.
  - Analysis to derive stellar parameters and abundances

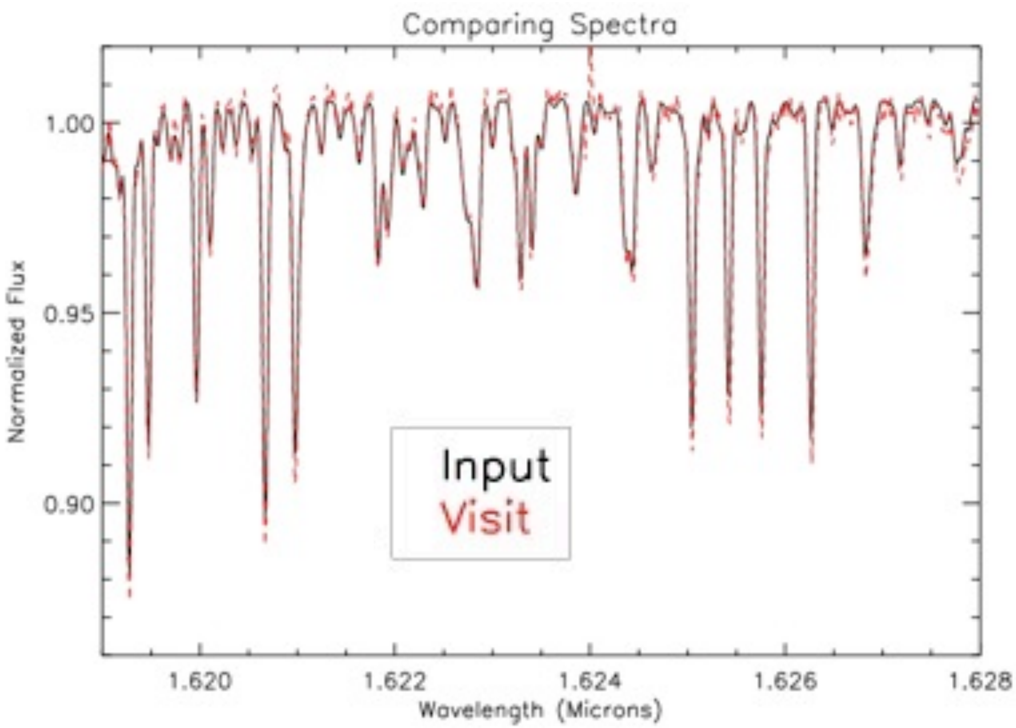

Raw data
Mountain Software
(real time quality assurance)
APOGEE 3D software (AP3D)
2D software (AP2D)
1D visit (AP1DVisit) and
Object software (AP1DObject)
APOGEE Stellar Parameters and
Chemical Abundance Pipeline (ASPCAP)
External Calibration
Data Products
Spectral products
1-D calibrated spectra
error vectors
pixel flag vectors
PSF vectors
RV products
RV, error
RV variability, error
$v \sin i$, error
Atmospheres products
T_{eff}, log g, [Fe/H], [X/Fe],
uncertainties, covariances
best fitting model

Software Status

- Preliminary end-to-end reduction *and* analysis pipeline exists.
  - Fairly realistic "fake" data have been generated from fake plugmap data.
  - These fake data have been run through fairly well-developed reduction pipeline.
  - Output from reduction pipeline has been run through simple abundances pipeline (stellar parameters + 1-2 elements).



One portion of one of the three chips



APOGEE Reduction Pipeline

The preliminary reduction pipeline in place:

- Currently consists of 118 programs (72 new).
- 17,000 lines of new code written.

- Simulated raw science frames can be processed from start to finish through the reduction pipeline and final data products (spectra) created.
- Documentation for most major modules/programs is complete.
- The code has been regularly checked-in to the SDSS3 trac SVN repository.

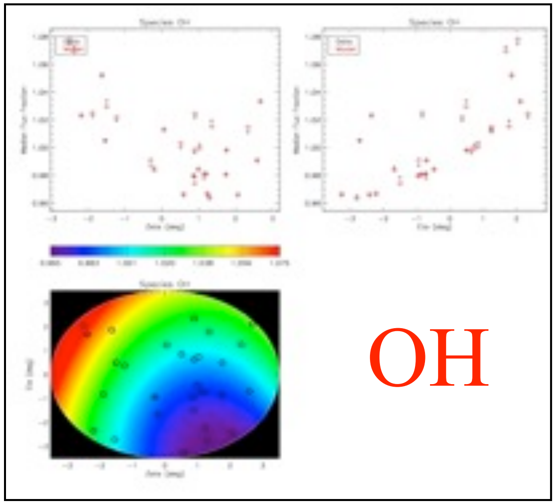
- To run:

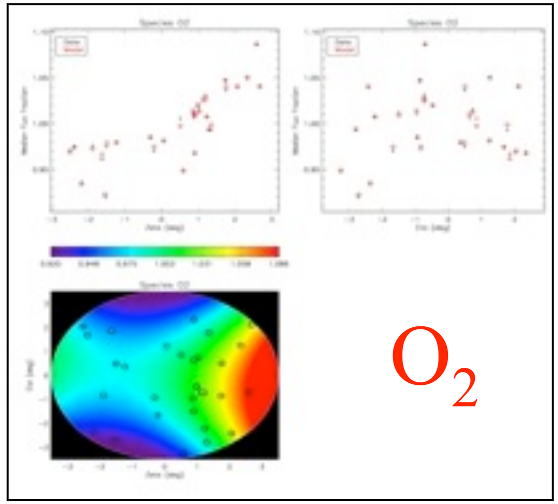
  IDL>apogeepipe,”/apogee/rawdata/MJD/”

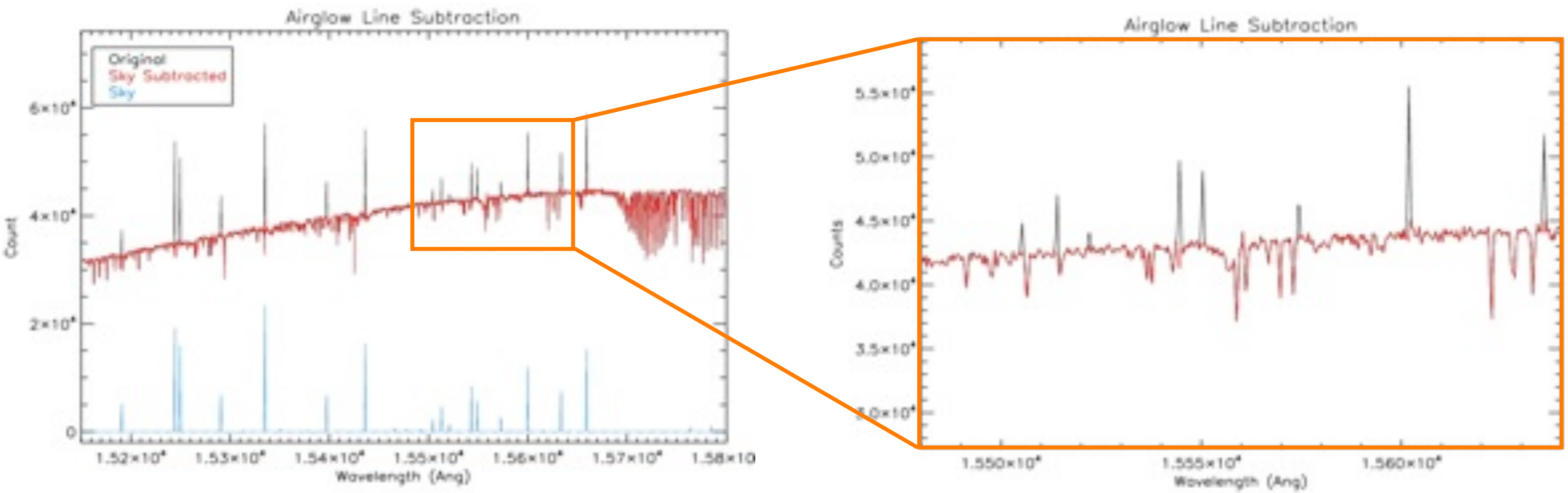
- Current estimate is 5.5 hours for 1 plate visit (six 10 min. integrations) to run through the pipeline.

Special Features of APOGEE Software

- Airglow subtraction done separately for each species (OH, O2).
  - Measure the median species "normalization" for each fiber.
- Fit 2D spatial polynomial (3rd order) to the species normalization.

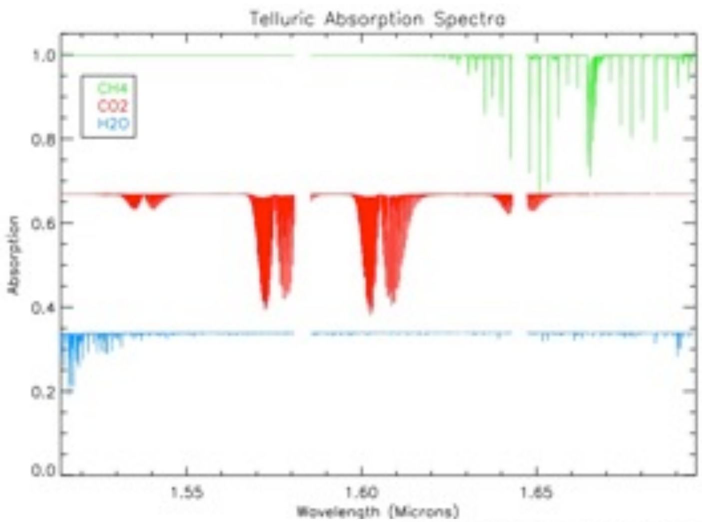


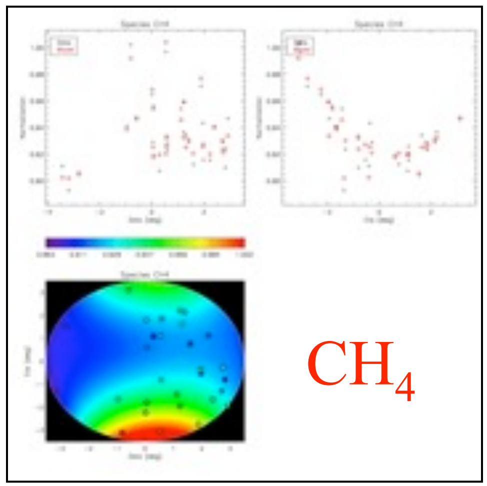


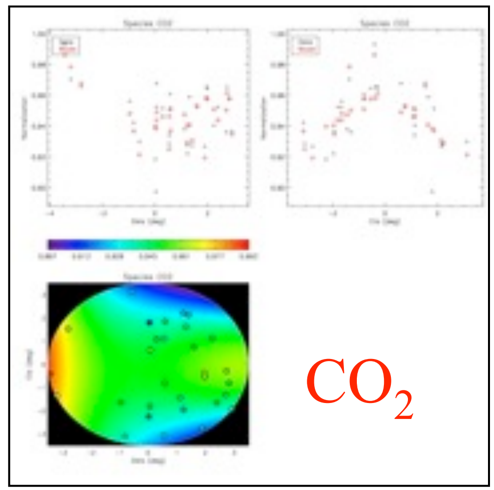


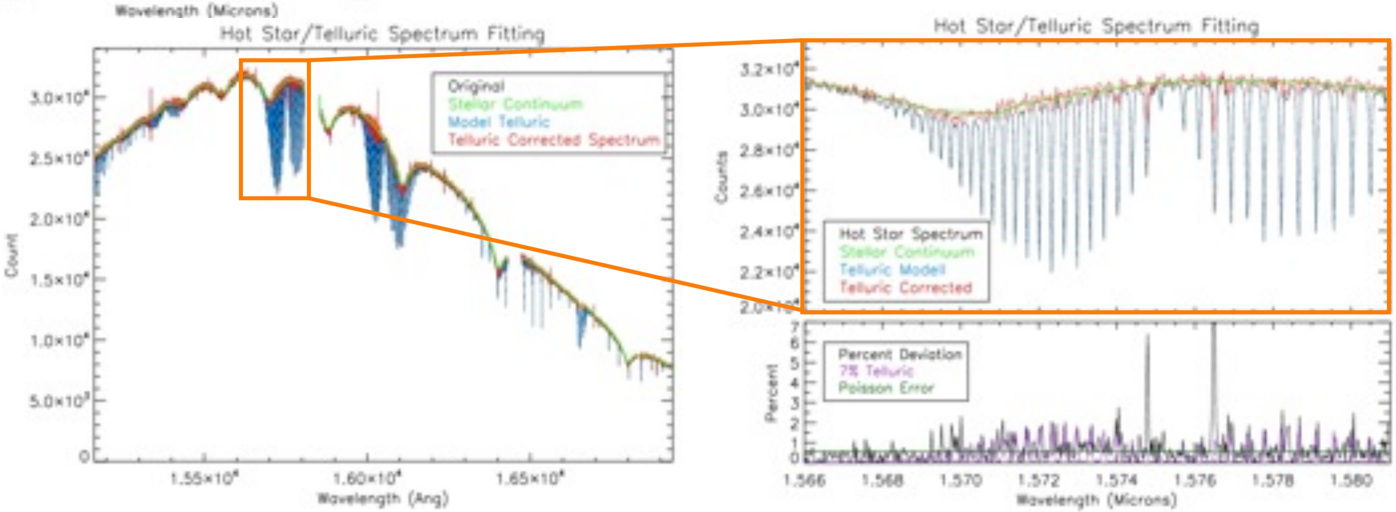
Special Features of APOGEE Software

- Telluric absorption correction.
  - Measure the median species “normalization” for each fiber.
- Fit 2D spatial polynomial (3rd order) to the species normalization.



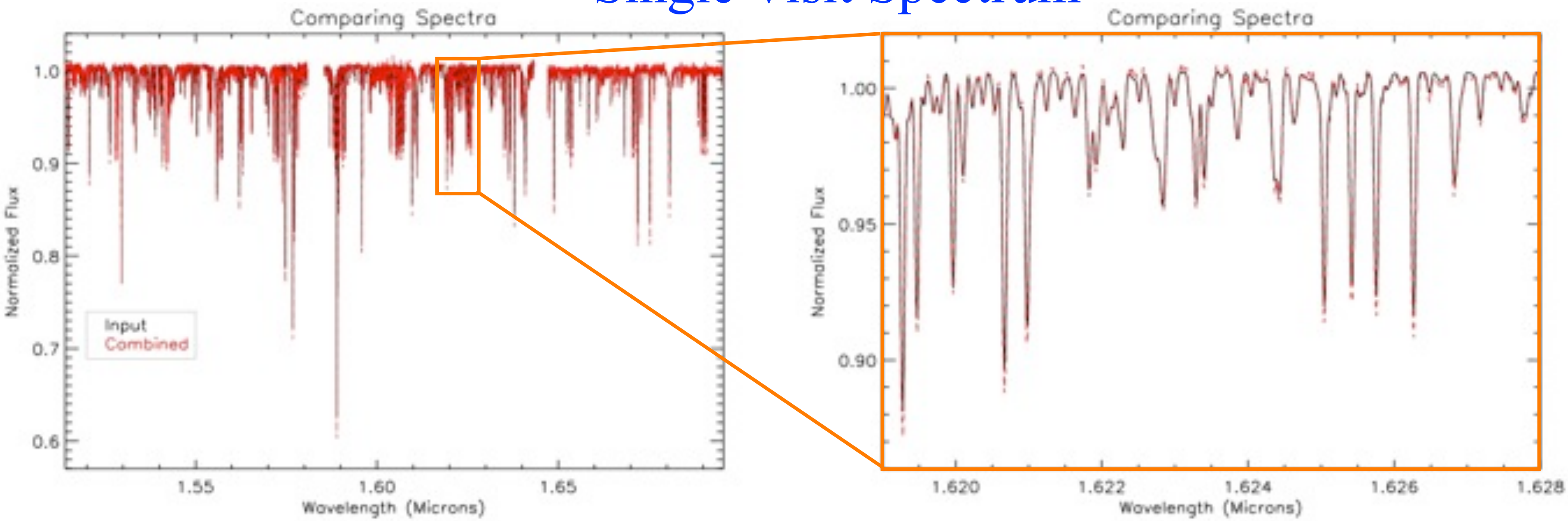


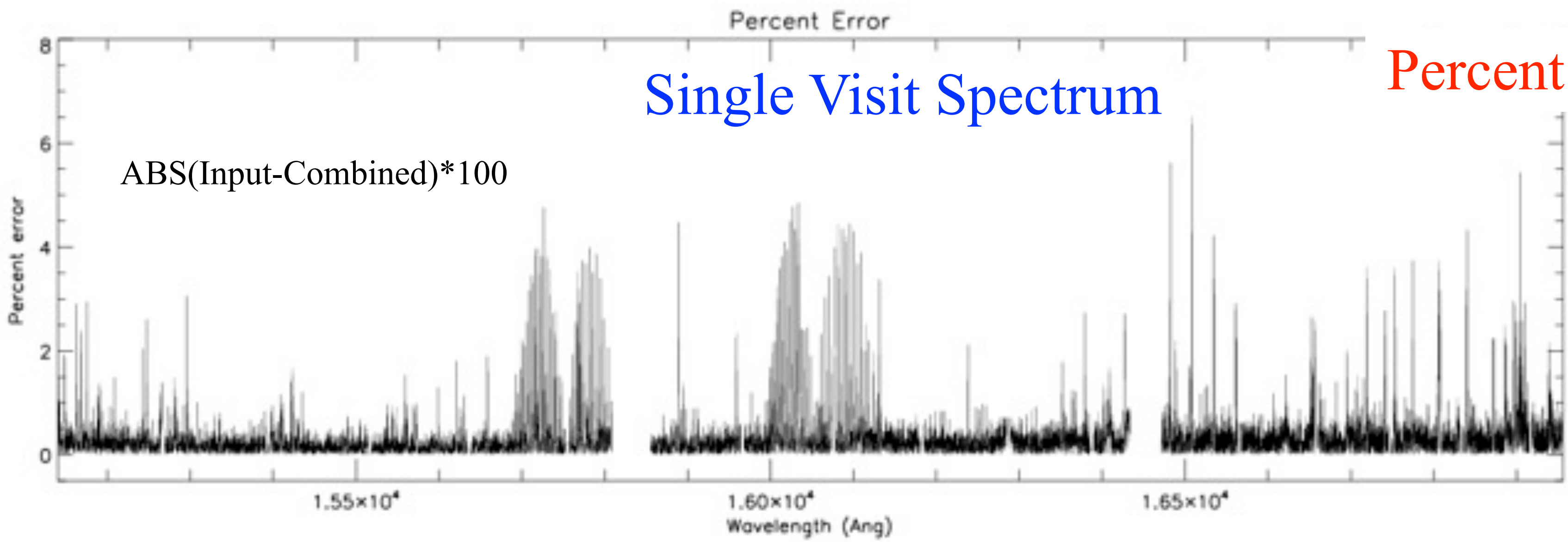




Current Check on Pipeline

Single Visit Spectrum



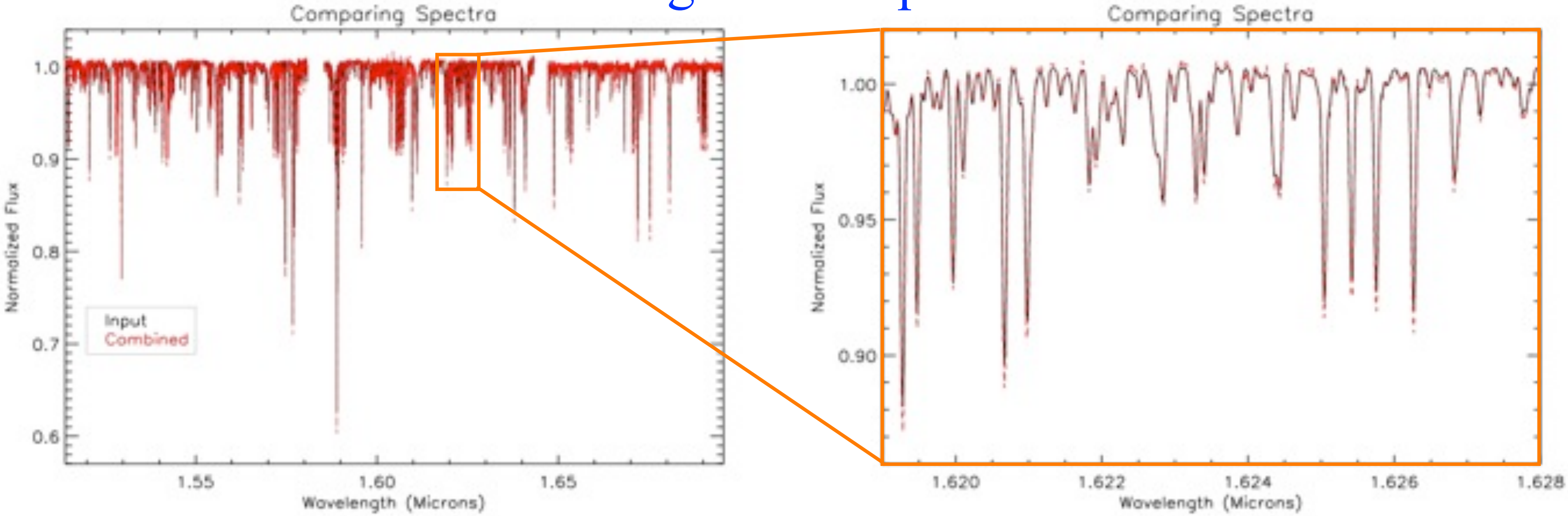


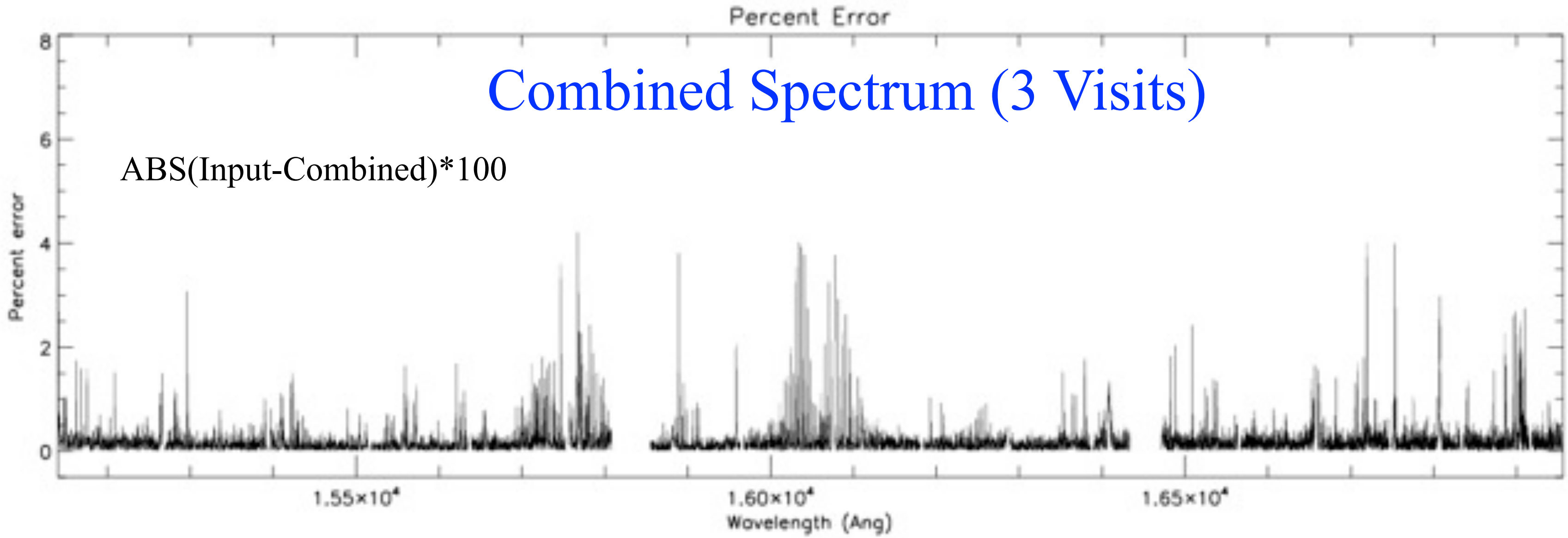
Percent Deviation

Typically <1% except for airglow & tellurics

Current Check on Pipeline

Single Visit Spectrum





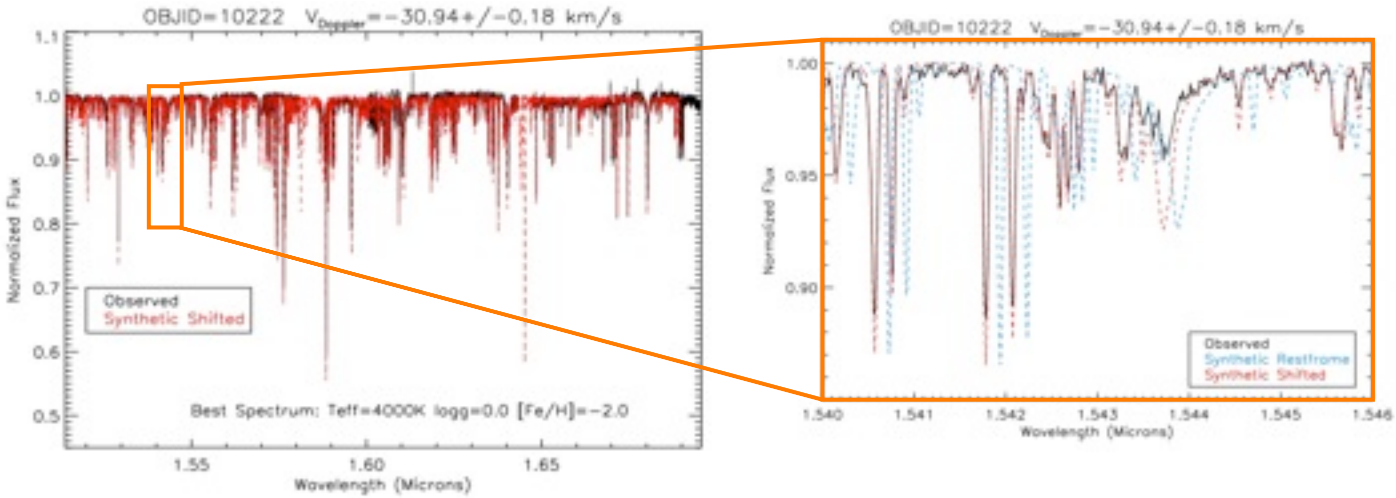
)eviation

Better for combined spectra.

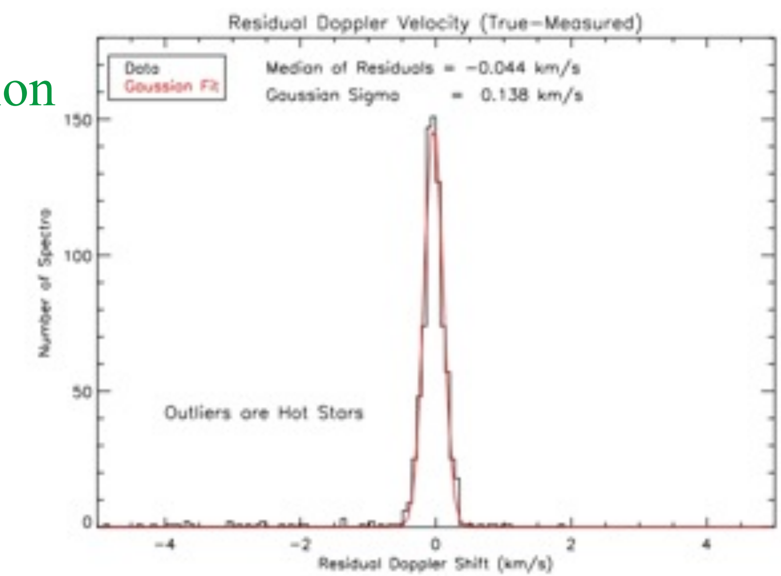
Radial Velocities

Two step process:

1. Cross-correlate with grid of synthetic spectra to obtain initial guess for RV and template:



2. Weighted average of RVs derived using χ^2 minimization of ~50A spectral pieces against chosen template



RV accuracy against input simulation RVs:

1. Median offset of -0.044 km/s.

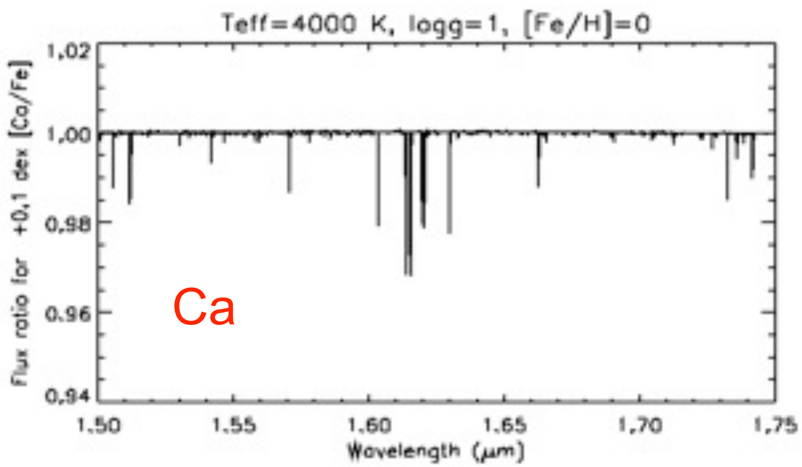
Abundances & Stellar Parameters

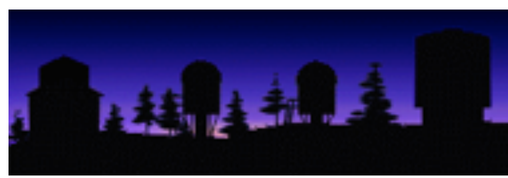
• ASPCAP c^2 optimization against pre-computed synthetic spectral libraries.

1. Determine fundamental parameters (e.g., T_{eff}, log g, [Fe/H], C/Fe, O/Fe) using large fraction of APOGEE window (1.51-1.69 mm).

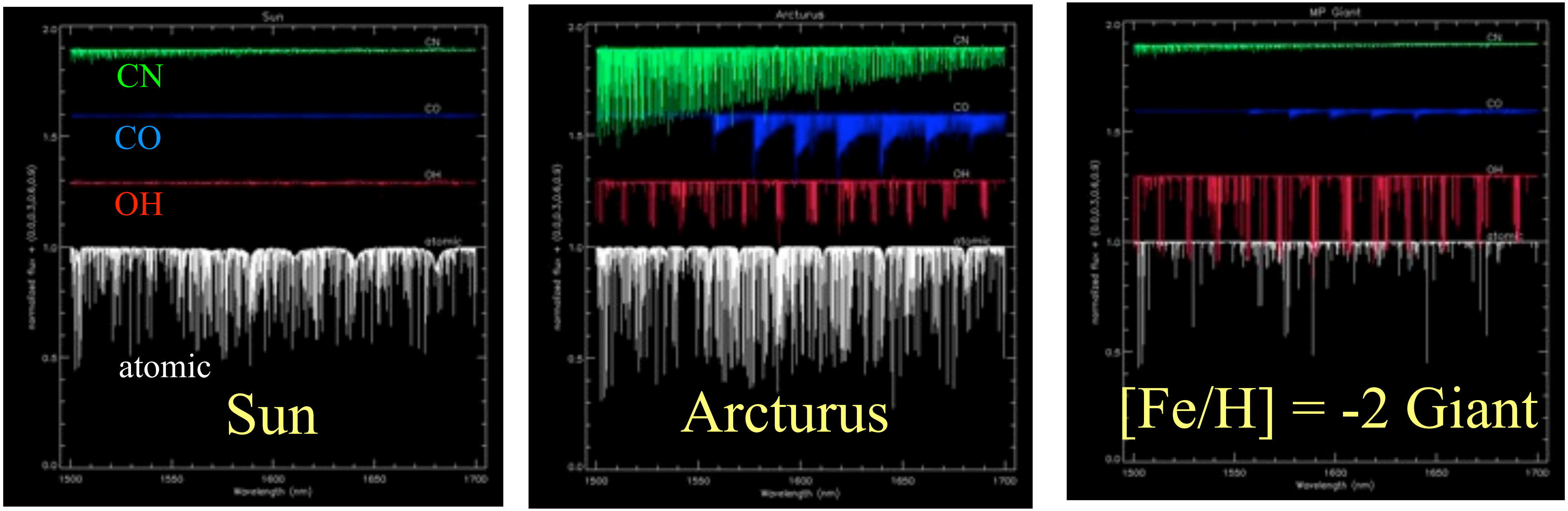
   - Abundant elements with profound impact on eqn. of state need to be considered consistently in model atmospheres and spectral synthesis (e.g., C and O).

- Derivation of other elemental abundances (Na, Mg, Al, Si, S, K, Ca, Ti, V, Mn, Co, Ni) from narrow, optimal windows for each element.





Synthetic Spectra



- TBD: Kurucz (1-D plane-parallel) or MARCS (spherical or plane-parallel) atmospheres.
- Detailed continuum & line opacities, including scattering, perhaps 3D corrections.

- At least 3000 < T_{eff} < 7000 K; hope to handle nearly all objects falling on fibers.
- Focusing on single stars, later will worry about double-lined binaries.

- Parameter space divided into classes: limits size of spectral libraries used, acknowledges different analyses for different sources (e.g., number of basic parameters, elements).

Abundances & Stellar Parameters

SDSS III

Testing minimum needed fundamental parameters for libraries:

3 (T_{eff}, log g, [Fe/H])

4 (T_{eff}, log g, [Fe/H], [C/Fe])

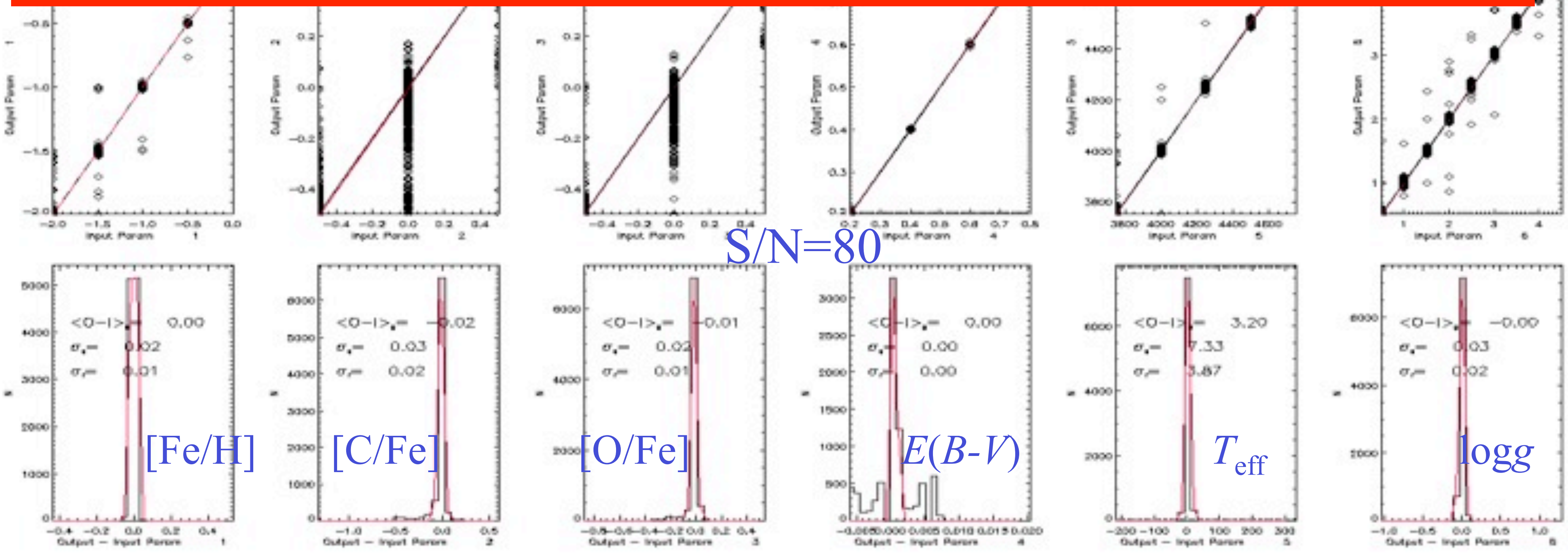
5 (T_{eff}, log g, [Fe/H], [C/Fe], x)

5 (T_{eff}, log g, [Fe/H], [C/Fe], [O/Fe])

6 (T_{eff}, log g, [Fe/H], [C/Fe], [O/Fe], E(B-V))

- For many/most targets (disk cool giants):
  - T_{eff}, log g, Fe/H, C/Fe, N/Fe, O/Fe, maybe x.
- Simplify for metal-poor stars ([Fe/H] < -1 or -2):
  - T_{eff}, log g, Fe/H, O/Fe, maybe x.
- Simplify for warmer types (G-F):
  - T_{eff}, log g, Fe/H, C/H, maybe x.

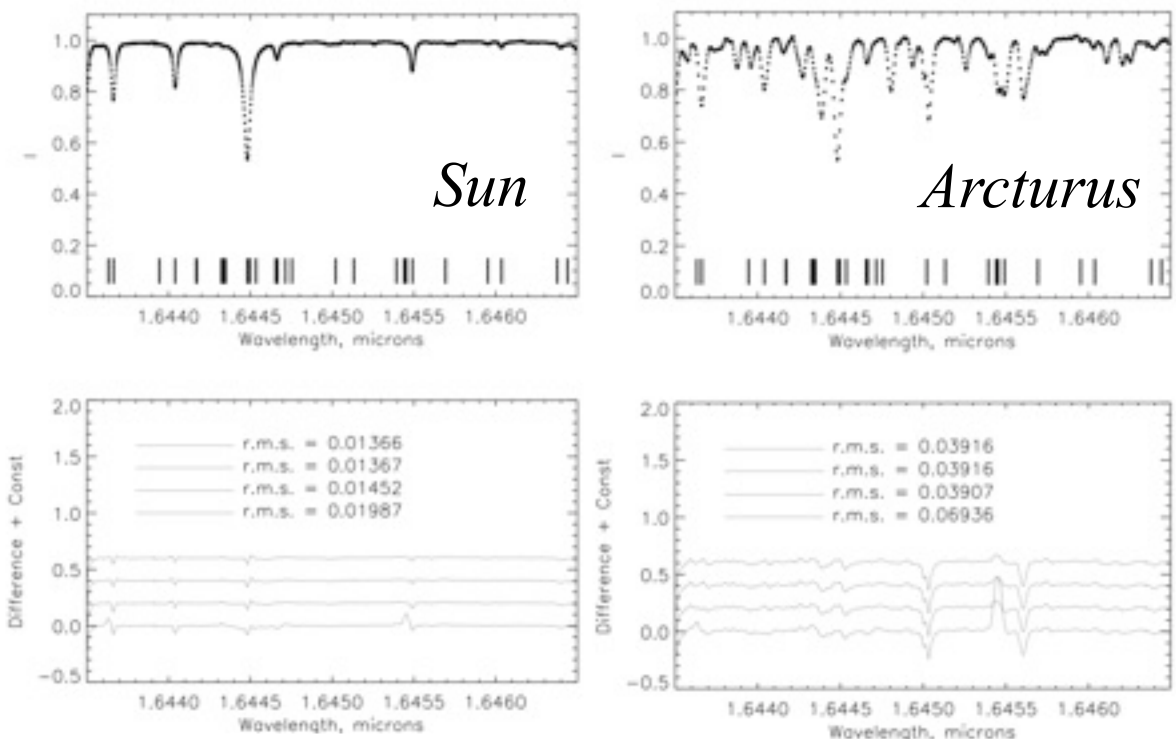
<u>A minute/star/processor (3.5 days on 20 processors for 100,000 stars)</u>



Laboratory Line Data

- Lab data, esp'ly atomic transition probabilities, poorly known in *H*-band.
- Many dozens of lines in *H*-band still unidentified.

- Three parallel efforts to develop and test linelists:
  - ❑ laboratory efforts to refine key elements parameters
    - Jim Lawler at Wisconsin Atomic Transition Probability Program, w/Shetrone, Allende-Prieto
  - ❑ basic linelist construction from literature sources
    - test against Sun or Arcturus
  - ❑ software development to create astrophysical linelists
    - simultaneously adjust *gf*-values against Sun and Arcturus (Bizyaev)

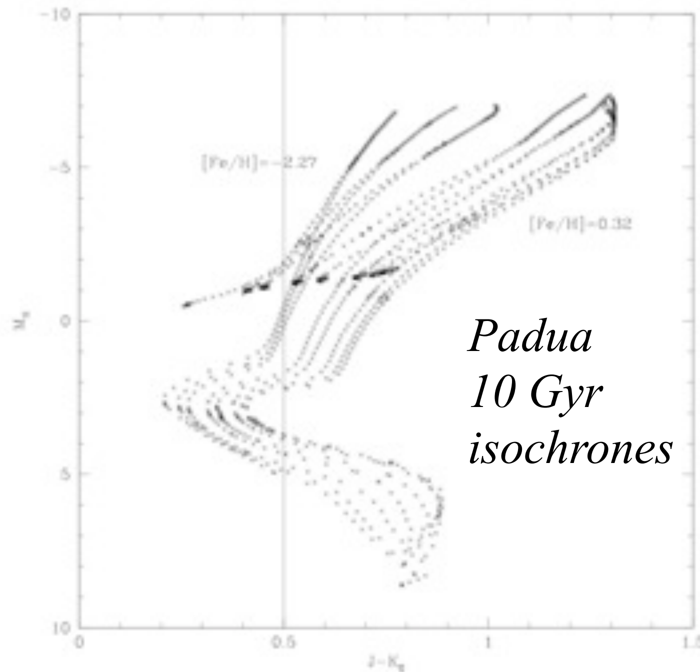


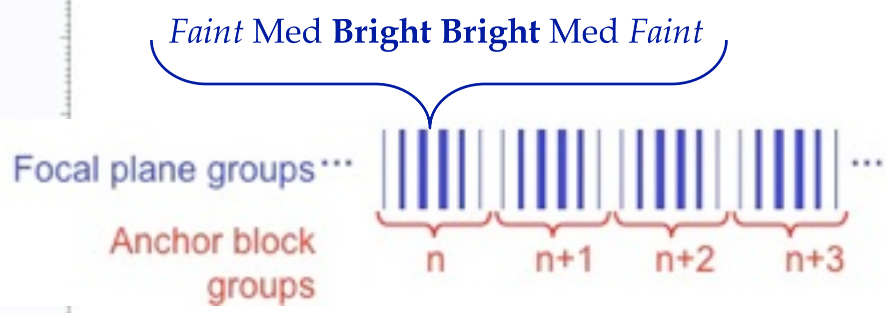
Top shows observed spectra, bottom shows residuals for each iteration.

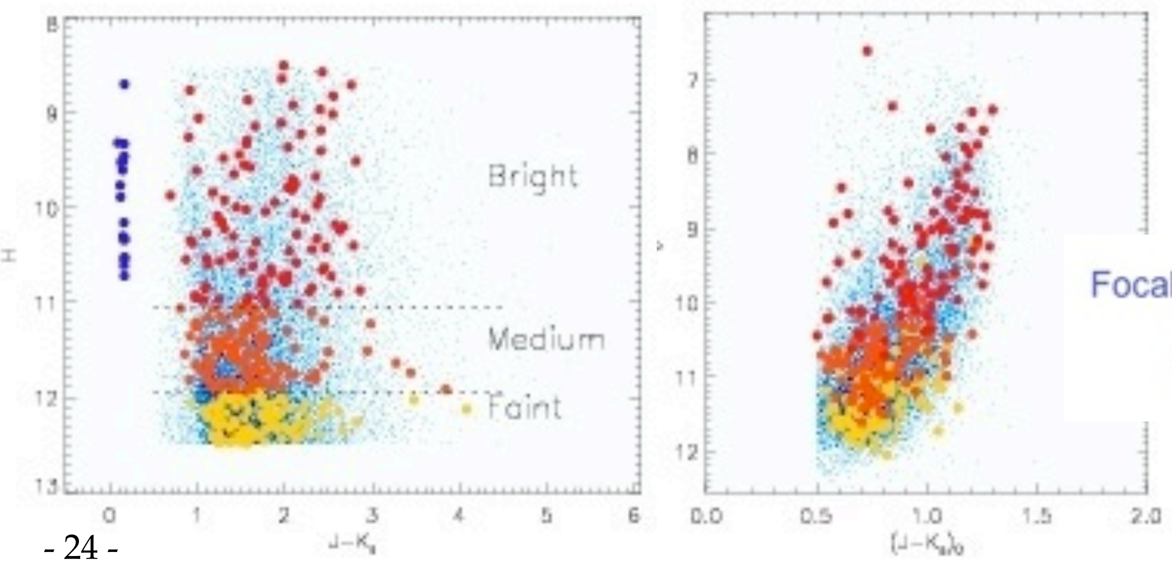
APOGEE Target Selection

Colors & Magnitudes

- Science targets
  - $0.5 \leq (J\text{-}K_s)_0$
    (no upper color limit [yet])
  - 3 flexible magnitude divisions, for consistent sampling of populations having different brightness distributions







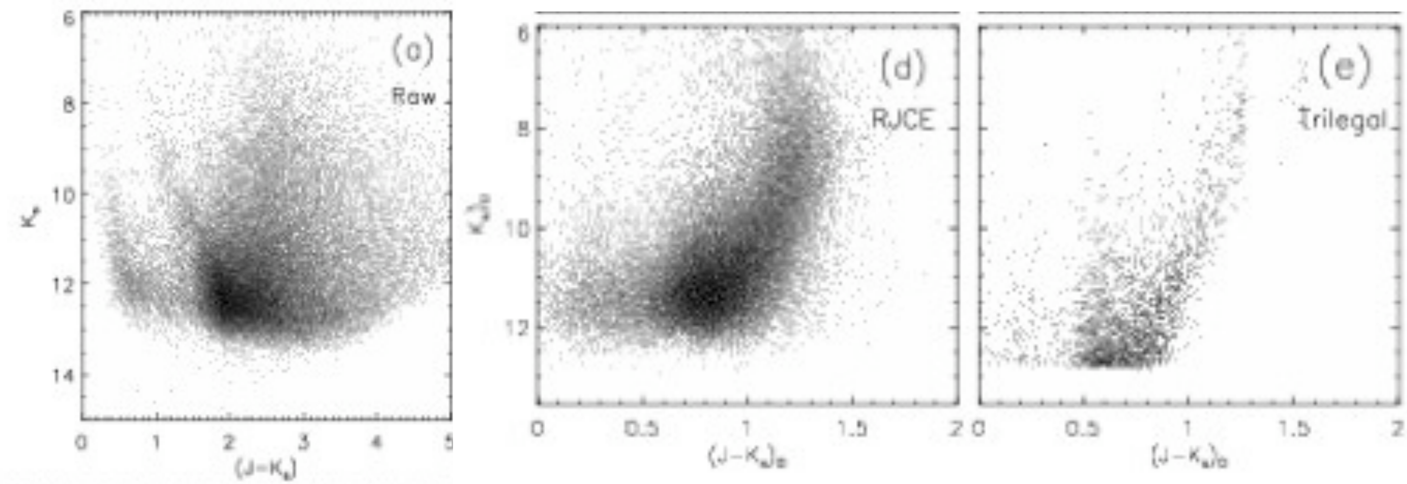
Example selection at (l,b) = (60,0)°

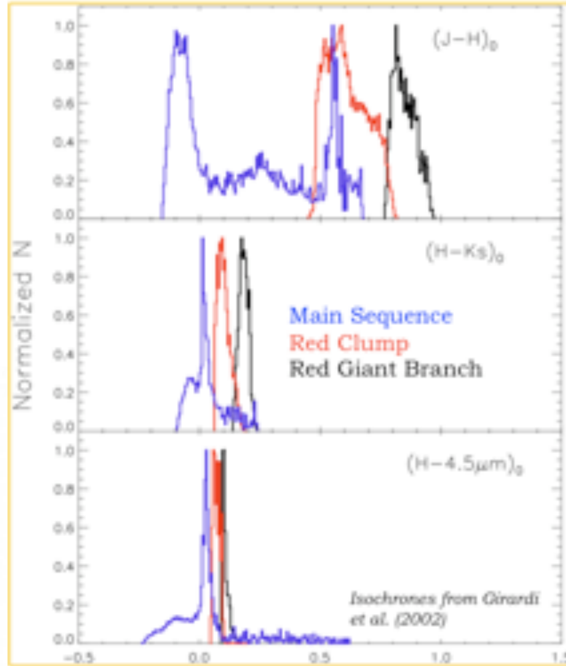
APOGEE Target Selection

Science Target Dereddening

- NIR+MIR color-excess dereddening
- Calculated on a star-by-star basis
- $\sigma(A_{Ks}) < 0.1$ mag
- Estimate $A(K_s)$ with IRAC where available (higher resolution), fill in with WISE

Observed 2MASS, (42,0)° *Corrected 2MASS* *TRILEGAL model*





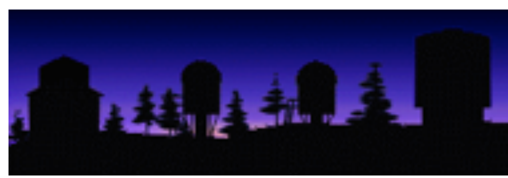
See Gail Zasowski's Talk

MARVELS/APOGEE OVERLAP FIELDS:

- 75% of stars in overlap fields (only 25% of field centers)
- 25% APOGEE only (75% of field centers)

1. LONG MARVELS OVERLAP STRATEGIES (24-hr)
   - 8 x 3-hr (H = 12.2, 2500 targets)
   - 4 x 6-hr (H = 12.8, 1500 targets)
   - 1 x 24-hr (H = 13.9, 250 targets)
   - Combination of the above

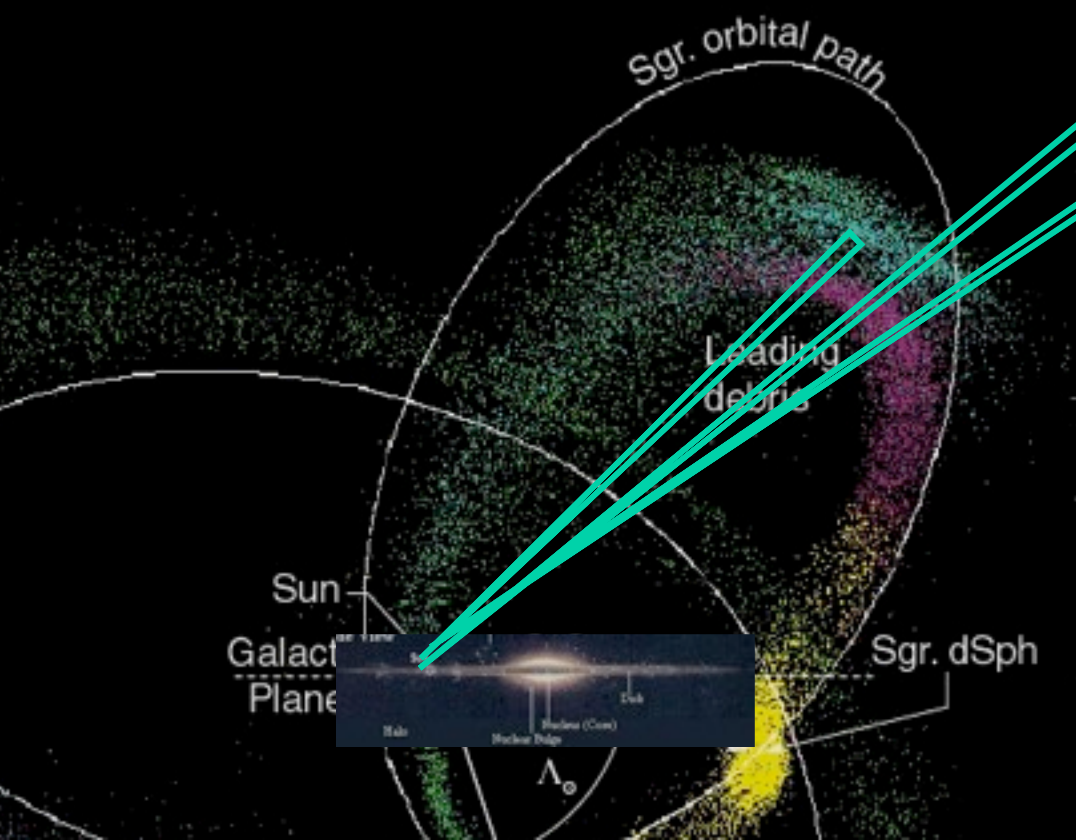
2. INTERMEDIATE MARVELS OVERLAP STRATEGIES (10-hr or 16-hr)
   - 3 x 3-hr (H = 12.2, 750 targets) -OR- 4 x 4-hr (H = 12.3, 750 targets)
   - 2 x 5-hr (H = 12.7, 500 targets) -OR- 2 x 8-hr (H = 13.0, 500 targets)
   - 1 x 10-hr (H = 13.2, 250 targets) -OR- 1 x 16-hr (H = 13.4, 250 targets)



Survey Depth: Deep Fields

Solar metallicity RGB tip star:

int (hr)	H_{lim}	A_V	d(kpc)
3	12.5	5	27
10	13.4	10	27
30	14.1	15	26



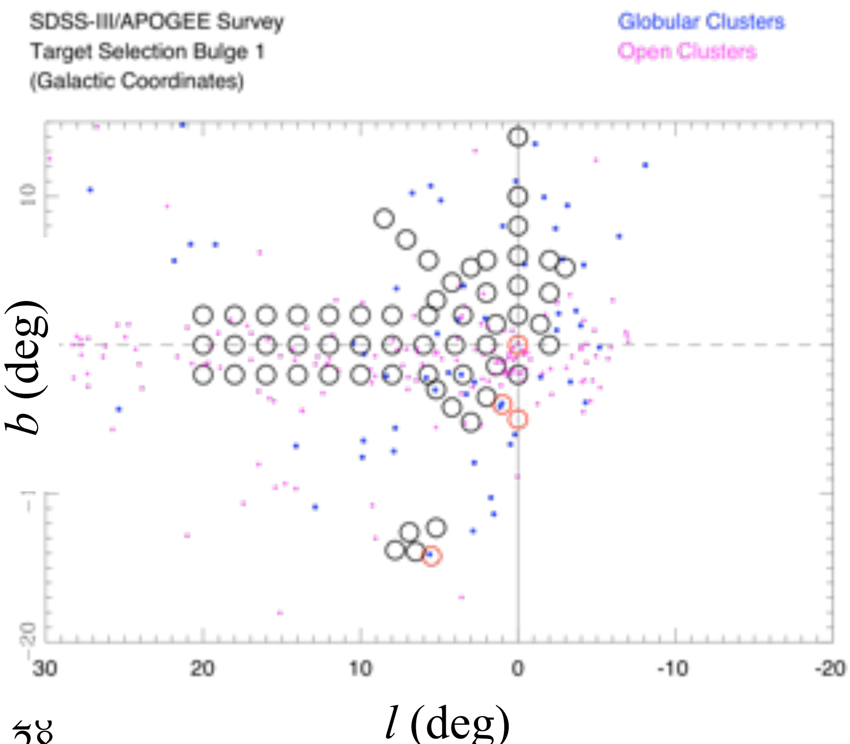
[Fe/H]= -1.5 RGB tip star:

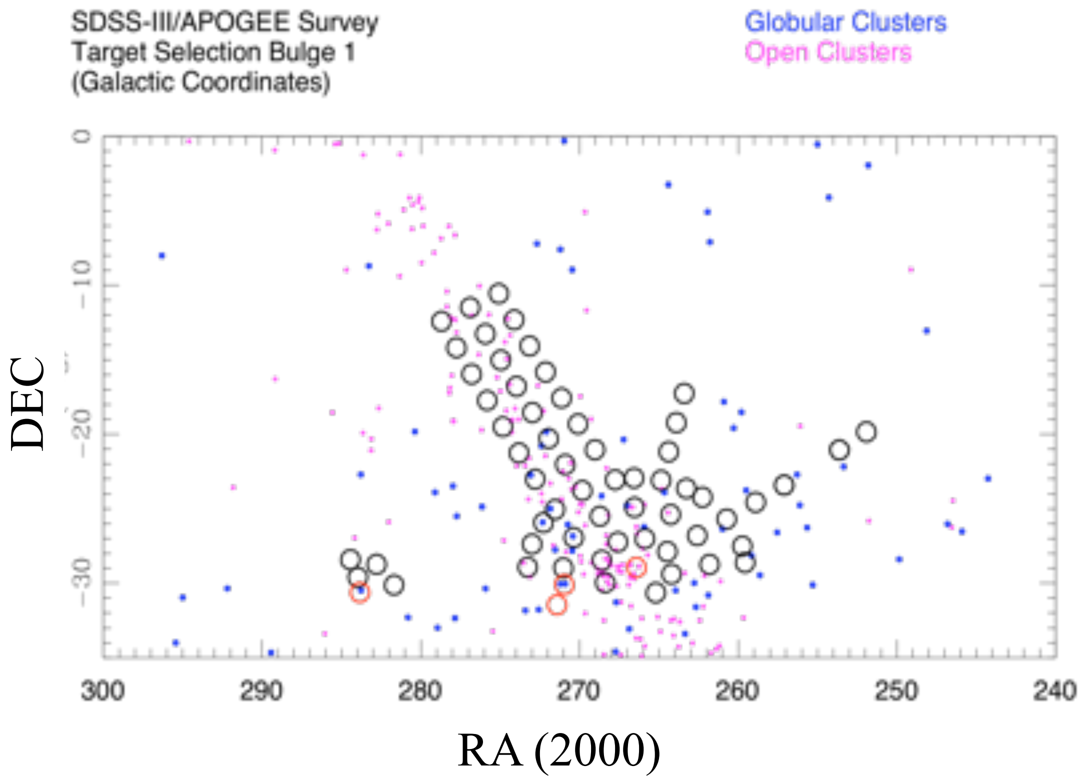
int (hr)	H_{lim}	A_V	d(kpc)
3	12.5	0	40
10	13.4	0	60
30	14.1	0	83

APOGEE Field Selection: Bulge

Inner Galaxy Observing Plan:

- Grid survey of bulge & inner disk
- Some Sgr dwarf pointings
- Selected deep pointings (Red)

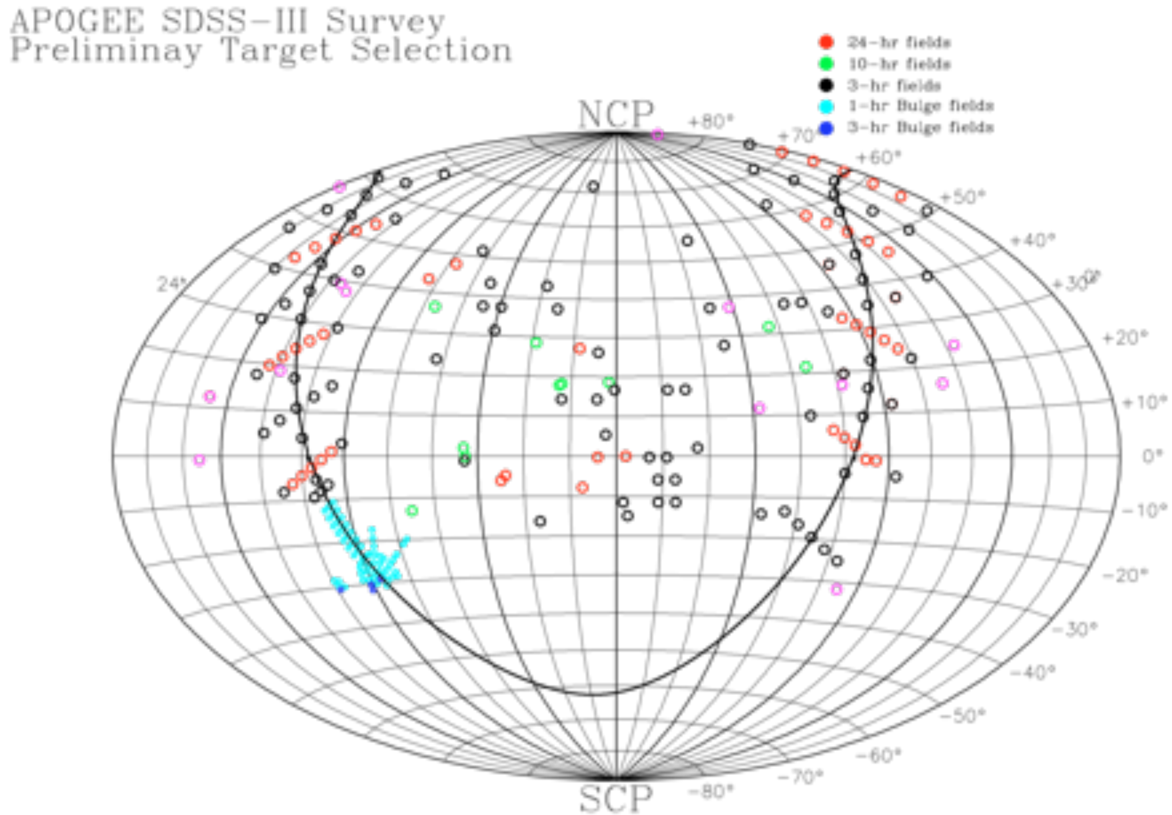




Field Selection: Disk & Halo

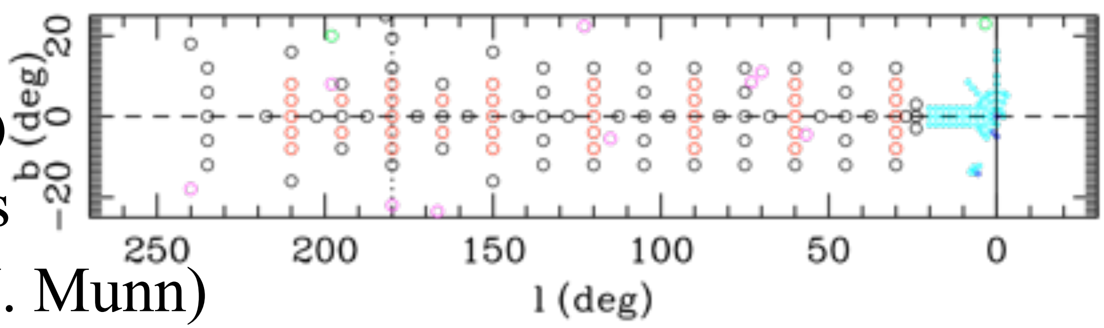
Disk Plan:

- ❑ Deep pointings (24-hr)
  - $b = 0, \pm4, \pm8$
- ❑ Nominal pointings (3-hr)
  - Fill-in between deep fields.
  - $-16 < b < 16$ for thick disk.
- ❑ Calibration (3-hr)
  - key open star clusters



Halo Plan:

- ❑ 10-hr fields – globulars (calibration & science)
- ❑ $b = 45$ grid + tidal streams
- ❑ Wash+DDO51 imaging (J. Munn)

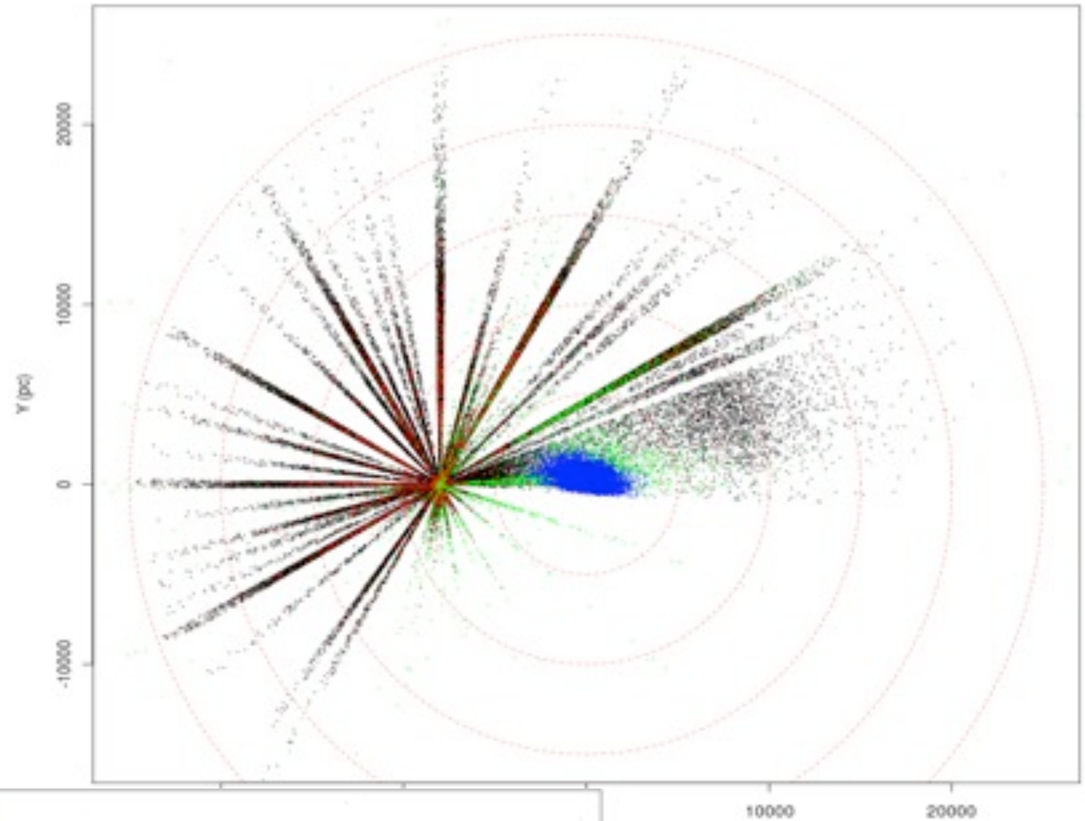


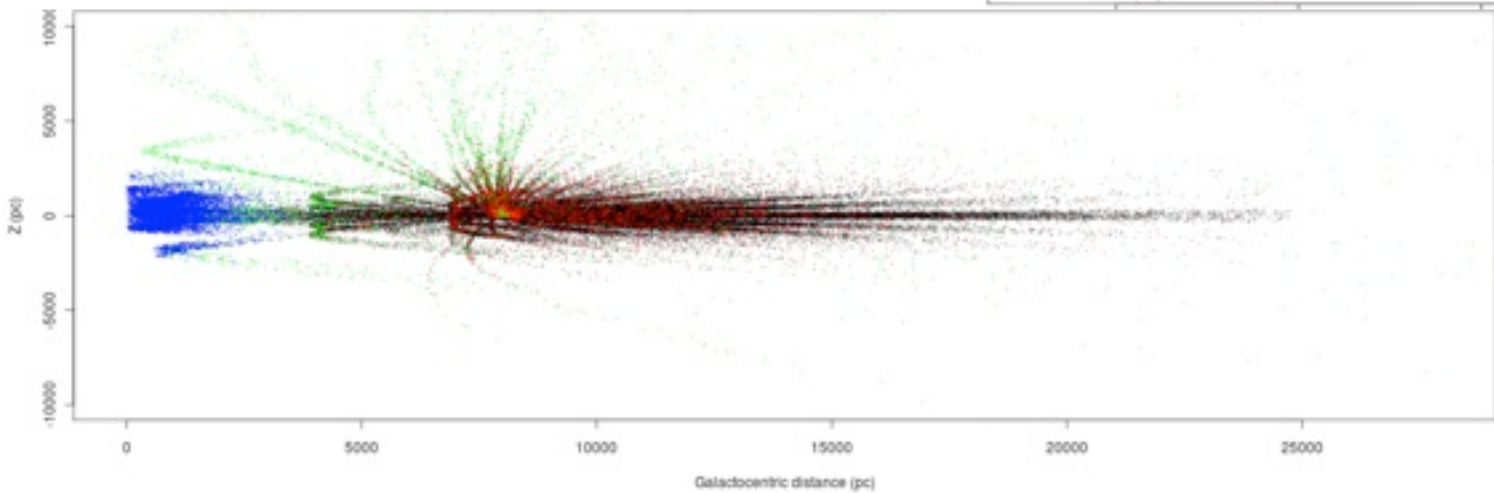
Anticipated Spatial Distribution

For currently selected fields

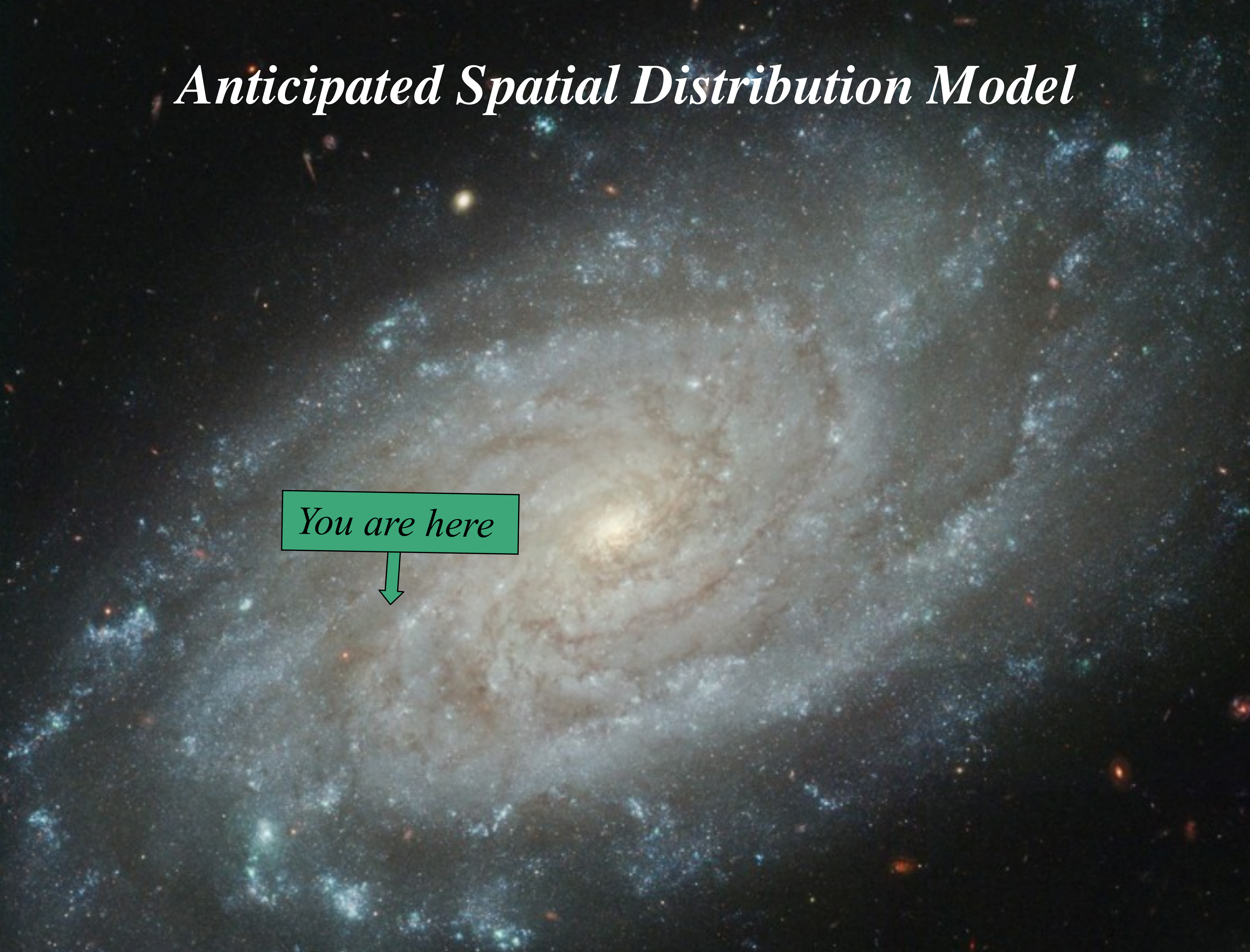
Bulge	*8000 stars*
Thin disk	*84100 stars*
Thick disk	*4300 stars*
Halo	*4500 stars*

79% giants of 101,000 stars





Anticipated Spatial Distribution Model



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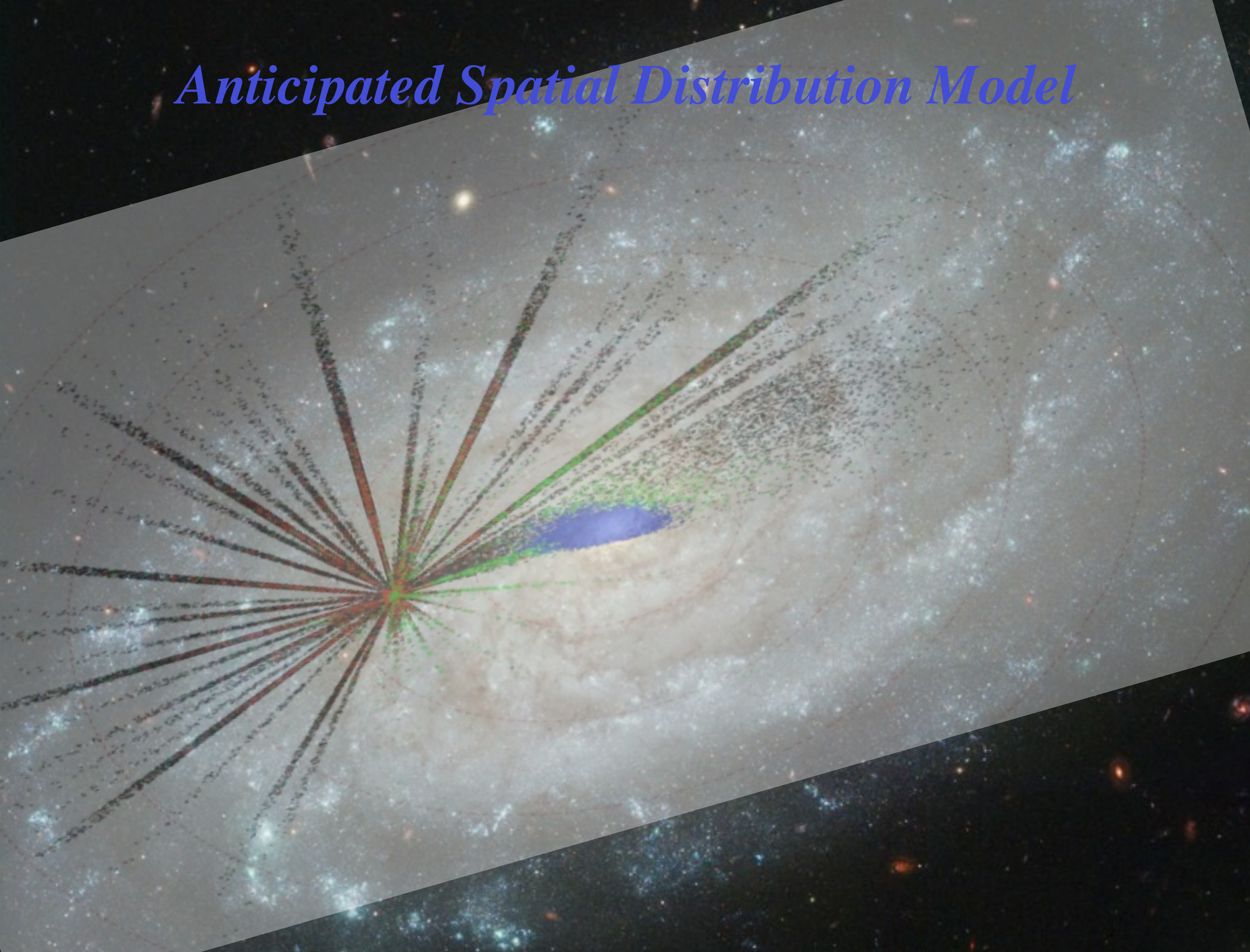

Anticipated Spatial Distribution Model

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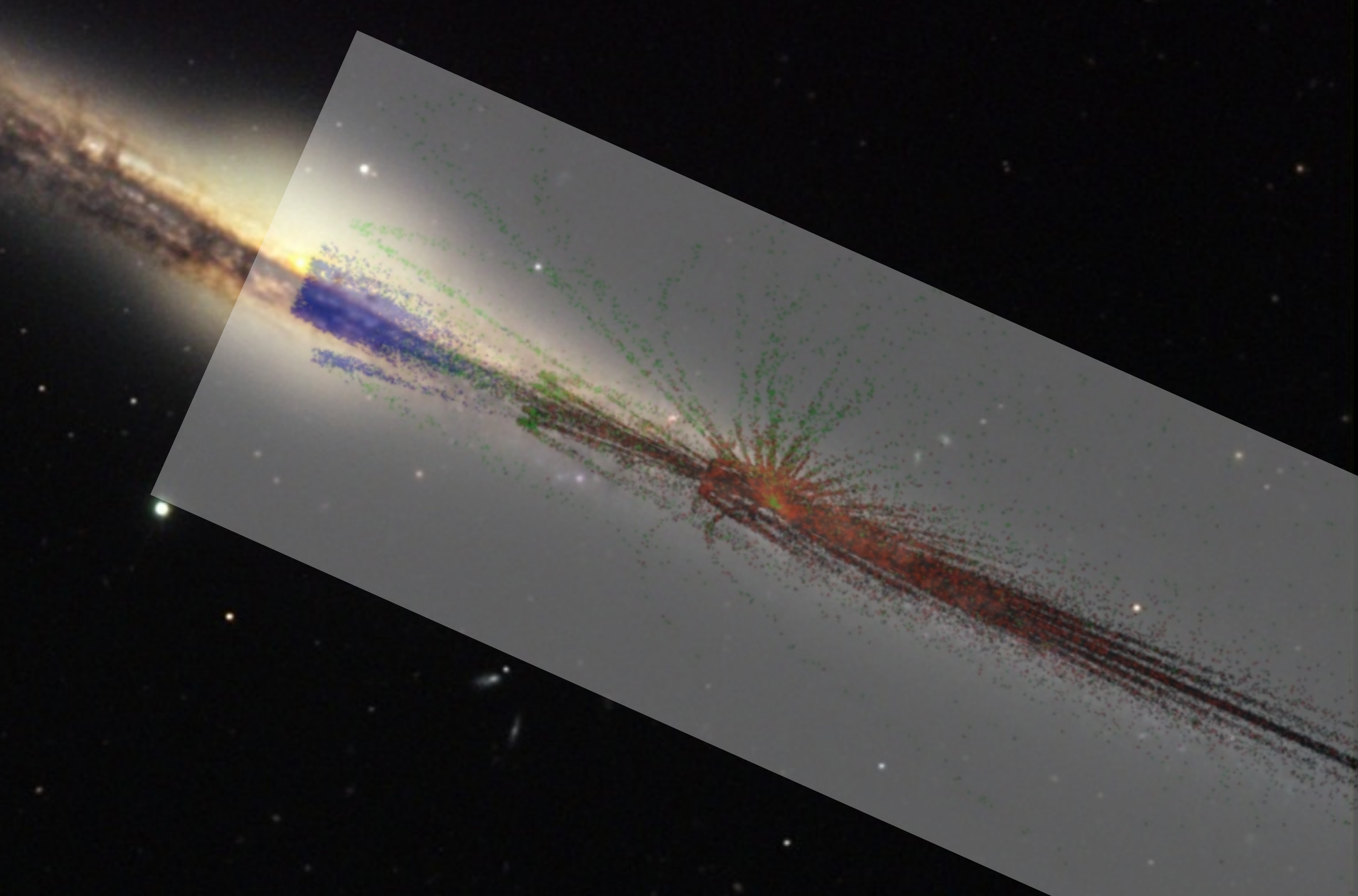

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  - PI: Steven Majewski (Virginia)
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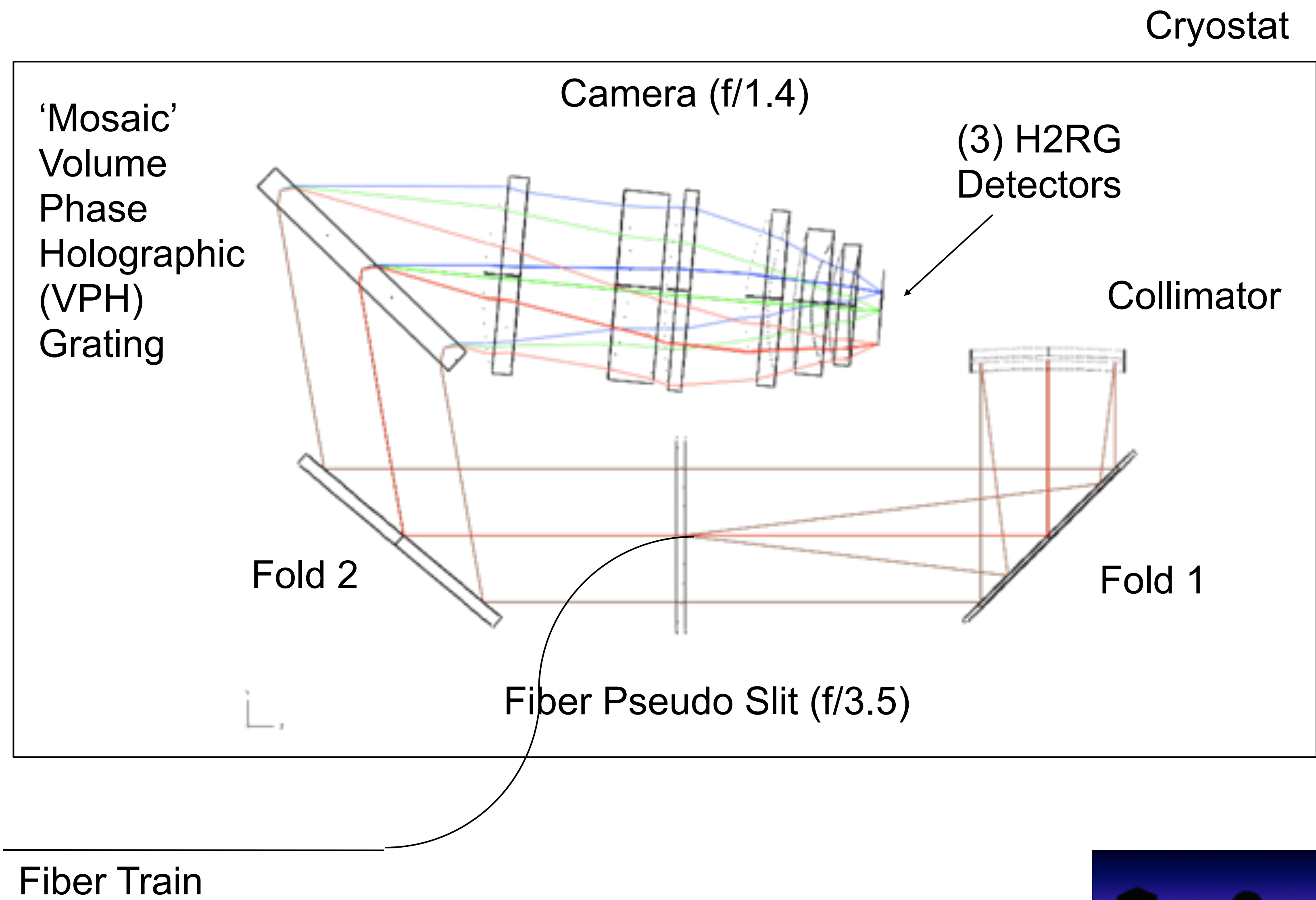
APOGEE

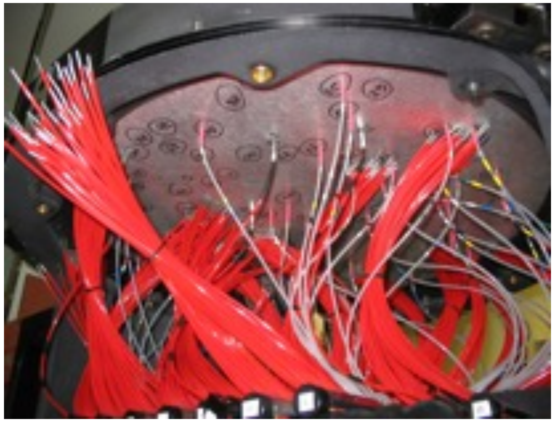
Two Million Years of Scientific Progress

Extra Slides

The APOGEE Spectrograph



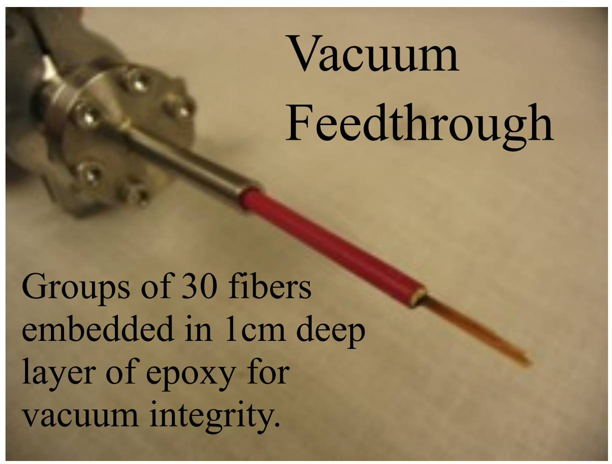
Special Features of the Instrument: 40-m Fiber Train

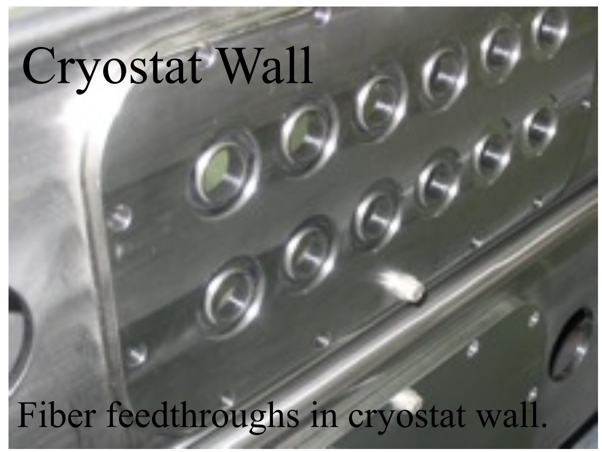


2.5-meter

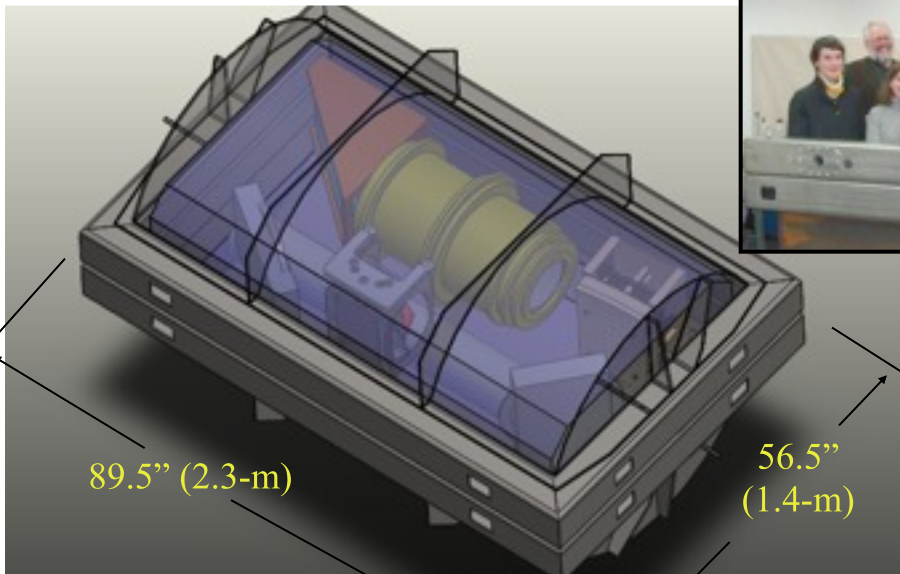
Unlike previous SDSS spectrographs, APOGEE dewar in support building 40 meters from 2.5-m.

- Connected by long optical fiber run (blue line).
- Requires fiber couplers ("gang connectors") from cartridge fibers to instrument fibers.
- Slit head is cryogenic and permanently housed in the instrument -- requires vacuum feedthroughs.





Special Features of the Instrument: LN2 Cryostat (It's Large!)



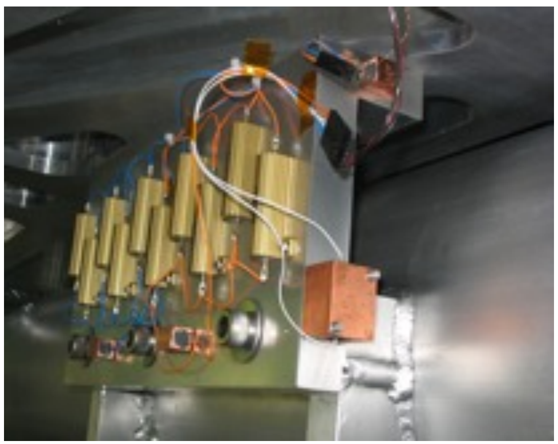
Cryostat Assembly at PulseRay.

Vacuum Shell

90 liter LN2 tank (3-day hold time)

Lightweighted cold plate.

Alum shield encloses entire cold volume.



One of two banks of heaters – each capable of 0.5kW input.

One of two charcoal getter banks – each contains 300 grams.

Aluminized mylar sheets on inner-surface of warm vessel walls.

Custom thermal blankets surround shields: 10-layers

of double-sided aluminized mylar interspersed with wedding veil

Special Features of the Instrument: First Mosaiced VPH Grating

- Volume Phase Holographic grating:
  - Transmissive dispersing element – keeps camera size reasonable.
  - Excellent theoretical efficiencies.
- APOGEE pupil size is 290 mm. With 54 deg AOI, width of the VPH must be 465 mm.
- No VPH vendors have such large recording optics.
- Mosaic VPH has never been deployed before …

…but now successfully manufactured by Kaiser Optical Systems to better than specified!

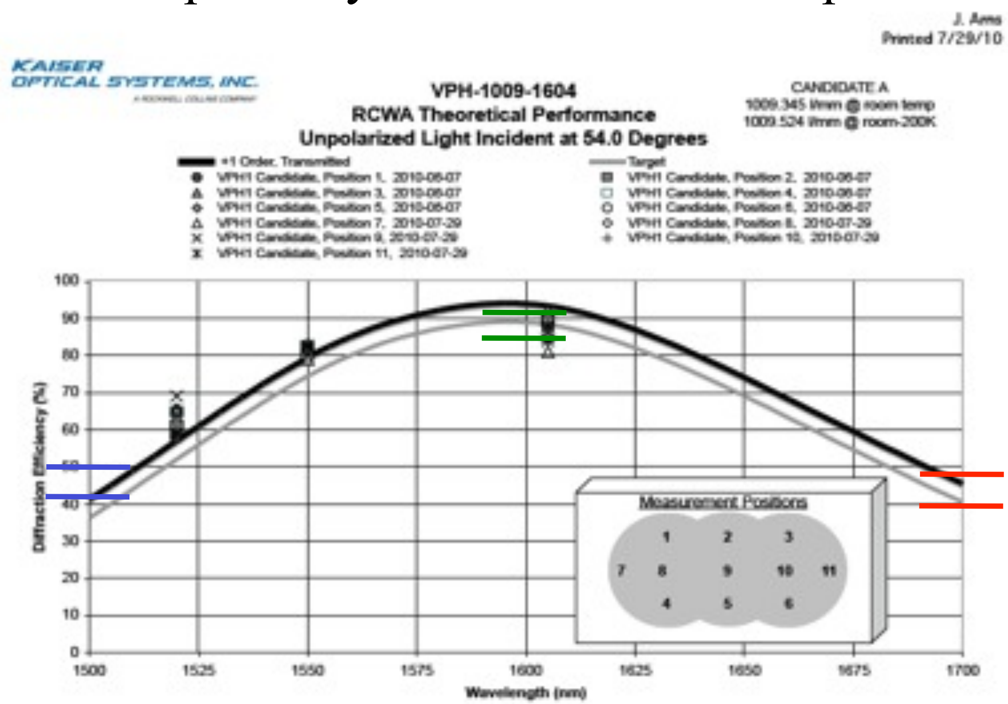
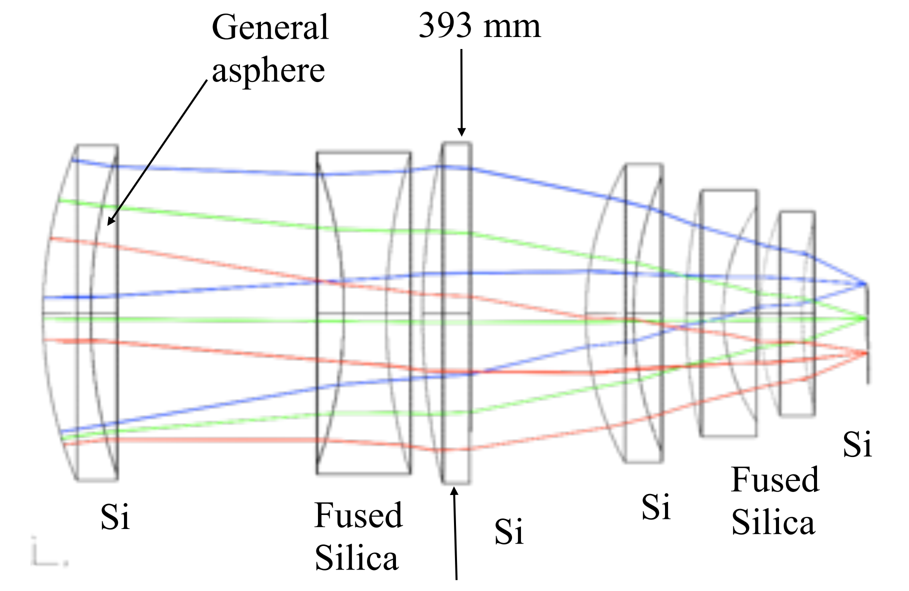


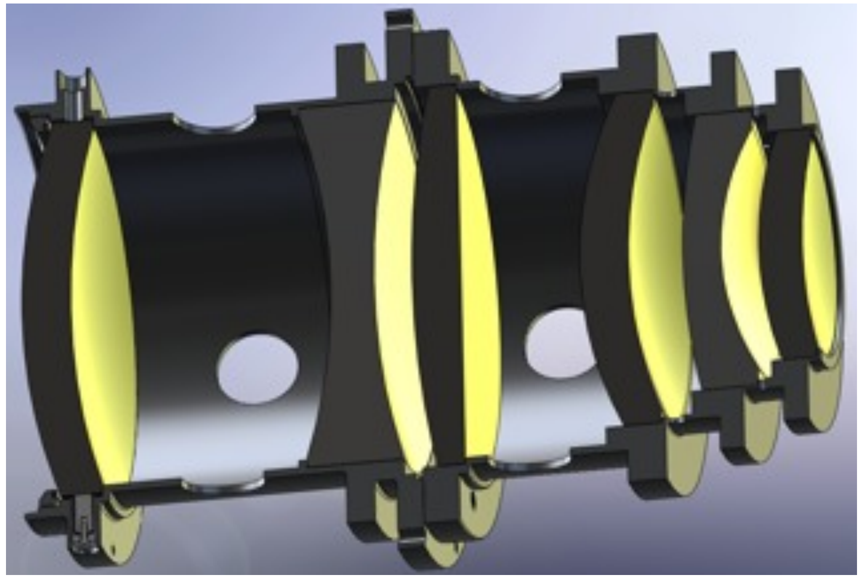
FIGURE OF ACTUAL GRATING WILL GO HERE.

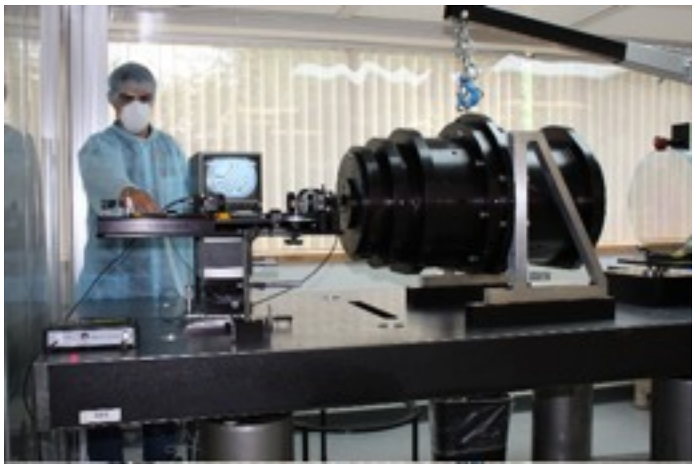
REMOVED/ EMBARGOED

Special Features of the Instrument: Six Element, f/1.4, Cryogenic Camera

- Designed and fabricated by New England Optical System (NEOS).





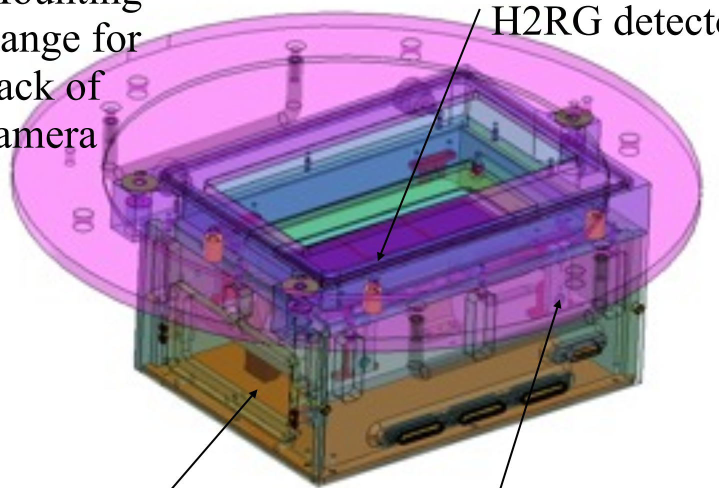


Special Features of the Instrument: Pixel-Dithering Detector Mosaic

- Designed and fabricated by Todd Horne and U. Arizona.

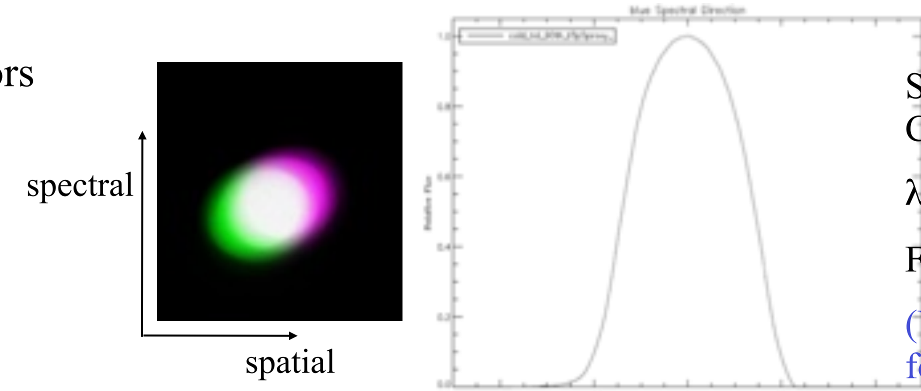
Mounting flange for back of camera

(3) Adjacent H2RG detectors



Pad for drive pin contact

Swing Arms

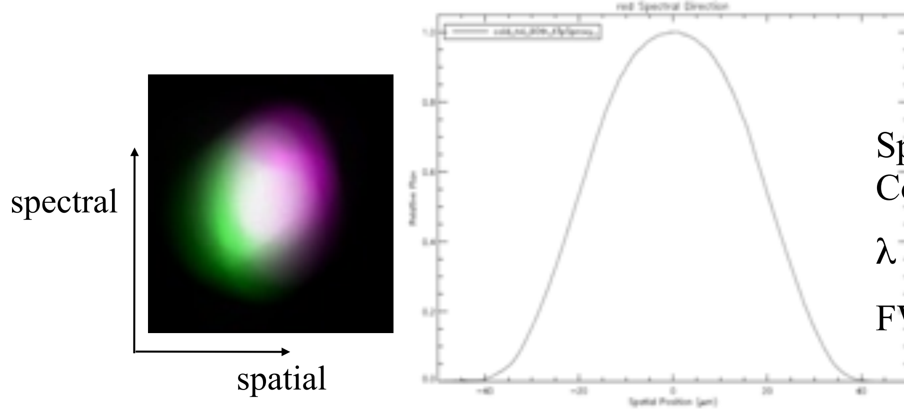


Spectral 1-D Collapse

λ = 1.5163 μm

FWHM 28.4 μm

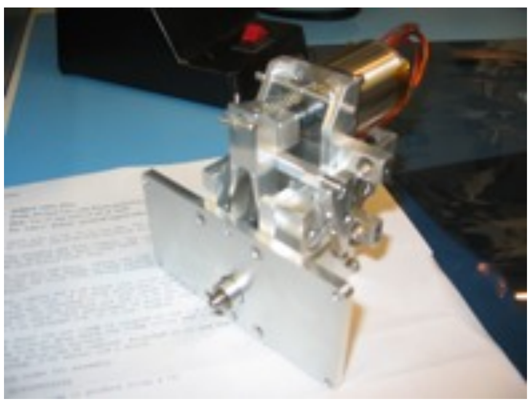
(Undersampled for 18 μm pixels)



Spectral 1-D Collapse

λ = 1.6775 μm

FWHM 41.8 μm



Note: expected performance of actual grating implies even greater undersampling than top example.

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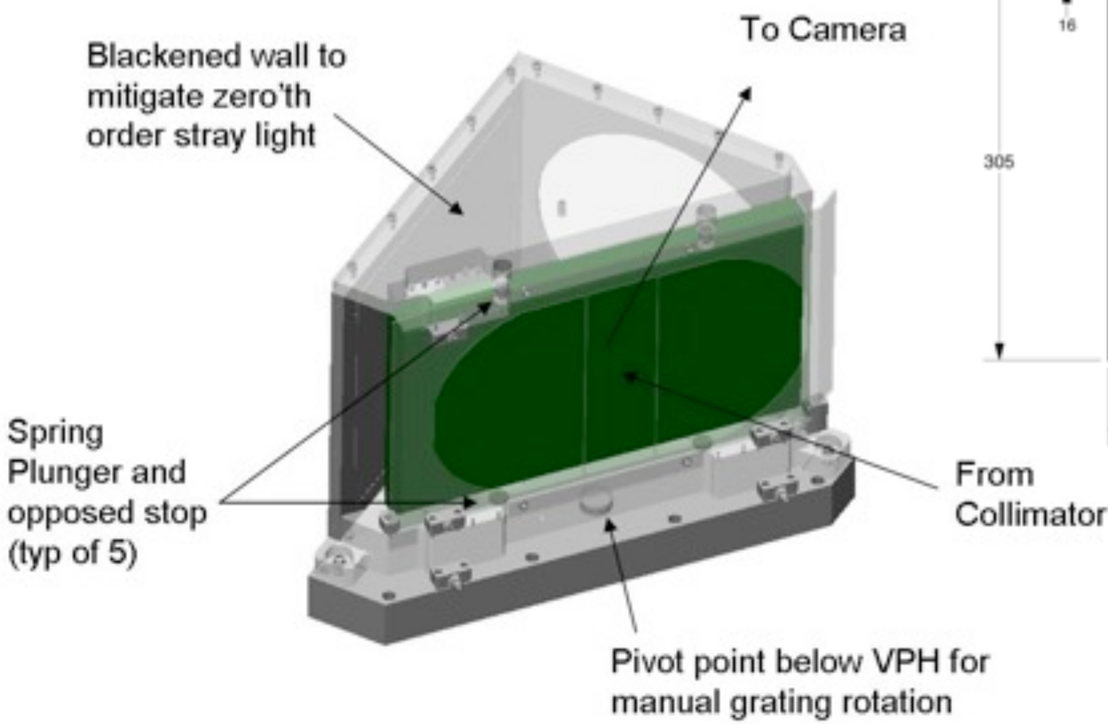
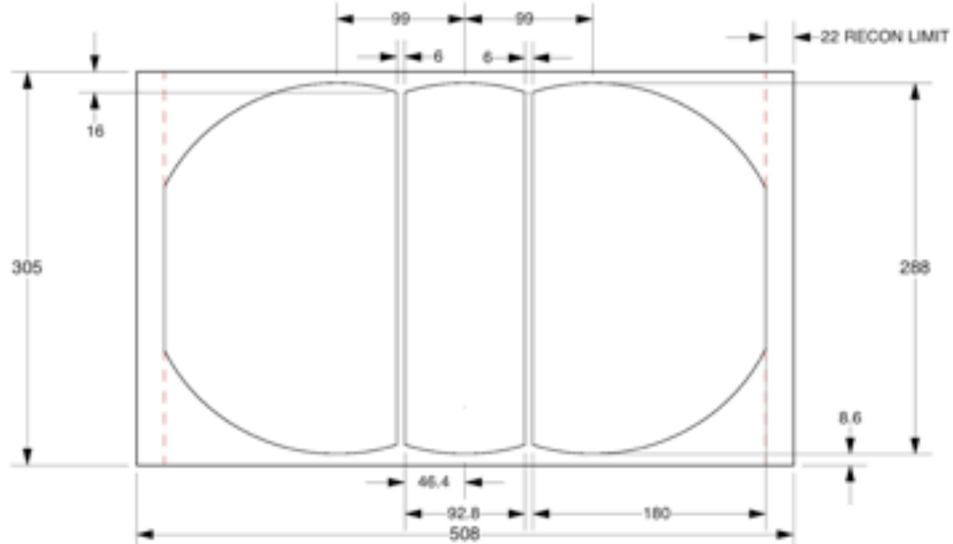




Special Features of the Instrument: First Mosaiced VPH Grating

- Successfully manufactured by Kaiser Optical Systems to better than specified!

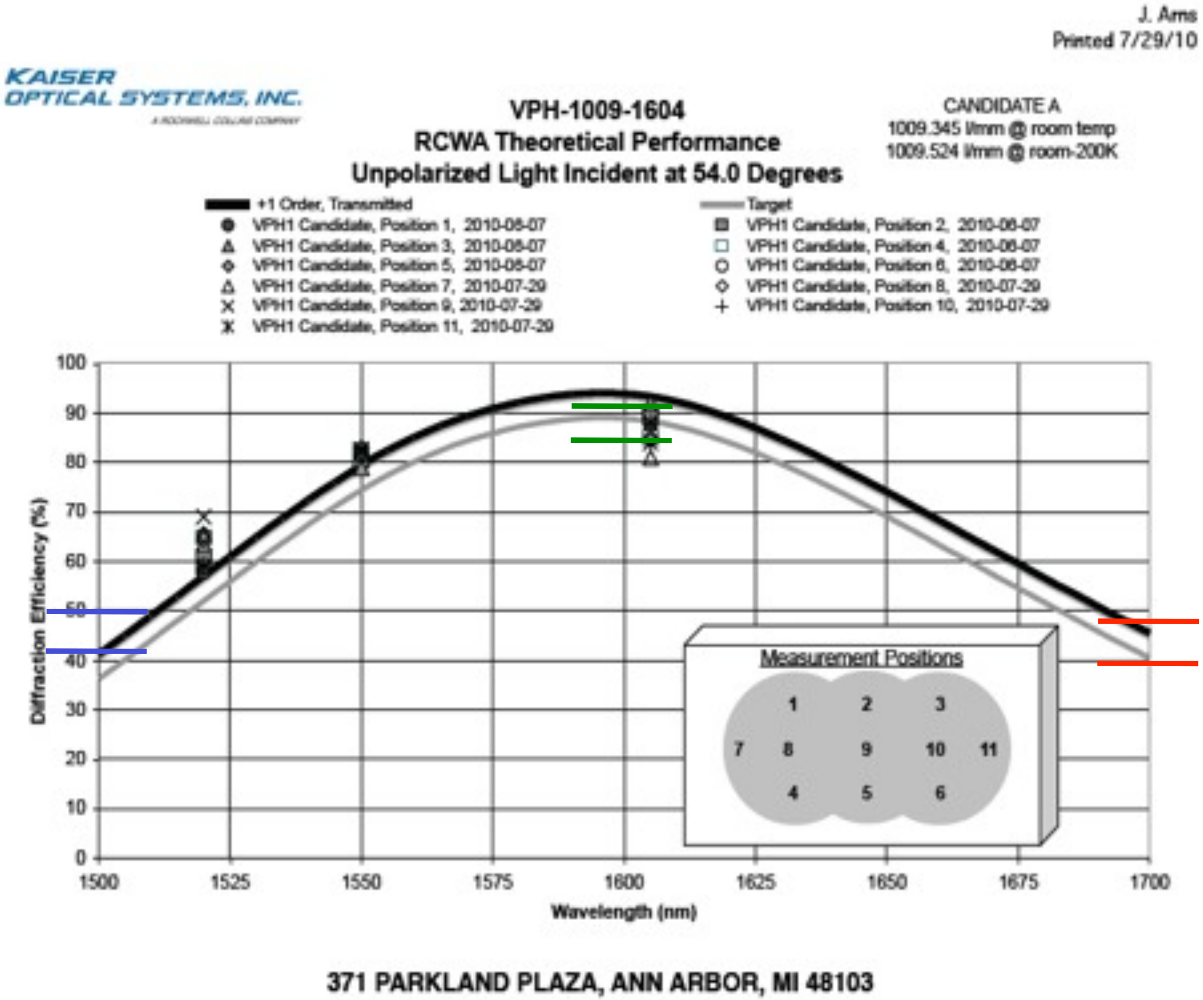
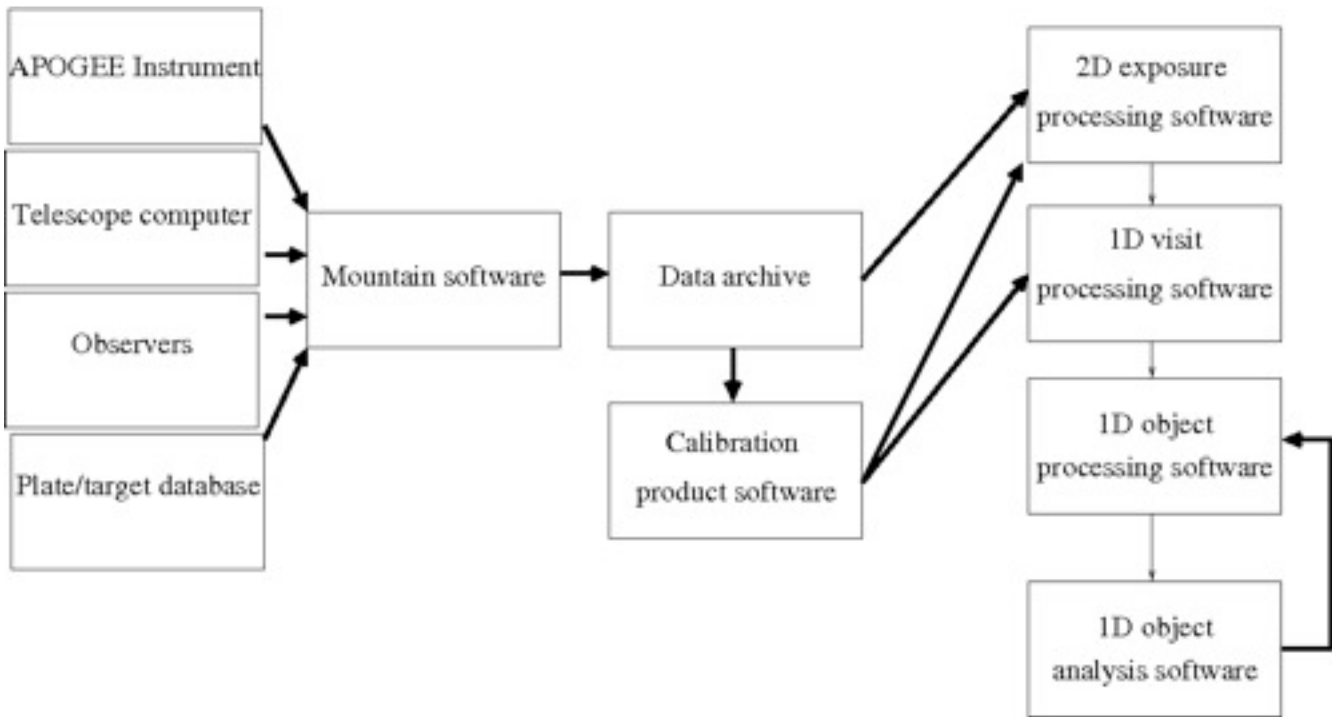


FIGURE OF ACTUAL GRATING WILL GO HERE.

REMOVED/EMBARGOED

How APOGEE Data Are Taken

- Instrument can takes multiple non-destructive reads for each exposure.
  - Can monitor build up of exposure.
  - With “up the ramp” sampling can improve noise and remove certain exposure defects (CRs, saturation).
- Multiple exposures are taken for each field visit (with pixel dithering)
- Multiple visits are combined for each object (with RV shifting)
- Abundances are derived from combined object spectra



Overview of Major Software Modules

Raw data

APOGEEPIPE

APCALS

Create Calibration files

- Trace
- Wavelength
- LSF
- BPM
- Detector
- Superdark
- Superflat
- Flux
- PSF

APPLAN

Create “plan” files for each plate visit

APREDUCE

Process the science frames for each plate visit

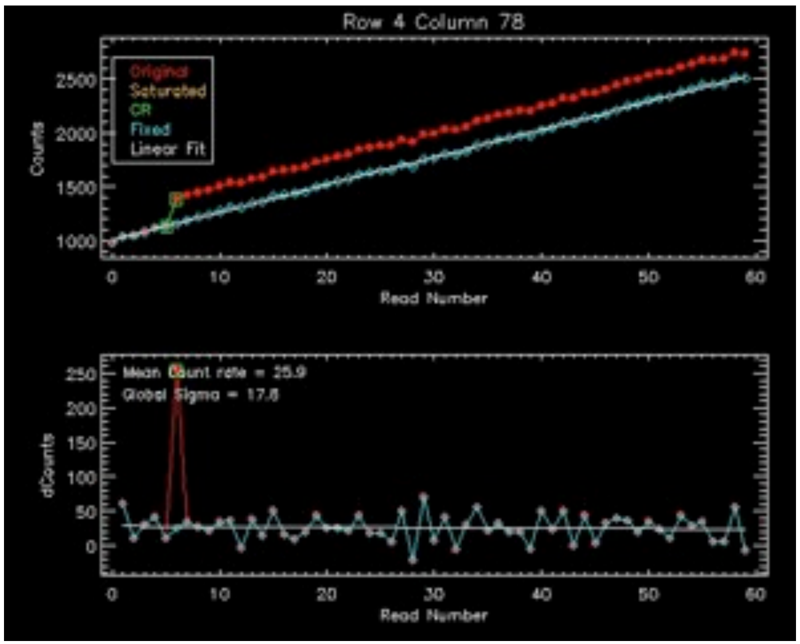
- Wavelength calibrate
- Sky correction
- Dither combine
- Flux calibrate
- Measure RV

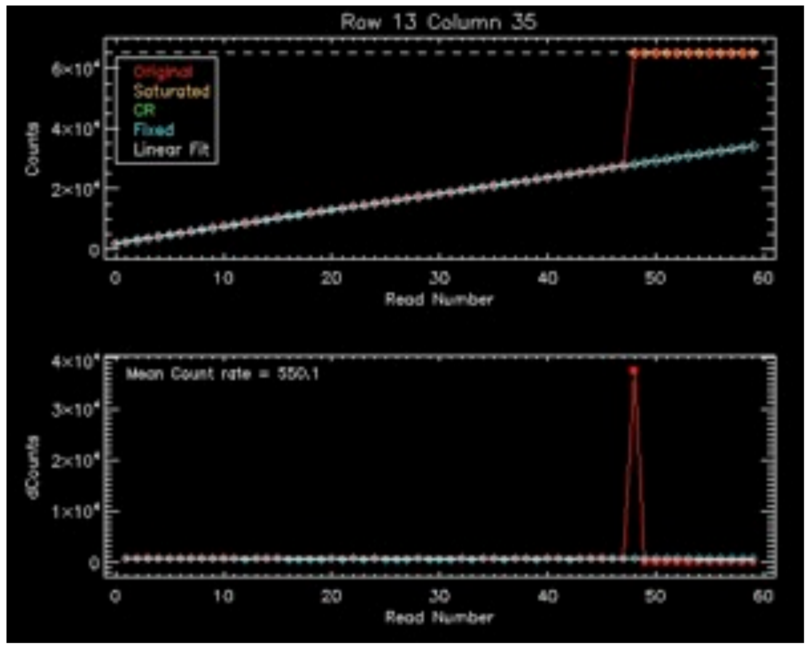
ASPCAP

Stellar Parameters and Abundances

Special Features of APOGEE Software

- Detect and remove cosmic rays (CRs) from datacube:
  - Each pixel treated separately.
  - Work with count "rates" *Δcounts =counts[i+1]-counts[i] (i is the read #).*
  - "Bad" Δcounts are replaced by a local median value (not including the bad value).
- Fix saturated pixels:
  - Replace saturated Δcounts with the median Δcounts of the non-saturated values.
  - Future improvements: take count rate variability into account (for saturated reads).



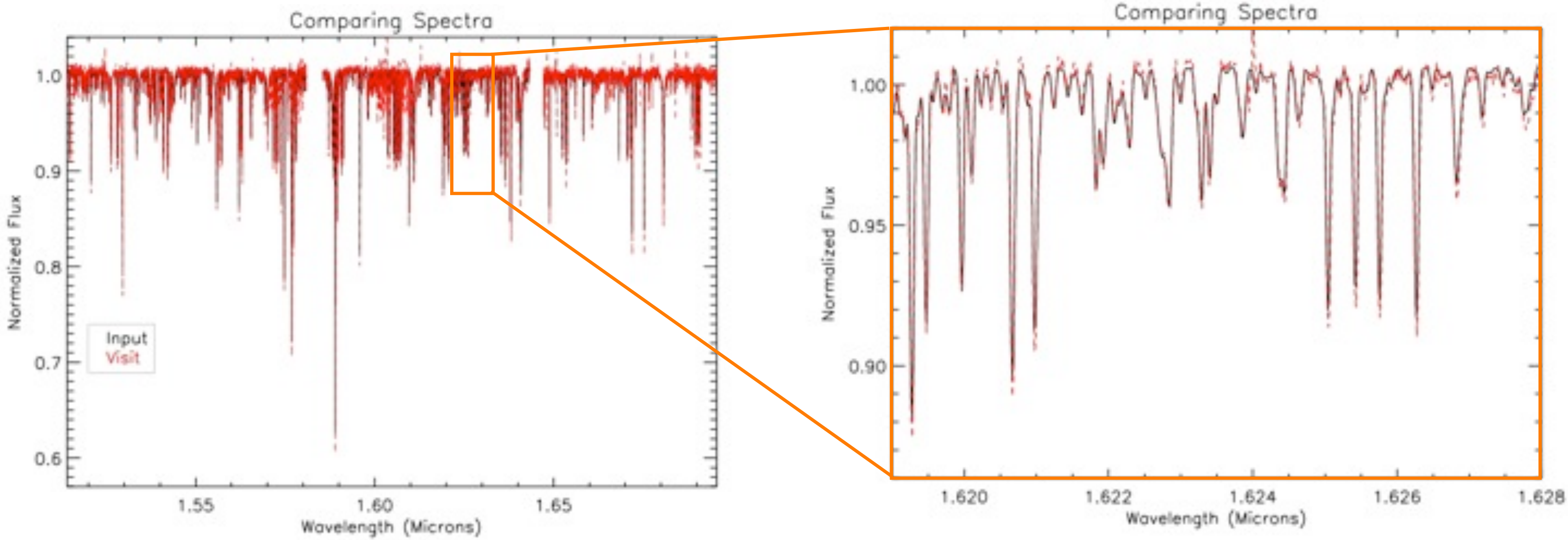


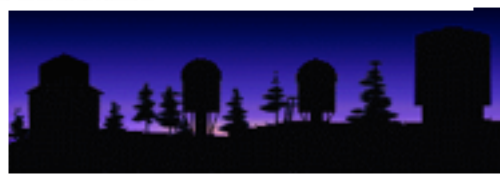
AP1DVISIT Output

Output well-sampled and calibrated spectra:

- apPlate files contain all spectra in a plate
- apVisit files are for single spectra

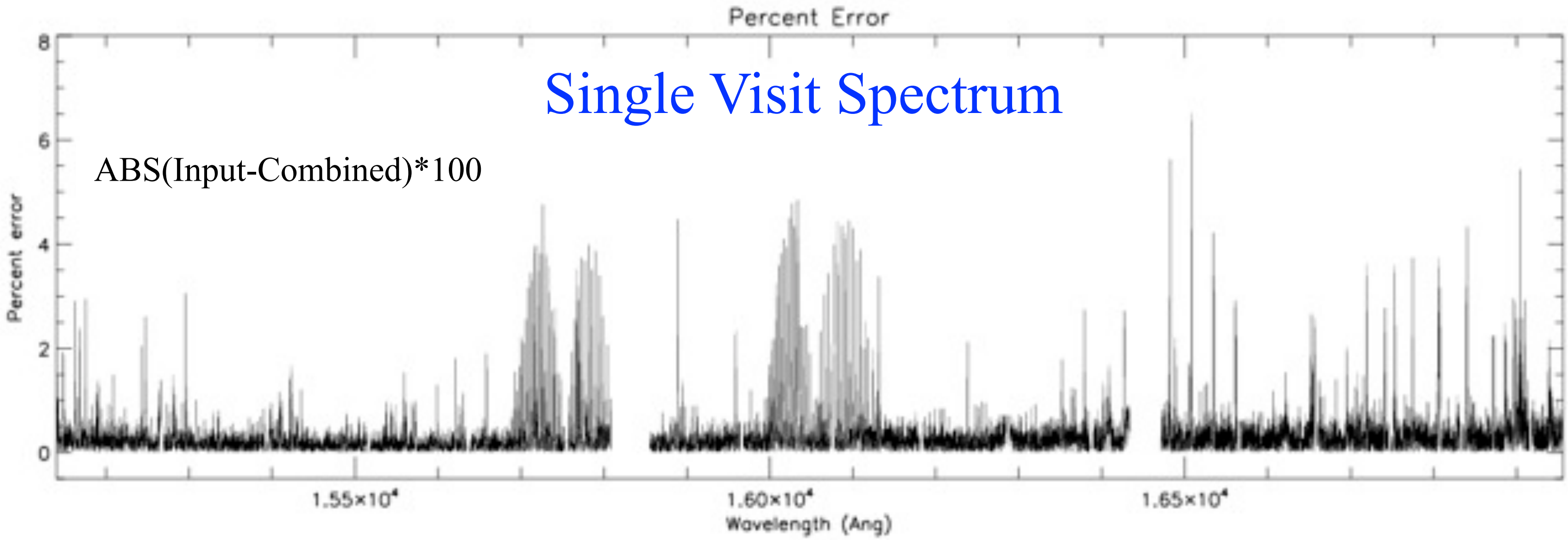
Comparing with “true” input synthetic spectrum



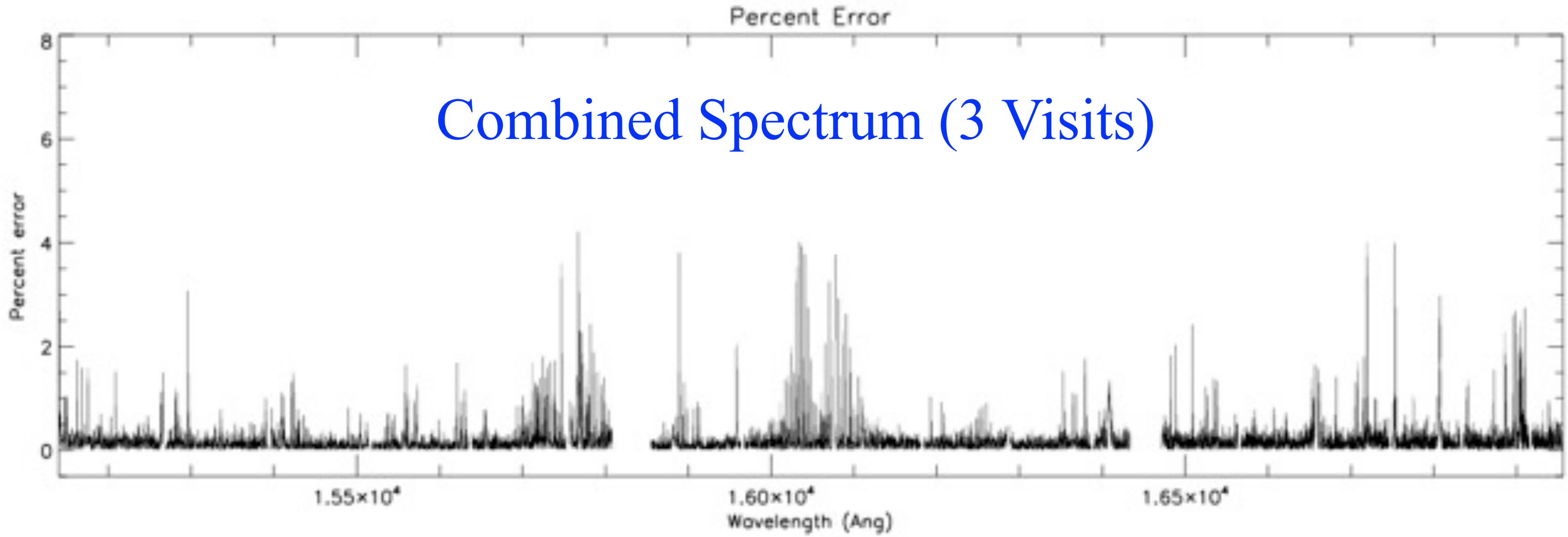


Current Check on Pipeline

Percent Deviation



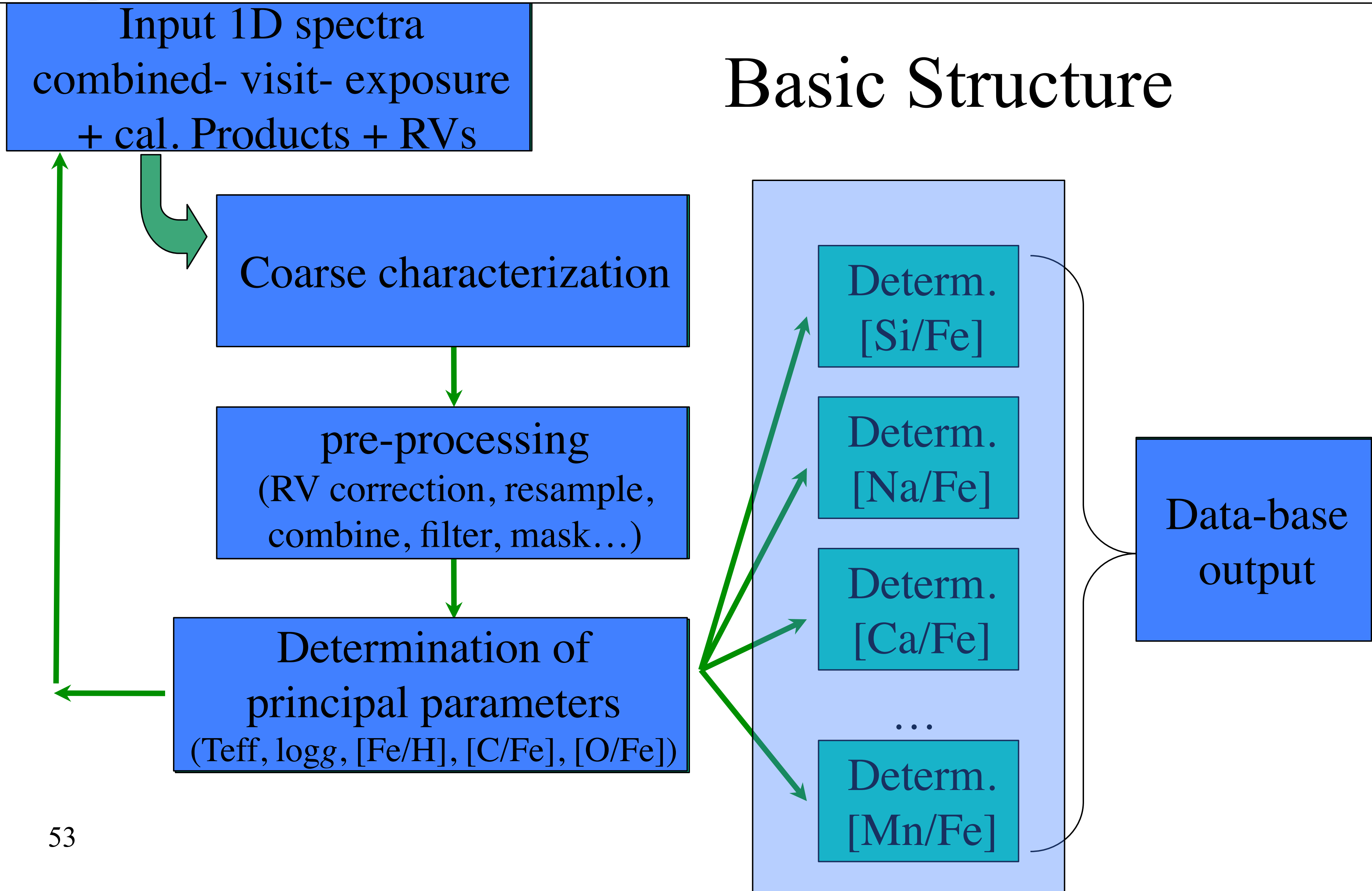
Typically <1-2% except for airglow & tellurics



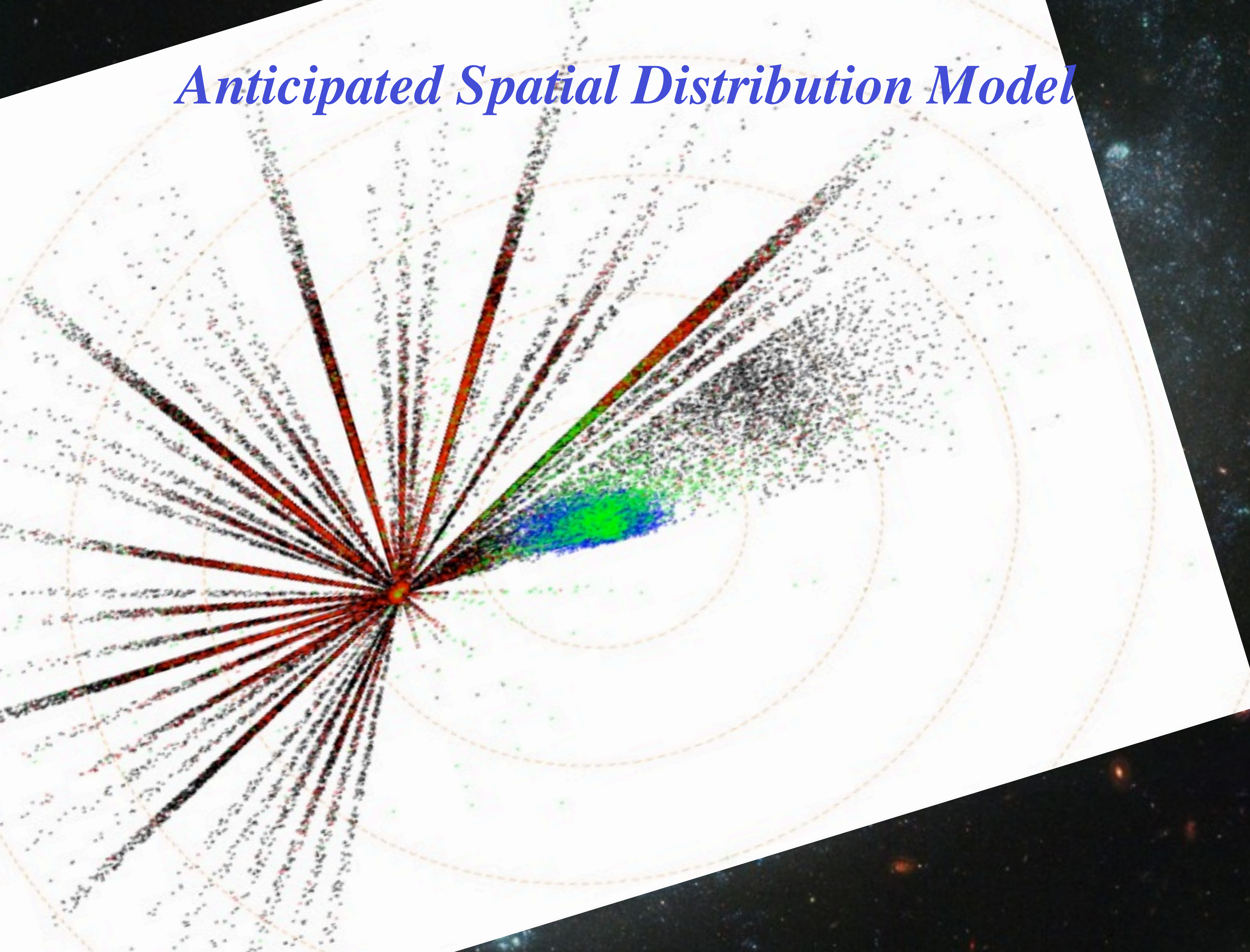
Better for combined spectra.

Abundances & Stellar Parameters

Basic Structure



Anticipated Spatial Distribution Model



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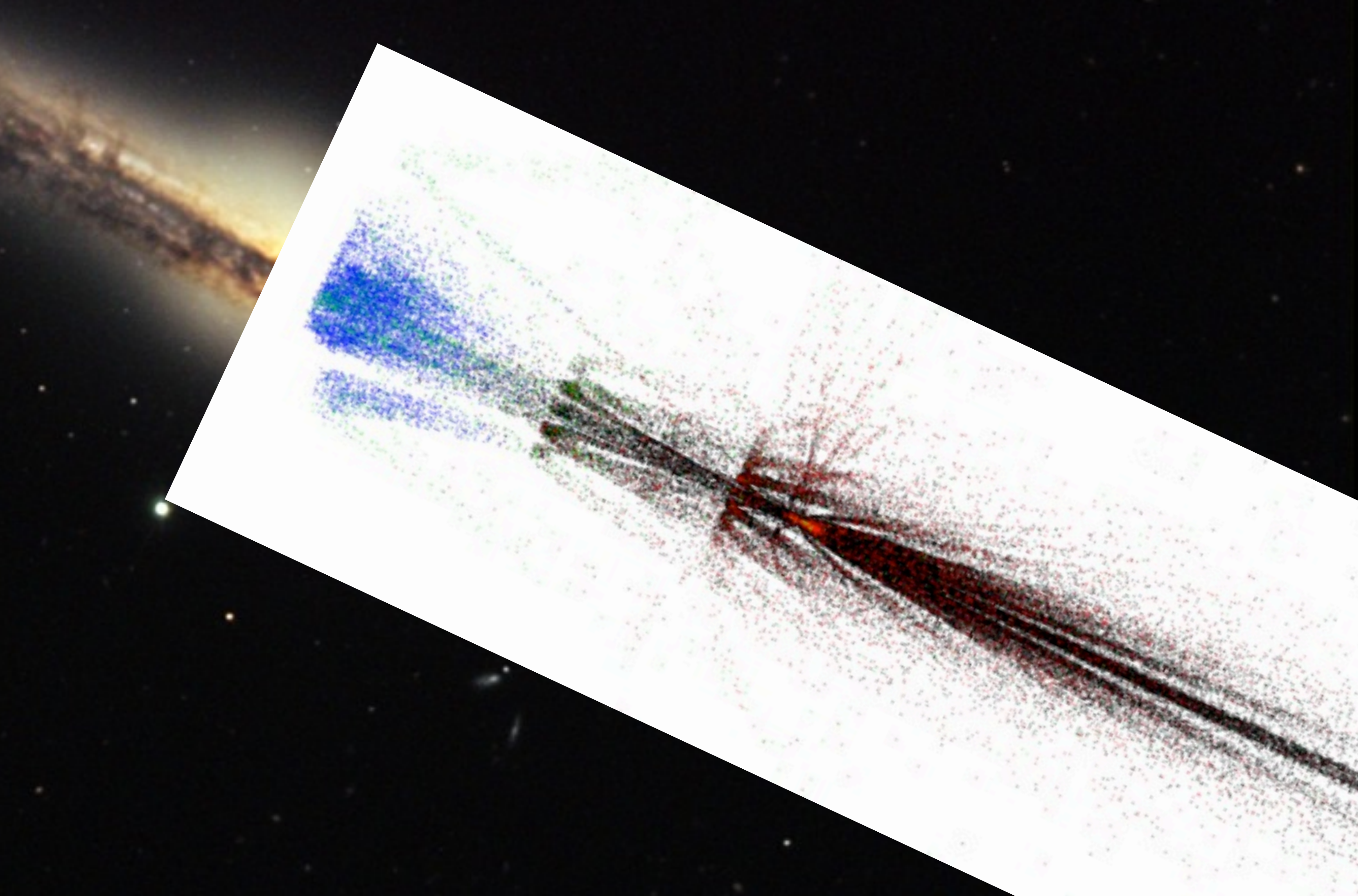
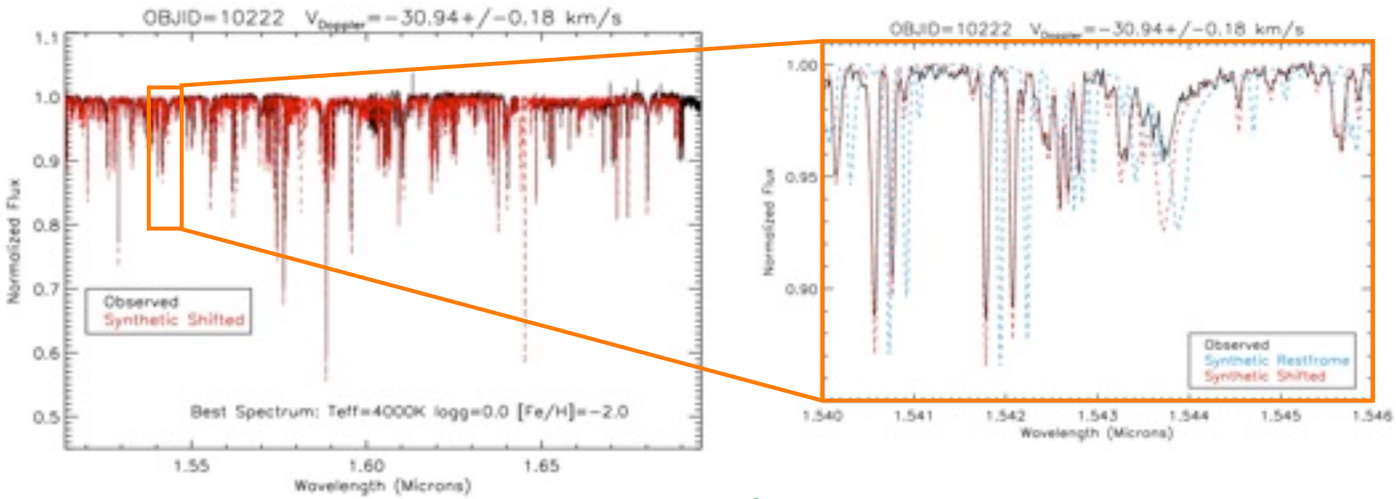
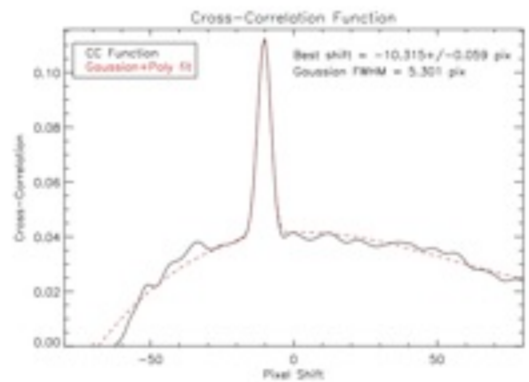


Radial Velocities

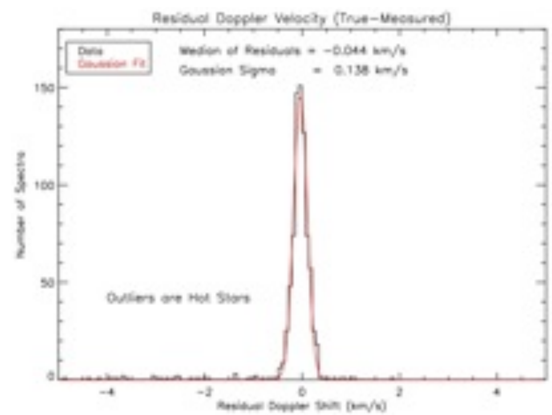
Two step process:

1. Cross-correlate with grid of synthetic spectra to obtain initial guess for RV and template:





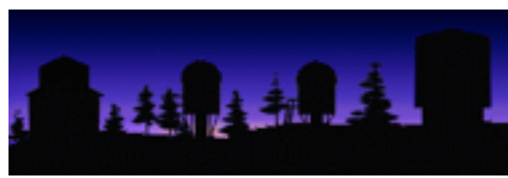
2. Weighted average of RVs using χ^2 minimization of ~50A spectral pieces with chosen template:
   - Break up spectrum into 30 pieces (~50A each) and for each:
     - Perform χ^2 minimization with only RV as the free parameter.
   - Weighted average RV from all pieces w/outlier rejection.
     - Weight accounts for S/N, χ^2 and EW (over entire spectral piece).
3. Check of RV accuracy against input simulation RVs:
   1. Median offset is -0.044 km/s.



Software Overview/Status

- Three Primary Software Modules
  - Target selection and plate design
    - I.e. making input catalogs, dereddening, target selection, plate design files.
    - Process and criteria well developed, software to generate plate input files developed.
  - Data reduction and quicklook
    - Full pipeline developed,
      albeit with some shortcuts and uncertainty about what real data will require.
    - Ready for analysis of commissioning data (lab and on-sky).
    - Quicklook not developed, but basic tools come from reduction pipeline (started!).
  - Analysis: stellar parameters and abundances
    - Significant algorithm and pipeline development done, though not finished.

- Pipeline End-to-End Status
  - Fairly realistic "fake" data have been generated from fake plugmap data.
  - These fake data have been run through reduction pipeline.
  - Output from reduction pipeline has been run through simple abundances pipeline (stellar parameters + 1-2 elements).



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