LSST-DESC Calibration Workshop '18

Slitless spectro-photometry

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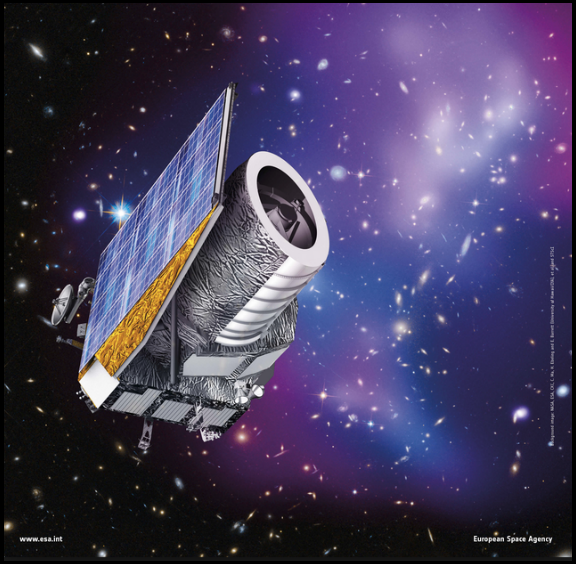
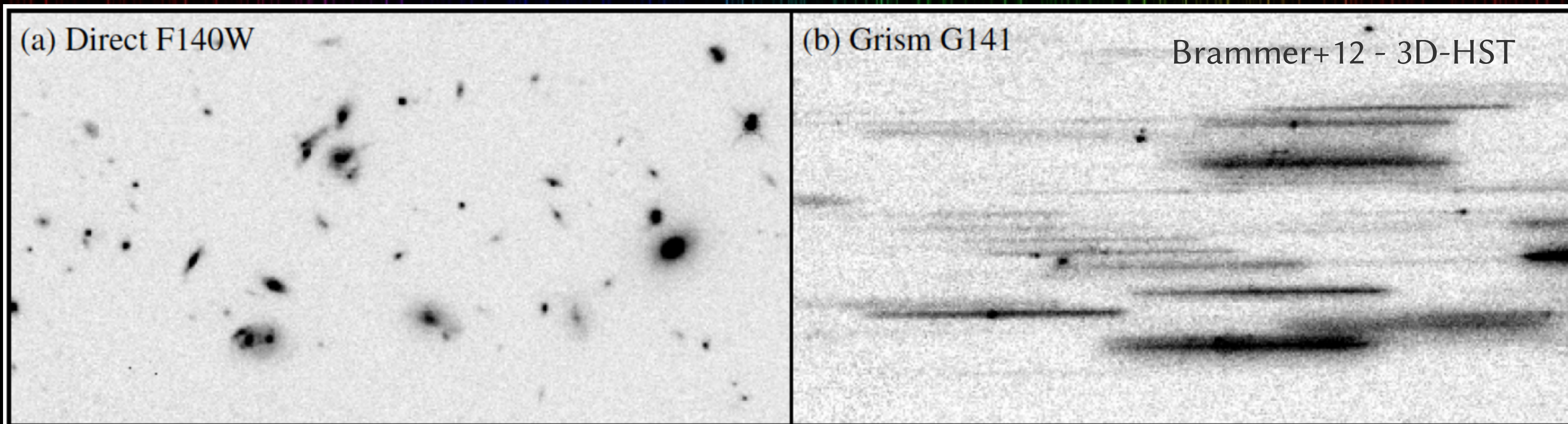
Disclaimer

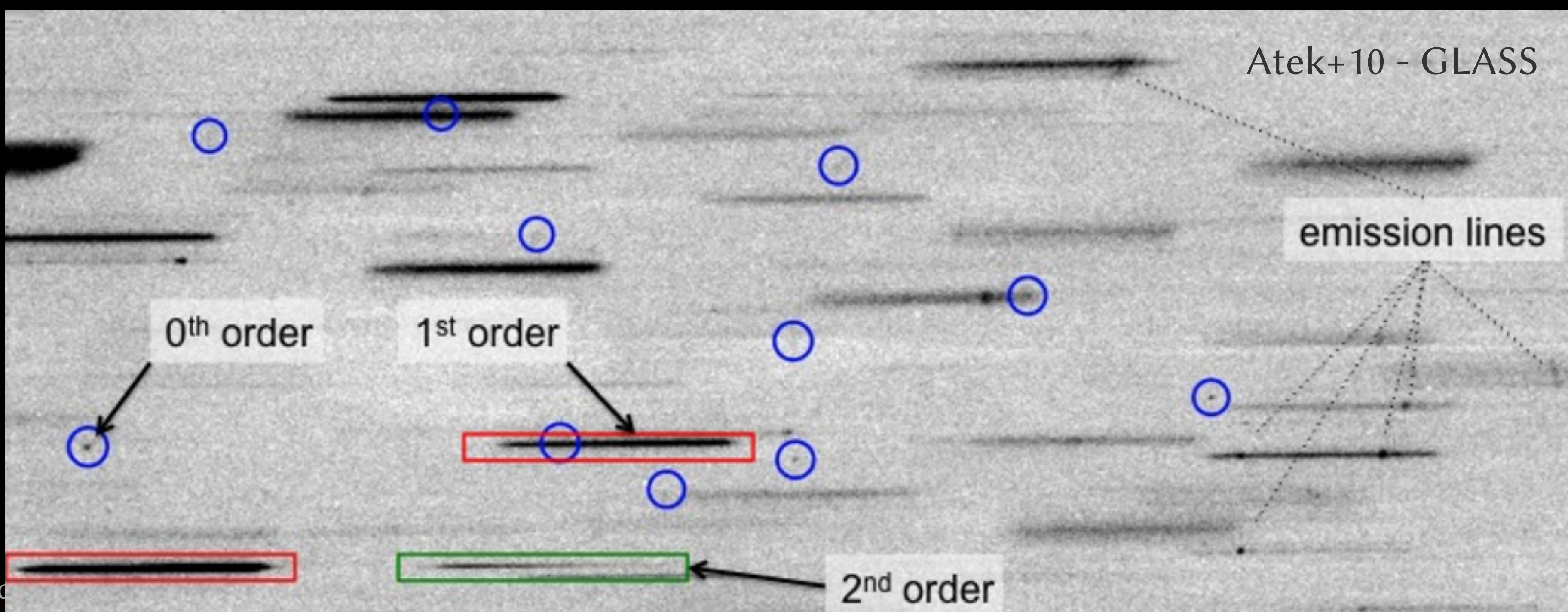
- 1^{st} time around, hi!
- No specific info. on AuxTel spectrograph properties nor observing modes
- Experience in ground-based *integral field* spectro-photometry (SNfactory/SNIFS) and space-born slitless spectrography (Euclid/NISP-S)



Modeling slitless spectroscopy

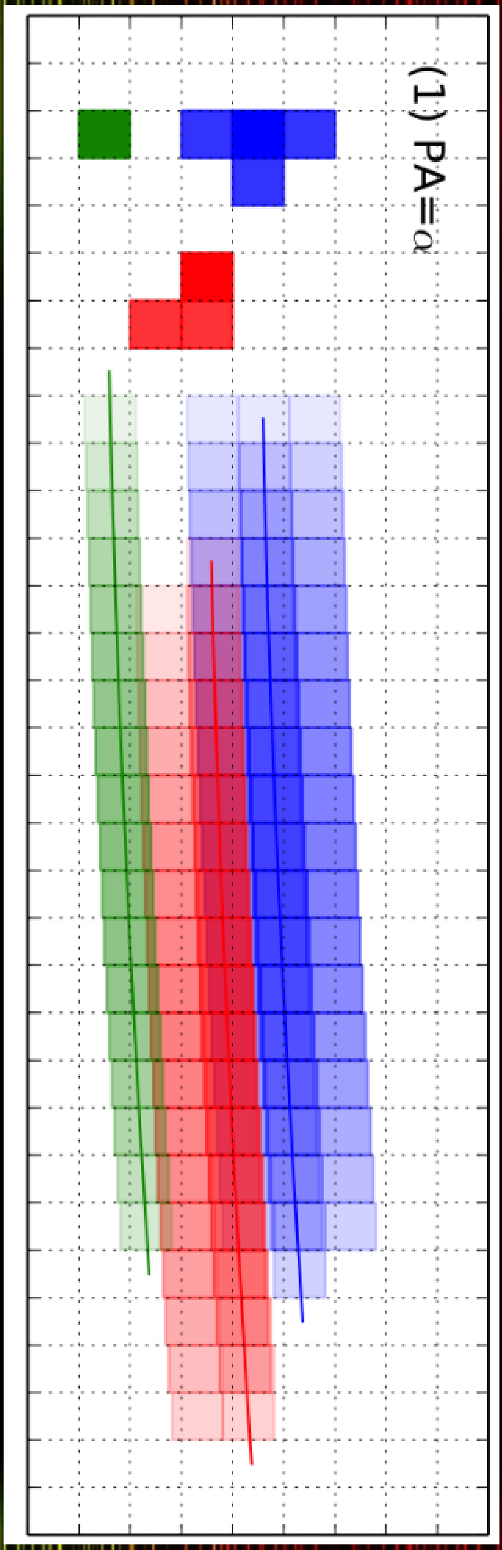
Slitless spectroscopy





Slitless spectroscopy

- Advantages
  - Large FoV and high multiplexing
  - Simple to build and to use
- Drawbacks
  - Cross-contamination: overlap of different objects (potentially at different orders)
    - Mitigation: multi-PA observations & decont. model
  - Self-contamination: mixing of spatial and spectral information
    - Spectral resolution is dependent of source size/seeing conditions
  - High background level



Traditional approach

- Standard "aXe-like" (Kümmel+09)
  - Empirical modeling of the spectral trace
    - Cross-dispersion: geometric distortions
    - Along dispersion: wavelength solution
  - Decontamination from neighbor sources
  - Cross-dispersion integration ⟶ 1D spectrum
    - Potentially x-disp. profile weighted ("optimal extraction")
  - Multi-PA spectra are averaged *a posteriori*
    - But see LINEAR (Ryan+18) for 1st steps toward a forward model
- No handling of self-confusion
  - Spectral resolution is degenerate with source size (extent/PSF/seeing)
  - Correct for point sources observed in space, suboptimal otherwise

Intrinsic & observable flux

- Source is characterized by intrinsic flux distribution $C(\mathbf{r}, \lambda)$
  - E.g. a star: $C(\mathbf{r}, \lambda) = S(\lambda) \times \delta(\mathbf{r} - \mathbf{r}_0)$
  - Separable source: $C(\mathbf{r}, \lambda) = S(\lambda) \times F(\mathbf{r})$
- Atmosphere + Instrument is characterized by *Impulse Response Function* (supposed stationary)
  - mapping from intrinsic coords to obs. coords (astrometry, λ-calib)
  - spread around mean position
  - may include transmission
- *Observable* flux $O(\mathbf{r}, \lambda) \equiv (C \otimes P)(\mathbf{r}, \lambda)$
  - Only if you have an Integral Field Spectrograph!

Direct imaging

- IRF can be decomposed in two components
  - a centered shape component P_0 (aka PSF/LSF)
  - an offset component P_Δ
    - usually ignored by *ad hoc* registration of the PSF
- Direct imaging (photometry)
  - P_0 = PSF, $P_\Delta \approx \delta(\mathbf{r})$
    - but chromatic aberrations & ADR correspond to a non-trivial P_Δ
  - Broadband image: $I(\mathbf{r}) = \int d\lambda\, O(\mathbf{r}, \lambda)$
    - $\approx (\overline{C} \otimes \overline{P}_0)(\mathbf{r})$ for a weakly chromatic separable source

Dispersed imaging

- Slitless spectroscopy
  - P_0 = Point/Line Spread Function
  - $P_\Delta(\mathbf{r}, \lambda) = \delta(\mathbf{r} - \mathbf{\Delta}(\lambda))$ where $\mathbf{\Delta}(\lambda)$ is the dispersion law
  - Dispersed image: $I(\mathbf{r}) = \int d\lambda\, (C \otimes P_0)(\mathbf{r} - \mathbf{\Delta}(\lambda), \lambda)$
  - In spatial Fourier domain:

    $\hat{I}(\mathbf{k}) = \int d\lambda\, \hat{C}(\mathbf{k}, \lambda)\, \hat{P}_0(\mathbf{k}, \lambda)\, e^{-i2\pi\, \mathbf{k}\cdot\mathbf{\Delta}(\lambda)}$
  - Under the separability assumption and a weakly chromatic PSF

    $\hat{I}(\mathbf{k}) \approx \hat{F}(\mathbf{k})\, \hat{\overline{P}}_0(\mathbf{k}) \int d\lambda\, S(\lambda)\, e^{-i2\pi\, \mathbf{k}\cdot\mathbf{\Delta}(\lambda)}$
    - Almost the Fourier Transform of $S(\lambda)$!

Dispersed image modeling

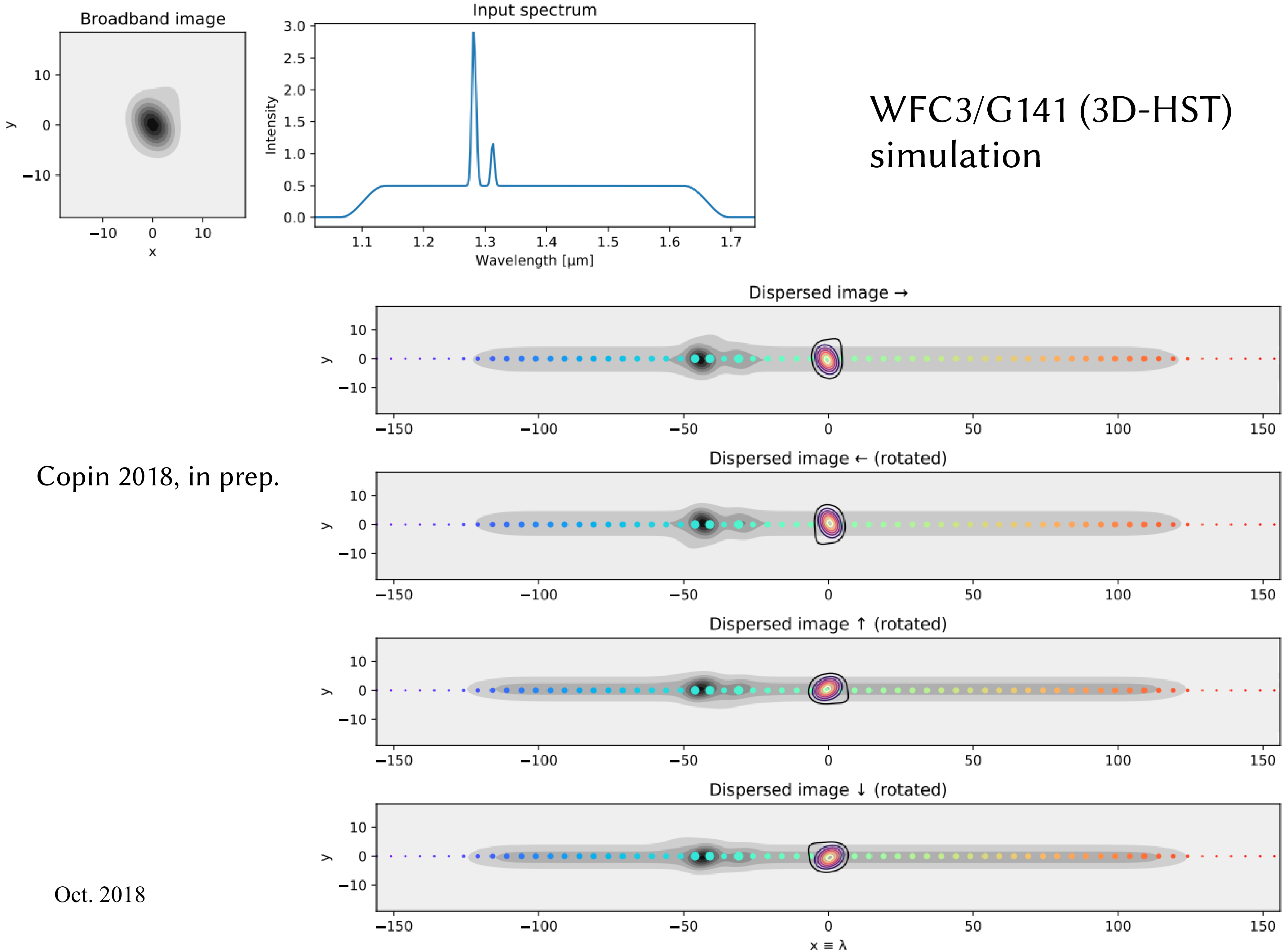
- $\hat{I}(\mathbf{k}) = \int d\lambda\ \hat{C}(\mathbf{k}, \lambda)\ \hat{P}_0(\mathbf{k}, \lambda)\ e^{-i2\pi\ \mathbf{k}\cdot\boldsymbol{\Delta}(\lambda)} \approx \hat{F}(\mathbf{k})\ \hat{\overline{P}}_0(\mathbf{k}) \int d\lambda\ S(\lambda)\ e^{-i2\pi\ \mathbf{k}\cdot\boldsymbol{\Delta}(\lambda)}$

  I = dispersed image, $F \otimes \overline{P}_0 \approx$ broadband image

  S = spectrum, $\boldsymbol{\Delta}$ = dispersion law

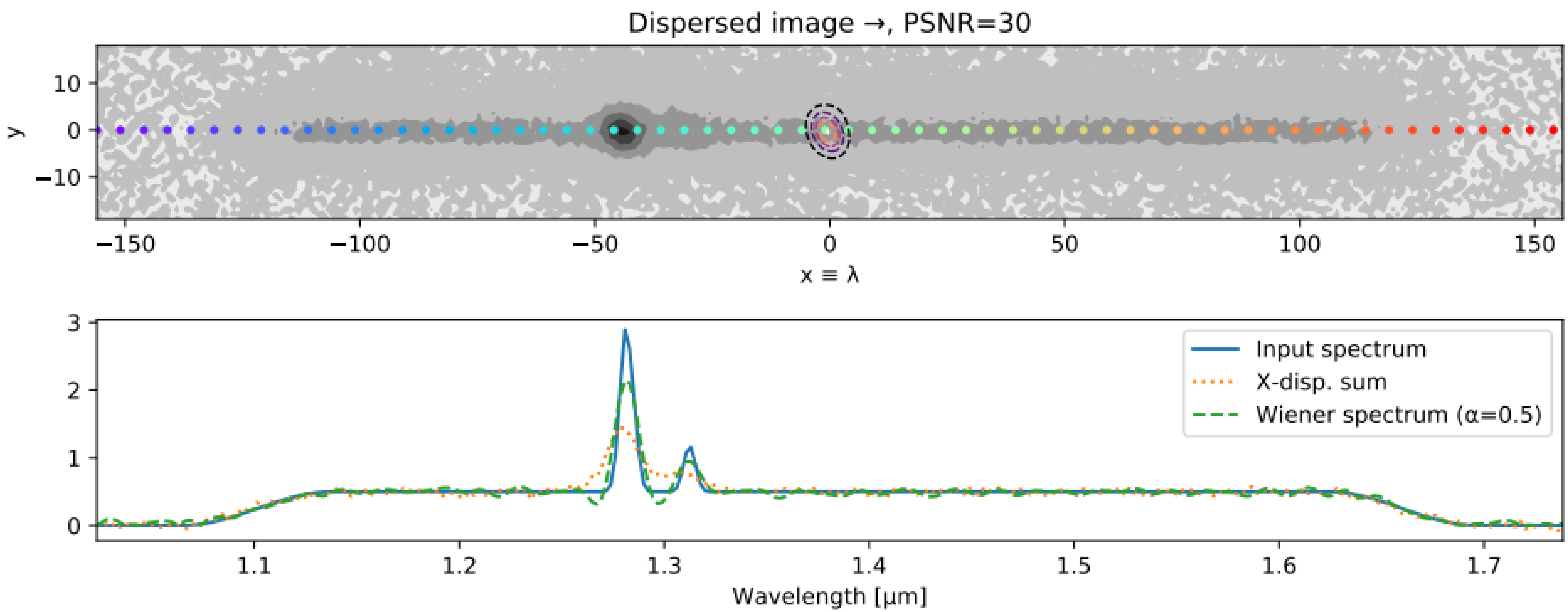
- Different approaches
  - Efficient simulation (for all dispersion orders)
  - Backward extraction of $S(\lambda)$
    - Assume dispersion law $\boldsymbol{\Delta}(\lambda)$ and broadband image $F \otimes \overline{P}_0$
    - Estimate $S(\lambda)$ from Wiener-Hunt deconvolution
  - Forward model of dispersed image $I(\mathbf{r})$, e.g.
    - Calibration of dispersion law $\boldsymbol{\Delta}(\lambda)$, of transmission $T(\lambda)$
    - Simple galaxy model: $S(\lambda)$ = template + redshift
    - More complex model, e.g. galaxy kinematics (Outini+18, in prep.)

WFC3/G141 (3D-HST) simulation



Copin 2018, in prep.

Oct. 2018



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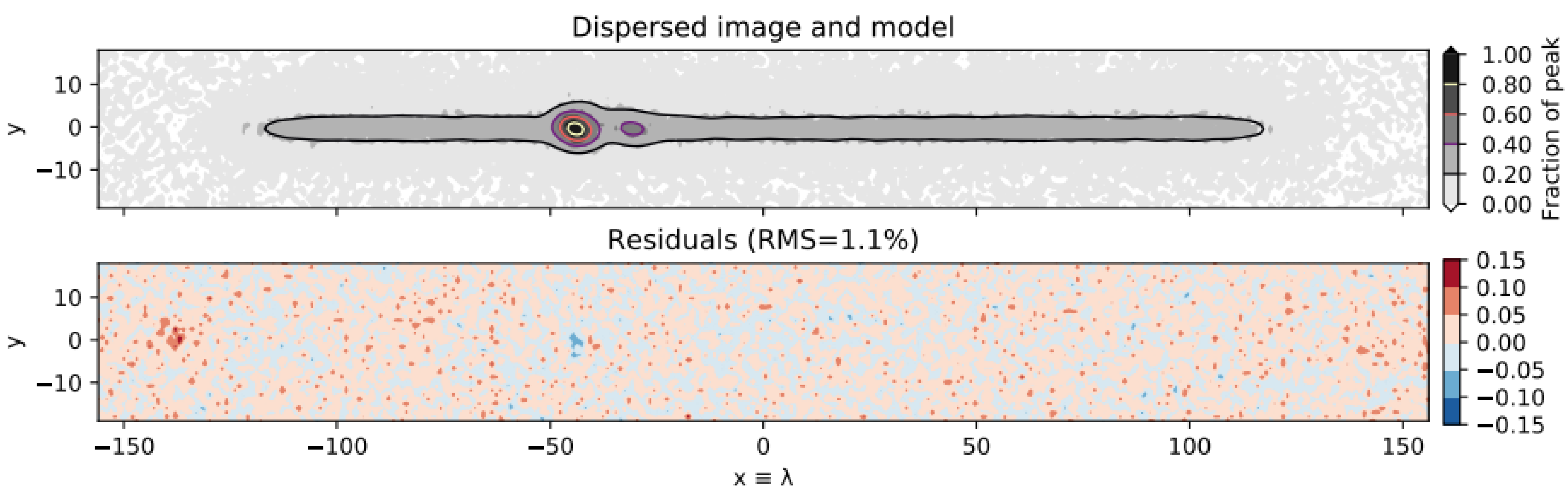

Outini & Copin
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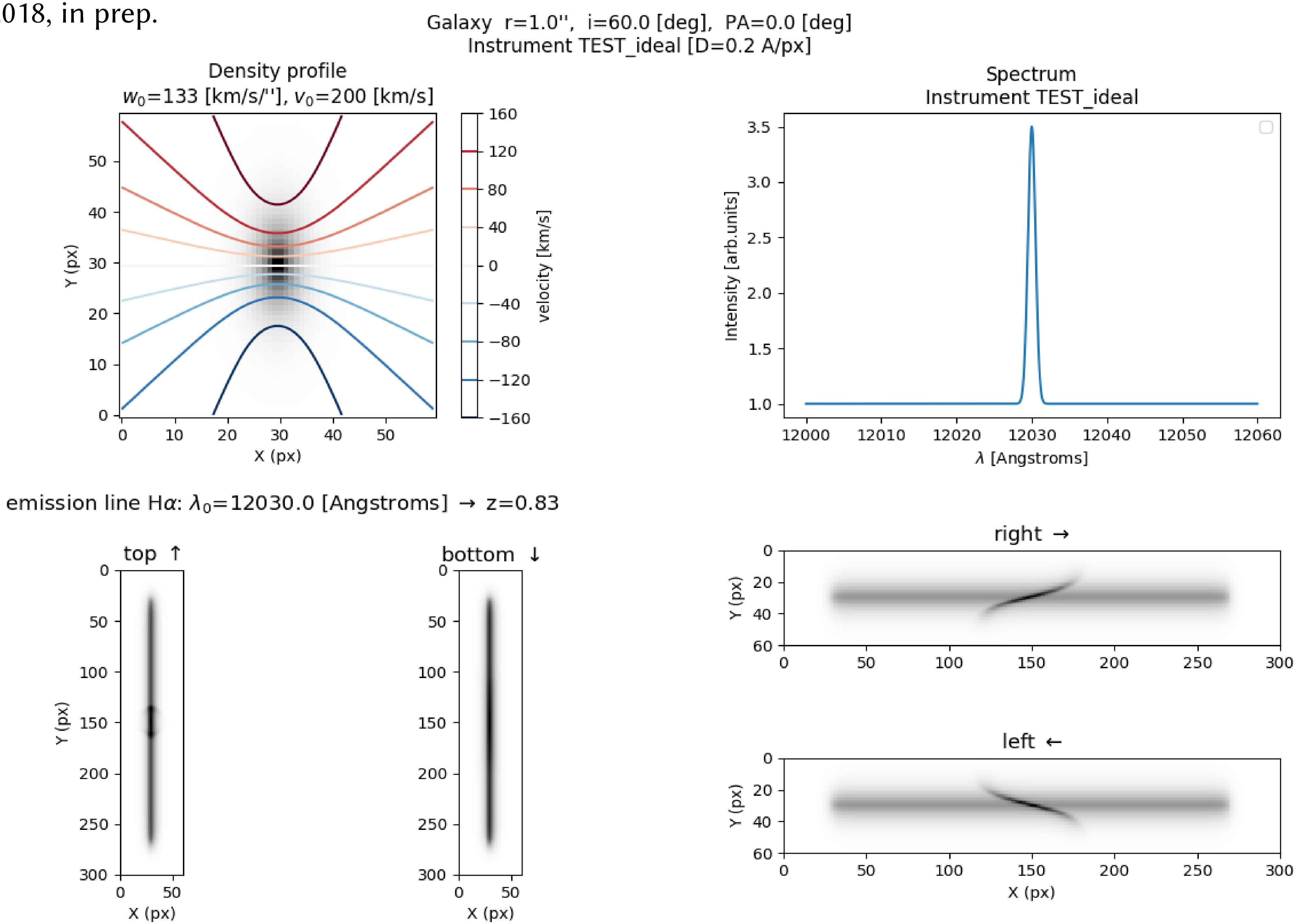
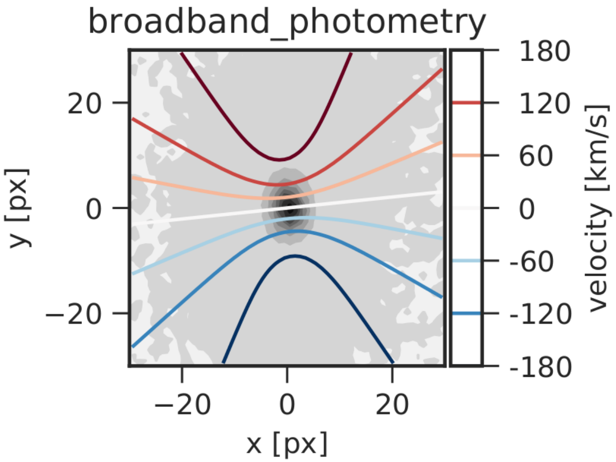
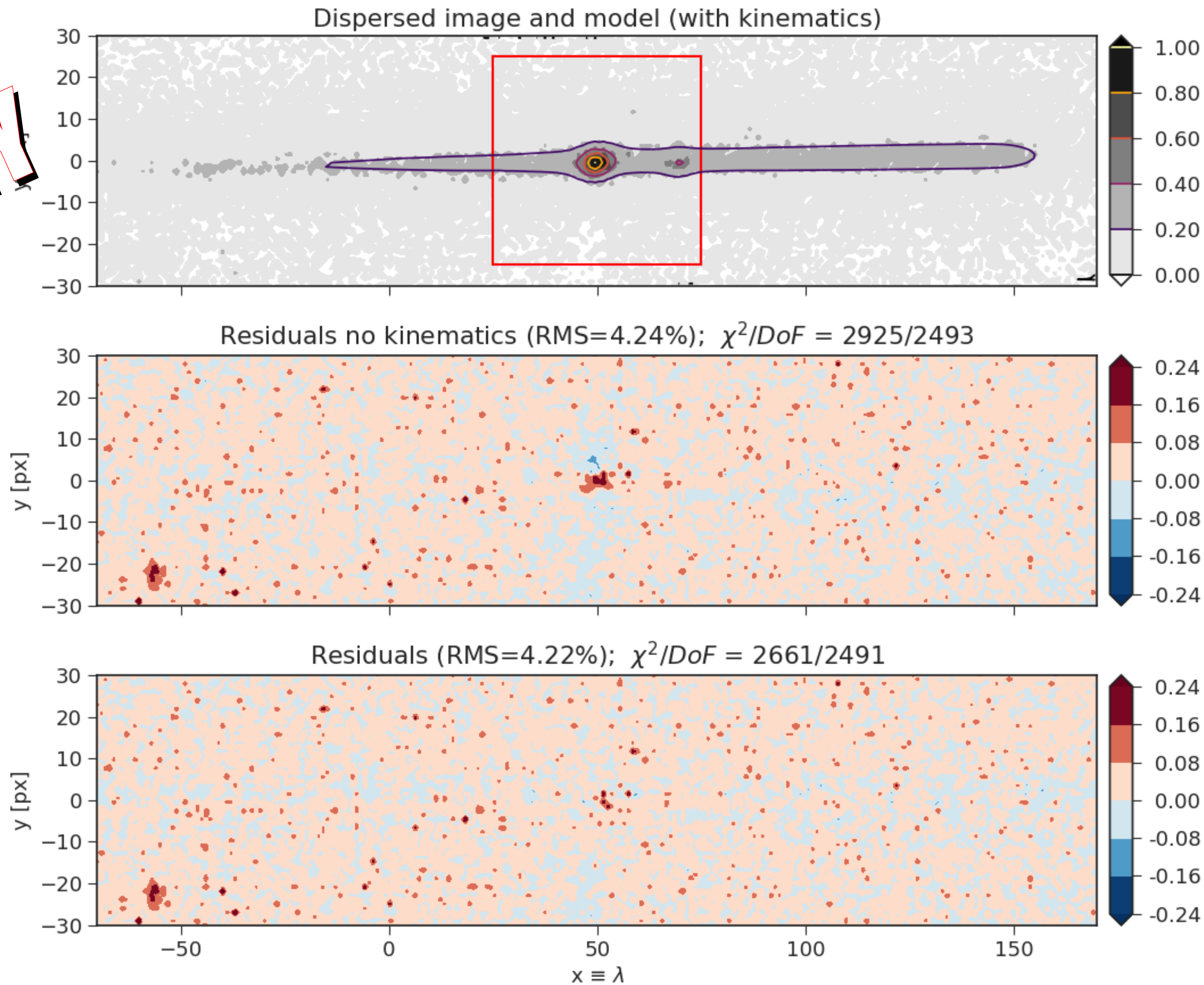


Outini & Copin
2018, in prep.

#1134 GLASS – G102 (24 A/px)

PRELIMINARY





Cold disk, velocity curve: $v(r) = v_0 \tanh(w_0 r / v_0)$

$v_0 \sin i = 205 \pm 24$ km.s^{-1}

$w_0 \sin i = 232 \pm 25$ km.s^{-1}.arcsec^{-1}

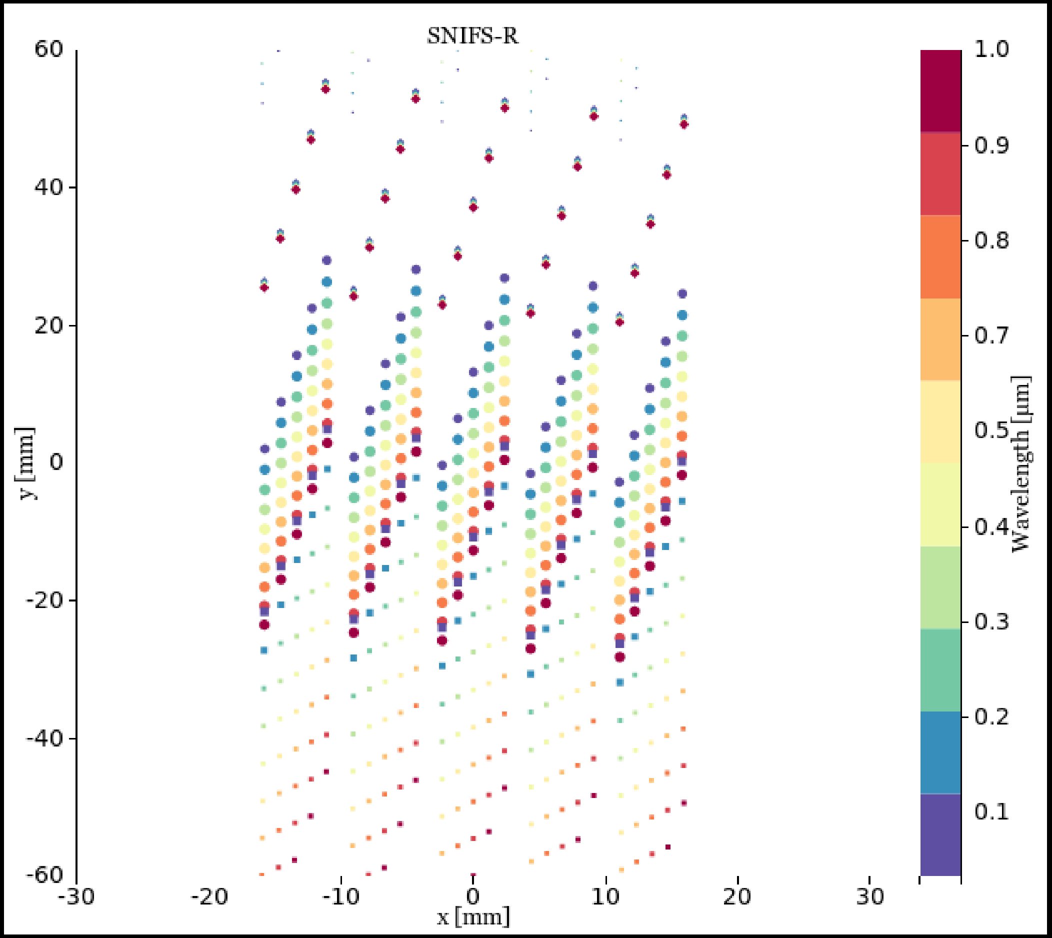
Dispersed imaging of stars

- Point sources are easier: $C(\mathbf{r}, \lambda) = \delta(\mathbf{r}) \times S(\lambda)$
  - $I(\mathbf{r}) = TF^{-1}(\int d\lambda\ \hat{P}_0(\mathbf{k}, \lambda)\ S(\lambda)\ e^{-i2\pi\ \mathbf{k}\cdot\mathbf{\Delta}(\lambda)})$
  - Simultaneous fit of dispersed image $I(\mathbf{r})$
    - spectral trace: dispersion law $\mathbf{\Delta}(\lambda)$
    - spectral shape: instrumental PSF and seeing P_0
    - flux: $S = T \times S^*$ where T = transmission, S^* = ref. flux
  - Spectro-photometry will derive from proper modeling of these different components
    - Dispersed imaging is *closer* to “imaging” than “spectroscopy”
    - Most tools are readily available from photometry

The (not so difficult?) path to slitless spectro-photometry

Instrumental model

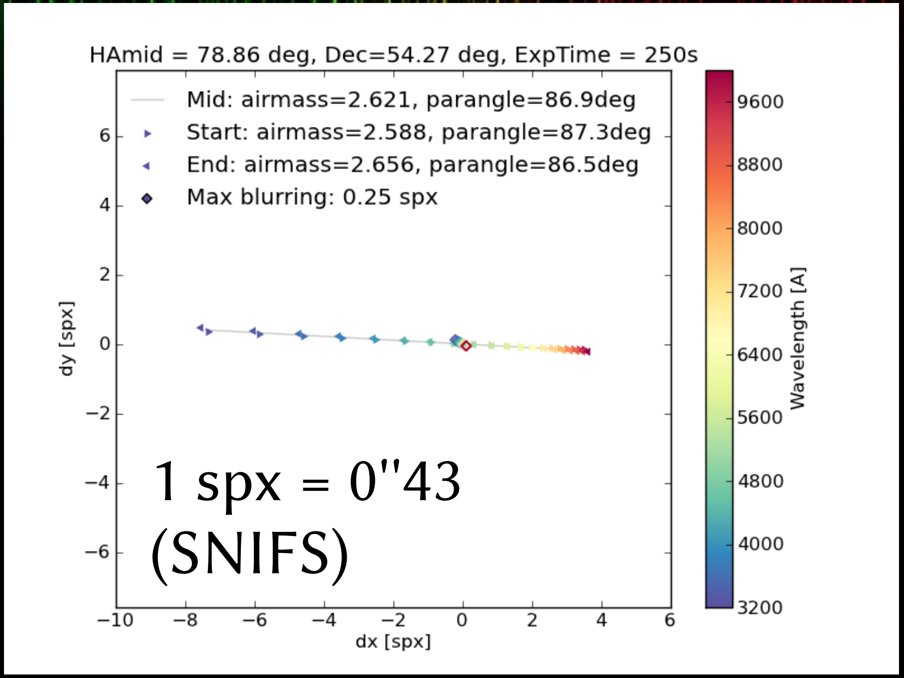
- Dispersion law Δ(λ) as a function of position in FP
  - Effective geometrical model
- Instrumental PSF as a function of position in FP
  - Can be derived from 1st principles (WF propagation)
  - or adjusted empirically
  - More naturally expressed in Fourier domain

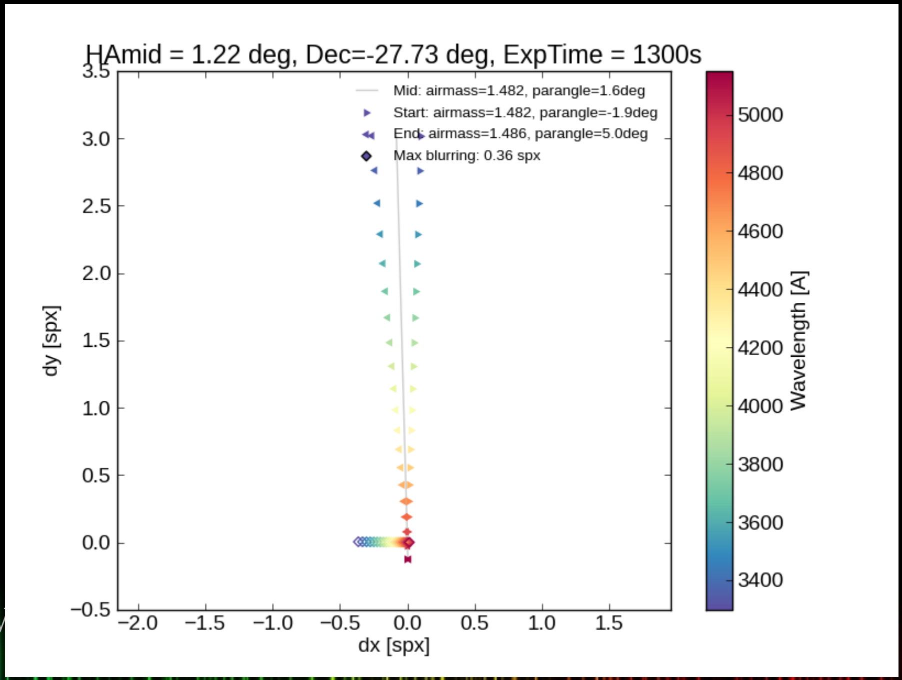


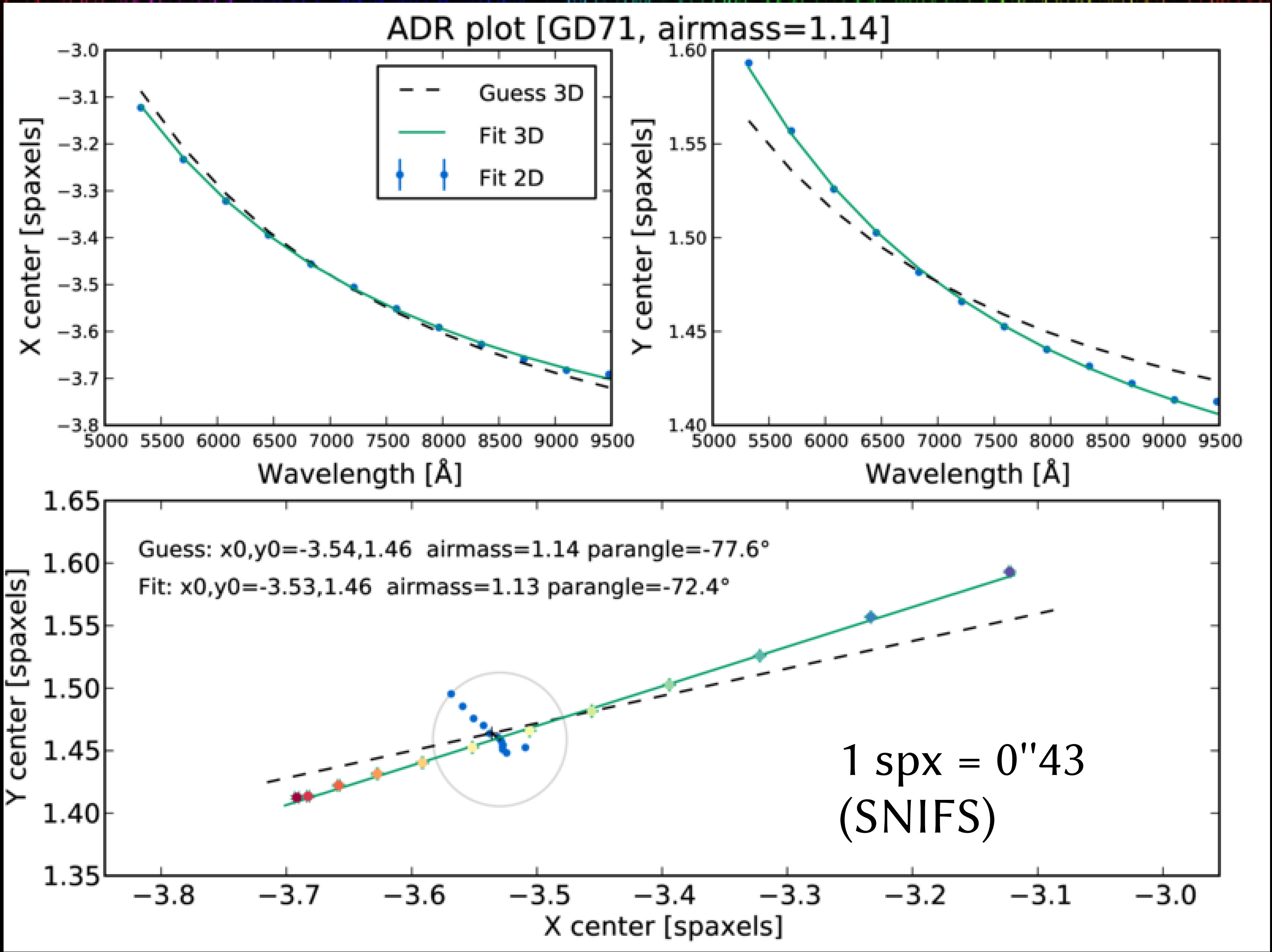
http://spectrogrism.readthedocs.org

Atmospheric Differential Refraction

- Instantaneous ADR:
  - distortion of spectral trace
  - distortion of wave. solution
  - $\Delta(\lambda) = \Delta_{Disp}(\lambda) + \Delta_{ADR}(\lambda)$
- Integrated ADR ($t_{exp} > 0$)
  - widening of spectral trace
  - spectral res. degradation
  - flux-weighted time-average
  - same formalism w/ $\Delta_{ADR}(\lambda, t)$



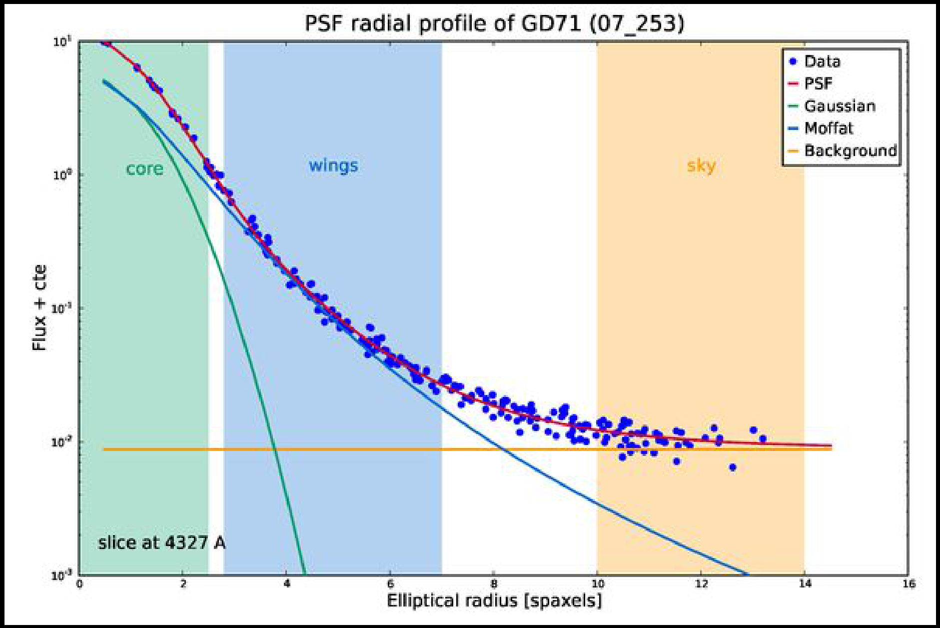




1 spx = 0''43 (SNIFS)

Seeing (atmospheric PSF)

- Historical SNIFS PSF (Buton09)
  - Gaussian for the core
  - Moffat for the wings
  - Correlated parameters
- Observed PSF has more wings than plain Kolmogorov profile
  - $n_{eff} \sim 4.5/3$ rather than 5/3
  - Chrom. dependency is OK
- Current development (see also Xin+18):
  - Seeing: Kolmogorov/von Kármán profile
  - Instrument: eff. profile ($K \otimes G$)
  - Guiding: Gaussian



Atmospheric transmission

- You know better than me
  - Multi-component expansion
  - Constraints from external probes
- What is a photometric night? At which level? Over which time-scale?

Reference spectra

- Recalibration of the spectro-photometric standard stars (S*)
  - Intrinsic consistency wrt/within Calspec: “standard star network”
  - Absolute flux/color calibration (e.g. StarDice, SCALA: Lombardo+17)
- Work in Progress in SNfactory
  - 14 years of repeated observations of 70 stars
  - spectro-photometry at mmag-scale

Conclusions

- Slitless spectro-photometry is within reach
- Good understanding of dispersed image
  - Self-confusion is properly handled for punctual sources
  - **Assuming proper cross-contamination**
    - flexibility in dispersion orientation and/or multi-PA observations
    - multi-order decontamination
- Appropriate models of the different components
  - spectral trace: dispersion law $\Delta(\lambda)$
  - spectral shape: instrumental PSF and seeing P_0
  - flux: $S = T \times S^*$ where T = transmission, S^* = ref. flux