

Archive-Mining the Galaxy Cluster Kinematic Lensing

Master's Thesis Defense

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Stony Brook
University

Archive-Mining the Galaxy Cluster Kinematic Lensing

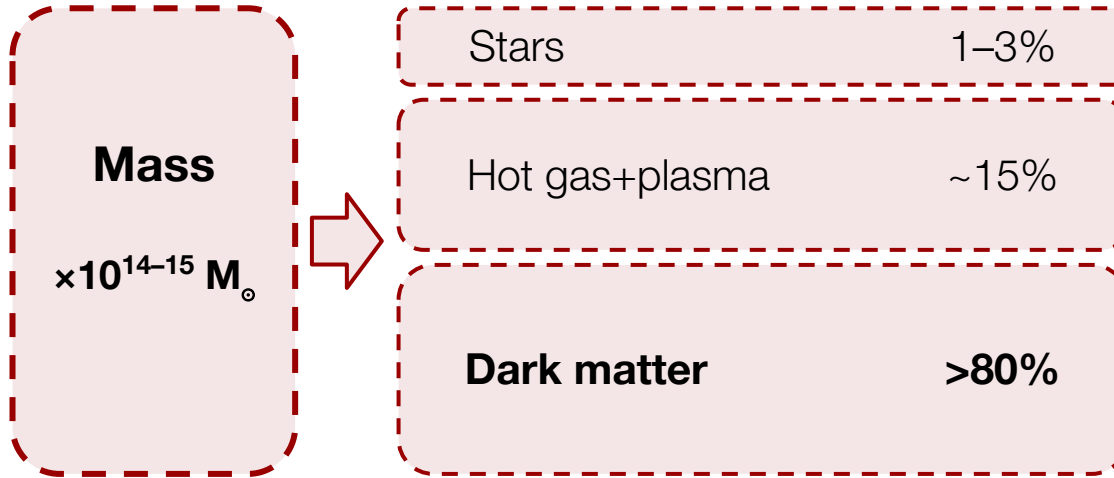
Outlines

1. Introduction
2. Kinematic Lensing
3. Kinematic Lensing on “Weighing the Giants”
Galaxy Clusters with Keck/DEIMOS



Cluster of Galaxies

- $\times 100\text{--}1000$ galaxies
- Locates at nodes of large-scale structure webs
- Largest gravitationally-bounded structures in the Universe



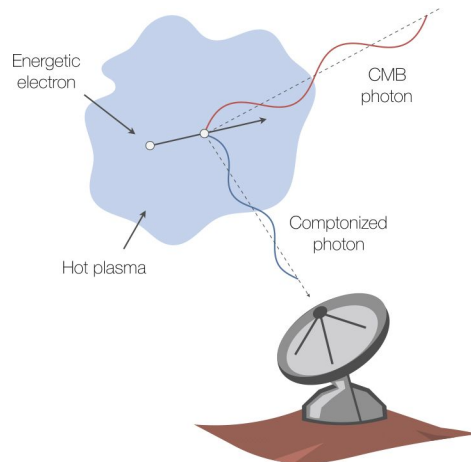
*JWST/NIRCam image of galaxy cluster
SMACS 0723 at $z \sim 0.3$*

<https://www.nasa.gov/image-article/nasas-webb-delivers-deepest-infrared-image-of-universe-yet/>

Cluster of Galaxies

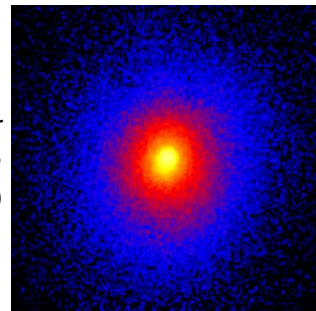
Detection

- **X-ray** — emission from intracluster medium (ICM)
- **Optical** — over-densities of galaxies at similar z
- **Millimeter-wave** — cosmic microwave background (CMB) distortion, according to **Sunyaev-Zel'dovich effect**.



Mroczkowski et al. 2019

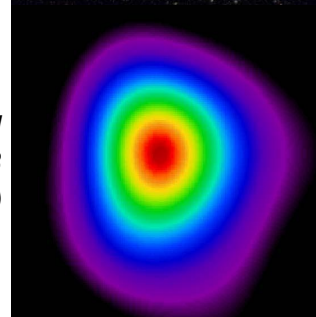
Intracluster
medium
(X-ray)



Concentrated
galaxies
(optical)



SZ-distorted
CMB
(mm)



Allen et al. 2011

Cluster of Galaxies

Detection

- **X-ray** — emission from intracluster medium (ICM)
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Cosmology

- **Large masses**
- **Gravitational Lensing** — Tightly relates the dark matter (DM) and cluster mass

*Intracluster
medium
(X-ray)*

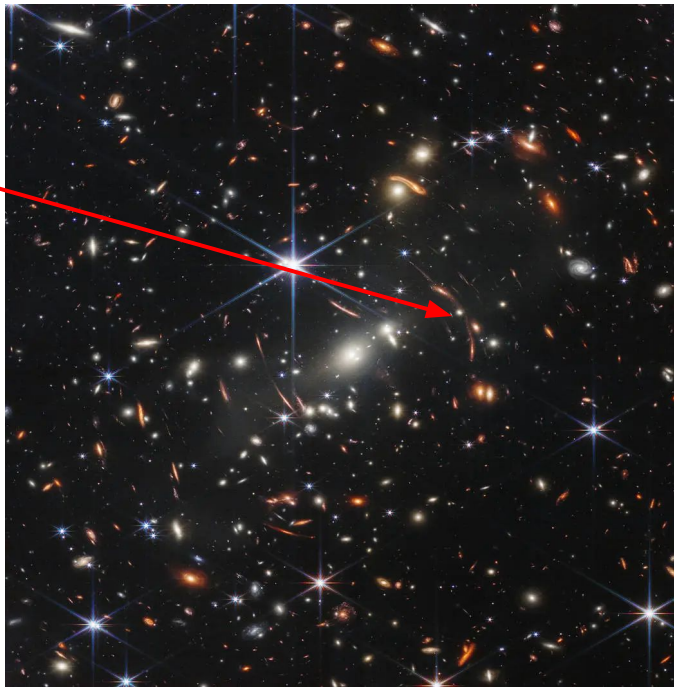
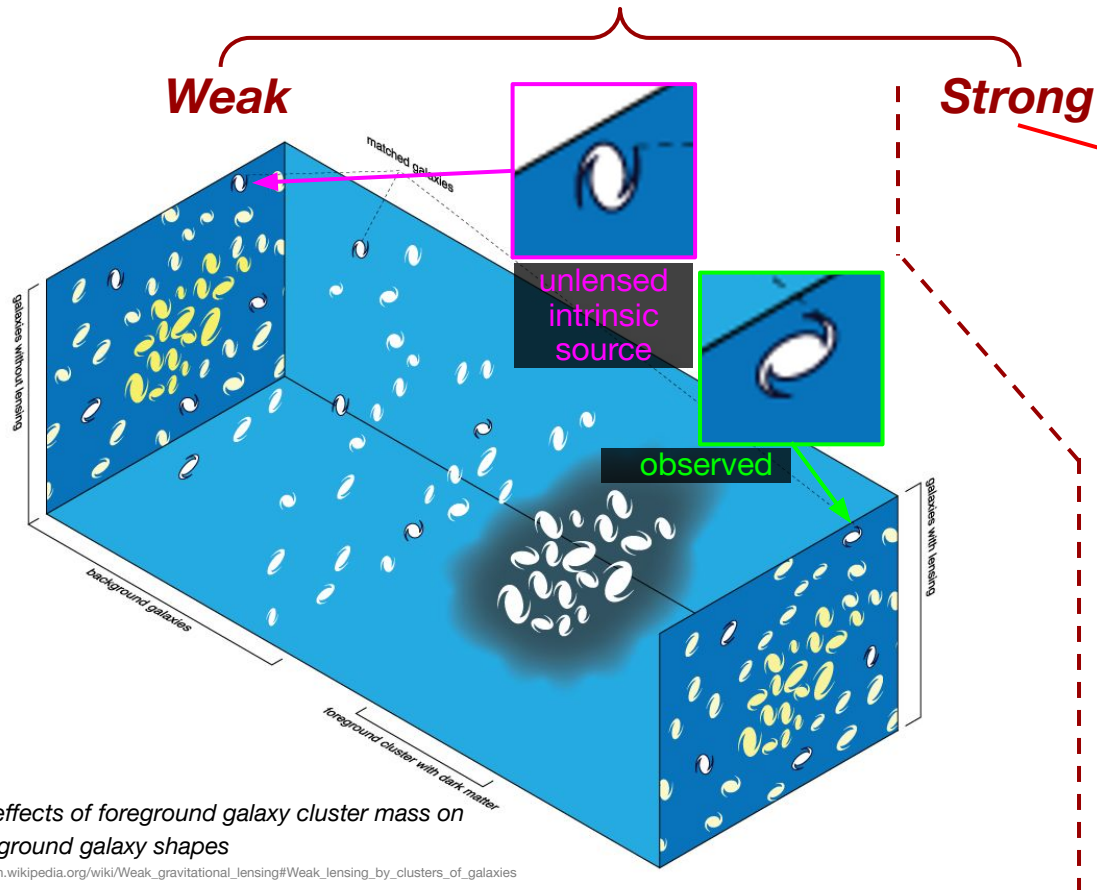
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Gravitational Lensing



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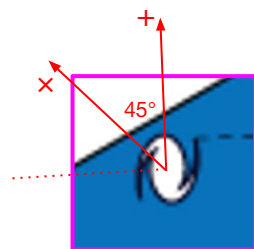
<https://www.nasa.gov/image-article/nasas-webb-delivers-deepest-infrared-image-of-universe-yet/>

*The effects of foreground galaxy cluster mass on
background galaxy shapes*

https://en.wikipedia.org/wiki/Weak_gravitational_lensing#Weak_lensing_by_clusters_of_galaxies

Weak Lensing

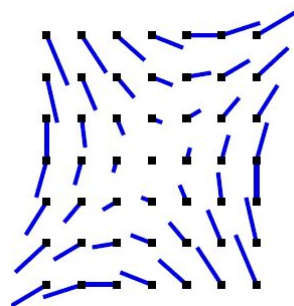
To measure weak shear



unlensed
intrinsic
source

$$\epsilon_{\text{int}} = \epsilon_{\text{int},+} + i\epsilon_{\text{int},\times}$$

(ellipticity, in complex form)



Shear field

$$\gamma = \gamma_{+} + i\gamma_{\times}$$



lensed
observed
image

$$\epsilon_{\text{obs}} = \epsilon_{\text{obs},+} + i\epsilon_{\text{obs},\times}$$

$$\gamma + \epsilon_{\text{int}} = \epsilon_{\text{obs}}$$

+ the component aligned with the major axis of the galaxy
× the component rotated by 45° relative to +.

Weak Lensing

To measure weak shear

Traditionally people assume a mean intrinsic shape = round

- Take **average of shears** $\langle \gamma \rangle$
- Weak-lensing cosmological constraints, shear-shear correlation, ...

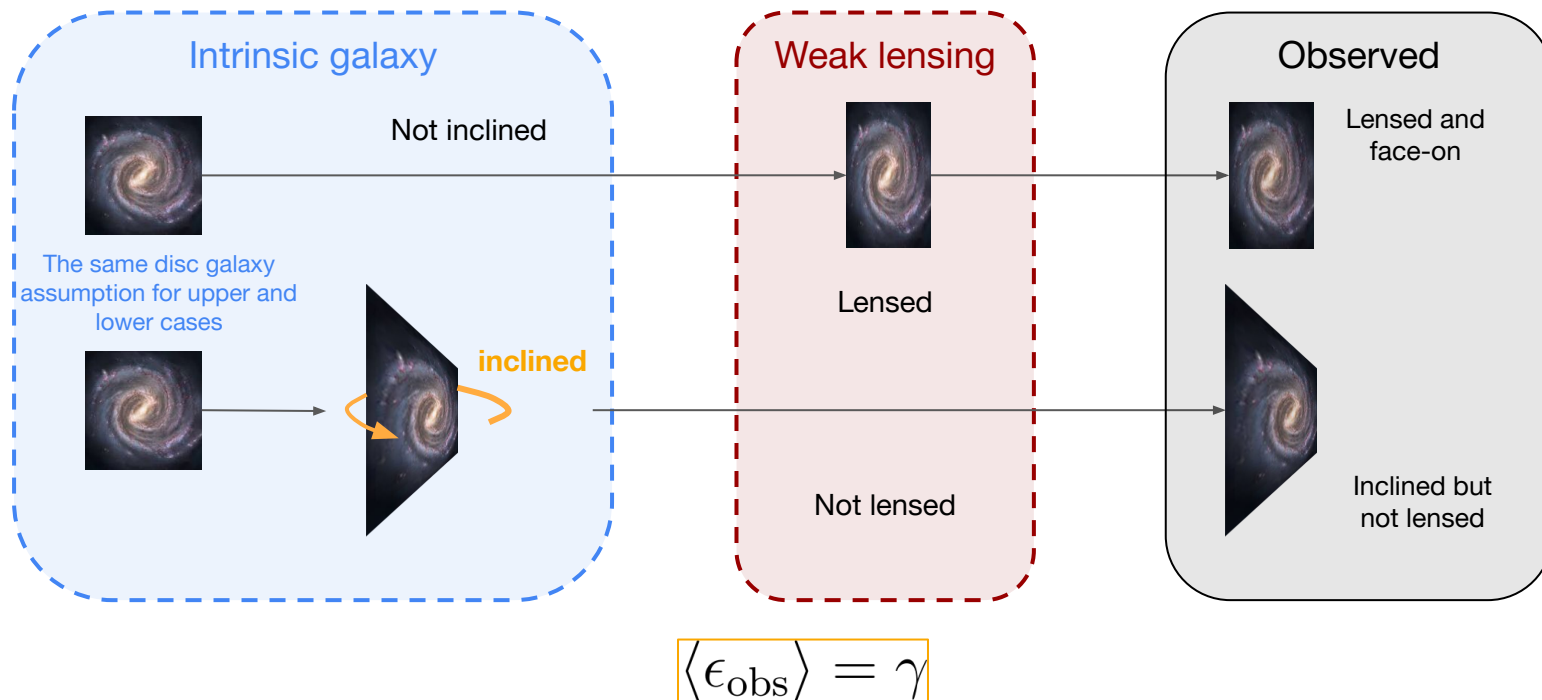
$$\gamma + \epsilon_{\text{int}} = \epsilon_{\text{obs}}$$

$$\langle \epsilon_{\text{int}} \rangle = 0$$

$$\langle \epsilon_{\text{obs}} \rangle = \gamma$$

Weak Lensing

To measure weak shear



Weak Lensing - Shape Noise

To measure weak shear

Traditionally people assume a mean intrinsic shape = round

- Take **average of shears** $\langle \gamma \rangle$
- Weak-lensing cosmological constraints, shear-shear correlation, ...

Shape noise can be as high as

$$\sigma_e \sim 26\% \text{ (from LSST results),}$$

This is the maximal potential of photometry, unluckily.

$$\gamma + \epsilon_{\text{int}} = \epsilon_{\text{obs}}$$

$$\langle \epsilon_{\text{int}} \rangle = 0$$

with σ_e

$$\langle \epsilon_{\text{obs}} \rangle = \gamma$$

Weak Lensing - *Shape Noise*

Better to find:

- **Intrinsic shape** (ϵ_{int}) of source galaxy
- **Resolve individual shears** γ

$$\gamma + \epsilon_{\text{int}} = \epsilon_{\text{obs}}$$

Other magics than normal photometric imaging?

— “*Kinematic Lensing*”.

Kinematic Lensing (*KL*)

An approach that utilizes both **imaging galaxy shape information** and **kinematics from slit-spectroscopy** for breaking the degeneracy between intrinsic shape and weak-lensing shear

(Huff et al. 2013)

Kinematic Lensing (*KL*)

Galaxy **spectra** → Light-of-sight rotational velocity

Tully-Fisher scaling relation → Rotational velocity

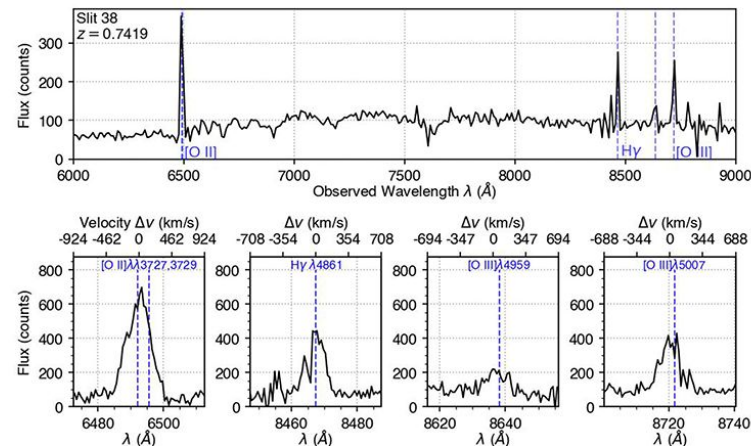


Galaxy inclination
(intrinsic shape)

(Huff et al. 2013)

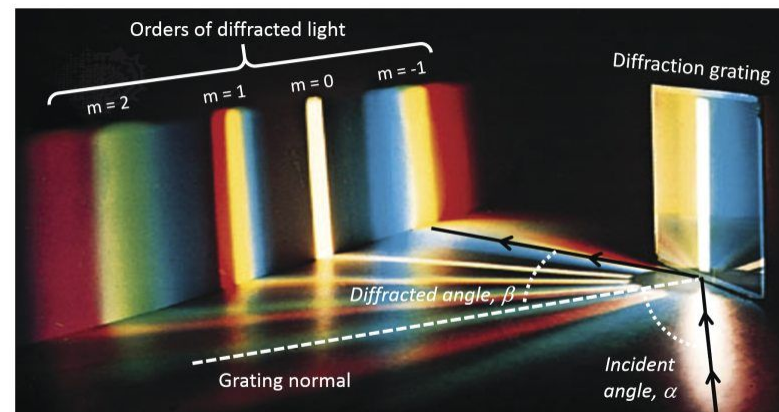
Galaxy Spectroscopy

- Spectra $\longleftrightarrow$ Kinematic information
- Absorption and emission features on spectrum
- With templates, we'll know
 - Redshift, Galaxy type, Chemical composition



Broad and zoomed 1D spectra Slit 38

Thesis Figure



Polychromatic light diffracted from a grating

<https://www.newport.com/n/diffraction-grating-physics>

Galaxy Spectroscopy

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Spectrographs

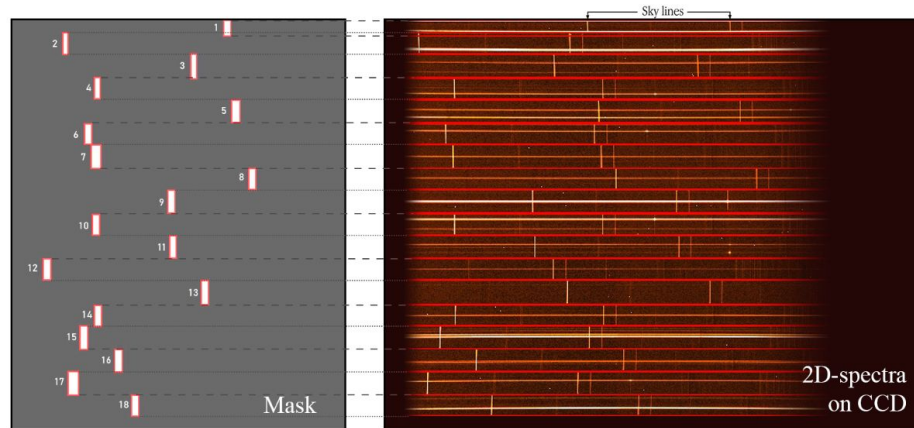
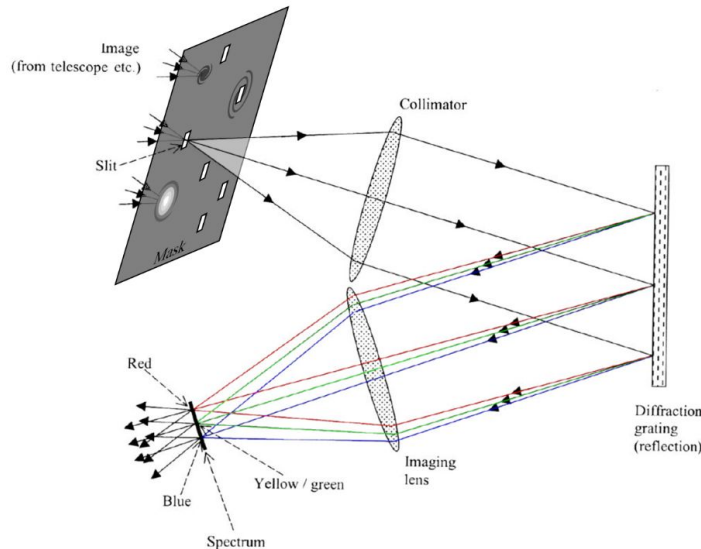
1. **Wide field slitless:** for space-based
2. **Long slit:** for nebulae
3. **Multi-object (MOS)**
 - **Mask + Slit** — slit is a key to recover one-dimensional kinematics of galaxy
 - **Fiber + IFU** — any position but fewer targets

Upper — Multi-object spectrograph (MOS).

Lower Left — A mask design.

Lower Right — 2D spectra horizontally diffracted.

Thesis Figure



1. Rotation Curve

Rotational velocity profile (Courteau 1997, Green et al. 2014)

Disk galaxies:

$$V(R) = \frac{2V_a}{\pi} \arctan\left(\frac{R}{R_t}\right)$$

❖ As $R \rightarrow \infty$, $V(\infty) = V_a$ (asymptotic velocity).



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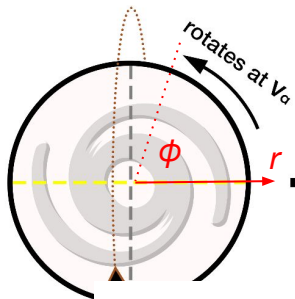
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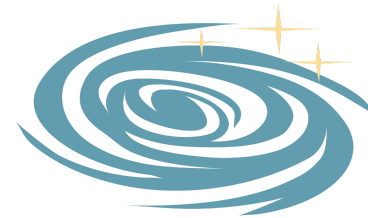
Velocity Field $\Delta v(r, \phi)$

$$\Delta v(r, \phi) := V(R) = \frac{2V_a}{\pi} \arctan\left(\frac{r(\phi)}{r_t(\phi)}\right)$$

- ❖ r = projected R
- ❖ r_t = projected R_t
- ❖ $V_a = V_a$



1. Rotation Curve



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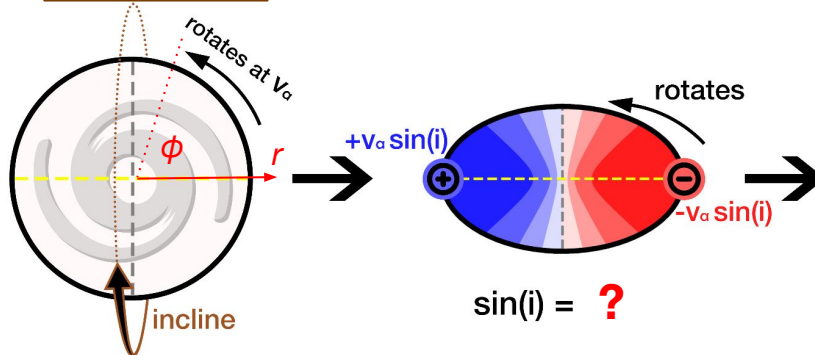
❖ As $R \rightarrow \infty$, $V(\infty) = V_a$ (asymptotic velocity).

Velocity Field $\Delta v(r, \phi)$ of an inclined galaxy

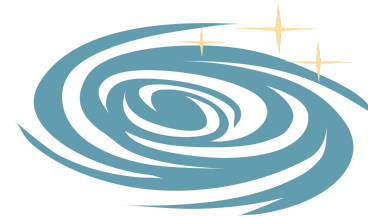
$$\Delta v_{\text{los}}(r, \phi) := V(R) \boxed{\cos(\phi) \sin(i)} = \frac{2V_a}{\pi} \boxed{\cos(\phi) \sin(i)} \arctan\left(\frac{r(\phi)}{r_t(\phi)}\right)$$

Light-of-sight component

- ❖ r = projected R
- ❖ r_t = projected R_t
- ❖ $V_a = V_a$



1. Rotation Curve



Rotational velocity profile (Courteau 1997, Green et al. 2014)

Disk galaxies:

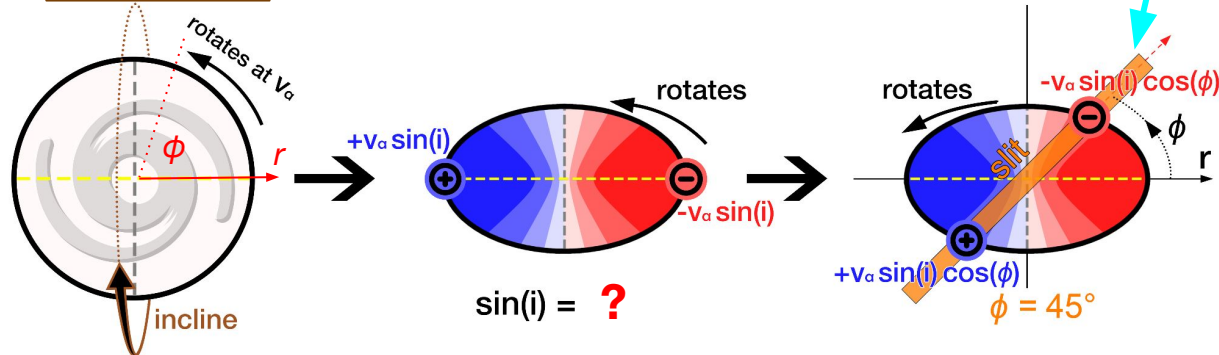
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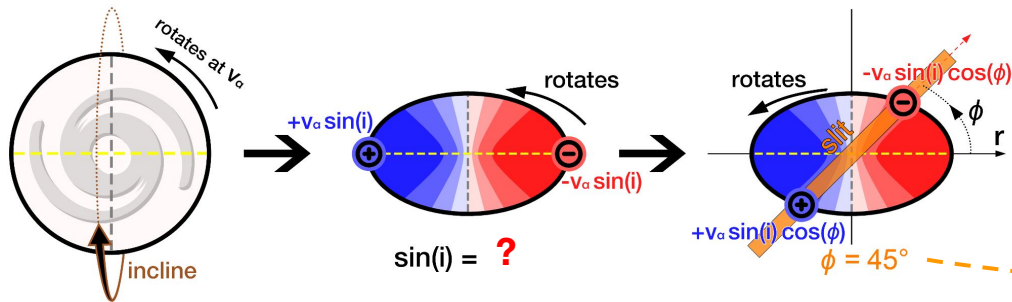
Velocity Field $\Delta v(r, \phi)$ of an inclined galaxy

$$\Delta v_{\text{los}}(r, \phi) := V(R) \cos(\phi) \sin(i) = \frac{2V_a}{\pi} \cos(\phi) \sin(i) \arctan\left(\frac{r(\phi)}{r_t(\phi)}\right)$$

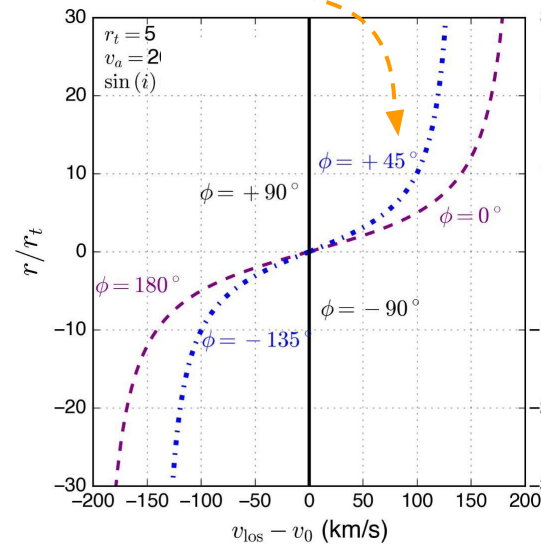
- ❖ r = projected R
- ❖ r_t = projected R_t
- ❖ $V_a = V_a$



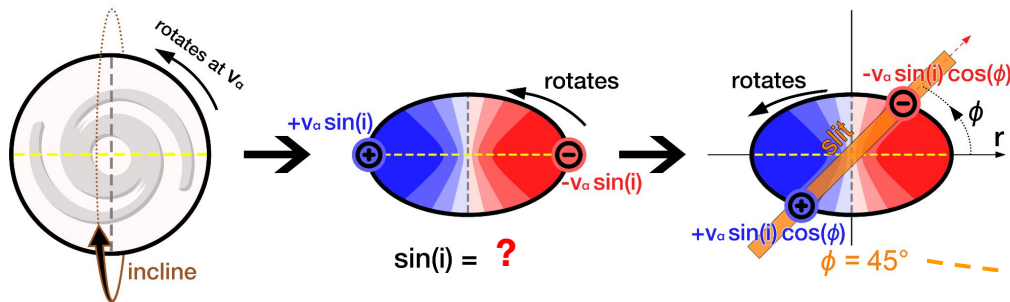
1. Rotation Curve



$$\Delta v_{\text{los}}(r, \phi) := V(R) \cos(\phi) \sin(i) = \frac{2V_a}{\pi} \cos(\phi) \sin(i) \arctan\left(\frac{r(\phi)}{r_t(\phi)}\right)$$

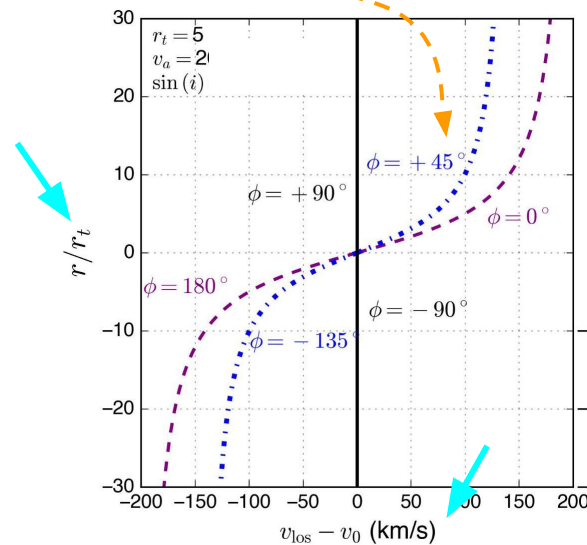


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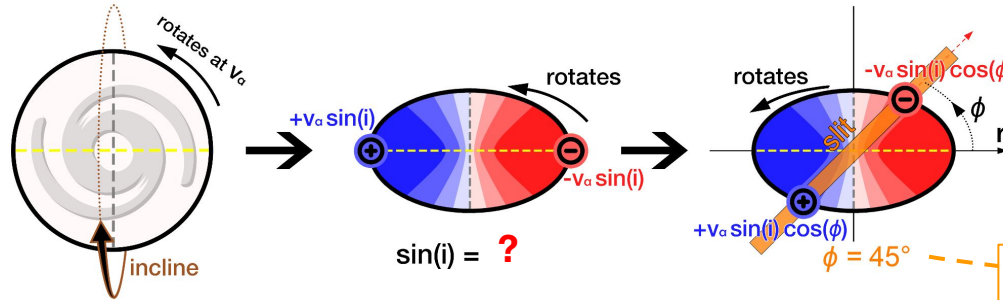


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$\Delta v(r, \phi)$ with known $\phi \rightarrow$ **Rotation Curve**

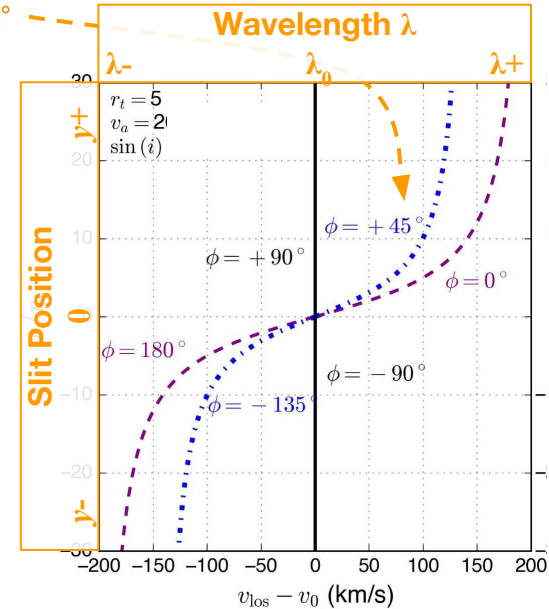


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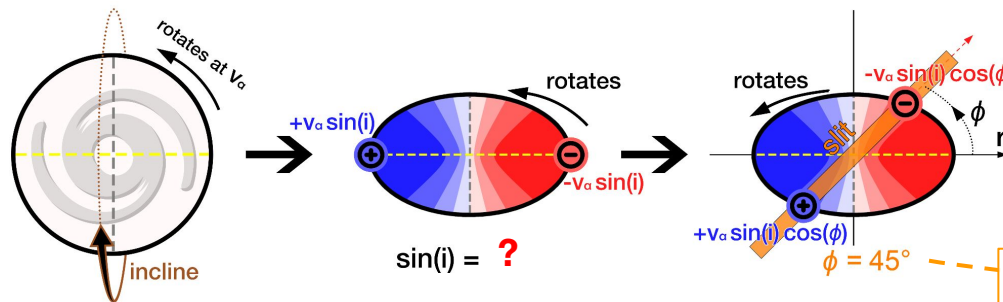


Rotation Curve is an **observable** emission line on spectrum (λ)

$$\Delta v = c \frac{\lambda - \lambda_0}{\lambda_0}$$



1. Rotation Curve

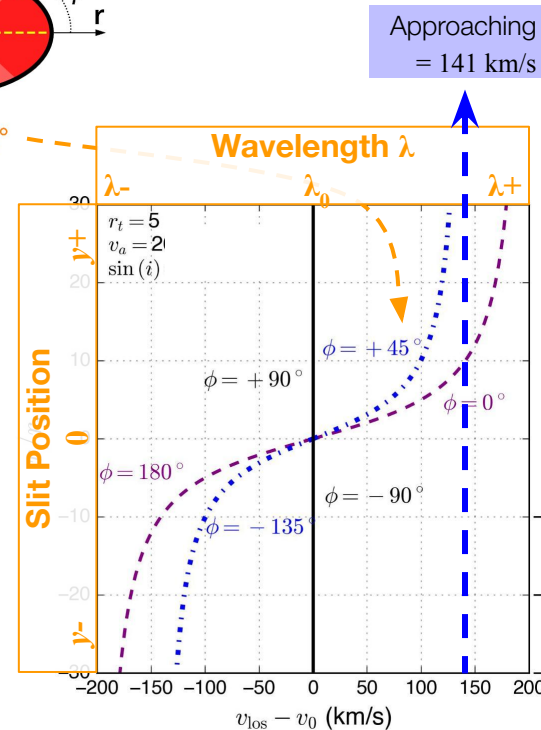


Find asymptotic light-of-sight velocity

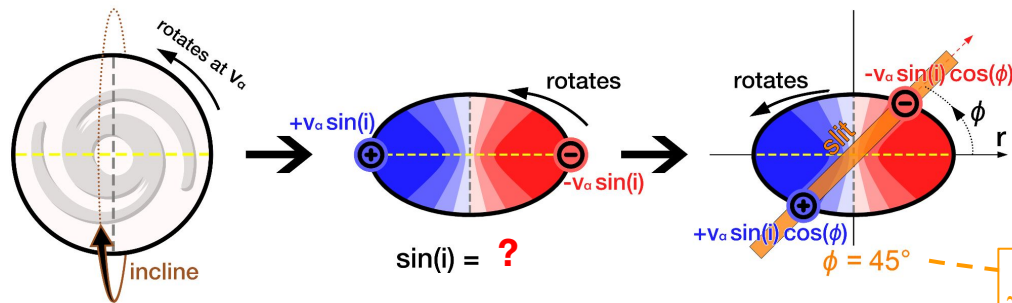
$$\lim_{r \rightarrow \infty} \left[\frac{2V_a}{\pi} \cos(\phi) \sin(i) \arctan \left(\frac{r(\phi)}{r_t(\phi)} \right) \right]$$



$$v_a \cos(\phi) \sin(i)$$



1. Rotation Curve



Find asymptotic light-of-sight velocity *along major axis*

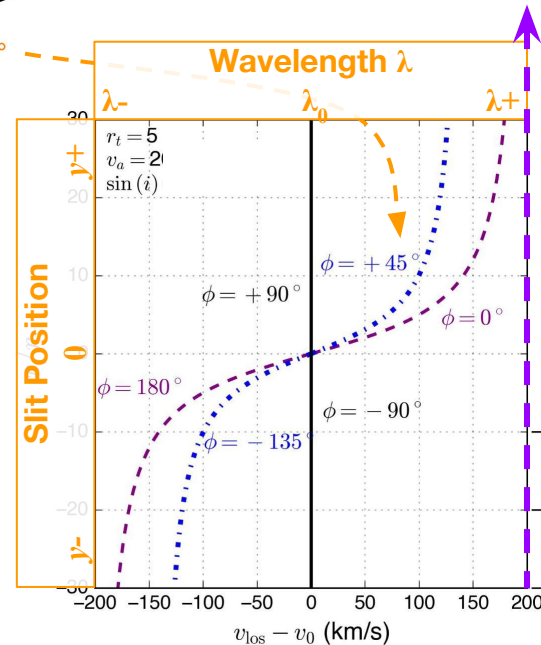
$$\lim_{\substack{r \rightarrow \infty \\ \phi \rightarrow 0}} \left[\frac{2V_a}{\pi} \cos(\phi) \sin(i) \arctan\left(\frac{r(\phi)}{r_t(\phi)}\right) \right]$$

known known

$$\lim_{\phi \rightarrow 0} \left[v_a \cos(\phi) \sin(i) \right]$$

known

$$\Delta v_{\max} = v_a \sin(i)$$



2. Maximum Rotational Speed $v_{\text{rot,TF}}$

Tully-Fisher scaling relation (Tully & Fisher 1977)

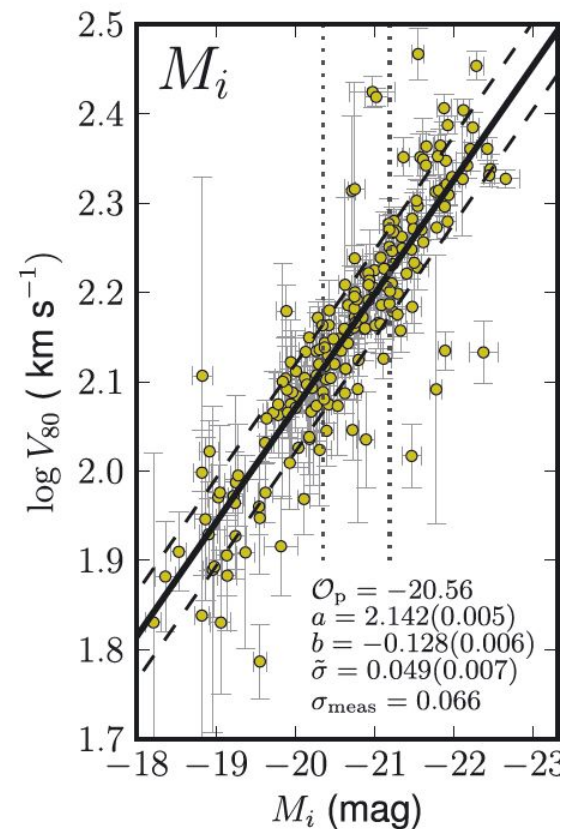
Disk galaxies:

$$\log(v_{\text{rot,TF}}) = a(M_B - M_0) + b$$

↑
Absolute magnitude

SDSS *r*-band galaxies: (Reyes et al. 2011)

$$\log\left(\frac{v_{\text{rot,TF}}}{139_{-2}^{+1} \text{ km s}^{-1}}\right) = \left(-0.130_{-0.007}^{+0.007} \frac{\log(\text{km s}^{-1})}{\text{mag}}\right) (M_r + 20.375 \text{ mag})$$



ITFRs between rotation velocities V_{80} and photometric M_i for the 189 galaxies.

Reyes et al. (2011) Figure 20

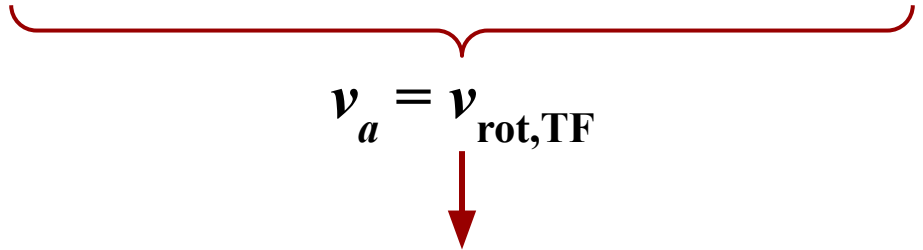
Takeaways:

**Maximum Rotational Speed of
Tully-Fisher Relation**

$$\log(v_{\text{rot,TF}}) = a(M_B - M_0) + b$$

**Asymptotic Velocity of
Rotation Curve**

$$\Delta v_{\text{max}} = v_a \sin(i) = \lim_{r \rightarrow \infty} [\Delta v(r, 0)]$$


$$v_a = v_{\text{rot,TF}}$$

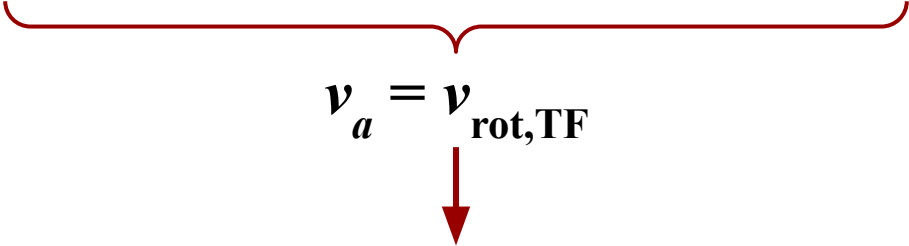
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$$\Delta v_{\text{max}} = v_a \sin(i) = \lim_{r \rightarrow \infty} [\Delta v(r, 0)]$$


$$v_a = v_{\text{rot,TF}}$$

Galaxy inclination
(intrinsic shape)

$$\sin(i) = \frac{\Delta v_{\text{max}}}{v_{\text{rot,TF}}}$$

Expectations of Kinematic Lensing

KL improves 3 important aspects of
traditional weak lensing systematics from $\sigma_{\epsilon} \sim 0.26$ (LSST)

1. Reduced Shape Noise.

- *Infer the velocity/frequency field of the source galaxy.*
- *Direct outcomes by using those spectrographs with IFUs.*

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2. Redshift Uncertainties.

- *Spectroscopic redshifts' better precision, with error of $\Delta_{\text{spec-z}} \sim 0.001$.*
- *Photometric redshifts ($\Delta_{\text{photo-z}} \sim 0.05$, Tanaka et al. 2018).*

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3. More Bright Galaxy Samples.

- Traditional lensing: **must include low SNR galaxies** (e.g., J+H band combined SNR>18, Eifler et al. 2021) to increase the sample size and statistical precision.
- However, **KL: r-band SNR>50**, emission-line-well-resolved, unblended (relatively isolated) galaxies, improving the photometric shape measurement for smaller biases (Pranjal et al. 2023, Xu et al. 2023).

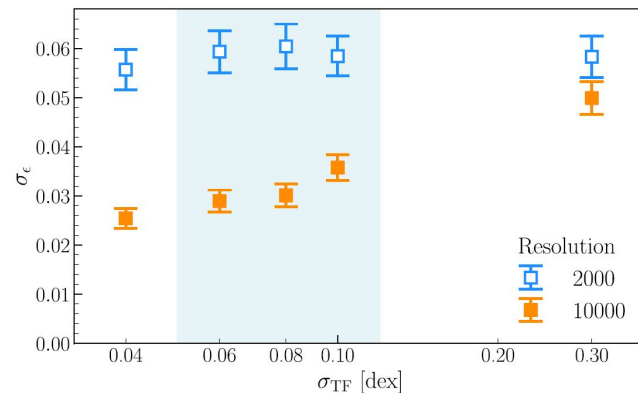
KL Shape Noise: $\sigma_{\epsilon}^{\text{KL}} = 0.04$ from the recent mock observations (Pranjal et al. 2023)

Expectations of Kinematic Lensing

KL shape noise $\sigma_{\epsilon}^{\text{KL}} = 0.04$ depends on the following systematics:

1. Tully-Fisher Relation Intrinsic Scatter (σ_{TF})

- $R = 2000$ resolving power + spectral SNR=30,
an average of $\sigma_{\epsilon}^{\text{KL}} = 0.06$ (Pranjal et al. 2023)

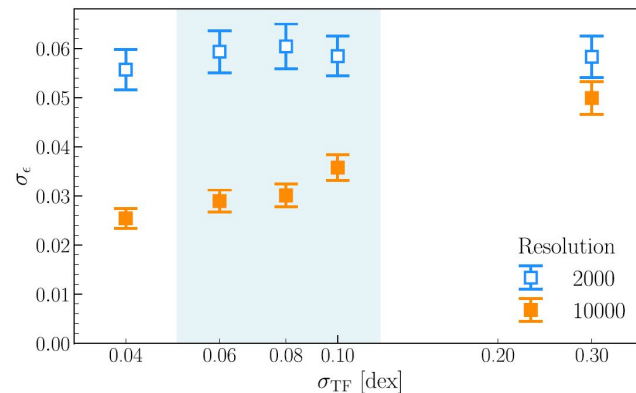


Expectations of Kinematic Lensing

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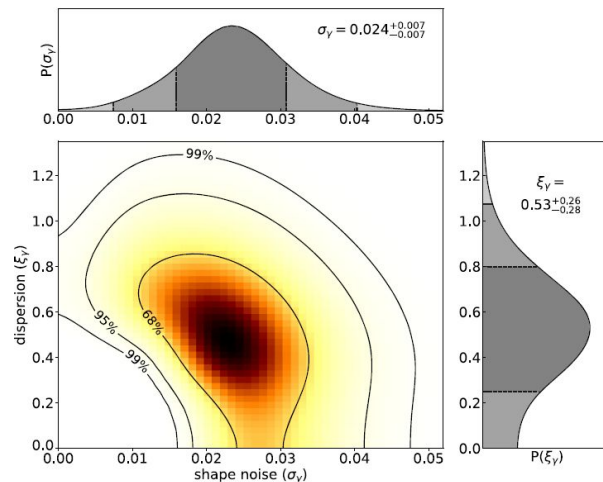
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Importance of the velocity fields inferred by spectroscopy

- Gurri et al. (2020) — galaxy-galaxy lensing systems;
use the lens-source position relation to infer v_a
- Gurri et al. (2021) and DiGiorgio et al. (2021) — effective shape noise $\sigma_{\epsilon} = 0.017\text{--}0.031$
- Wittman & Self (2021) — involve Tully-Fisher relation; shape noise of $\sigma_{\epsilon} \sim 0.04$



Kinematic Lensing on “Weighing the Giants” Galaxy Clusters **with Keck/DEIMOS**

Mining in the archived slit-spectroscopic data

Target Selection

“Weighing the Giants” project galaxy cluster sample
(51 clusters; von der Linden et al. 2014a,b, Kelly et al. 2014, and Applegate et al. 2014)

“Weighing the Giants” (WtG) clusters

- calibrated with robust weak-lensing masses from X-ray observations
- span an intermediate redshift range of $0.15 < z_{\text{cl}} < 0.7$.
 - (1) Photometric imaging observed with Subaru/SuprimeCam and CFHT/MegaPrime;
 - (2) Maps of the total mass distribution measured from weak lensing;
 - (3) **Robust weak-lensing shape measurement at hand;**
 - (4) Central galaxy determination; and
 - (5) Photometric redshifts.

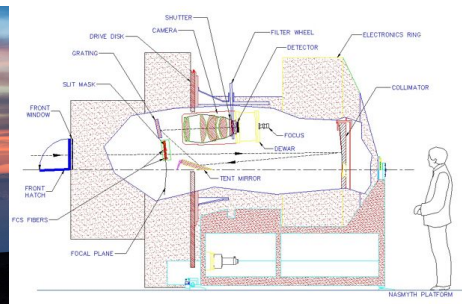
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Keck/DEIMOS instrument
(Faber et al. 2003)

Keck/DEIMOS (DEep Imaging Multi-Object Spectrograph; Faber et al. 2003)

- Visible-wavelength, faint-object, multi-slit imaging spectrograph of Keck II telescope
- Wavelength range of 4100–11000 Å
 - Ca H&K $\lambda\lambda 3933, 3968$ doublet (absorption)
 - [O II] $\lambda\lambda 3727, 3729$ doublet
 - [S II] $\lambda\lambda 6716, 6731$ doublet, [O III] $\lambda\lambda 4959, 5007$ doublet, N II $\lambda\lambda 6548, 6584$ doublet, & H γ $\lambda 4340$, H β $\lambda 4861$, H α $\lambda 6563$.



Spectroscopic Grating (lines/mm)	Blaze Wavelength (Å)	Dispersion Scale (Å/pixel)	FWHM Spectral Resolution (1" slit) $\Delta\lambda$ (Å)	Resolving Power R
600	7500	0.65	4.7	1606
1200	7500	0.33	1.5–2.1	3571–5000

This thesis
(6 clusters + 17 masks)

“Weighing the Giants” project galaxy cluster sample
(51 clusters; von der Linden et al. 2014a,b, Kelly et al. 2014, and Applegate et al. 2014)

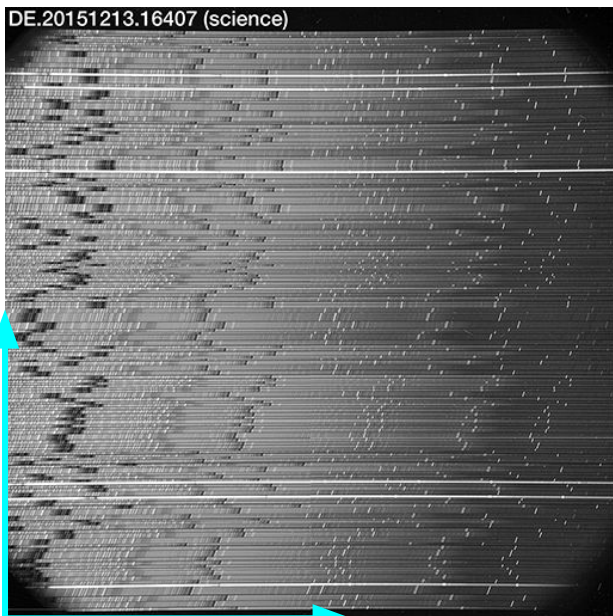
Keck/DEIMOS instrument
(Faber et al. 2003)

	Cluster	RA (deg)	Dec. (deg)	z_{Cl}	M10	Mask	Grating	Date	Set
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	A2552	347.88818	3.63514	0.302	M	25521B	1200G	2015-12-13	A
2	A611	120.23674	36.05709	0.288	–	sna611	600ZD	2012-10-15	E
3	A1758N	203.18111	50.54398	0.279	–	ejc	600ZD	2018-07-16	I
4	A1758N	203.18111	50.54398	0.279	–	ejc1	600ZD	2018-07-17	C
5	A1758N	203.18111	50.54398	0.279	–	ejc2	600ZD	2018-07-18	D
6	M1115	168.96617	1.49861	0.355	M	sn1115	600ZD	2012-02-26	B
7	M1115	168.96617	1.49861	0.355	M	1115m1	600ZD	2014-02-25	A
8	M1115	168.96617	1.49861	0.355	M	jc9	600ZD	2015-06-16	B
9	A2261	260.61244	32.13275	0.224	B	a2261aB	1200G	2014-07-01	A
10	A2261	260.61244	32.13275	0.224	B	a2261b	1200G	2014-07-01	B
11	A2261	260.61244	32.13275	0.224	B	a2261c	1200G	2014-07-01	C
12	A2261	260.61244	32.13275	0.224	B	a2261d	1200G	2015-06-18	A
13	A2261	260.61244	32.13275	0.224	B	a2261e	1200G	2015-06-18	B
14	A2261	260.61244	32.13275	0.224	B	a2261b	1200G	2015-06-18	C
15	A2261	260.61244	32.13275	0.224	B	a2261a	1200G	2015-06-18	D
16	A370	39.97186	-1.57718	0.375	–	A37017B1	1200G	2017-09-28	A
17	A370	39.97186	-1.57718	0.375	–	A37017B2	1200G	2017-09-28	B

Data Reduction

Raw and Calibration Data

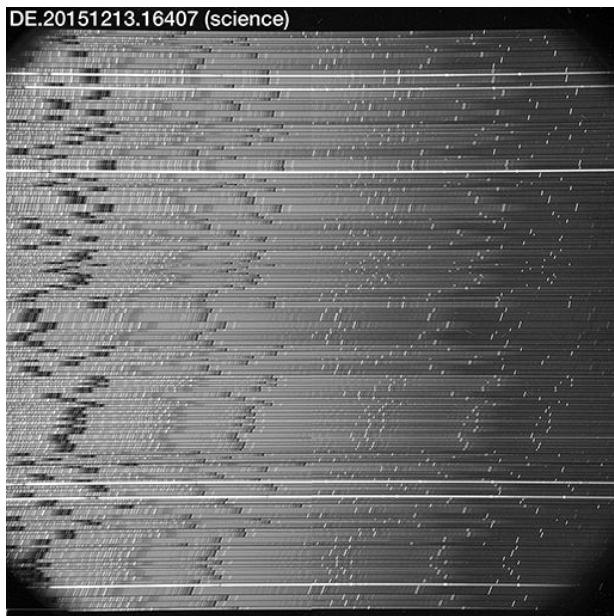
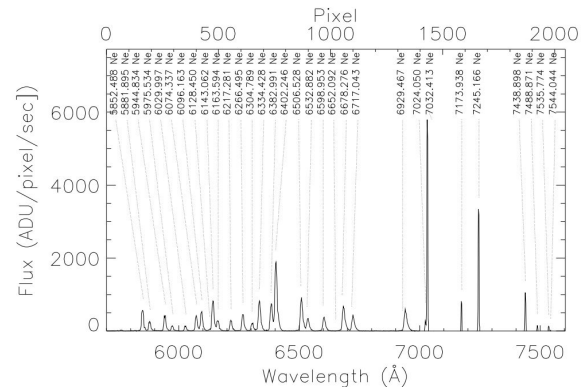
CCD 8192×8192 pixel² science image of
the cluster A2552's spectra



Data Reduction

Raw and Calibration Data

“Arc image” maps the pixel position to wavelengths → Identify wavelength at each x-pixel (Right plots: $_{10}\text{Ne}$ arc lamp flux-wavelength plot from Keck/Iris)



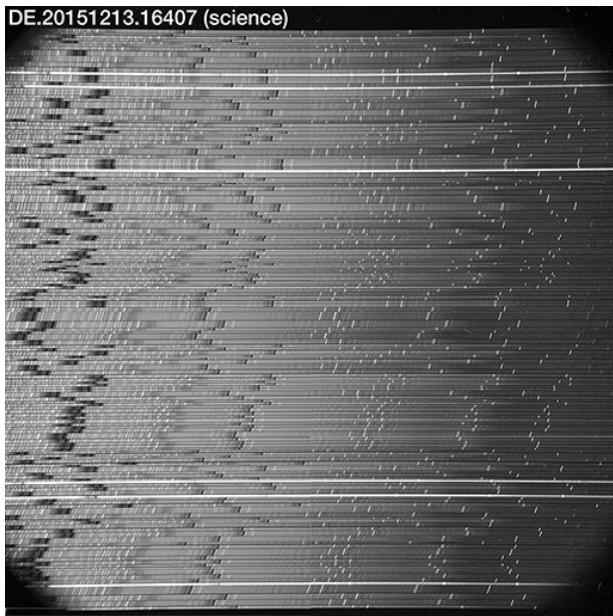
Data Reduction

Raw and Calibration Data

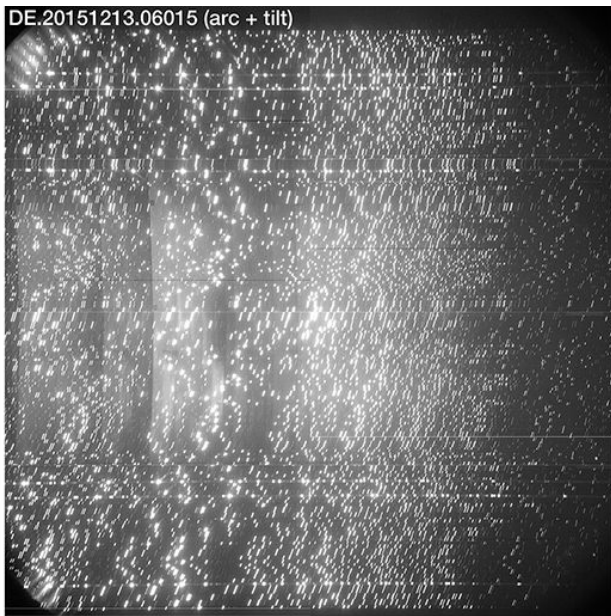
“Trace image” also **traces the dispersion directions of slits.**

They are edges of slits.

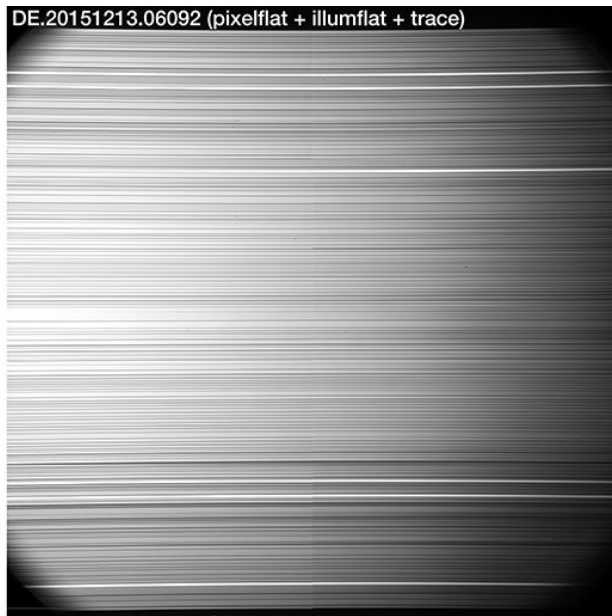
DE.20151213.16407 (science)



DE.20151213.06015 (arc + tilt)



DE.20151213.06092 (pixelflat + illumflat + trace)



Data Reduction — PypeIt *Python-based pipeline for the popular MOS instruments*

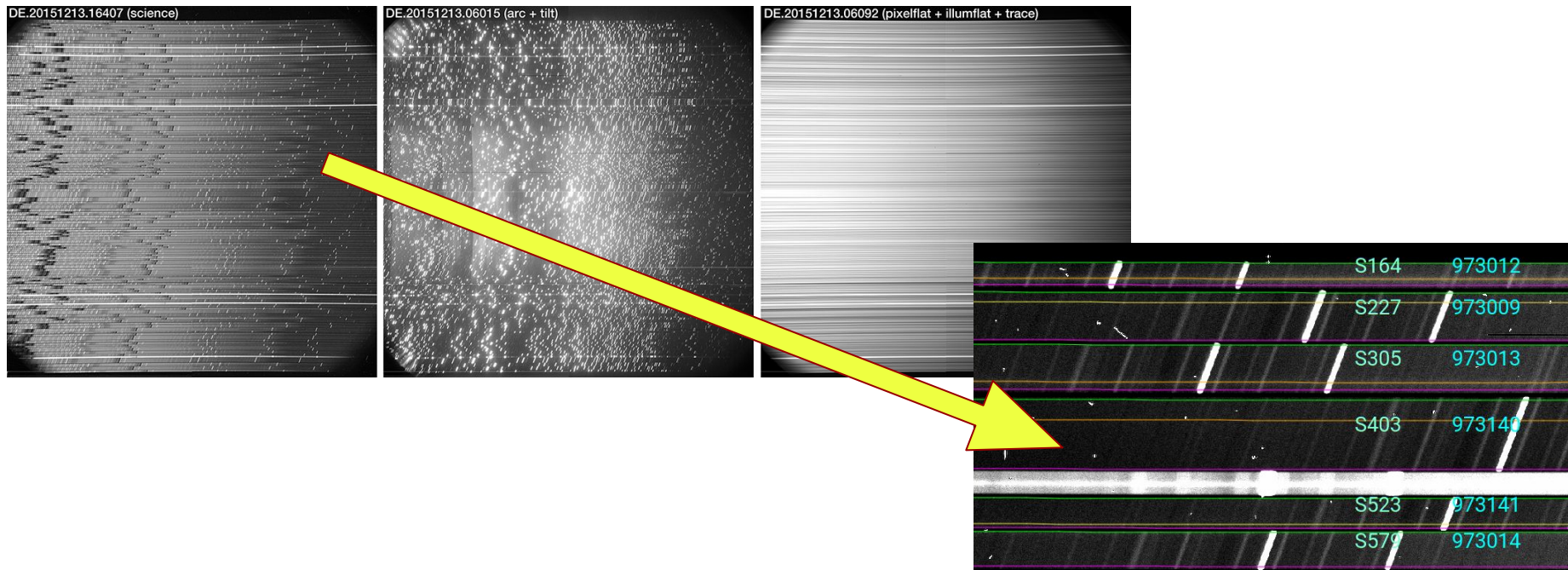


Data Reduction — PyperIt *Python-based pipeline for the popular MOS instruments*



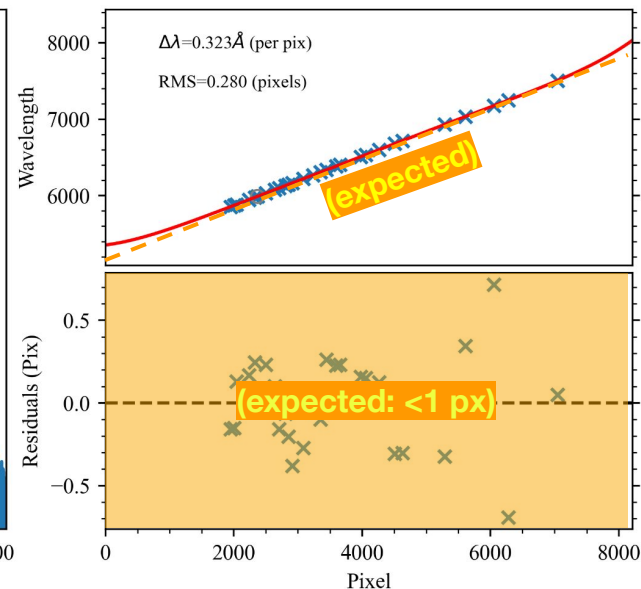
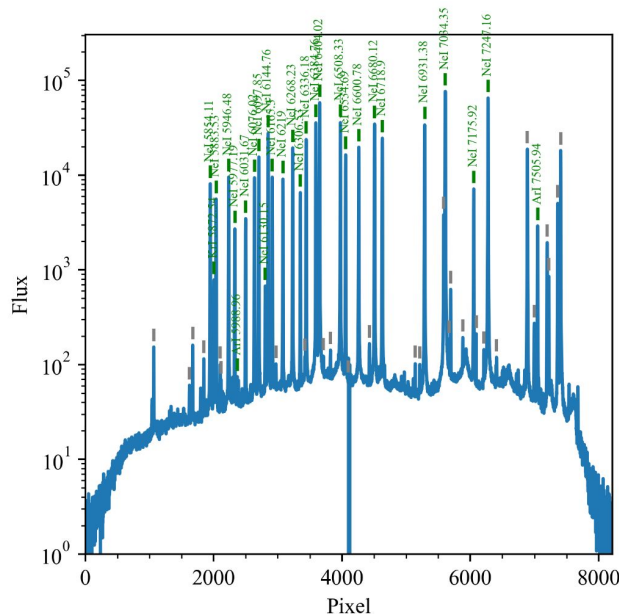
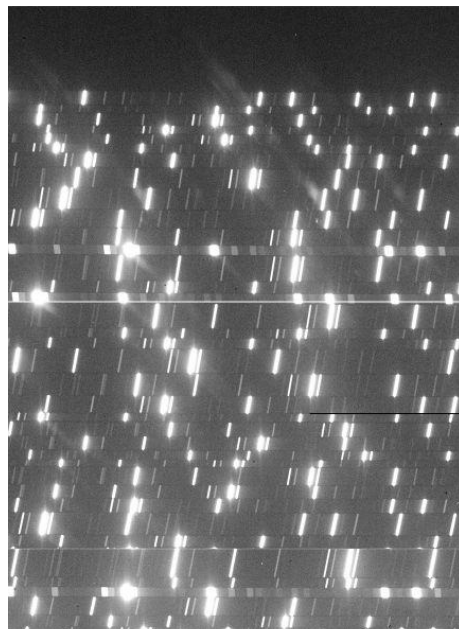
Slit Identification

Which slit $\longleftrightarrow$ which 2D spectrum strip



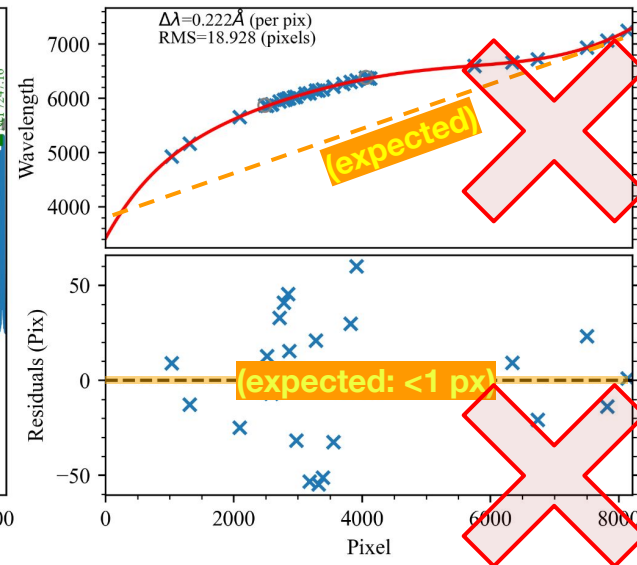
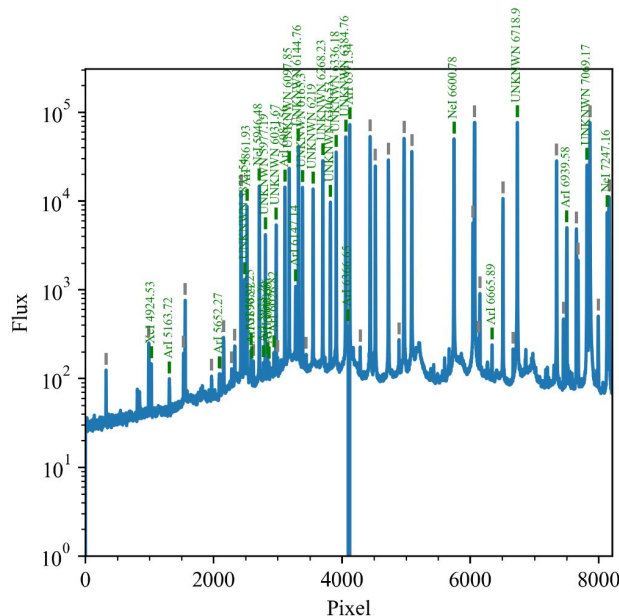
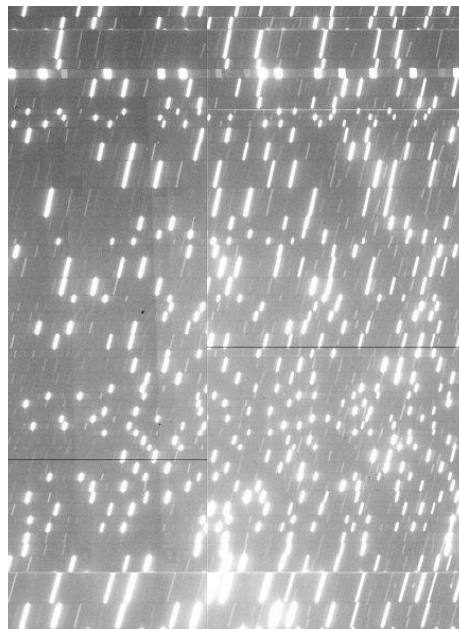
PytypeIt identifies arc lines.

PyPeIt determines pixel-wavelength mapping and gives analytic polynomial fit.



PypeIt identifies arc lines.

PyPeIt determines pixel-wavelength mapping and gives analytic polynomial fit.

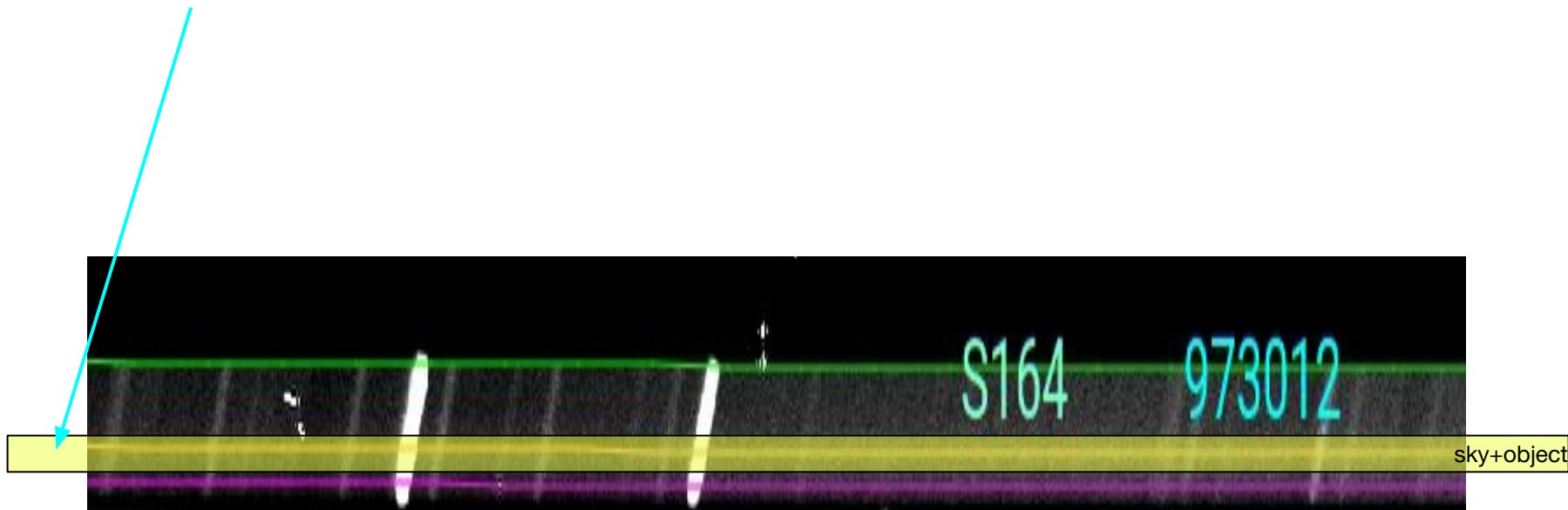




Object Finding and Sky Line Subtraction

Sky lines are a series of lines illuminated by atmospheric airflow

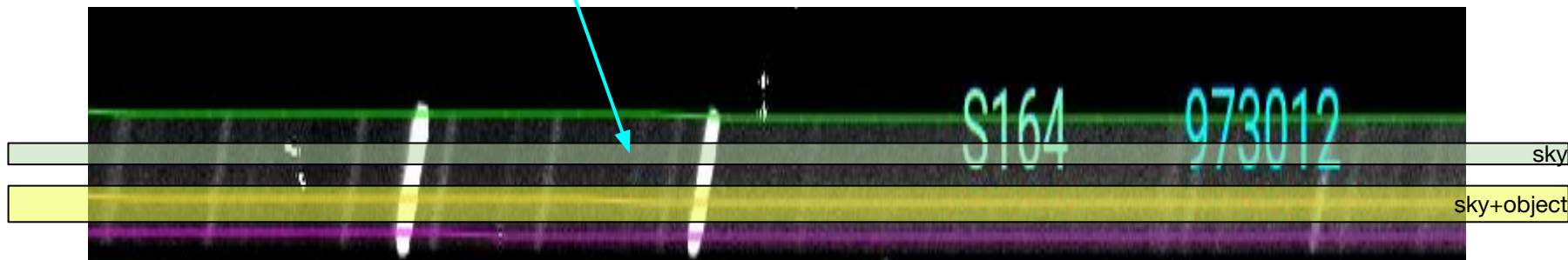
- **2D object** model (continuum-like) — Pixels with **higher SNRs** (e.g., $\text{SNR} > 5\sigma$)



Object Finding and Sky Line Subtraction

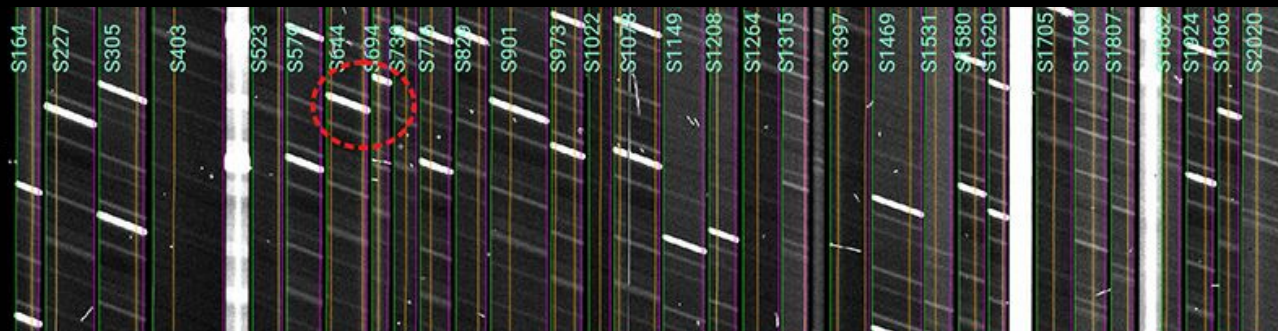
Sky lines are a series of lines illuminated by atmospheric airflow

- **2D object** model (continuum-like) — Pixels with **higher SNRs** (e.g., $\text{SNR} > 5\sigma$)
- **2D sky** model — **parallel pixels** next to 2D object
- Science = object + sky

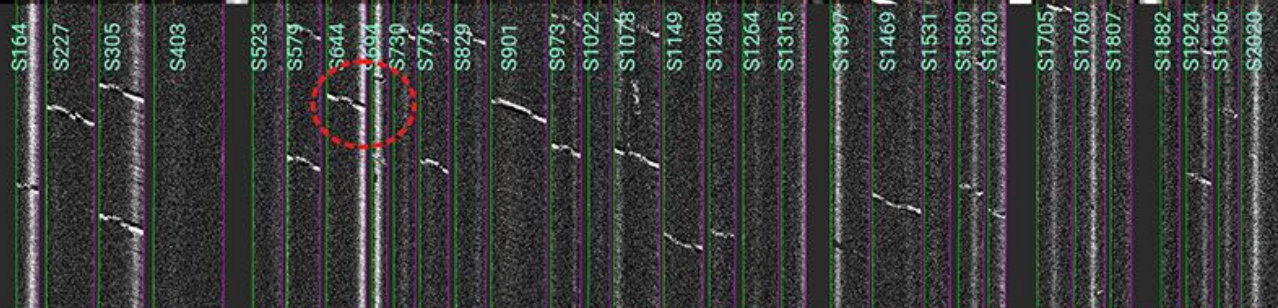


Sky Line Subtraction

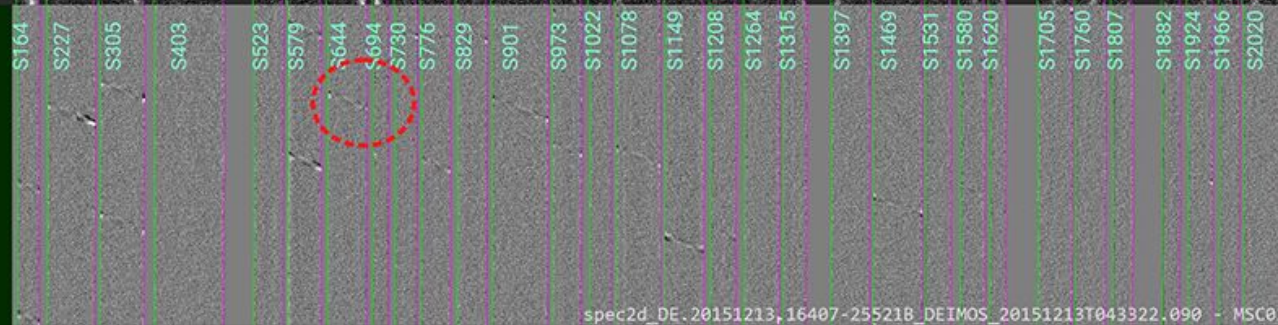
science



science
-
sky model



science
- sky model
- object model



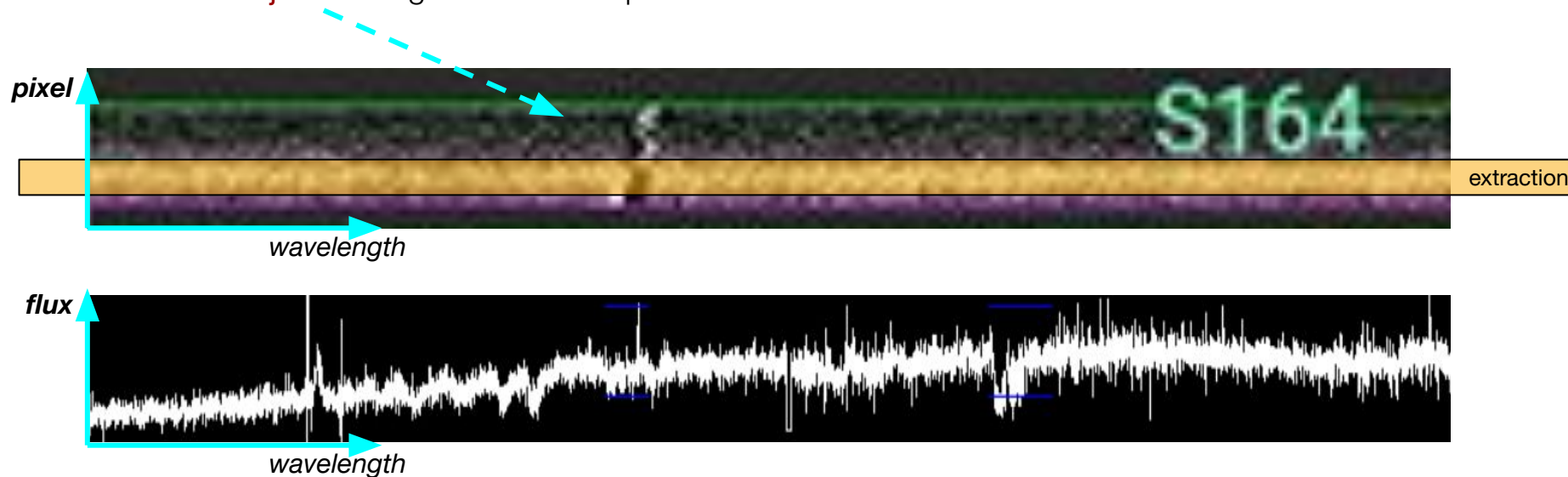
Data Reduction — PyperIt *Python-based pipeline for the popular MOS instruments*



1D spectrum

Define an extraction width.

The flux of **2D object** is integrated into 1D spectrum model.



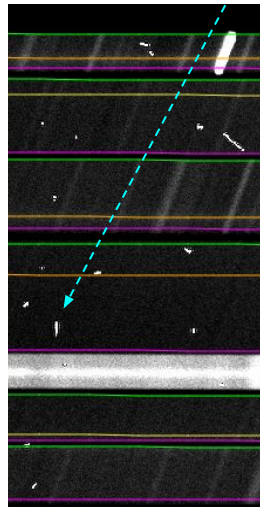
Data Reduction — **PyperIt** *Python-based pipeline for the popular MOS instruments*



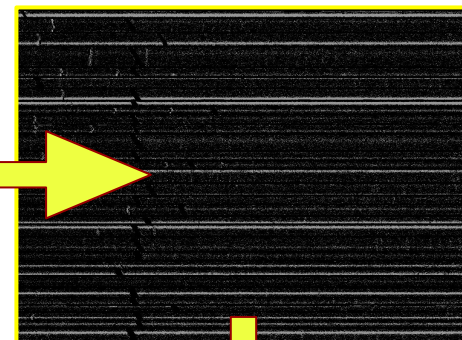
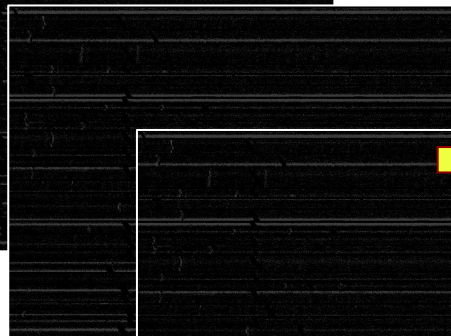
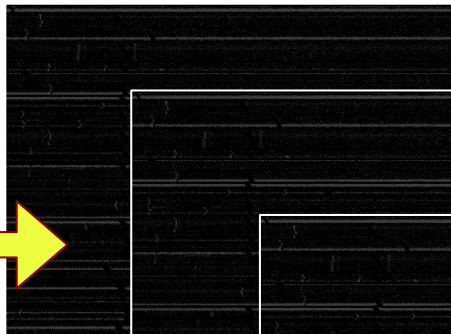
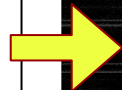
Co-addition

Remove cosmic rays

Co-add multiple frames to the weighted mean (an average image using uniform weighting).



Slit Identification
Wavelength Calibration
Object Finding
Sky Line Subtraction



1D Extraction again

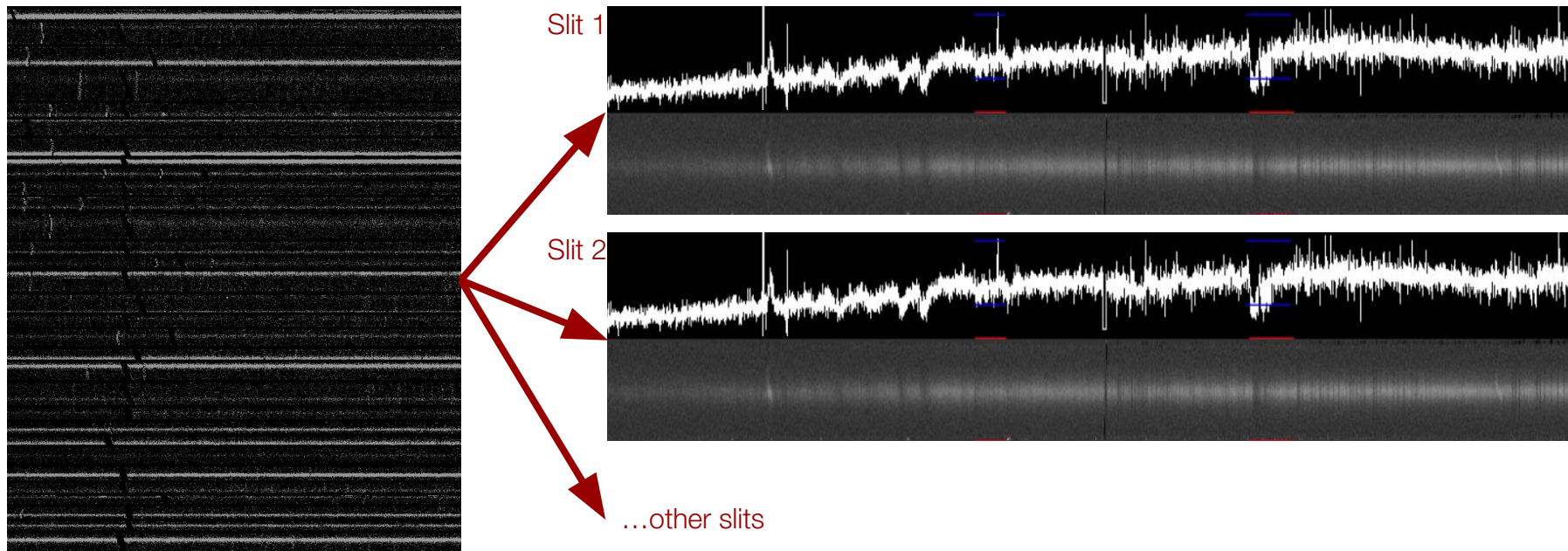
Results

Spectroscopic Redshift

Results

Spectroscopic Redshift

1. Spectrum Cutting-off by Slit — [pypeittospecpro.py](#) | 1338 spectra | 1125 targets



Results

Spectroscopic Redshift

1. Spectrum Cutting-off by Slit
2. Templates

Table 2.3: Spectral Templates For Cross-Correlation

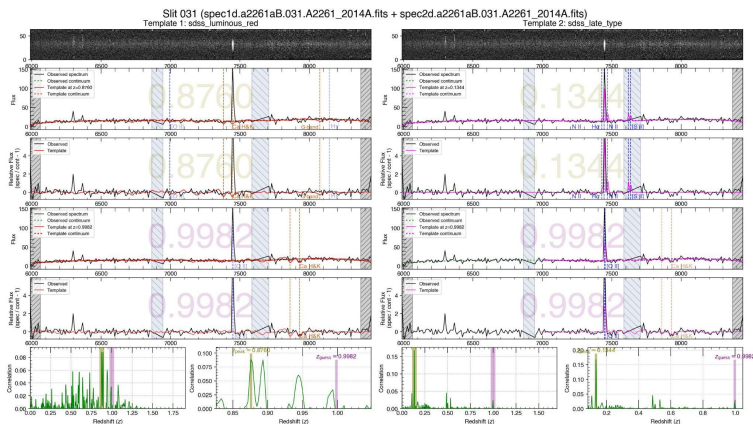
Template	Source	Dispersion Scale (Å/pixel)	Spectral Resolution $\Delta\lambda$ (Å)	Resolving Power R
LBG Shapley	Lyman break galaxy ^o	1.0	8–12	417–625
SDSS QSO	Broad-line quasar [△]	1.0	2	2000
SDSS LoBAL	Low-ionization BAL quasar [†]	0.7	1.8–5.1	2000
SDSS HiBAL	High-ionization BAL quasar [†]	0.7	1.8–5.1	2000
SDSS Luminous Red	Luminous red galaxy*	1.6	1.8–5.1	2000
SDSS Early Type	Early-type galaxy*	2.1	1.8–5.1	2000
SDSS Low Emission	Low-emission-peak galaxy*	2.1	1.8–5.1	2000
SDSS Normal Emission	Normal-emission-peak galaxy*	2.1	1.8–5.1	2000
SDSS High Emission	High-emission-peak galaxy*	2.1	1.8–5.1	2000
SDSS Late Type	Late-type galaxy*	2.1	1.8–5.1	2000
Red galaxy	PEGASE passive galaxy	2.0	1.4	
Green galaxy	PEGASE early spiral	2.0	1.4	
Blue galaxy	PEGASE spiral/starburst	2.0	1.4	
A0 star	A0 stellar templates [‡]	5	5	500
F0 star	F0 stellar templates [‡]	5	5	500
G0 star	G0 stellar templates [‡]	5	5	500
K0 star	K0 stellar templates [‡]	5	5	500
M0 star	M0 stellar templates [‡]	5	5	500
M6 star	M6 stellar templates [‡]	5	5	500

NOTE — Sources: ^o Shapley et al. (2003), [△] Schneider et al. (2010), [†] Reichard et al. (2003),
[‡] Pickles (1998), and *SDSS DR2 (Abazajian et al. 2004) spectral templates:
<https://classic.sdss.org/dr5/algorithms/spectemplates/index.php>

Results

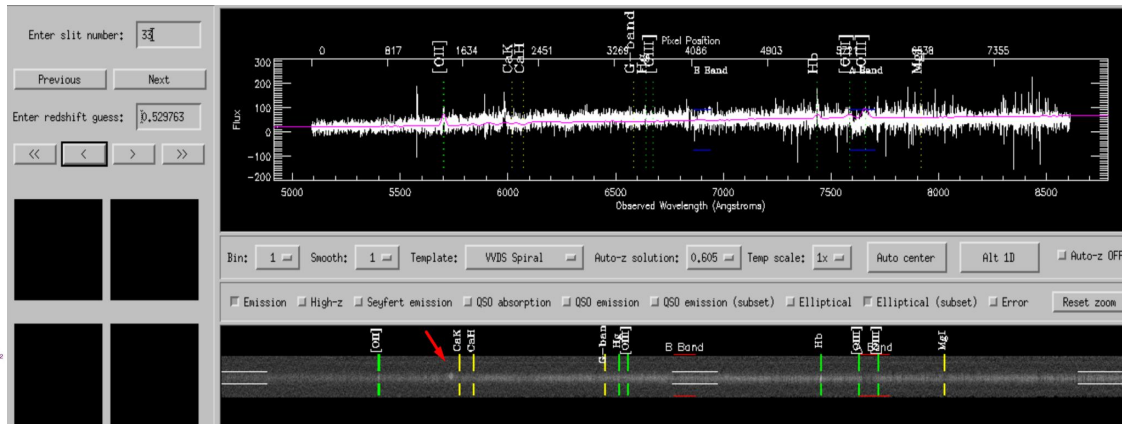
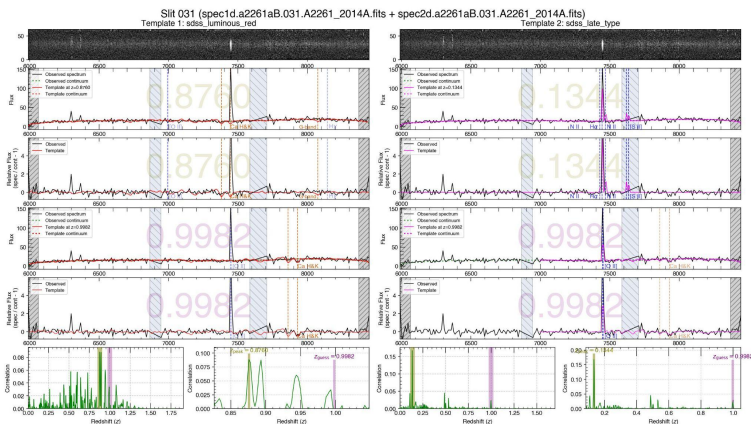
Spectroscopic Redshift

1. Spectrum Cutting-off by Slit — `pypeittospecpro.py` | 1338 spectra | 1125 targets
2. Templates
3. Tools
 - **FIREFLY** (Fast Initial REDshift Fitting of cLUster galaxY) — for rapid fittings to guess the approximate redshift solutions with probability distribution.



Spectroscopic Redshift

1. Spectrum Cutting-off by Slit — `pypeittospecpro.py` | 1338 spectra | 1125 targets
2. Templates
3. Tools
 - **FIREFLY** (Fast Initial REdshift Fitting of cLuster galaxY) — for **rapid fittings** to guess the **approximate redshift** solutions with probability distribution.
 - **IDL/SpecPro** (Masters & Capak 2011) — user **visual** inspections in GUI + **manual** redshift adjustments to fit with the template best visually.



Results

Spectroscopic Redshift

1. Spectrum Cutting-off by Slit — `pypeittospecpro.py` | 1338 spectra | 1125 targets
2. Templates
3. Tools — FIREFLY + IDL/SpecPro
4. Secure Redshifts
 - “confidence” flags — indicate the reliability of spec-z
 - i. **3 = secure** (two or more lines are identified and outcome one redshift)
 - ii. **2 = likely** (one line is identified and outcomes a redshift)
 - iii. 1 = no determination

Results

Spectroscopic Redshift

1. Spectrum Cutting-off by Slit — `pypeittospecpro.py` | 1338 spectra | 1125 targets
2. Templates
3. Tools — FIREFLY + IDL/SpecPro
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 - “confidence” flags — indicate the reliability of spec-z (**3 = secure**, **2 = likely**, 1 = no determination)
 - confidence-flag distribution of 60, 1, and 39% for confidence = 1, 2, and 3

Results

Spectroscopic Redshift

1. Spectrum Cutting-off by Slit — `pypeittospecpro.py` | 1338 spectra | 1125 targets
2. Templates
3. Tools — FIREFLY + IDL/SpecPro
4. Secure Redshifts
 - “confidence” flags — indicate the reliability of spec-z (3 = secure, 2 = likely, 1 = no determination)
 - confidence-flag distribution of 60, 1, and 39% for confidence = 1, 2, and 3
 - 1125 slit targets produce 451 redshifts of confidence ≥ 2
 - 8 redshifts with confidence = 3 are for stars
 - **443 redshifts** with the **confidence ≥ 2** for non-stellar objects are defined as **secure redshifts**

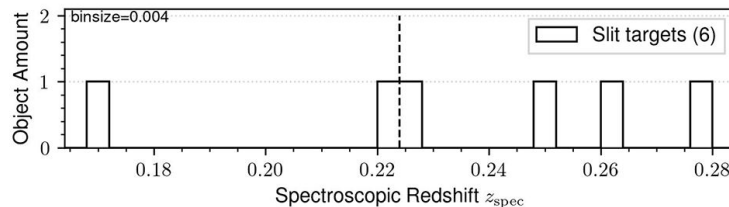
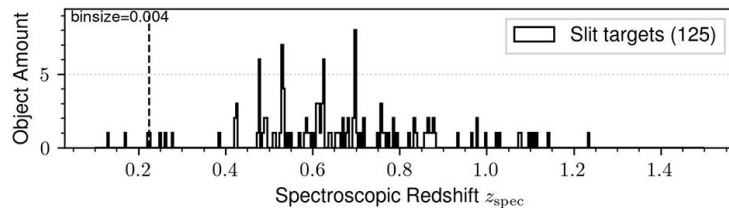
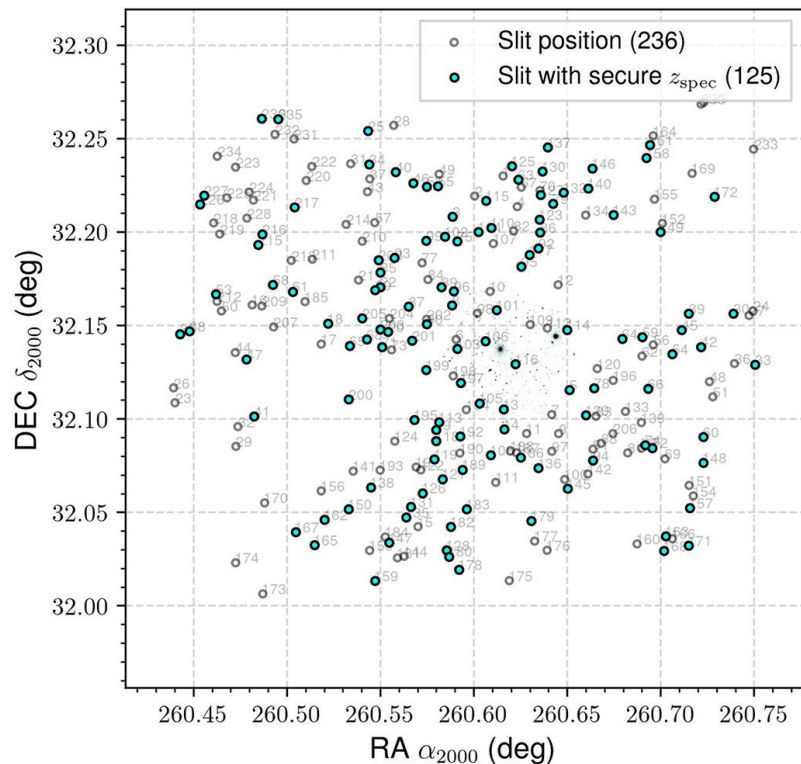
Results

Spectroscopic Redshift

	Cluster	RA (deg)	Dec. (deg)	z_{Cl}	M10	Mask	Grating	Date	Set	N_{slits}	N_z	N_b	N_c	N_{bc}
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
1	A2552	347.88818	3.63514	0.302	M	25521B	1200G	2015-12-13	A	143	72	9	7	2
2	A611	120.23674	36.05709	0.288	–	sna611	600ZD	2012-10-15	E	48	16	3	2	1
3	A1758N	203.18111	50.54398	0.279	–	ejc	600ZD	2018-07-16	I	76	22	0	0	0
4	A1758N	203.18111	50.54398	0.279	–	ejc1	600ZD	2018-07-17	C	63	22	1	0	0
5	A1758N	203.18111	50.54398	0.279	–	ejc2	600ZD	2018-07-18	D	39	17	2	4	0
6	M1115	168.96617	1.49861	0.355	M	sn1115	600ZD	2012-02-26	B	120	60	37	15	11
7	M1115	168.96617	1.49861	0.355	M	1115m1	600ZD	2014-02-25	A	147	76	15	20	3
8	M1115	168.96617	1.49861	0.355	M	jc9	600ZD	2015-06-16	B	31	11	0	4	0
9	A2261	260.61244	32.13275	0.224	B	a2261aB	1200G	2014-07-01	A	63	41	37	28	24
10	A2261	260.61244	32.13275	0.224	B	a2261b	1200G	2014-07-01	B	66	31	31	25	25
11	A2261	260.61244	32.13275	0.224	B	a2261c	1200G	2014-07-01	C	62	27	26	22	21
12	A2261	260.61244	32.13275	0.224	B	a2261d	1200G	2015-06-18	A	65	25	25	13	13
13	A2261	260.61244	32.13275	0.224	B	a2261c	1200G	2015-06-18	B	62	30	29	22	20
14	A2261	260.61244	32.13275	0.224	B	a2261b	1200G	2015-06-18	C	64	30	28	20	17
15	A2261	260.61244	32.13275	0.224	B	a2261a	1200G	2015-06-18	D	65	32	29	26	23
16	A370	39.97186	-1.57718	0.375	–	A37017B1	1200G	2017-09-28	A	121	14	1	4	1
17	A370	39.97186	-1.57718	0.375	–	A37017B2	1200G	2017-09-28	B	103	11	4	7	1
Total										1338	451	277	219	162
Non-duplicate and Non-Stellar Objects Total										1125	443	187	149	105

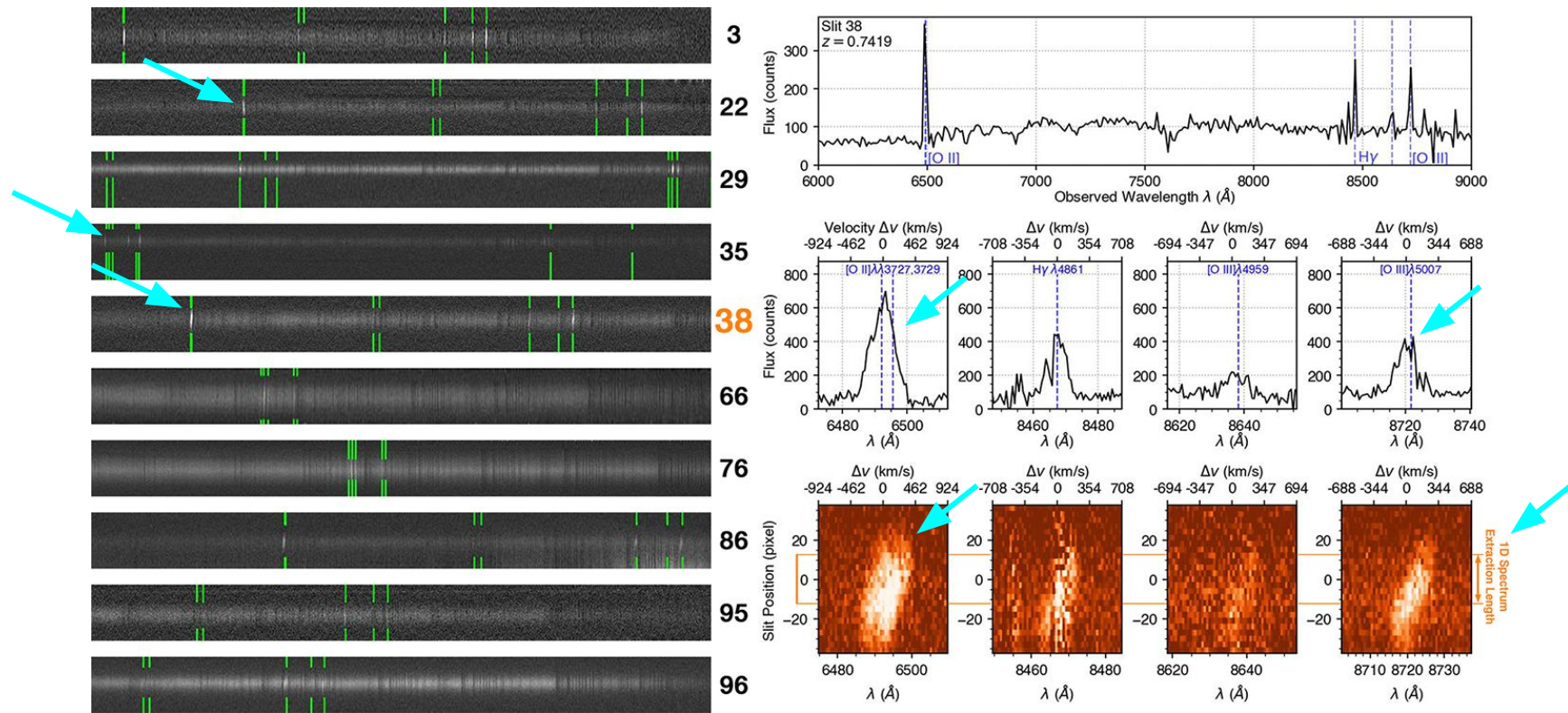
Results

Spectroscopic Redshift



Results

Rotation Curves and Velocity Fields

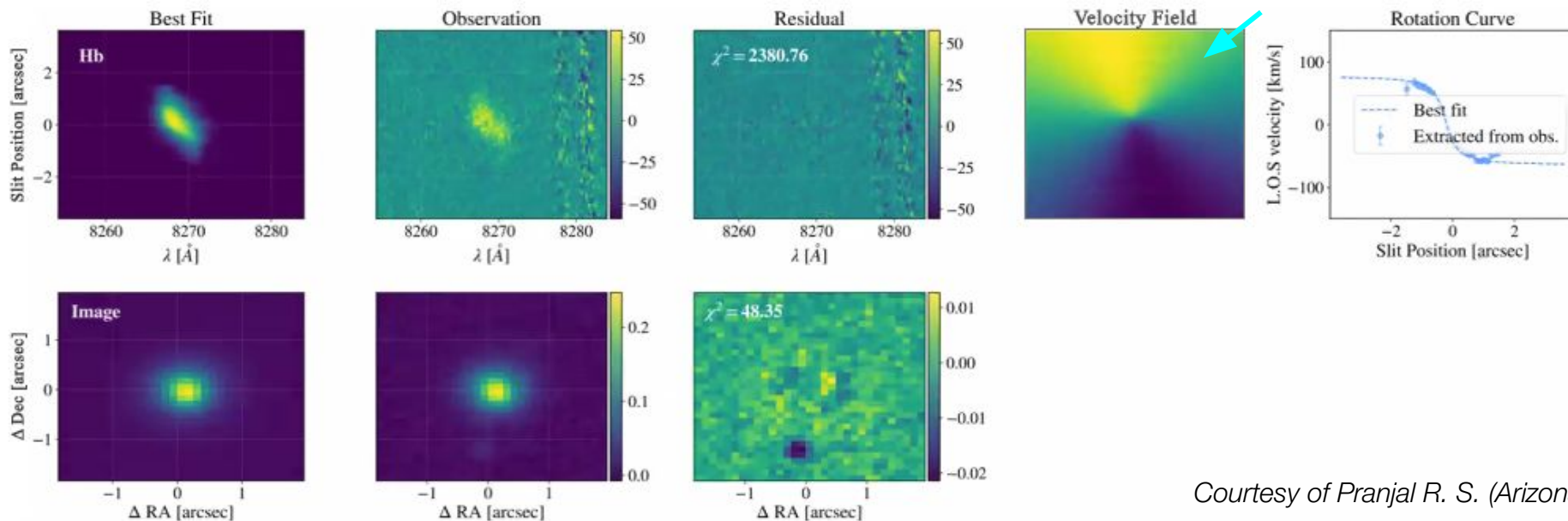


Results

Rotation Curves and Velocity Fields

KL measurement pipeline developed by Pranjal et al. (2023) and fit with the fast-forward model of 20 free parameters:

- $\mathbf{y}_t$ — perpendicular shear component relative to the cluster center
- $\mathbf{v}_{\text{circ}}$ — Maximum rotational speed constrained by Tully-Fisher
- $\mathbf{v}_{\text{sys}}$ — Galaxy systemic velocity
- $\cos(i)$ — Inclination
- ...

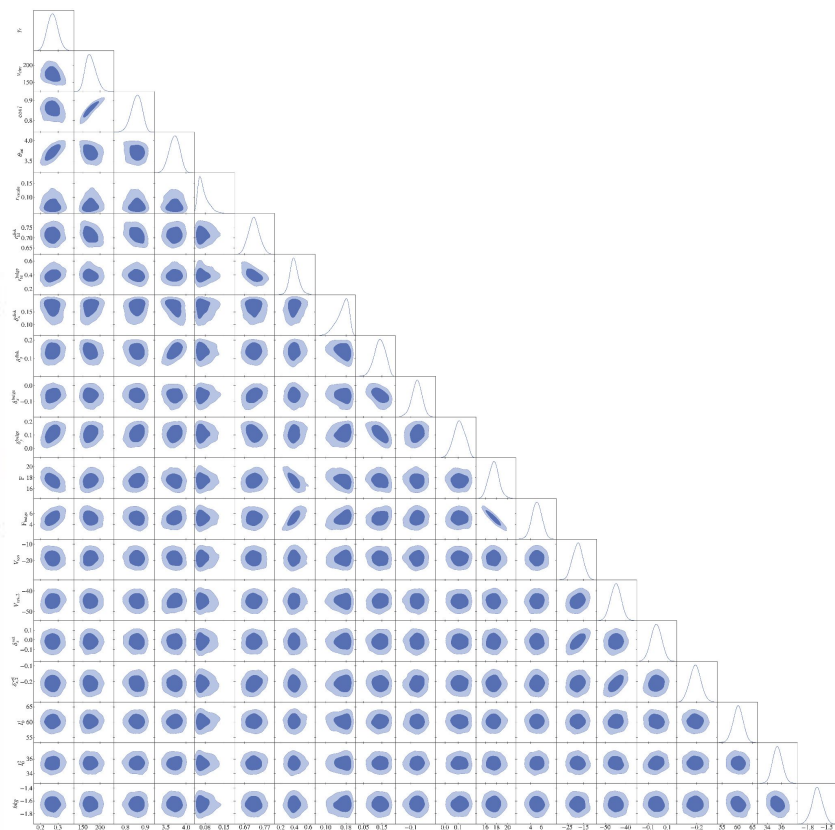
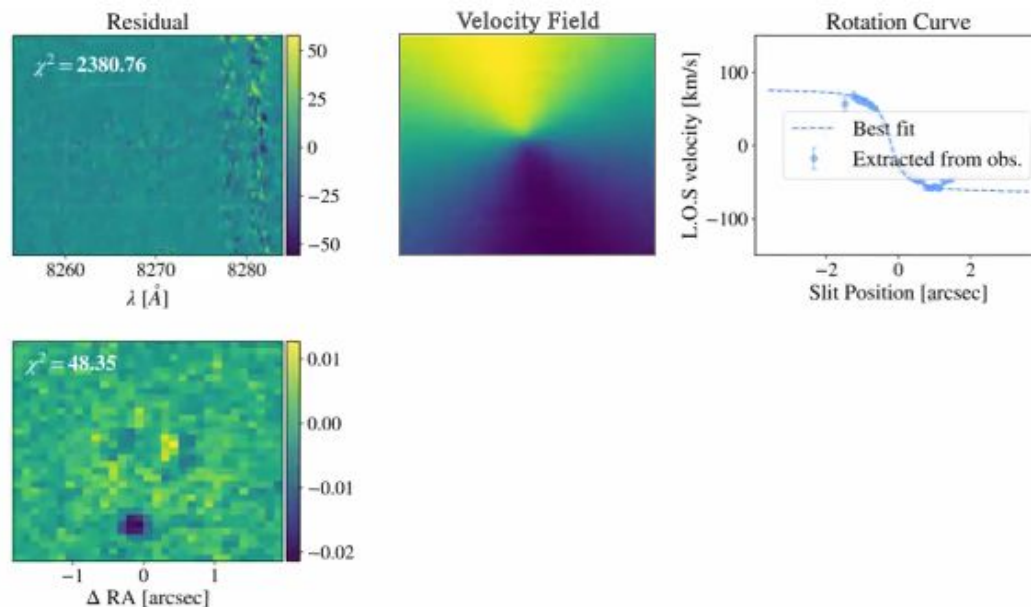


Courtesy of Pranjal R. S. (Arizona)

Results

Rotation Curves and Velocity Fields

KL measurement pipeline developed by Pranjal et al. (2023) and fit with the fast-forward model of 20 free parameters:

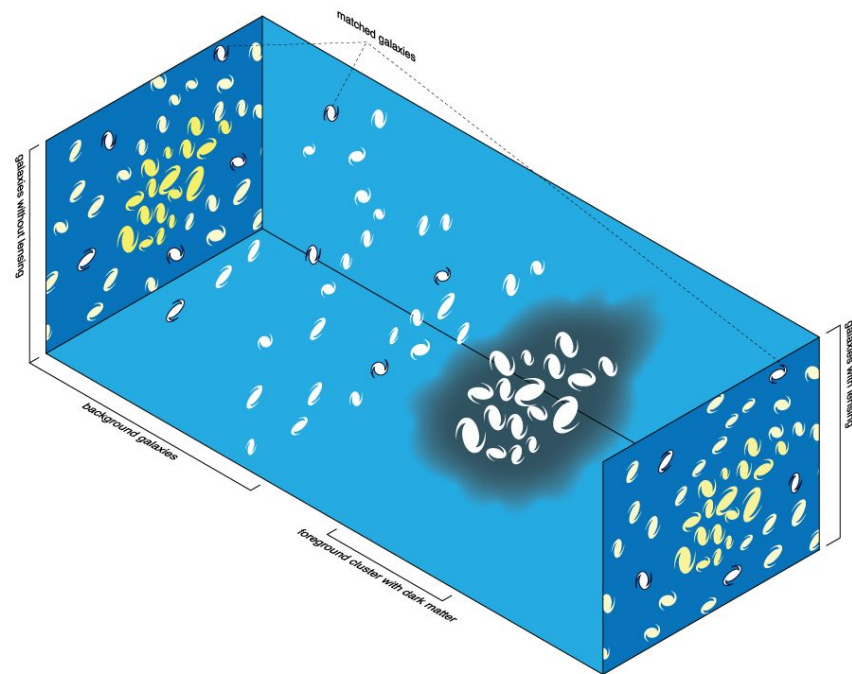


Courtesy of Pranjal R. S. (Arizona)

Results

Rotation Curves and Velocity Fields

- Background: $z > z_{\text{cl}} + 0.1$
- 149 rotation curves
- 105 rotation curves are background source galaxies



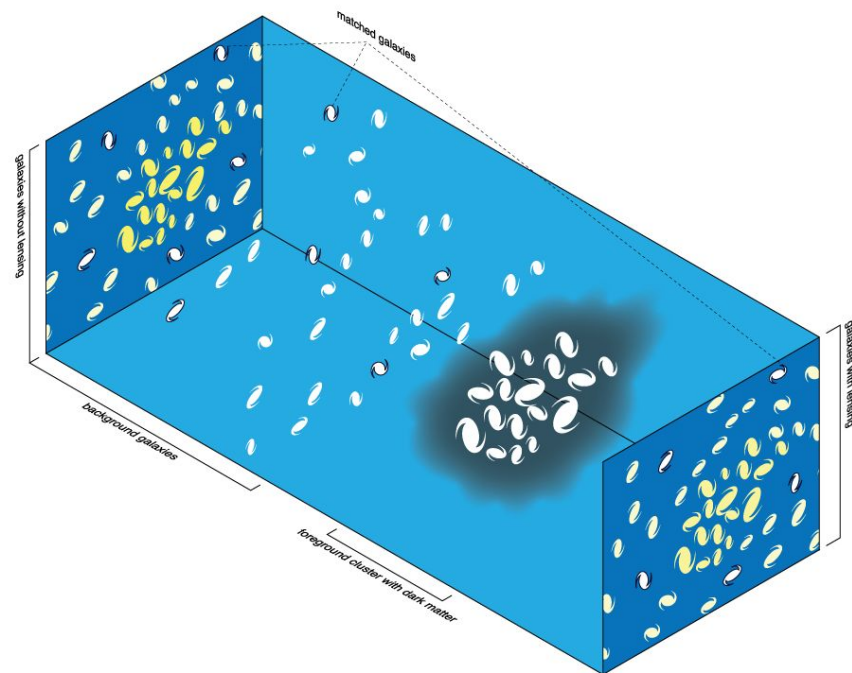
*The effects of foreground galaxy cluster mass on
background galaxy shapes*

https://en.wikipedia.org/wiki/Weak_gravitational_lensing#Weak_lensing_by_clusters_of_galaxies

Results

Rotation Curves and Velocity Fields

- Background: $z > z_{\text{cl}} + 0.1$
- 149 rotation curves
- 105 rotation curves are background source galaxies
- Rotation curves whose redshifts $z \leq z_{\text{cl}} - 0.1$ can be a key sample for training fittings
 - The galaxy is not weak-lensed
 - From photometry, it is exactly the intrinsic shape



The effects of foreground galaxy cluster mass on background galaxy shapes

https://en.wikipedia.org/wiki/Weak_gravitational_lensing#Weak_lensing_by_clusters_of_galaxies

Discussions and Future Works

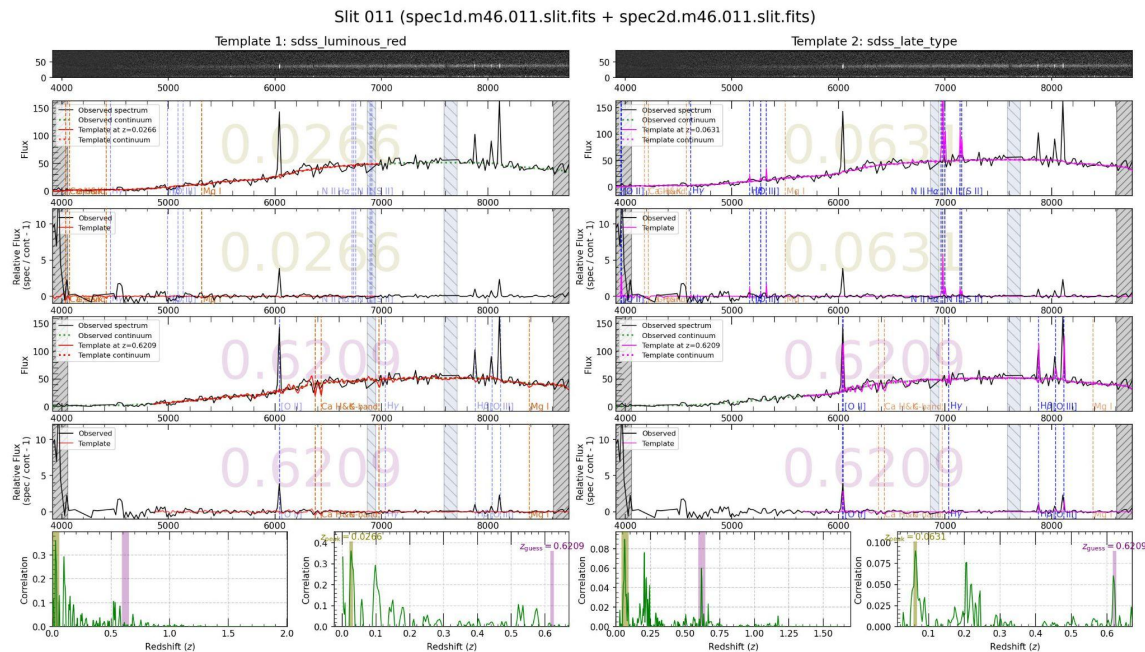
Redshift Pipeline

- The remaining 14 clusters and 40 masks in the cluster sample

Discussions and Future Works

Redshift Pipeline

- The remaining 14 clusters and 40 masks in the cluster sample
- Improve **FIREFLY** so that most spectroscopic redshifts can be assessed automatically
 - Manually-inspected confidence flag $\rightarrow$ cross-correlation parameter
 - Identify the significant emission lines such as [O II], [O III], and H β



Discussions and Future Works

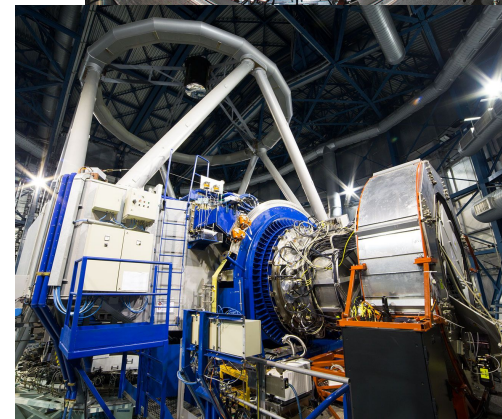
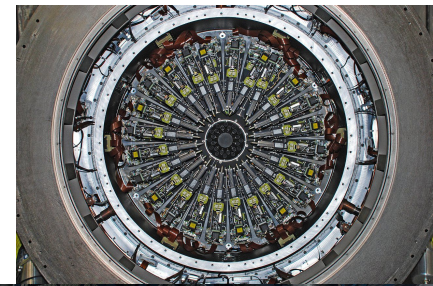
Shear Measurement

- Rotation curves give the magnitude and direction of the perpendicular shear component ($\gamma_{\perp}$).
- Cross-check with the previous and current generation weak lensing surveys.
- Cluster projected weak lensing mass map.

Discussions and Future Works

Future MOS Instruments

- VLT/KMOS (Sharples et al. 2013)
 - An integral-field MOS with 14×14 fibers
 - Wavelength-calibration-free data
 - Data cubes of x-pixels, y-pixels, and spectroscopic λ -pixels (spaxels)
 - Directly mapping the velocity fields
 - Up to 24 targets at one observation
- **9 clusters are with VLT/KMOS data**
- VLT/KMOS will show its potential in future KL analysis

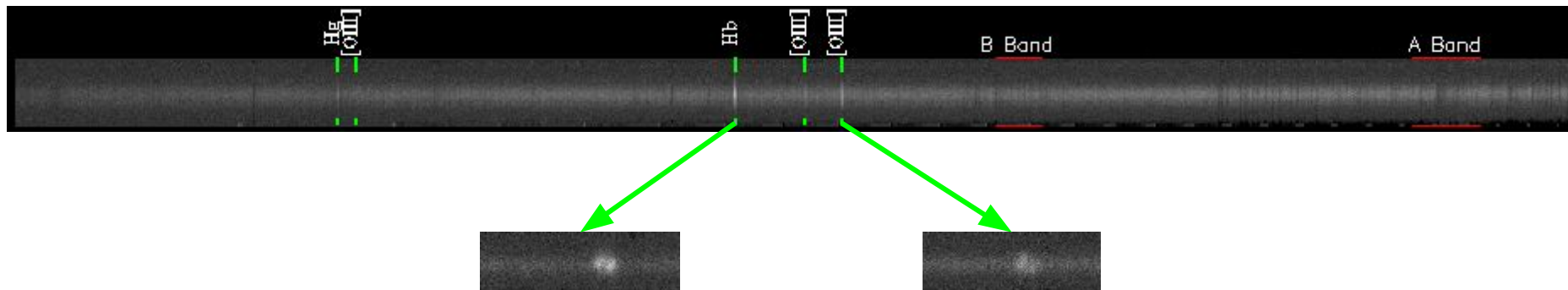


Discussions and Future Works

Discoveries of Active Galactic Nucleus

Emission line has **two distinct bright dots** separated for a few Å on the faint continuum

A2552 Slit 68: an irregular spiral galaxy (NASA/IPAC Extragalactic Database)



Conclusions

We reduced slit-spectroscopic data, discussed WL ideas, and showed rotation curves that can be fitted with resultant shears.

- A total of **443 secure spectroscopic redshifts** are measured by 1125 slits in 6 clusters.
- Rotation curves can solve for intrinsic shapes of galaxies, **without regarding if the galaxy is weak-lensed by a cluster**. They are also **valuable databases** for researchers who test and train for the rotation curve fitting by their models and algorithms.
- We find **149 rotation curves** that can solve for the weak lensing shear and reduce shape noise. They are also valuable databases for future KL studies.
- This paper utilizes and develops multiple pipelines by combining automatic template fittings and redshift measurements.
- Spectroscopic redshifts can be further analyzed for dynamical masses and cross-checking with weak-lensing masses.

References

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<https://doi.org/10.1146/annurev-astro-081710-102514>
- Applegate, D. E.,** von der Linden, A., Kelly, P. L., et al. **(2014)**, MNRAS 439(1), 48–72. <https://doi.org/10.1093/mnras/stt2129>
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<https://ui.adsabs.harvard.edu/abs/2023arXiv231202140D>
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Spectroscopy Team of Anja's Group

Anja von der Linden, associate professor, Physics & Astronomy

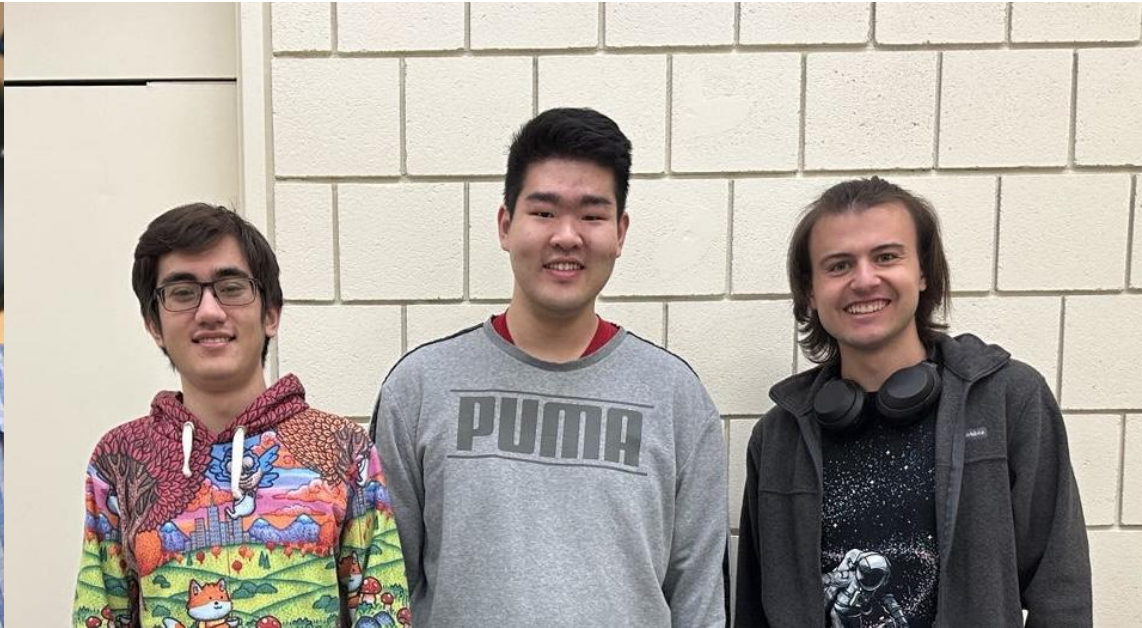
Jiyun Di, Joined Sep 2022, 2nd-year MA student

Alden Beck, Joined Nov 2022, Nevis Labs, Columbia U

Aaron Burke, Joined Jan 2023, 1st-year MA student



Anja



Aaron

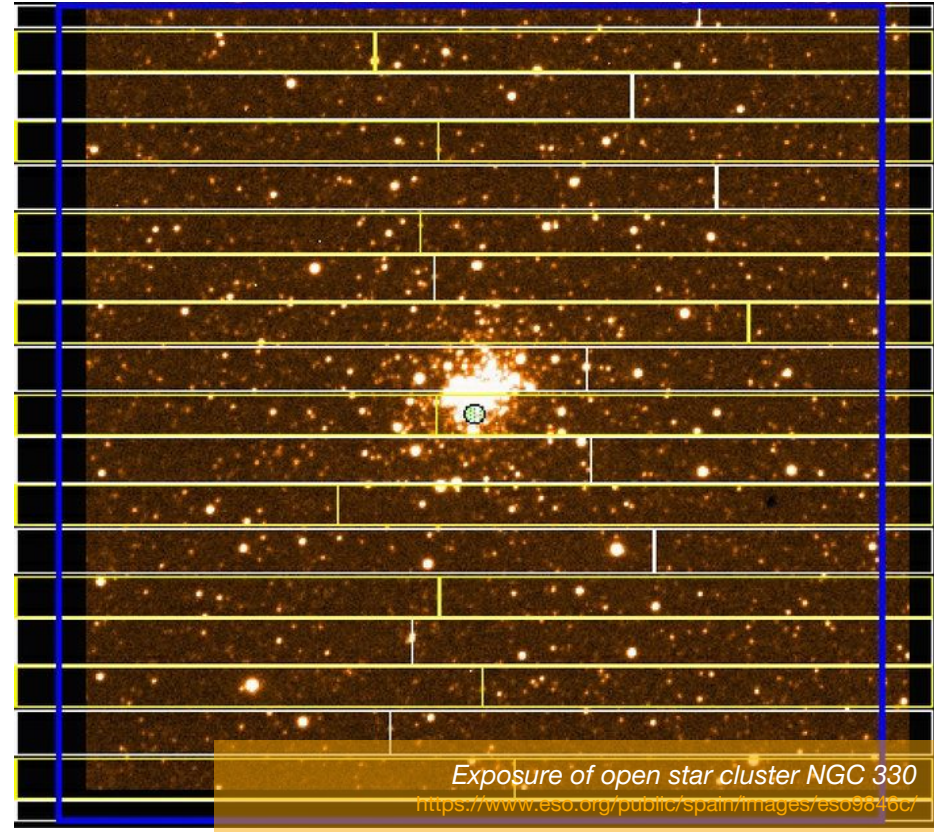
Jiyun

Alden

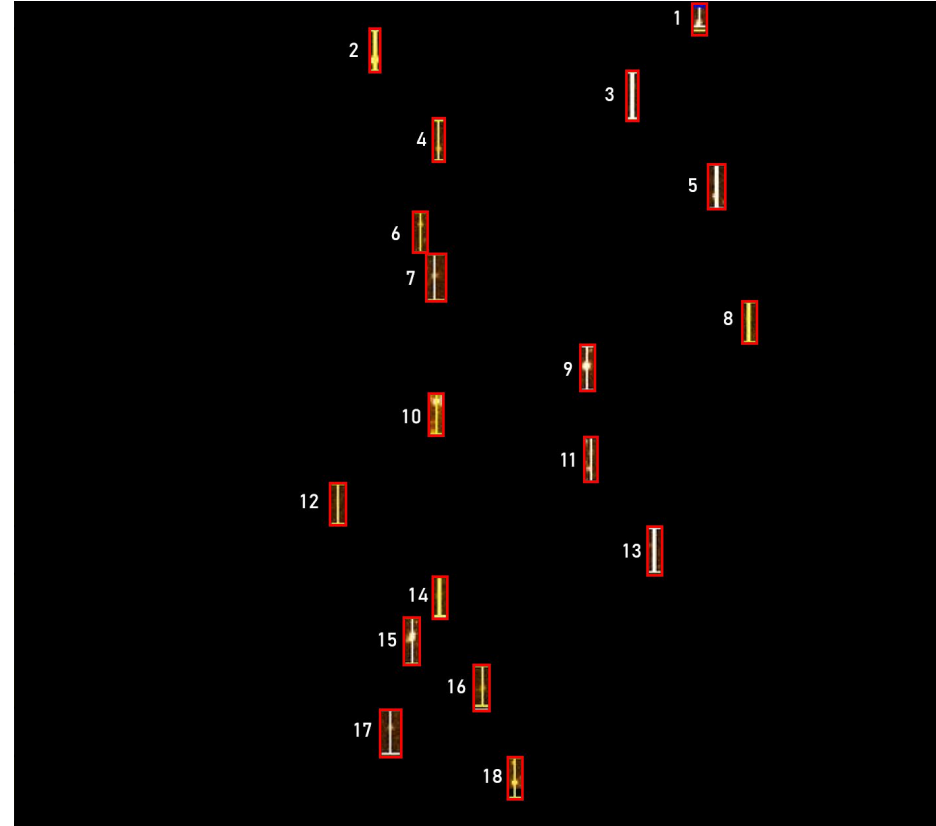
Appendix



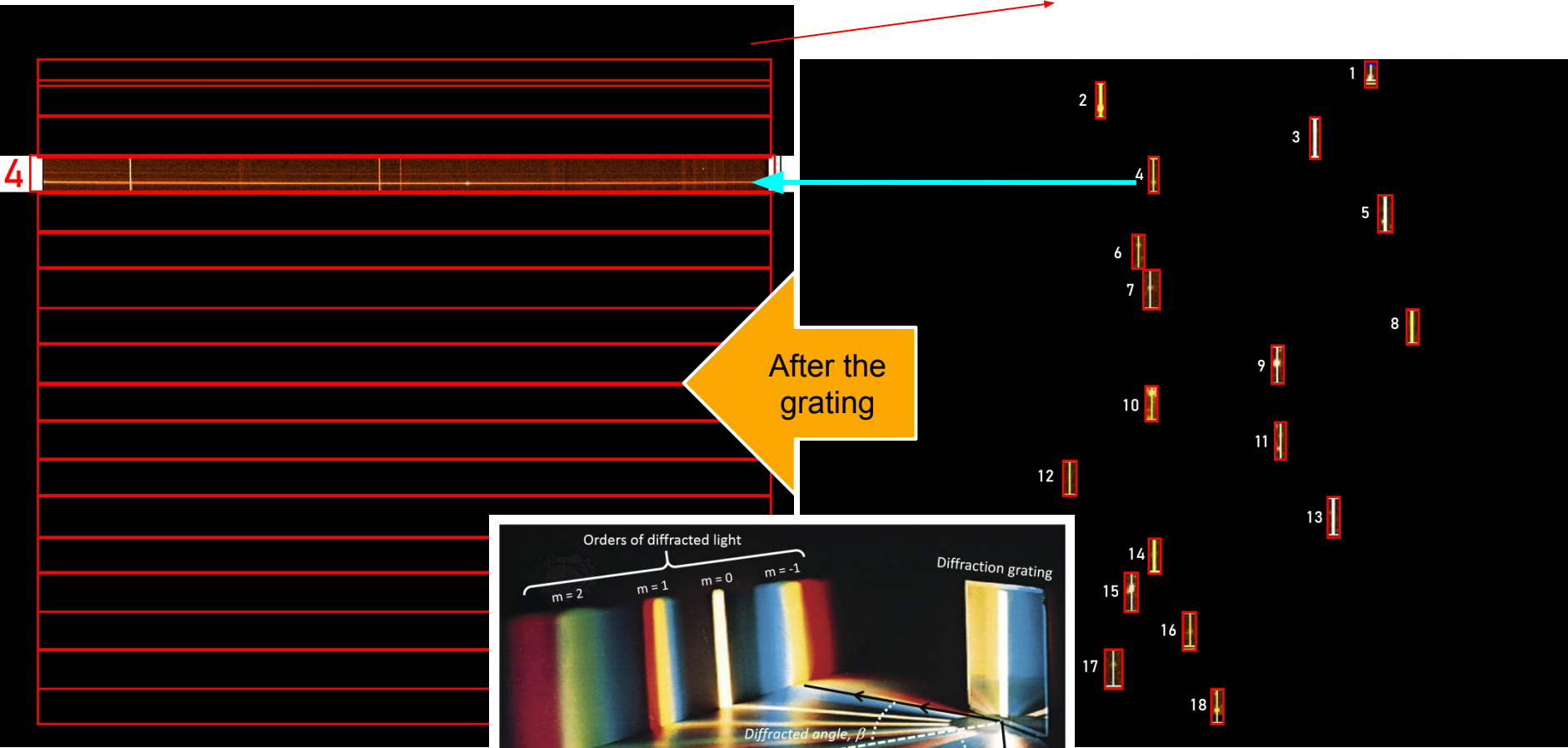
Galaxy Spectroscopy *Multi-object Spectrograph (MOS)*



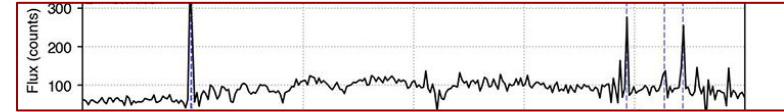
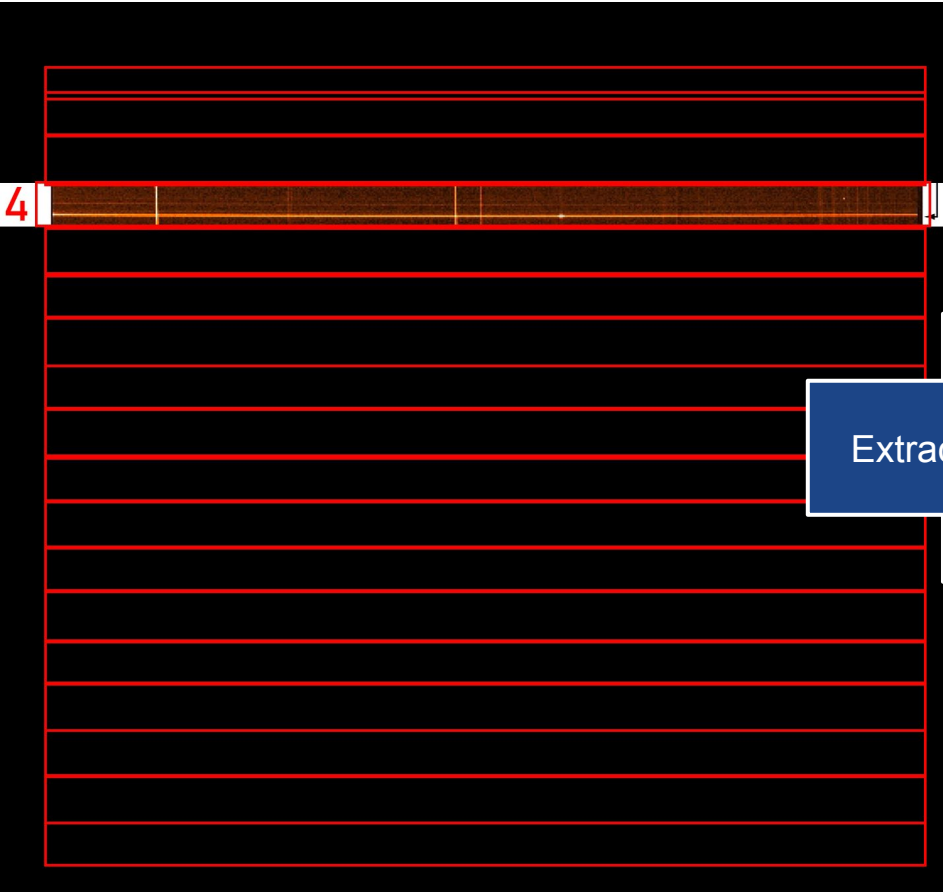
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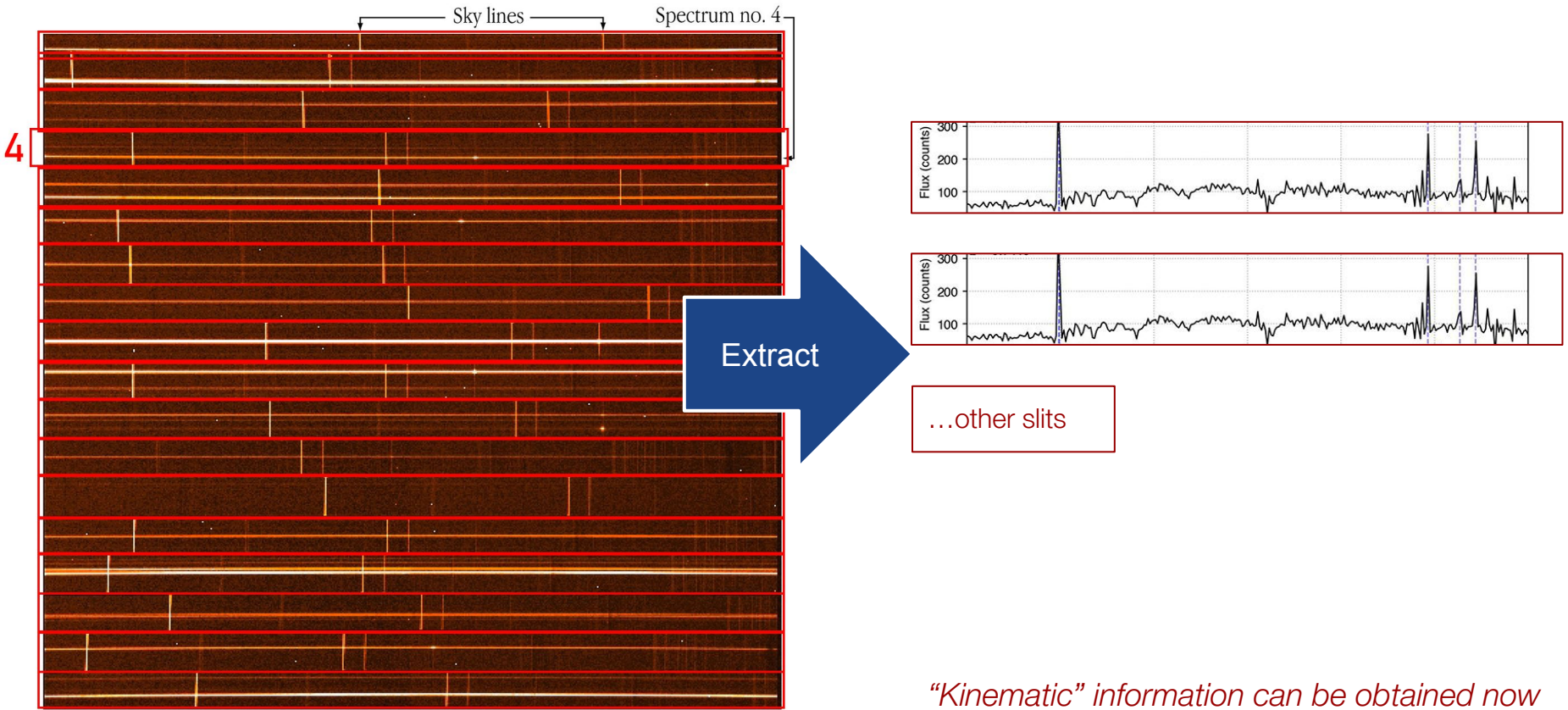
Galaxy Spectroscopy *Multi-object Spectrograph (MOS) - 2D spectrum*



Galaxy Spectroscopy *Multi-object Spectrograph (MOS) - 2D spectrum*



Galaxy Spectroscopy *Multi-object Spectrograph (MOS) - 2D & 1D spectra*



"Kinematic" information can be obtained now