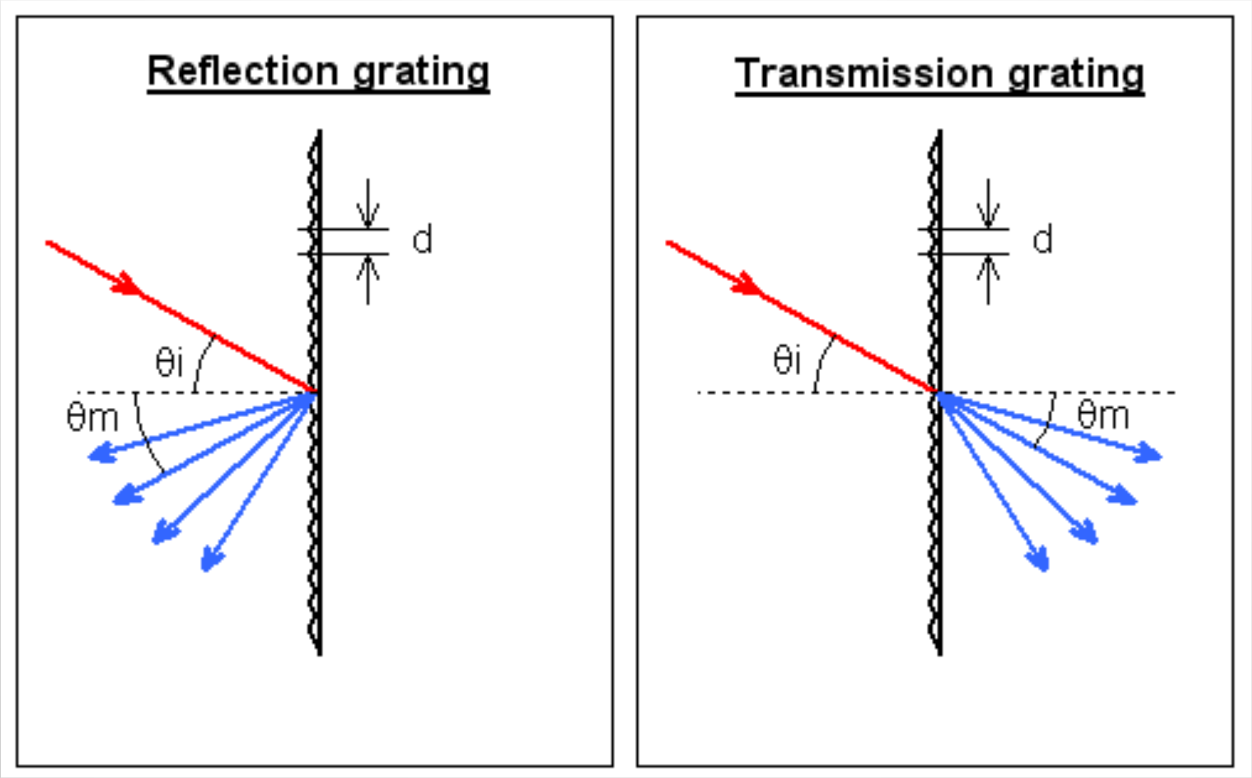
Sebastian Sanchez

2020, ARA&A, 58, 99

Spatially-Resolved Spectroscopic Properties of Low-Redshift Star-Forming Galaxies

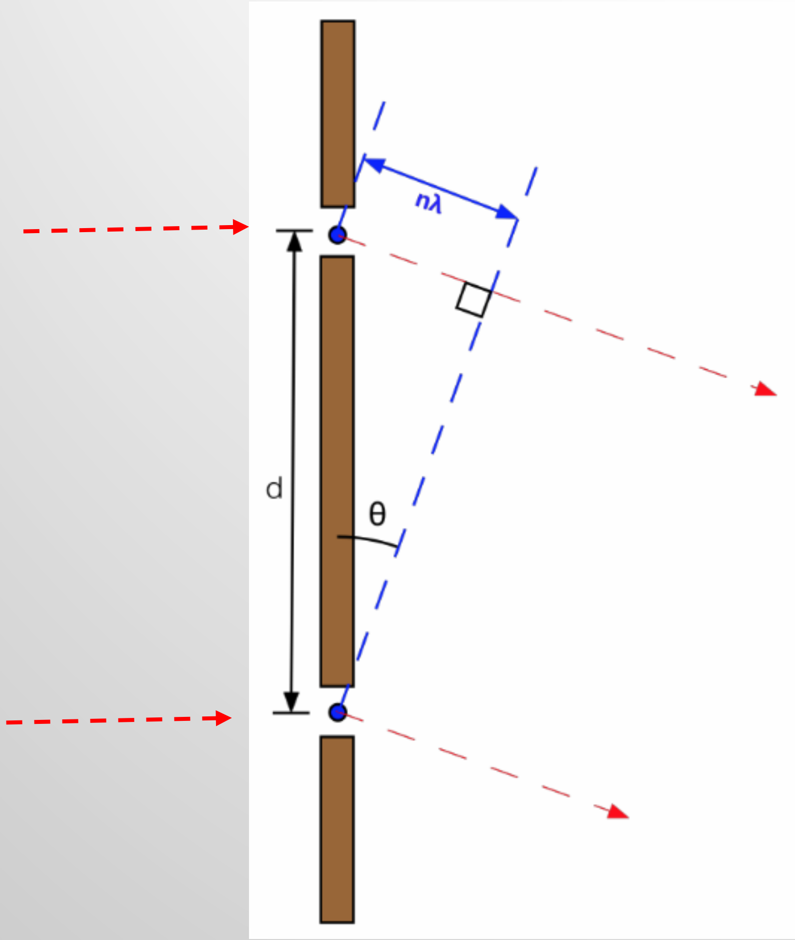
Spatially-Resolved Spectroscopic Properties of Low-Redshift Star-Forming Galaxies

Producing a spectrum requires dispersing the white light image: diffraction gratings



Gratings can be either reflection (reflective surface with grooves) or transmission (transparent surface interrupted by opaque lines).

Example with a transmission grating



For 2 light rays normally incident on a grating with ruling separation *d* the path length is $d \sin \theta$.

When this path length is equal to an integer number of wavelengths we get constructive interference. This is called the grating equation:

$$n\lambda = d \sin \theta$$

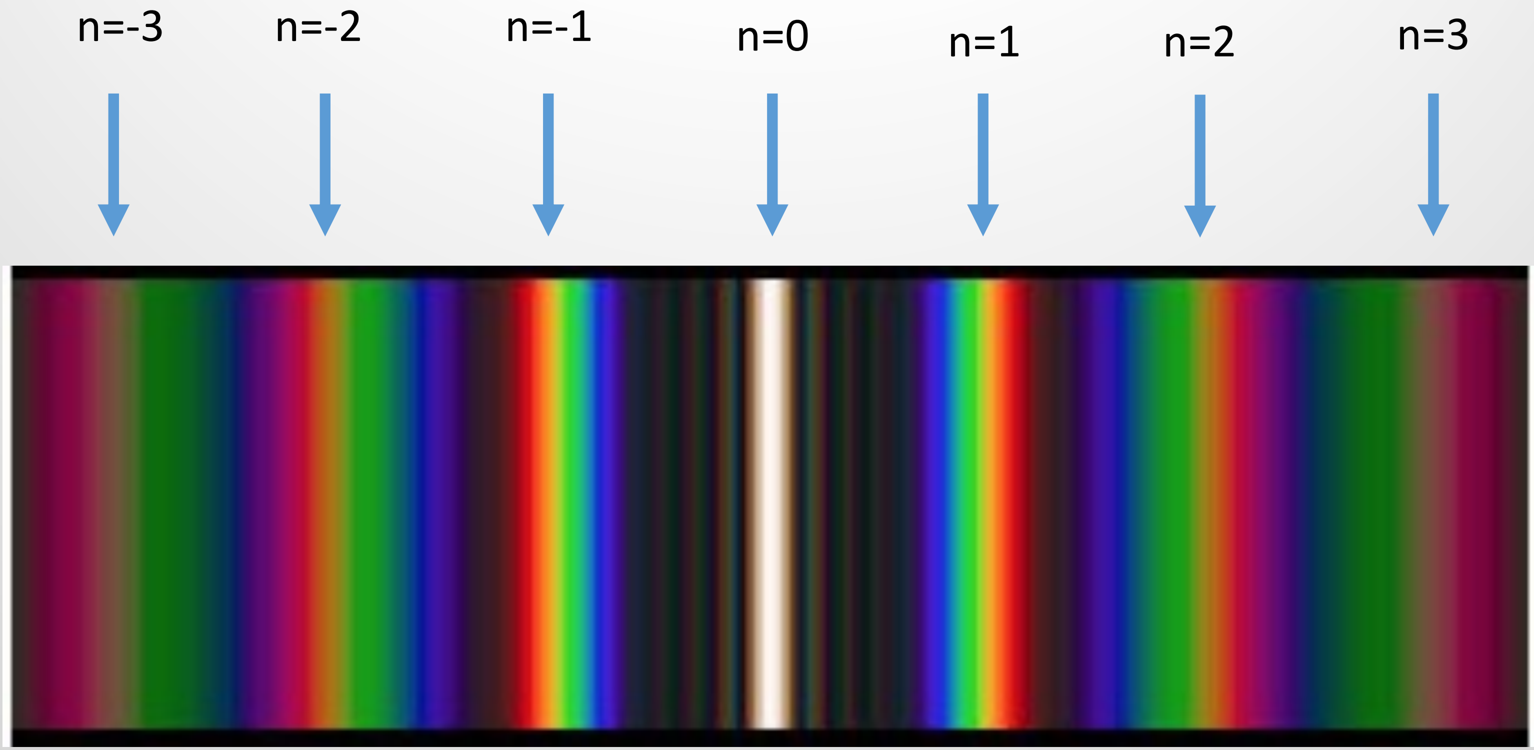
Where n is called the ‘order’.

If n=0, θ is independent of wavelength, hence no dispersion occurs and we get a white light image.

For non-zero n (n= +-1,+-2,+-3 …) light is dispersed and we get a spectrum.

$$n\lambda = d \sin\theta$$

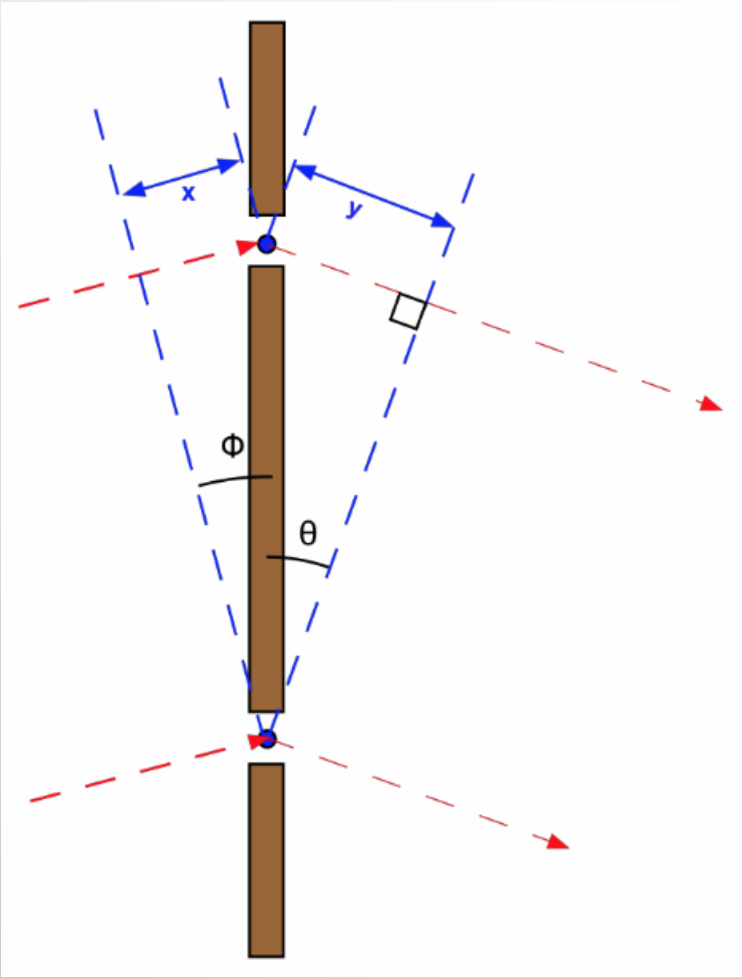
Diffraction pattern from a white light source



Note that higher orders:

- Are fainter
- Have higher dispersion (more spread out), as expected from the grating equation
- Can contain the superposition of several nλ combinations, e.g. 400 A in n=3 occurs at the same CCD position as 600 A in n=2. No superpositions in n=1

Example with a transmission grating



In practice, light rays usually arrive at an angle (not perpendicular) so now the path difference is composed of x+y:

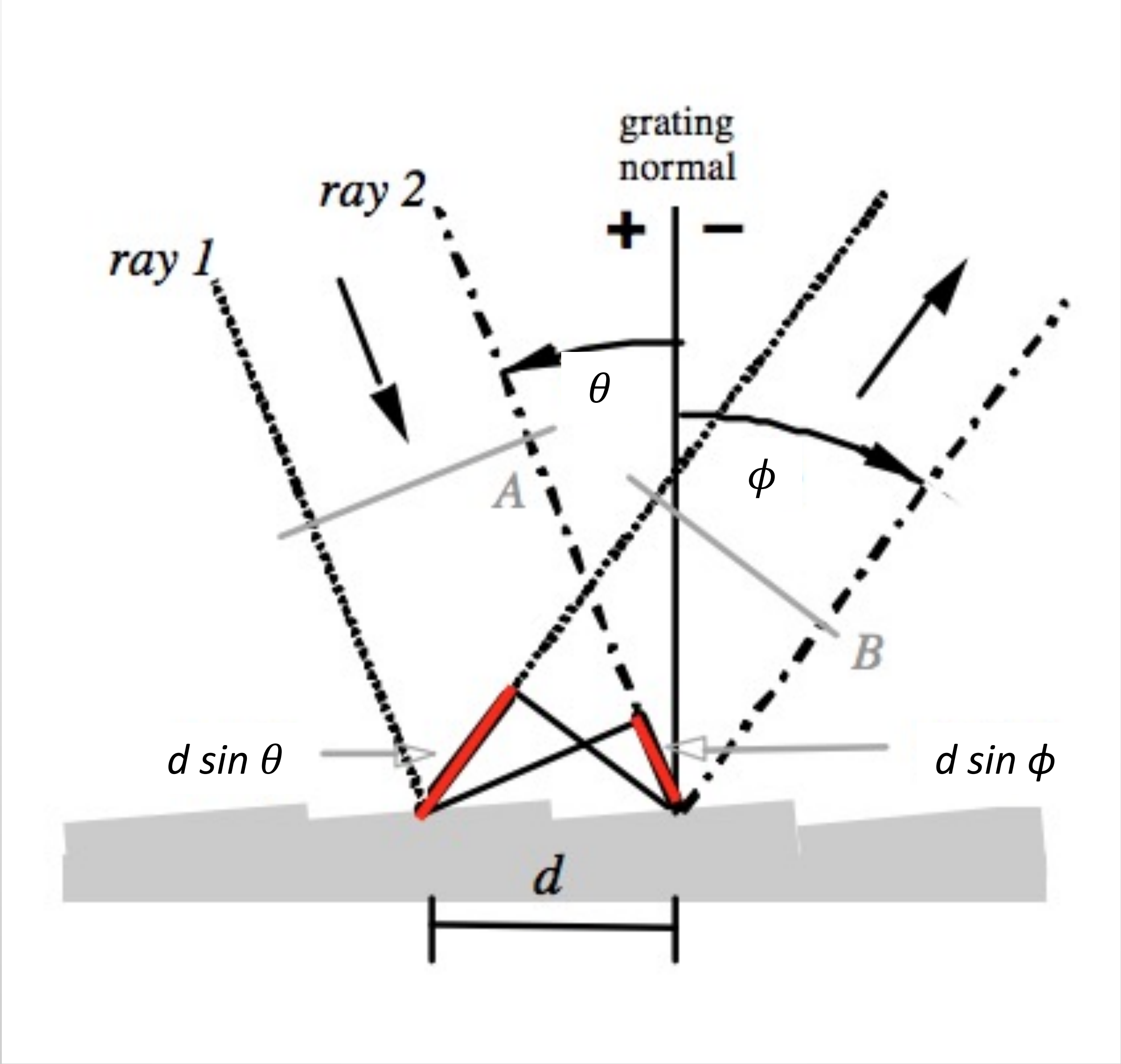
$d \sin\theta + d \sin\phi.$

Leading to the generalized grating equation:

$$n\lambda = d\,(\sin\theta + \sin\phi)$$

In order that rays are all diffracted at same θ (for a given n, d, λ) all rays must arrive at the same ϕ (requiring a collimator, as we'll see in a few slides time).

Same principle with a reflection grating



Jargon alert: Dispersion and resolution

Dispersion measures how spread out the spectrum is, e.g. in radians per Angstrom. It can be determined from differentiating the grating equation:

$$\frac{d\theta}{d\lambda} = \frac{n}{d\cos\theta}$$

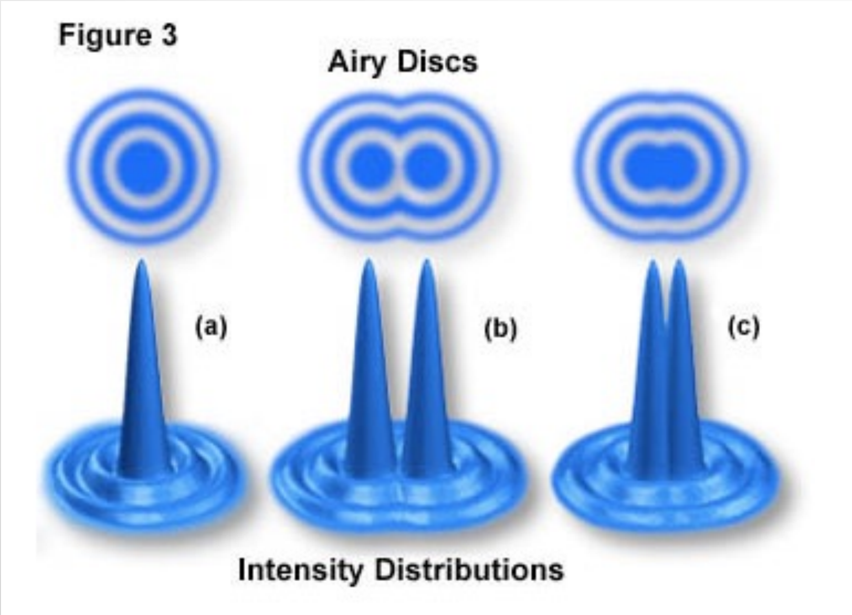
Dispersion can be increased by

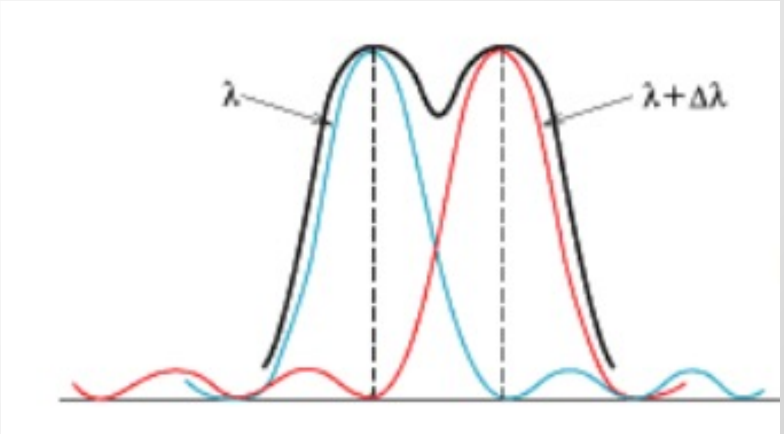
- More finely ruled gratings
- Working at higher order (we will return to this in a later lecture where we look at cross-dispersers for echelle spectrographs).
- Changing the angle of incidence

It is more common to translate the above to a linear dispersion at the focal plane and quoted in inverse units of, say Angstroms/mm or Angstroms/pixel.

Jargon alert: Dispersion and resolution

Resolution is the smallest wavelength interval that a spectrograph can distinguish. Concept is similar to the 2D version for image resolution:

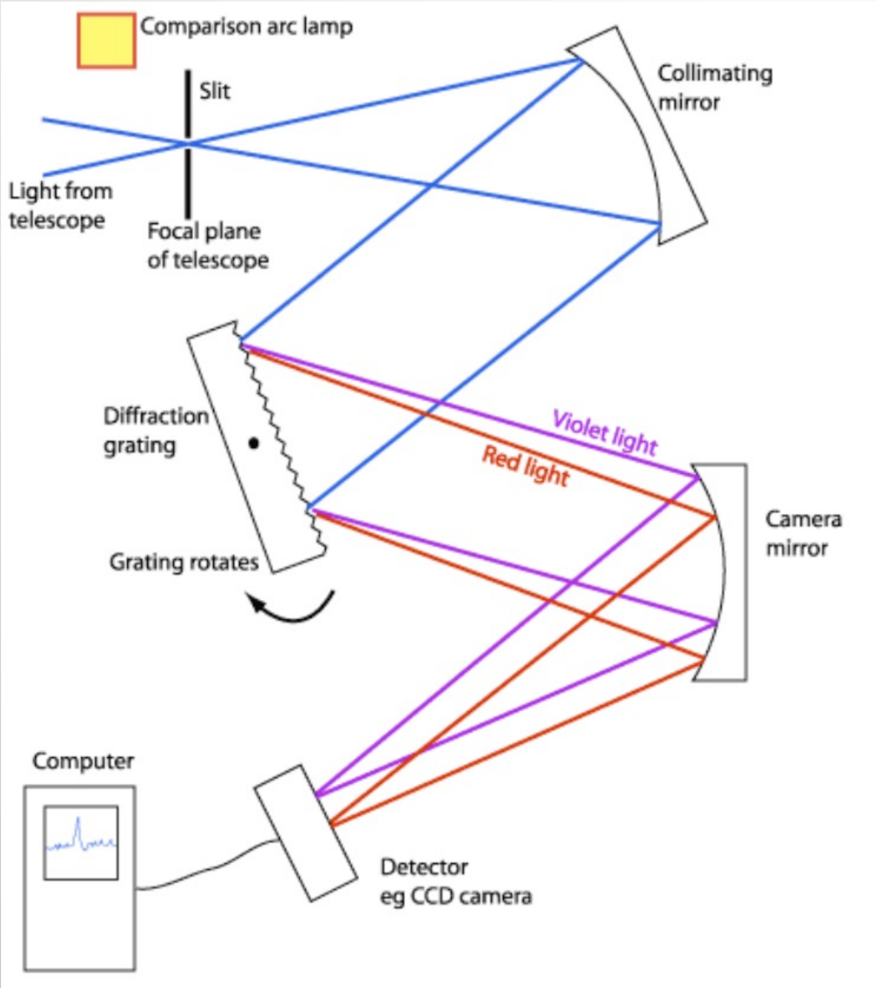




$$R = \frac{\lambda}{\Delta\lambda} = \frac{c}{v}$$

Low values of R are a few hundred, moderate R is a few thousand, high R is tens of thousands. Choice of resolution depends on scientific goals (e.g. resolving closely spaced lines, measuring kinematics) vs trade-off with S/N.

Spatially-Resolved Spectroscopic Properties of Low-Redshift Star-Forming Galaxies



Basic components of a spectrograph:

- **Slit** has two functions 1) isolate the target from other objects and sky, 2) provide stable spectral resolution.
- Light emerging from the slit is diverging, but it needs to hit the grating at a fixed angle (ϕ) to achieve a constant θ (otherwise order would be blurred), hence the need for a **collimator.**
- **Diffraction grating** disperses the light.
- **Camera** re-focuses the collimated light.
- **CCD** records the spectrum.

Spatially-Resolved Spectroscopic Properties of Low-Redshift Star-Forming Galaxies

This article focuses on gas and HII regions:

Giant molecular clouds (GMCs): 10-100 pc
HII regions: 0.1 – 100 pc

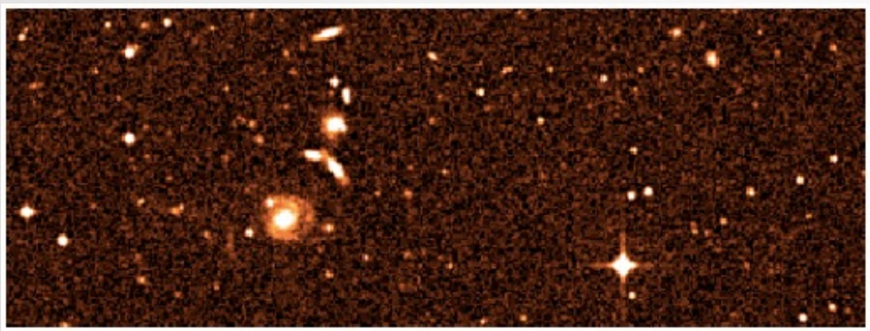
Angular size of 10 pc in M31 (765 kpc):
Angular size (") = (physical size/ distance) * 206265
= (10/765,000) * 206265
= 2.7"

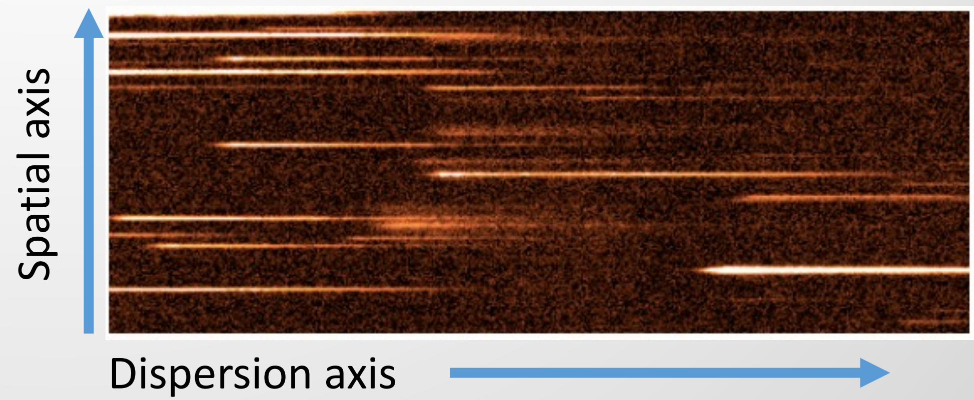
But at z=0.01 (considered very low z), 10 pc = 0.05"
We are mostly not mapping individual GMCs

Handy tool: http://www.astro.ucla.edu/~wright/CosmoCalc.html

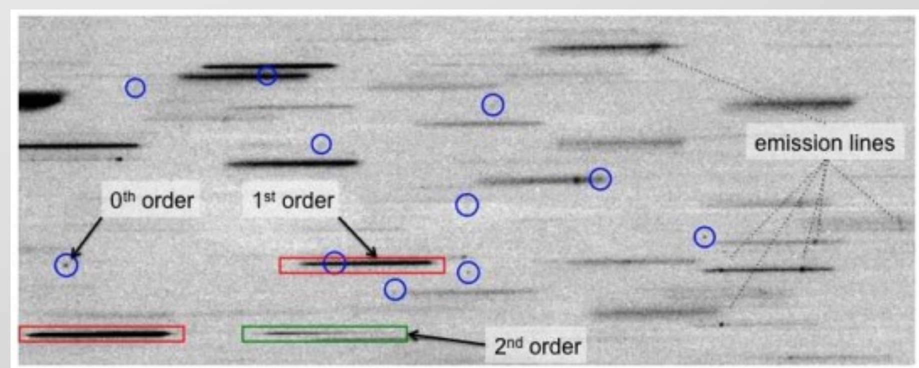
Methods for obtaining “spatially resolved” galaxy spectra

Slitless spectroscopy.





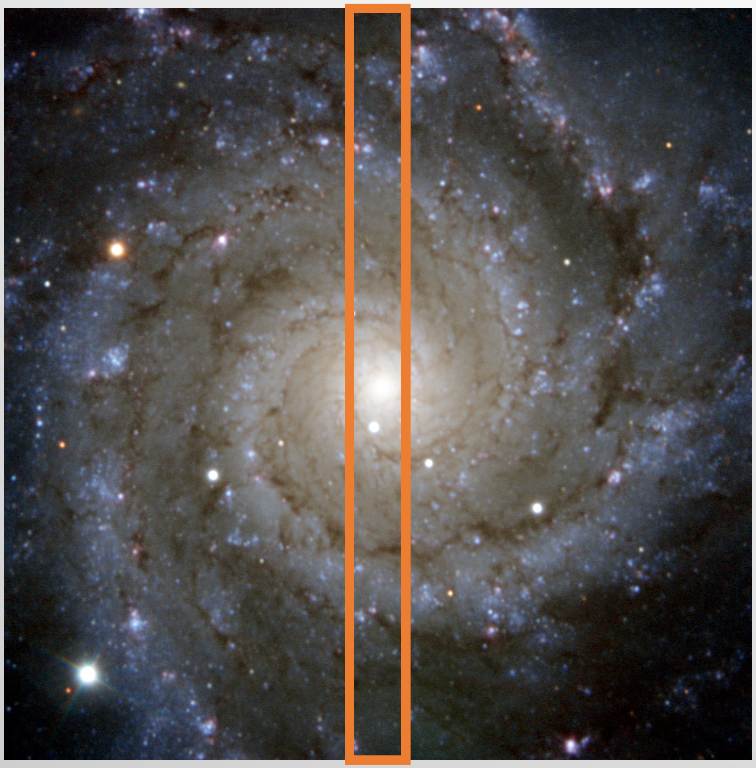
- Large field of view.
- Spectrum for everything.
- High contamination. Not practical for extended objects (e.g. galaxy mapping).
- Without filters, will often get higher orders (a pro and a con).
- E,g, 3D HST survey.

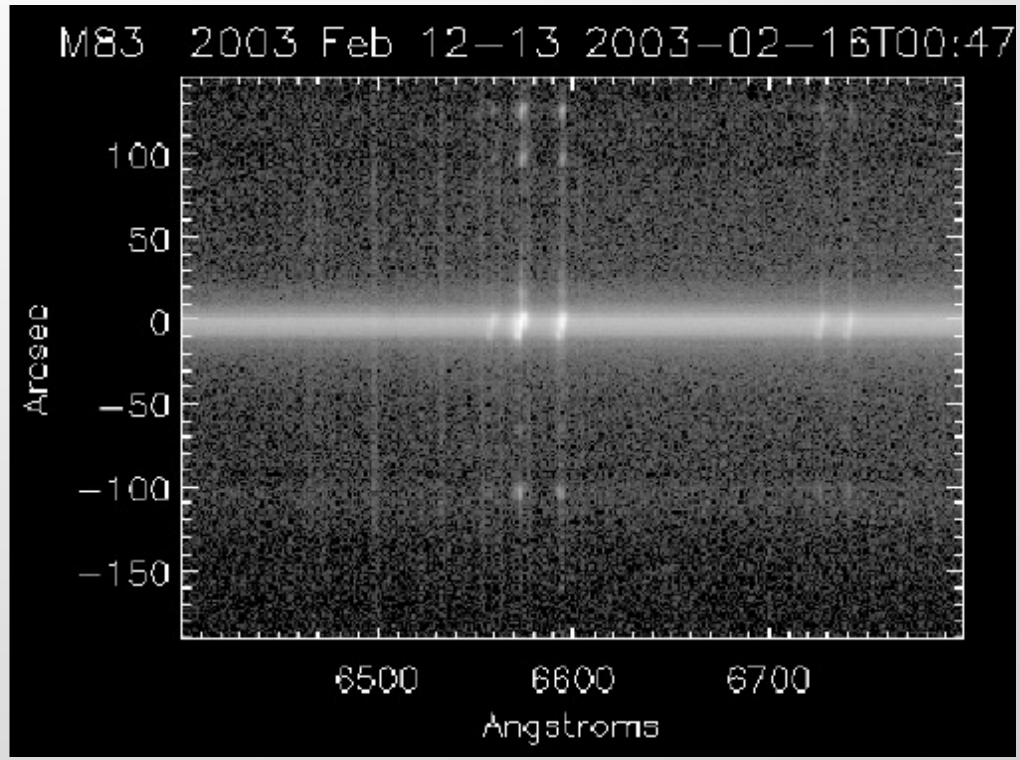


Jargon alert: 2D spectrum

Methods for obtaining “spatially resolved” galaxy spectra

Long slit spectroscopy.





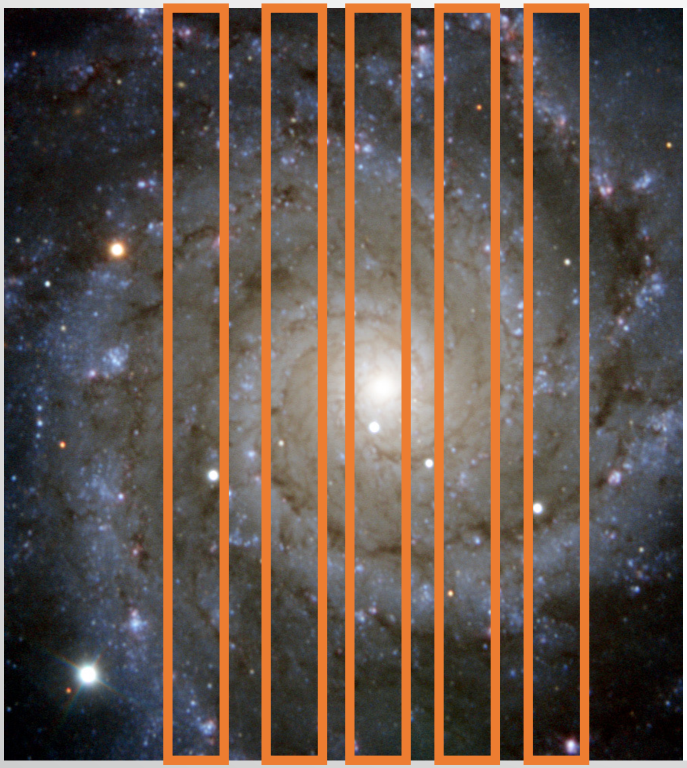
Spatial axis

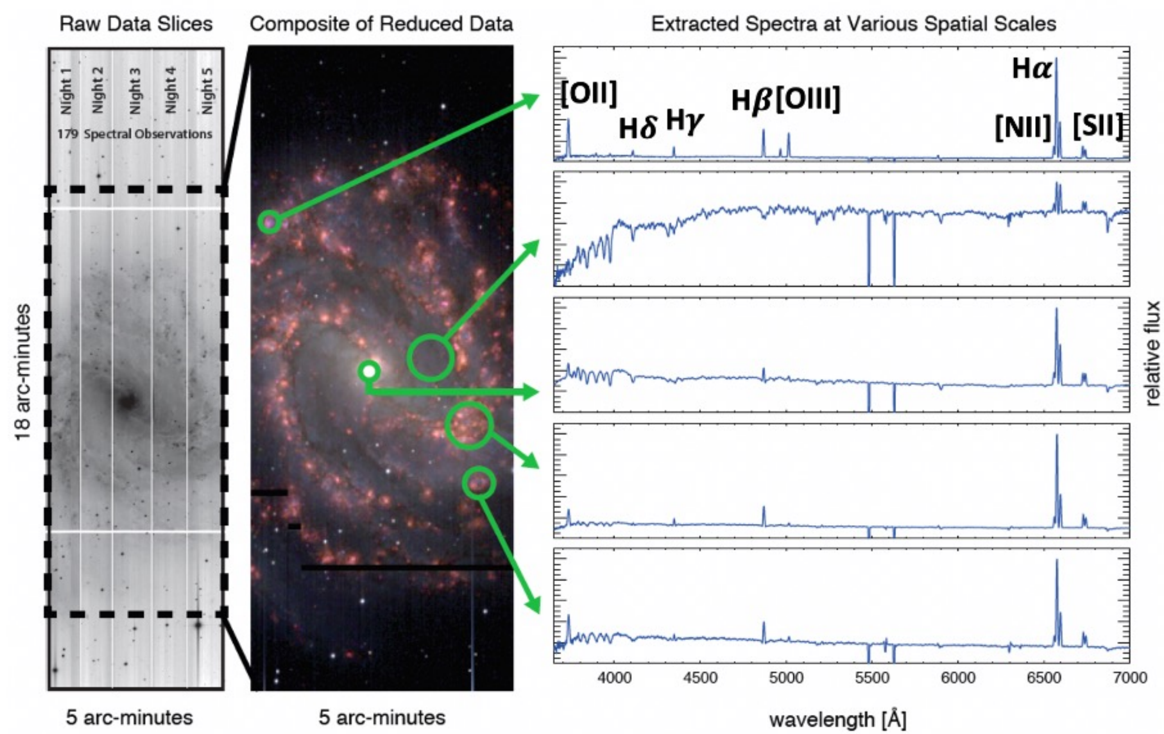
Dispersion axis

Long slit spectroscopy (LSS). A single slit is placed on an extended object and the spectrum is `sliced’ in post processing. Quick and cheap, but doesn’t cover whole galaxy. Often used just for rotation curves (edge on galaxies).

Methods for obtaining "spatially resolved" galaxy spectra

Long slit spectroscopy – multiple slits.

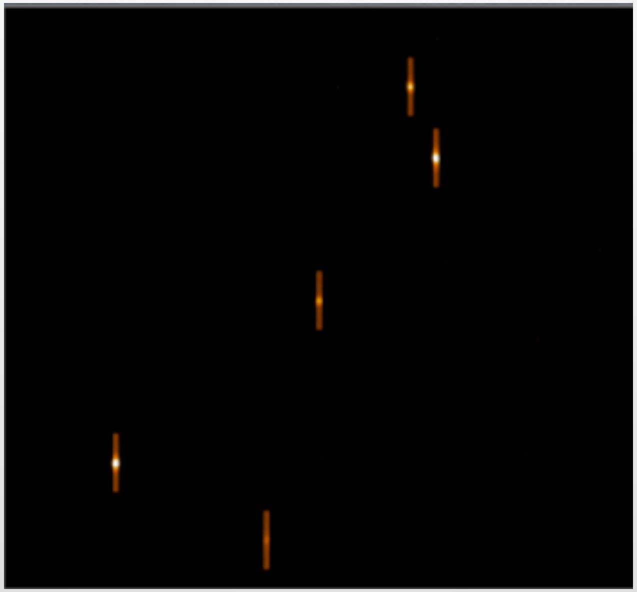
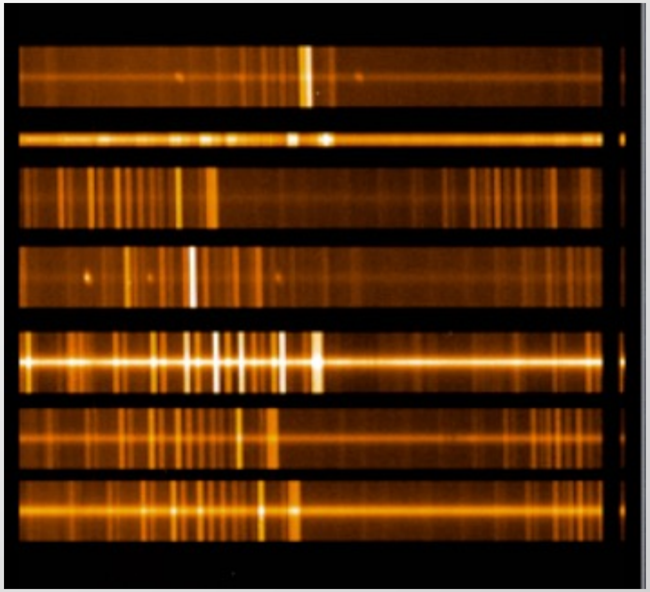




Multiple LSS placements (or drift scan). Overlap on CCD means you can only do one LSS at a time. E.g. TYPHOON survey.

Methods for obtaining "spatially resolved" galaxy spectra

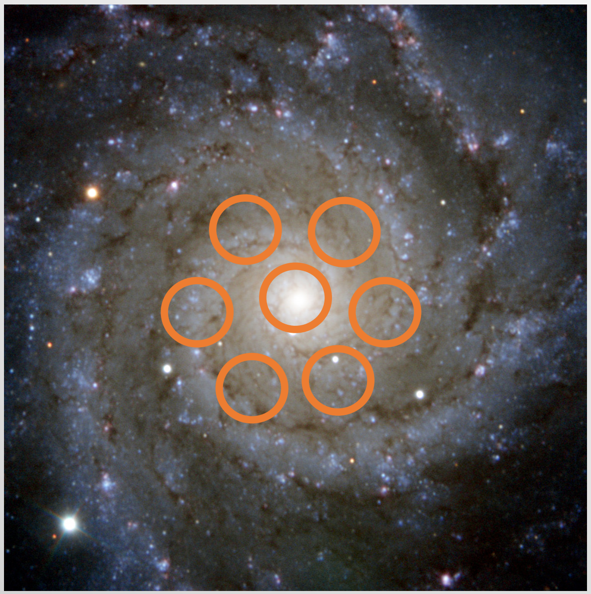
Multi-object spectroscopy (MOS)

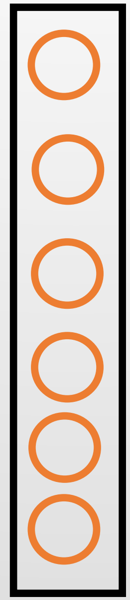




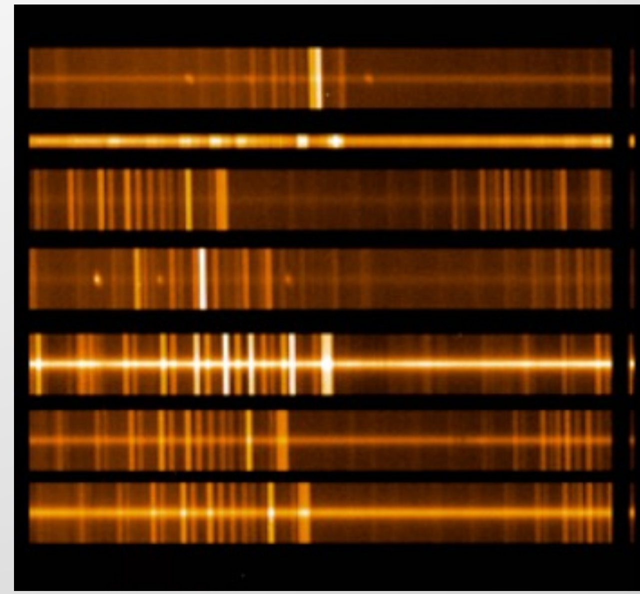
- No overlap between slitlets.
- Doesn't cover whole galaxy.
- Mask produced by drilling, or slitlet array.
- Notice how wavelength range is different for each position.
- Hundreds of spectra can be obtained at once.

Methods for obtaining “spatially resolved” galaxy spectra

Integral field spectroscopy (IFS) - fibres





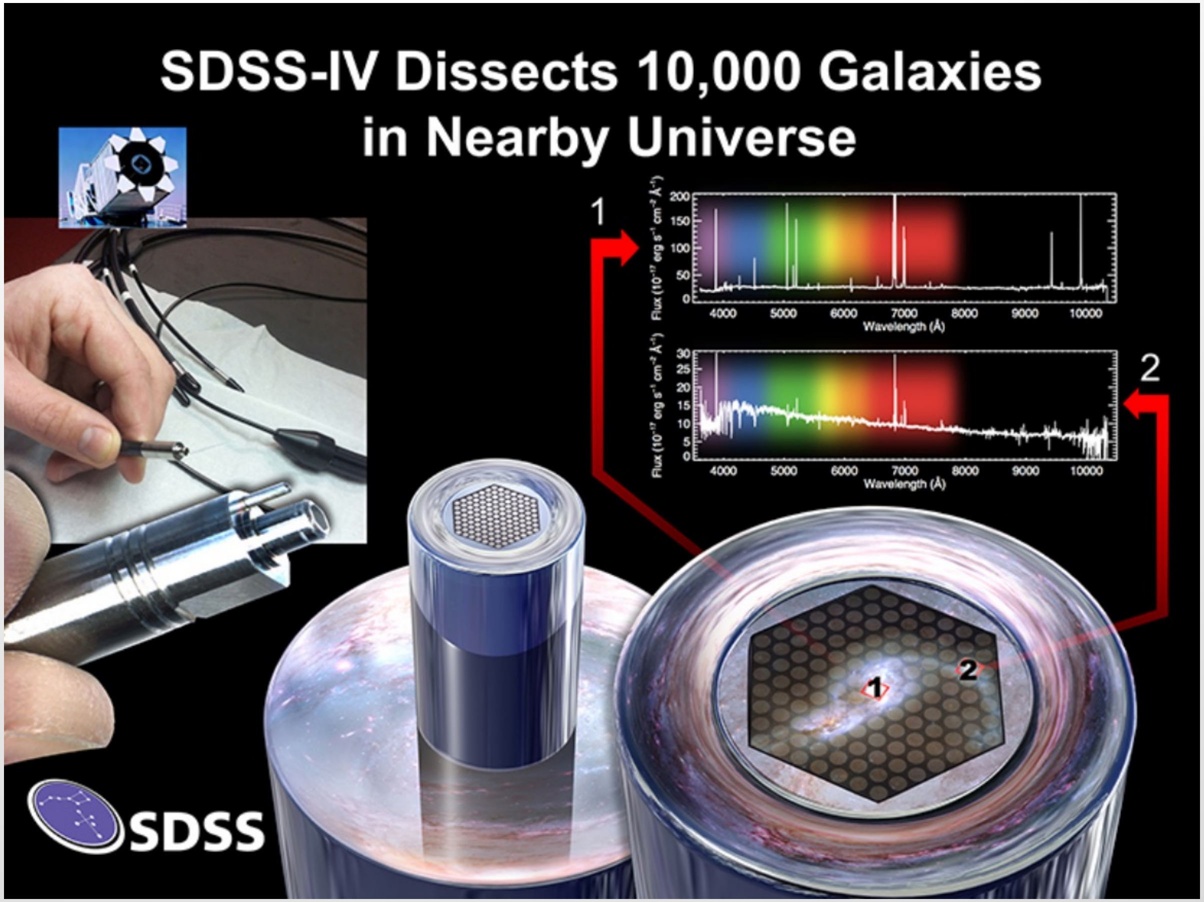


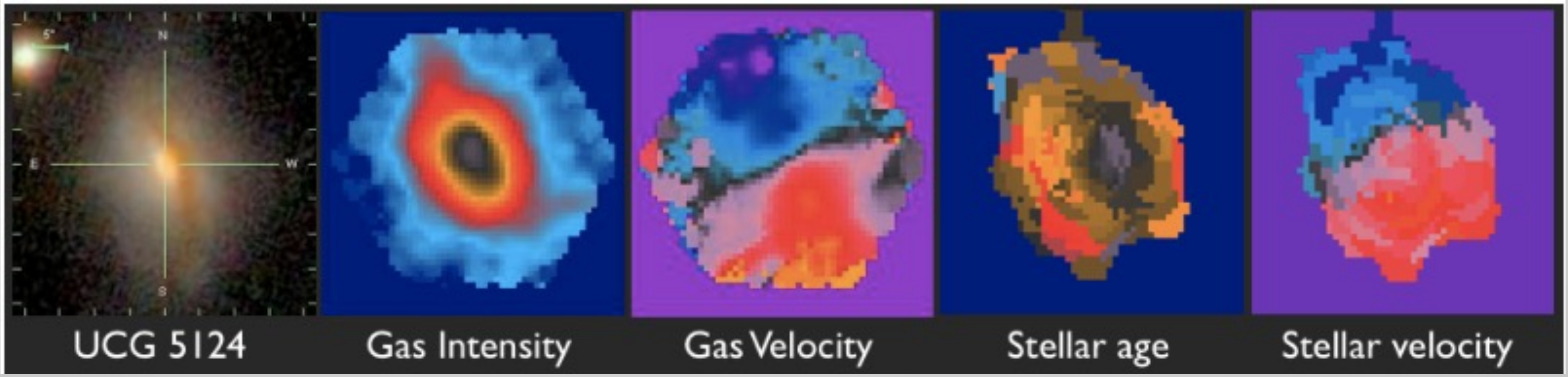
Fibres lined up to make “pseudo slit”

Integral Field Spectroscopy (IFS), uses an integral field unit (IFU). Lenslets attached to fibres feed spectrograph allowing whole galaxy sampling in one shot (dithering required to fill gaps). Most popular method.

Jargon alert:
spaxel = spectral pixel

SDSS IV MaNGA survey = Mapping Nearby Galaxies at Apache Point Observatory.





Methods for obtaining "spatially resolved" galaxy spectra

Integral field spectroscopy (IFS) –image slicer

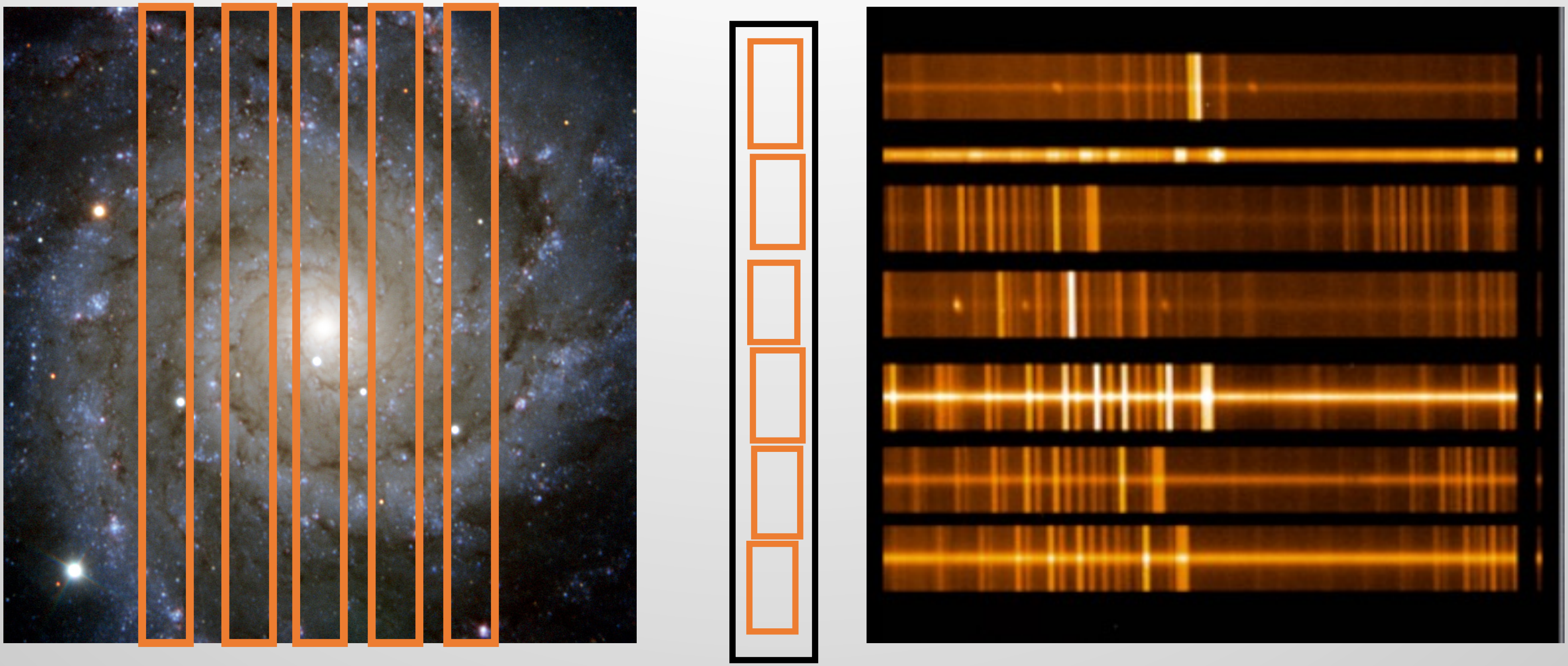
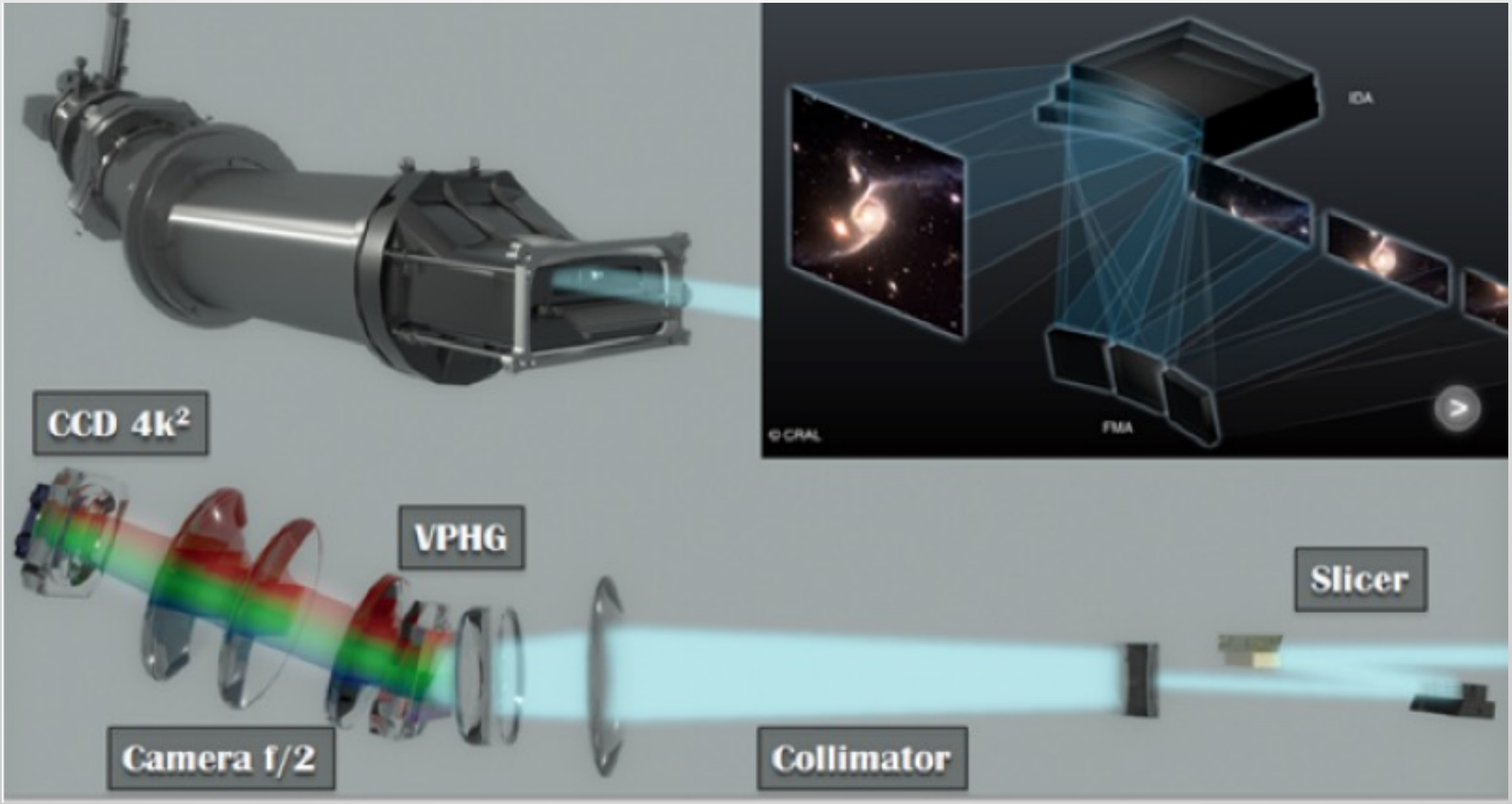


Image is sliced into sections using a segmented mirror. The mirror imaged slices are repositioned on the slit for dispersal.

Methods for obtaining "spatially resolved" galaxy spectra

Integral field spectroscopy (IFS) –image slicer



MUSE on the VLT

See Appendix A of Sanchez (2020)

Table 1 Summary of the main properties of different IFS-GS

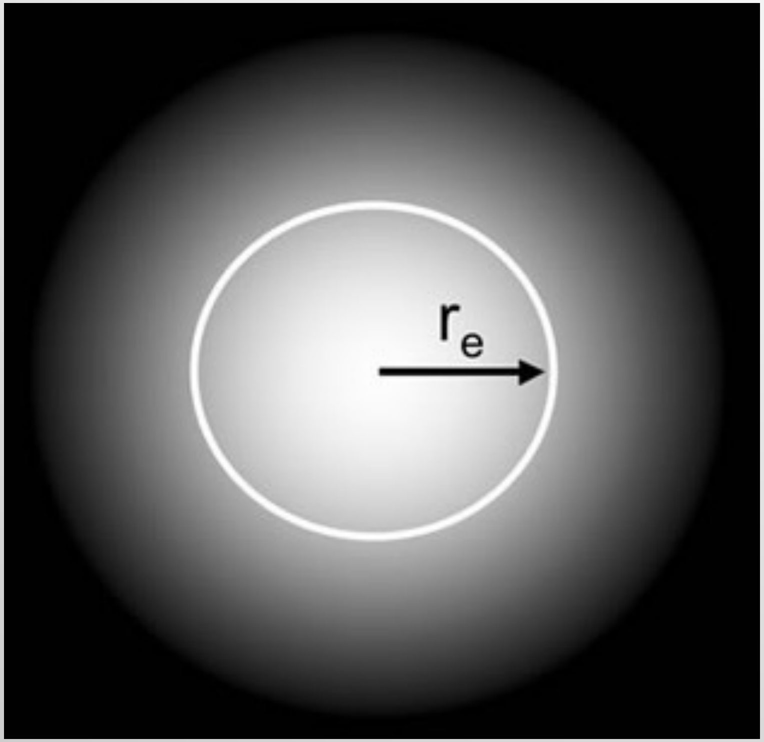
Jargon alert – effective radius

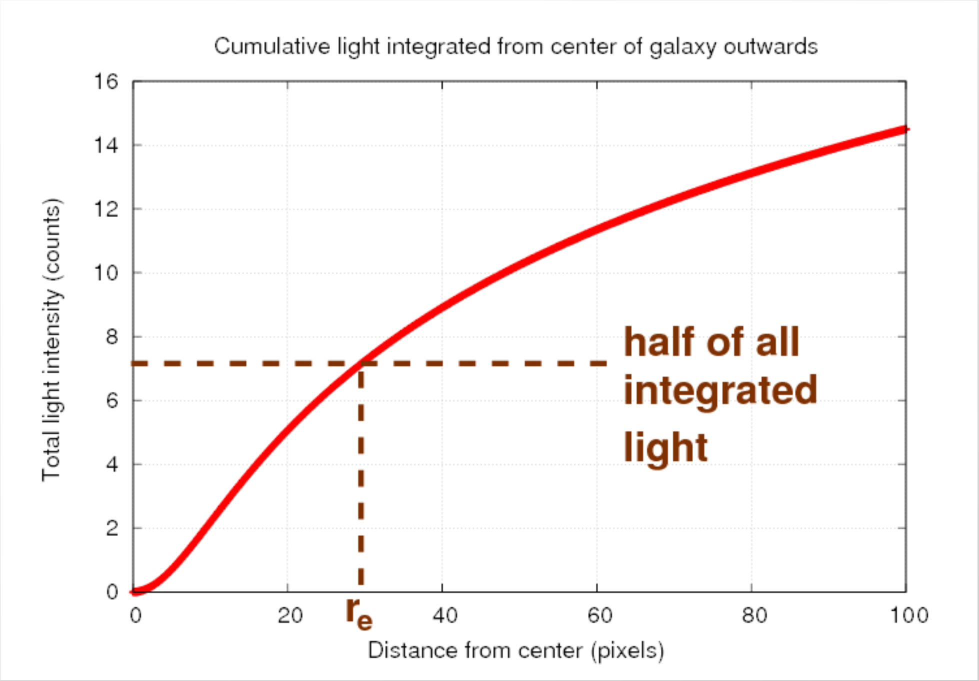
Parameter	MaNGA	SAMI	CALIFA	AMUSING++
Current sample size	6850	2400	974	540
Selection	M_* flat distribution	Volume limited	Diameter	Compilation
Redshift range	0.01-0.15	0.01-0.1	0.005-0.03	0.001-0.1
Mean redshift	0.03	0.04	0.015	0.017
Coverage	1.5 R_e (2/3), 2.5 R_e (1/3)	~1 R_e	>2.5 R_e	>2 R_e
S/N at $1r_e$ per spaxel	20	10	50	5
S/N at $1r_e$ per arcsec	40	20	50	25
Wavelength range (Å)	3600-10300	3700-5700/6250-7350	3700-7500	4650-9300
Original sampling elements	3×127[a]	n×61[b]	3×331	90,000
Spectral resolution (σ)	80 km/s	75/28 km/s	85/150 km/s	40 km/s
Spatial resolution (FWHM)	2.5″	2.3″	2.5″	~0.7″
Physical spatial res. (kpc)	2.5 [0.5,6.5]	2.2 [0.4,4.6]	0.8 [0.3,1.5]	0.3 [0.1,1.3]
Telescope size	2.5m	3.6m	3.5m	8.2m
Gal. in sample	4655	910	2222	447
Gal. with morphology	2796	910	1062	343
Gal. in *resolved* sample	728	534	0[c]	256

[a] This corresponds to the largest MaNGA bundle. Each MaNGA plate provides with 17 bundles of different amount of fibers: 2x19; 4x37; 4x61; 2x91; 5x127. [b] The dithering scheme in SAMI is repeated until a certain S/N is reached. Therefore the number of independent sampling elements is variable target to target. [c] Excluded due to the FoV of the SAMI IFU.

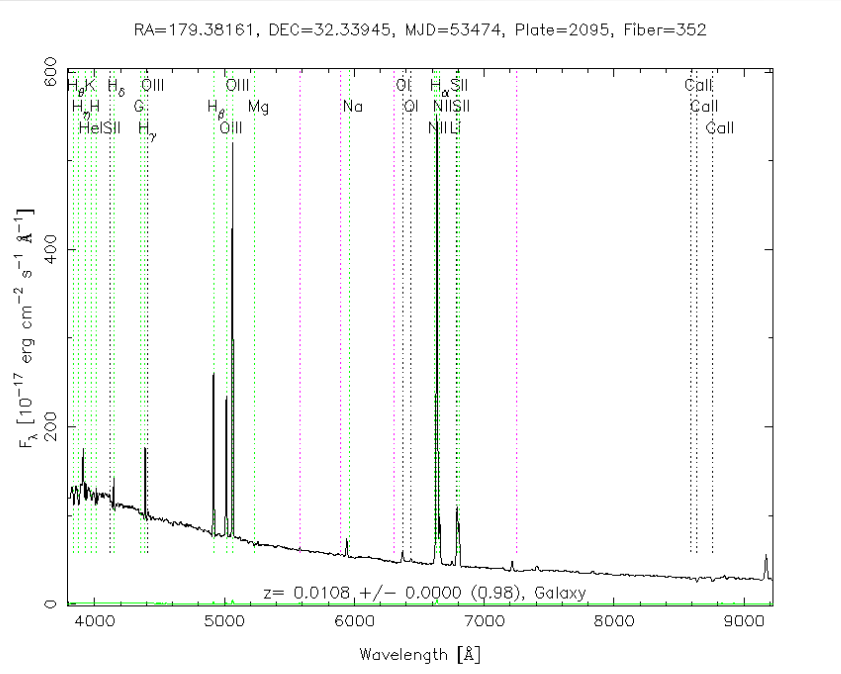
Typical spatial resolution corresponds to ~kpc scales for these samples (useful rule of thumb: 1" = 1 kpc at z=0.05).

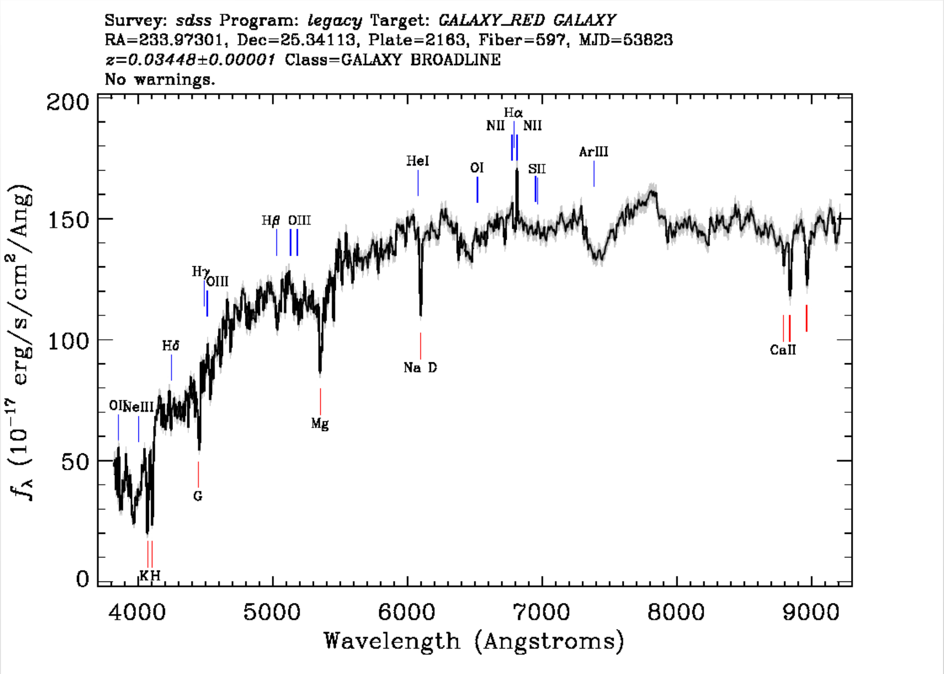
R_e: The effective or half-light radius is the distance that contains half of the galaxy's light. Other size metrics used in extragalactic astronomy include the Holmberg radius, the Petrosian radius, r_{50} and r_{90}.





Composition of a spectrum: combination of stellar continuum (including stellar absorption features), ISM absorption and HII regions.

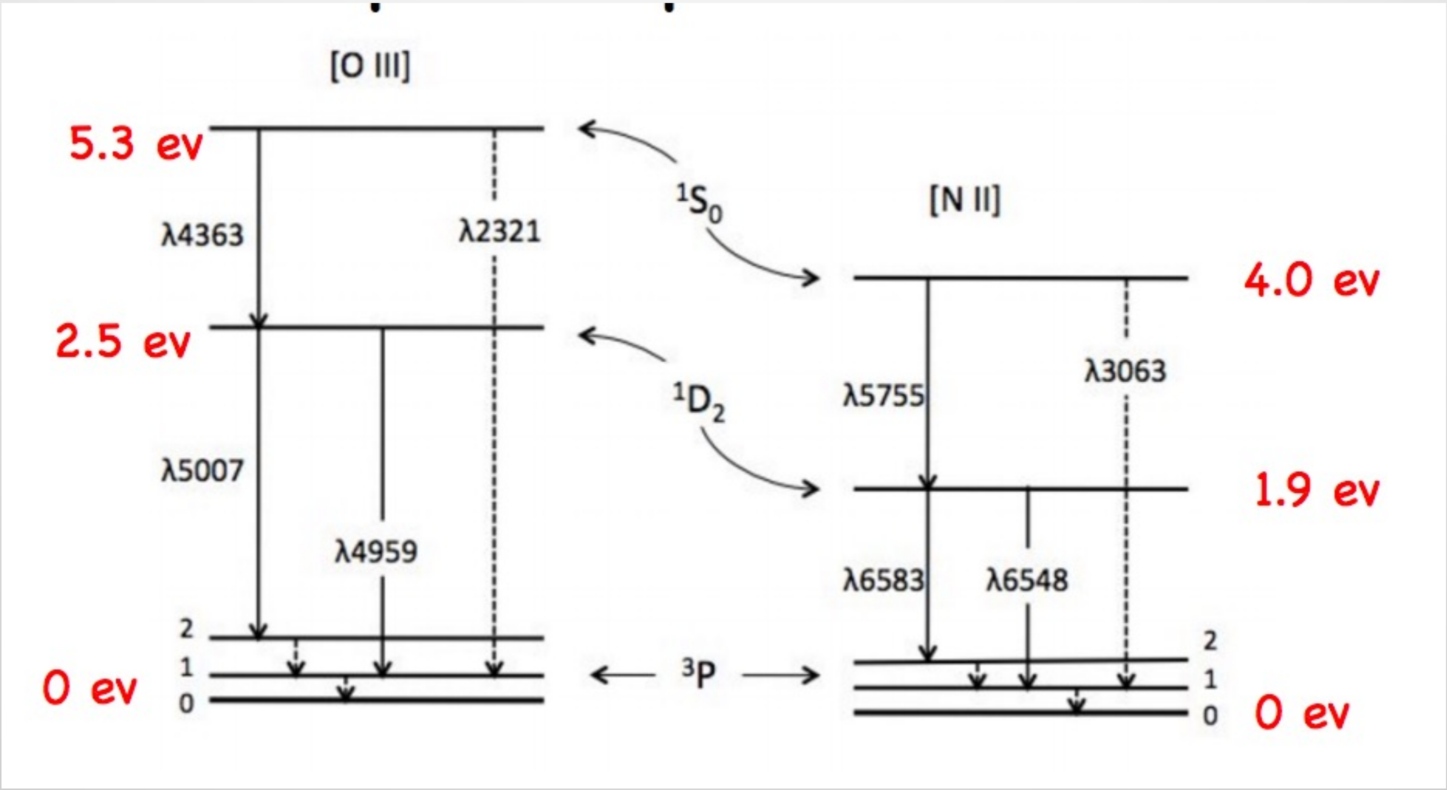




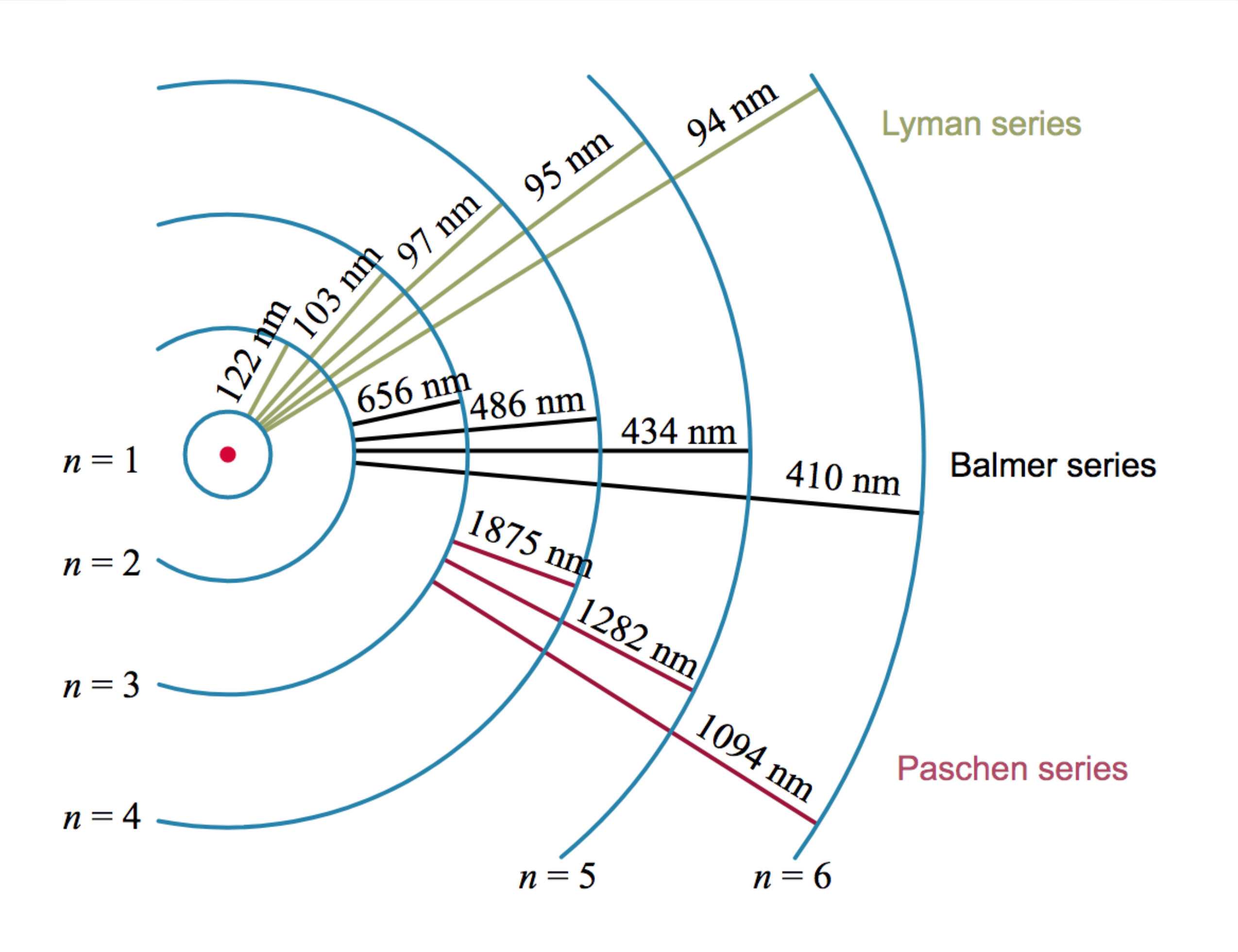
Star forming galaxy dominated by strong emission lines (from HII regions) and blue continuum due to the presence of hot young stars.

Elliptical galaxy spectrum lacks emission lines, has absorption lines from stars and ISM, and a strong 4000 Angstrom "break" (deficit of young blue stars plus line blanketing by metals in old stars)

Collisionally excited “forbidden” lines metal lines. Forbidden lines (identified with []) are rarely observed in the lab because collisional excitation keeps them in the higher energy state. Low densities in HII regions sufficient for radiative de-excitation to take place (transition time << time between collisions).



Hydrogen emission lines occur due to **recombination**. Balmer series in optical, usually just referred to as $H\alpha, H\beta, H\gamma\ etc.$



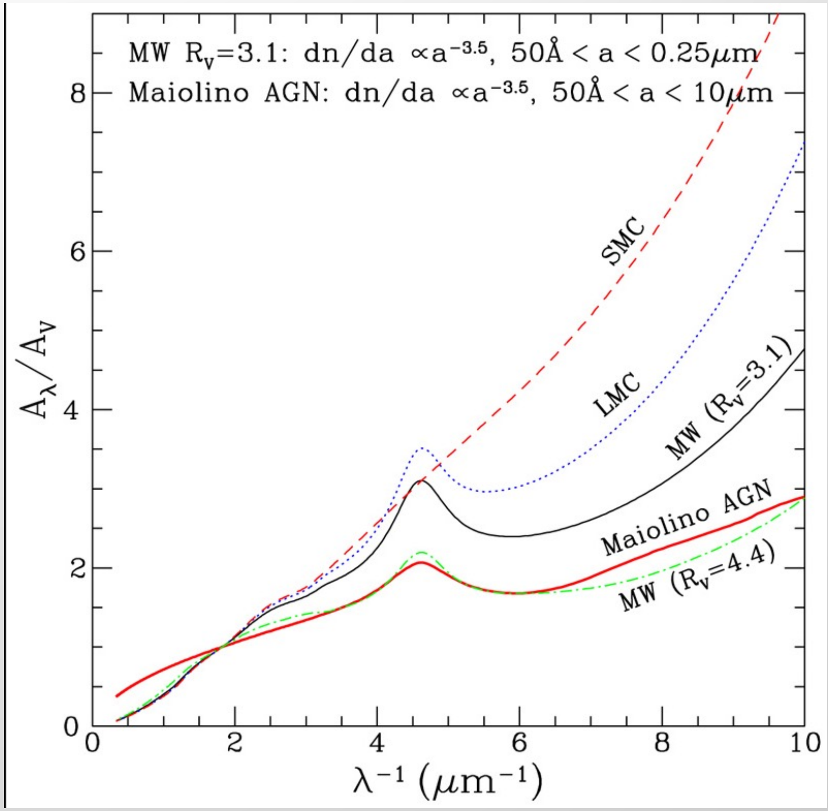
What can we do with emission lines?

Extinction correction (recap from Salim & Narayanan lecture)

Dust correction must be the first step in order to recover “true” fluxes from the observed ones.

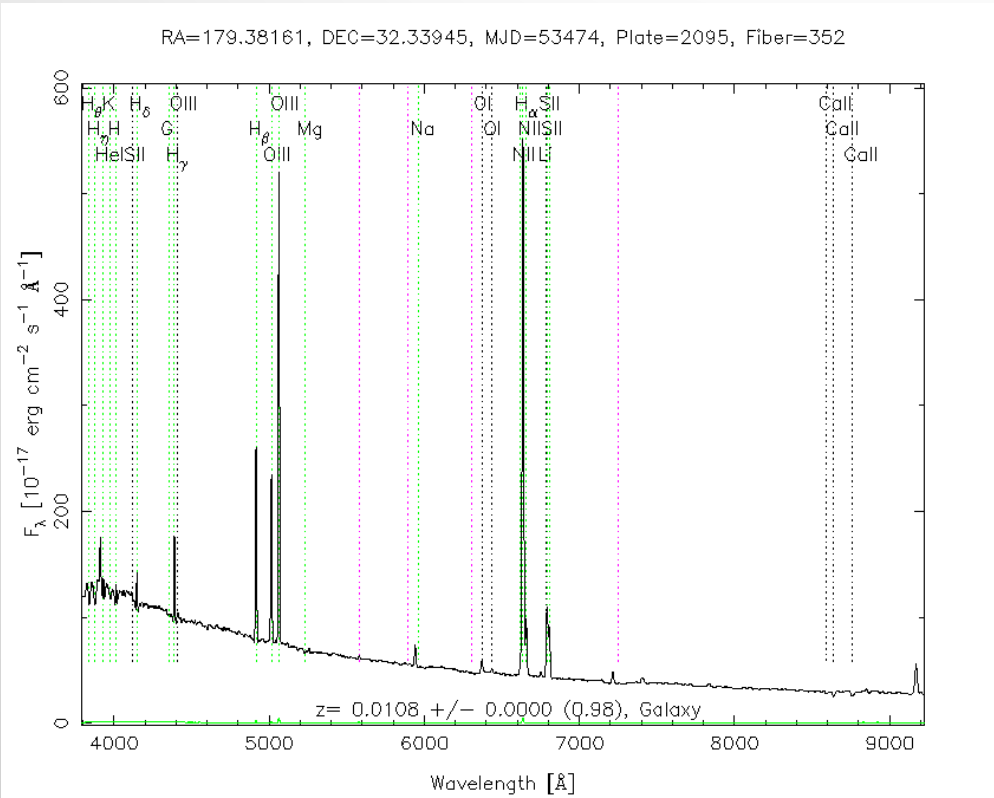
The ratio of $H\alpha/H\beta$ = constant (depends on temperature and density, but often taken to be 2.85).

Compare measured ratio to 2.85 – discrepancy tells you how much extinction is present (once you have assumed an
extinction curve).



What can we do with emission lines?

SFR (recap from Saintonge & Catinella lecture)



Step 1: Correct spectrum for Galactic extinction.

Step 2: Correct spectrum for internal extinction.

Step 3: Correct Balmer emission line fluxes for stellar absorption.

Step 4: $LH\alpha = FH\alpha * 4\pi D_L^2$

Step 5: For a Kroupa IMF
$SFR\ (M_\odot/yr) = LH\alpha\ (erg/s) - 41.27$

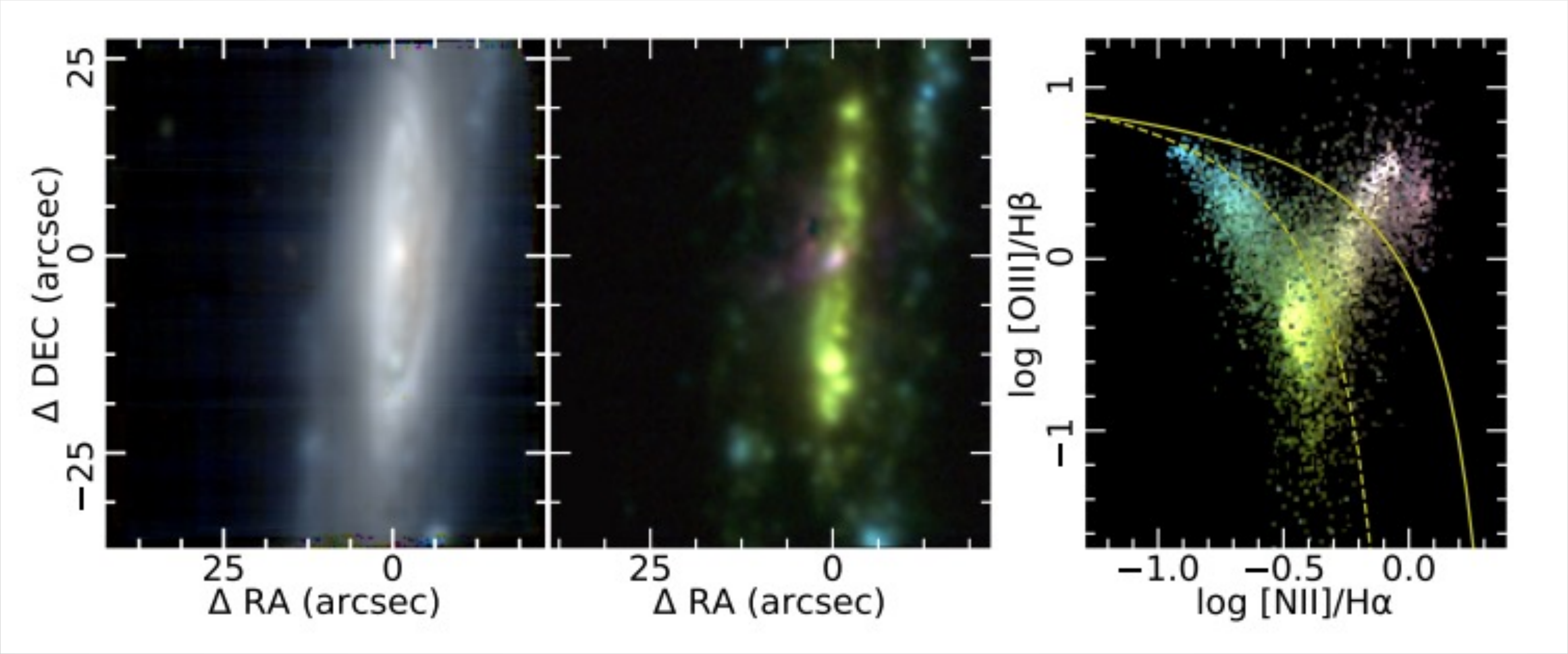
Star forming galaxy dominated by strong emission lines (from HII regions) and blue continuum due to the presence of hot young stars.

See Kennicutt & Evans (2013) ARA&A for a review on SFR indicators

What can we do with emission lines?

AGN diagnostics (recap from Hickox & Alexander lecture)

Using a BPT (Baldwin, Philips and Terlevich) diagram. BPT demarcations are calibrated either empirically or using photo-ionization models. The simplest (and most used) classification is just dividing into star-forming (i.e. HII regions ionized by hot stars) and AGN, with a composite region in between. BPT classification done for entire galaxy for integrated spectra or on a per spaxel basis for IFU.

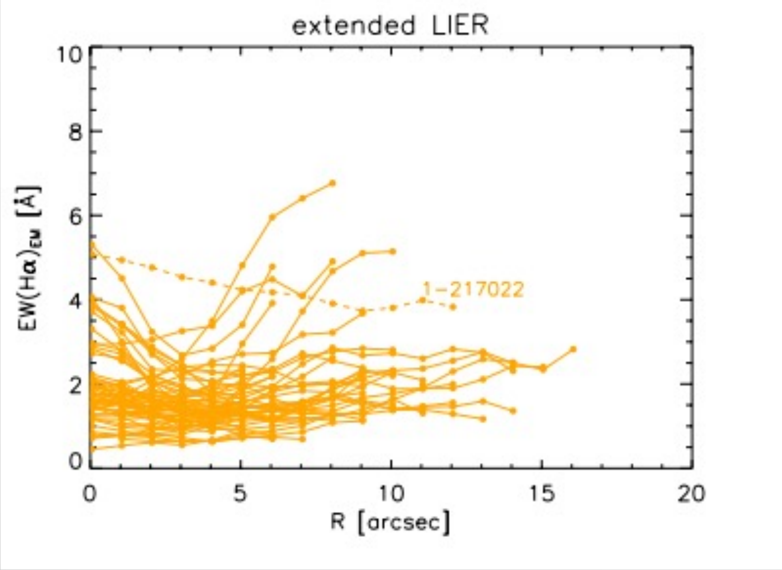


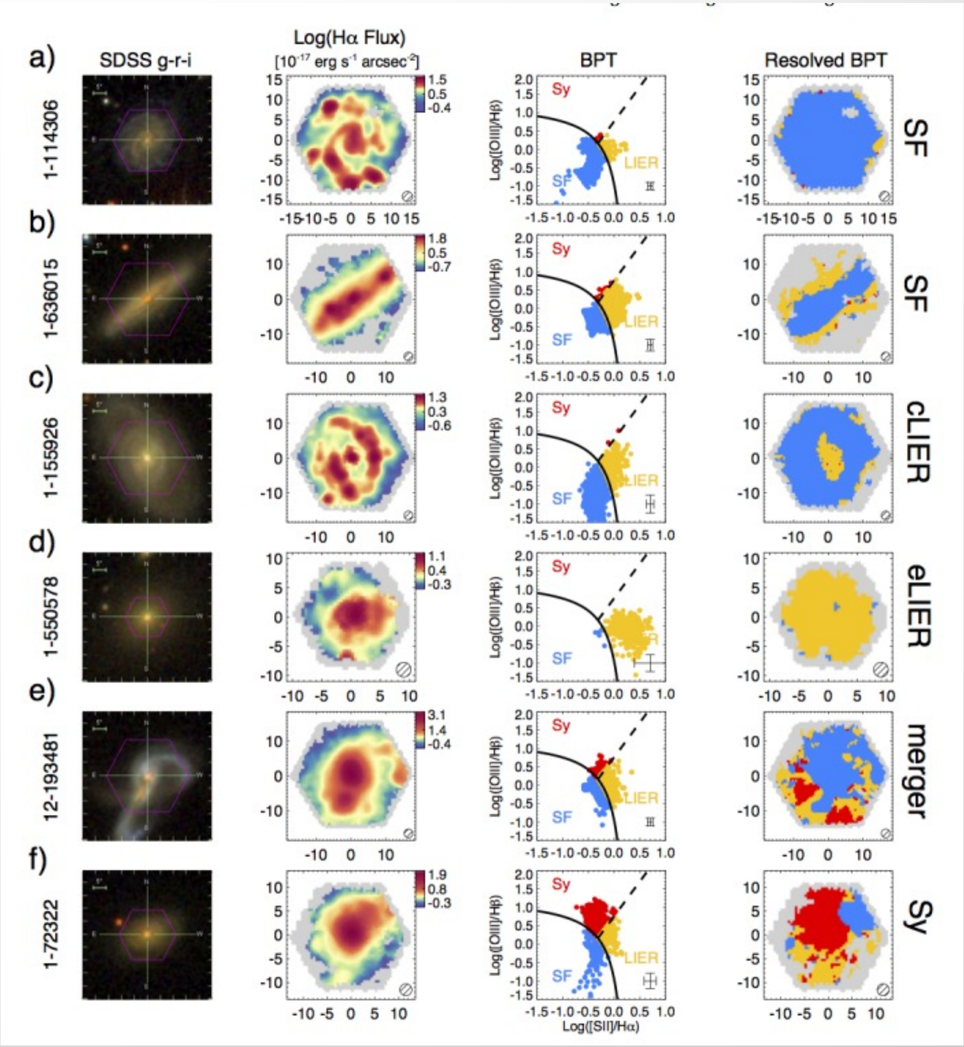
Adapted from Lopez-Coba et al. (2020)

From AGN - > LINER -> LIER

Many spaxels on the AGN branch lie in the “LINER” region, but are not nuclear. The H alpha EWs are also small (<3A).

Much of this LIER emission is therefore likely to come from old stellar populations, not AGN.





Belfiore et al. (2016)

What can we do with emission lines?

Measure gas-phase metallicities (if the spaxel is located on the SF branch of the BPT diagram).

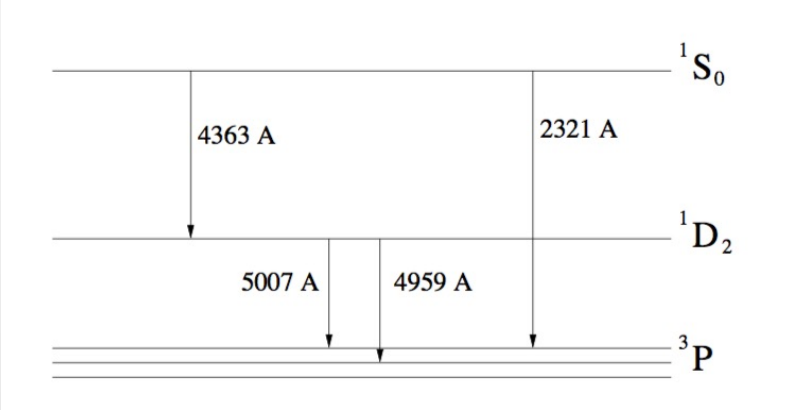
Direct method: Emission line strengths depend on both abundance and local conditions. The direct (or T_e) method solves for temperature and metallicity.

In a 3 level atom, line ratio intensity is given by:

$$\frac{I(\nu_{32})}{I(\nu_{21})} = \frac{N_3 A_{32} h\nu_{32}}{N_2 A_{21} h\nu_{21}} = \frac{\Omega_{13} A_{32} \nu_{32}}{\Omega_{12}(A_{31} + A_{32})\nu_{21}} e^{\frac{-E_{23}}{kT}}$$

(where Omega is collision strength and A is Einstein A coefficient), see ISM lecture 2 for more details: http://www.astro.uvic.ca/~sara/A503.html

For [OIII] we can use the 4363 A line and the 5007 A line (4959 also possible, but 3 times weaker than 5007 line).

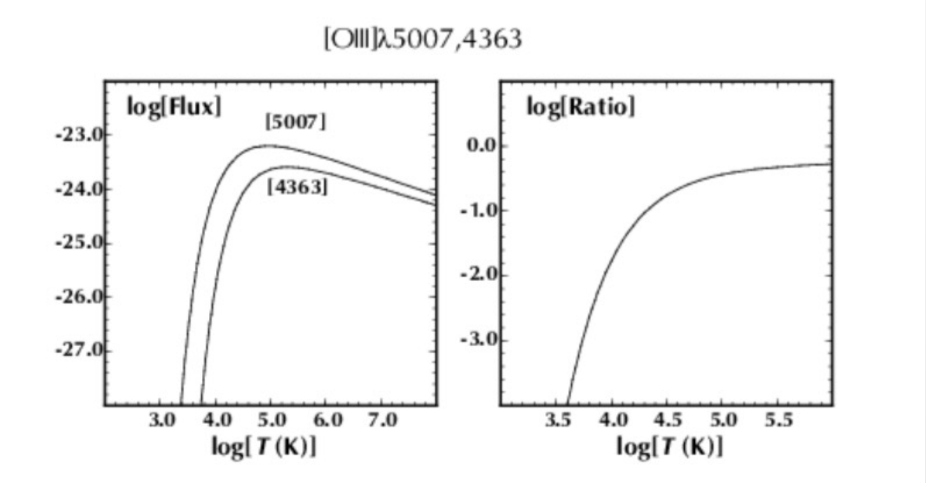


What can we do with emission lines?

Measure gas-phase metallicities (if the spaxel is located on the SF branch of the BPT diagram).

The ratio of these two [OIII] lines tells us the temperature. Solve computationally (not analytically) with multi-zone ionization model.

$$\frac{I(\nu_{32})}{I(\nu_{21})} = \frac{N_3 A_{32} h\nu_{32}}{N_2 A_{21} h\nu_{21}} = \frac{\Omega_{13} A_{32} \nu_{32}}{\Omega_{12}(A_{31} + A_{32})\nu_{21}} e^{\frac{-E_{23}}{kT}}$$



See Curti et al. (2017) for a recent paper on measuring metallicities this way.

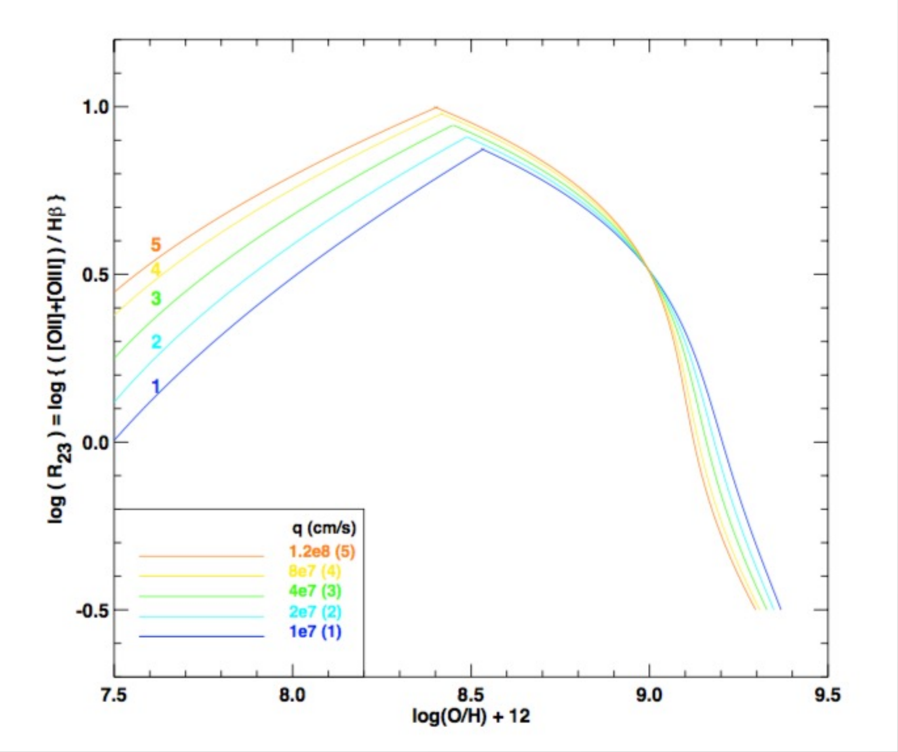
Limitation: [OIII] 4363 line is extremely weak in all but the most metal-poor regions (high T) and usually not detected.

What can we do with emission lines?

Measure gas-phase metallicities (if the spaxel is located on the SF branch of the BPT diagram).

Strong line methods: Use only strong lines, such as Balmer lines, [OIII], [OII], [NII]. Calibrate various combinations of these strong lines against either theoretical models, or metallicities derived from the T_e method.

The most common strong line ratio is R_{23}. The main problem is that it is double valued – a given R_{23} has both a high metallicity and low metallicity solution. A further line ratio is needed to break this degeneracy (usually involving [NII]).



Kobulnicky & Kewley (2004)

What can we do with emission lines?

Measure gas-phase metallicities (if the spaxel is located on the SF branch of the BPT diagram).

Strong line methods: Use only strong lines, such as Balmer lines, [OIII], [OII], [NII]. Calibrate various combinations of these strong lines against either theoretical models, or metallicities derived from the T_e method.

Other line ratios include:

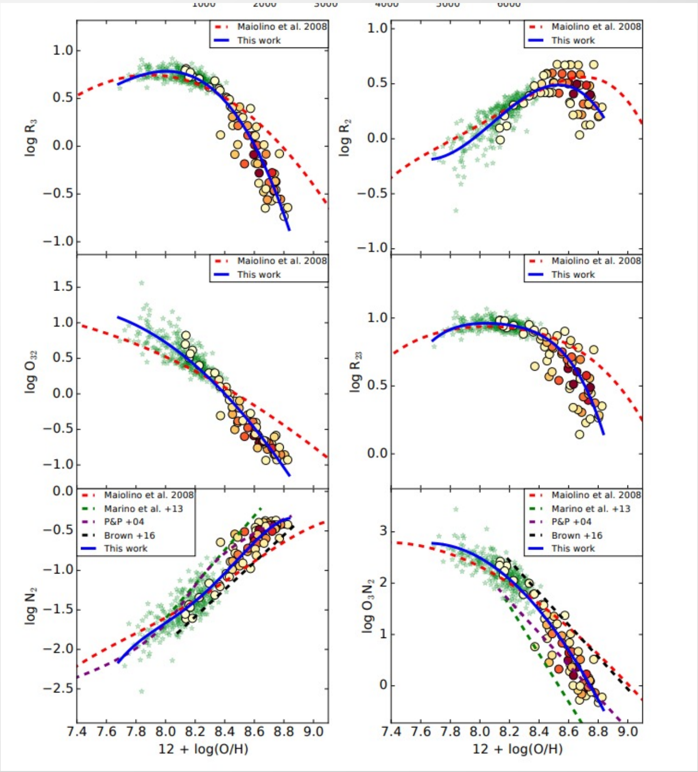
N_2 = N[II] 6584 /Hα

O_{32} = [OIII] 5007 / [OII] 3727

O_3N_2 = ([OIII] 5007/Hβ) / ([NII] 6584/Hα)

Pros: Easy to use
Cons: Many exist and they all have offsets from each other! No absolute measurements.

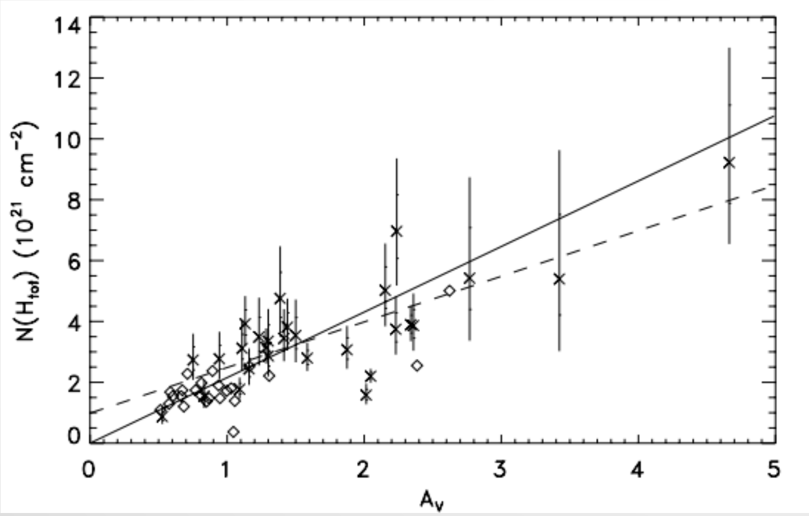
See Kewley & Ellison (2008) and Scudder et al. (2021) for a full account of strong line methods.



Curti et al. (2017)

Spatially resolved gas maps

Rachford et al. (2009)



"Indirect" estimates of gas from optical spectroscopy. Gas and dust are intimately linked in the ISM (molecules form on dust grains).

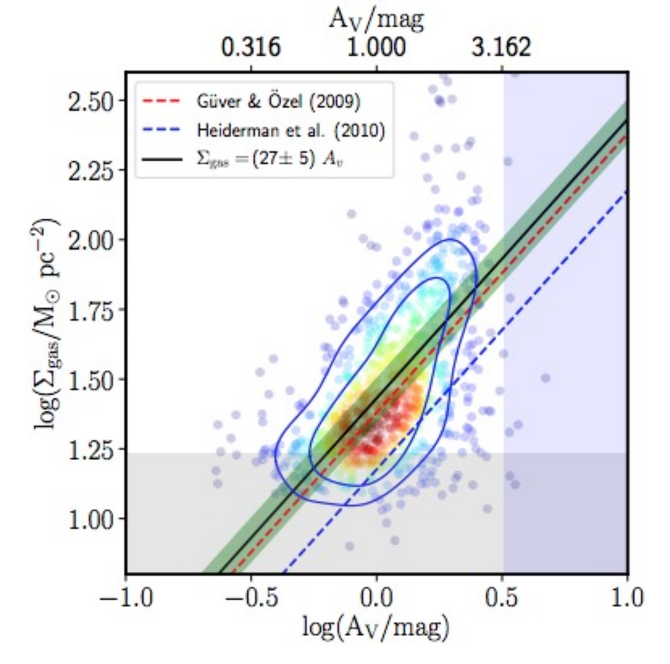
Total gas content correlates with A_V where:

$\Sigma_{tot} = \Sigma_{HI} + \Sigma_{H2}$

Determine A_V from Balmer decrement and calibrate the relationship between Σ_{tot} for a dataset with known gas surface densities.

See also Concas & Popesso (2019), Piotrowska et al. (2020) Yesuf & Ho (2019) for other calibrations for "global" H_2 using similar principles.

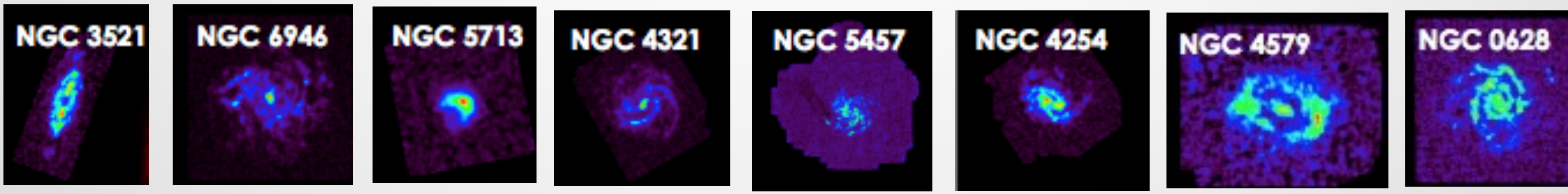
Caveats that this approach assumes an average (not applicable in all conditions).



Barrera-Ballesteros et al. (2020)

Spatially resolved gas maps

- Very nearby galaxies can be mapped with single dish (as long as the beam size is not too big), e.g. HERACLES survey of CO with the IRAM 30-metre (e.g. Leroy et al. 2009).



- But really, spatially resolved gas requires interferometry (certainly in HI where single dishes are large). E.g. VLA. THINGS survey (Leroy et al. 2008).

- Interferometry has been revolutionized with ALMA.

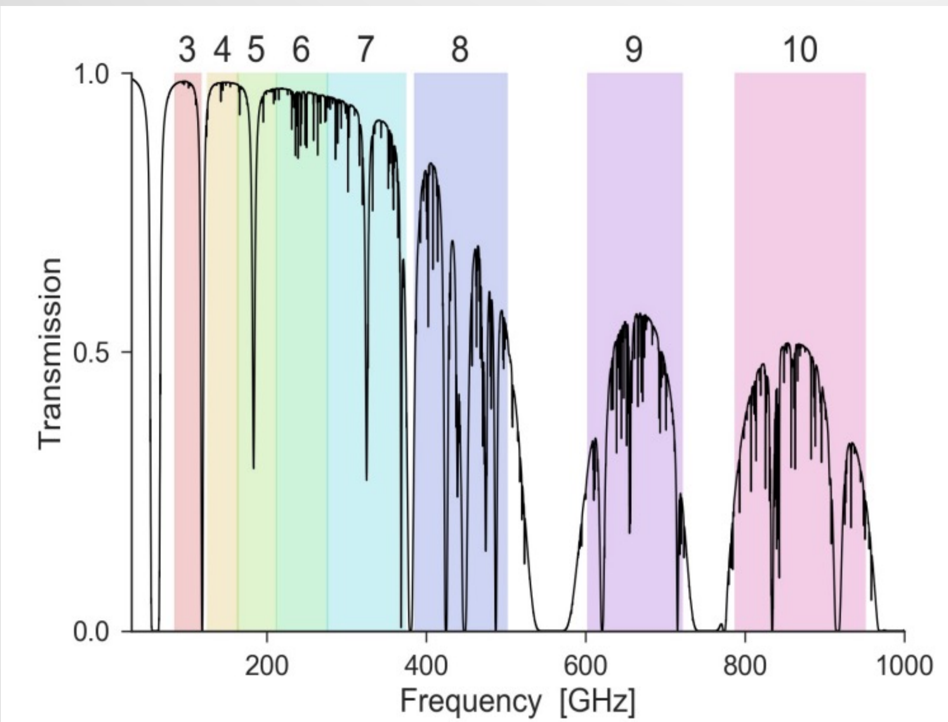
The Atacama Large mm/submm Array (ALMA)

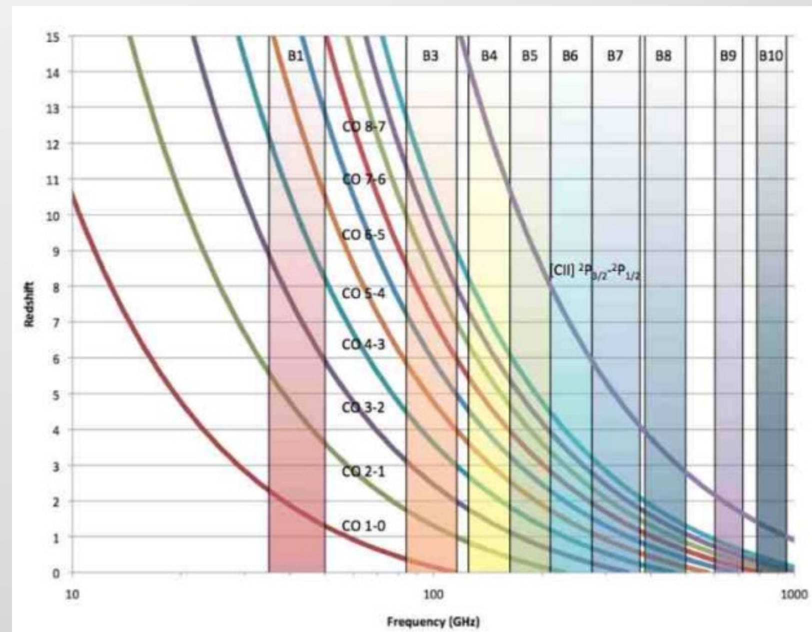
- Fifty 12-meter antennas for sensitive, high resolution imaging.

- Four additional 12-meter antennas, providing total power (TP array), and twelve 7-meter antennas comprising the ALMA Compact Array (ACA), enhancing the fidelity of wide field imaging.

The Atacama Large mm/submm Array (ALMA)

The CO(1-0) line is well placed in ALMA's Band 3 for low redshift observations (higher excitation lines often chosen for higher redshifts), but CO(2-1) often chosen because it is brighter and yields higher resolution images in a given configuration (why?). Downside – a further uncertainty in conversion factor.





Di Francesco et al. (2013)

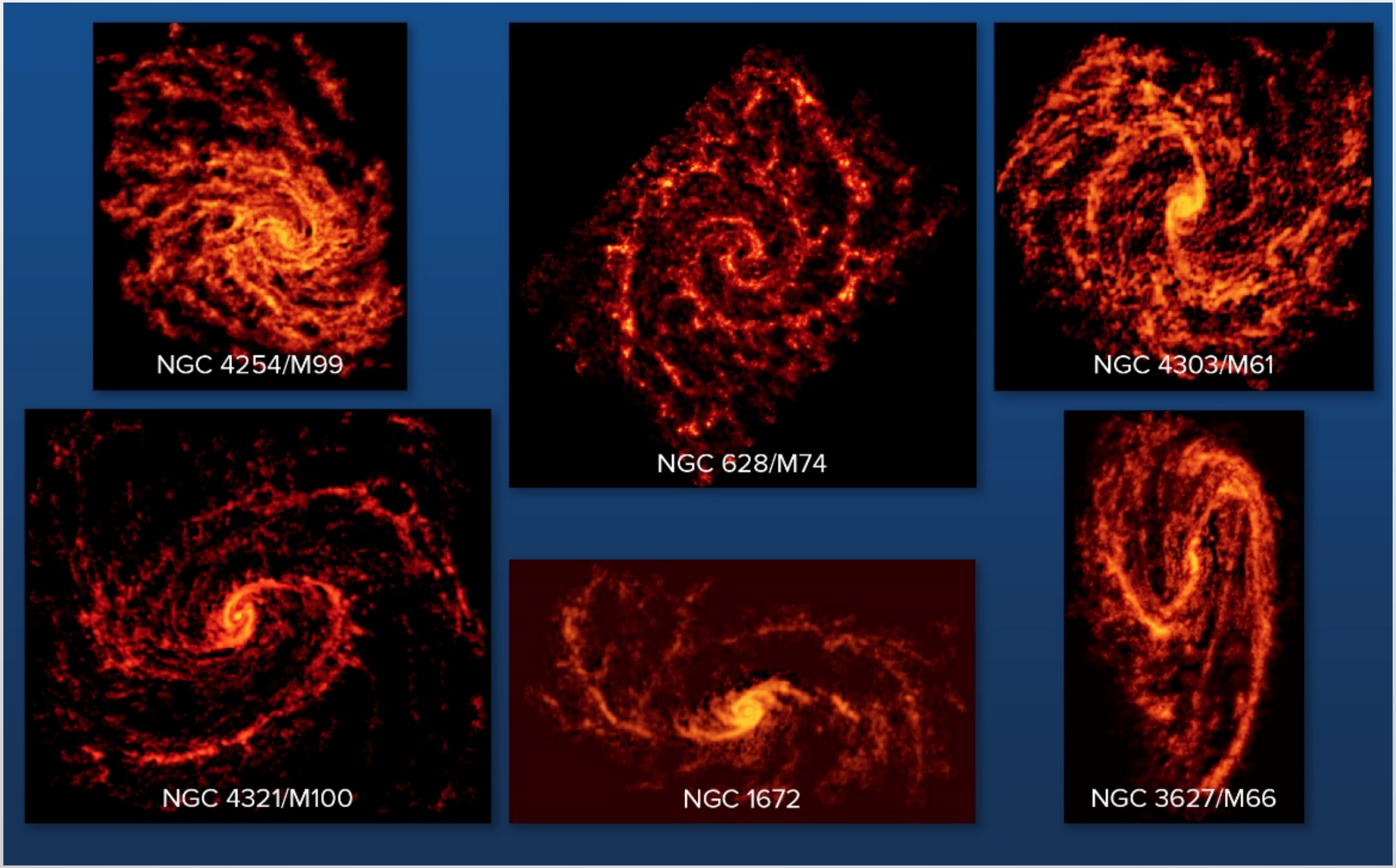
The Atacama Large mm/submm Array (ALMA)

Most compact

Most extended

Config.	L_{max} / L_{min}	Band / Freq. (GHz)	1 / 40	3 / 100	4 / 150	5 / 185	6 / 230	7 / 345	8 / 460	9 / 650	10 / 870
7-m	45 m	θ_{res} (arcsec)	31.5	12.5	8.35	6.77	5.45	3.63	2.72	1.93	1.44
	9 m	θ_{MRS} (arcsec)	167	66.7	44.5	36.1	29.0	19.3	14.5	10.3	7.67
C-1	161 m	θ_{res} (arcsec)	8.45	3.38	2.25	1.83	1.47	0.98	0.74	0.52	0.39
	15 m	θ_{MRS} (arcsec)	71.2	28.5	19.0	15.4	12.4	8.25	6.19	4.38	3.27
C-2	314 m	θ_{res} (arcsec)	5.75	2.30	1.53	1.24	1.00	0.67	0.50	0.35	0.26
	15 m	θ_{MRS} (arcsec)	56.5	22.6	15.0	12.2	9.81	6.54	4.90	3.47	2.59
C-3	500 m	θ_{res} (arcsec)	3.55	1.42	0.94	0.77	0.62	0.41	0.31	0.22	0.16
	15 m	θ_{MRS} (arcsec)	40.5	16.2	10.8	8.73	7.02	4.68	3.51	2.48	1.86
C-4	784 m	θ_{res} (arcsec)	2.30	0.92	0.61	0.50	0.40	0.27	0.20	0.14	0.11
	15 m	θ_{MRS} (arcsec)	28.0	11.2	7.50	6.08	4.89	3.26	2.44	1.73	1.29
C-5	1.4 km	θ_{res} (arcsec)	1.38	0.55	0.36	0.30	0.24	0.16	0.12	0.084	0.063
	15 m	θ_{MRS} (arcsec)	16.8	6.70	4.47	3.62	2.91	1.94	1.46	1.03	0.77
C-6	2.5 km	θ_{res} (arcsec)	0.78	0.31	0.20	0.17	0.13	0.089	0.067	0.047	0.035
	15 m	θ_{MRS} (arcsec)	10.3	4.11	2.74	2.22	1.78	1.19	0.89	0.63	0.47
C-7	3.6 km	θ_{res} (arcsec)		0.21	0.14	0.11	0.092	0.061	0.046	0.033	0.024
	64 m	θ_{MRS} (arcsec)		2.58	1.72	1.40	1.12	0.75	0.56	0.40	0.30
C-8	8.5 km	θ_{res} (arcsec)		0.096	0.064	0.052	0.042	0.028	0.021	0.015	0.011
	110 m	θ_{MRS} (arcsec)		1.42	0.95	0.77	0.62	0.41	0.31	0.22	0.16

The PHANGS Survey



State of the art in high resolution mapping. Total of 74 galaxies mapped with ALMA in CO(2-1) at 100 pc resolution. 18 also have MUSE data.

Summary

- There are several techniques for obtaining spatially resolved spectroscopy. IFU approaches are the most powerful.

- Several large surveys now exist that include many thousands of galaxies (millions of spaxels) for mapping nearby galaxies at ~ kpc resolution.

- Optical spectroscopy allows us to measure M*, SFR, O/H, extinction and classify AGN (and more).

- The ability to measure gas on the same spatial scales has provided an enormous advantage. Revolutionized by ALMA.