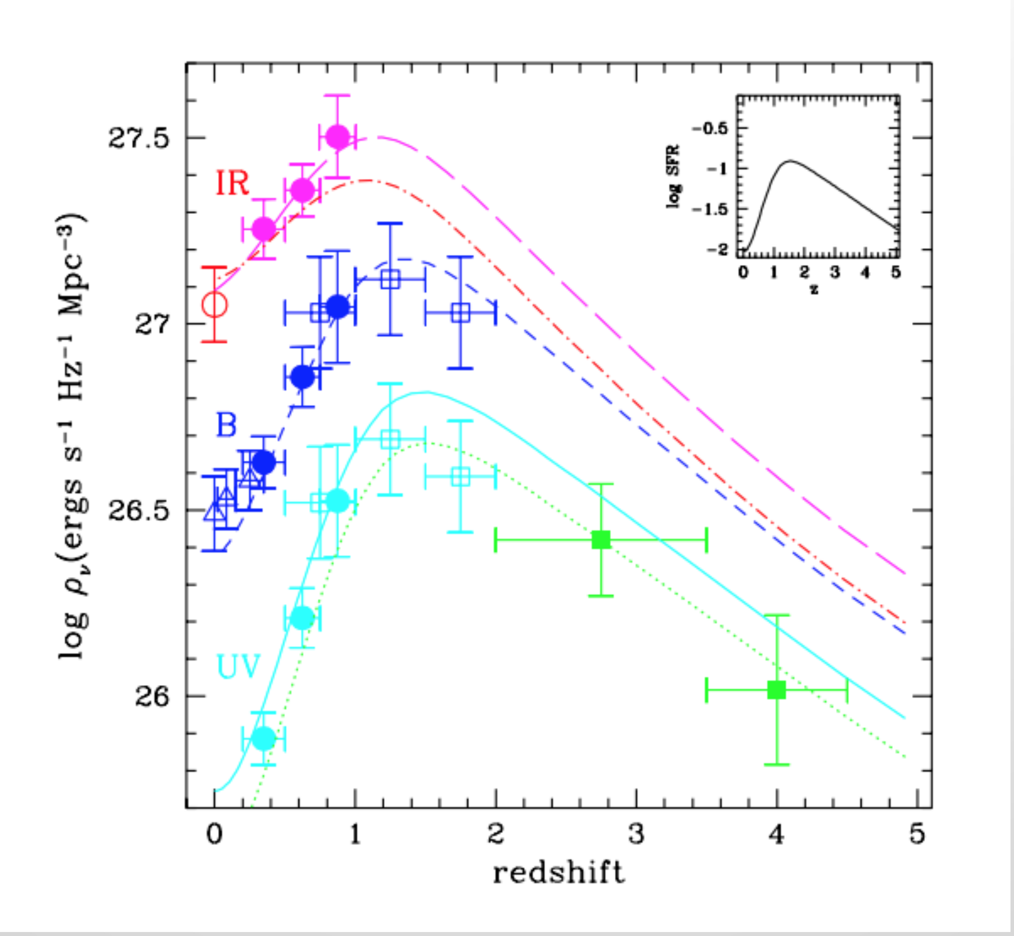
Natascha Forster-Schreiber & Stijn Wuyts
2020, ARA&A, 58, 661

Star-forming galaxies at cosmic high noon.

Other reviews:
Madau & Dickinson 2014 ARAA
Kennicutt & Evans 2012 ARAA
Kewley, Nichols & Sutherland 2019 ARAA

Jargon alert:
Cosmic noon = z~2

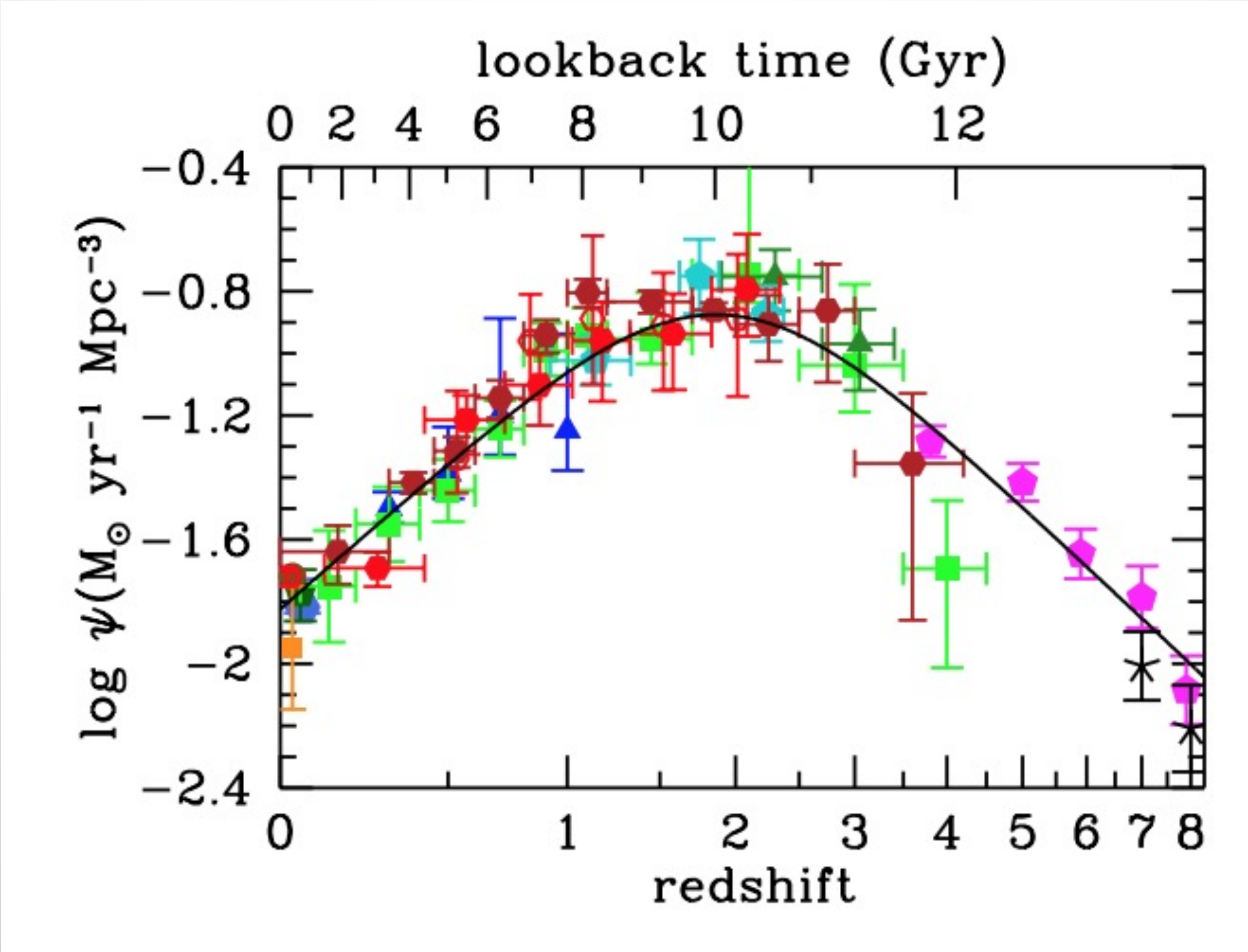
Cosmic star formation history



Madau et al. (1998)

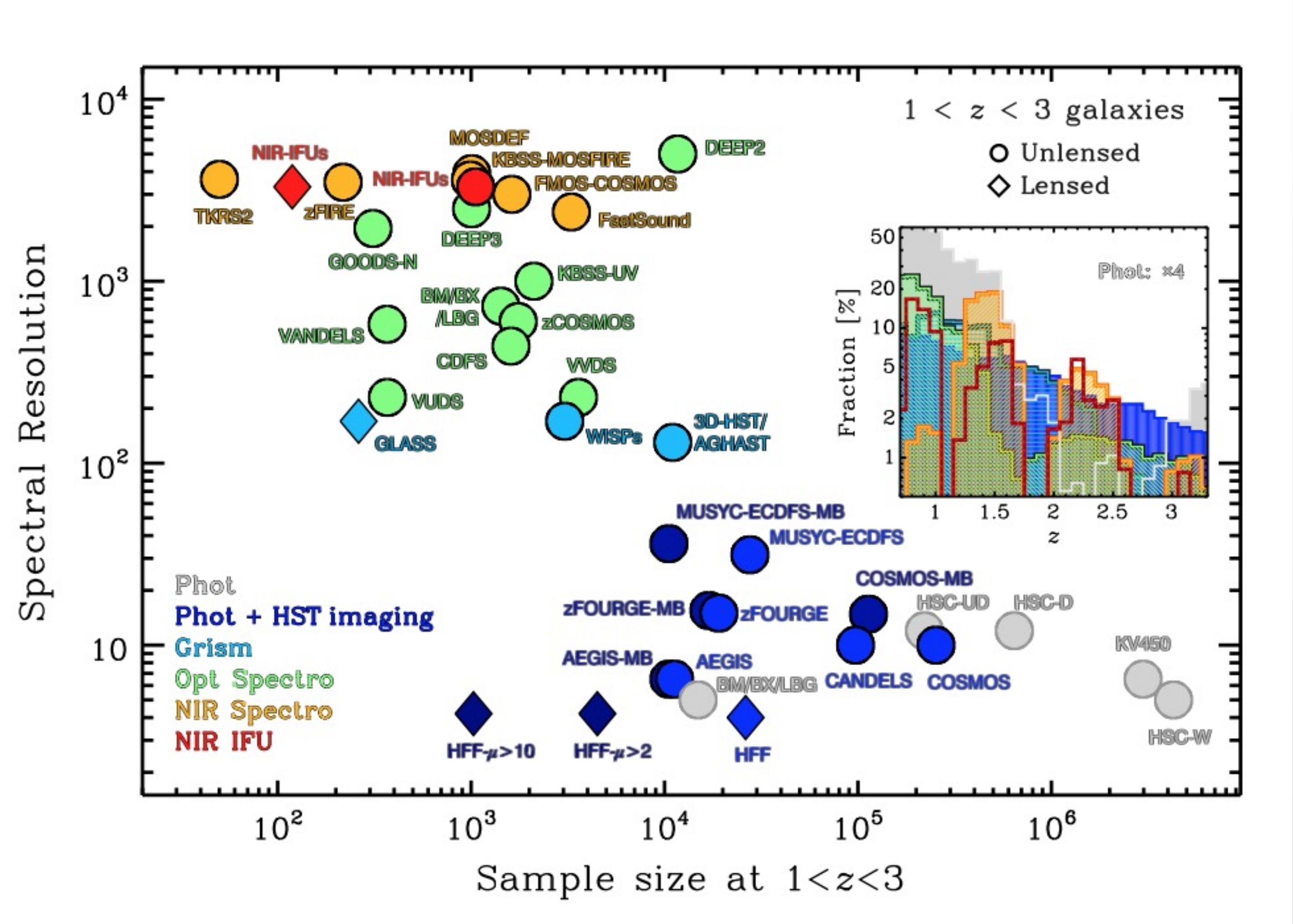
Jargon alert: “The Madau Plot” or “Lilly-Madau plot”

Cosmic noon – the peak of galaxy growth 2<z<3



Madau & Dickinson (2014)

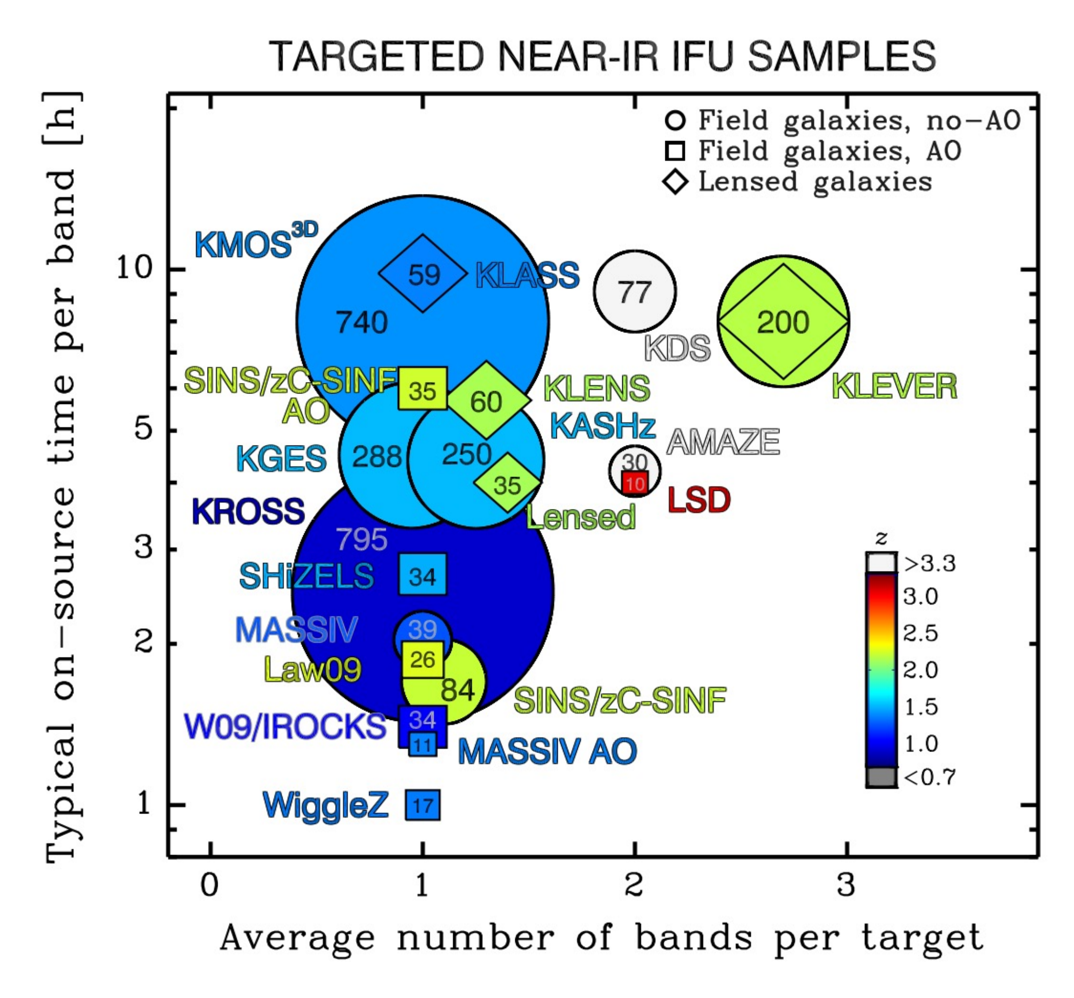
Survey summary – (mostly) single spectrum



What drives the choice of resolution?

Forster-Schreiber & Wuyts (2020)

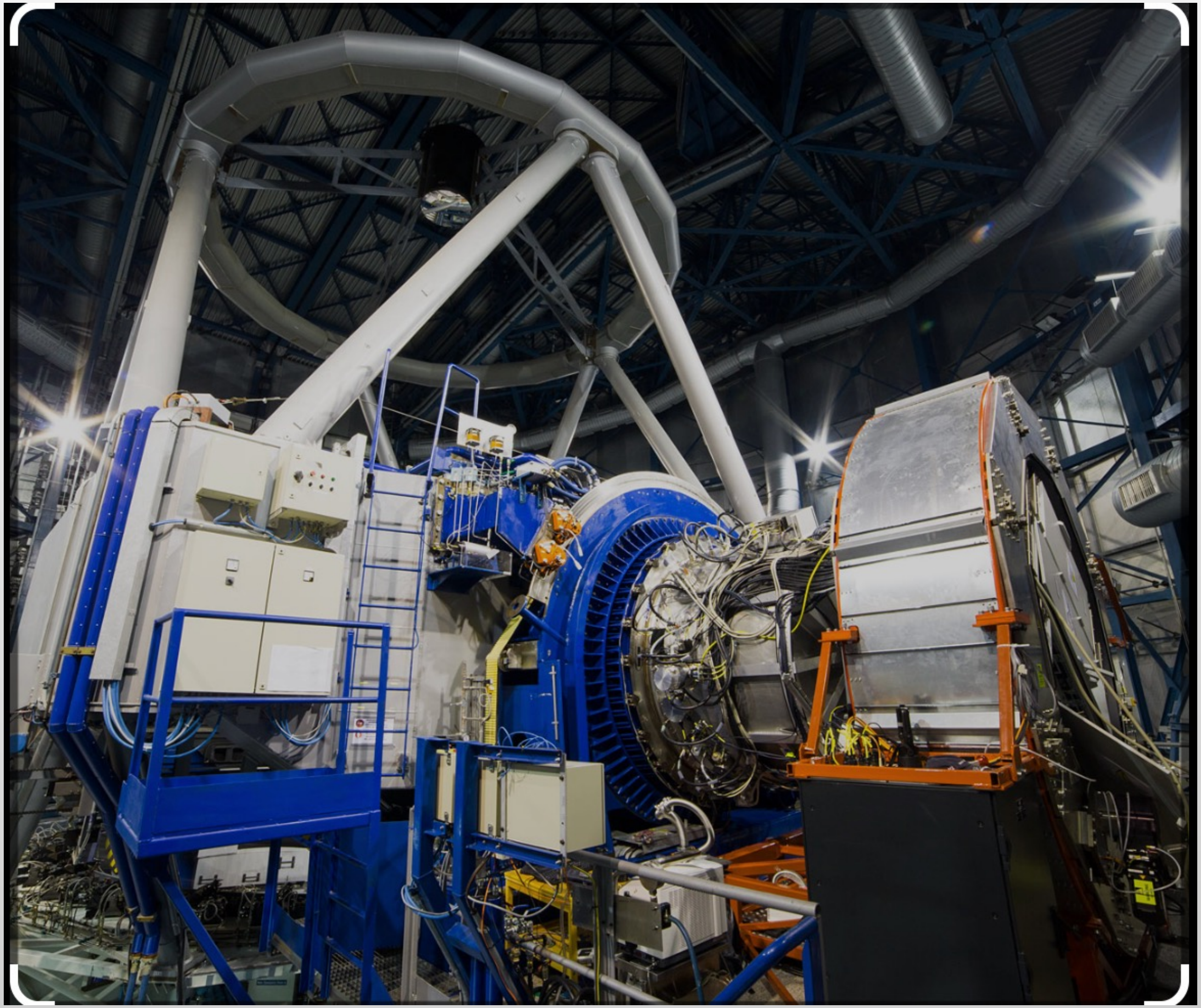
Survey summary – IFU



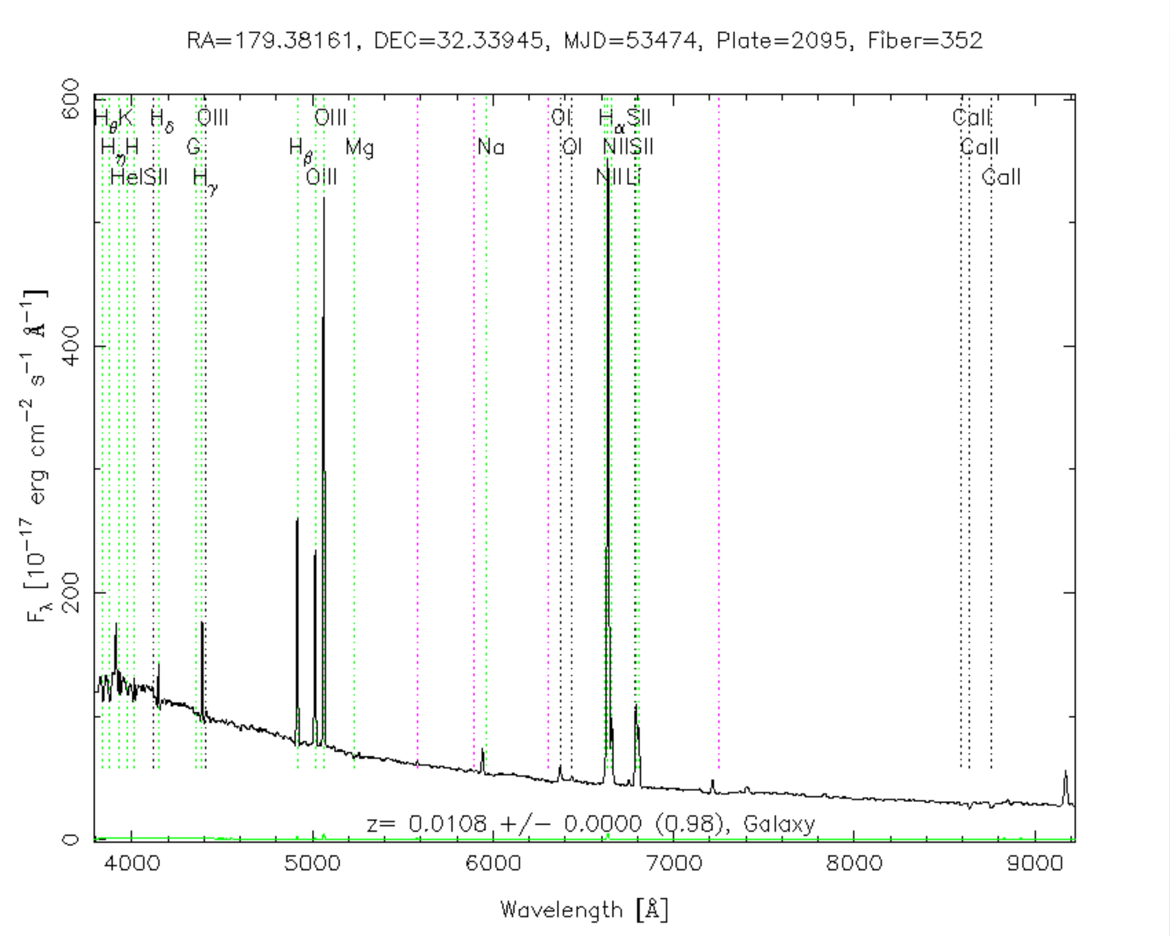
Much smaller samples!

Forster-Schreiber & Wuyts (2020)

Notice all the “K”s in the acronyms? The VLT instrument KMOS revolutionized the high-z IFU landscape with 24 NIR IFUs.



Finding high z galaxies



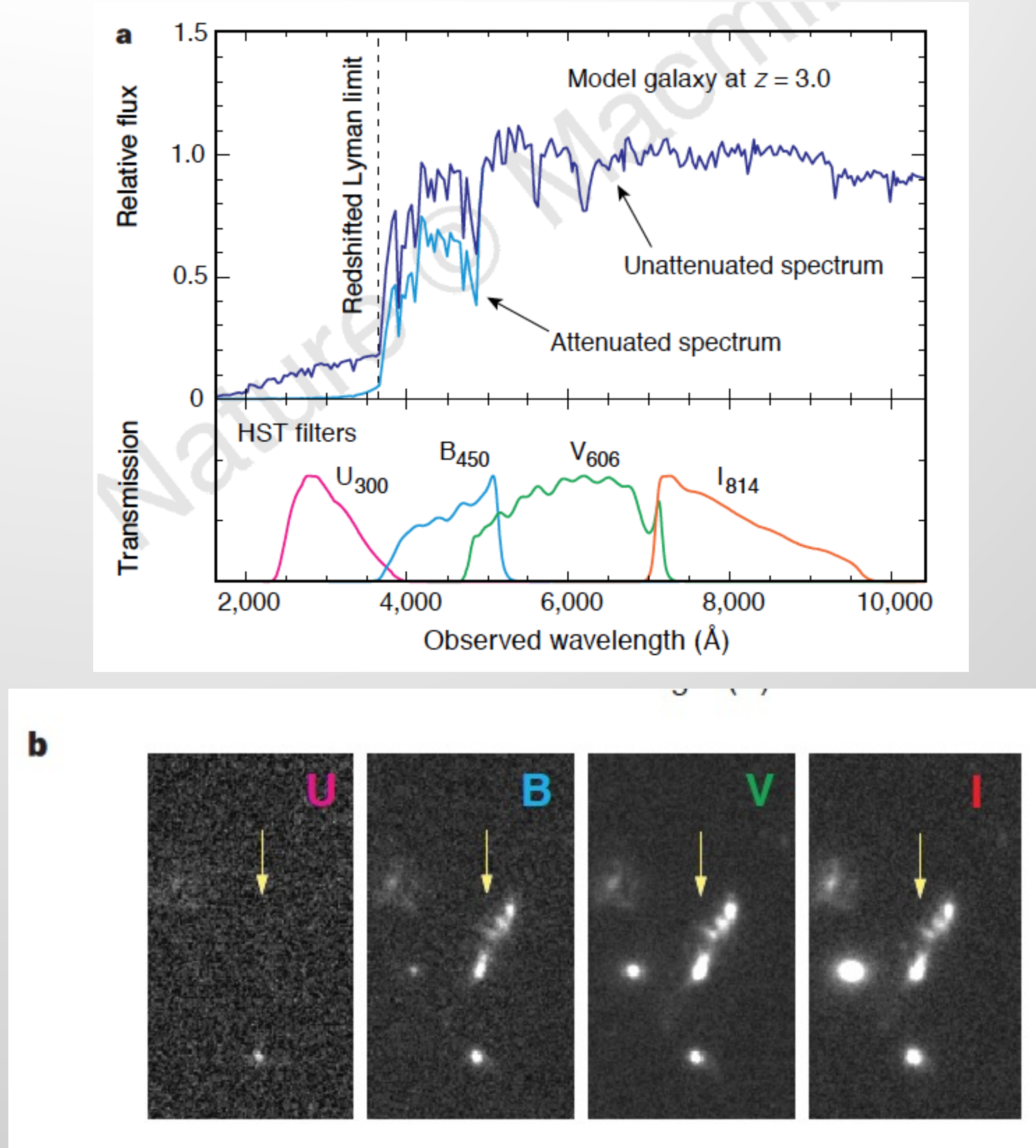
Emission lines are an easy way to determine redshifts. Redshifted in the NIR by z~1. But not all galaxies have emission lines. More importantly, need a way to **pre-select** spectroscopic targets.

Finding (pre-selecting) high z galaxies

Continuum breaks, e.g. the Lyman Break Galaxy (LBG) technique, AKA “dropouts”.

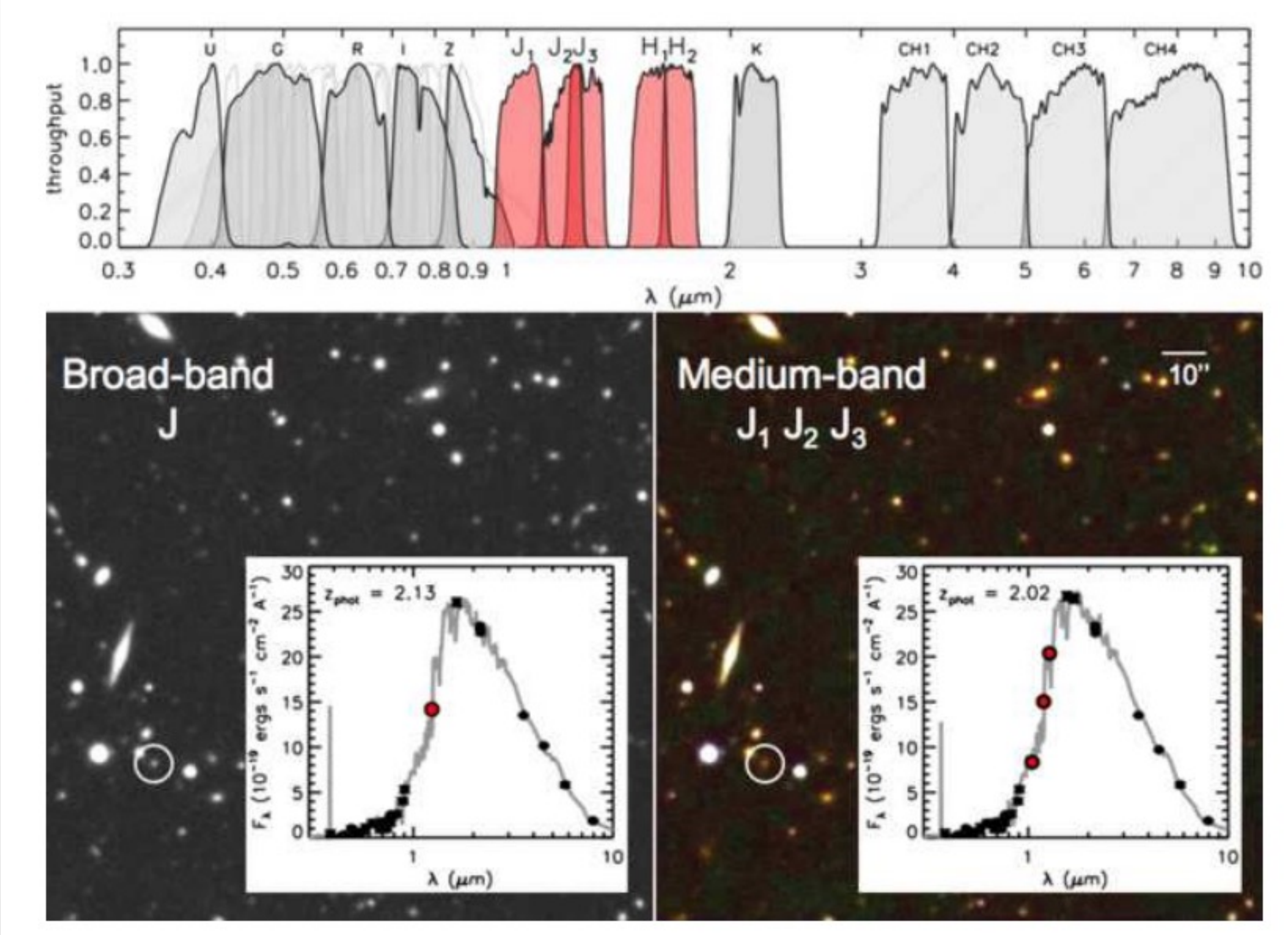
Galaxies “dropout” in progressively redder filters towards higher z. Good method for finding high z candidates, but doesn’t give a redshift.

Jargon alert: Lyman break = 912 A. Bluer emission is largely absorbed by neutral hydrogen.



Ellis (1996)

Finding (pre-selecting) high z galaxies

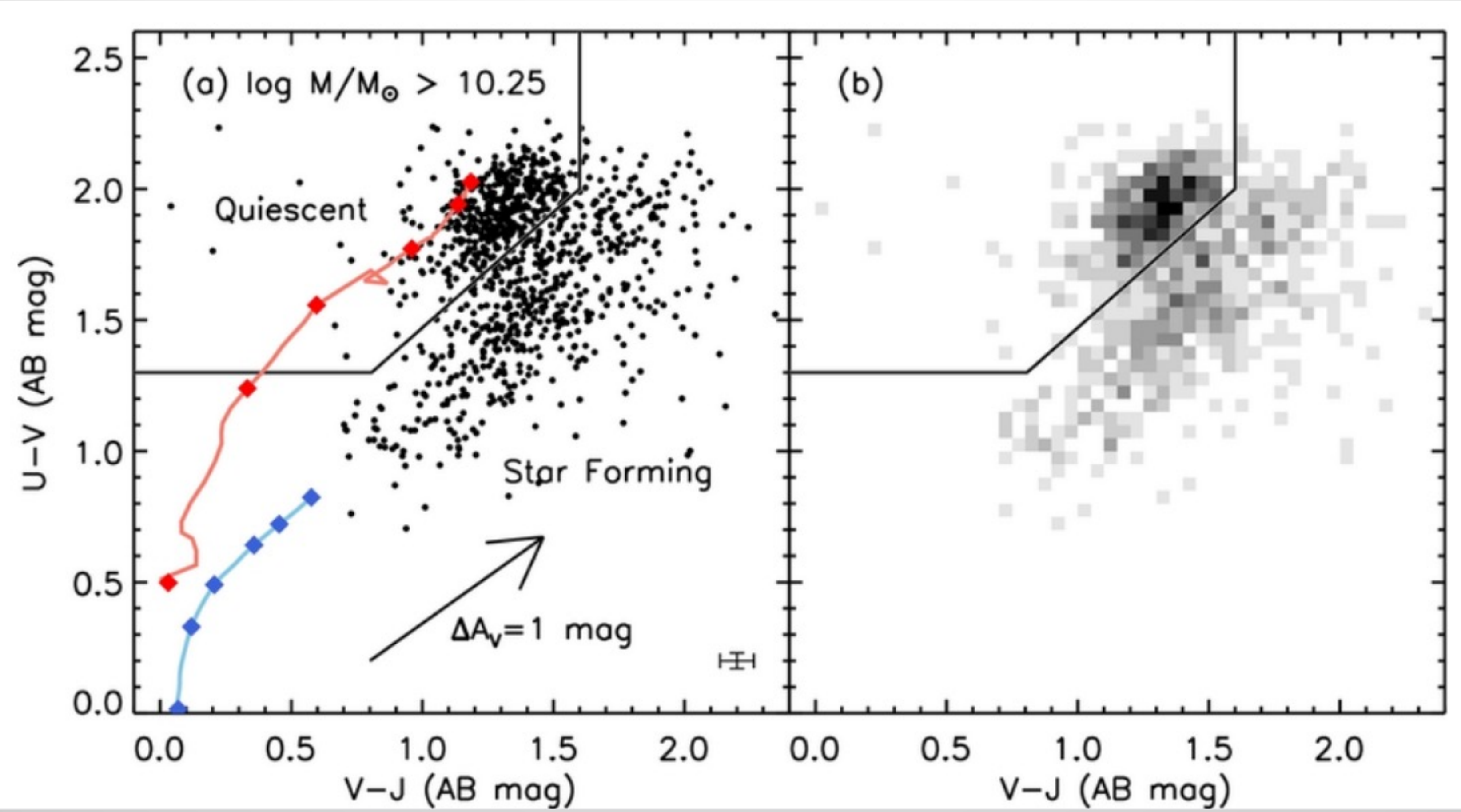


Photometric redshifts, e.g. COSMOS. IR is critical for spanning the 4000 A break.

Whitaker et al. (2011)

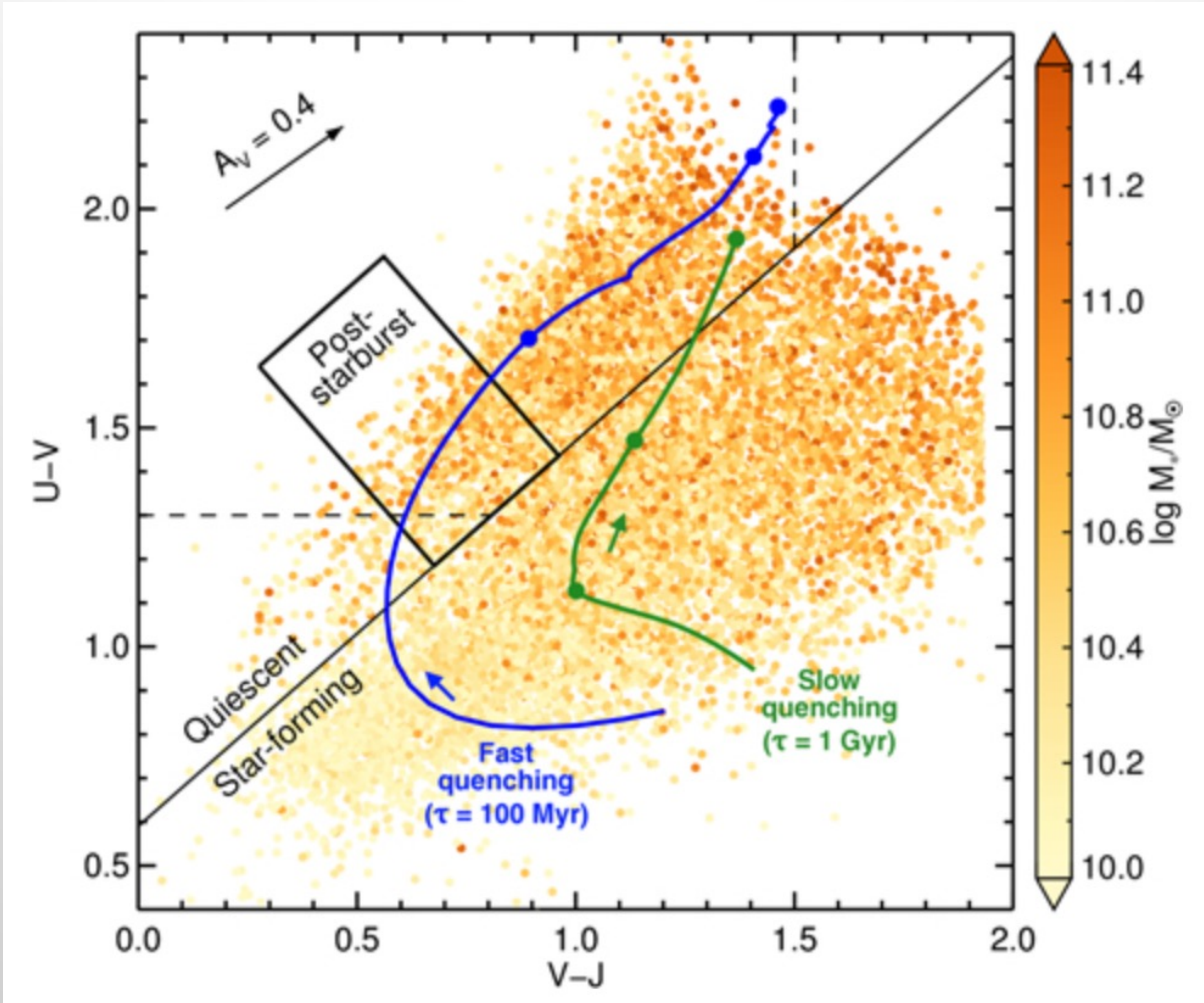
Aside/Jargon alert: The UVJ diagram – another pre-selection tool

This colour-colour diagram is a tool used to separate quiescent from star-forming galaxies



Patel et al. (2011)

The UVJ diagram can also be used to pre-select post-starburst galaxies.

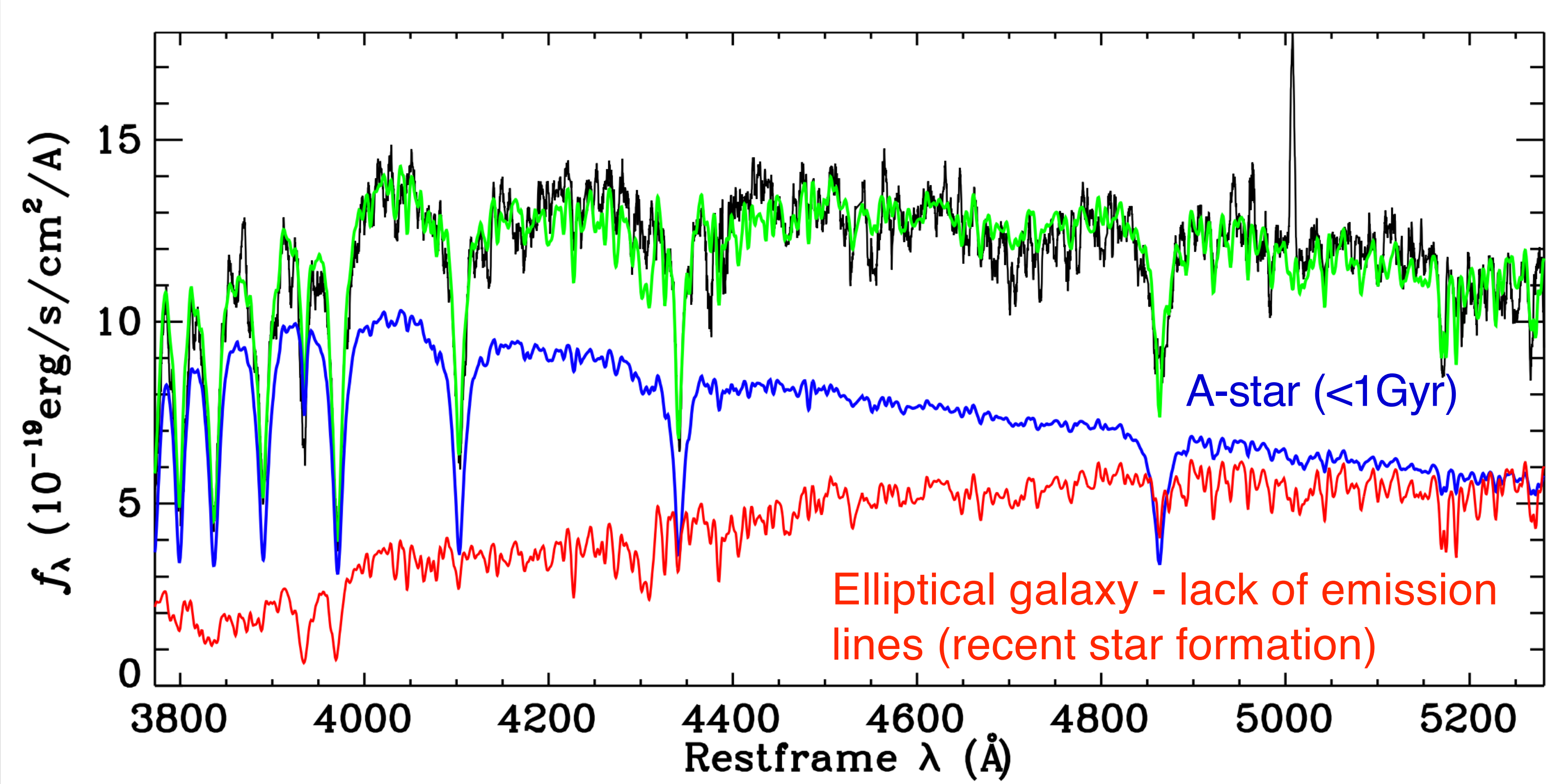


Belli et al. (2019)

Post-starburst galaxies

Jargon alert: Post-starburst (PSB) = E+A = K+A

Galaxies with no strong emission line (K-star, or elliptical galaxy like spectrum), but strong Balmer absorption (A-stars).

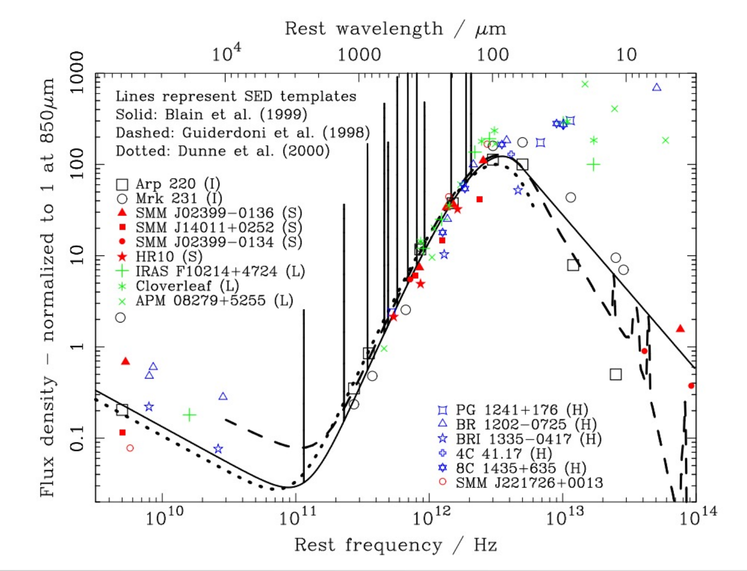


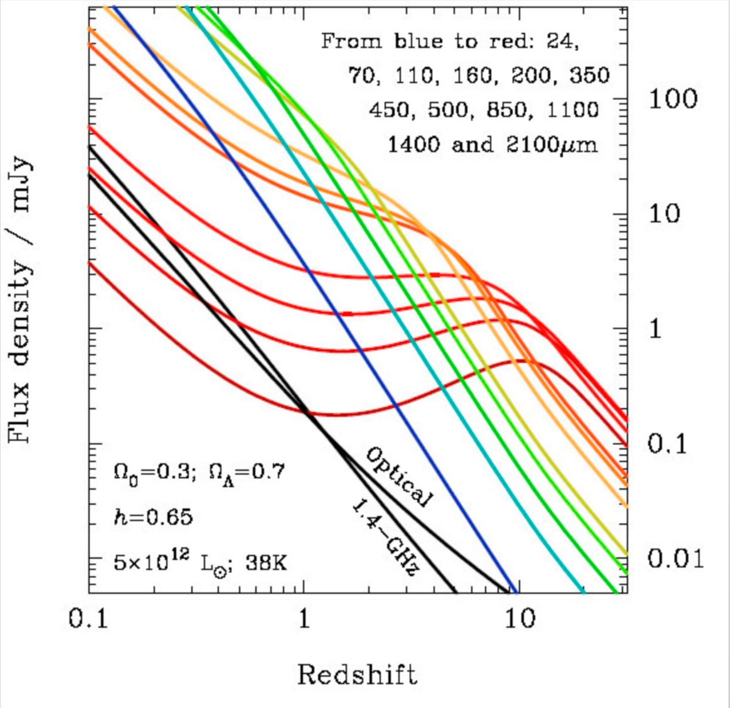
Yan et al. (2009)

Sub-mm galaxies

In addition to the LBG technique, the early 2000s saw another z~2 population discovered: sub-mm galaxies, AKA SMGs.

Rather than tracing rest-frame optical (stellar) light, the thermal dust can be used to identify high z sources.



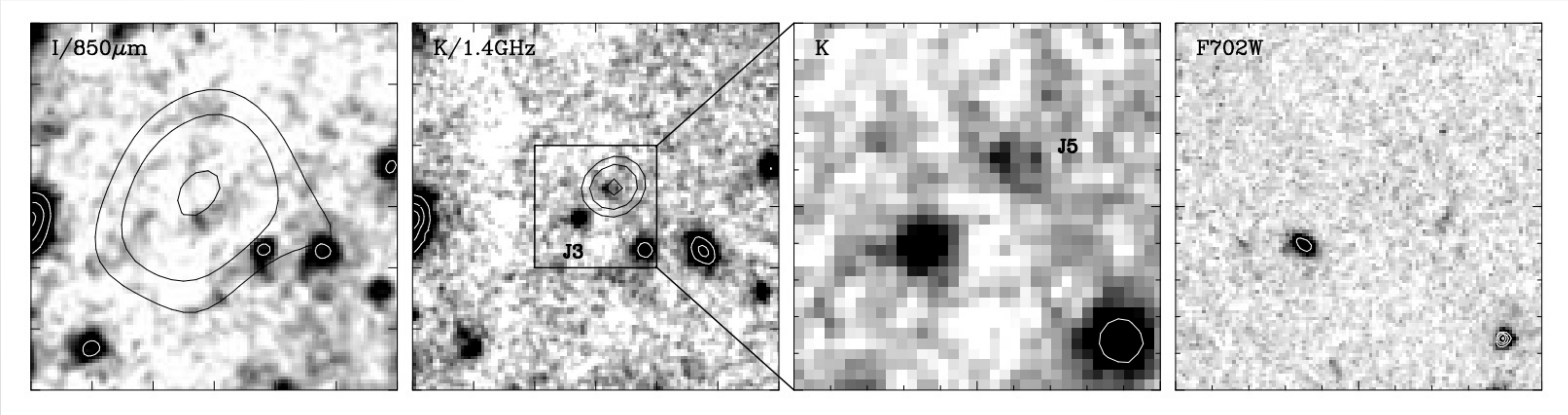


Jargon alert: negative k-correction.

Blain et al. (2002)

In the radio, galaxies get brighter at higher redshifts!

Sub-mm galaxies

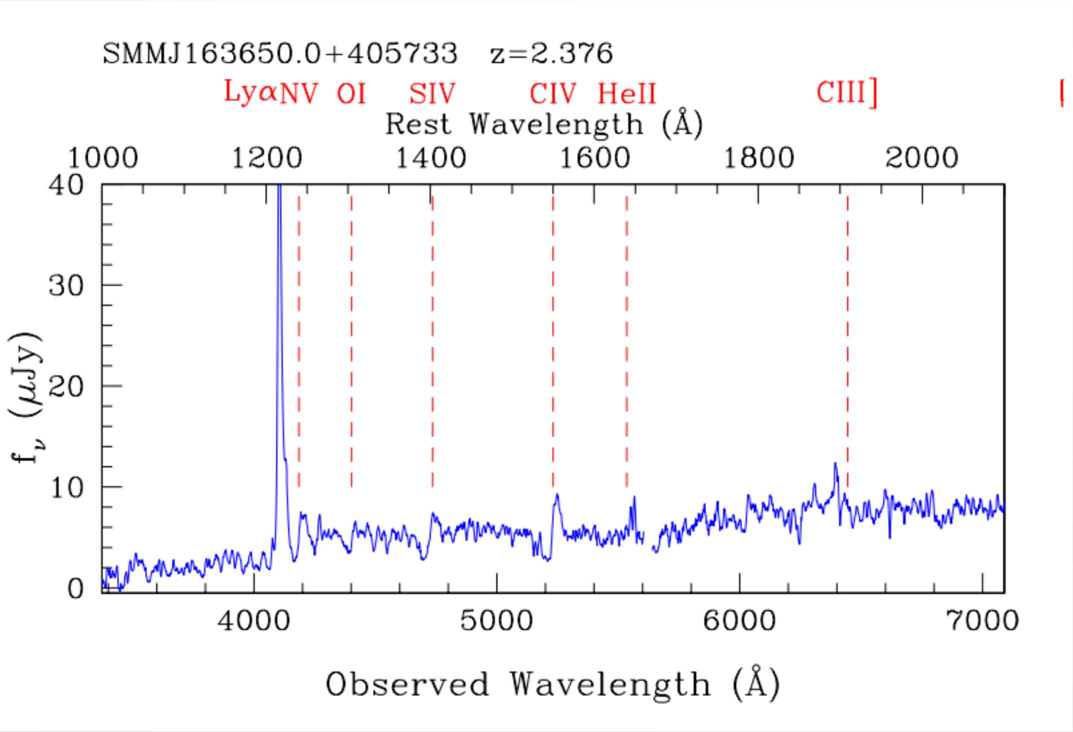


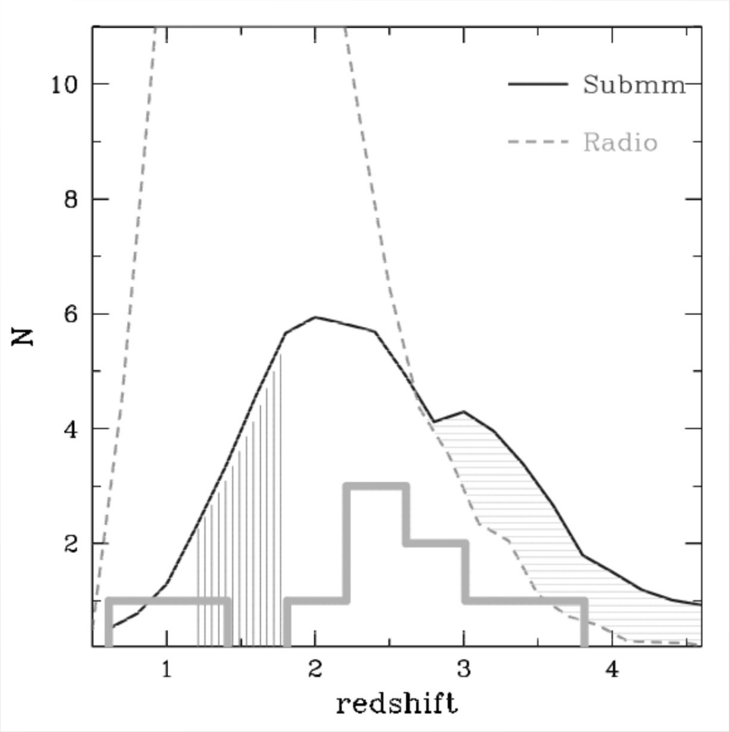
Blain et al. (2002)

Work with the SCUBA-2 instrument on JCMT made a big splash with discoveries of very bright objects at 850 microns. But the 15” beam made target identification a problem.

Follow-up with radio (1” accuracy) and near-IR. Objects still often invisible in the optical!

Sub-mm galaxies

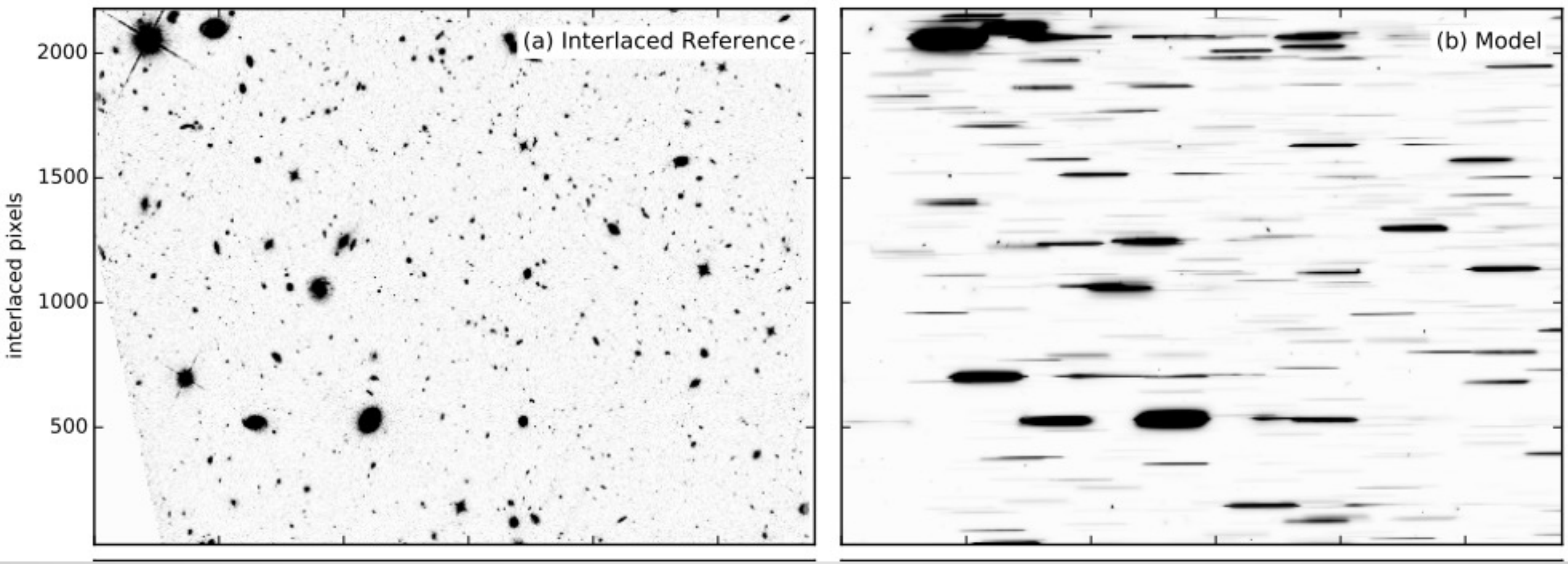




Radio positions used to do “blind” optical spectroscopy with Keck to get redshifts.
Most are at cosmic noon.

Chapman et al., Nature (2003)

Or don't pre-select at all…

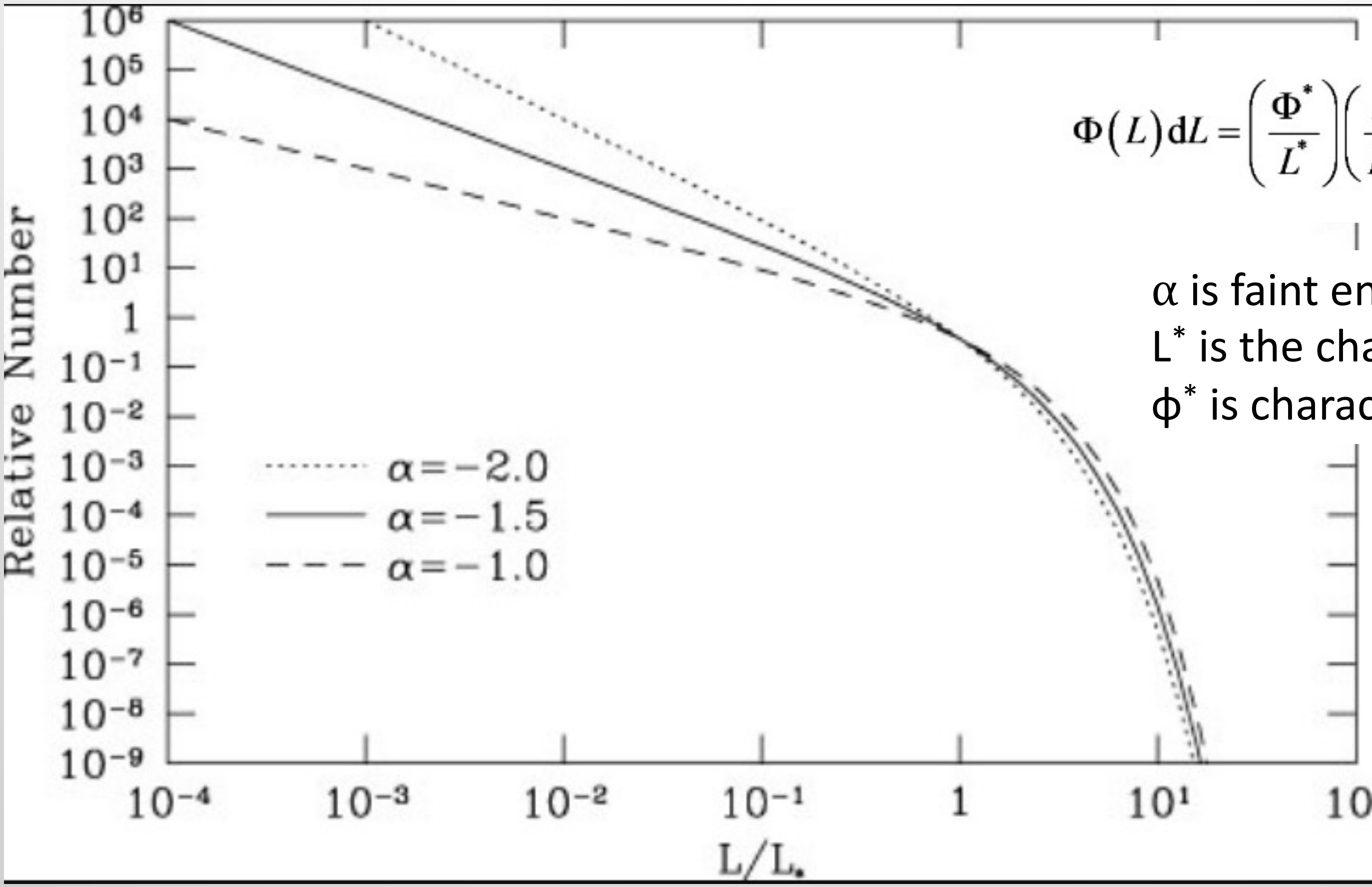


Momcheva et al. (2016)

And just take a spectrum of everything!!

Spectroscopic redshifts, e.g. 3D-HST. Emission line galaxies much easier than quiescent galaxies (continuum only).

Characterizing the luminosity (or mass) distribution



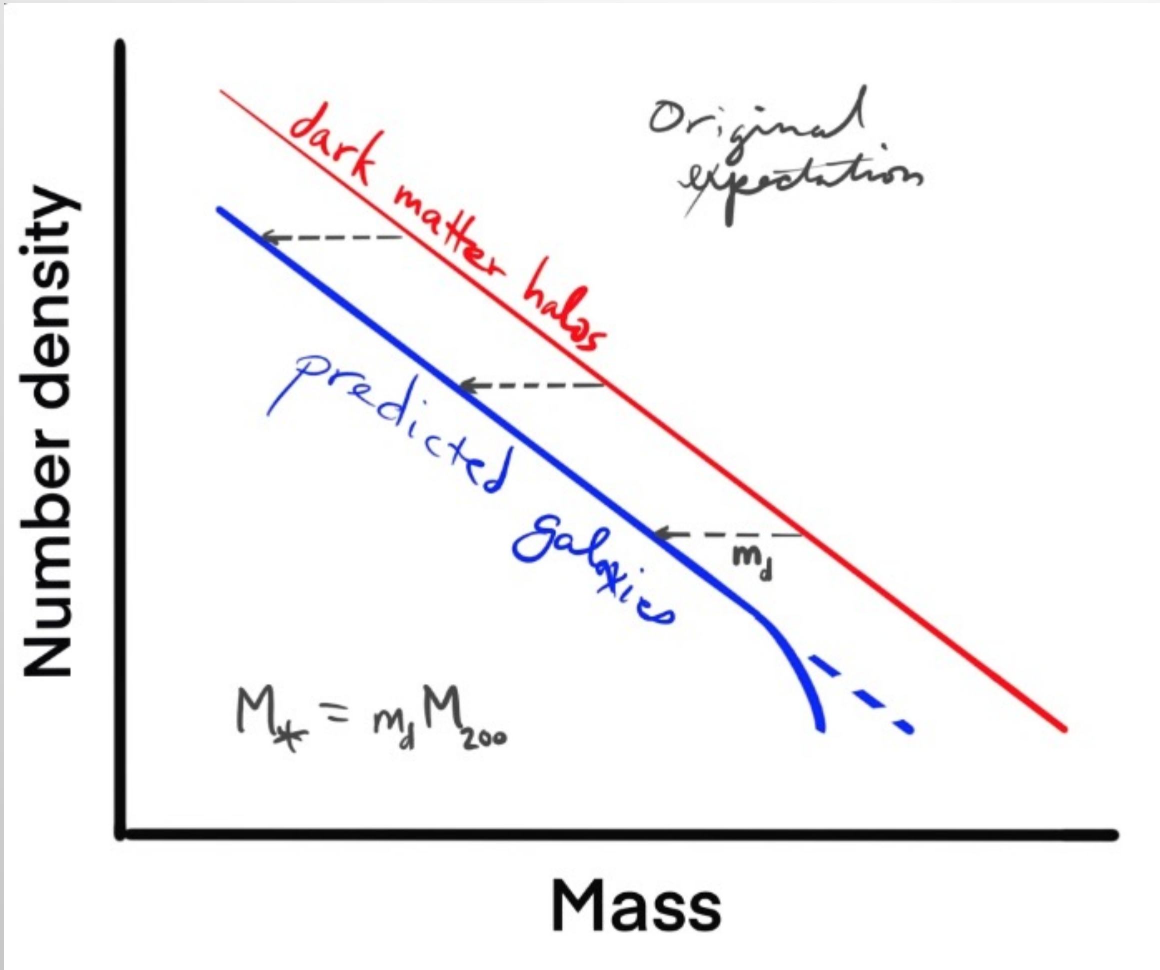
$$\Phi(L)\mathrm{d}L = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)\mathrm{d}L,$$

α is faint end (power law) slope
L^* is the characteristic luminosity
ϕ^* is characteristic density

The luminosity function quantifies the number of galaxies per unit luminosity. Often characterized with a Gaussian plus power law, referred to as a Schechter function. The "knee" of this distribution (transition between Gaussian and power law) is characterized by L^*. Galaxy luminosity often quoted in L* units (convenient because the Milky Way is an approximately L^* galaxy.

From light to stellar mass to halo mass

We have already seen how a galaxy's M_* is estimate from light (assuming stellar populations). Many theoretical predictions though are based on a total halo mass. How can we relate a halo mass to a stellar mass? Jargon alert: abundance matching



Jargon alert: Virial radius. The radius at which the density of a halo reaches some factor (often x200) of the critical density of the universe. E.g. expressed as r_{200}.

Virial mass: mass within the virial radius, e.g. M_{200}.

$$M_{200} = \frac{4}{3}\pi r_{200}^3 200\rho_c$$

From light to stellar mass to halo mass

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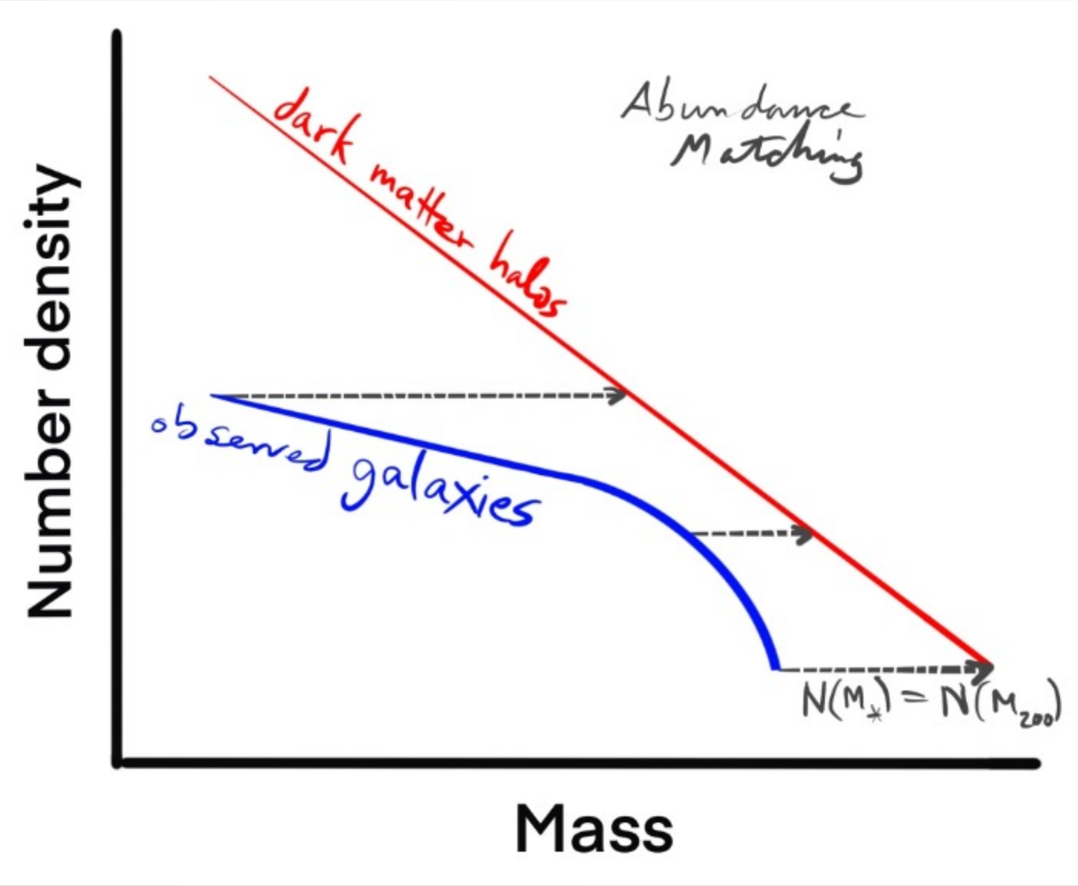
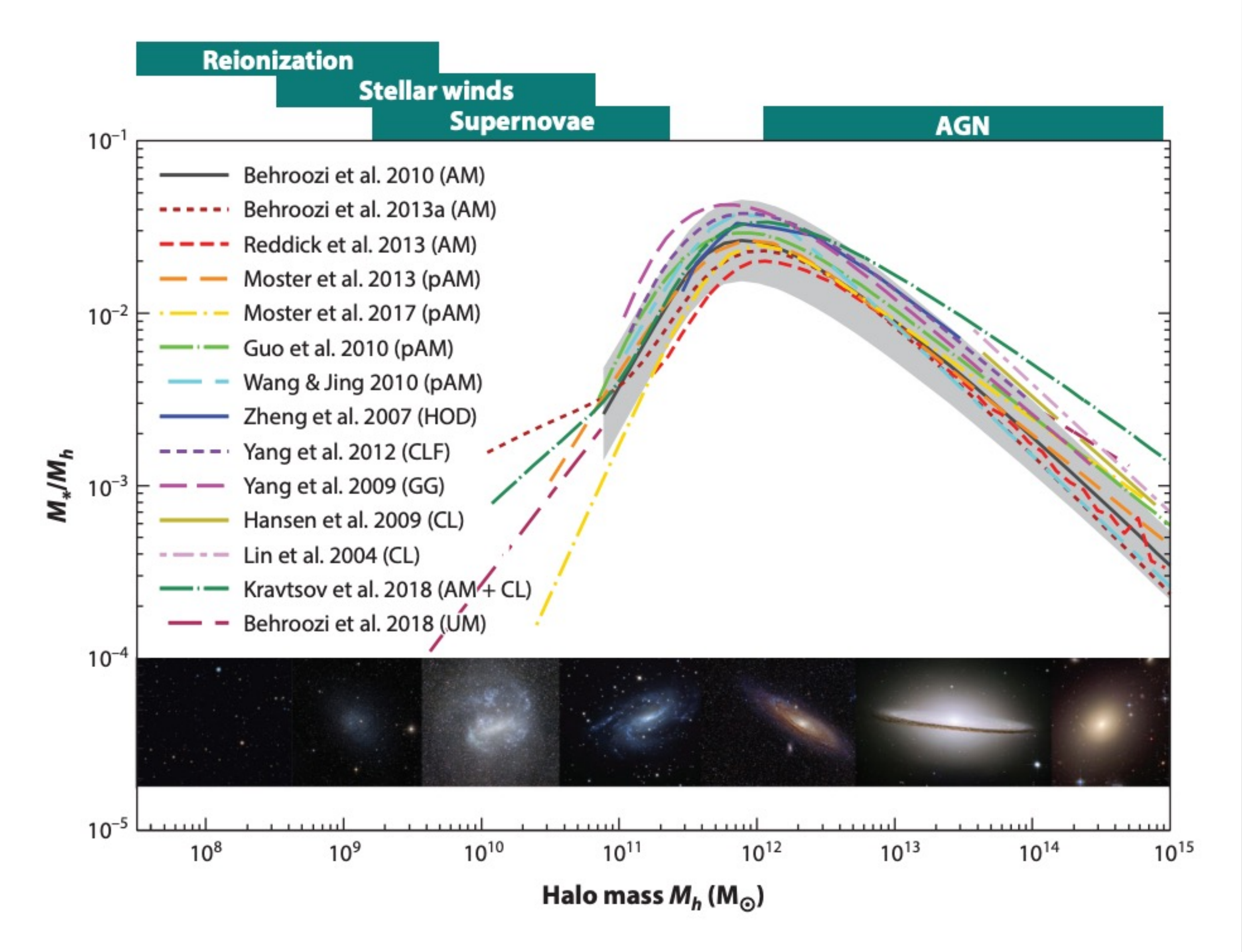


In practice, the observed galaxy luminosity function is not simply a down-shifted version of the halo mass function.

Jargon alert: overcooling problem or missing satellites problem.

From light to stellar mass to halo mass



Jargon alert: stellar halo mass relation (SHMR). See ARA&A by Wechsler & Tinker 2018 on the connection between galaxies and their dark matter halos.

Characterizing galaxy structure

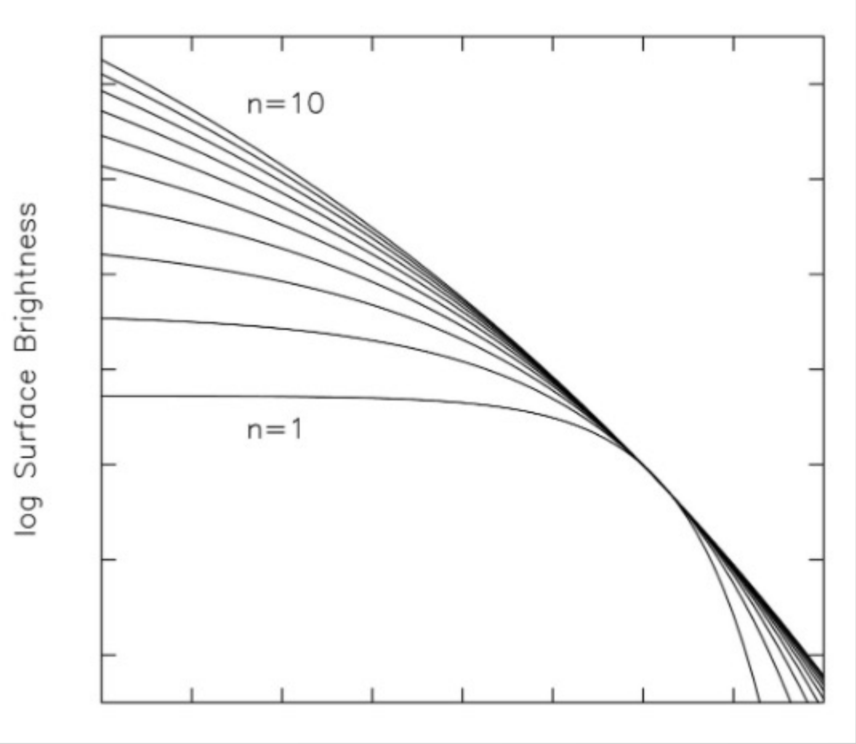
- R_e effective radius. The radius that contains have of the light.
- R_d disk scale length. For an exponential profile $R_e = 1.68\ R_d$.
- b/a axial ratio.
- $R_{e,circ}$ the circularized effective radius. R_e * sqrt(b/a).

Jargon alert: Sersic profile. Describes the light profile.

$$I(R) = I_e \exp\left\{-b_n\left[\left(\frac{R}{R_e}\right)^{1/n} - 1\right]\right\}$$

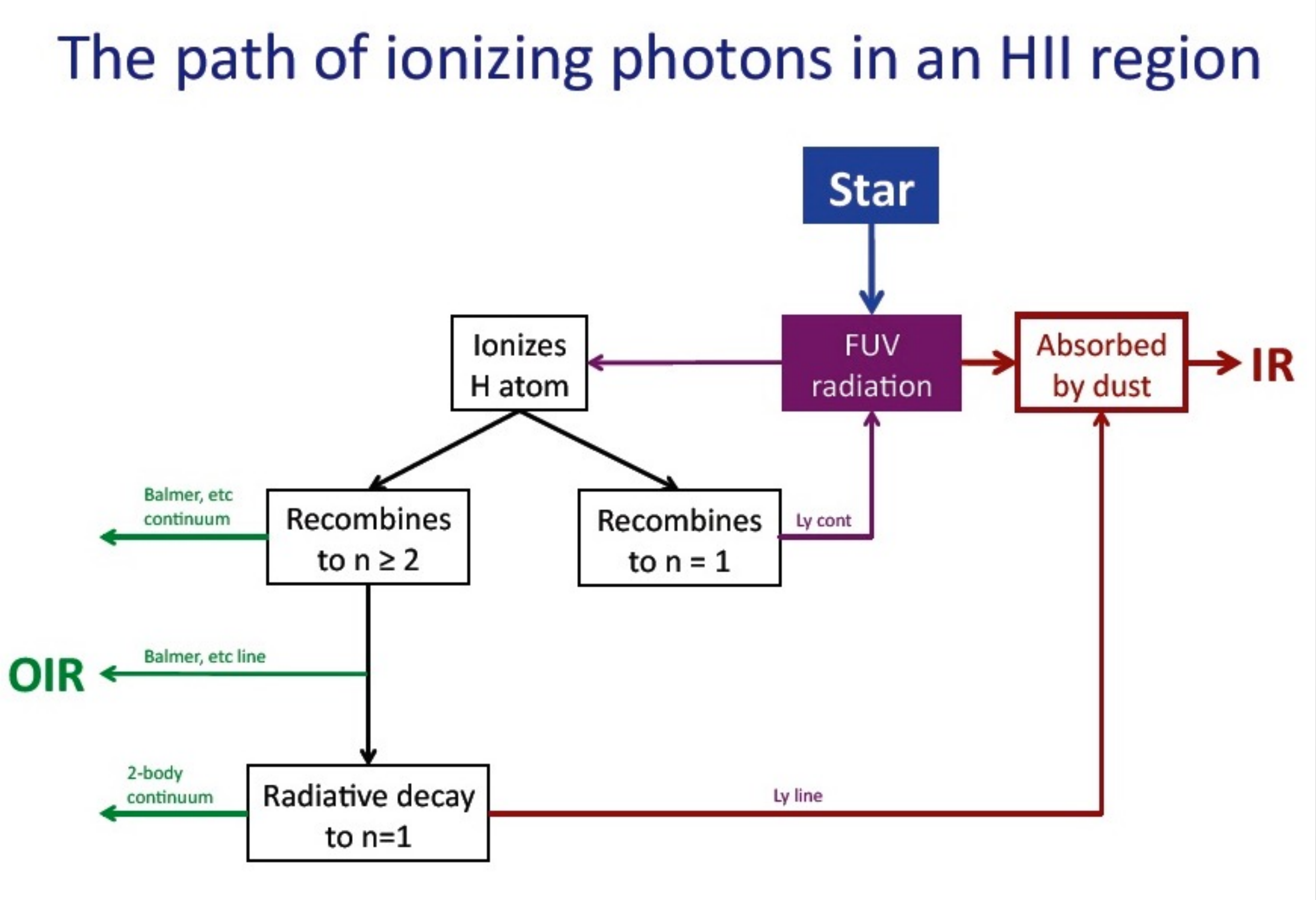
Where I_e is the intensity at R_e and b_n is a scaling such that half of the light occurs within R_e for a given index n. Most galaxies have $0.5 < n < 10$.

Exponential (disk) profile: n=1, b_n=1.68
De Vaucouleurs (elliptical): n=4, b_n=7.67



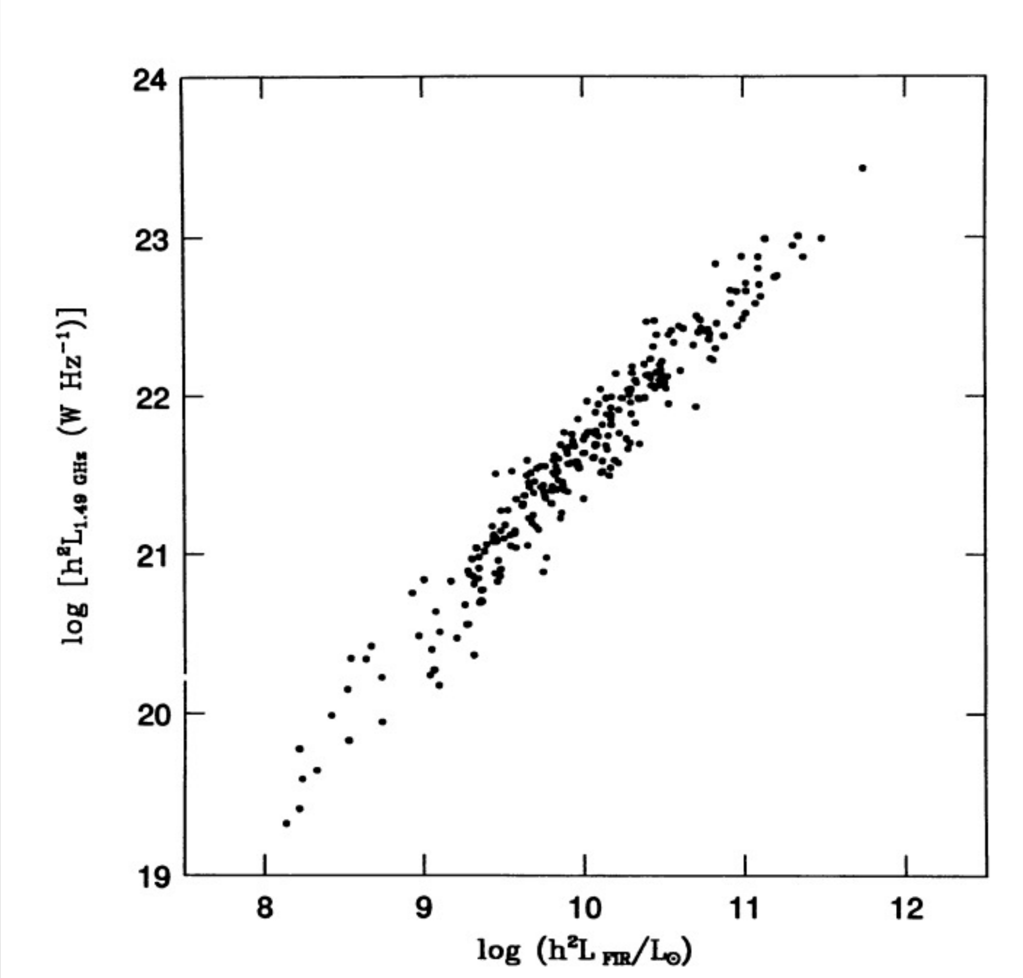
How to measure star formation rates?

Various indicators in the UV, optical and IR, related to emission of ionizing radiation and dust heating.



How to measure star formation rates?

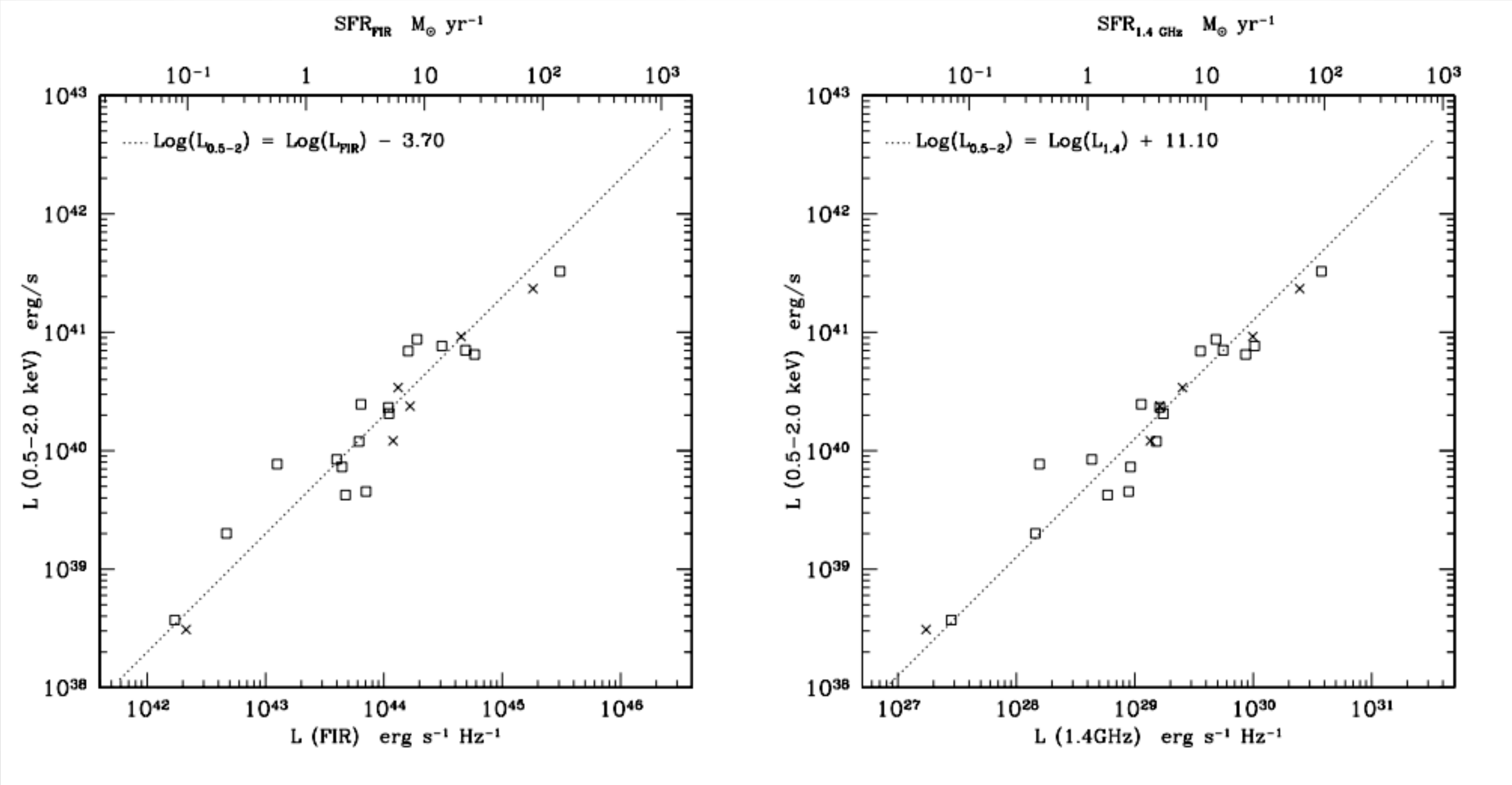
The radio-Far-IR relation motivates 1.4 GHz (from SN remnants) as a SFR indicator.



Condon (1992)

How to measure star formation rates?

X-ray emission from X-ray binaries.



Ranalli et al (2003)

How to measure star formation rates?

$$\log \dot{M}_*(\mathrm{M}_\odot\ \mathrm{yr}^{-1}) = \log L_x - \log C_x$$

Scaling between Salpeter and Kroupa IMFs

UV+IR often combined

TABLE 1
STAR FORMATION RATE CALIBRATIONS

Band	Age Range (Myr)[a]	L_x Units	$\log C_x$	$\dot{M}_\star/\dot{M}_\star$(K98)	References
FUV	0 – 10 – 100	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	43.35	0.63	1, 2
NUV	0 – 10 – 200	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	43.17	0.64	1, 2
Hα	0 – 3 – 10	$\mathrm{ergs\,s^{-1}}$	41.27	0.68	1, 2
TIR	0 – 5 – 100[b]	$\mathrm{ergs\,s^{-1}}$ (3–1100 μm)	43.41	0.86	1, 2
24 μm	0 – 5 – 100[b]	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	42.69		3
70 μm	0 – 5 – 100[b]	$\mathrm{ergs\,s^{-1}}$ (νL_ν)	43.23		4
1.4 GHz	0 – 100 :	$\mathrm{ergs\,s^{-1}\,Hz^{-1}}$	28.20		1
2–10 keV	0 – 100 :	$\mathrm{ergs\,s^{-1}}$	39.77	0.86	5

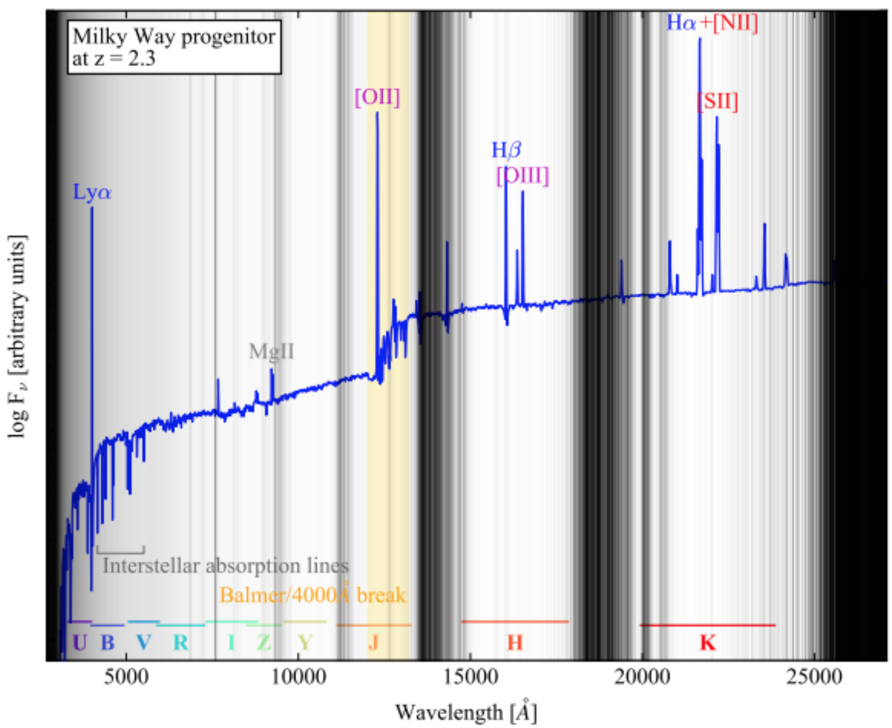
NOTE. — References: (1) Murphy et al. (2011); (2) Hao et al. (2011); (3) Rieke et al. (2009); (4) Calzetti et al. (2010a); (5) Ranalli et al. (2003)

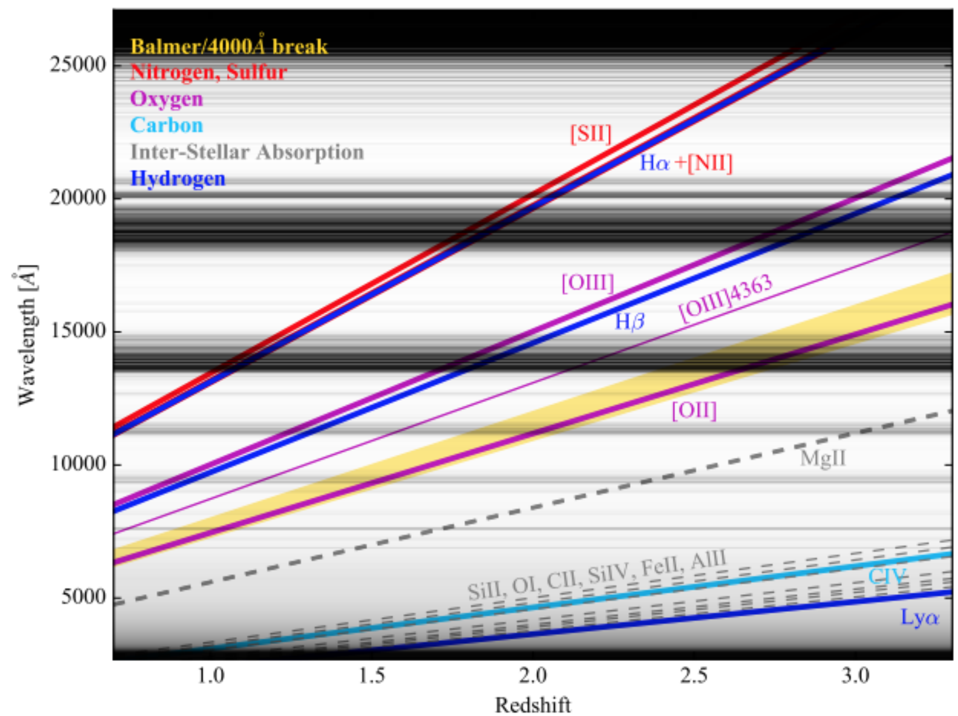
Only stars above about 20 solar masses (O and B) produce significant ionizing flux. Such massive stars have short lives, hence Hα measures a SFR on a very short timescale. UV radiation additionally comes from A stars, so longer timescale.

Kennicutt & Evans (2012)

Star formation rate indicators at high z

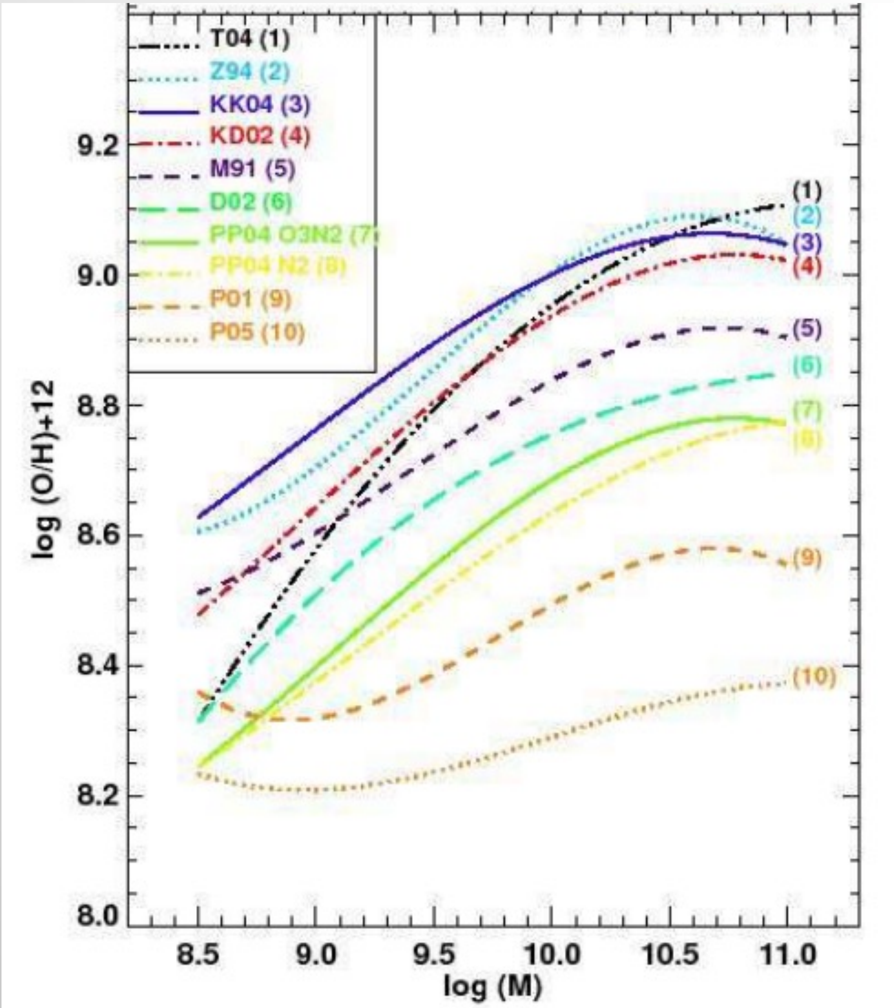
Many “standard” SFR calibrators (plus metallicity, temperature and density dependent lines) shift into the IR. High redshift work depends critically on IR access.





Forster-Schreiber & Wuyts (2020)

Additional complications with high z measurements



Metallicity calibrations can vary by almost 1 dex.

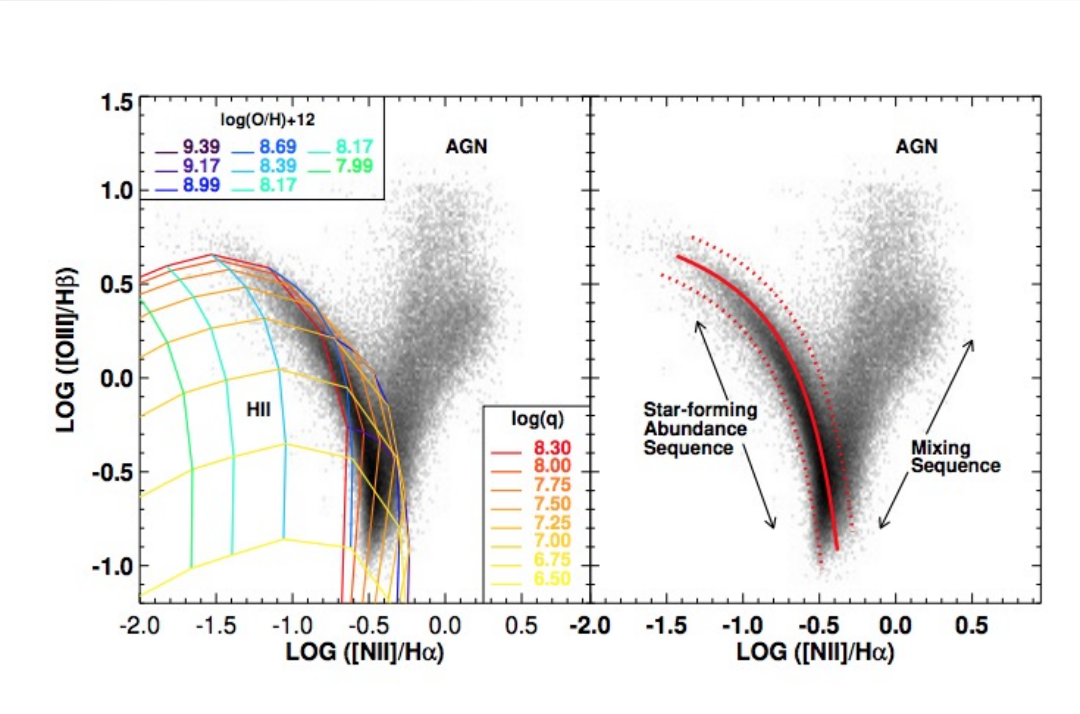
At high z, different sets of lines available, so have to worry about cross calibration.

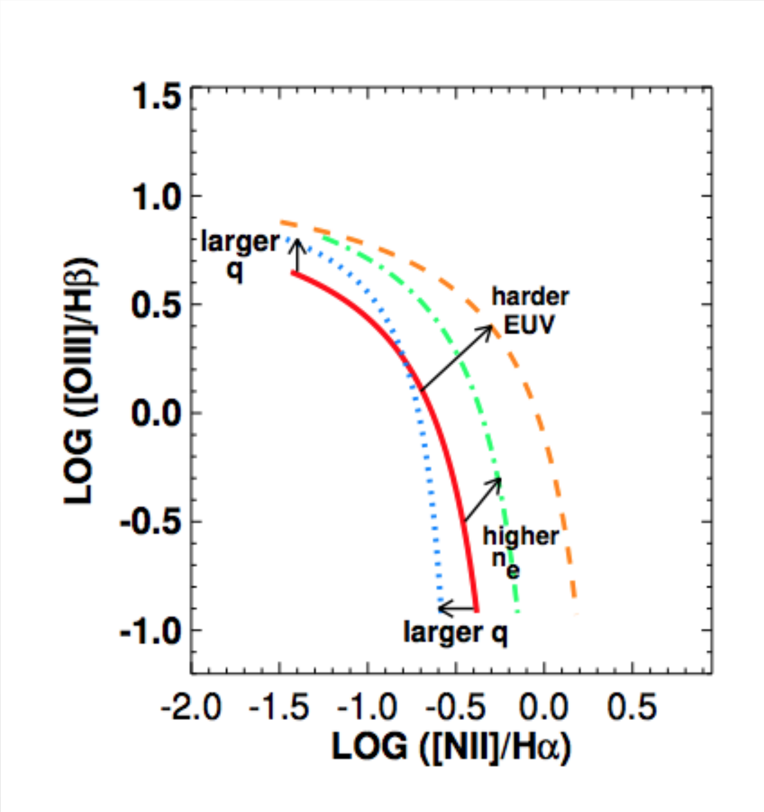
Jargon alert: dex = decade, i.e. unity in log space.
0.3 dex = factor 2
0.5 dex = factor 3

Kewley & Ellison (2008)

Additional complications with high z measurements

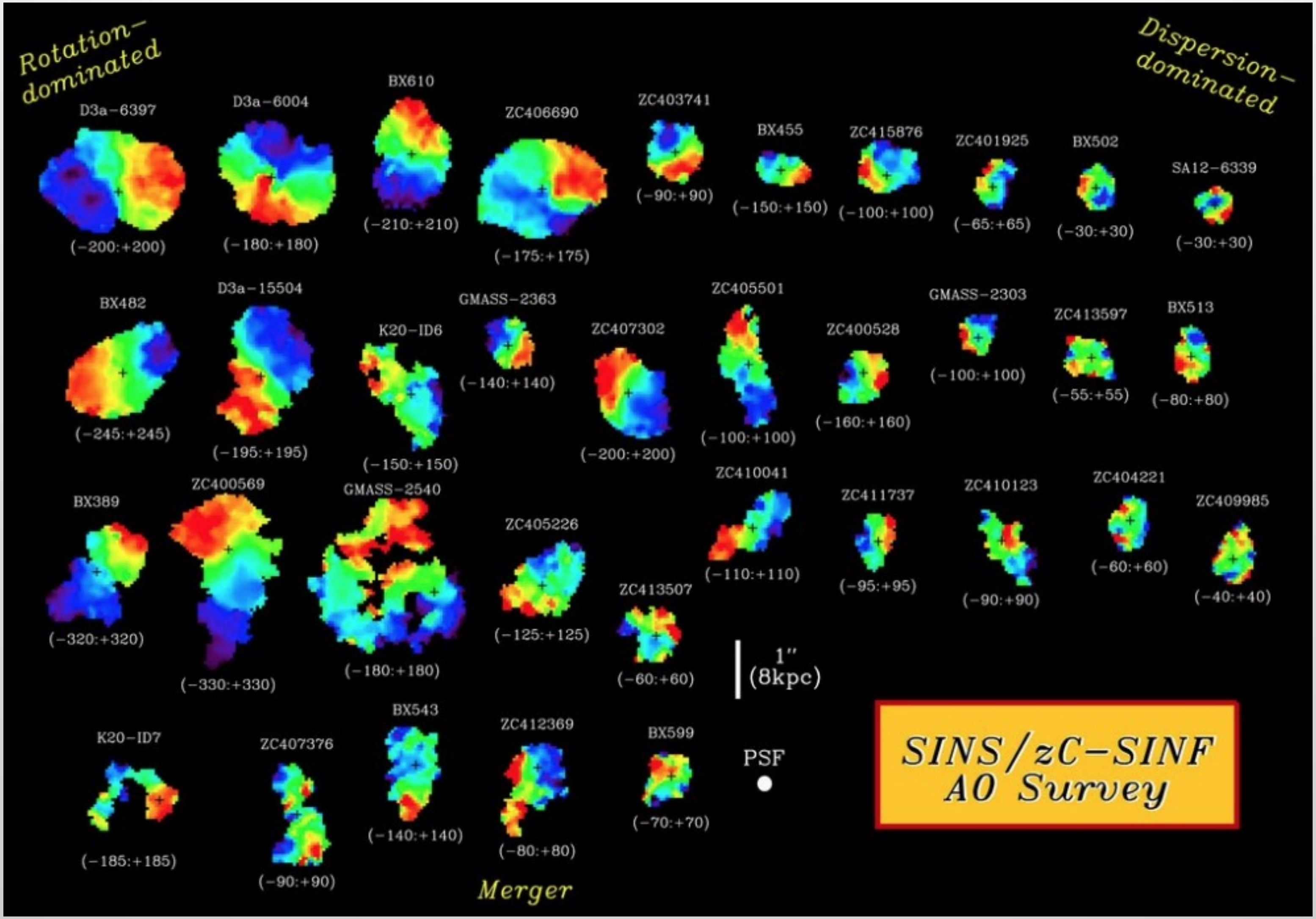
BPT (AGN) diagnostic diagrams may also need revision.





Kewley et al. (2019)

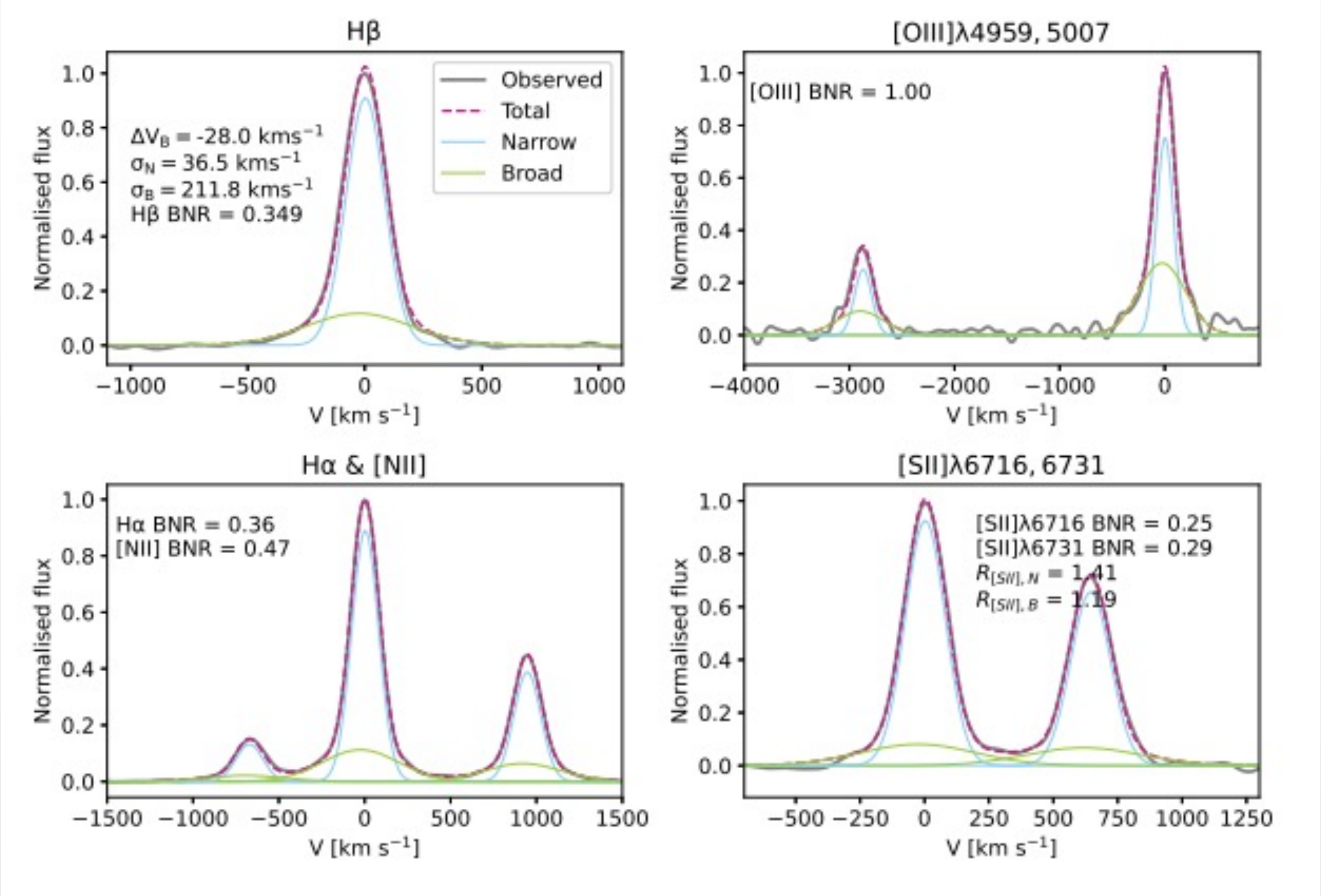
Characterizing kinematics



IFU surveys at high z in the Infra-red (with adaptive optics)

Searching for outflows

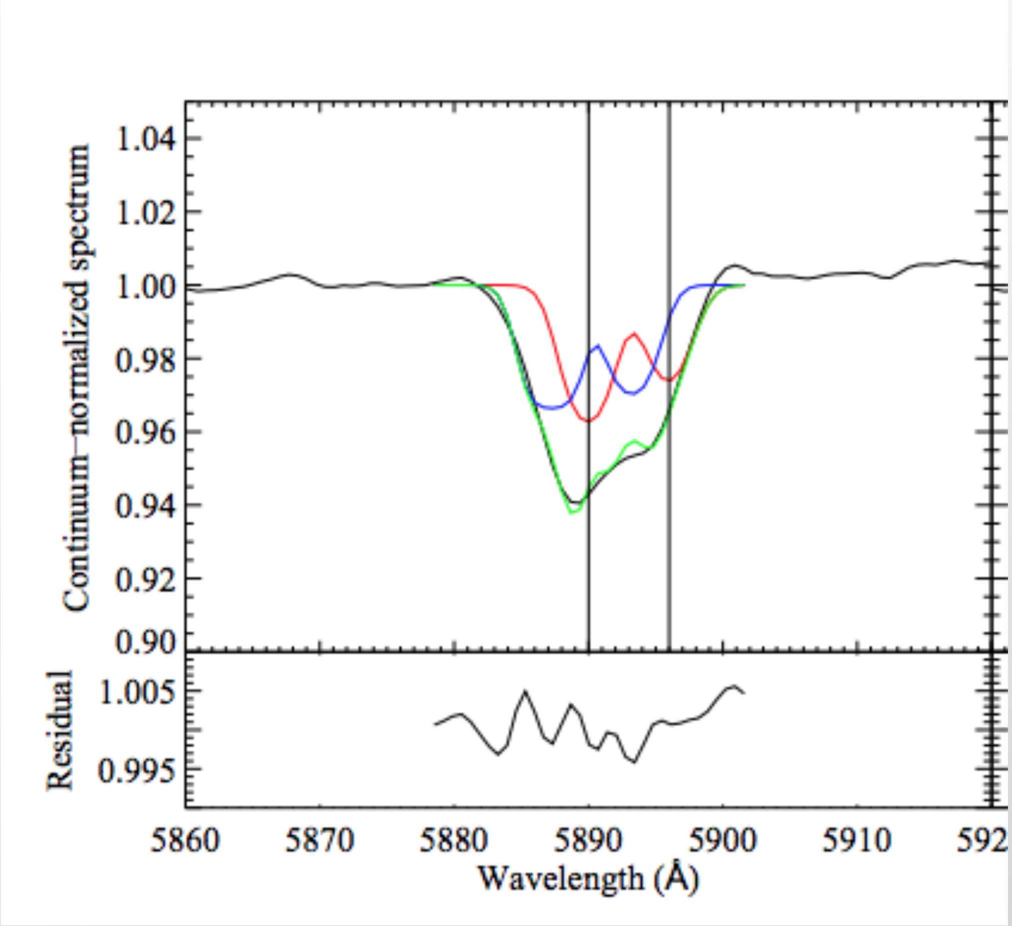
Method 1: Ionized outflows. Multiple Gaussians fit to emission lines.



Avery et al. (2021)

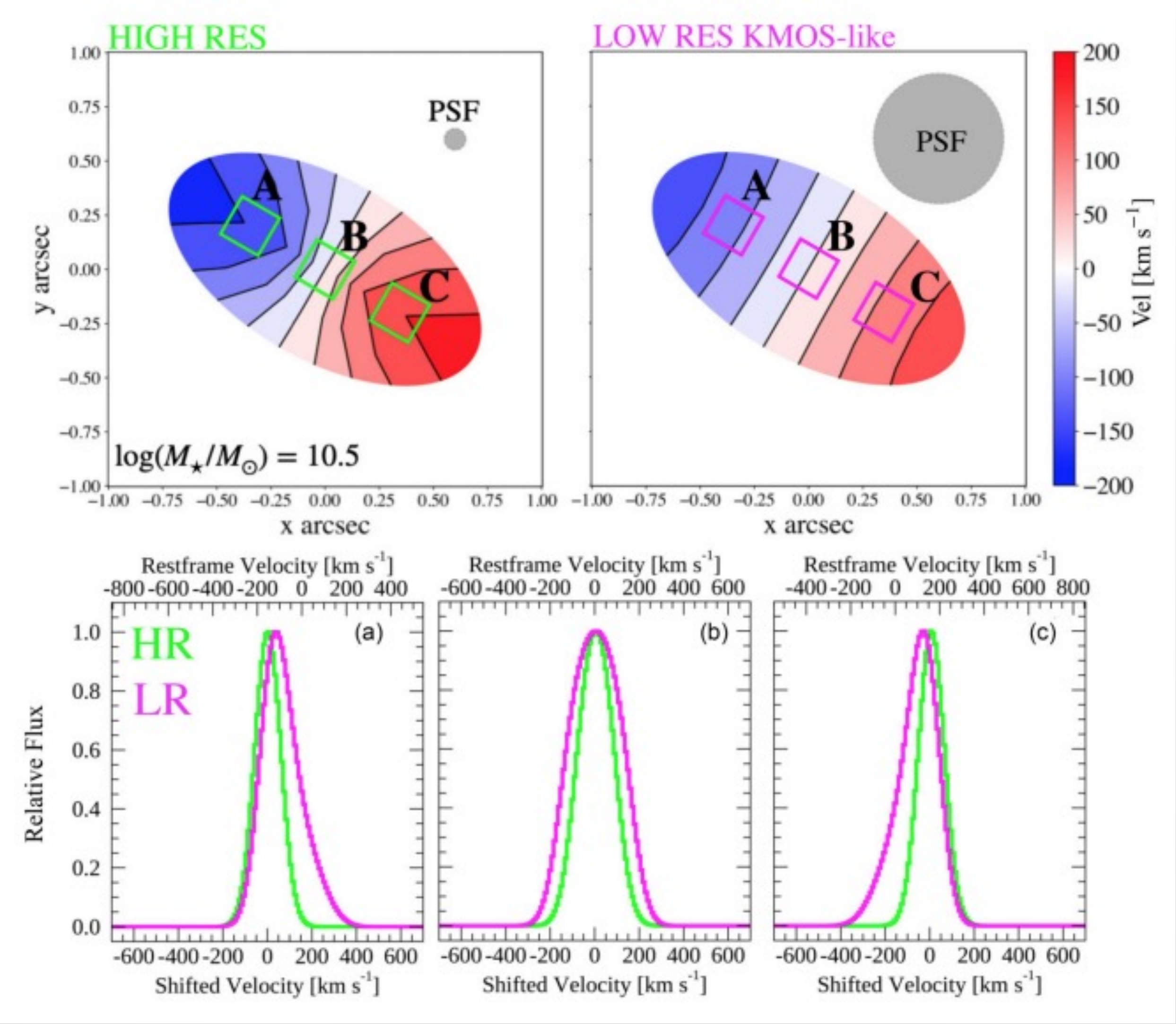
Searching for outflows

Method 2: neutral gas outflows. Multiple components fit to NaI (doublet) absorption.



Chen et al. (2010)

Beware beam smearing!



Concas et al. (2022)

Beam smearing can give the impression of additional components.

Summary

- Finding high z galaxies in a targeted way is usually approached with some kind of pre-selection, often using broad band optical and NIR colours.
- The Lyman break technique and the use of sub-mm detections revolutionized our ability to detect z~2 galaxies in the late 1990s and early 2000s.
- Spectroscopy is required for accurate redshifts.
- Spectroscopy also allows the measurement of physical properties, such as SFR, metallicity, detection of winds, PSB features etc (although many properties can also be inferred from photometry alone).