The Redshift Problem in Cosmology

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Dedale Tutorial Day

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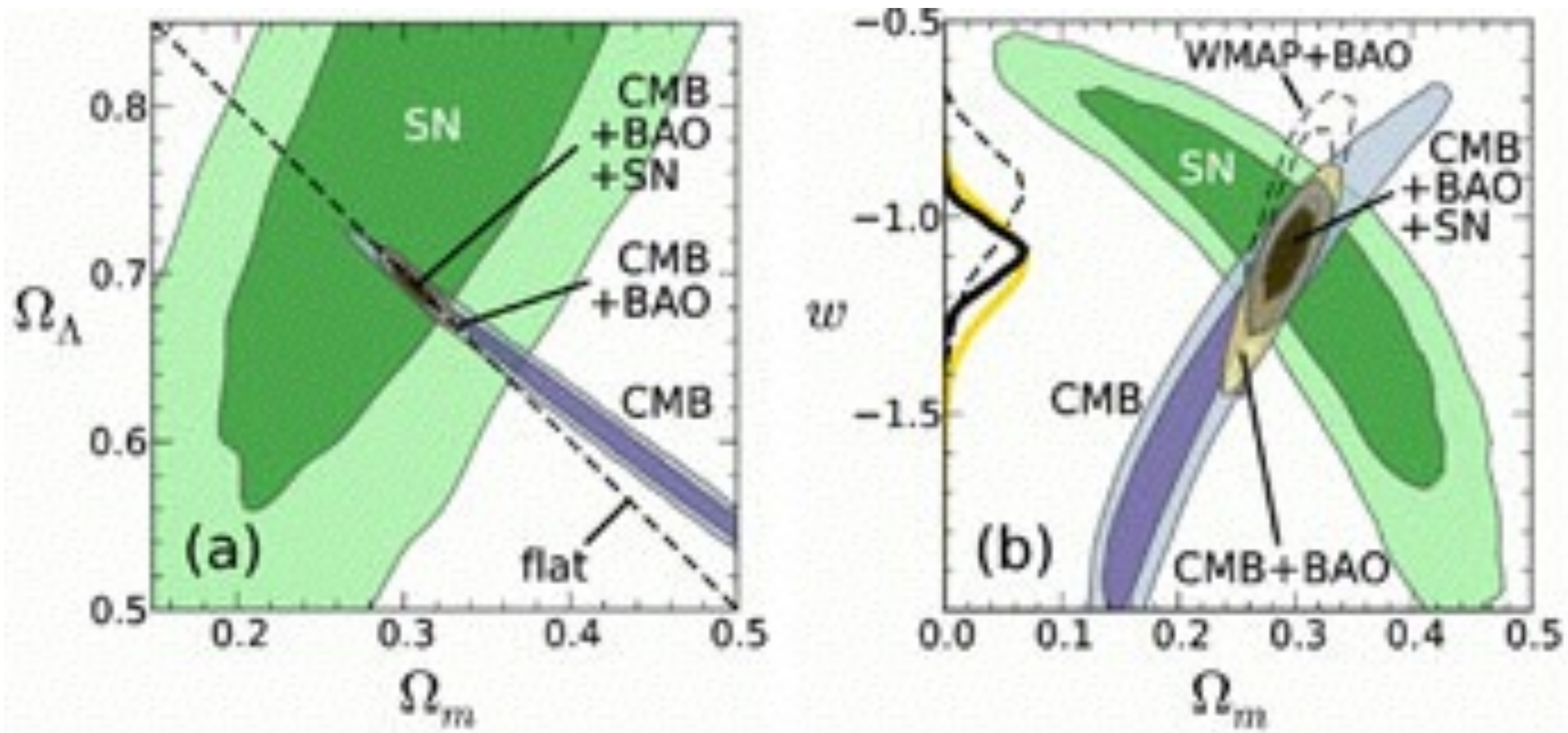
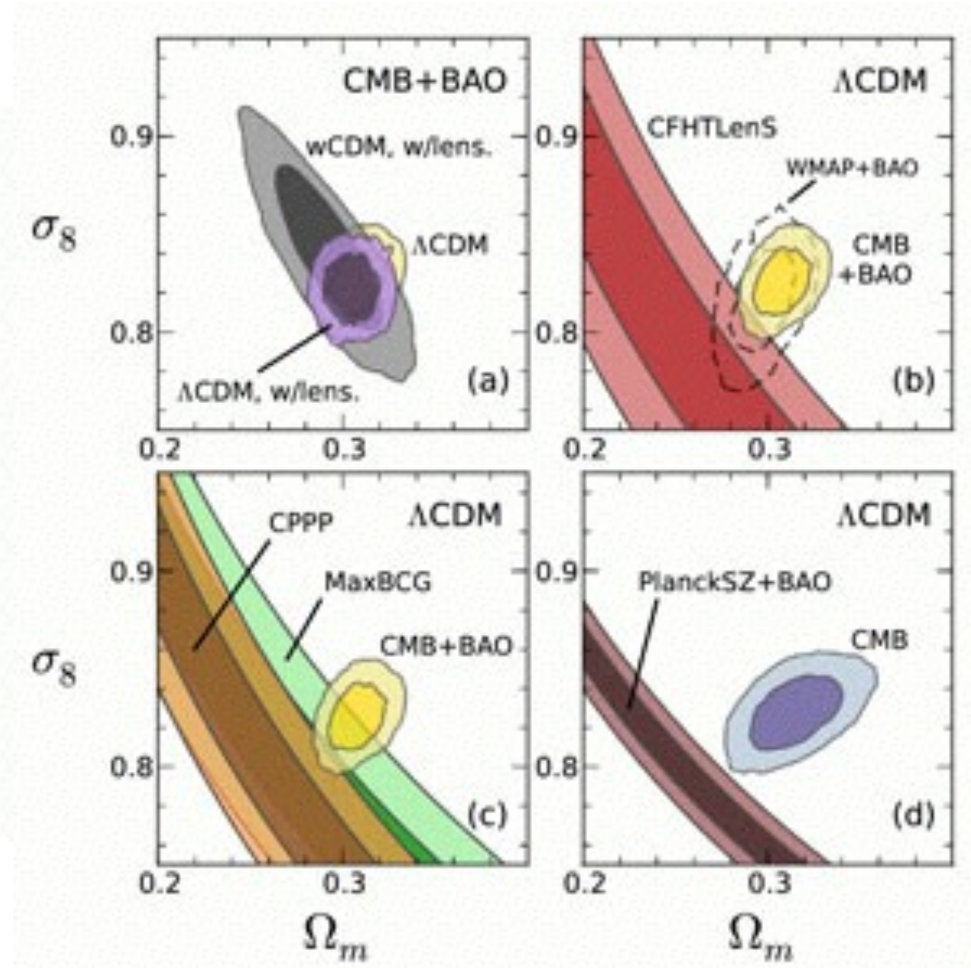
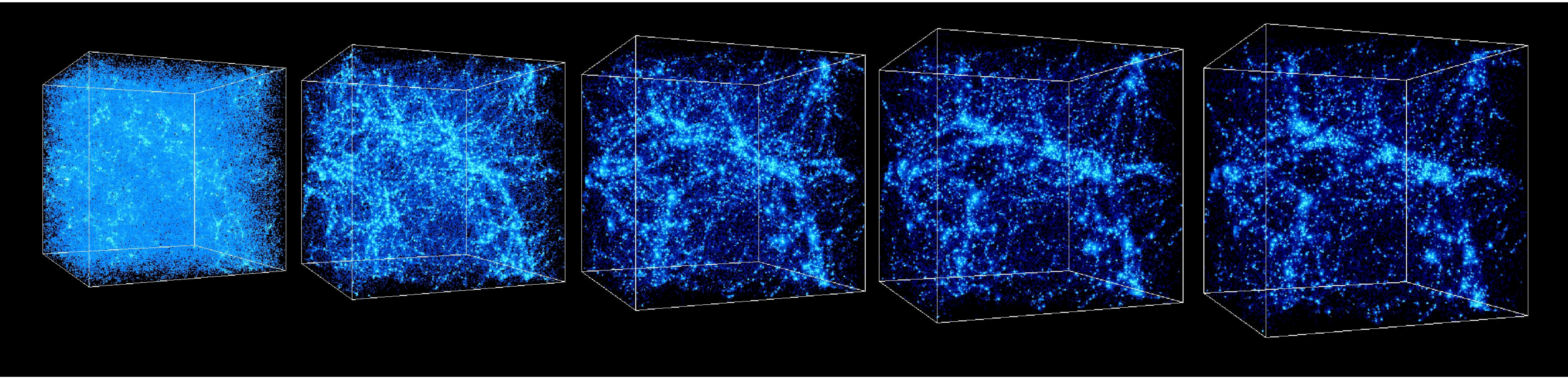
Outline

- ✓ Cosmological probes
- ✓ Distances and redshifts
- ✓ Galaxy spectra
- ✓ Spectroscopic redshifts
- ✓ Photometric redshifts

Large-scale structure

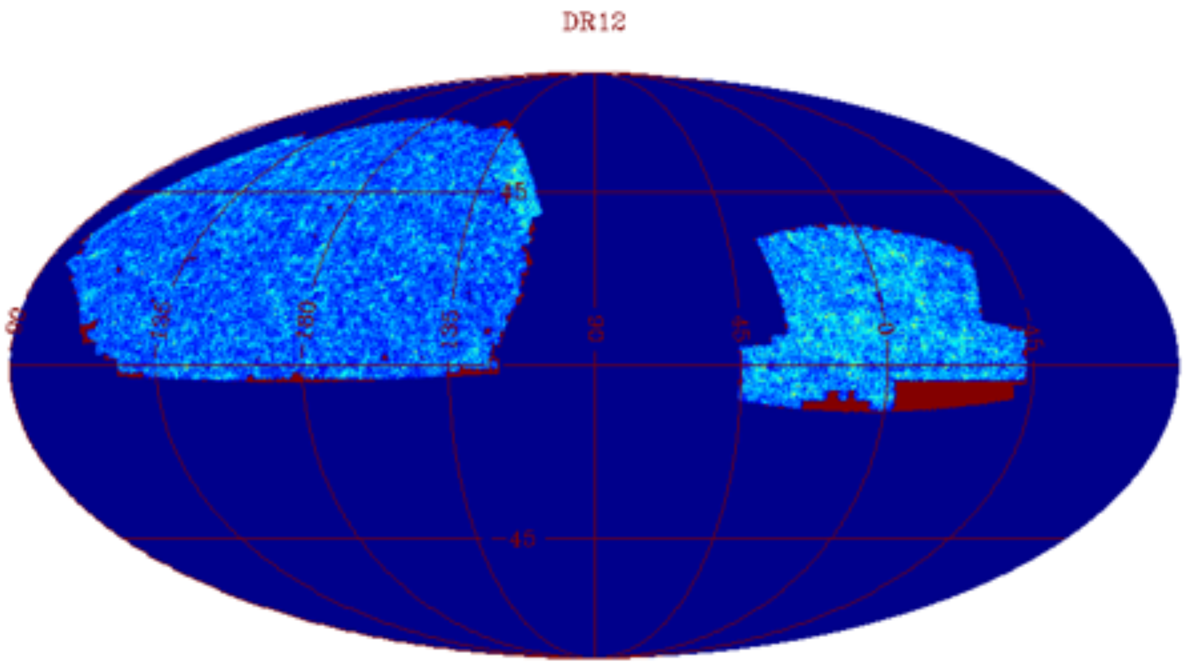






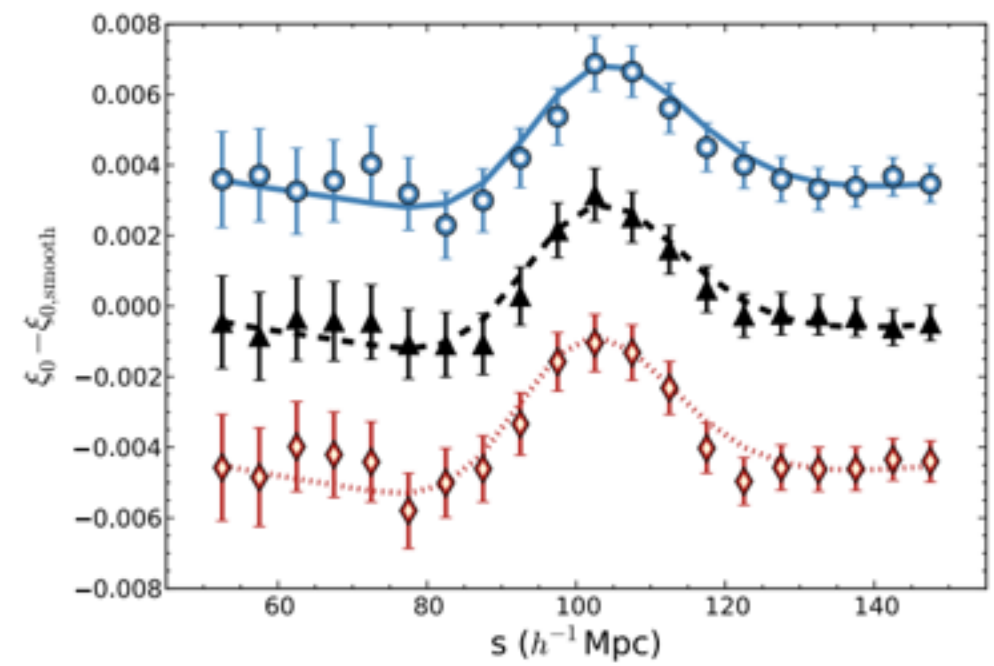
Large-scale structure

SDSS-III/BOSS footprint

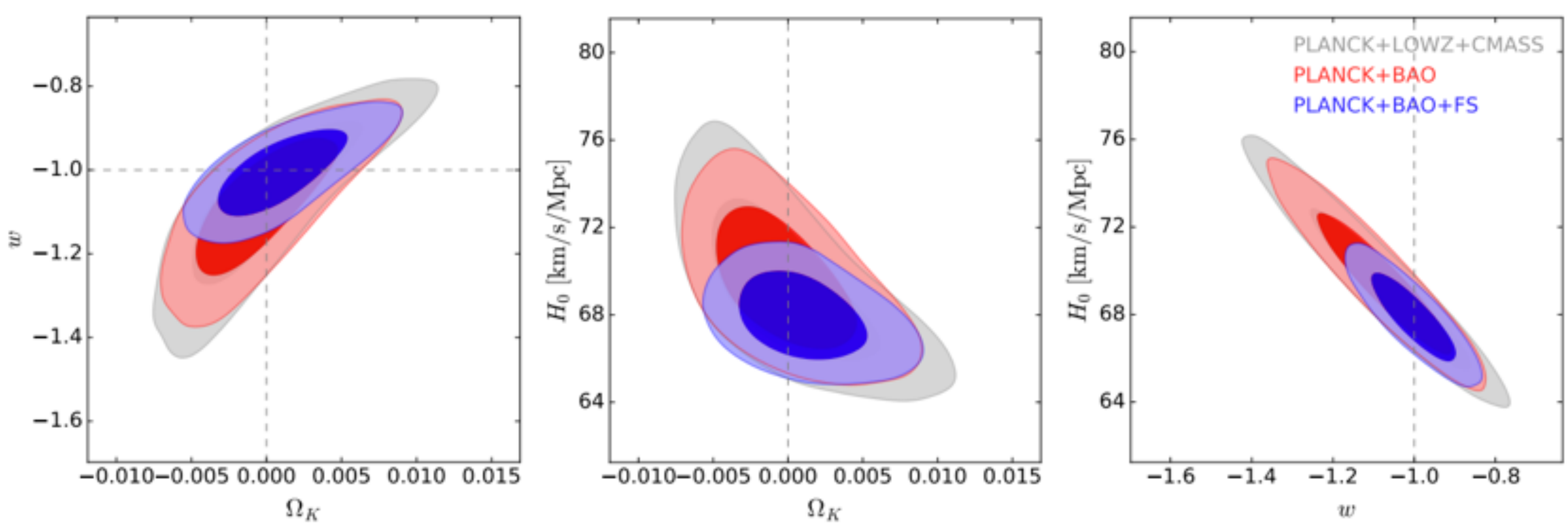


Credit: http://blog.sdss.org/

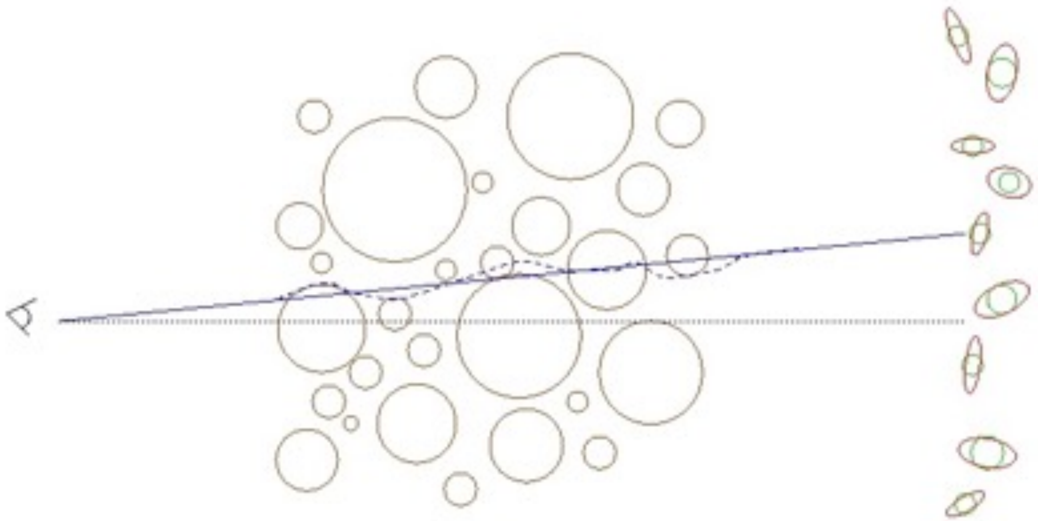
BAO scale



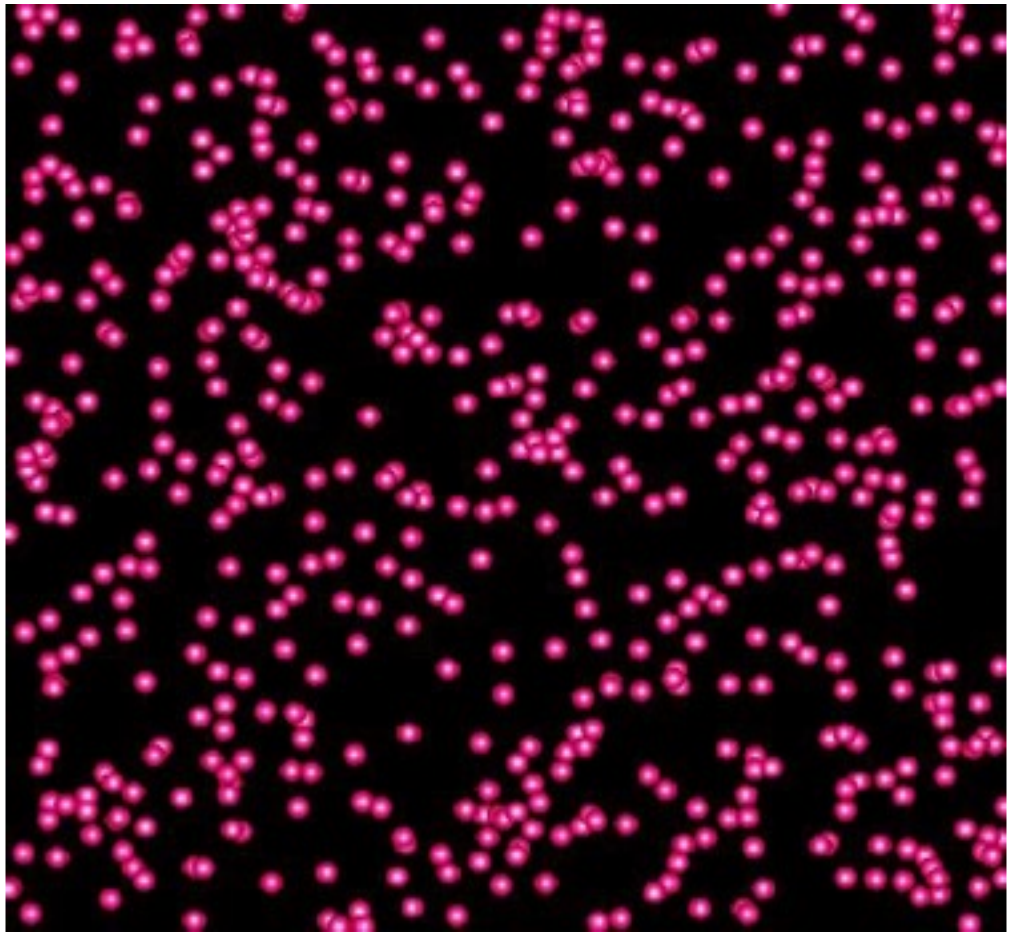
Cosmological constraints (Alam+2016)



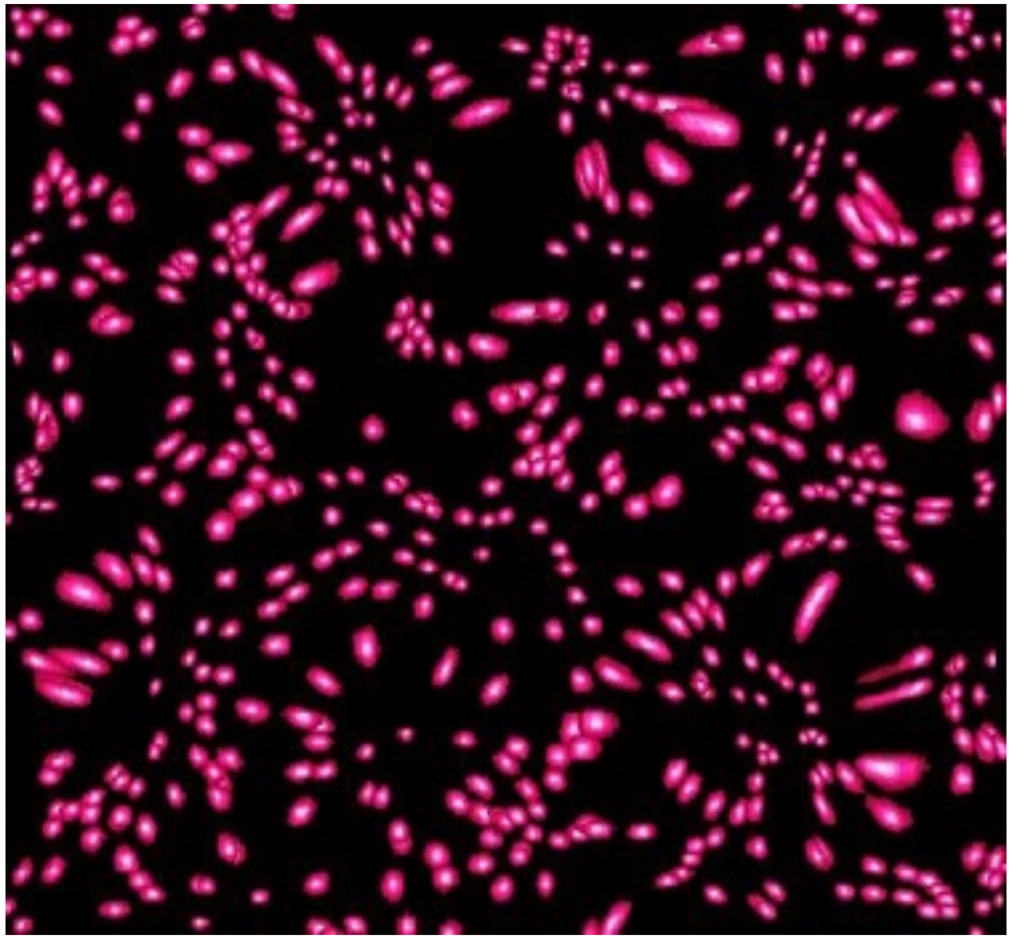
Weak lensing



Distortion of background images by foreground matter

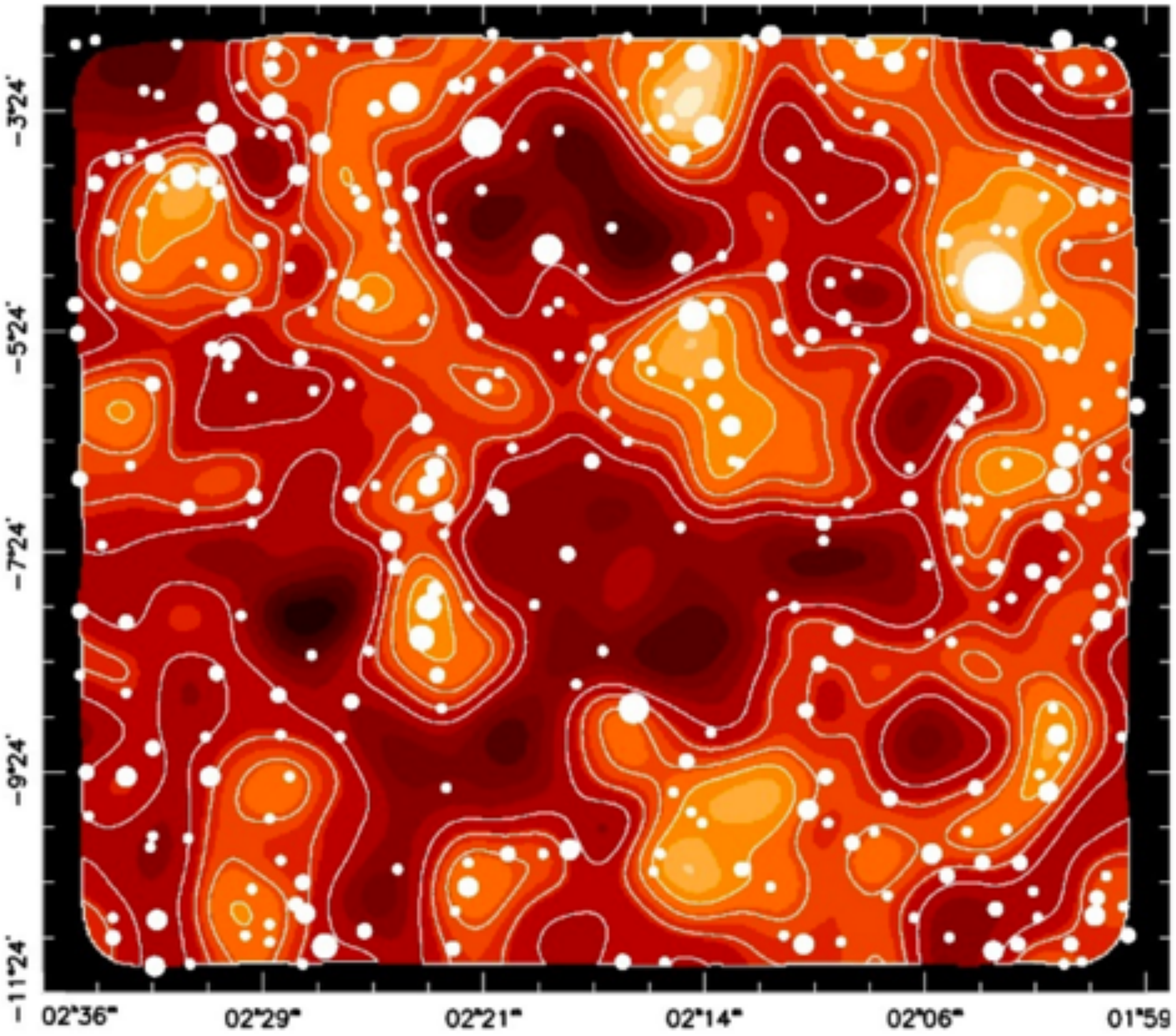


Unlensed



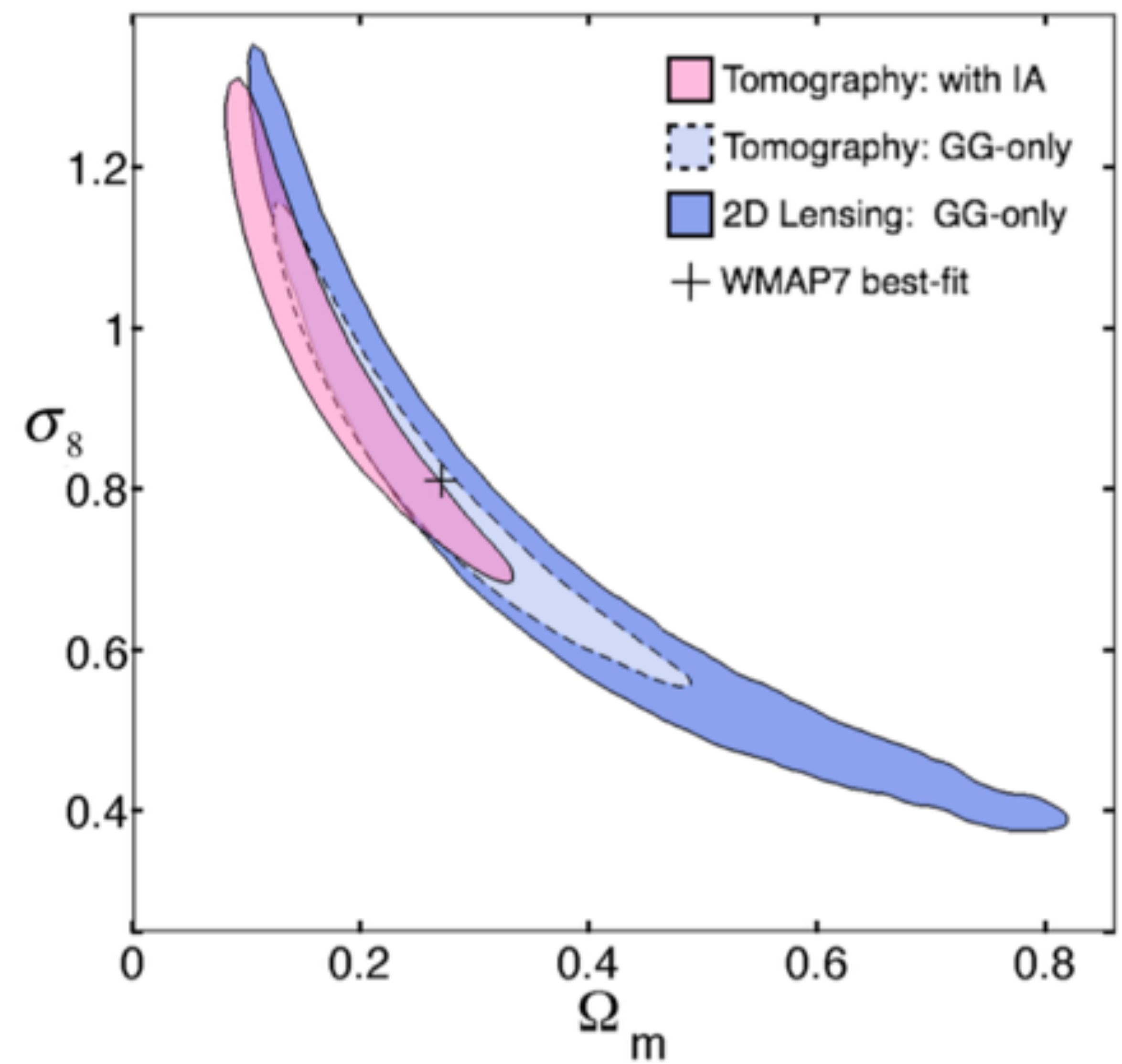
Lensed

Weak lensing



2D mass maps (Van Waerbeke+2013)

Cosmological constraints (Heymans+2013)



How do we measure radial distances?

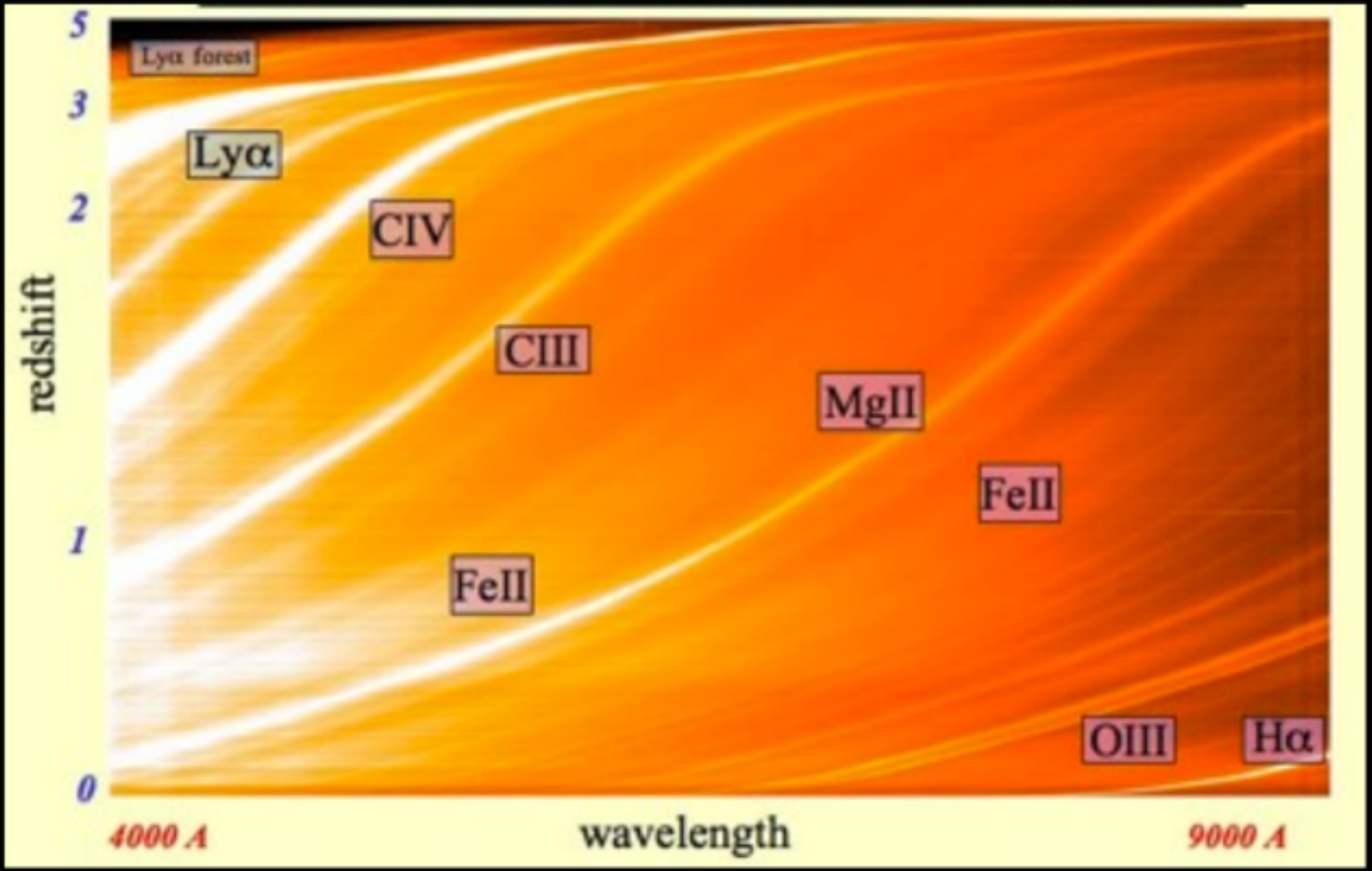
Credit: Abdalla, Cosmology course UCL

The derivation of the redsfhit

- For a photon, using the FRW metric we have: $$c^2\mathrm{d}t^2 = a^2(t)\frac{\mathrm{d}r^2}{(1-kr^2)}$$
- How if we take a photon arrival and emission time: $$\frac{1}{c}\int_0^{r_e}\frac{\mathrm{d}r}{\sqrt{1-kr^2}} = \int_{t_e}^{t_o}\frac{\mathrm{d}t}{a(t)}$$
- The second equality is because we can take the second crest given that the photon is a wave. $$\frac{1}{c}\int_0^{r_e}\frac{\mathrm{d}r}{\sqrt{1-kr^2}} = \int_{t_e+\Delta t_e}^{t_o+\Delta t_o}\frac{\mathrm{d}t}{a(t)}$$
- So equating the two we have $$\int_{t_o}^{t_o+\Delta t_o}\frac{\mathrm{d}t}{a(t)} = \int_{t_e}^{t_e+\Delta t_e}\frac{\mathrm{d}t}{a(t)}$$
- If we assume a(t) is unchanging during these small intervals we can take a out of the integral.
- Hence: $$\frac{\Delta t_e}{a(t_e)} = \frac{\Delta t_o}{a(t_o)}$$
- So if we take the time intervals to be the periods of the photon we have now: $$1+z = \frac{\lambda_0}{\lambda_e} = \frac{\Delta t_o}{\Delta t_e} = \frac{a_o}{a_e}$$

Redshift

Credit: Abdalla, Cosmology course UCL



$$1 + z = \frac{\lambda_{obs}}{\lambda_{em}} = \frac{a_{obs}}{a_{em}}$$

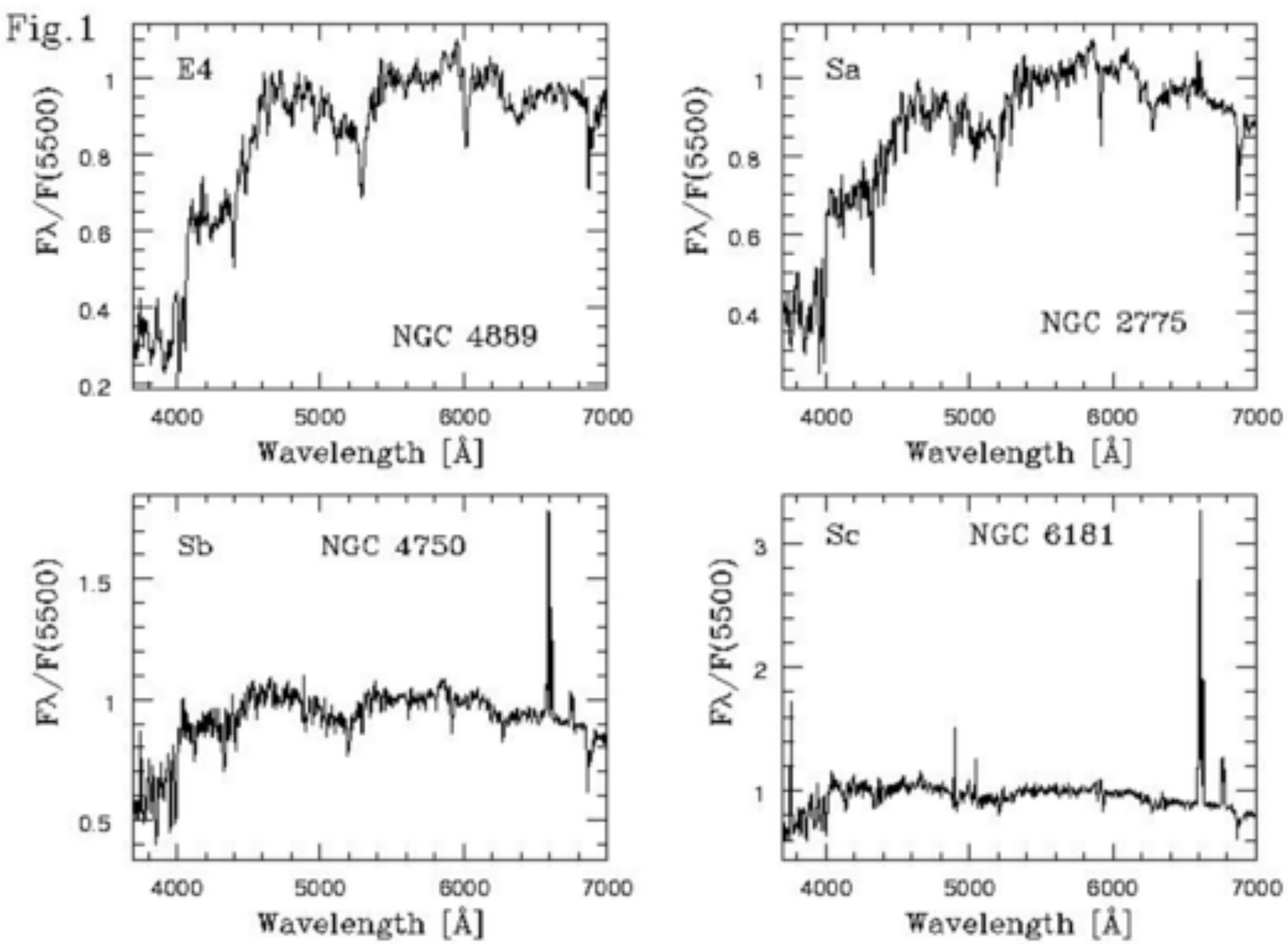
- For photons, we will prove later that redshift is indeed a stretching of the photon, i.e. a change in wavelength.
- Below all the quasars from the SDSS survey stacked in increasing redshift. We can see emission lines changing.
- a is the scale factor.

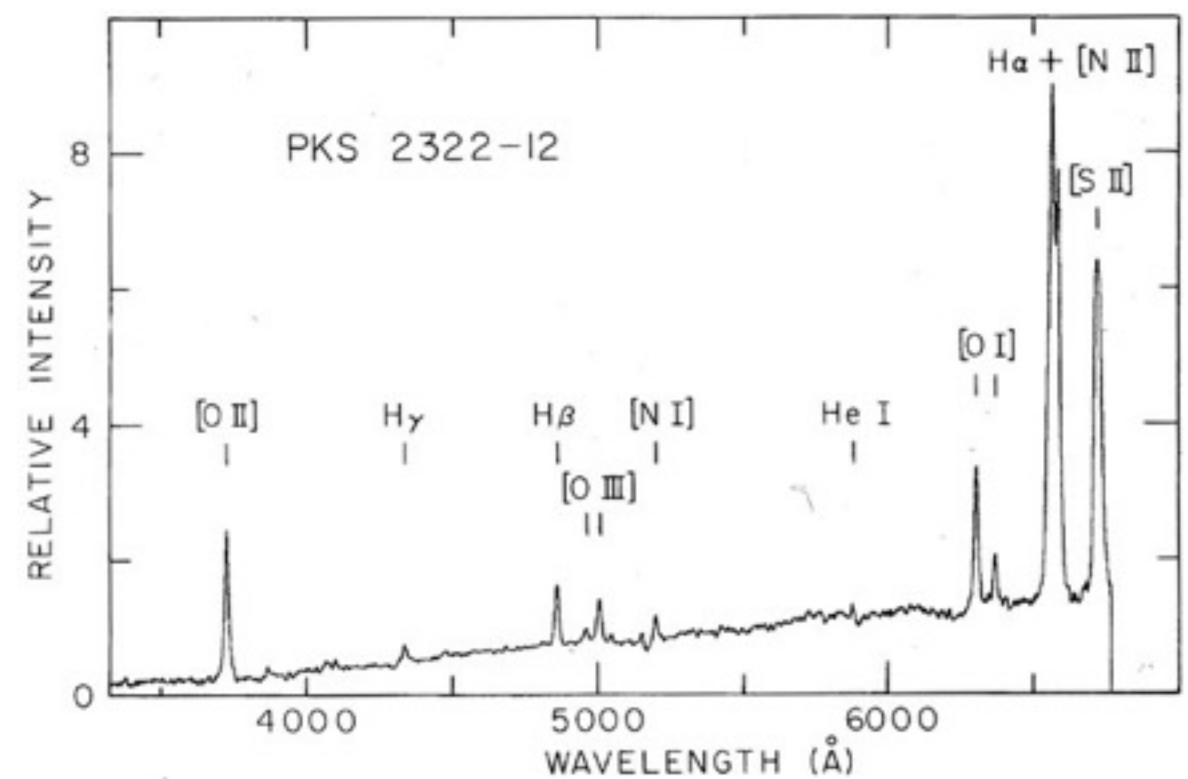
Explaining galaxy spectral energy distributions

Examples of galaxy spectra

Red Galaxies

Blue Spiral Galaxies



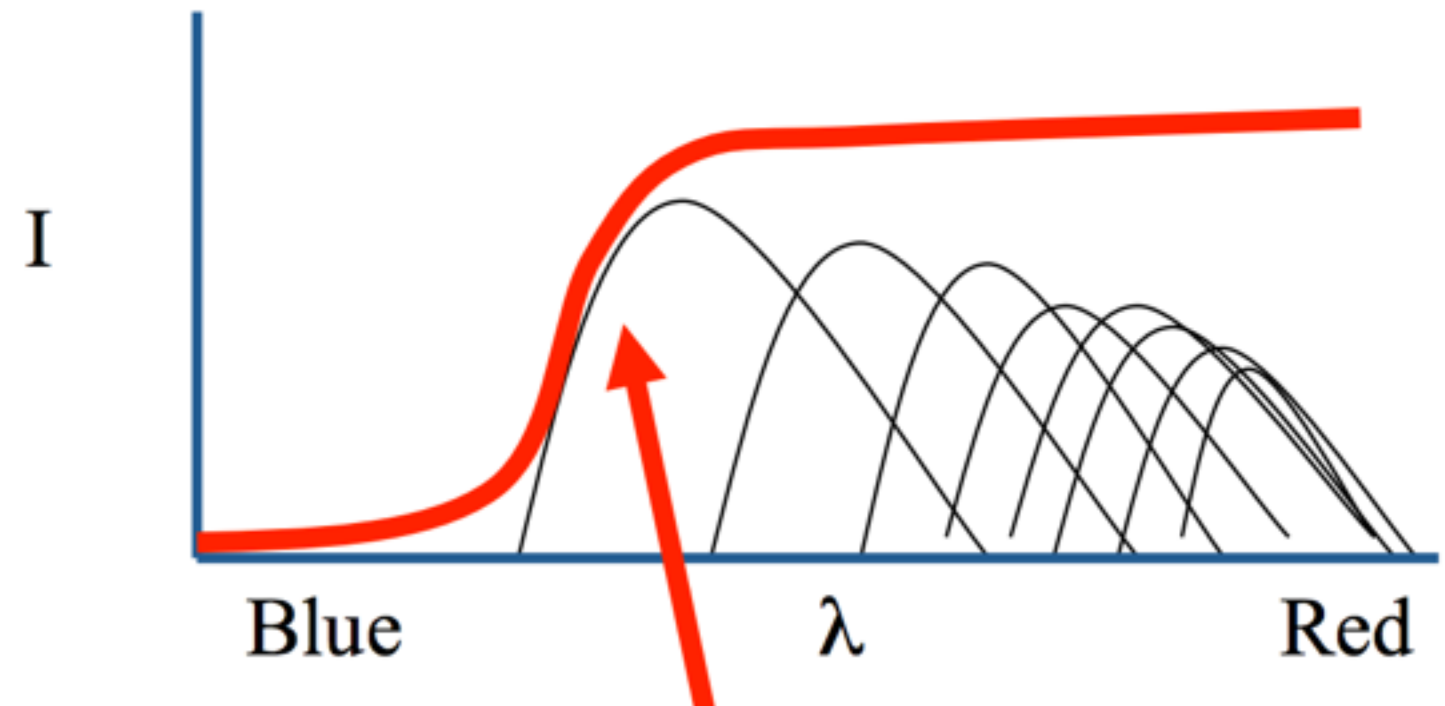


Credit: SDSS Collaboration

Credit: S Driver, PHYS1002 course U of St Andrews:
http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

Continuum

- The combination of many Black-Body spectra spanning a range in temperatures
- This produces a fairly flat overall spectrum



- The main feature is the 4000A-break

Credit: S Driver, PHYS1002 course U of St Andrews: http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

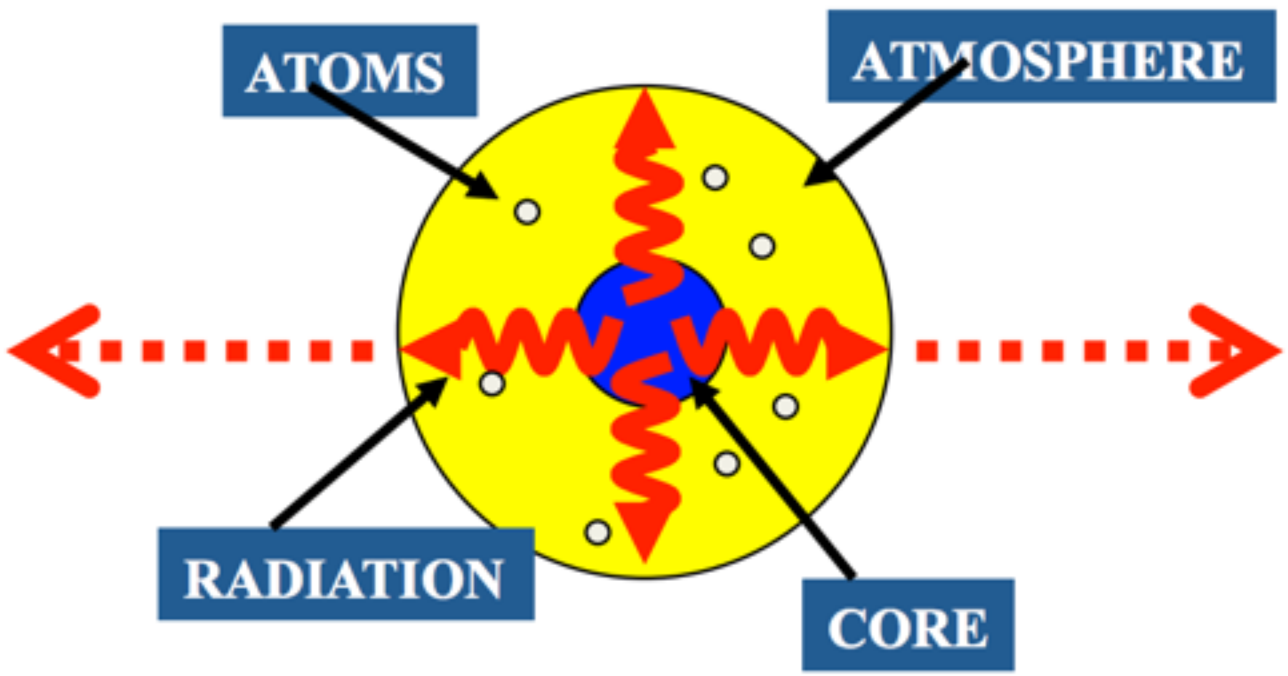
The 4000A-break

- Caused by:
  - blanket absorption of high energy radiation from metals in the stellar atmospheres
  - the lack of hot blue stars
- Hence:
  - Ellipticals => A strong 4000A-Break
  - Spirals => A weak 4000A-Break
  - Irregulars => No 4000A-Break

Credit: S Driver, PHYS1002 course U of St Andrews:
http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

Absorption Lines

- Mainly caused by Atoms/Molecules in a star's atmosphere that absorb specific wavelengths

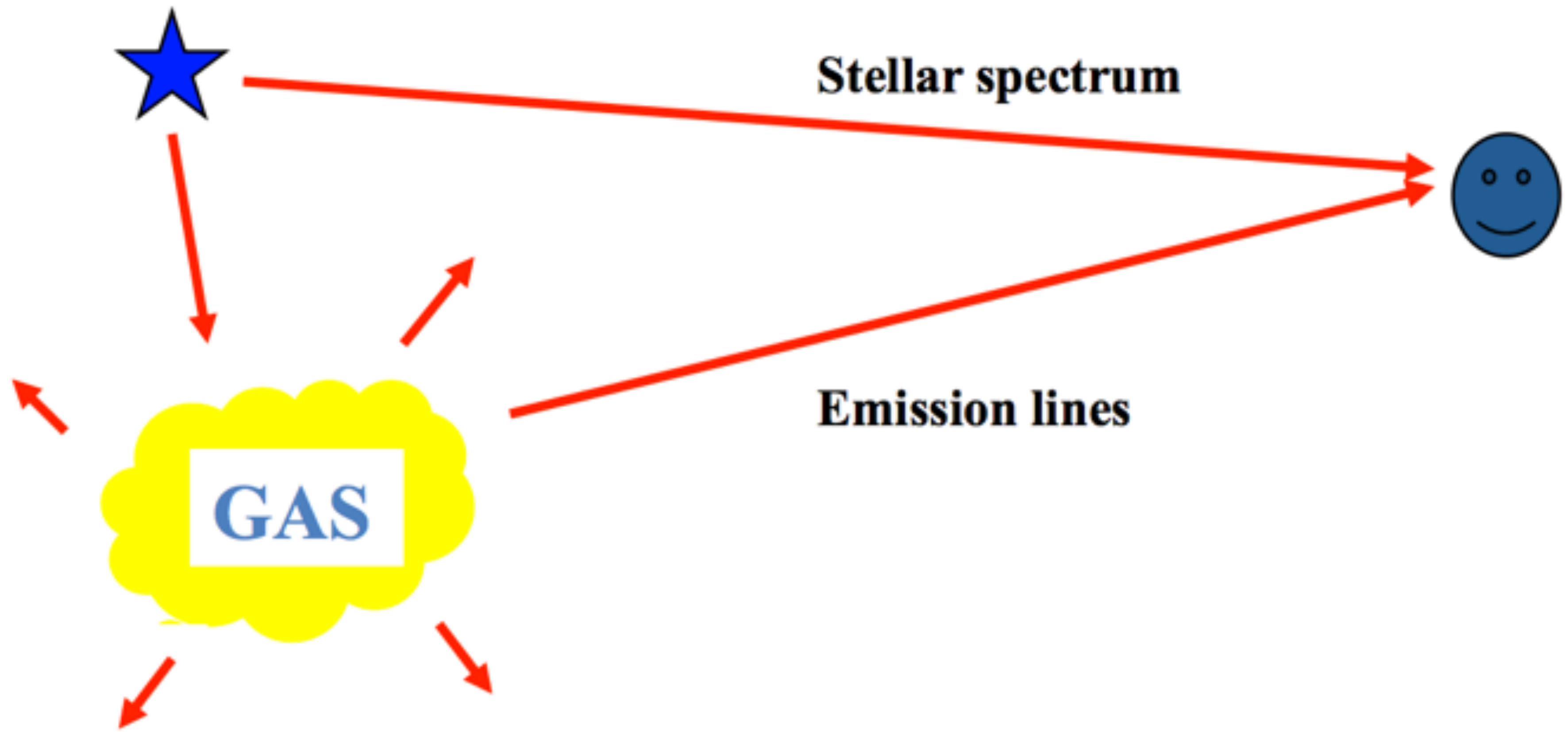


- Can also be due to COLD gas in the interstellar medium which can EXTRACT energy from the passing radiation

Credit: S Driver, PHYS1002 course U of St Andrews:
http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

Emission Lines

- Caused by gas being ionized and heated and then re-radiating at specific allowed wavelengths



- Stars form from gas so are often embedded
- Young stars ionise gas which releases radiation at a specific wavelength as it recombines

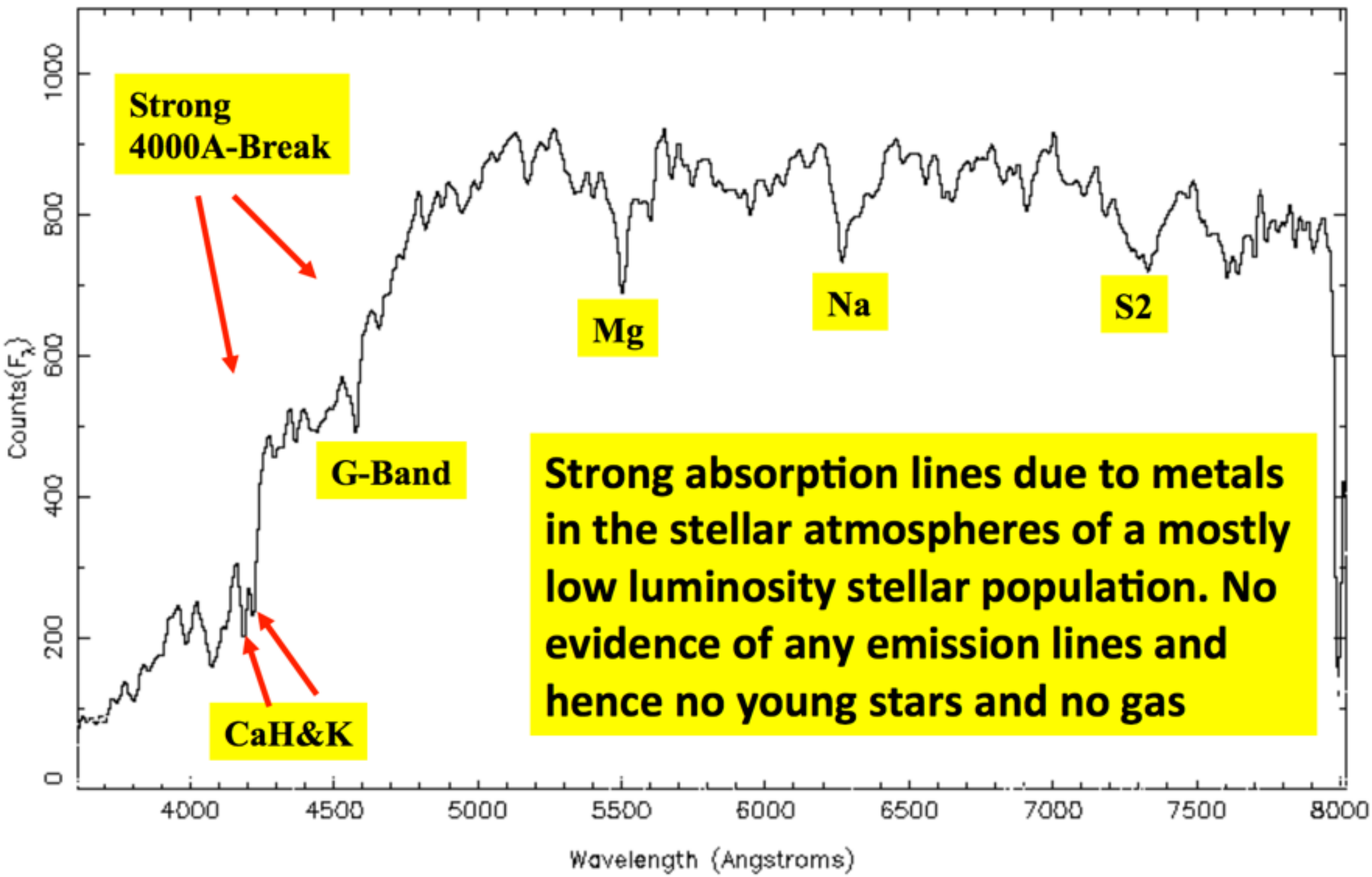
Credit: S Driver, PHYS1002 course U of St Andrews: http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

Typical Spectral features

- Absorption
  - Ca(H) = 3933.7A
  - Ca(K) = 3968.5A
  - G-band = 4304.4A
  - Mg = 5175.3A
  - Na = 5894.0 A
- Emission
  - [OII] = 3727.3A
  - Hδ = 4102.8A
  - Hγ = 4340.0A
  - Hβ = 4861.3A
  - [OIII] = 4959.0A
  - [OIII] = 5006.8A
  - Hα = 6562.8A
  - S_2 = 6716.0A

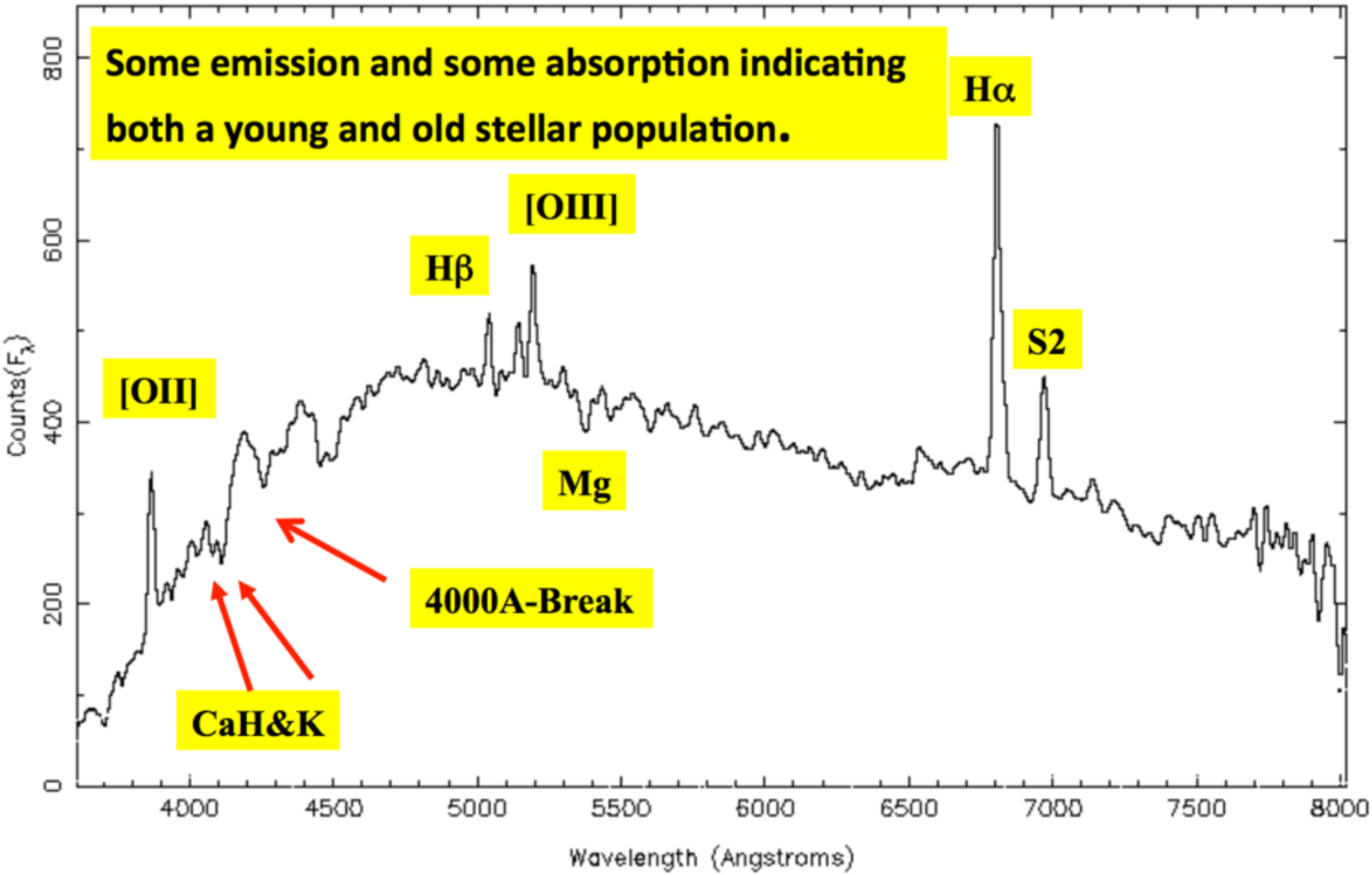
Credit: S Driver, PHYS1002 course U of St Andrews: http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

Example Spectrum: Elliptical



Credit: S Driver, PHYS1002 course U of St Andrews:
http://star-www.st-and.ac.uk/~spd3/Teaching/PHYS1002/phys1002.html

Example Spectrum: Spiral

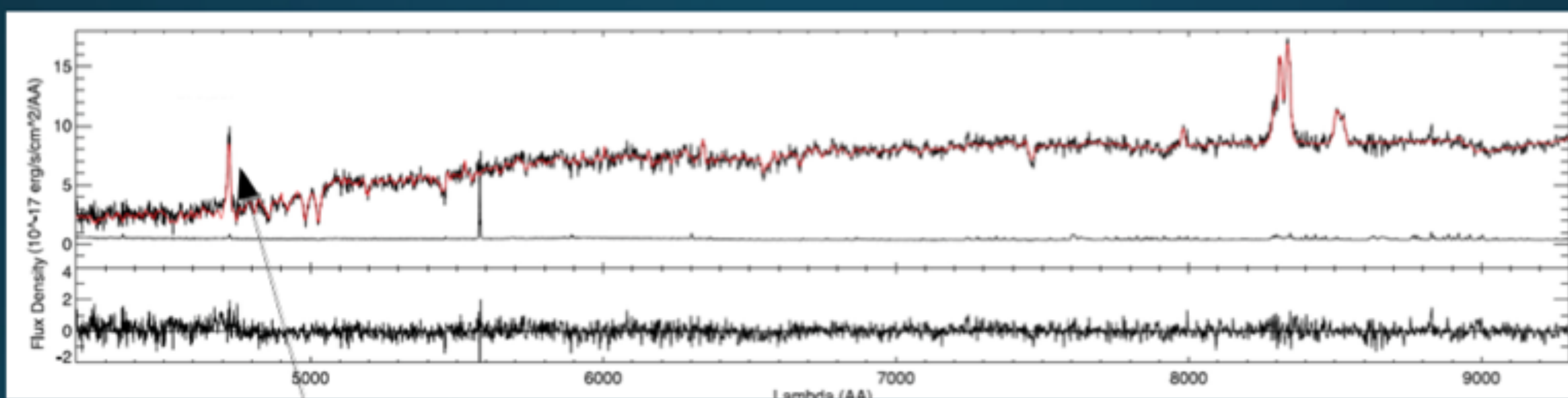


A concrete example

Credit: M Tanaka, "Photometric Redshifts" talk at Kavli IPMU event Sep/2015
http://indico.ipmu.jp/indico/event/75/material/slides/0?contribId=6

How to measure distances?

There are several distance measures, but for objects at cosmological distances, we do spectroscopy:

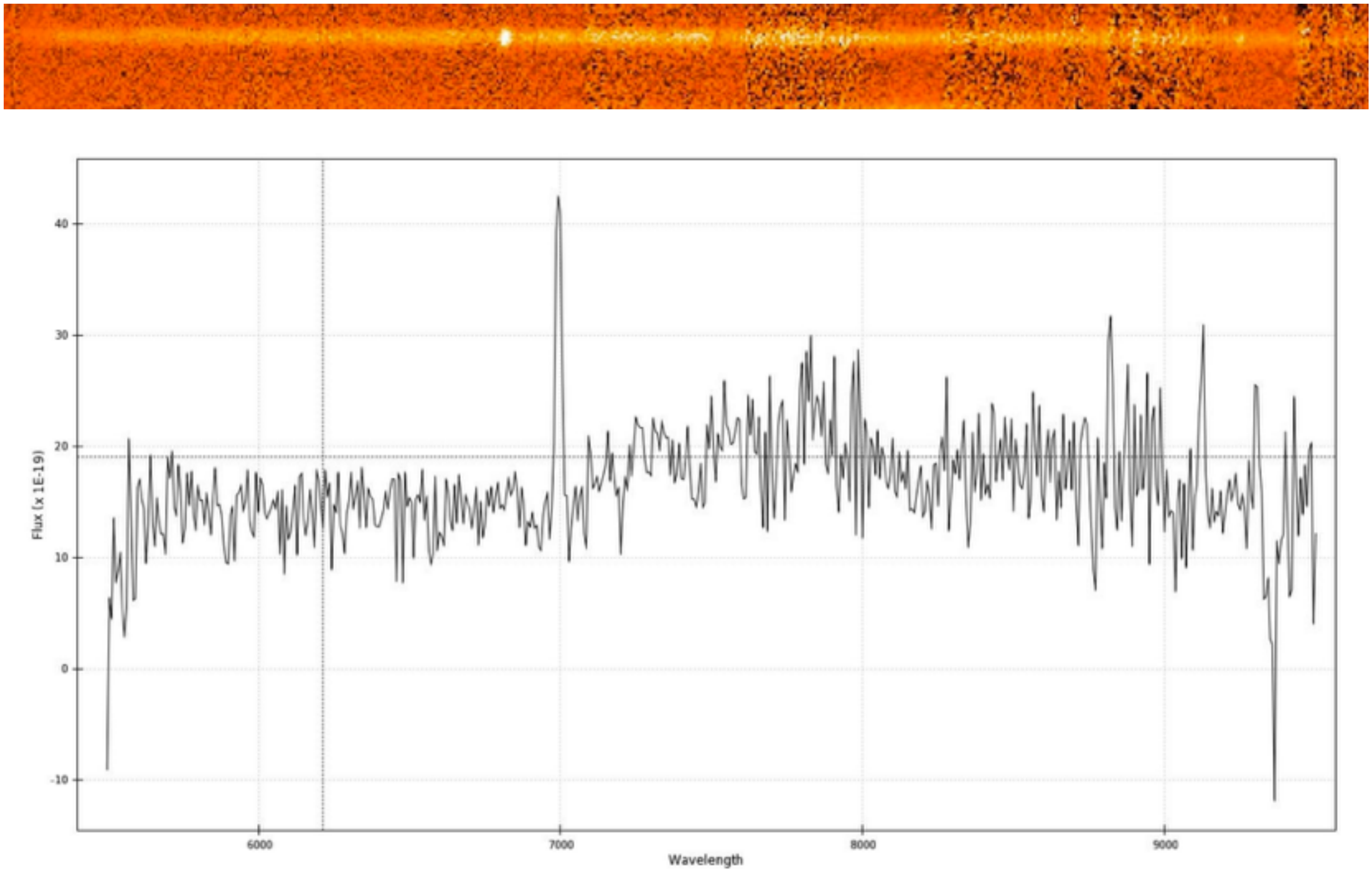


This is [OII] at rest-frame wavelength of 3727 Angstrom.
It is observed at 4700 Angstrom.

$$z = 4700 / 3727 - 1 = 0.26$$

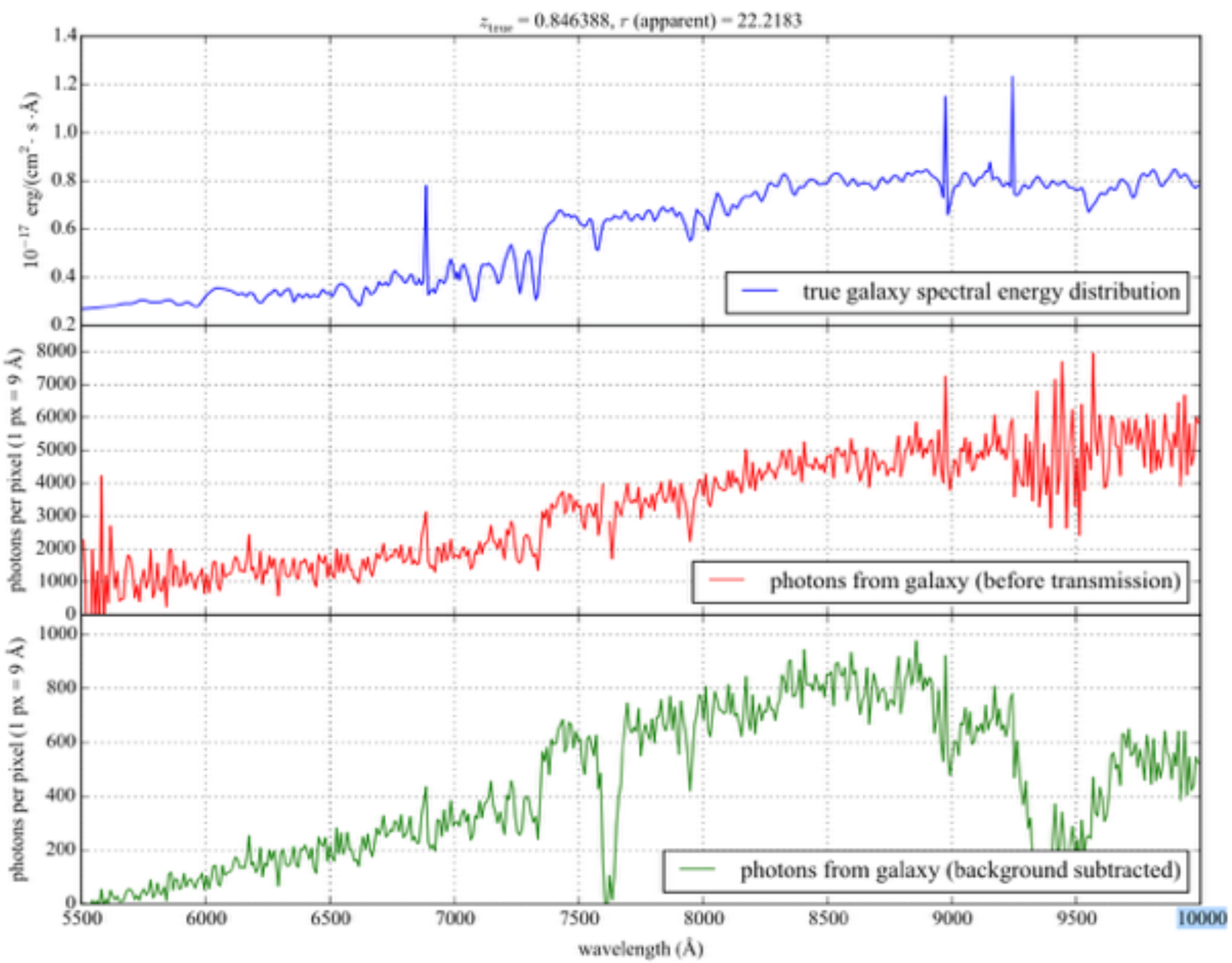
Spectroscopic redshifts

Measuring spectra



VIPERS spectrum from http://g-vo.org/cosadie-dcforum/slides/LuigiPaioro_Vipers.pdf

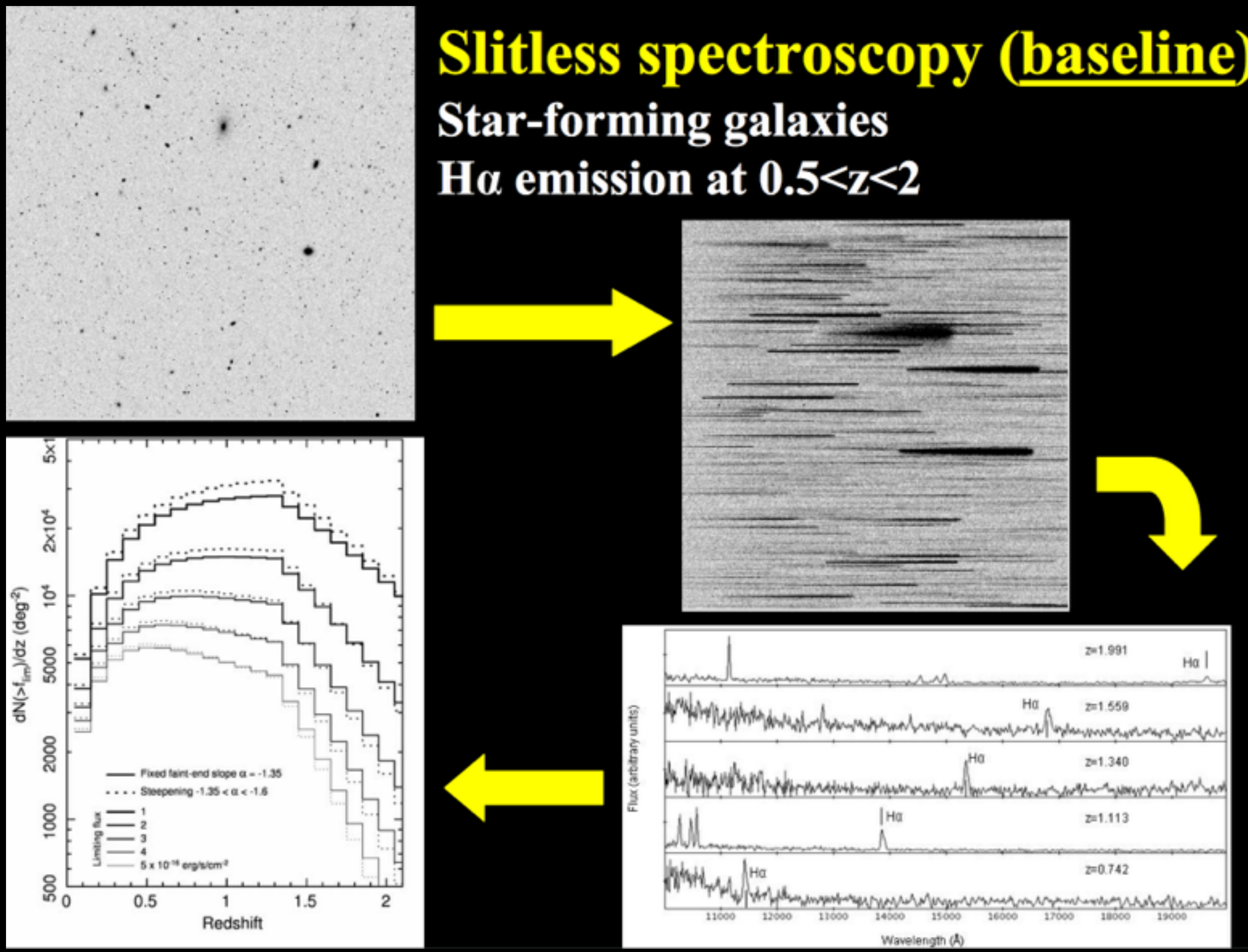
Measuring spectra



Nord et al. 2016

Figure 3: Example of galaxy spectrum simulated by SPOKES. Top panel: a noise-free galaxy spectrum reconstructed from a set of templates for a galaxy at a redshift of $z = 0.93$. Middle panel: galaxy spectrum with noise computed from multiple sources—including Poisson noise from photon counts, CCD readout noise and atmospheric sources—for an exposure time of 1200 seconds. Bottom panel: galaxy spectrum with noise, but before being transmitted through the atmosphere and telescope. More details of the spectrum and noise generation process can be found in §3.2.6 and §3.2.7

Measuring spectra

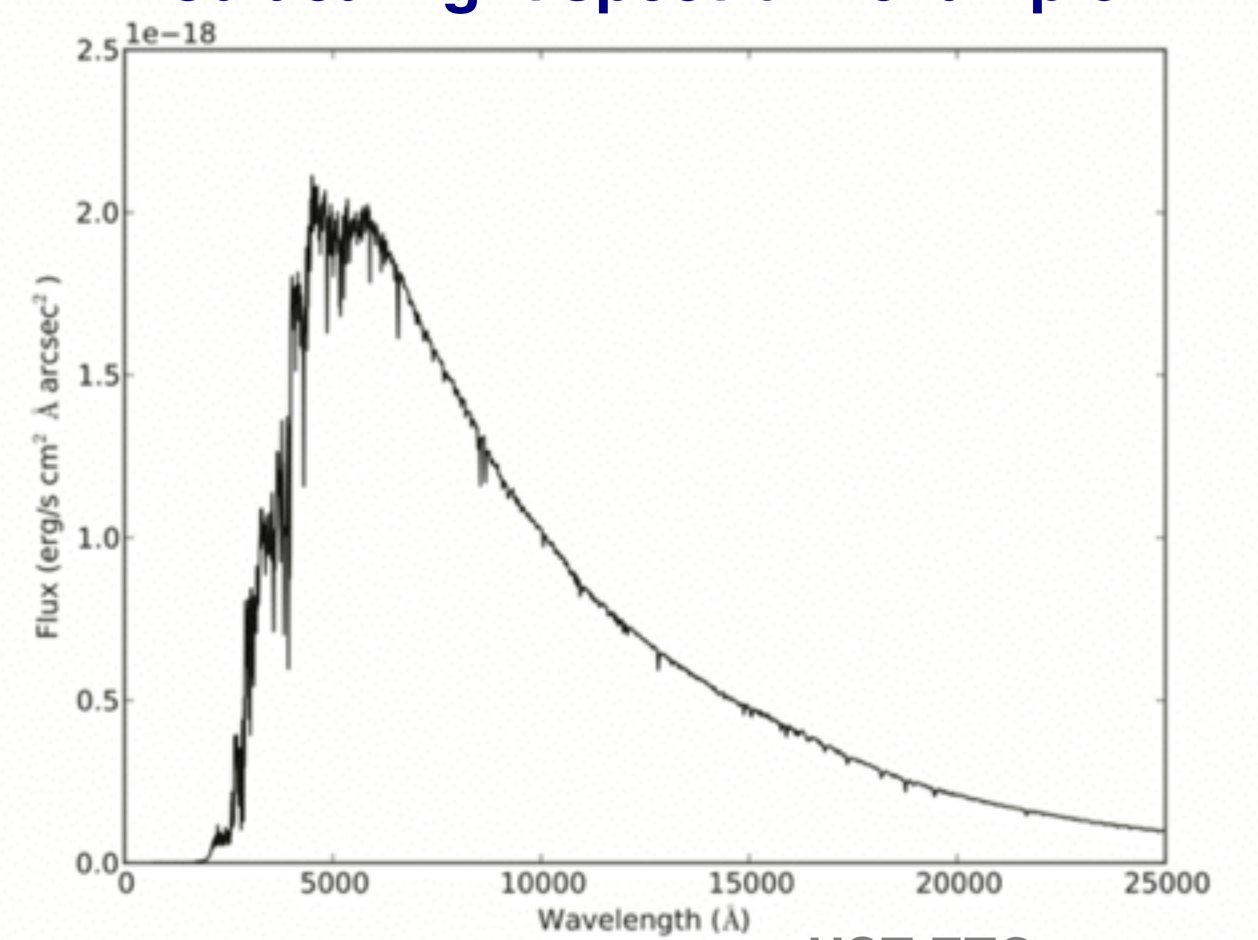


Slide from Cimatti, "Observing the Dark Universe with EUCLID"

Measuring spectra

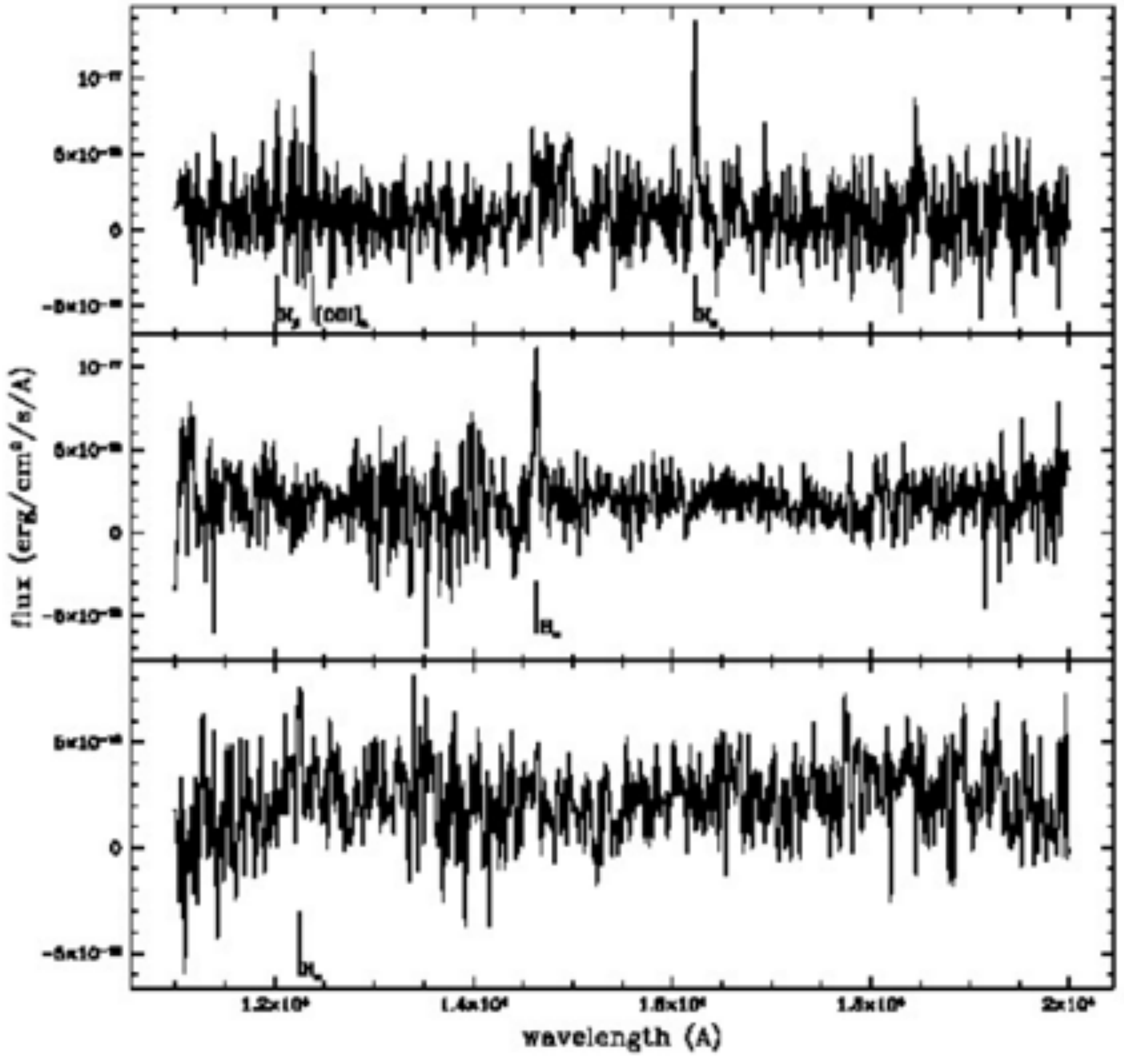
- Include fully-realistic Euclid noise in simulations.
- Add zodiacal light spectra.
- Integrate with SGS, OU-SPE in particular.

Zodiacal light spectrum example



HST-ETC

Example Euclid-like spectra



Laureijs+2011

But, spectroscopy is very expensive

In addition to redshifts, spectra contain a lot of information about the galaxies. However, spectroscopy is **very expensive** in terms of telescope time.

	HSC	PSF
i=22.5 objects	10sec	1 hour
Objects / FoV	10^4-5	2400

In addition, many of the objects that HSC detects are fainter than the spectroscopic sensitivity limits.

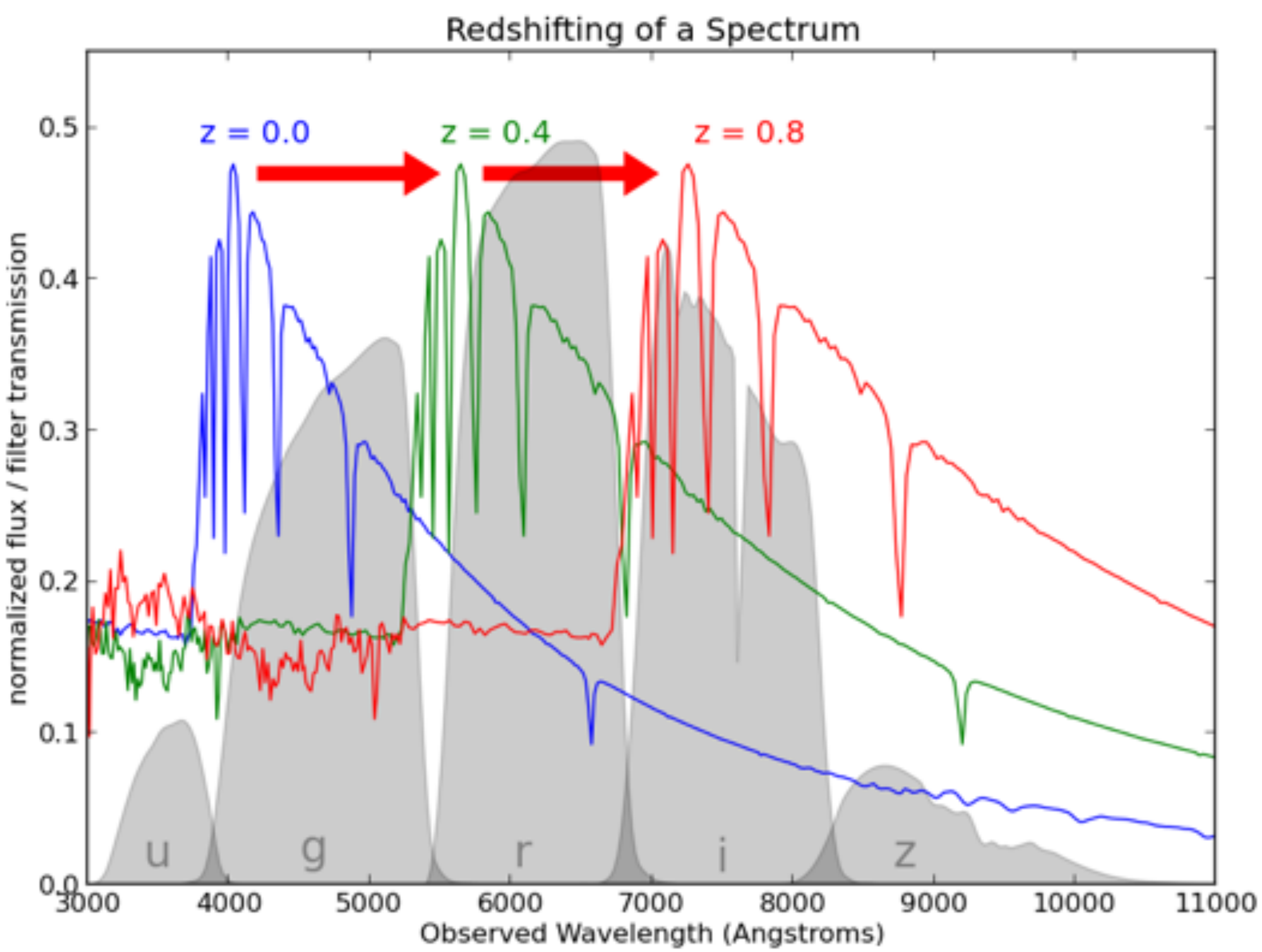
Can we use photometric information to infer redshifts?

Yes! That is photometric redshift.

Credit: M Tanaka, "Photometric Redshifts" talk at Kavli IPMU event Sep/2015
http://indico.ipmu.jp/indico/event/75/material/slides/0?contribId=6

Photometric redshifts

The idea behind photometric redshifts



AB magnitude definition:

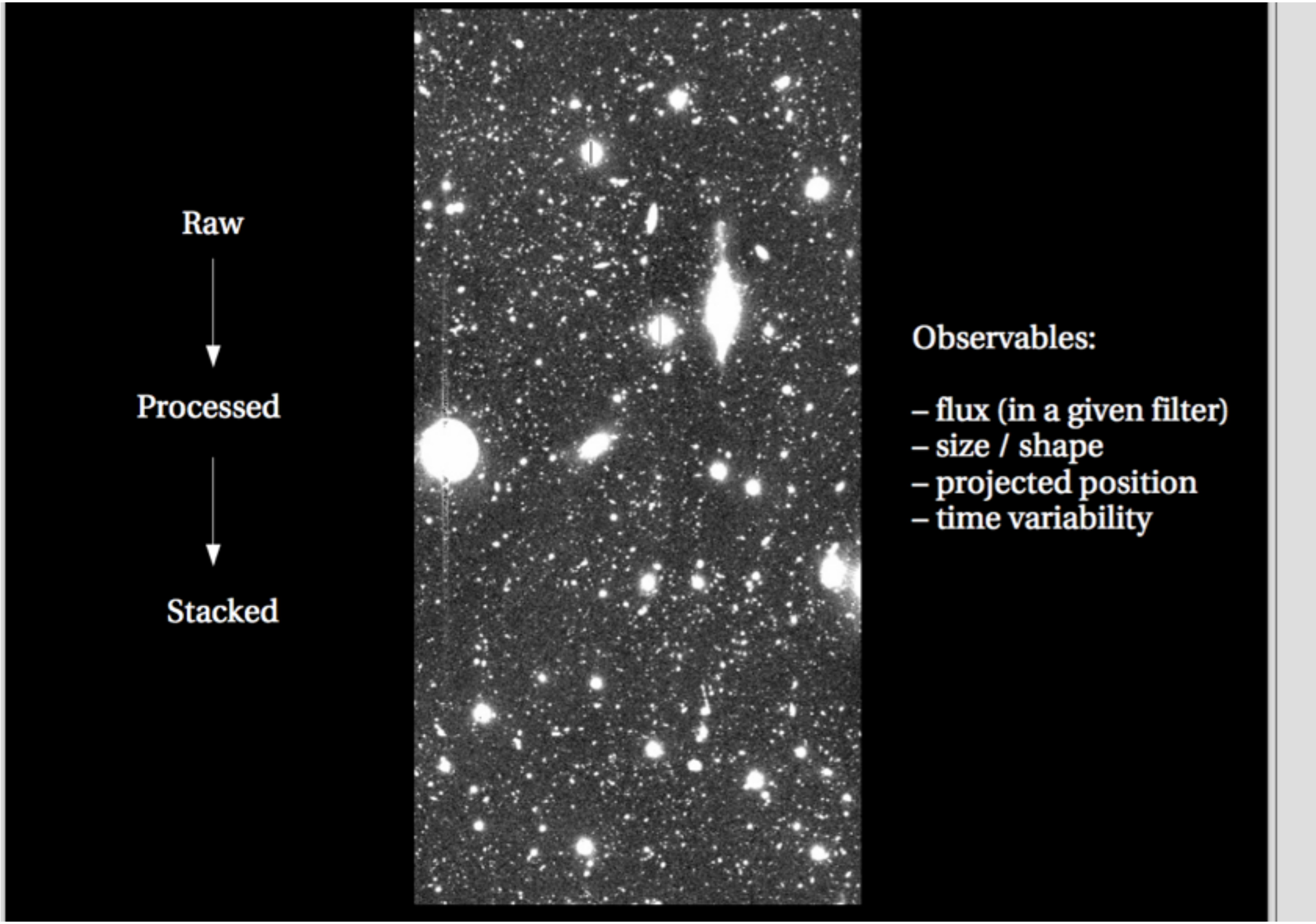
$$m_{\rm AB} = -\frac{5}{2}\log_{10}\left(\frac{f_\nu}{3631\ \rm Jy}\right),$$

Integrated flux through filter:

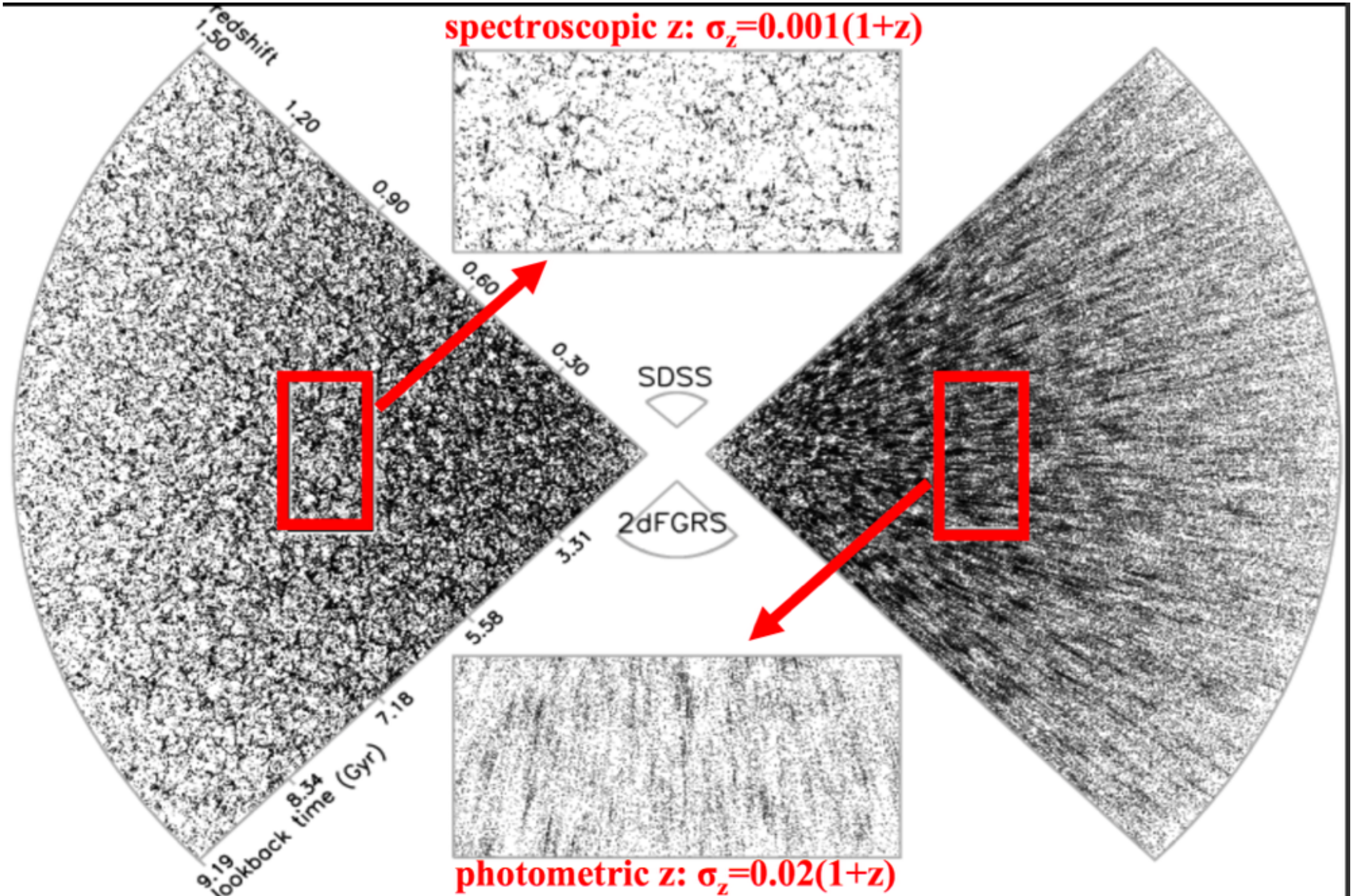
$$m_{\rm AB} = -\frac{5}{2}\log_{10}\left(\frac{\int f_\nu (h\nu)^{-1} e(\nu) d\nu}{\int 3631\ {\rm Jy} (h\nu)^{-1} e(\nu) d\nu}\right),$$

Jansky

From images to redshifts



Credit: M Tanaka, "Photometric Redshifts" talk at Kavli IPMU event Sep/2015
http://indico.ipmu.jp/indico/event/75/material/slides/0?contribId=6



spectroscopic z: σz=0.001(1+z)
photometric z: σz=0.02(1+z)
redshift
1.50
1.20
0.90
0.60
0.30
SDSS
2dFGRS
3.31
5.58
7.18
8.34
9.19
lookback time (Gyr)

Photometric redshift

Credit: M Tanaka, "Photometric Redshifts" talk at Kavli IPMU event Sep/2015
http://indico.ipmu.jp/indico/event/75/material/slides/0?contribId=6

In short, photometric redshift is a technique to make mapping between observables and redshift.

1 – template fitting:
We use spectral templates of galaxies. We put them at various redshifts, compute colors of these redshifted templates, and compare them with observed colors of galaxies.

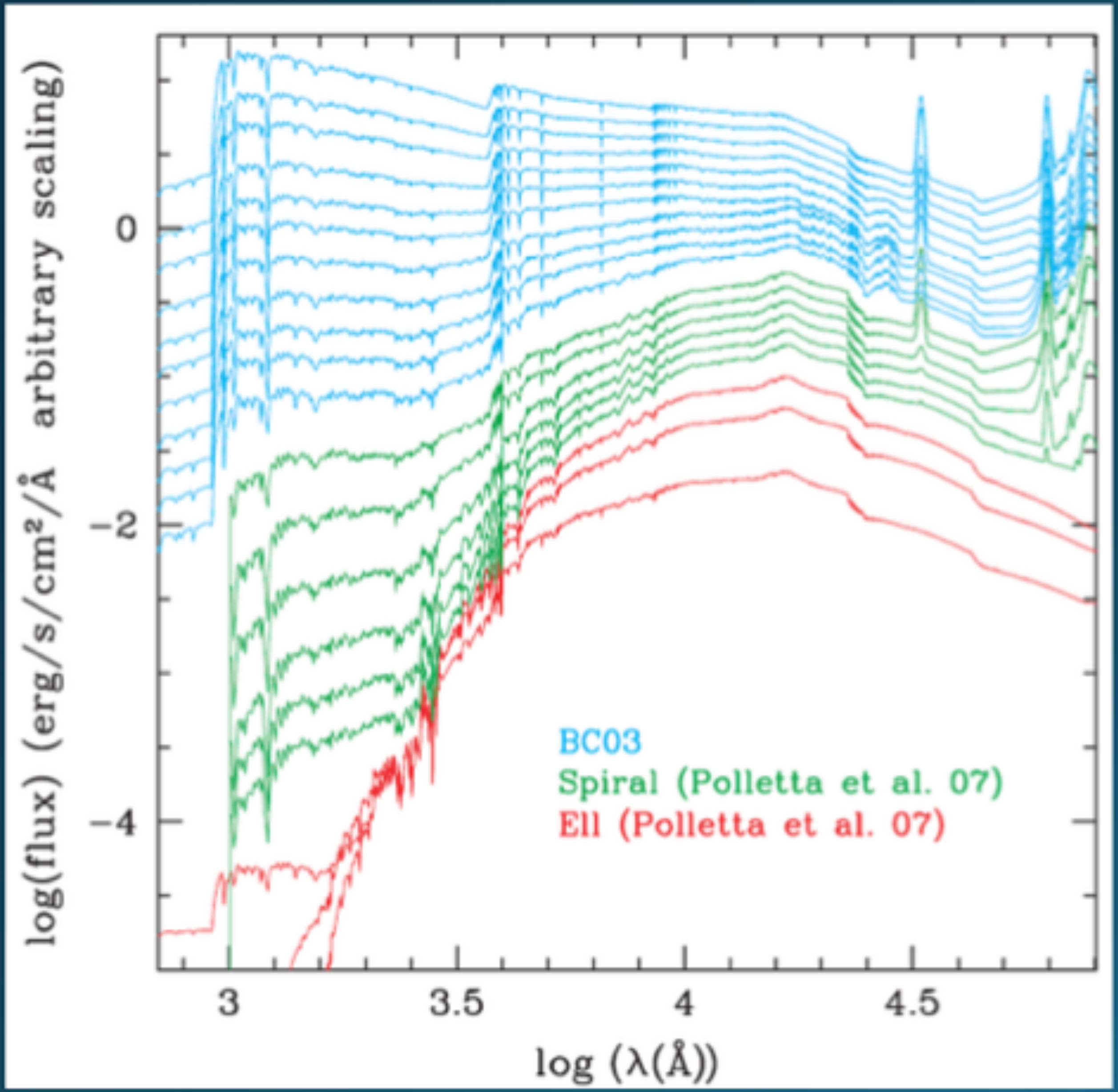
2 – numerical fitting:
We assume some function (e.g., polynomials) to make the mapping using spectroscopic redshifts:
$z = a * m1 + b * m2 + c * m1 * m2 + \ldots$

3 – machine learning:
Generalized form of #2. We use spectroscopic objects and let a machine learn and make the mapping by itself.

4 – clustering redshifts:
We use spatial information. Potentially a very powerful technique.

Credit: M Tanaka, “Photometric Redshifts” talk at Kavli IPMU event Sep/2015
http://indico.ipmu.jp/indico/event/75/material/slides/0?contribId=6

1 – Template fitting



Ilbert et al. 2009

Spectral templates can be either from observations or stellar population synthesis models.

Pros: we 'expect' to go fainter than the spectroscopic limits provided that our understanding of galaxy spectra is reasonable.

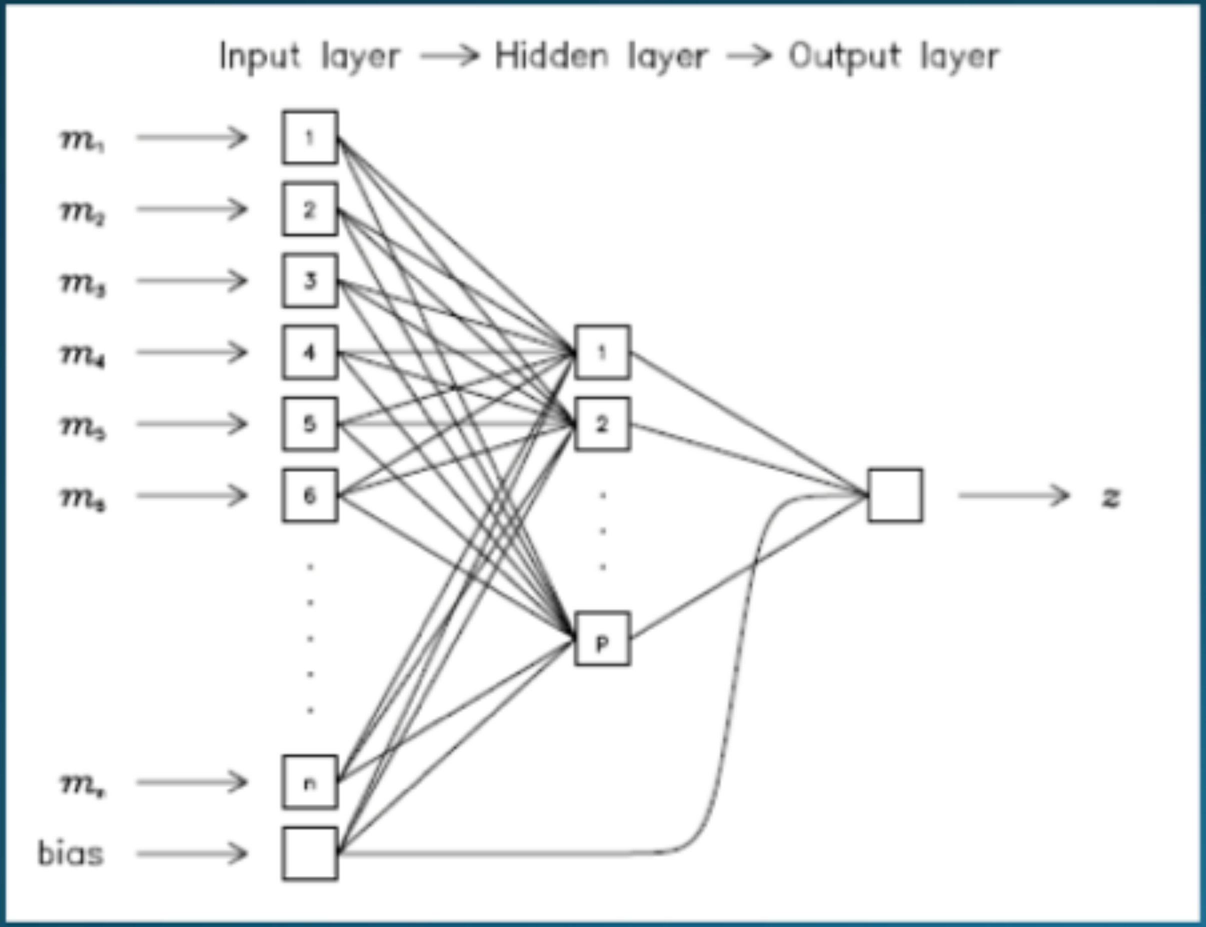
Cons: templates may not include all types of galaxies.

Credit: M Tanaka, "Photometric Redshifts" talk at Kavli IPMU event Sep/2015
http://indico.ipmu.jp/indico/event/75/material/slides/0?contribId=6

3 – Machine-Learning

We feed a 'training' sample of spectroscopic objects to a machine-learning code and let the machine learn by itself.

Pros: If trained well, it works better than template fitting methods.
Cons: The training spectroscopic sample has to represent an input catalog to which you apply your code.



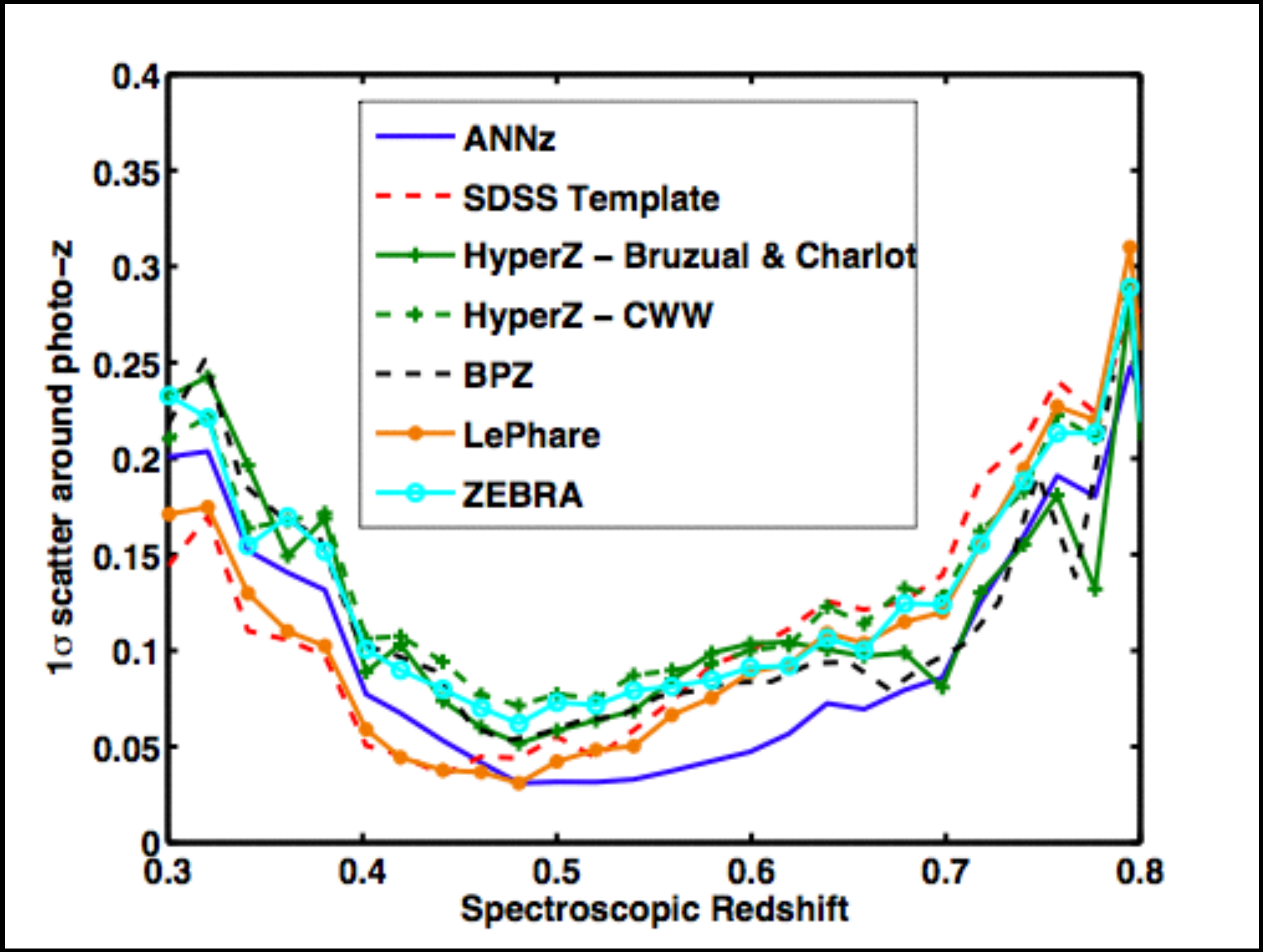
$$u_j = \sum_i w_{ij} g_i(u_i),$$

$$g_j(u_j) = 1/[1+\exp(-u_j)]$$

Collister and Lahav 2004

There are other techniques applied to photo-z: random forest, deep learning, etc.

Metrics 1:1σ scatter around photo-z



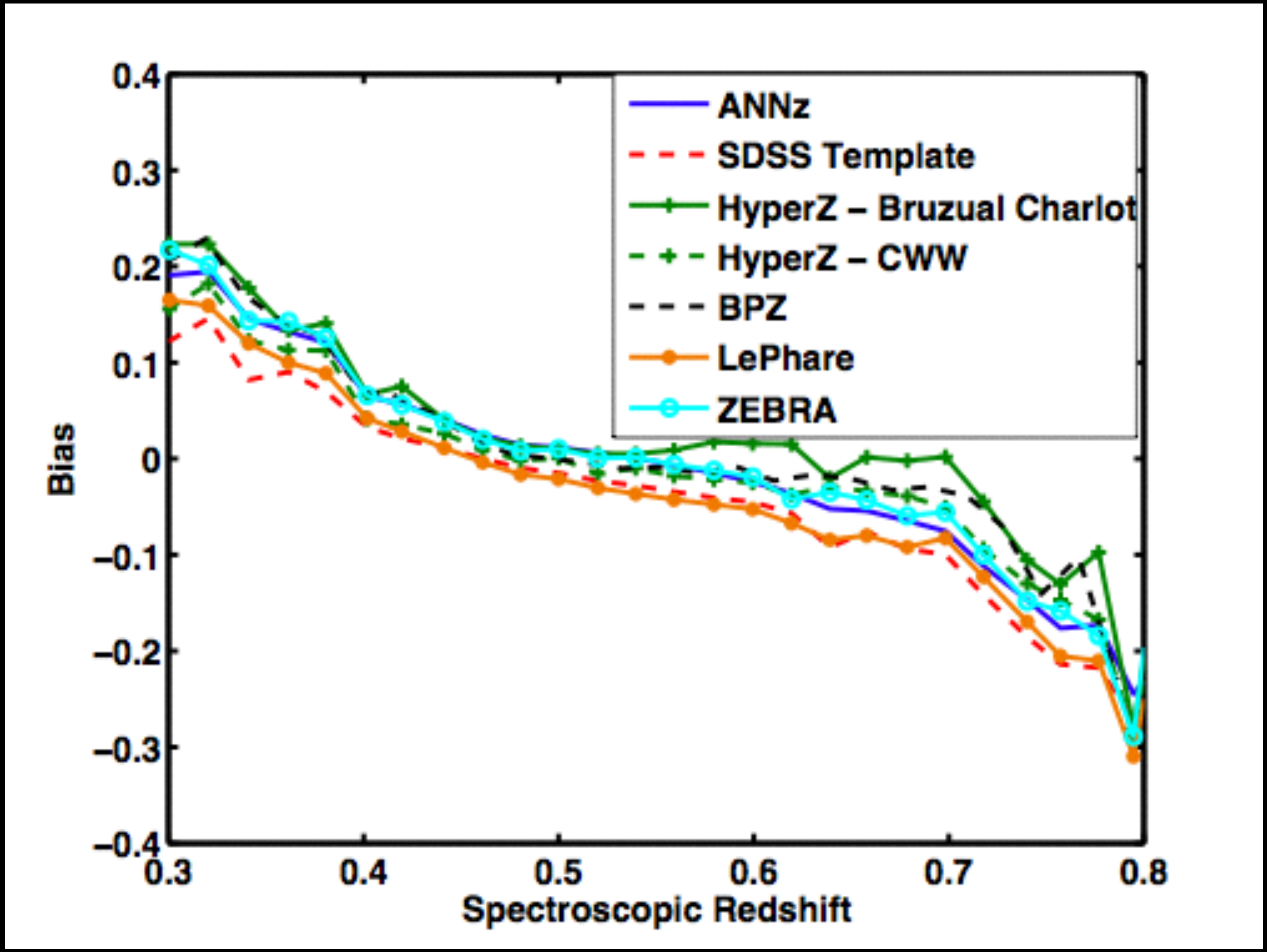
Abdalla+2009

$$\sigma_z = \left\langle \left(z_{spec} - z_{phot} \right)^2 \right\rangle^{1/2}$$

- Code + Library comparison
- Luminous Red Galaxies so good photo-z
- Training set method performs best at intermediate z - lots of galaxies
- Template methods that don't use CWW perform best at low and high-z

Credit: M Banerji, Photo-z testing workshop, JPL Dec/2008
http://www.astro.caltech.edu/twiki_phat/pub/Main/PHATMeetingJPL/Banerji.ppt

Metrics II: Bias vs spec-z



$$b_z = \left\langle z_{spec} - z_{phot} \right\rangle$$

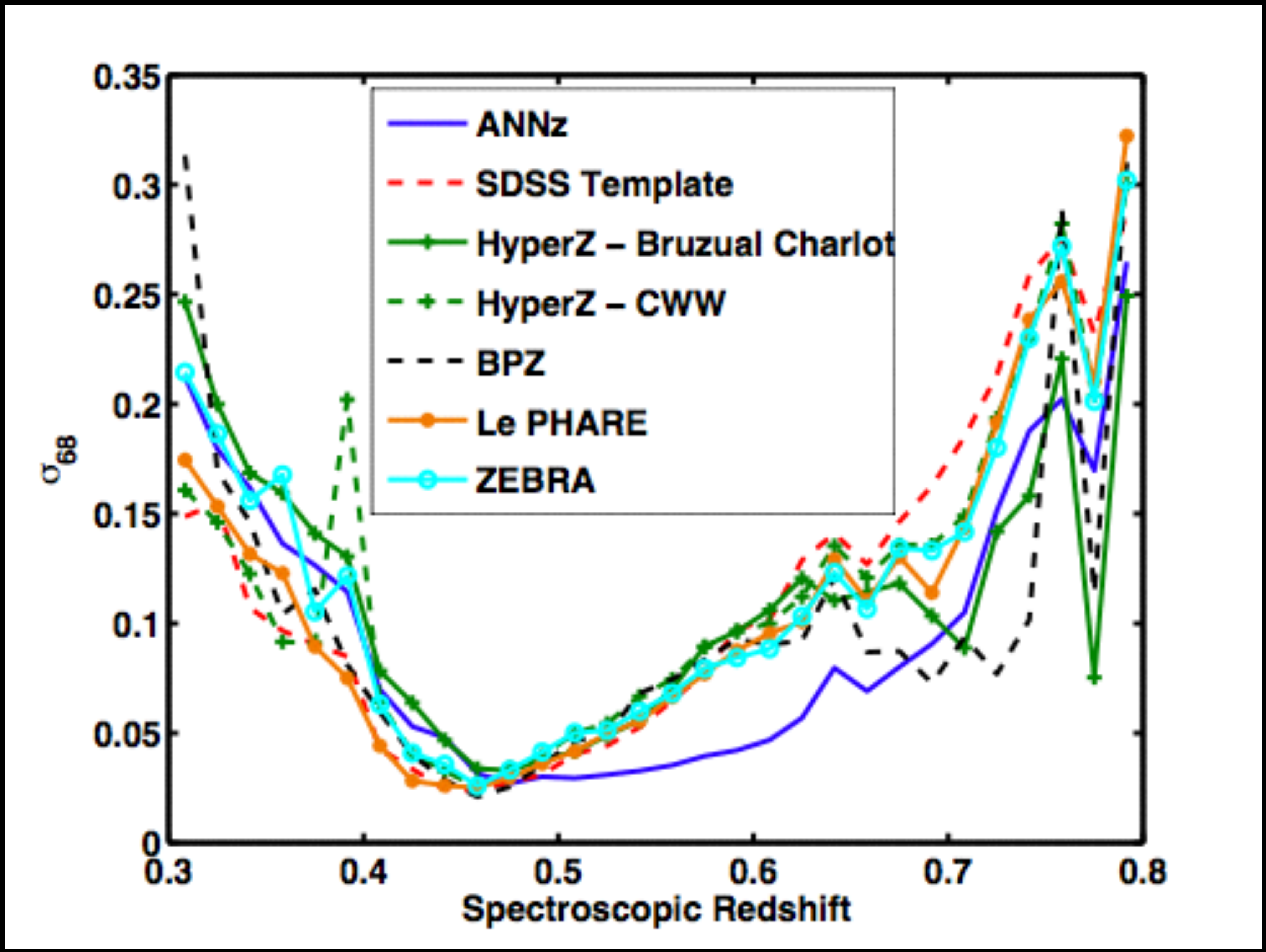
Bias typically large at low and high spec-z for all codes

Abdalla+2009

Credit: M Banerji, Photo-z testing workshop, JPL Dec/2008

http://www.astro.caltech.edu/twiki_phat/pub/Main/PHATMeetingJPL/Banerji.ppt

Metrics 3: σ_{68} vs spec-z



Interval in which 68% of galaxies have the smallest difference between their spectroscopic and photometric redshifts

Abdalla+2009

Credit: M Banerji, Photo-z testing workshop, JPL Dec/2008

http://www.astro.caltech.edu/twiki_phat/pub/Main/PHATMeetingJPL/Banerji.ppt

Summary

- ✓ Accurate redshifts are a fundamental part of key cosmological observations. Without them, nothing works. Already one of the major sources of systematic errors in WL observations.
- ✓ Basic principles from galaxy physical properties are well-understood. It is essentially a technical/astrophysical problem, not a cosmological one.
- ✓ Spectroscopy: very precise, but very expensive. Good for LSS measurements.
- ✓ Main current challenge: mot mainstream methods are quite artesanal, lots of human intervention.
- ✓ Photometry: loads of galaxies, low precision, needs spectra to calibrate. But WL needs those galaxies, so that's the way to go.
- ✓ Not accurate enough yet. Also, huge problem with representative training sets for machine learning methods!