Principles of IFS: data analysis:
spatial binning, continuum subtraction, line fitting

IFS Analysis tools and methods:
using Starlight to study stellar populations

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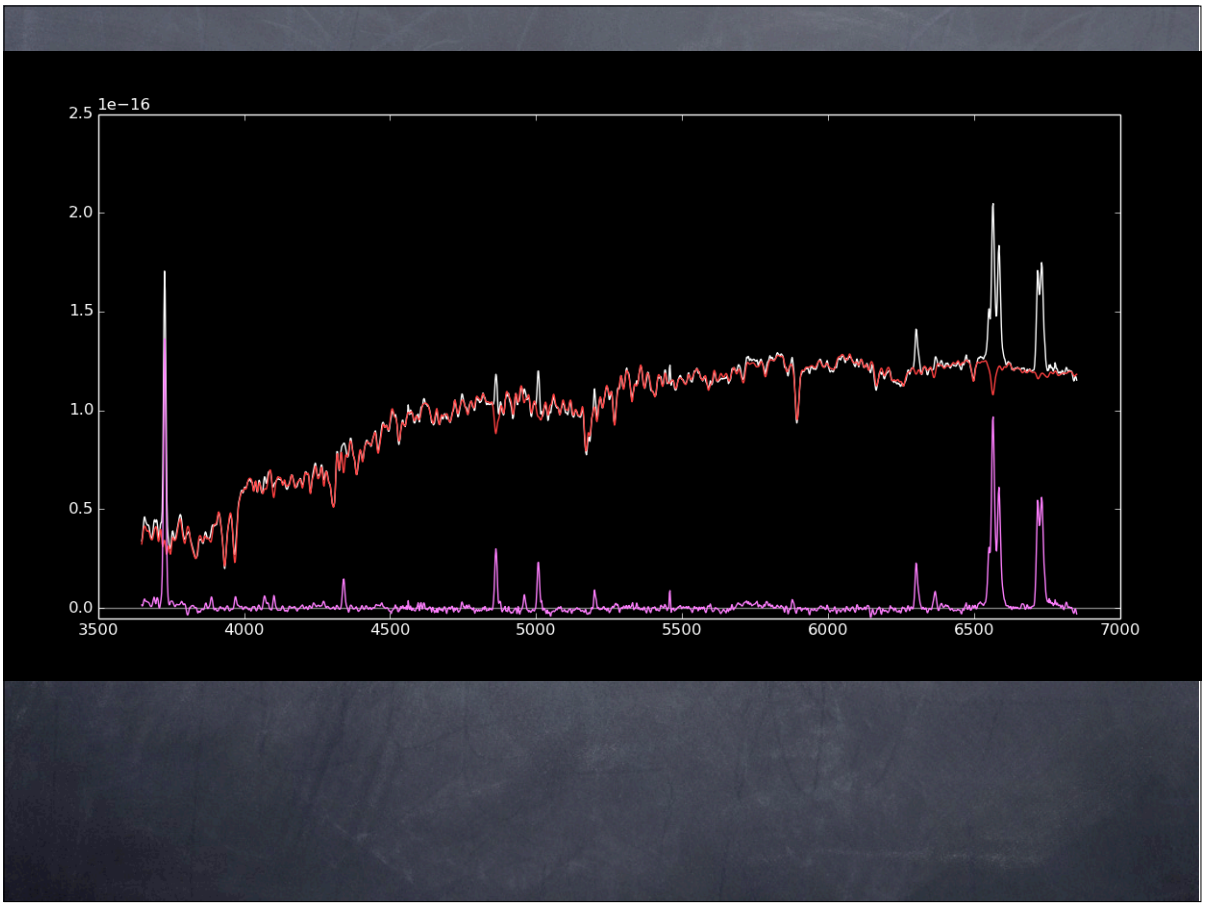
GH2014 IFS School

1



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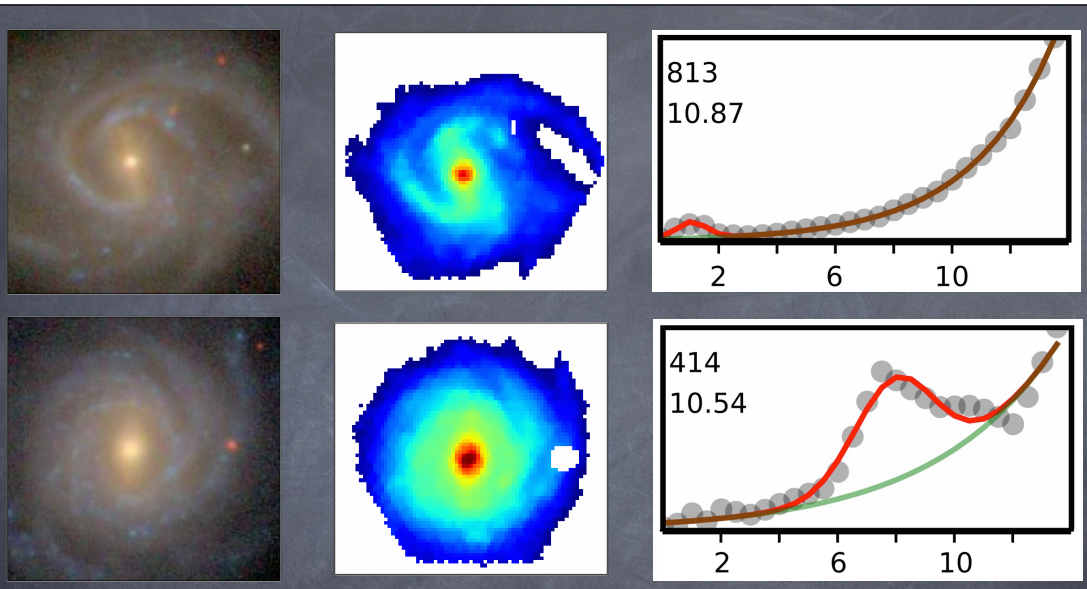


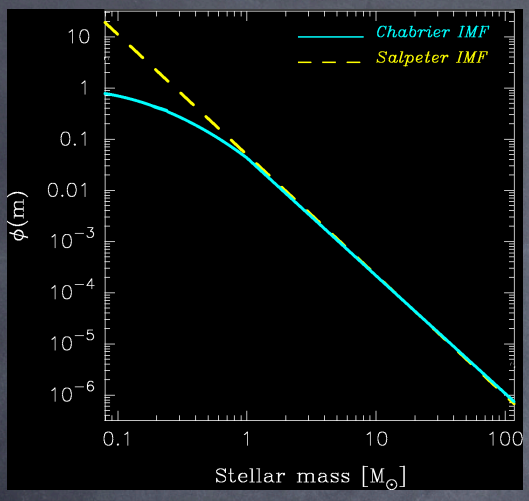
gas+stars stars gas

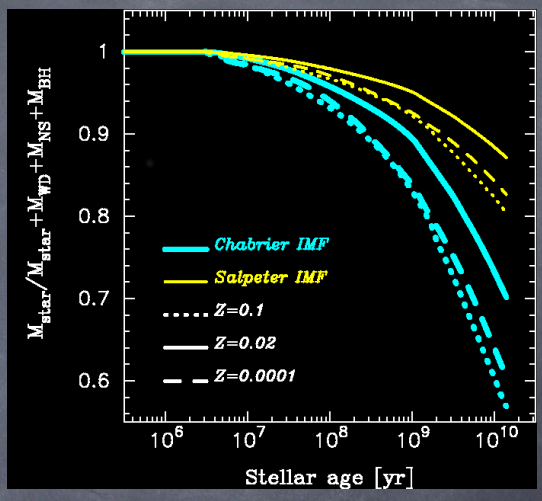
Star formation proceeds at different rates in different locations at different epochs.

Different SF diagnostics: Ha, UV, U-V vs. B-V, IR, etc

We characterize SF as: continuous, bursts, exponential decay, etc
These have more of less meaning depending on context.

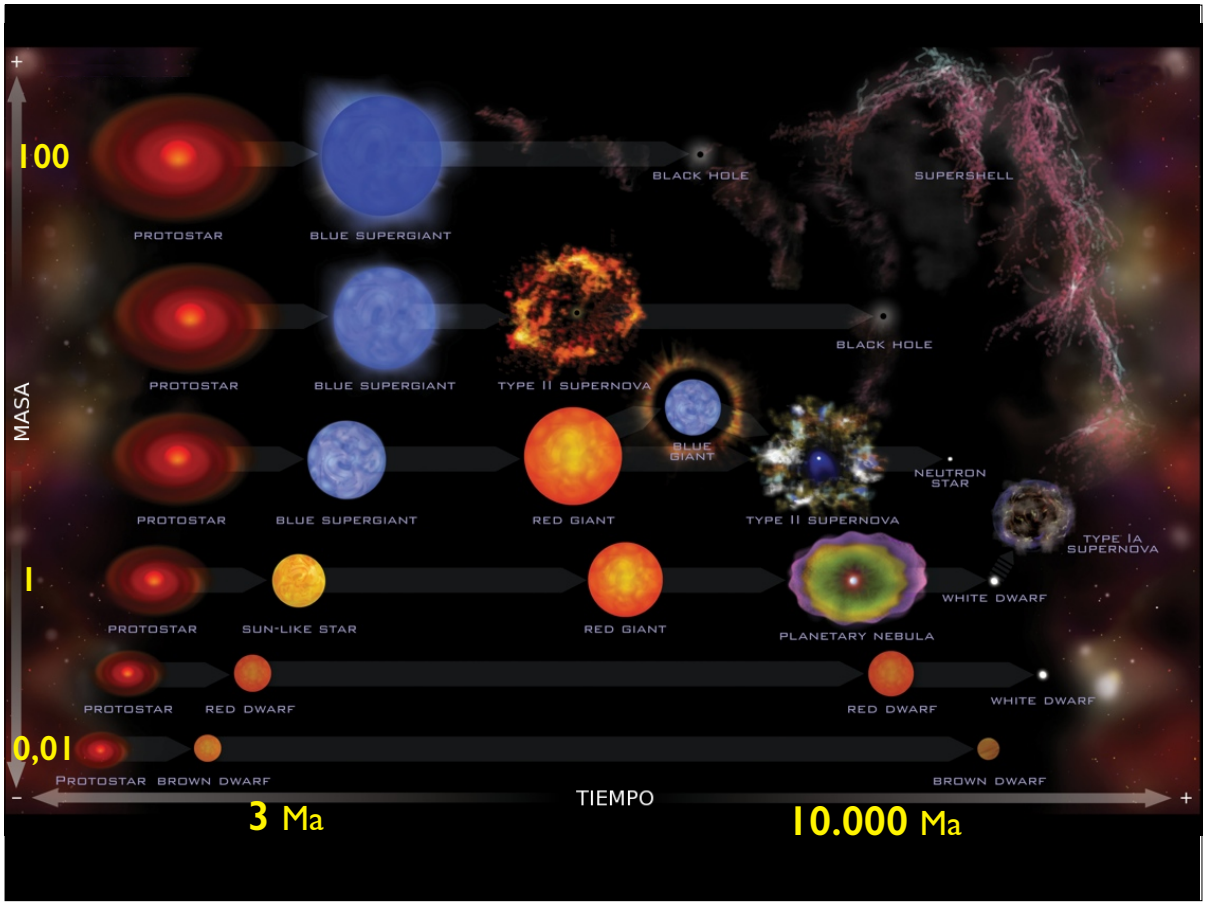
Initial Mass Function (IMF)



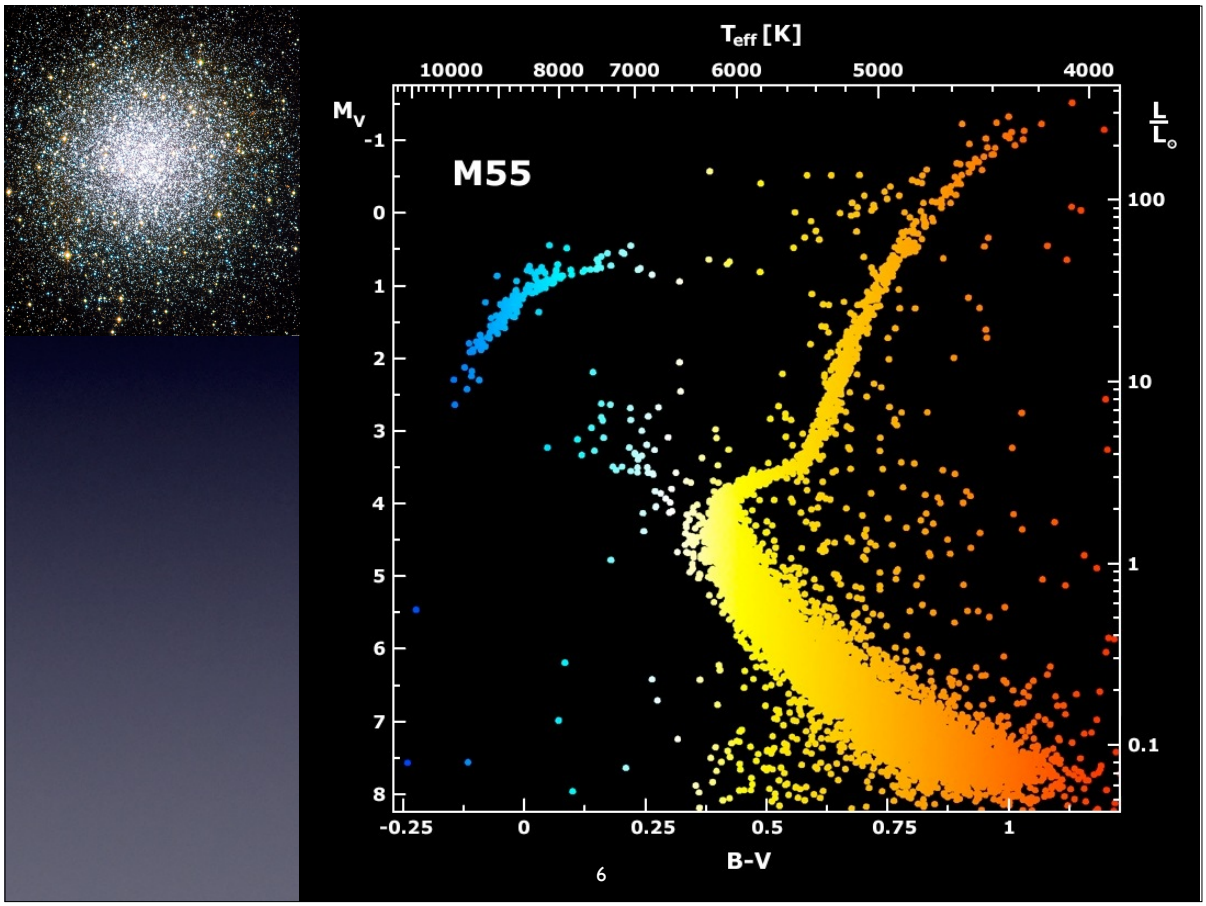


I. SHIMIZU, A. K. INOUE, 2013, PASJ 65, 96

- At what level can we talk about IMF? HIIr, galaxy, Starbursts,…
- Universal?
- Why is IMF important? stars of different mass evolve at wildly different rates


+
100
MASA
1
0,01
−
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
TYPE IA SUPERNOVA
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR BROWN DWARF
BROWN DWARF
TIEMPO
3 Ma
10.000 Ma
+

5


T_eff [K]
10000
8000
7000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
M55
L/L_o
100
10
1
0.1
-0.25
0
0.25
0.5
0.75
1
B-V
6

6

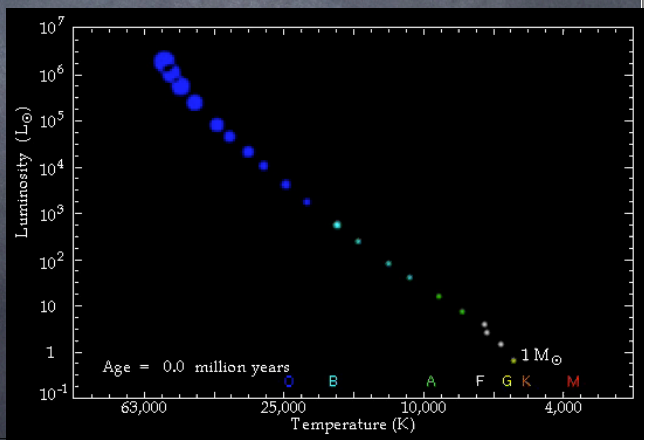
How well do we know stellar evolution?
There are phases difficult to understand: e.g. fast evolutionary stages,…
'Complications' that we are now starting to deal with: Mass loss, Rotation, Binarity, etc

All these change 'simple' stellar evolution …
We still use fairly naïve stellar evolution models for population synthesis.
These complexities are coming …

How well do we know the observables outcome of this evolution: the atmospheric spectrum or SED ?
More or less well in the optical, worse in the NIR and NUV, …
enormous uncertainties in the FUV ionizing: metallicity, evolution (mixing, etc), …

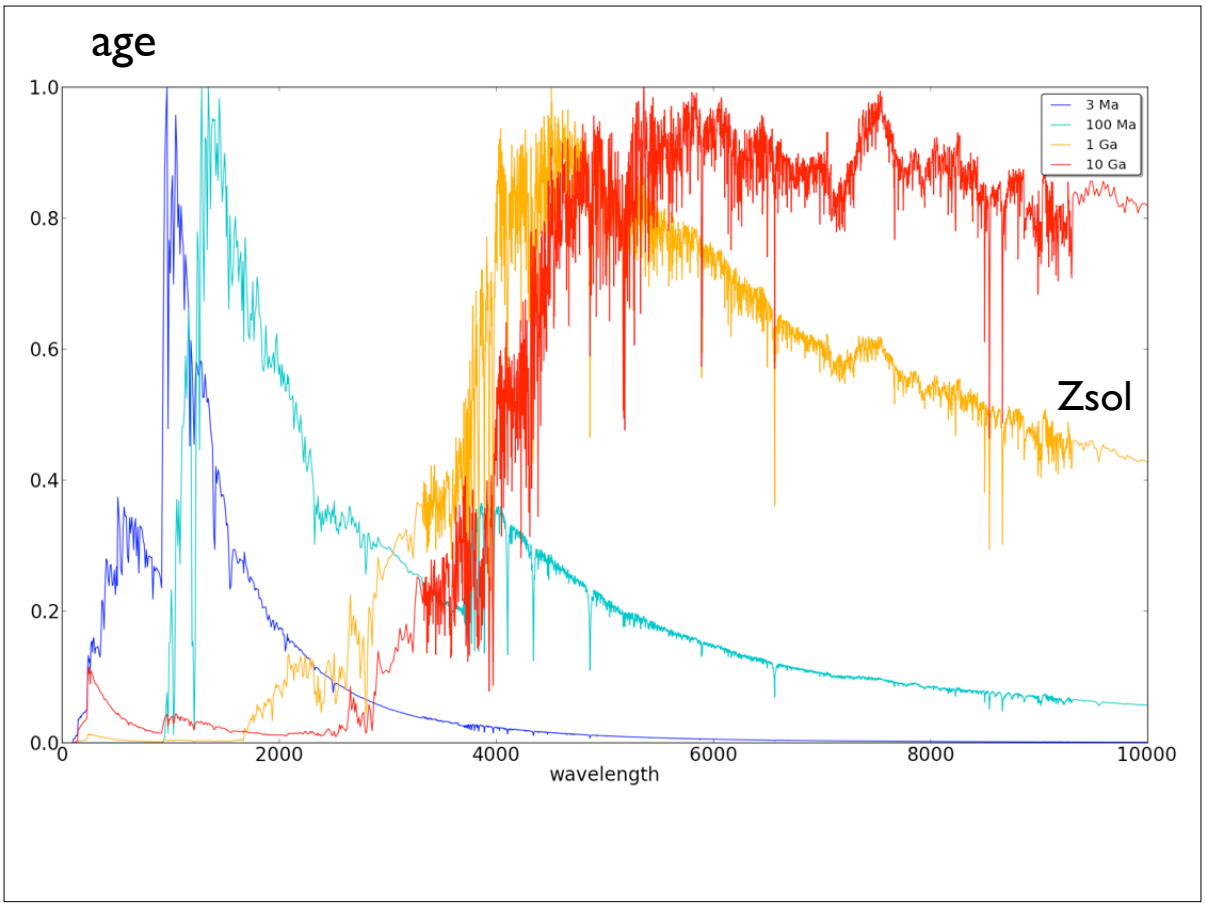
All these uncertainties translate into:
- shape of SED
- relative EW of absorption lines
- shape of absorption profile

We build ensembles of 'coeval' stars from a total mass of gas transformed into stars, with an IMF, and with a metallicity: add all individual spectra and obtain an SSP.



http://bcs.whfreeman.com/

7



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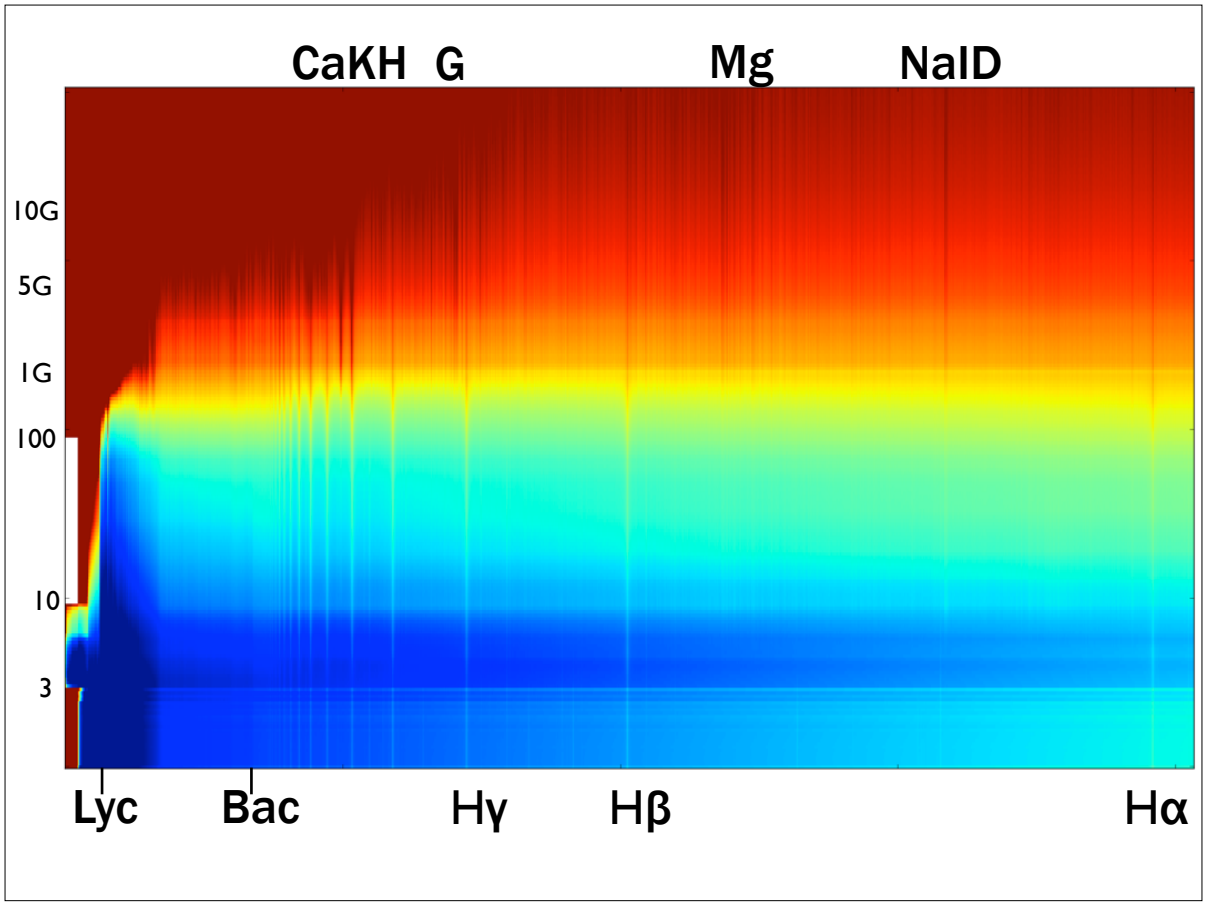
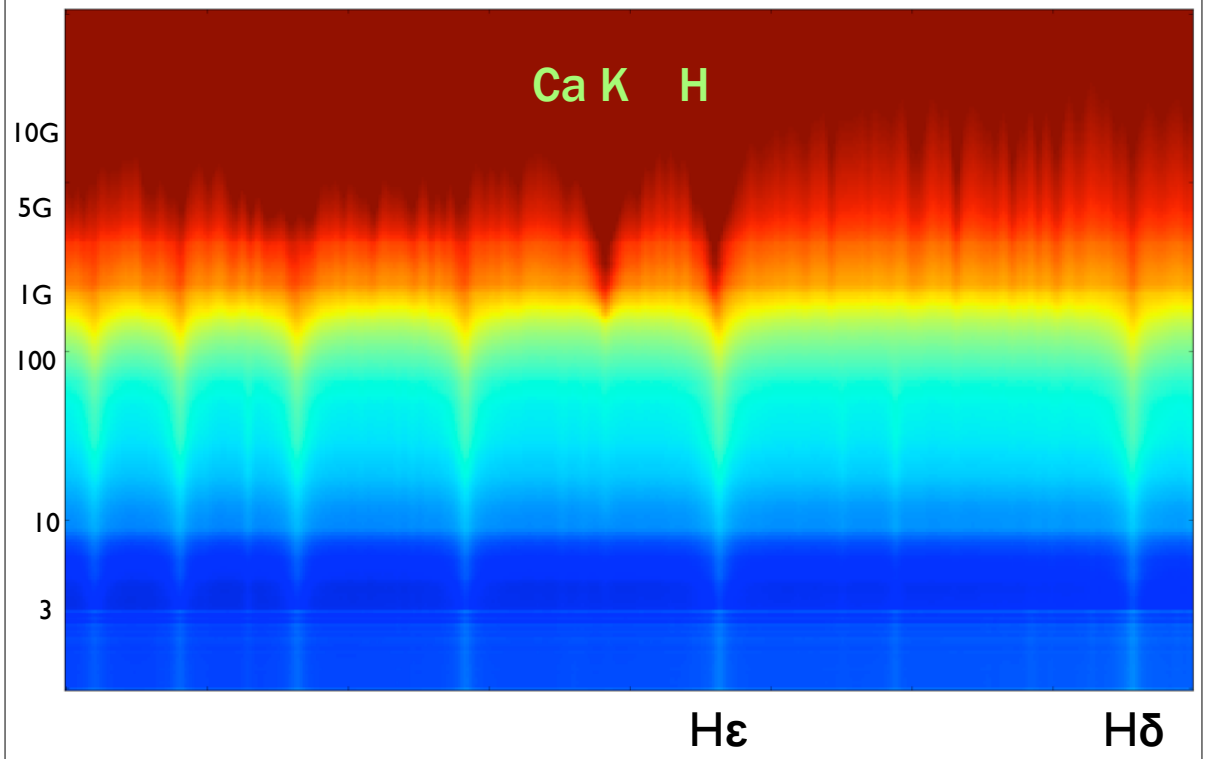
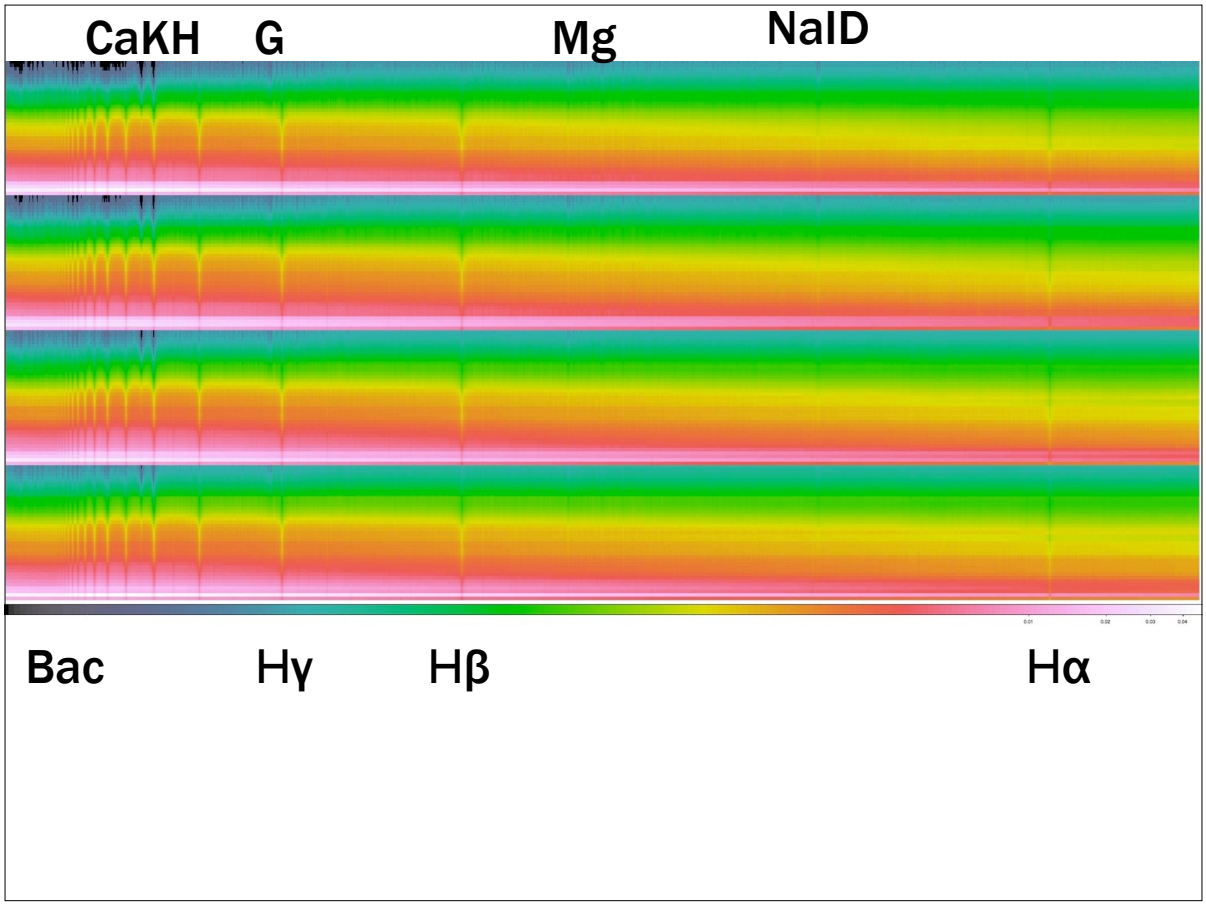


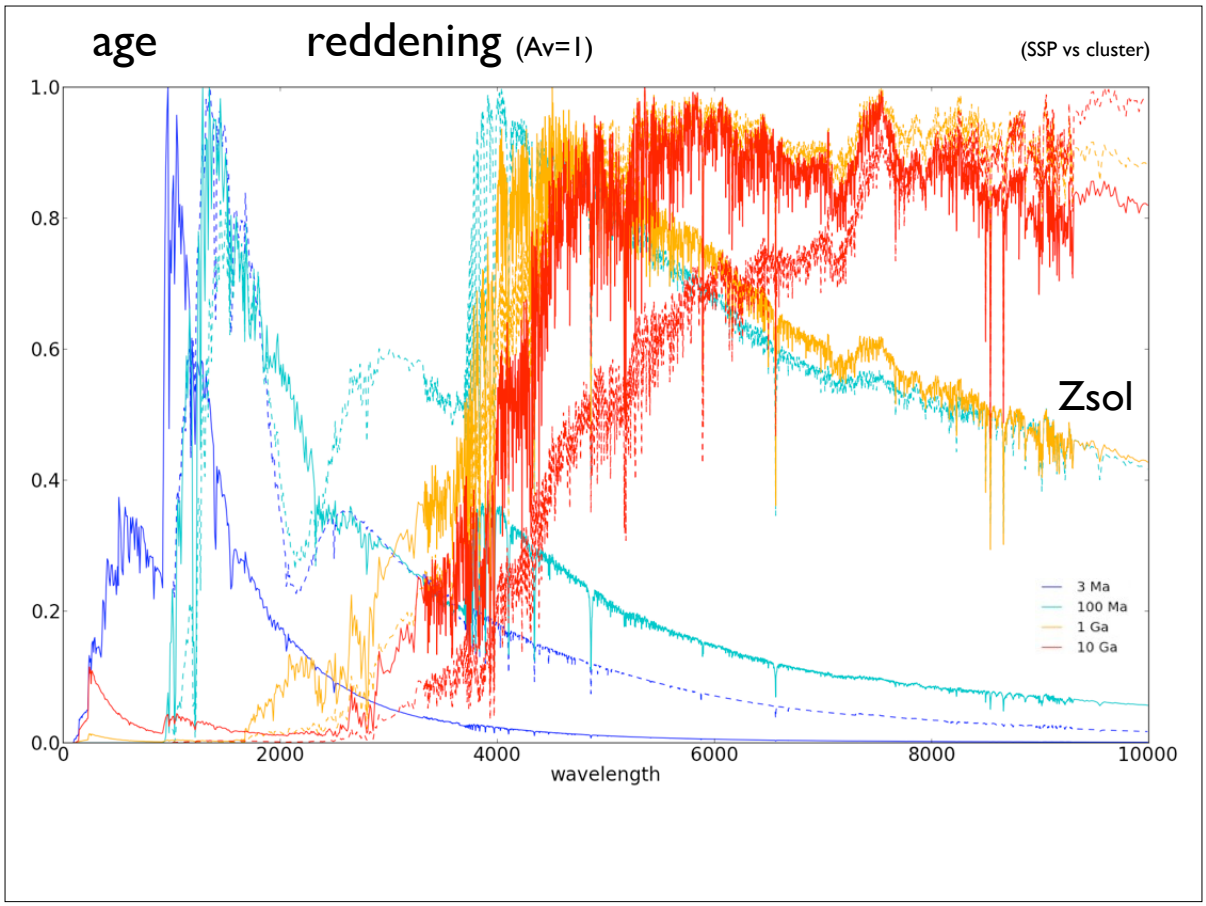
There is information in line profiles and in weak lines



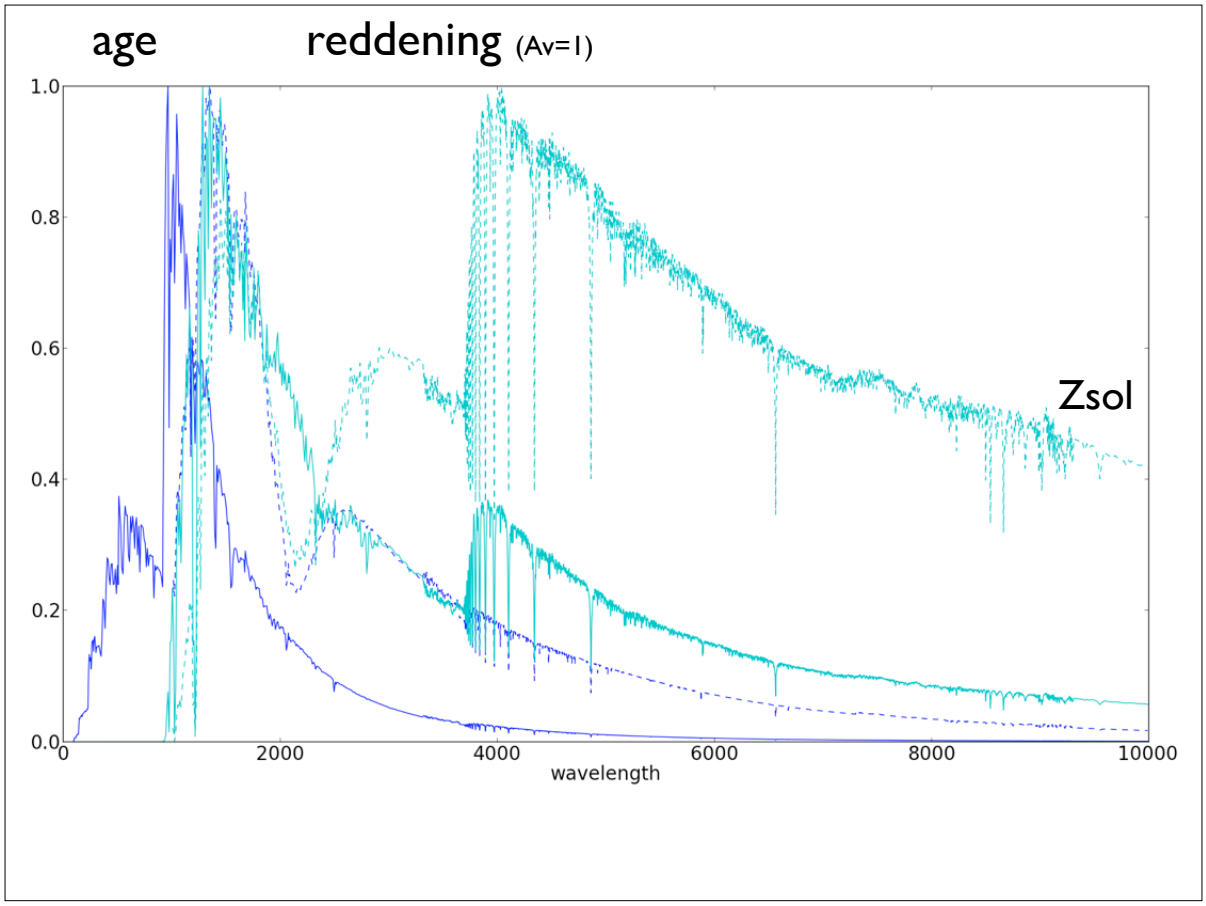
Younger spectra dominated by Balmer lines and continuum shape
Older spectra dominated continuum shape, metal lines (both strong and faint), and molecular bands


CaKH
G
Mg
NaID
Bac
Hγ
Hβ
Hα

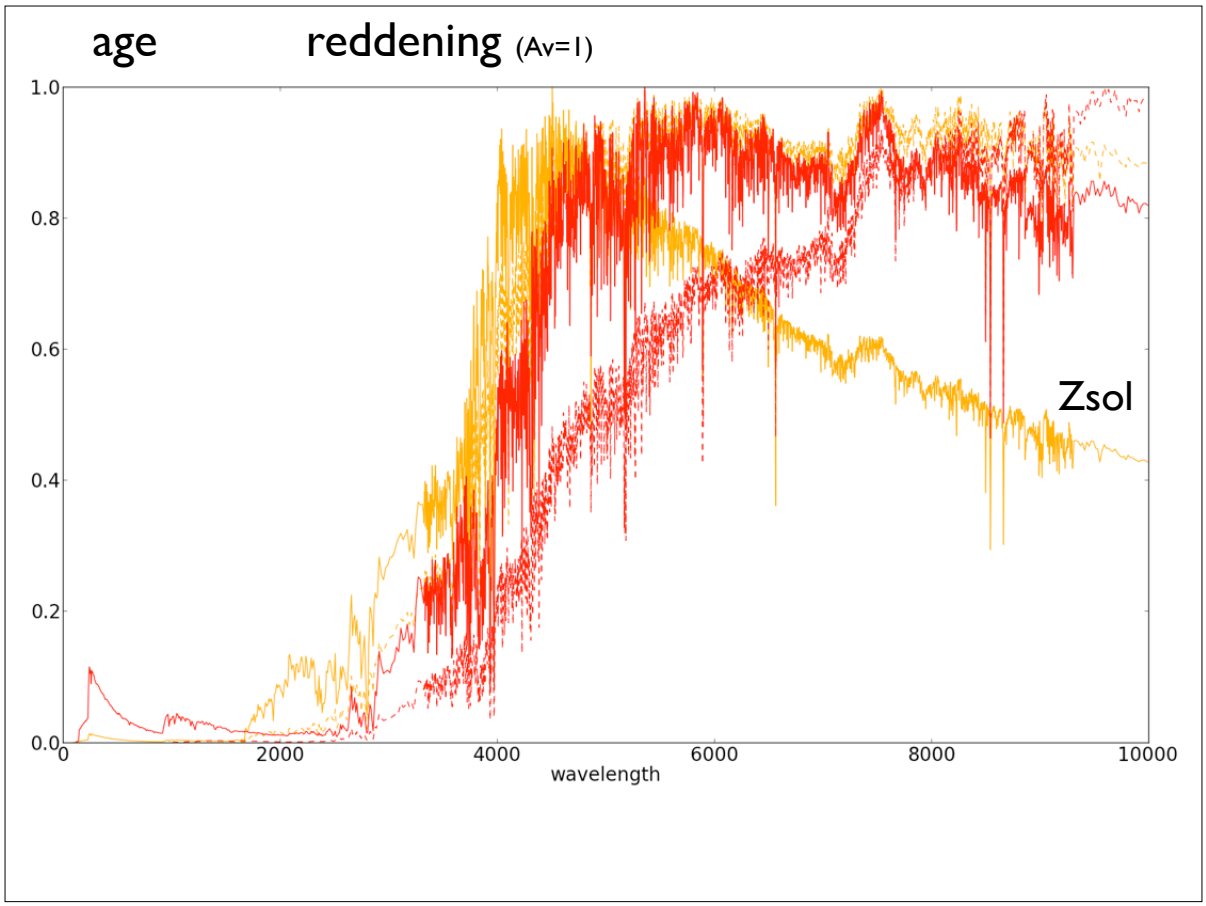
11


age
reddening (Av=1)
(SSP vs cluster)
Zsol
3 Ma
100 Ma
1 Ga
10 Ga
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
wavelength

12

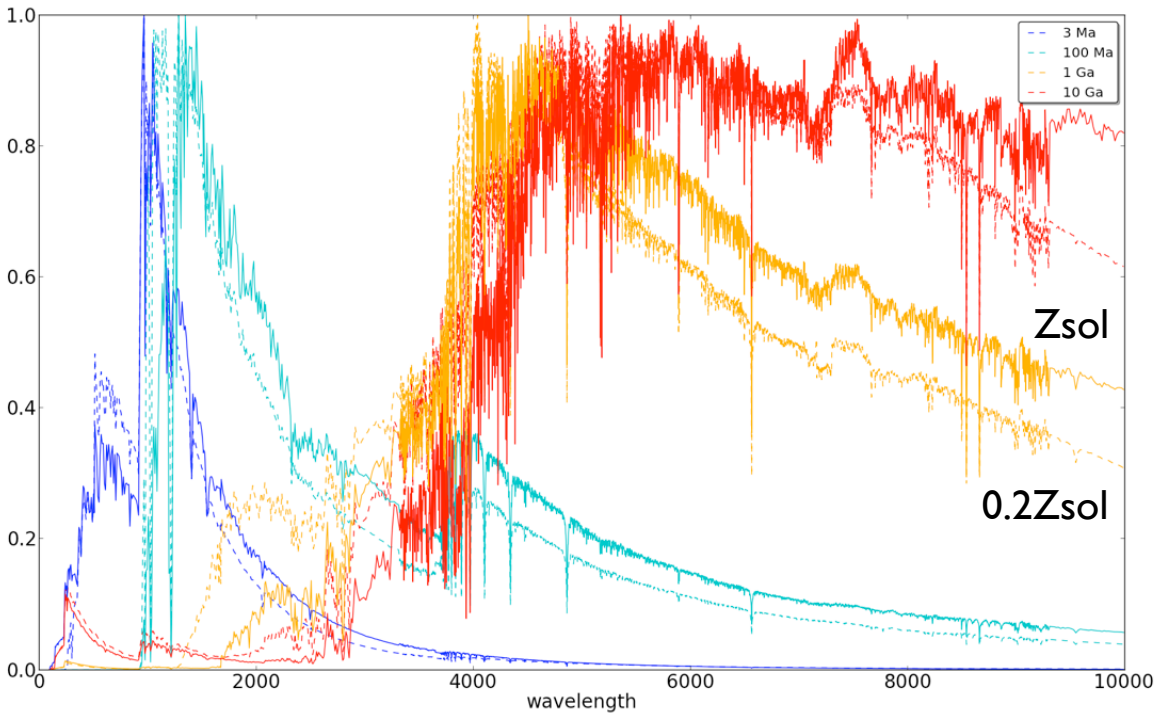

age
reddening (Av=1)
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
wavelength
Zsol

13


age
reddening (Av=1)
1.0
0.8
0.6
0.4
0.2
0.0
0
2000
4000
6000
8000
10000
wavelength
Zsol

14

age & metallicity



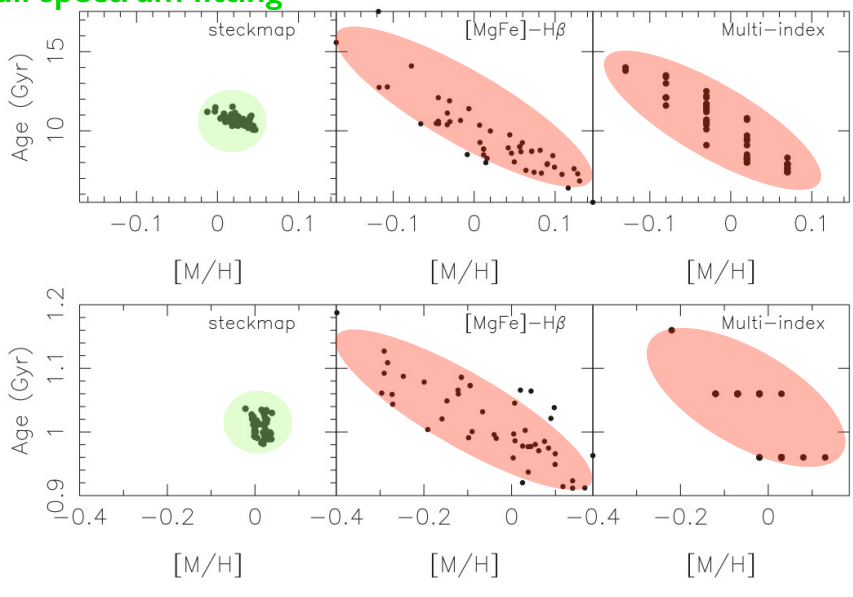
degeneracy

age - metallicity - extinction

redder - redder - redder

full spectrum fitting

line indeces



P. Sánchez Blázquez et al. 2011

absorption line profile degeneracy

age - metallicity - kinematics

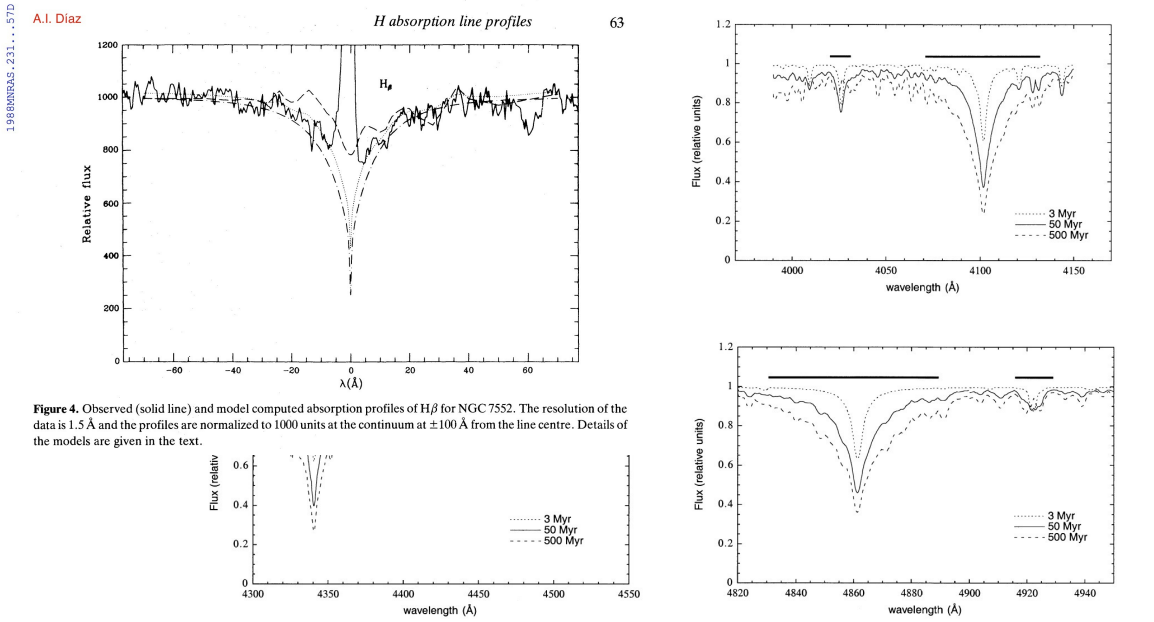


Figure 4. Observed (solid line) and model computed absorption profiles of Hβ for NGC 7552. The resolution of the data is 1.5 Å and the profiles are normalized to 1000 units at the continuum at ±100 Å from the line centre. Details of the models are given in the text.

FIG. 2.—Synthetic spectra from 3700 to 5000 Å predicted for an instantaneous burst formed following a Salpeter IMF between $M_{low} = 1\ M_\odot$ and $M_{up} = 80\ M_\odot$ at ages 3, 50, and 500 Myr. The horizontal lines indicate the windows used for measuring the equivalent widths.

GONZÁLEZ DELGADO, LEITHERER, & HECKMAN 1999

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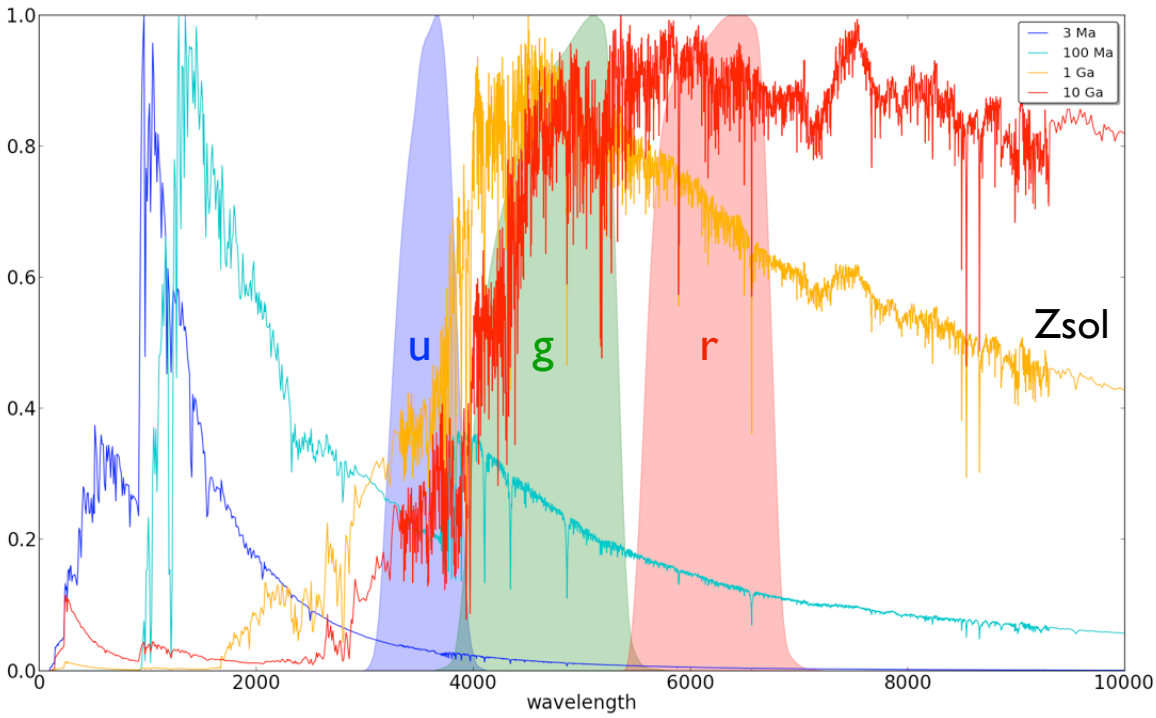
age

filters



sensitive to overall shape but not line info (EW or shape)

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There is information in:

- the shape of the continuum
- the shape of the strong lines
- in a host of weaker lines

This information changes with:

- age
- metallicity
- extinction
- kinematics

MUCH less degeneracy
in full spectral fitting
than using indeces or colors

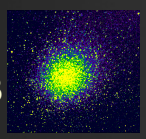
Use all available information
Go for full spectrum fits !

The METHOD

Decomposing galaxy spectra: The basics...

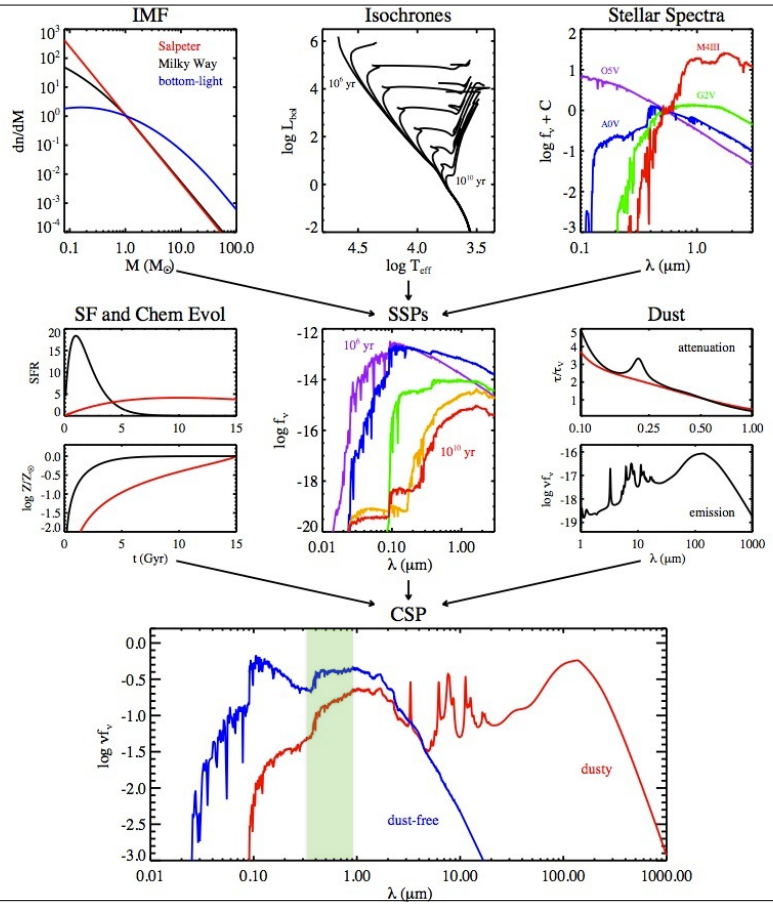

= M_1

+ M_2

+ M_3

+ ...

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$

Observables	SFH: mass or light fractions	Spectral Base	Dust:
Full spectrum: F_λ	→ Pop vector	SSPs from BC03, Granada, Pegase, "CB07", Vazdekis, …	1 τ_V? 2τ_V? $\tau_V(t,Z)$? …



C. Conroy, 2013 ARAA

where is the Mass and where the Luminosity

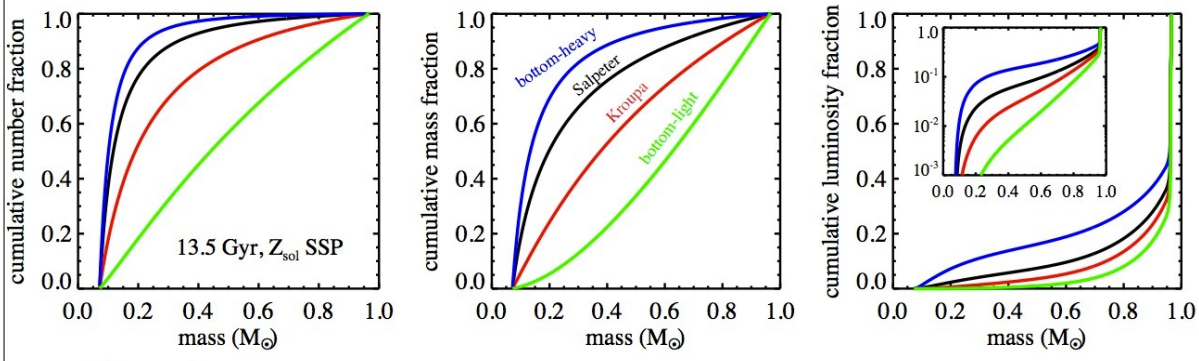


Figure 4:

Fractional contribution to the total number, mass, and bolometric luminosity as a function of stellar mass for a 13.5 Gyr solar metallicity model. Lines correspond to different IMFs: a bottom-heavy with logarithmic slope $x = 3.0$ (blue line); Salpeter ($x = 2.35$; black line); MW IMF (specifically a Kroupa IMF; red line); a bottom-light IMF (specifically of the form advocated by van Dokkum (2008); green line). The inset in the right panel shows the cumulative luminosity fraction in logarithmic units. Low mass stars dominate the total number and mass in stars, but contribute a tiny fraction of the luminosity of old stellar populations.

C. Conroy, 2013 ARAA

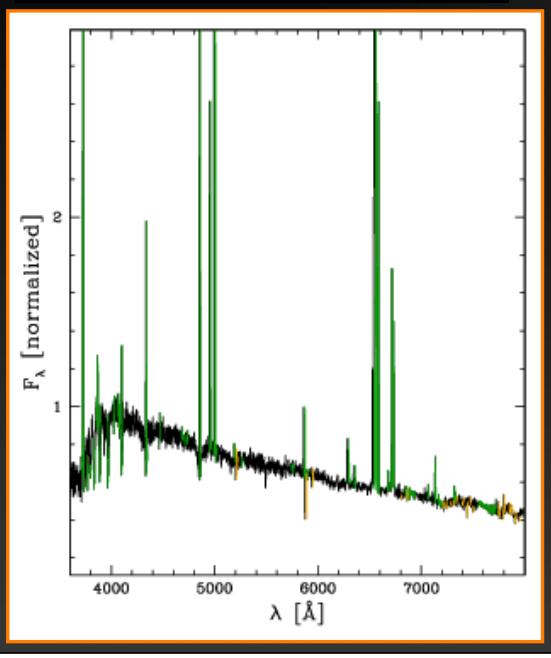
Input

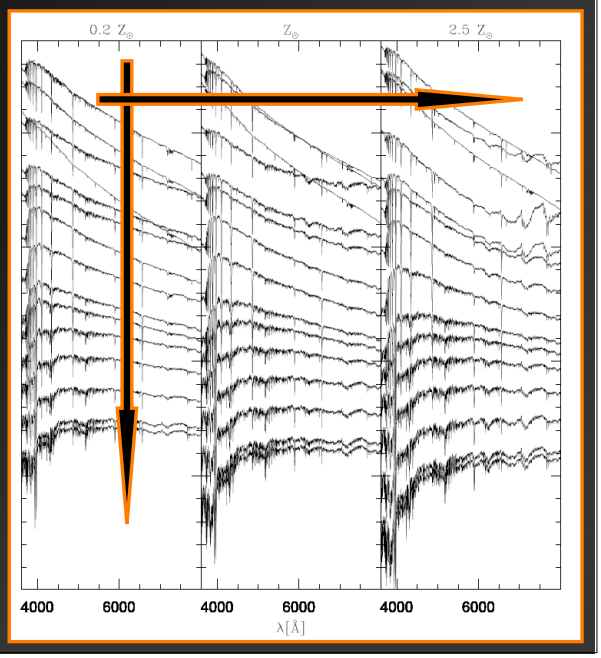
www.starlight.ufsc.br

(A) Observed spectrum

(B) Spectral Base

eg, N >> 1 SSPs from BC03





The METHOD

Inverse Population Synthesis: How?

Hypothesis space ("priors")

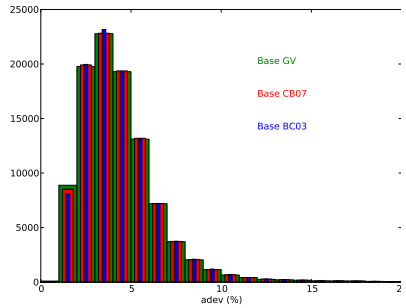
Only 1 Z? Z = Z(t)?
A_λ = ? Dust geometry? $A_\lambda(t,Z)$?
Kinematics?
Which base? (clusters, models,...)
Which SFH parameters?

Observables space → Parameter space

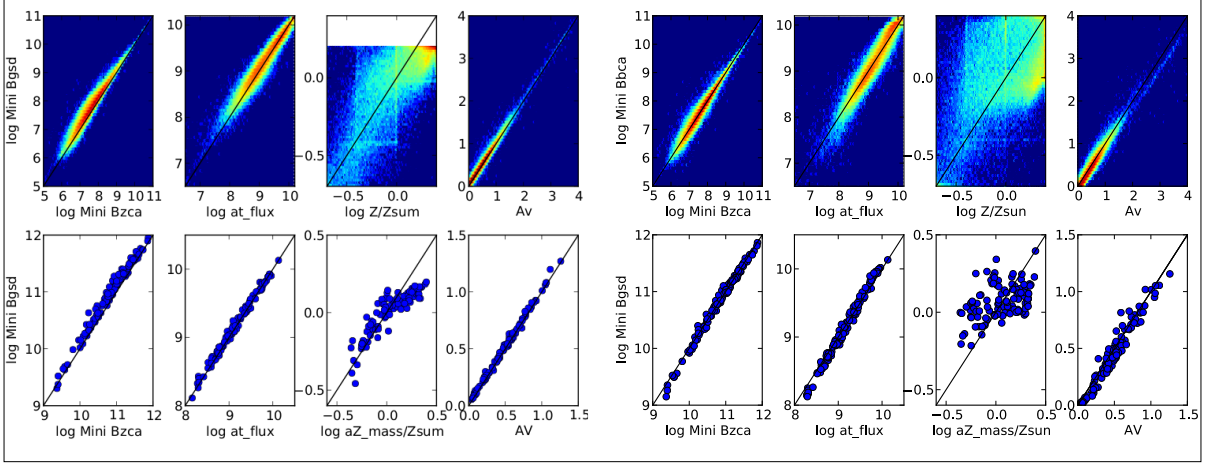
Method

Brute force discrete grid search?
Convex-algebra?
Markov-Chains?
PCA? AI-techniques?
Comparisons to library of models?
Compression on input or output?
How to deal with degeneracies?

$$L_{gal}(\lambda) = \sum_{t,Z} M_{SSP}(t,Z) \times SSP(\lambda;t,Z) \times e^{-\tau(\lambda)}$$



Base	Bzca	Bgsd	Bbca	Bbsb
IMF	Chabrier	Salpeter	Chabrier	Salpeter
trazas	Padova94	Padova2000 + Geneva (<4 Myr)	Padova94	Padova2000
Librería	MILES + Granada	MILES + Granada	STELIB	STELIB
Modelos	CB07	Vazdekis+ Granada	BC03	BC03



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2D maps (x,y):
- stellar velocity
- stellar velocity dispersion
- mean stellar age
- mean stellar metallicity
- ionized gas velocity
- ionized gas metallicity
- dust extinction

0D
1D (r)

3D maps (x,y,t):
- star formation history
- stellar metallicity assembly history
- element abundance ratio
- stellar mass surface density
- star formation rate

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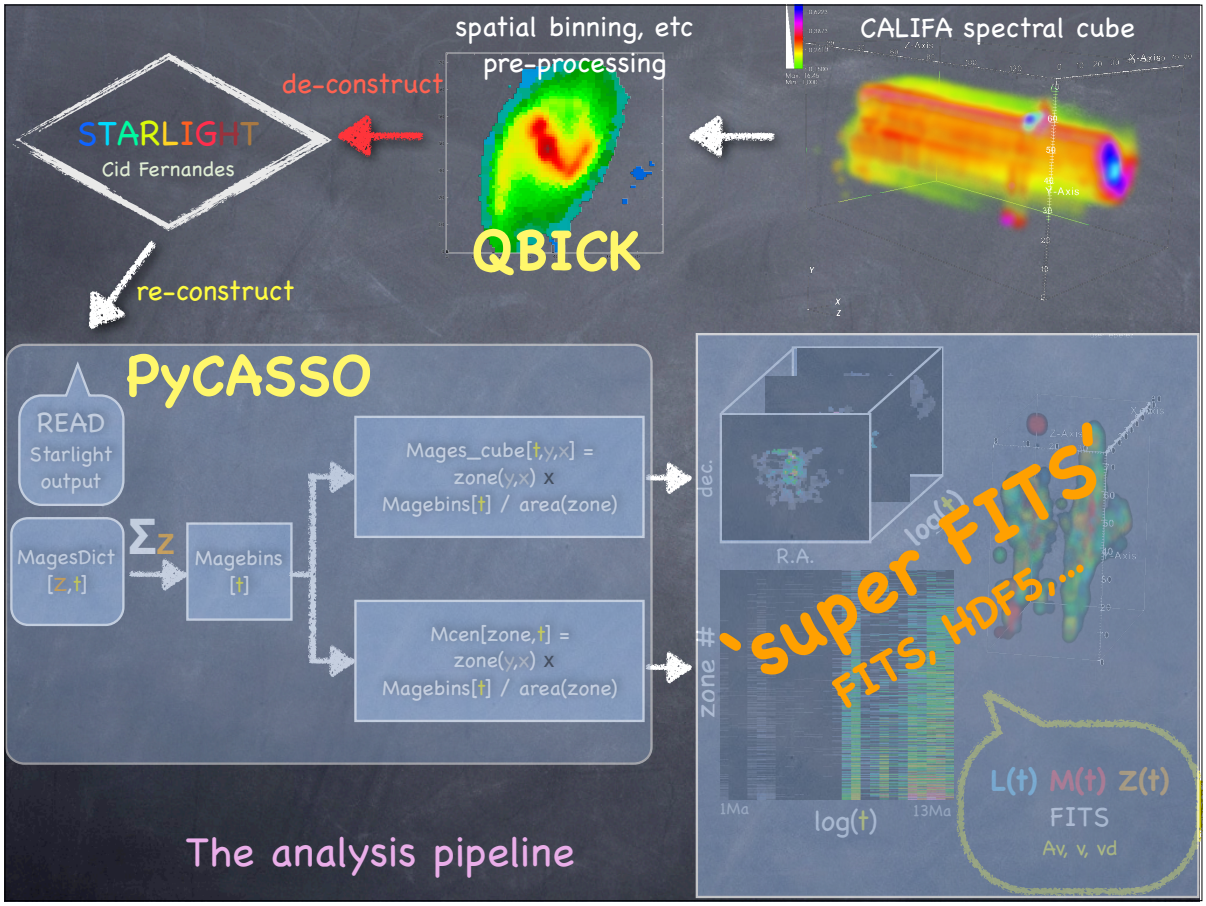

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Methods and procedures:

Cid Fernandes, R., et al. 2013, A&A, 557, 86

Uncertainties of SSP modelling:

Cid Fernandes, R., et al. 2014, A&A, 561, 130

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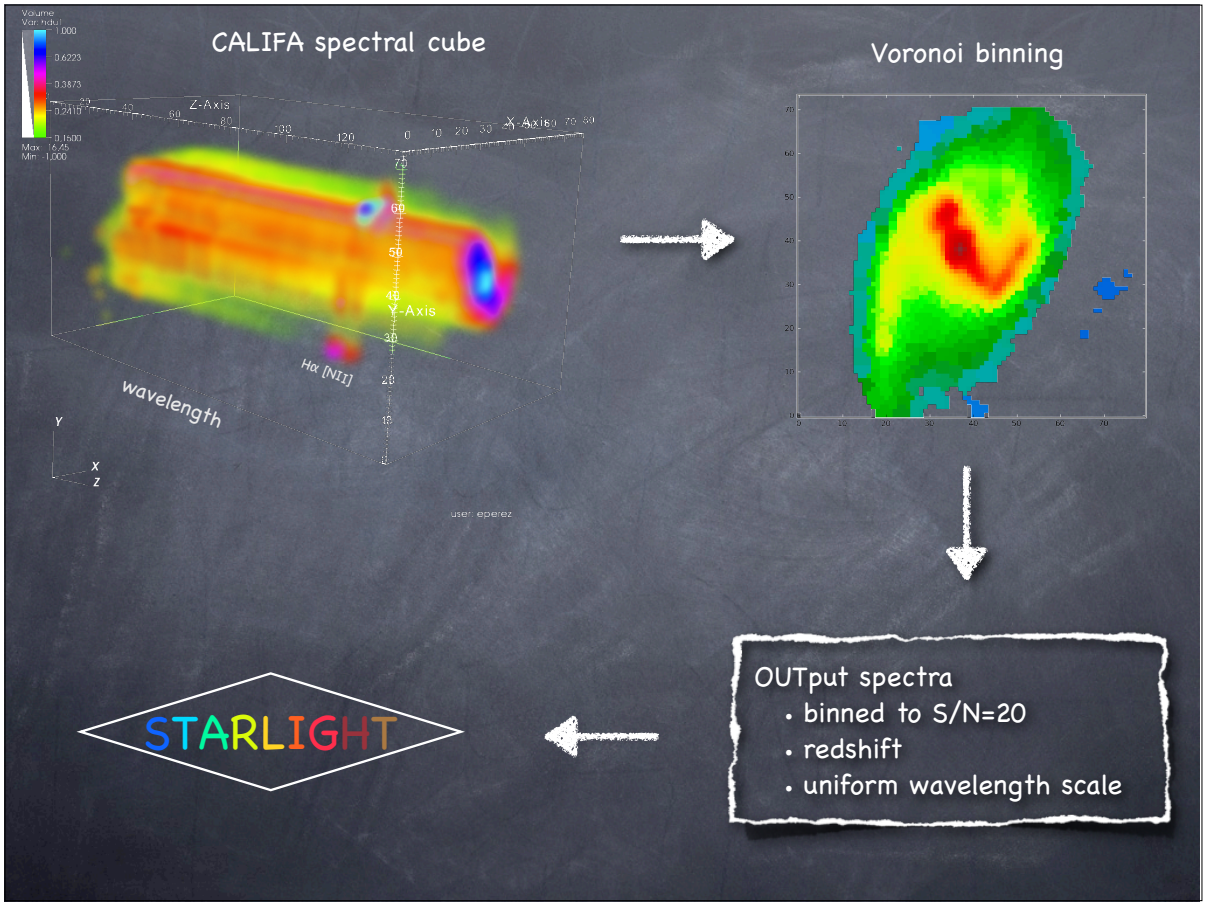
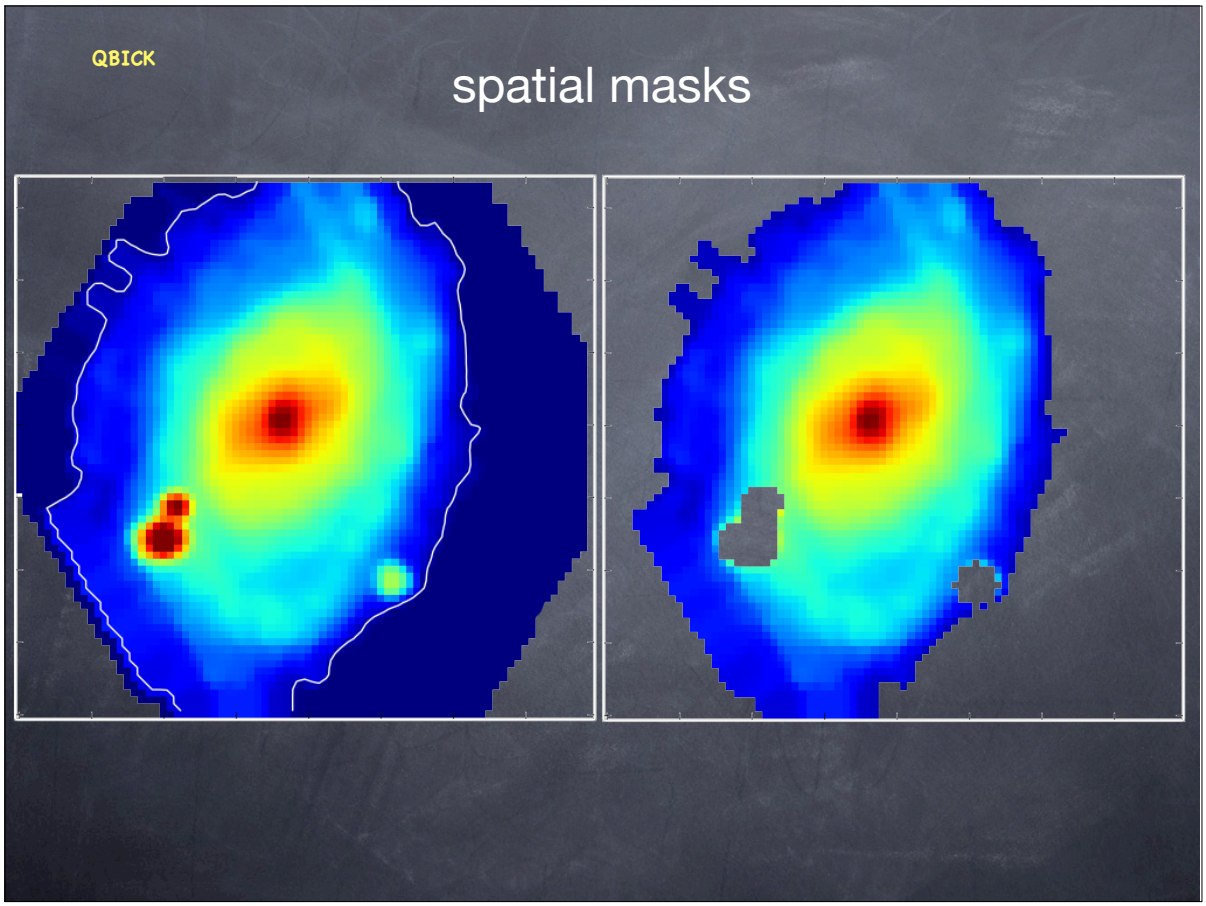

CALIFA spectral cube
Voronoi binning
Z-Axis
X-Axis
Y-Axis
wavelength
Hα [NII]
user: eperez
STARLIGHT
OUTput spectra
• binned to S/N=20
• redshift
• uniform wavelength scale

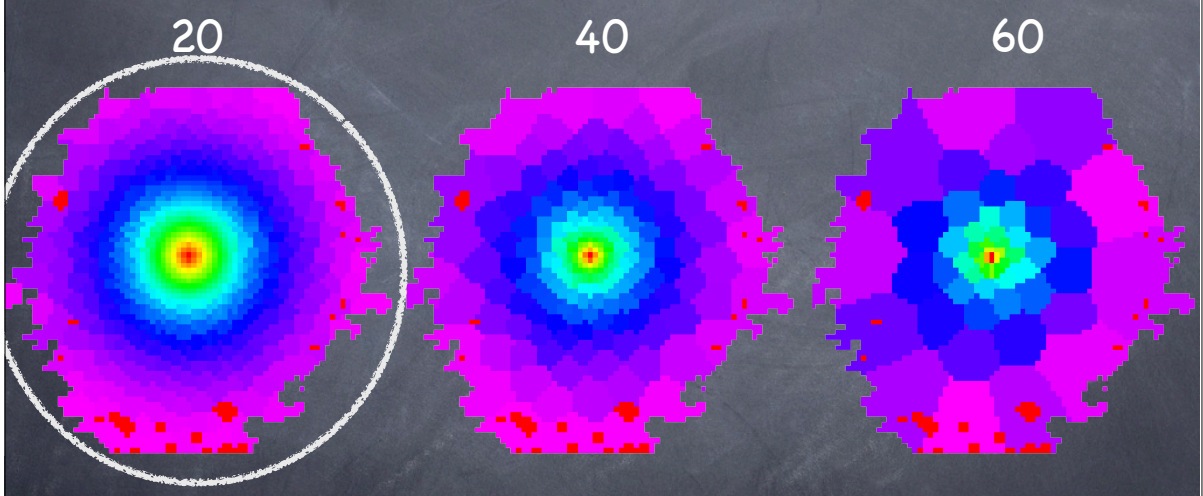
29


QBICK
spatial masks

30

QBICK

Spatial Binning to achieve a minimum S/N



Cappellari Voronoi code + error covariances

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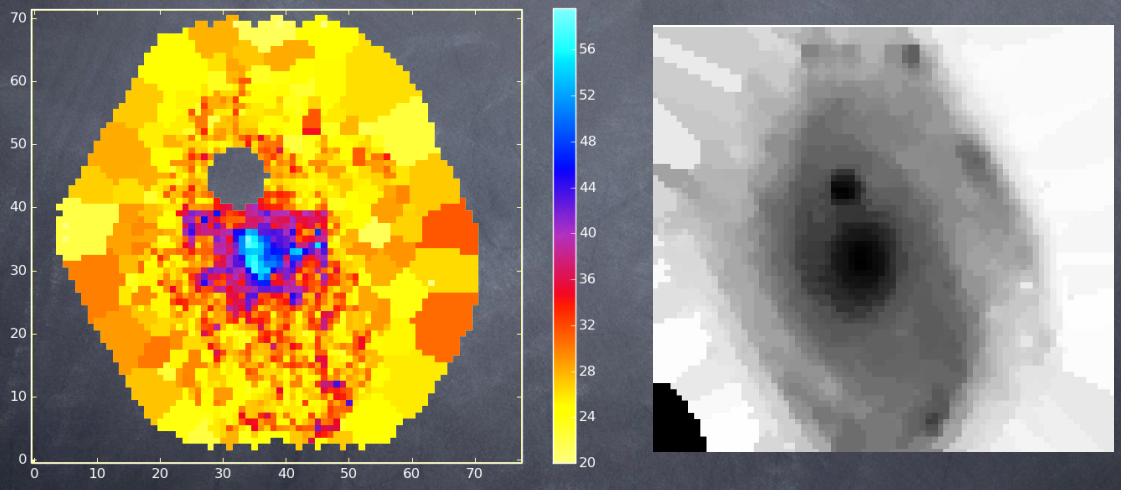
Spatial Binning to achieve a minimum S/N

Need for spatial binning: achieve target S/N
Options: stars vs. gas , geometry: Voronoi, surface brightness, …



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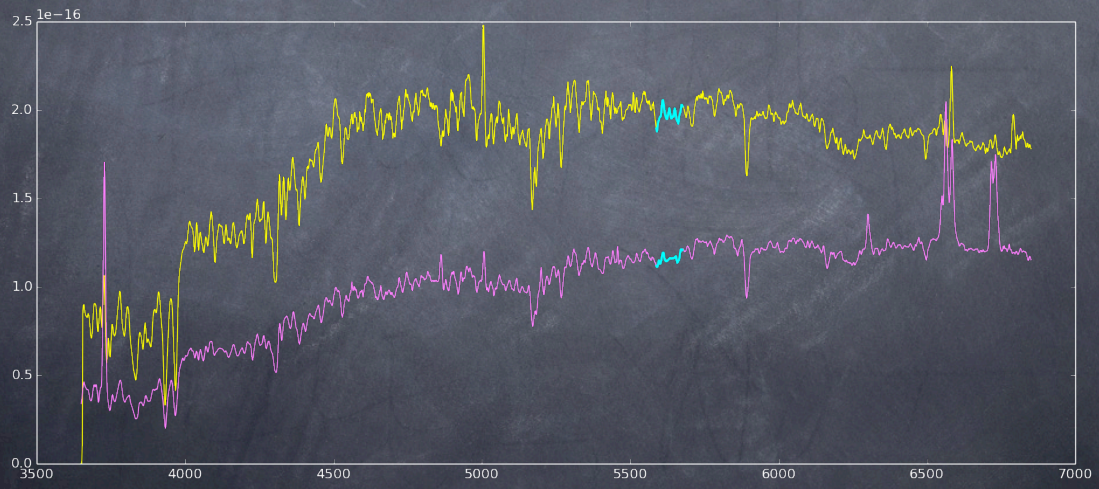
error measurement and propagation

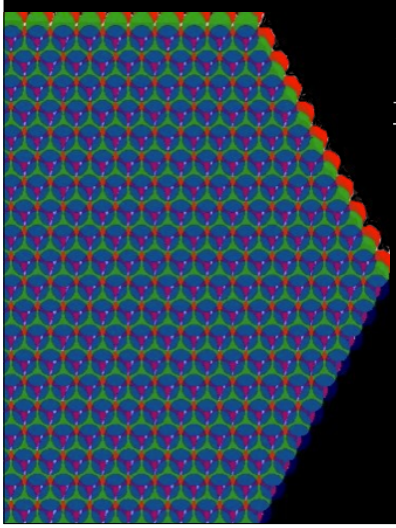
- Propagated from reduction pipeline

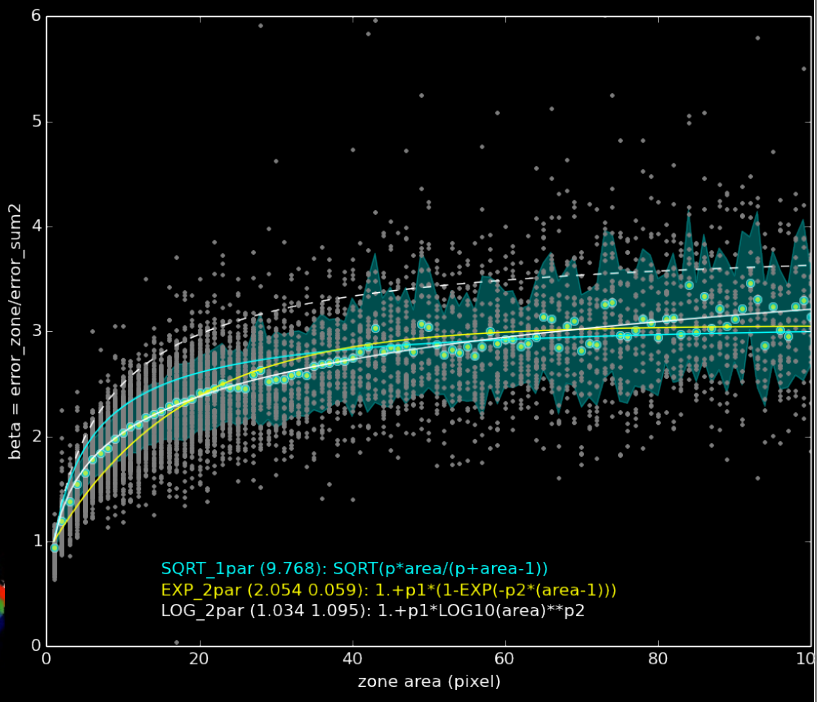
Husemann, B., et al. 2013, A&A, 549, 87

- re-measure by hand

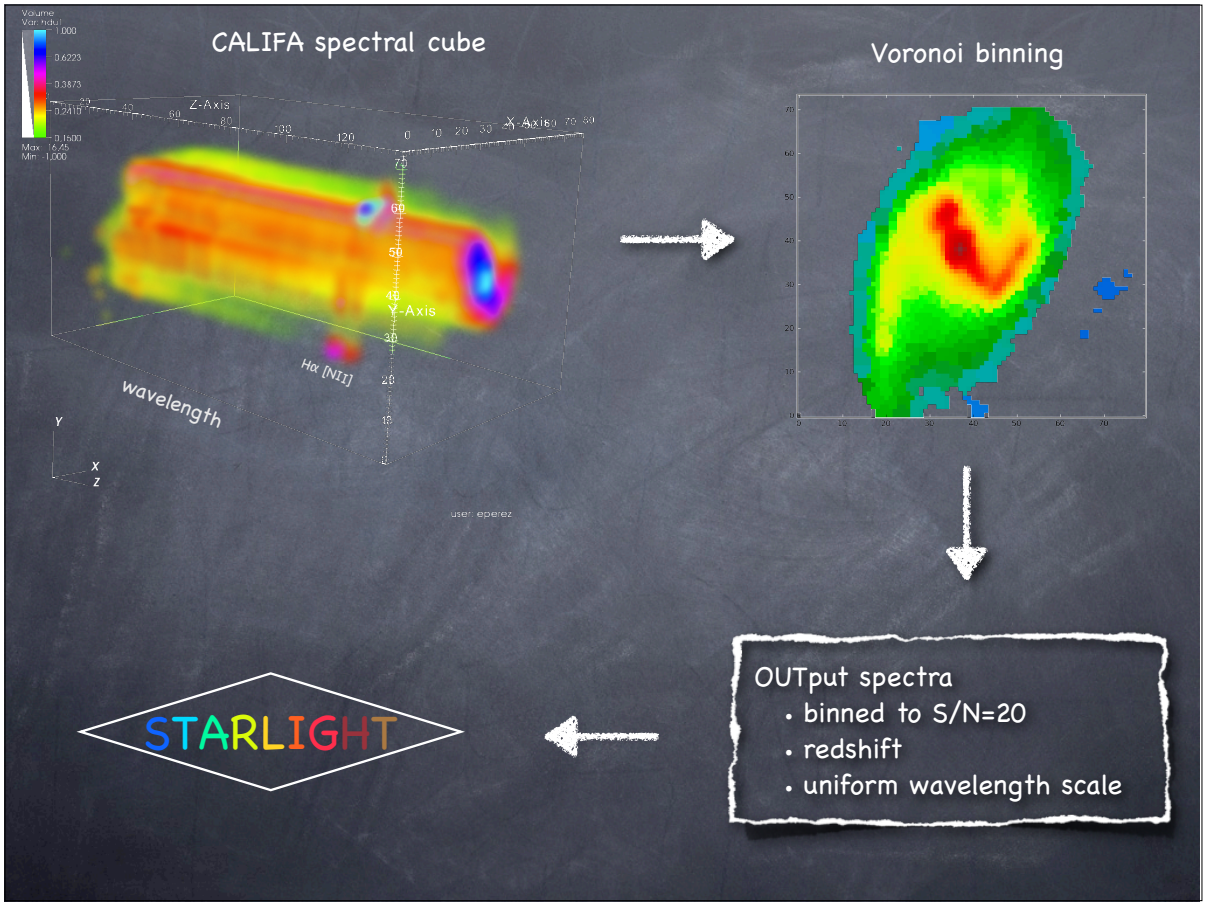


error propagation: spatial covariances





$$e_z = \beta_z(N_z)\sqrt{\sum_{k=1}^{N_z} \epsilon_k{}^2}$$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Voronoi binning
Z-Axis
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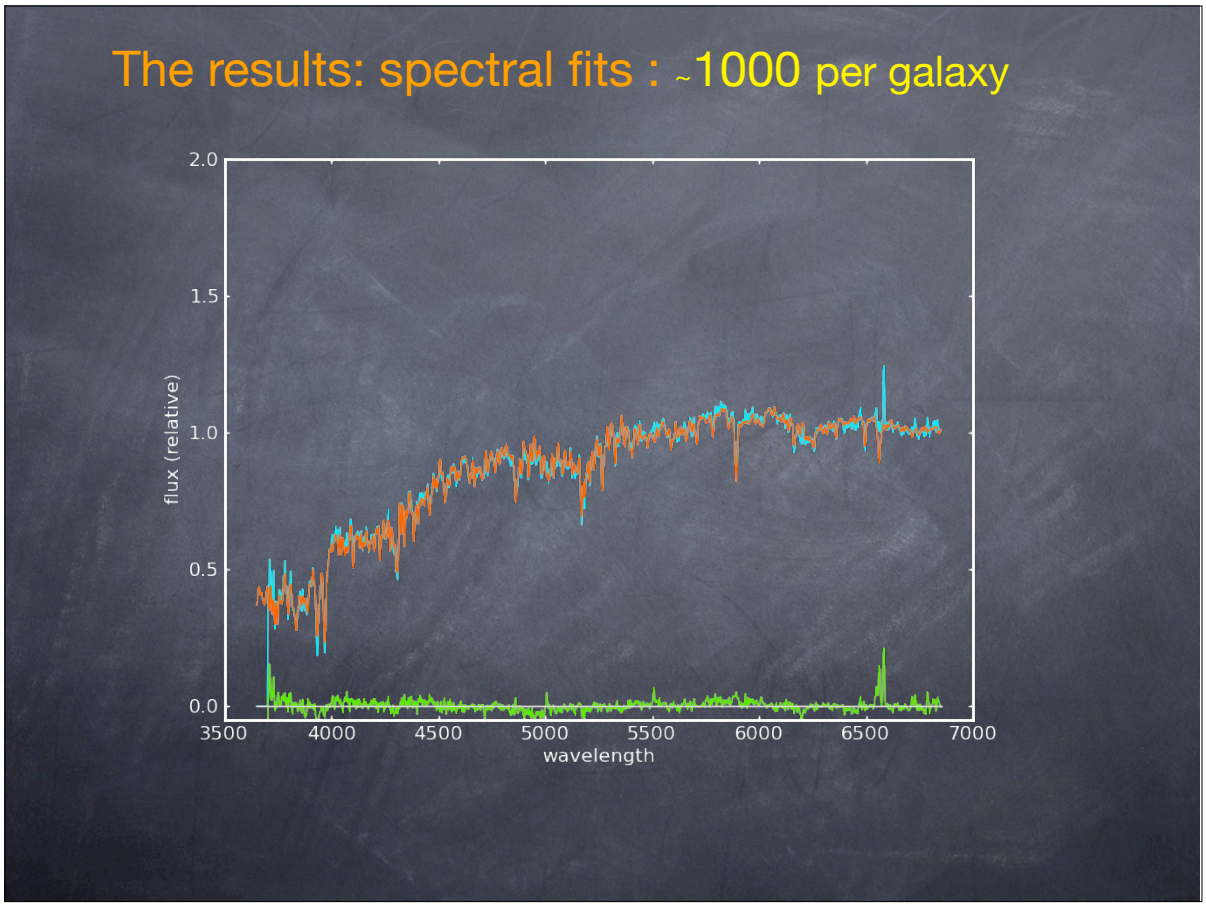
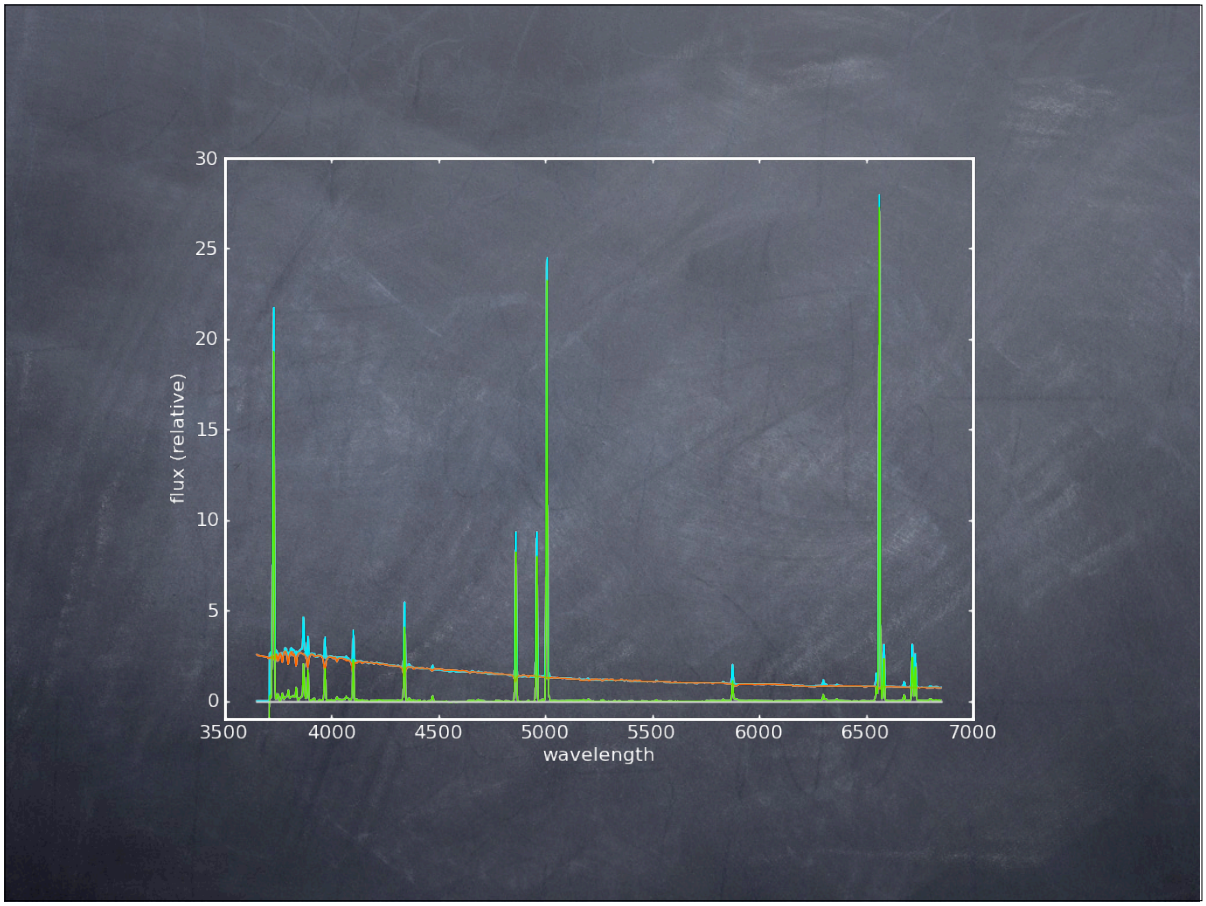
35


The results: spectral fits : ~1000 per galaxy
flux (relative)
wavelength
2.0
1.5
1.0
0.5
0.0
3500
4000
4500
5000
5500
6000
6500
7000

36


flux (relative)
wavelength
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4500
5000
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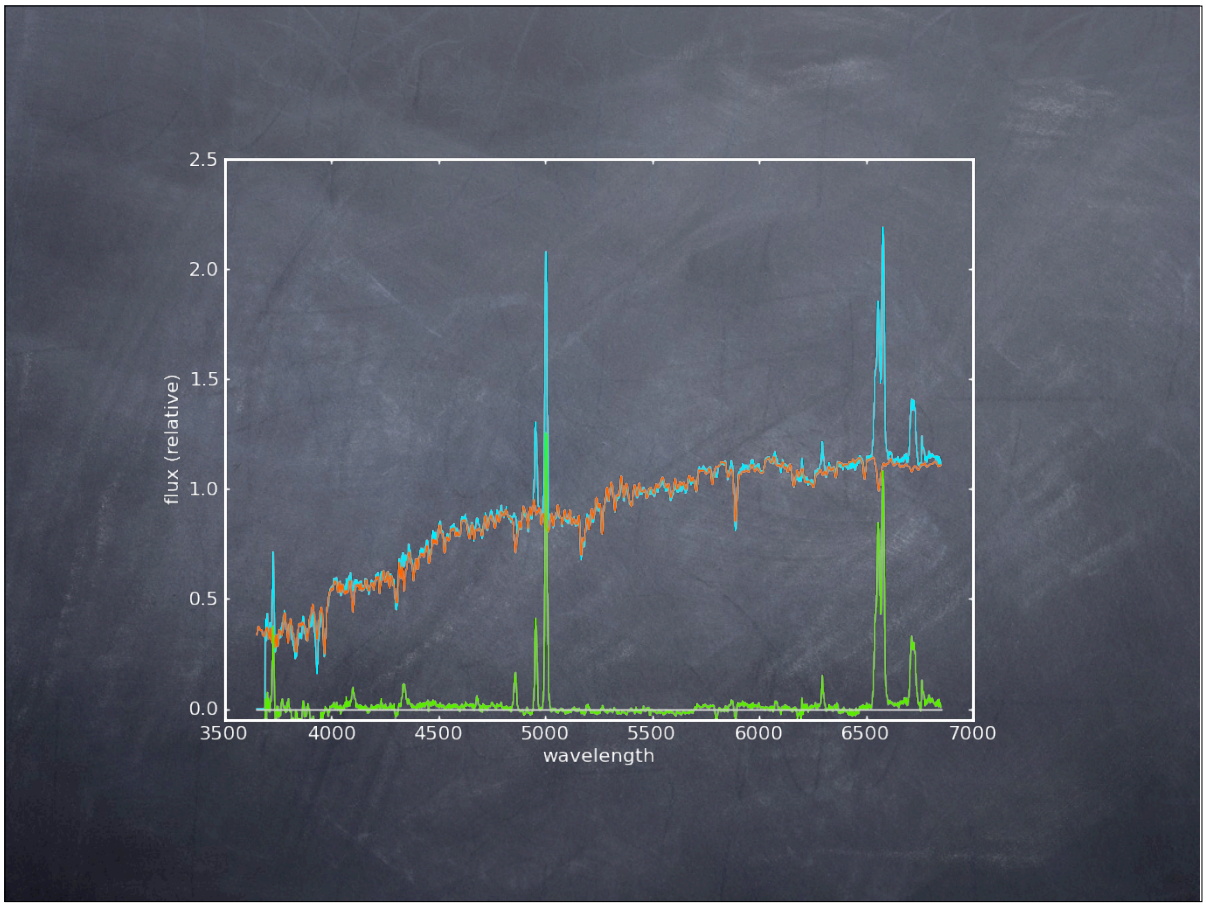
6500
7000

37


flux (relative)
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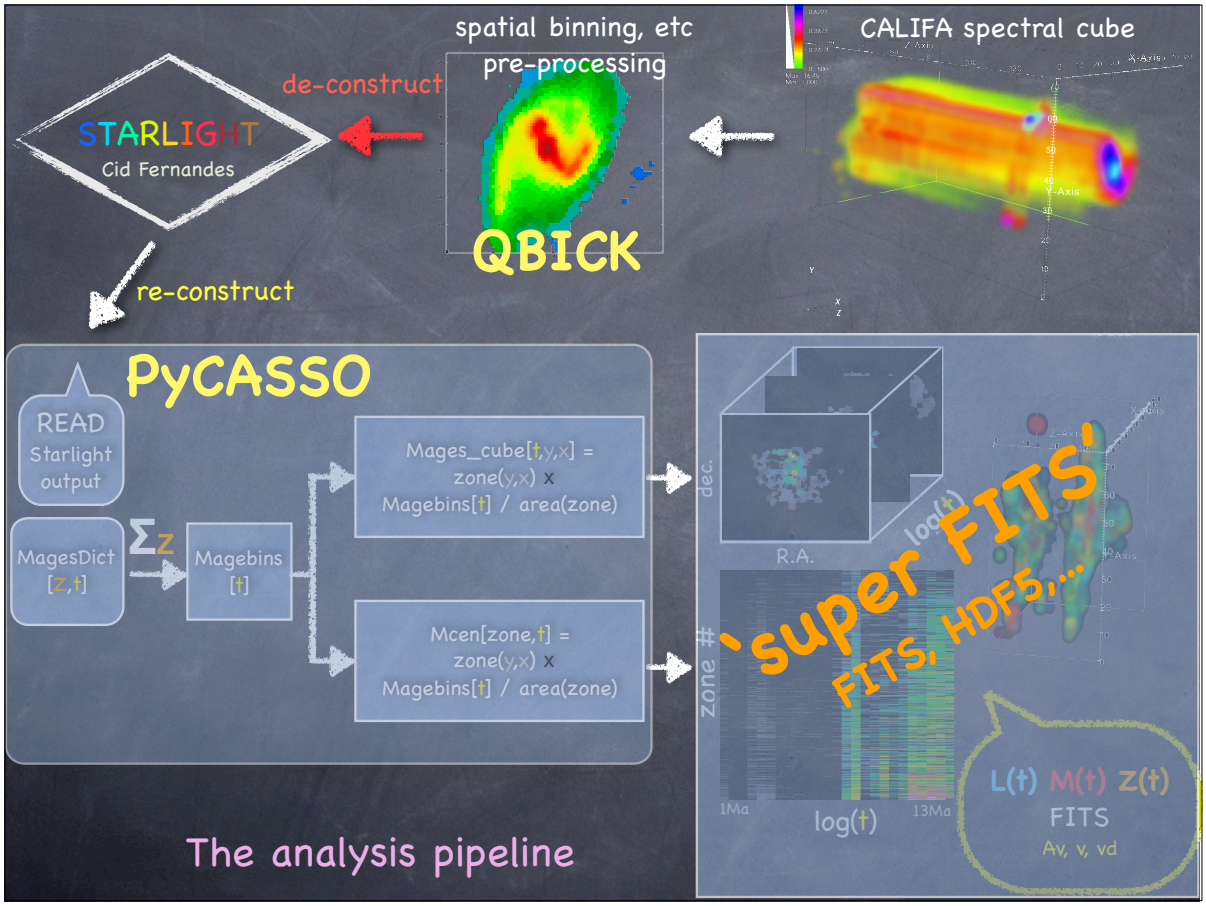
38


spatial binning, etc
pre-processing
CALIFA spectral cube
de-construct
STARLIGHT
Cid Fernandes
QBICK
re-construct
PyCASSO
READ
Starlight
output
MagesDict
[z,t]
Σz
Magebins
[t]
Mages_cube[t,y,x] =
zone(y,x) x
Magebins[t] / area(zone)
Mcen[zone,t] =
zone(y,x) x
Magebins[t] / area(zone)
dec.
R.A.
log(t)
zone #
1Ma
13Ma
log(t)
'super FITS'
FITS, HDF5,...
L(t) M(t) Z(t)
FITS
Av, v, vd
The analysis pipeline

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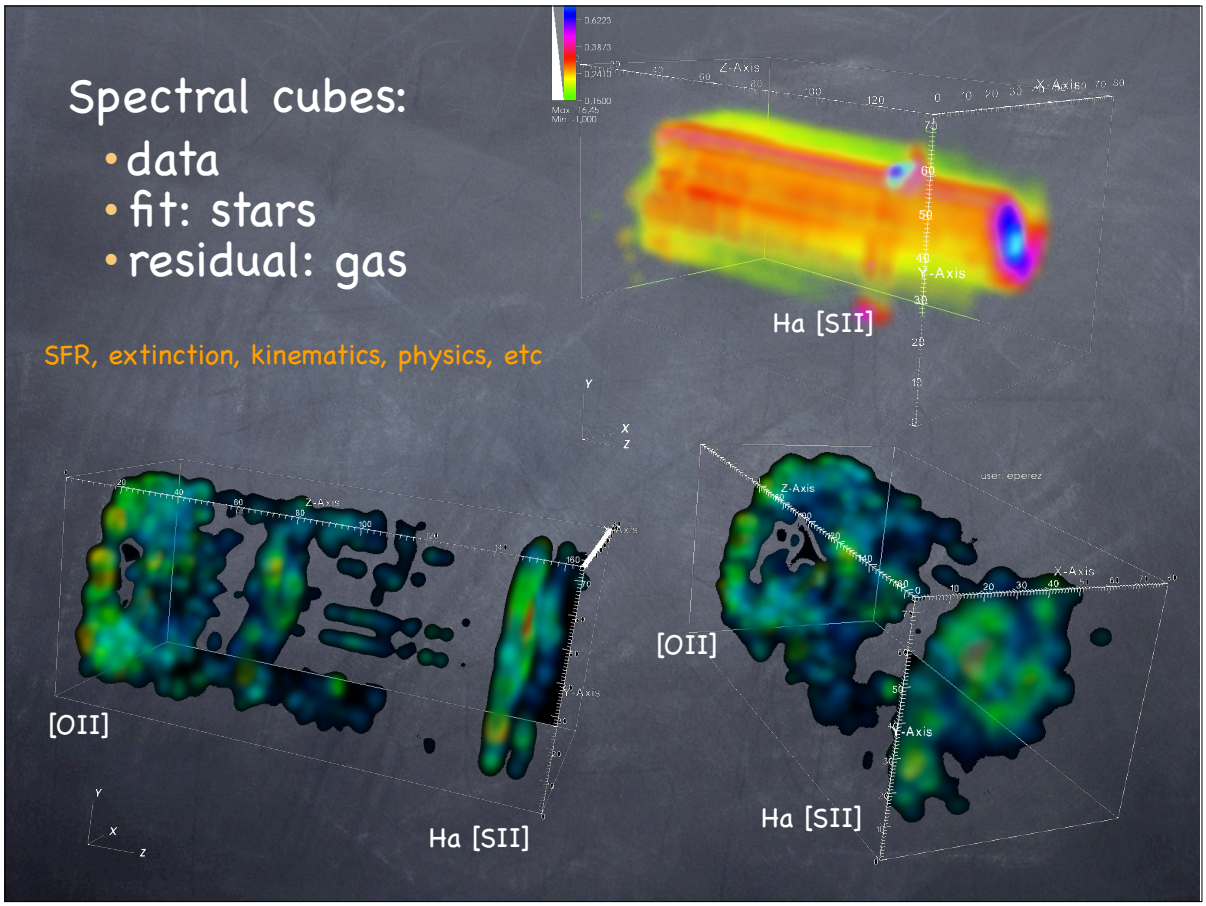
Spectral cubes:
• data
• fit: stars
• residual: gas
SFR, extinction, kinematics, physics, etc
Ha [SII]
[OII]
Ha [SII]
[OII]
Ha [SII]

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CALIFA spectra - STARLIGHT fits = 'residual' emission line spectra

and now … finally … science !

Pérez, E., et al. 2013, ApJ, 764, 1L
Cid Fernandes, R., et al. 2013, A&A, 557, 86
Cid Fernandes, R., et al. 2014, A&A, 561, 130
González Delgado, R. M., et al. 2014, A&A, 562, 47
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