An Analysis of Star Formation in M31 Using Resolved Stars and Ultraviolet Flux

Jake Simones

2014 10 28

Outline

I. **Introduction**
   - Estimating quantities from starlight
   - Stellar population synthesis
   - Star formation histories from resolved stars

II. **Synthetic flux maps of M31**
   - Star formation histories from PHAT data
   - Flux modeling
   - Comparison with observations

III. **SFR maps of M31**
   - Comparison with SFHs

IV. **Summary**

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

Jacob Bers (Bersonic)

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

Stellar population

A collection of associated stars
(clusters, galaxies, etc.).

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

Stellar population

A collection of associated stars (clusters, galaxies, etc.).

Light (integrated flux)

Total light from a stellar population measured in a specific wavelength range (optical, UV, etc.).

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

Darren Hester

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- Measure the brightness of the room
- ***If*** the brightness of each lightbulb is known,

> Can determine the total number of lightbulbs

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- Measure the brightness of the room
- ***If*** the brightness of each lightbulb is known,

> Can determine the total number of lightbulb

>> Total mass of the stellar population

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- Lightbulbs (and stars) have lifetimes

- ***If*** no lightbulbs are replaced, then the brightness of the room will decrease with time

> Can determine the age of the lightbulbs

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- Lightbulbs (and stars) have lifetimes
- ***If*** no lightbulbs are replaced, then the brightness of the room will decrease with time

> Can determine the age of the lightbulbs

>> Age of the stellar population

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- Lightbulbs (and stars) have lifetimes
- ***If*** no lightbulbs are replaced, then the brightness of the room will decrease with time

> Can determine the age of the lightbulbs

>> Age of the stellar population

Simple stellar population (SSP)

All stars formed at the same *time*, in the same *place*, from the same *material*.

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- ***If*** the total brightness of the room is maintained over time by replacing a lightbulb when it fails,
- Count the number of lightbulbs replaced over one year

> "Lightbulb replacement rate"

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- ***If*** the total brightness of the room is maintained over time by replacing a lightbulb when it fails,
- Count the number of lightbulbs replaced over one year

> "Lightbulb replacement rate"

>> Star formation rate

I. Introduction - lightbulbs

What can we learn about a collection of lightbulbs looking only at its light?

- ***If*** the total brightness of the room is maintained over time by replacing a lightbulb when it fails,

- Count the number of lightbulbs replaced over one year

> “Lightbulb replacement rate”

>> Star formation rate

Star formation rate (SFR)

Rate at which stars are formed from the gas in a given environment (M_{sun} yr^{-1}).

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

Jacob Bers (Bersonic)

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

- Mass
- Age (***if*** SSP)
- SFR (***if*** constant)

I. Introduction - starlight

What can we learn about a stellar population looking only at its light?

- Mass
- Age (***if*** SSP)
- SFR (***if*** constant)

Relationships between these quantities and integ-rated flux are based on stellar population synthesis (SPS).

I. Introduction - SPS

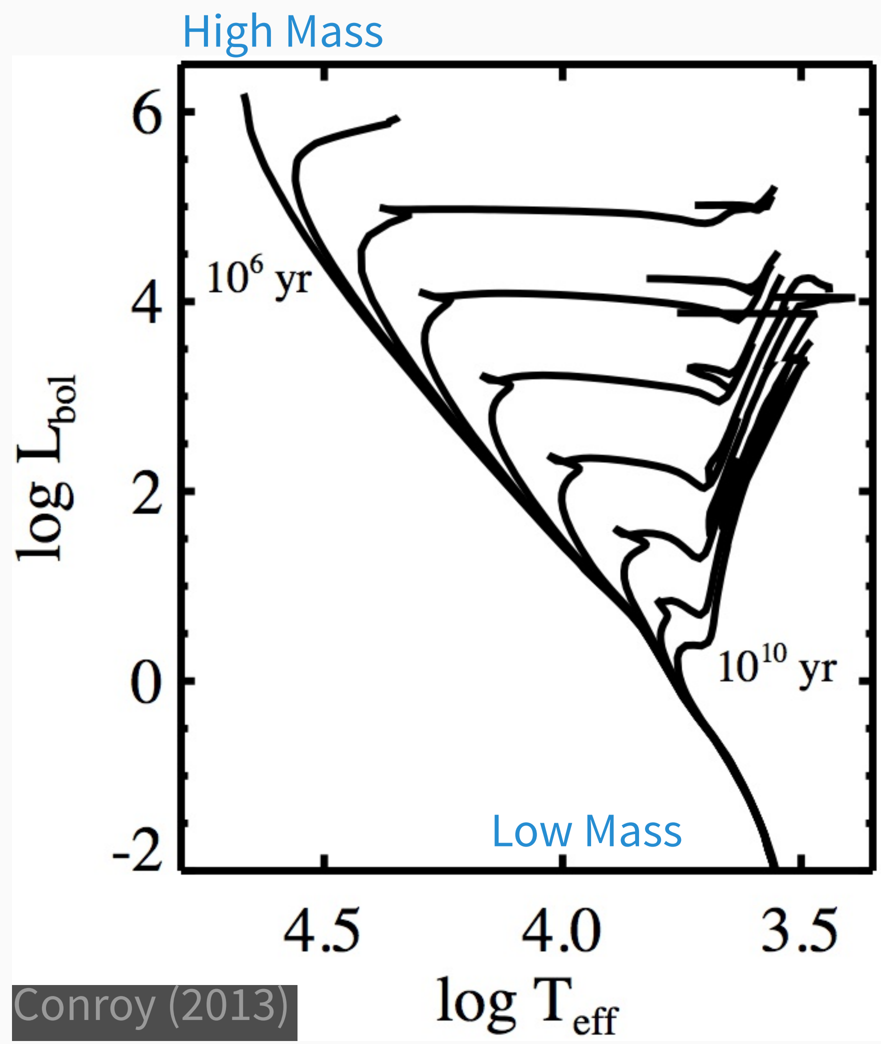
Stellar population synthesis (SPS)
Three main ingredients:

- Stellar isochrones
- Stellar spectra
- Initial mass function

I. Introduction - SPS

Stellar isochrones

Evolution of brightness and temperature as a function of mass.



Conroy (2013)

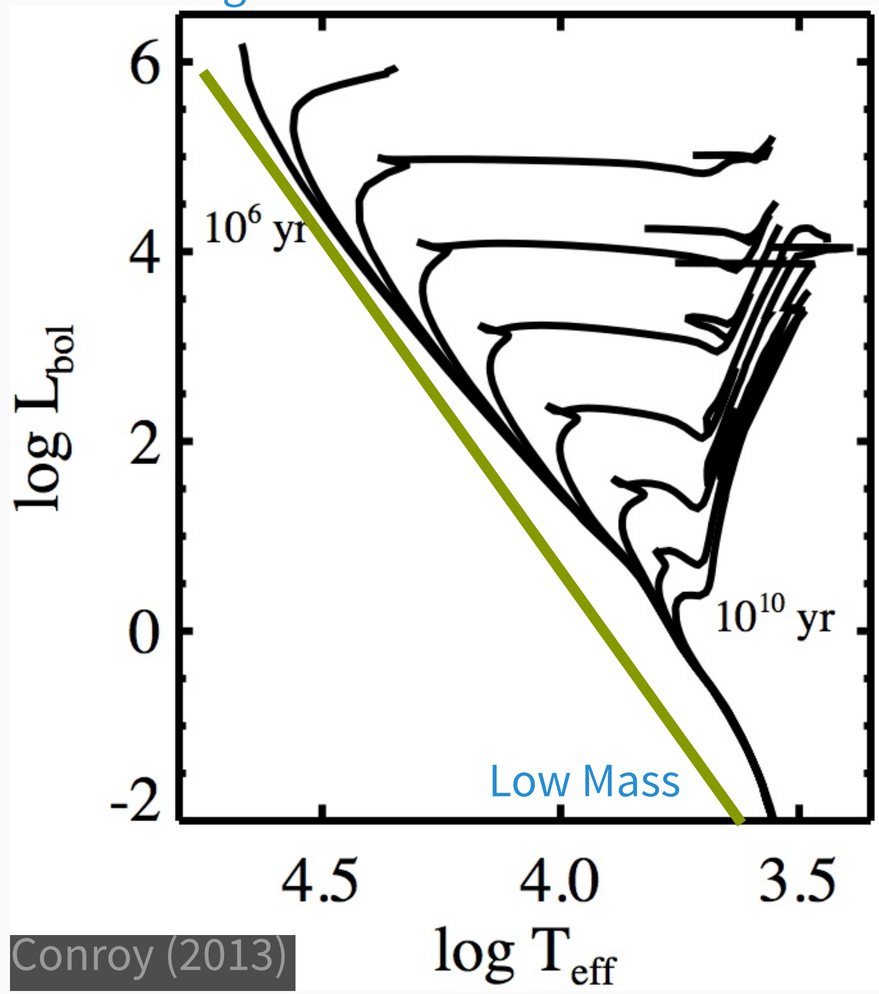
I. Introduction - SPS

Stellar isochrones

Evolution of brightness and temperature as a function of mass.

All stars start out on the main sequence (MS),

High Mass



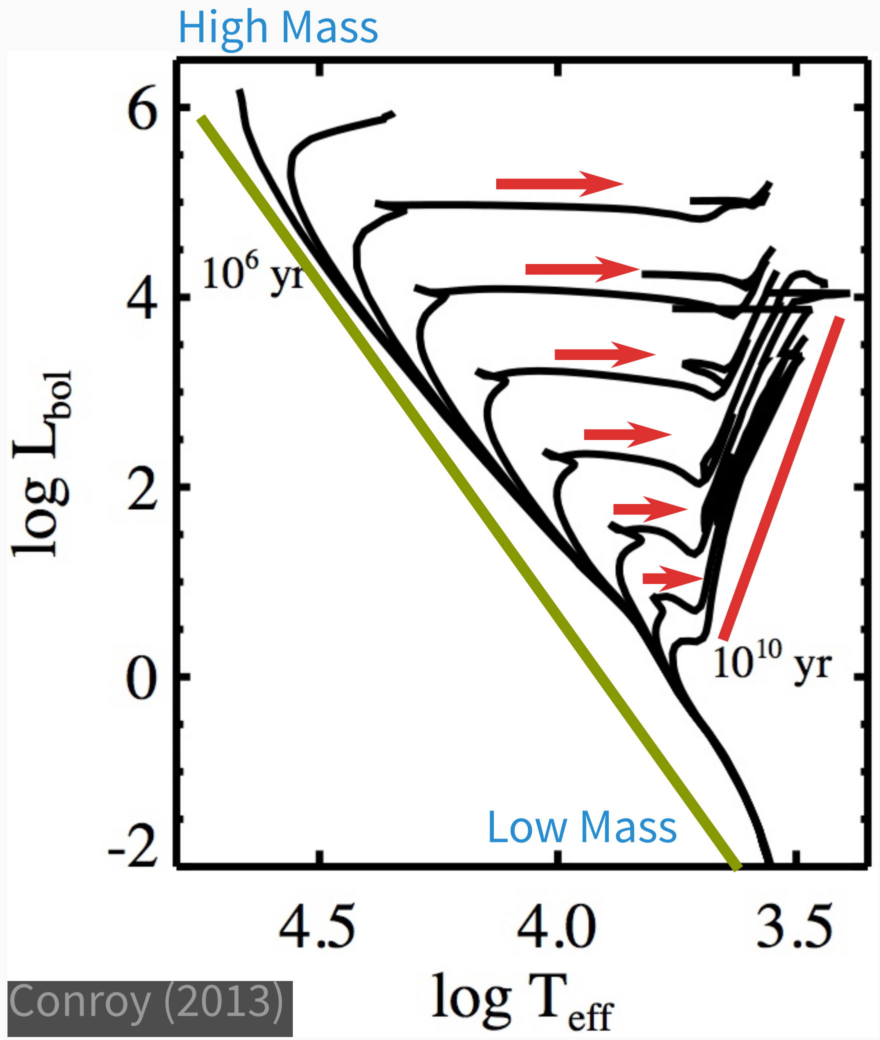
Conroy (2013)

I. Introduction - SPS

Stellar isochrones

Evolution of brightness and temperature as a function of mass.

All stars start out on the main sequence (MS), then evolve to the red giant branch (RGB), etc.



Conroy (2013)

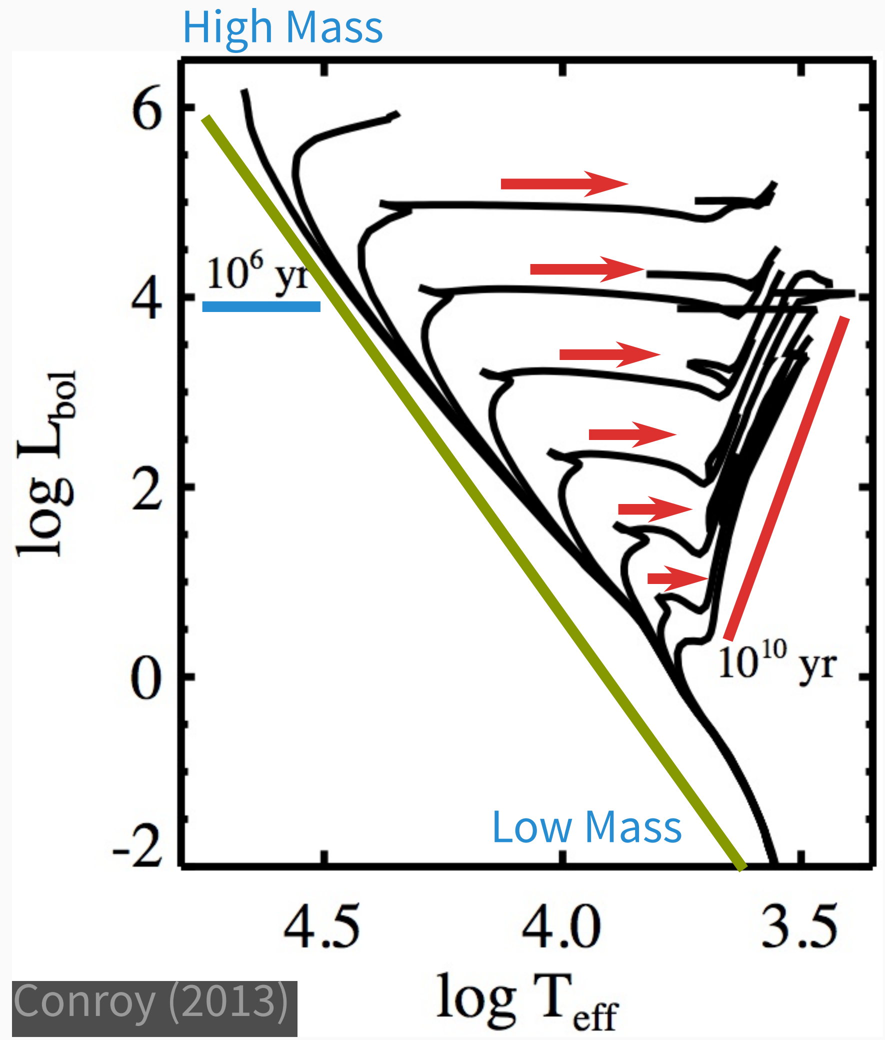
I. Introduction - SPS

Stellar isochrones

Evolution of brightness and temperature as a function of mass.

All stars start out on the main sequence (MS), then evolve to the red giant branch (RGB), etc.

Higher mass stars have shorter lifetimes.



Conroy (2013)

I. Introduction - SPS

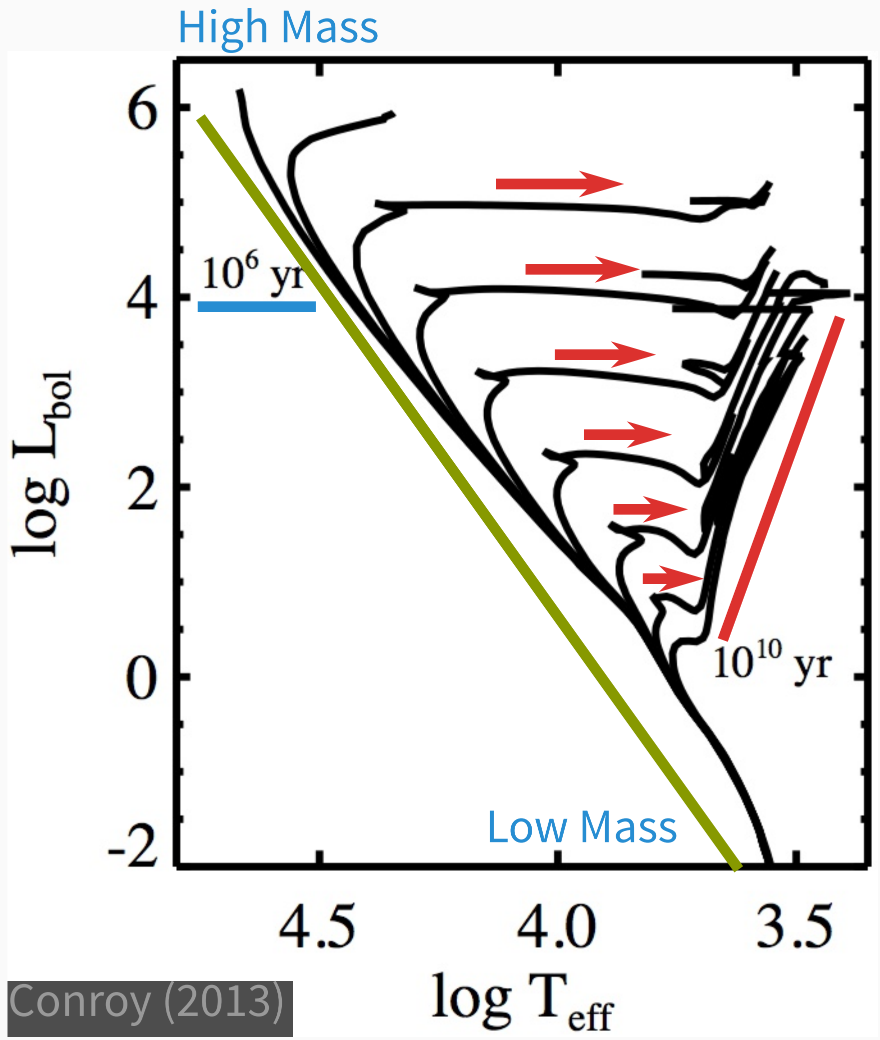
Stellar isochrones

Evolution of brightness and temperature as a function of mass.

All stars start out on the main sequence (MS), then evolve to the red giant branch (RGB), etc.

Higher mass stars have shorter lifetimes.

Mass and age determine the type of star (hot vs. cool, MS vs. RGB).

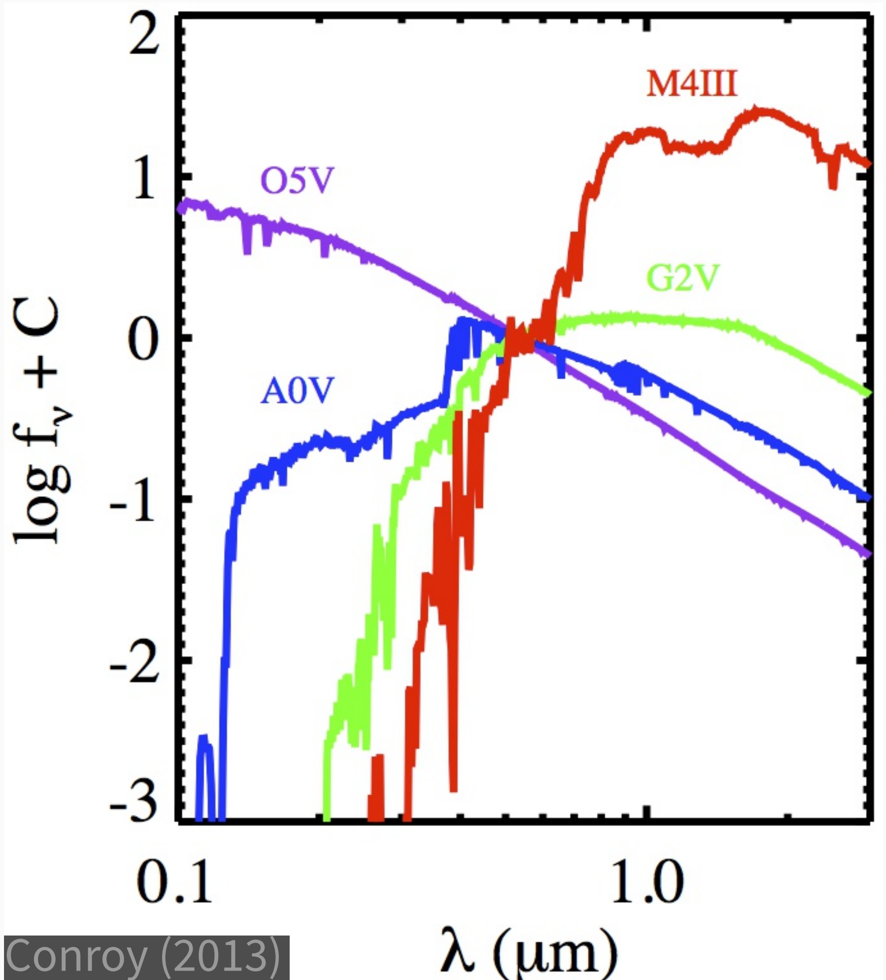


Conroy (2013)

I. Introduction - SPS

Stellar spectra

Spectrum (flux vs. wavelength) for each type of star.



Conroy (2013)

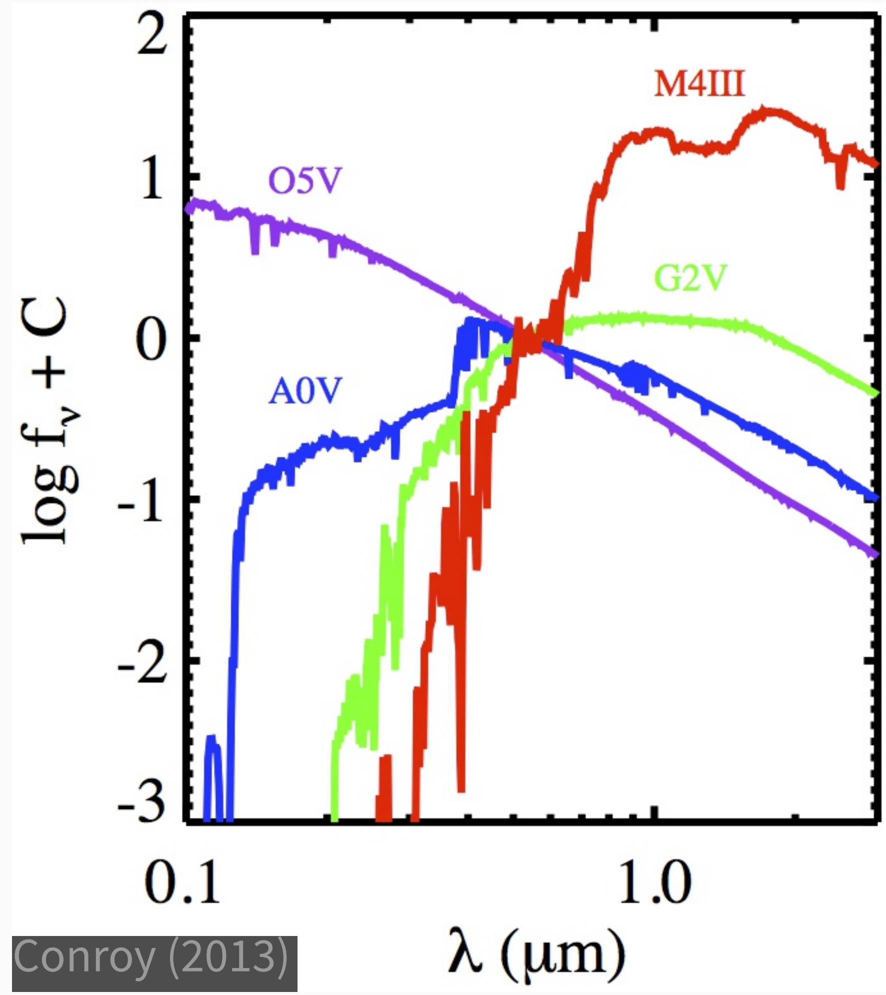
I. Introduction - SPS

Stellar spectra

Spectrum (flux vs. wavelength) for each type of star.

Hotter stars are “bluer”, cooler stars are “redder”.

hot
O5V
A0V
G2V
M4III
cool

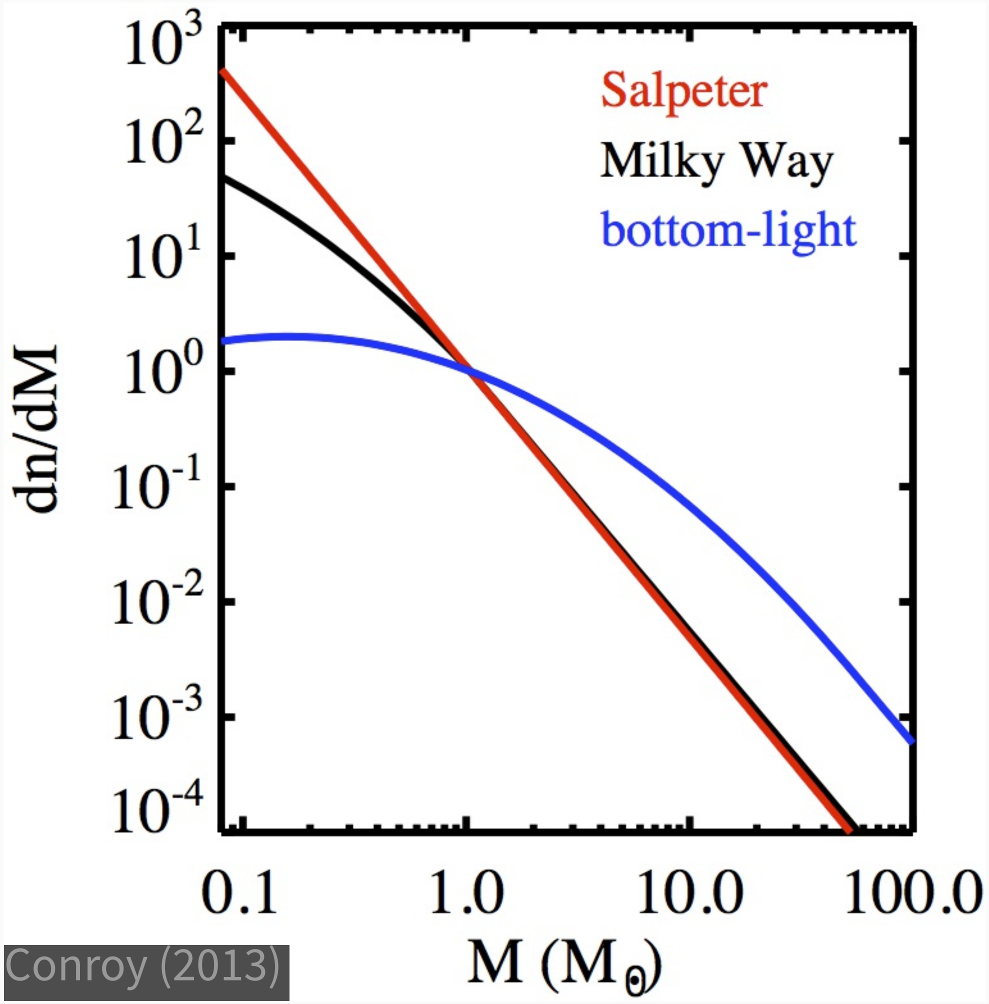


Conroy (2013)

Energy

I. Introduction - SPS

Initial mass function (IMF)
Empirical distribution of stellar masses for a newly formed population.



Conroy (2013)

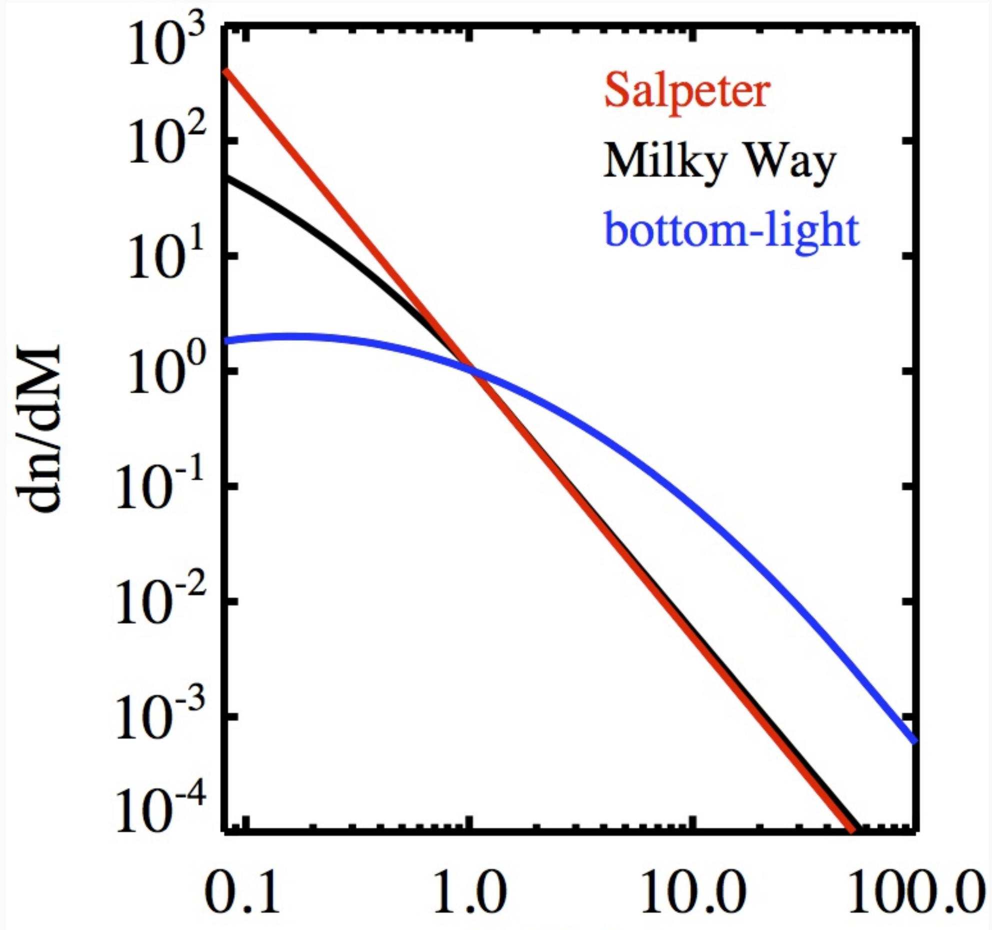
I. Introduction - SPS

Initial mass function (IMF)

Empirical distribution of stellar masses for a newly formed population.

Different studies determine different shapes.

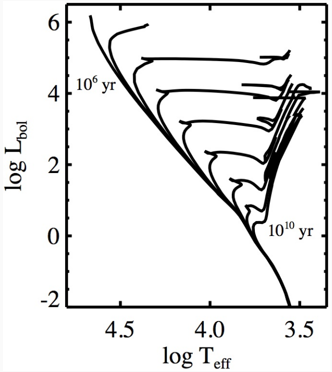
Universal or dependent on environonment?

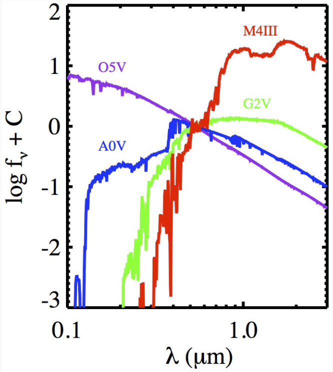


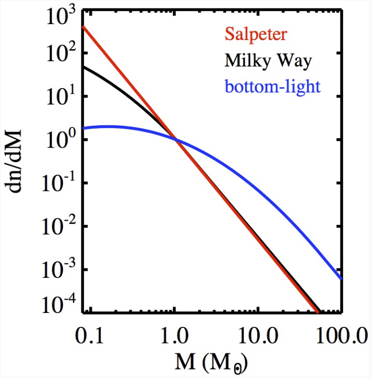
Conroy (2013)

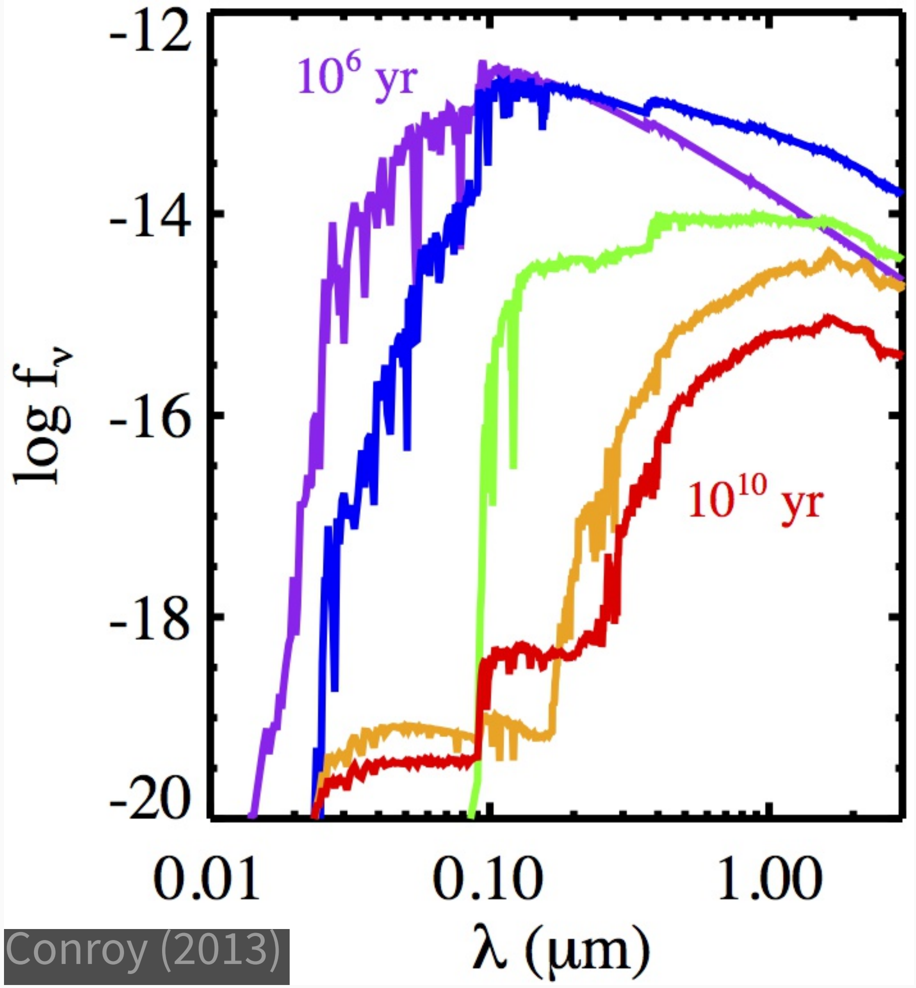
I. Introduction - SPS

SSP spectra







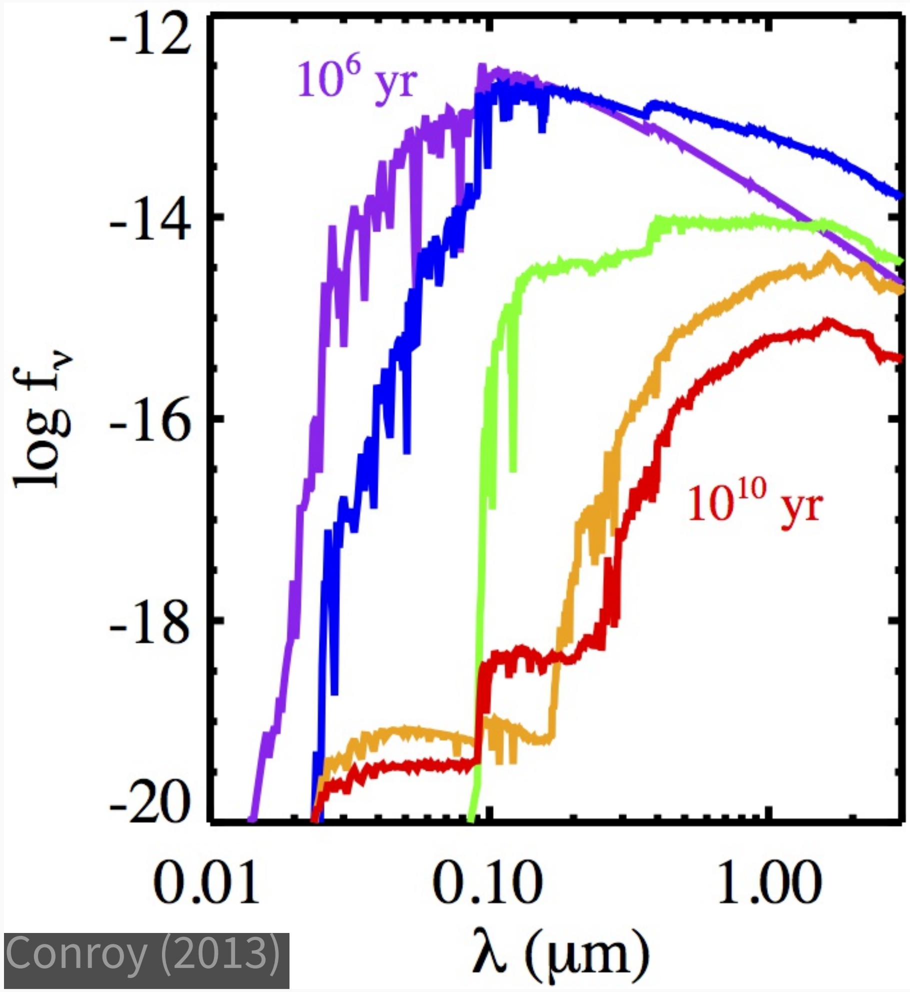


I. Introduction - SPS

SSP spectra

SSPs get fainter and redder with age.

(Stars are more complicated than lightbulbs.)



Conroy (2013)

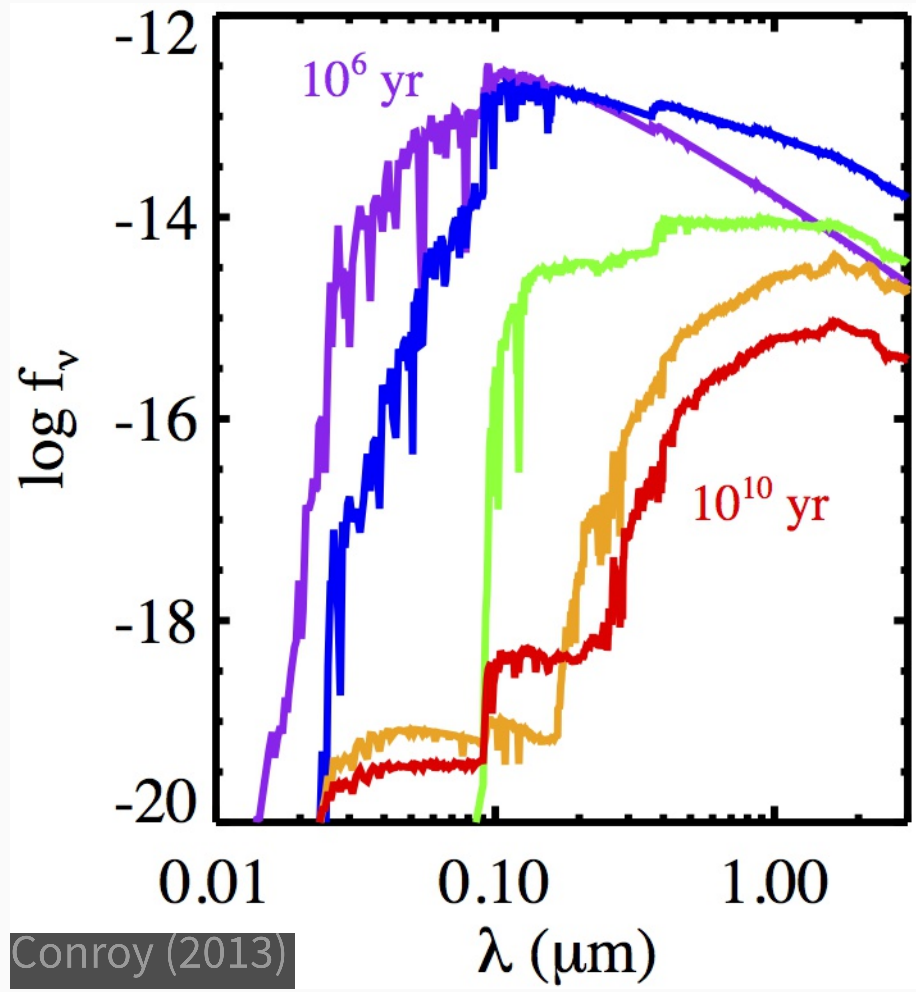
I. Introduction - SPS

SSP spectra

SSPs get fainter and redder with age.

(Stars are more complicated than lightbulbs.)

SSPs are the building blocks of SPS.



Conroy (2013)

I. Introduction - SPS

Composite stellar populations

Stellar populations are rarely SSPs.

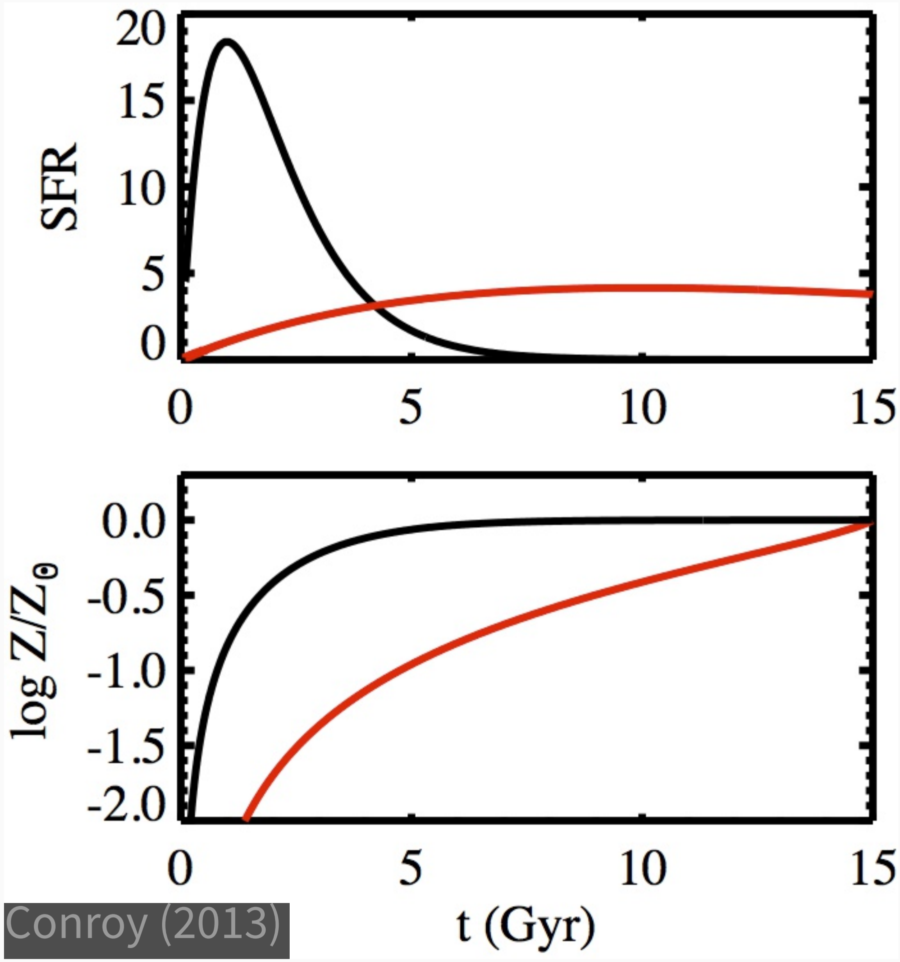
Use SSPs to build more complex (composite) stellar populations:

- Star formation history
- Dust model

I. Introduction - SPS

Star formation history (SFH)

Evolution of SFR and metallicity (chemical composition).

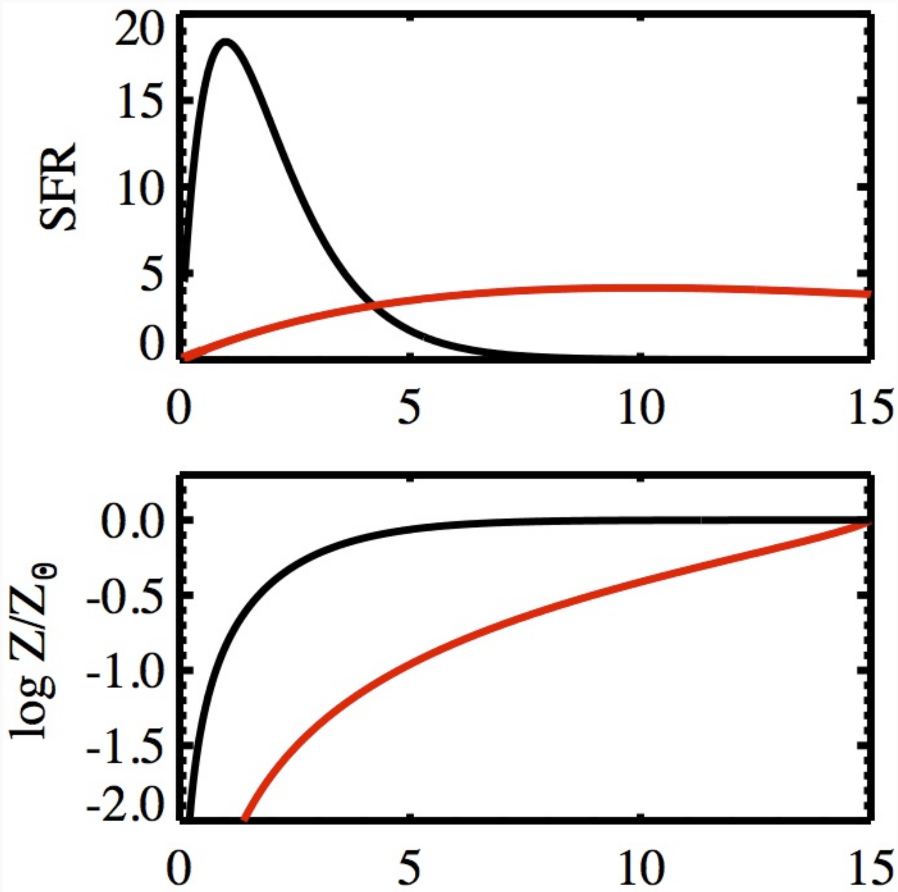


Conroy (2013)

I. Introduction - SPS

Star formation history (SFH)
Evolution of SFR and metallicity (chemical composition).

SFHs can be simple or complex.



Conroy (2013)

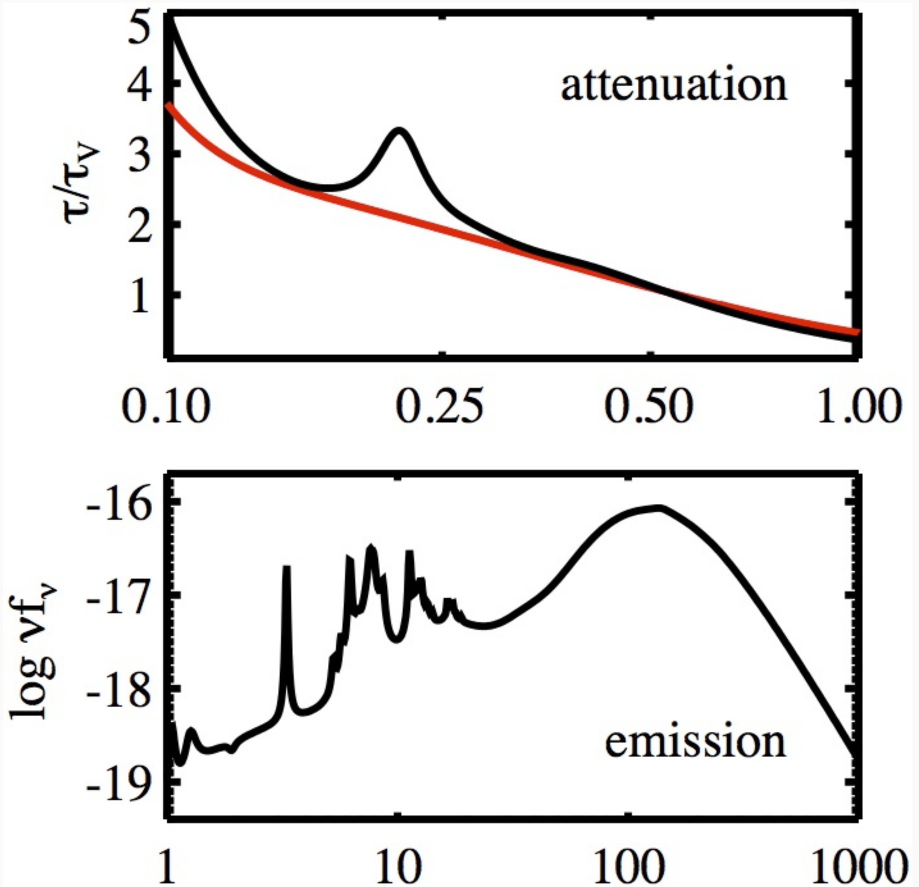
I. Introduction - SPS

Dust model

Dust can significantly affect the spectrum of a stellar population.

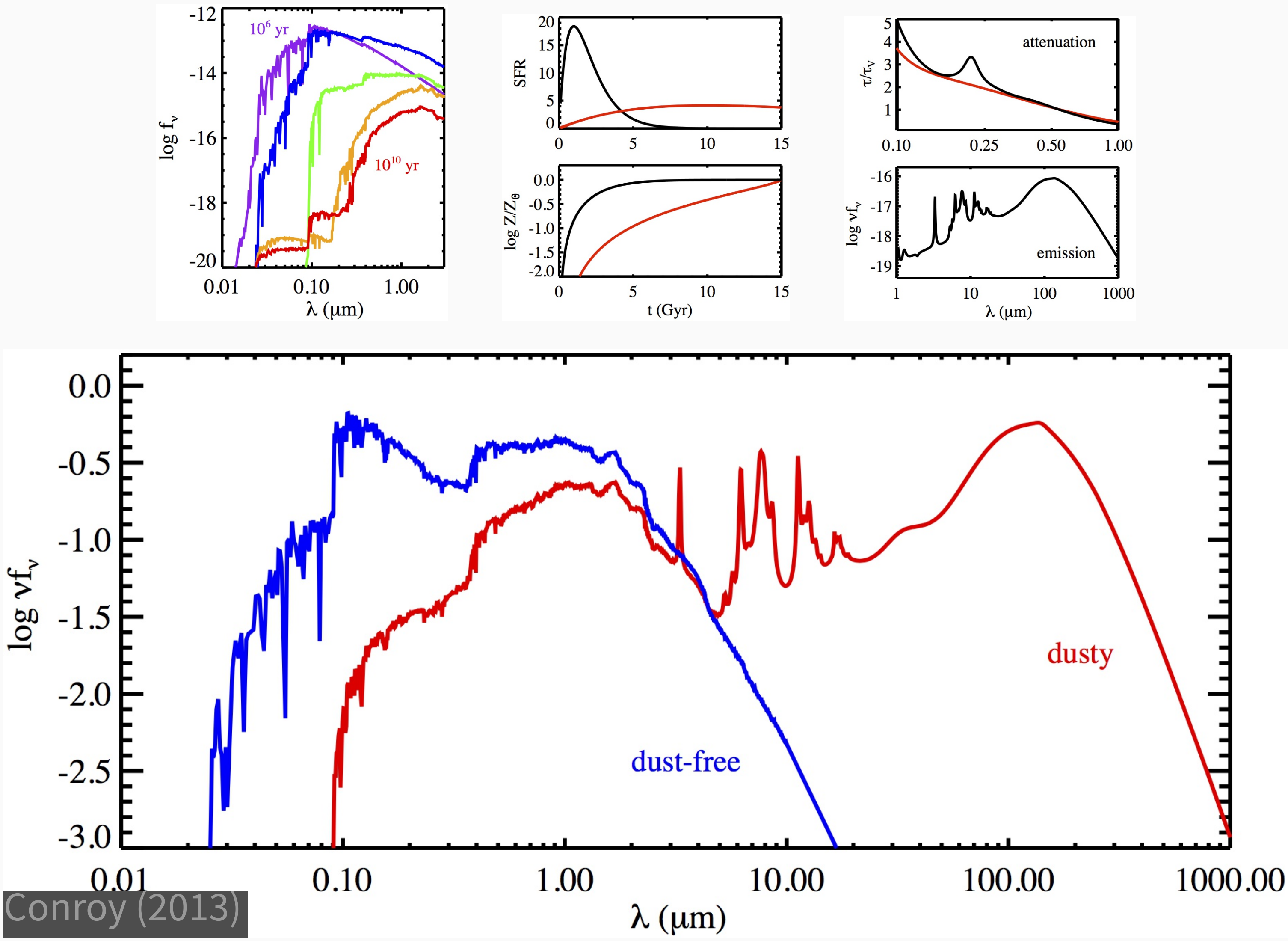
Dust absorbs high energy photons and emits infrared radiation.

Dust grain models predict how a given amount of dust will attenuate a stellar spectrum and what the dust emission spectrum will look like.



Conroy (2013)

Composite stellar population spectra



Conroy (2013)

I. Introduction - SPS

Can use this technique to model any stellar population (clusters, galaxies, etc.) given,

- Stellar evolution models (isochrones)
- Stellar spectra models
- IMF
- SFH
- Dust model

I. Introduction - SPS

What can we learn about a stellar population looking only at its light?

- Mass
- Age (***if*** SSP)
- SFR (***if*** constant)

Relationships between these quantities and integ-rated flux are based on stellar population synthesis (SPS).

- Model an SSP
- Model a constant SFR population

I. Introduction - SPS

My research:

How well can the integrated flux from a stellar population predict age, mass, and SFR?

I. Introduction - SPS

My research:

How well can the integrated flux from a stellar population predict age, mass, and SFR?

Who cares?

I. Introduction - SPS

My research:

How well can the integrated flux from a stellar population predict age, mass, and SFR?

Who cares?

Extragalactic astronomers.

SFRs of distant galaxies are routinely estimated using integrated flux.

I. Introduction - SPS

My research:

How well can the integrated flux from a stellar population predict age, mass, and SFR?

How?

I. Introduction - SPS

My research:

How well can the integrated flux from a stellar population predict age, mass, and SFR?

How?

By reconstructing SFHs from resolved stars.

I. Introduction - SPS

My research:

How well can the integrated flux from a stellar population predict age, mass, and SFR?

How?

By reconstructing SFHs from resolved stars.

Resolved stars

Stars appear is distinct points of light
in a sufficiently high resolution image.

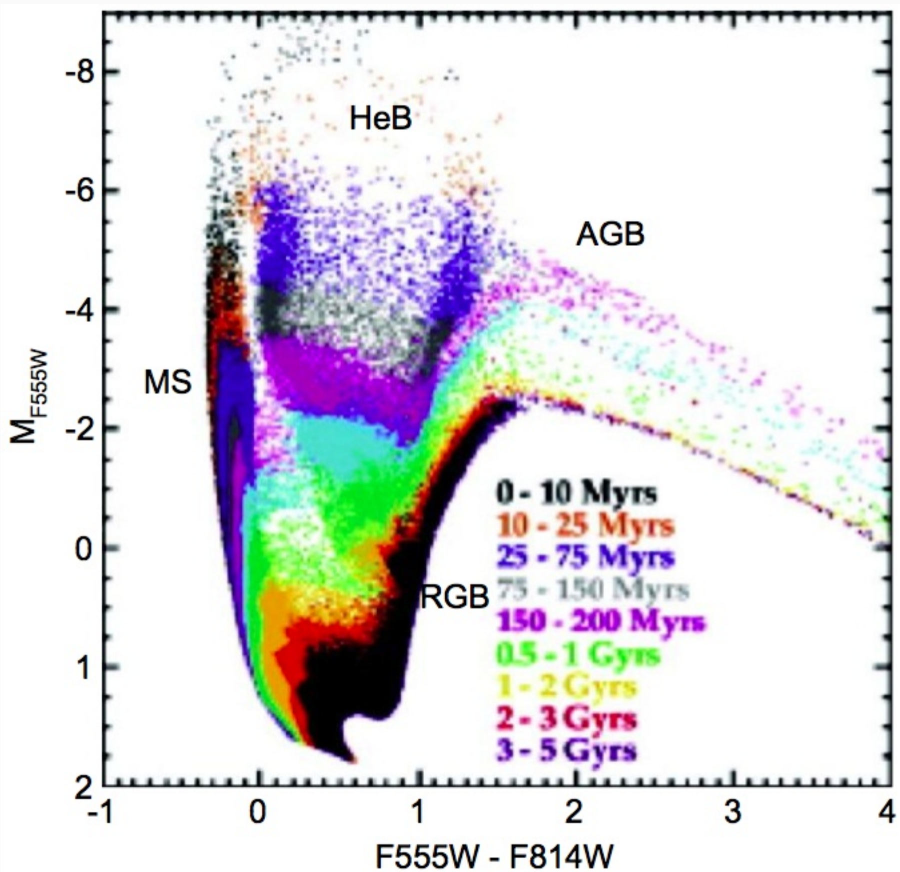
I. Introduction - SFHs

How is a SFH derived?

I. Introduction - SFHs

How is a SFH derived?

Color-magnitude diagram (CMD)



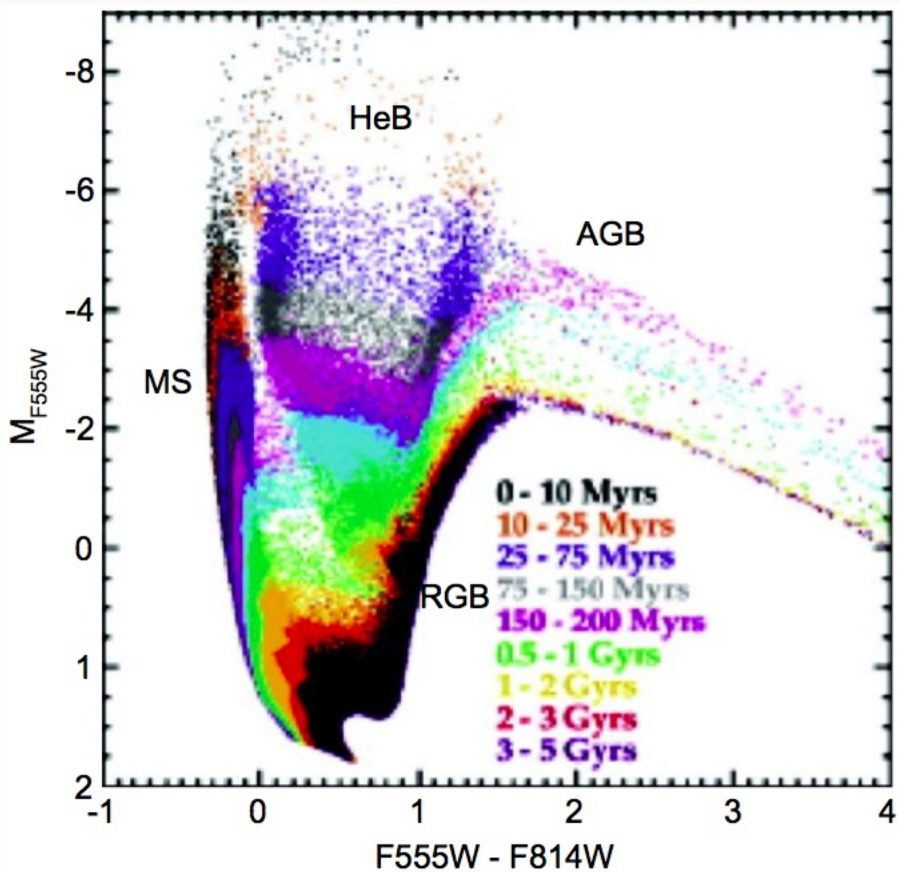
Magnitude	~	luminosity
"Color"	~	temperature

Resolved stars are distributed according to age and mass.

I. Introduction - SFHs

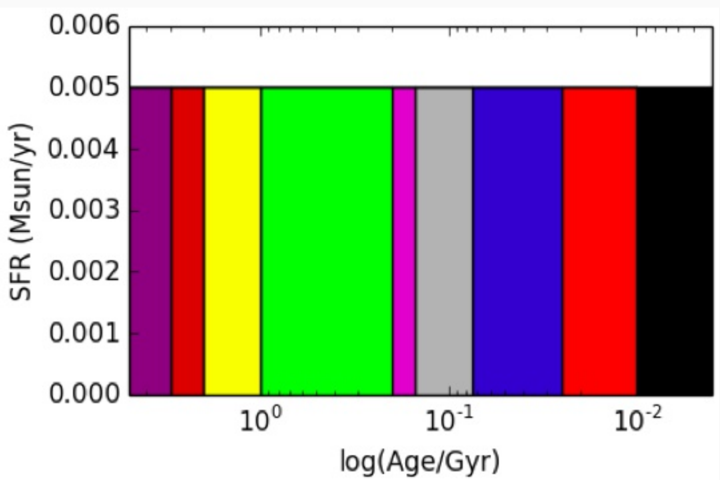
How is a SFH derived?

Color-magnitude diagram (CMD)



Magnitude	~	luminosity
"Color"	~	temperature

Resolved stars are distributed according to age and mass.



II. Synthetic flux maps of M31

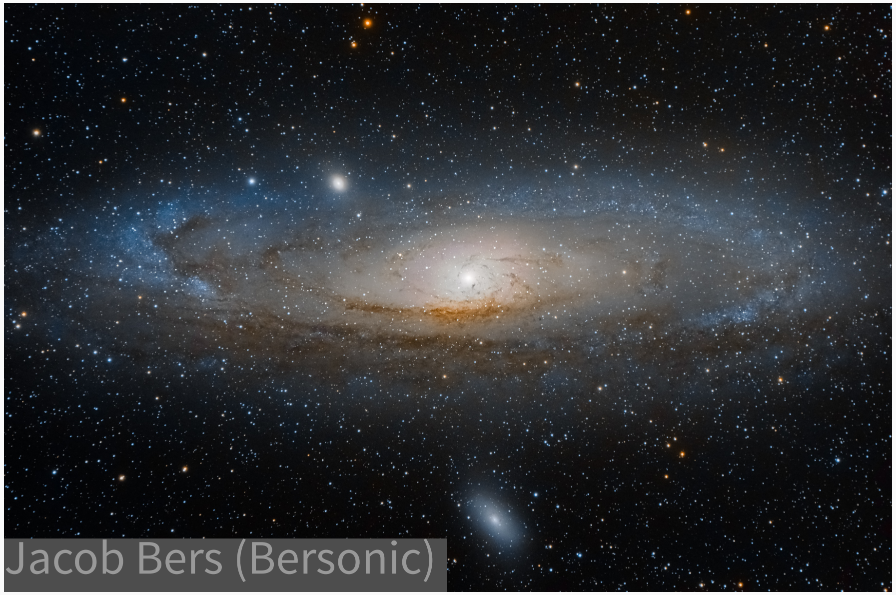
M31 — Andromeda

Our nearest (large) neighbor.

II. Synthetic flux maps of M31

Why study M31?

Large spiral galaxy like the Milky Way.

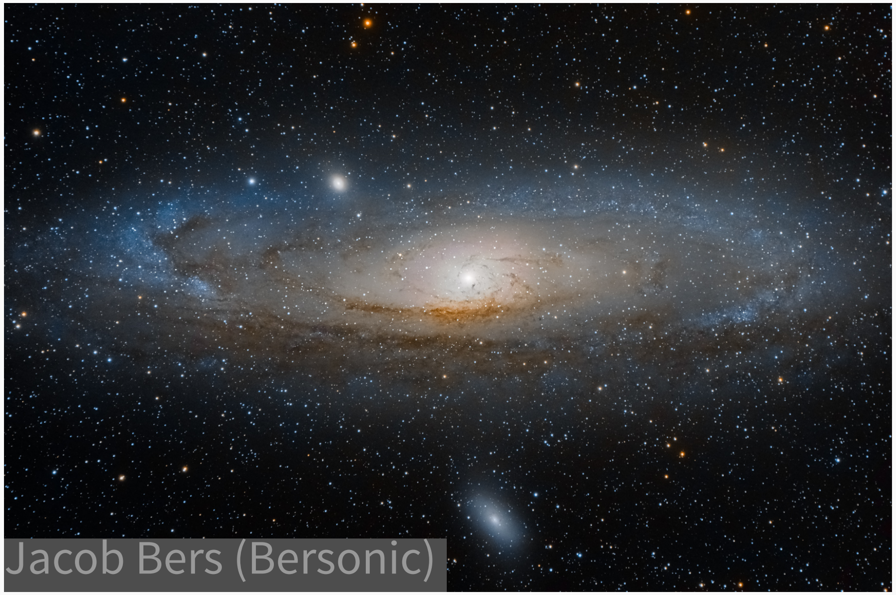

Jacob Bers (Bersonic)

II. Synthetic flux maps of M31

Why study M31?

Large spiral galaxy like the Milky Way.

“Close”: 783 kpc, 2.6 million lyr.


Jacob Bers (Bersonic)

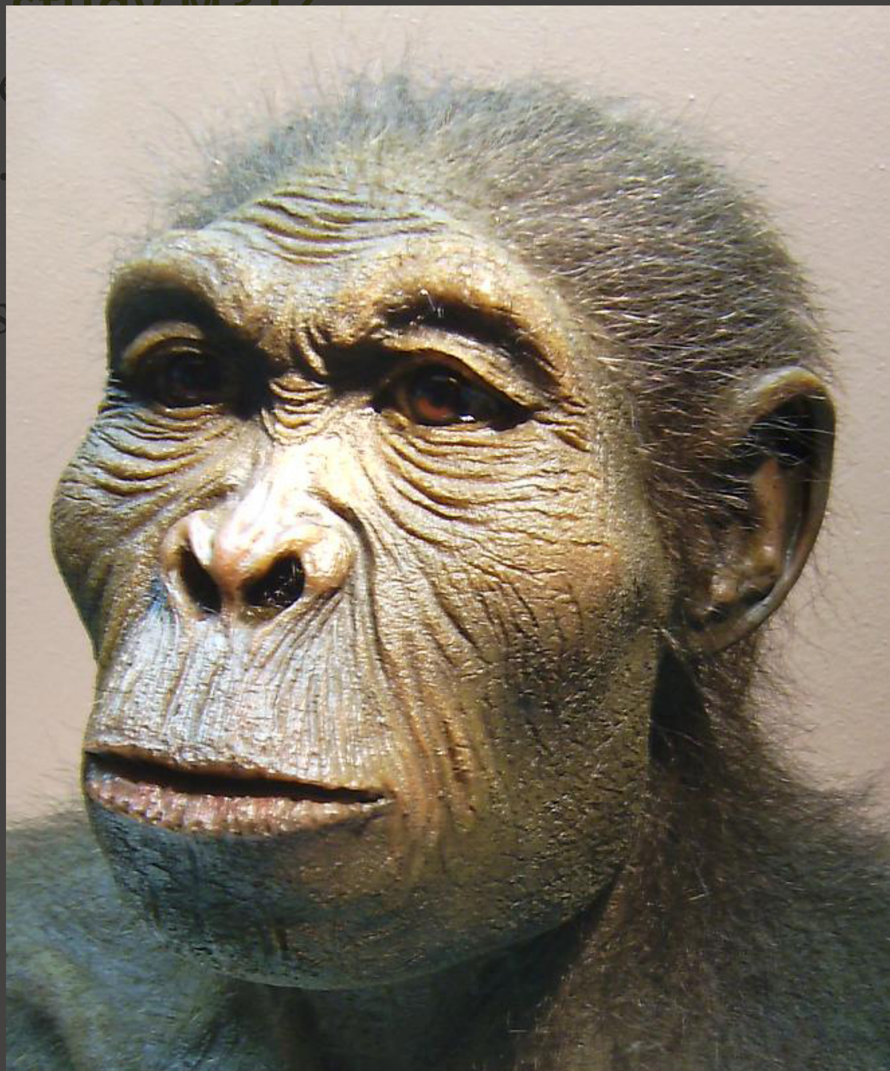
II. Synthetic flux maps of M31

Why study M31?

Larg

Way.

“Clos



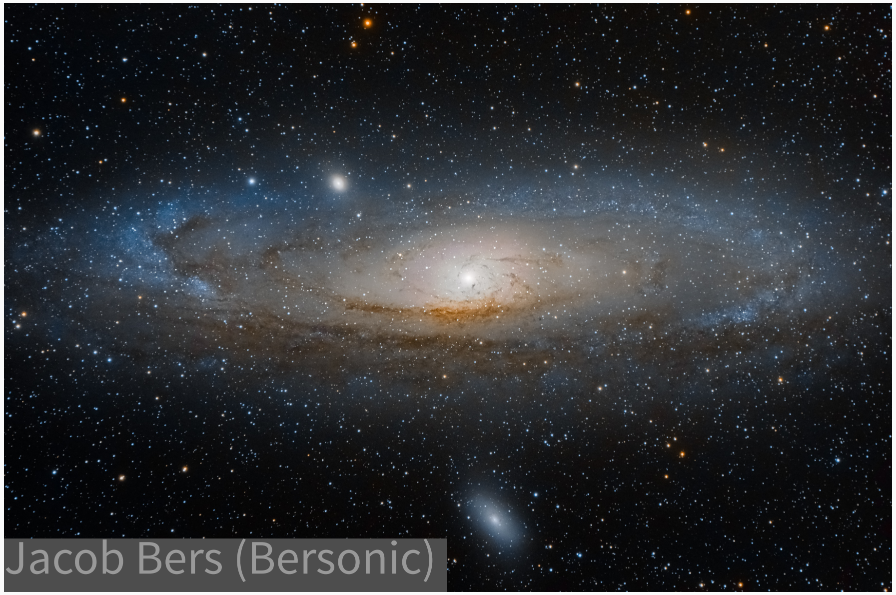
ob Bers (Bersonic)

II. Synthetic flux maps of M31

Why study M31?

Large spiral galaxy like the Milky Way.

“Close”: 783 kpc, 2.6 million lyr.
Easy to resolve individual stars.



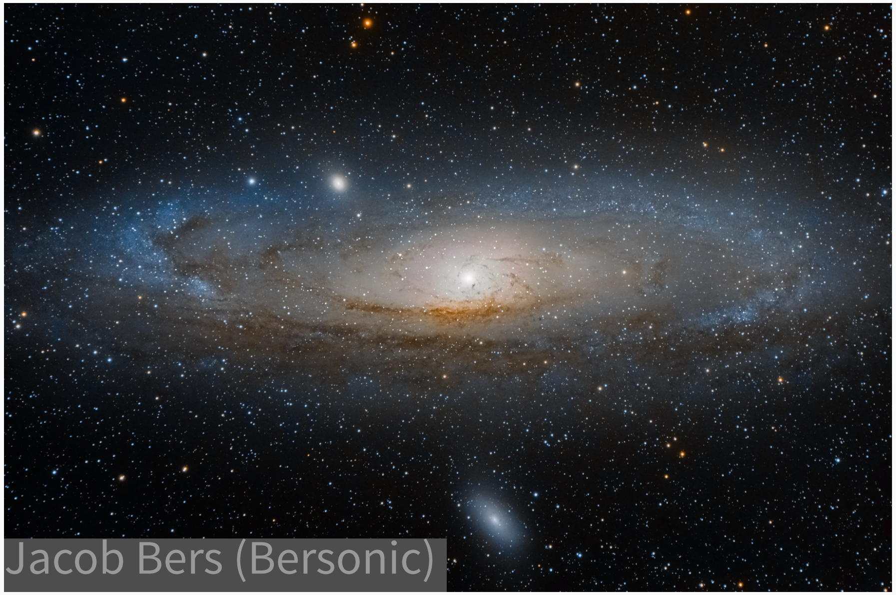
II. Synthetic flux maps of M31

Why study M31?

Large spiral galaxy like the Milky Way.

“Close”: 783 kpc, 2.6 million lyr. Easy to resolve individual stars.

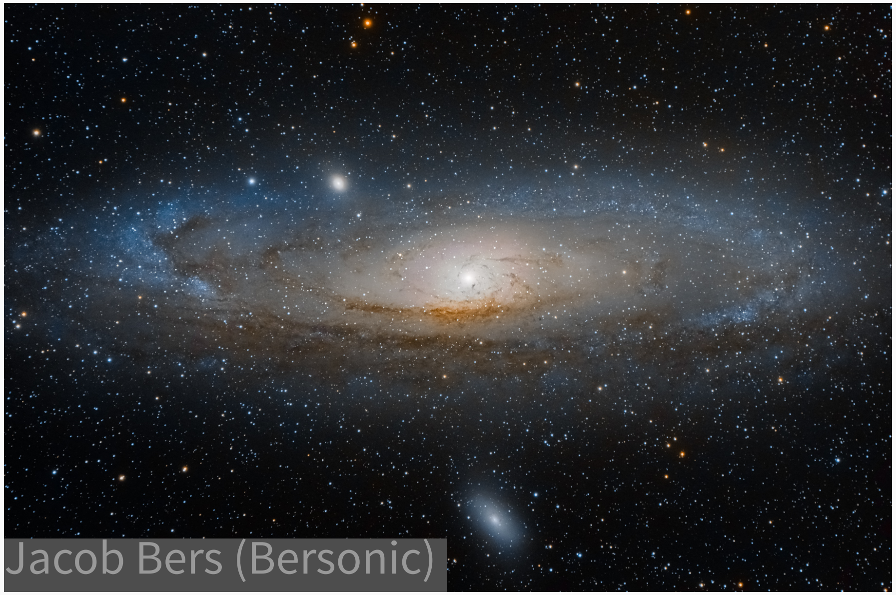
Good view of different environments (despite inclination).


Jacob Bers (Bersonic)

II. Synthetic flux maps of M31

Why study M31?

Well studied » a lot of data.


Jacob Bers (Bersonic)

II. Synthetic flux maps of M31

Why study M31?

Well studied » a lot of data.

GALEX: far-UV (FUV) and near-UV (NUV) light.

II. Synthetic flux maps of M31

Why study M31?
Well studied » a lot of data.

GALEX: far-UV (FUV) and near-UV (NUV) light.

Most UV photons are produced by massive MS stars » UV probes recent star formation (last ~100 Myr).

II. Synthetic flux maps of M31

Why study M31?

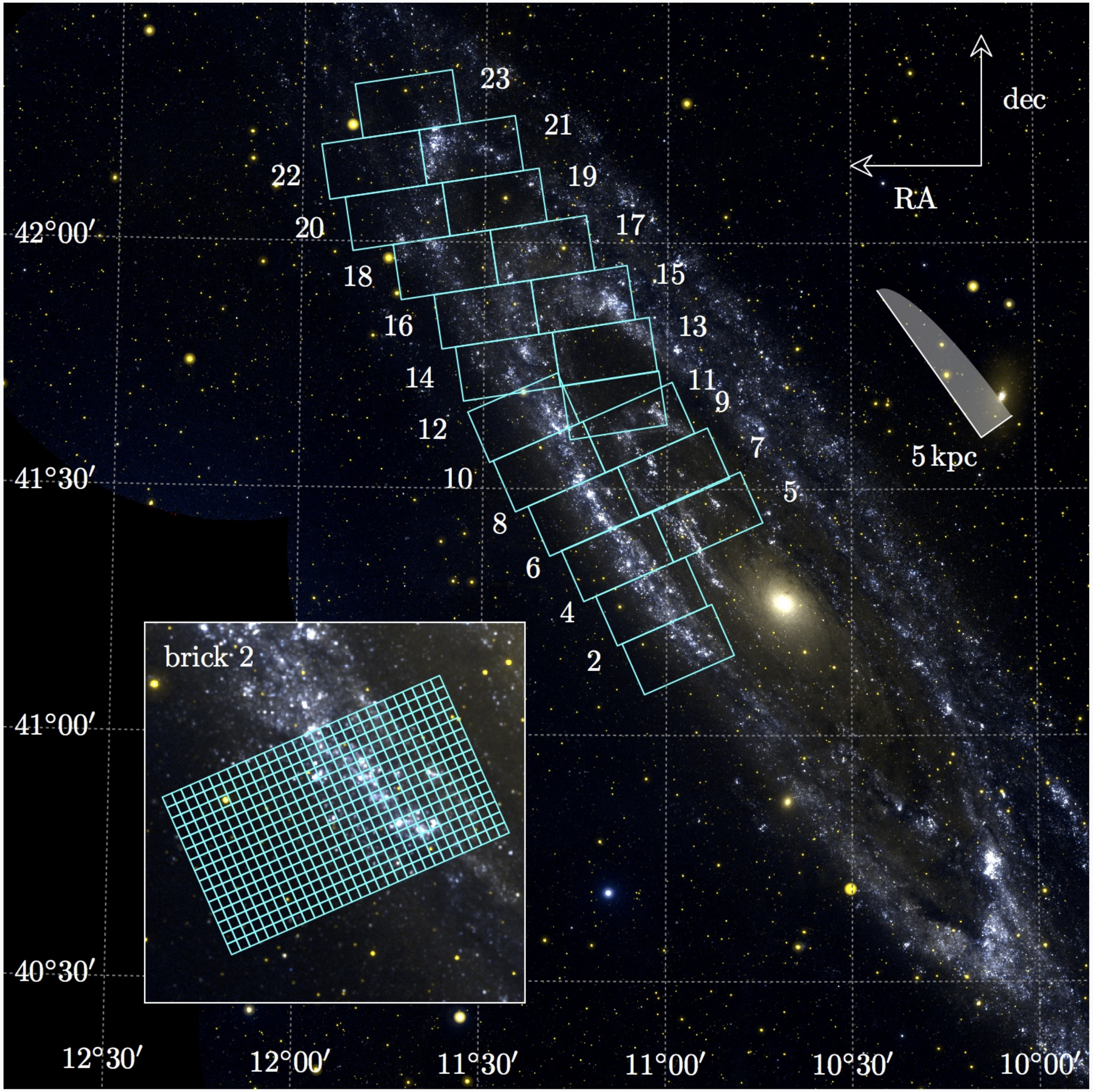
Well studied » a lot of data.

Panchromatic Hubble Andromeda Treasury (PHAT): photometry for over 100 million stars in six filters with the Hubble Space Telescope.

- Near UV
- Optical (F475W and F814W)
- Near infrared

Ideal dataset for deriving SFHs!

II. Synthetic flux maps of M31



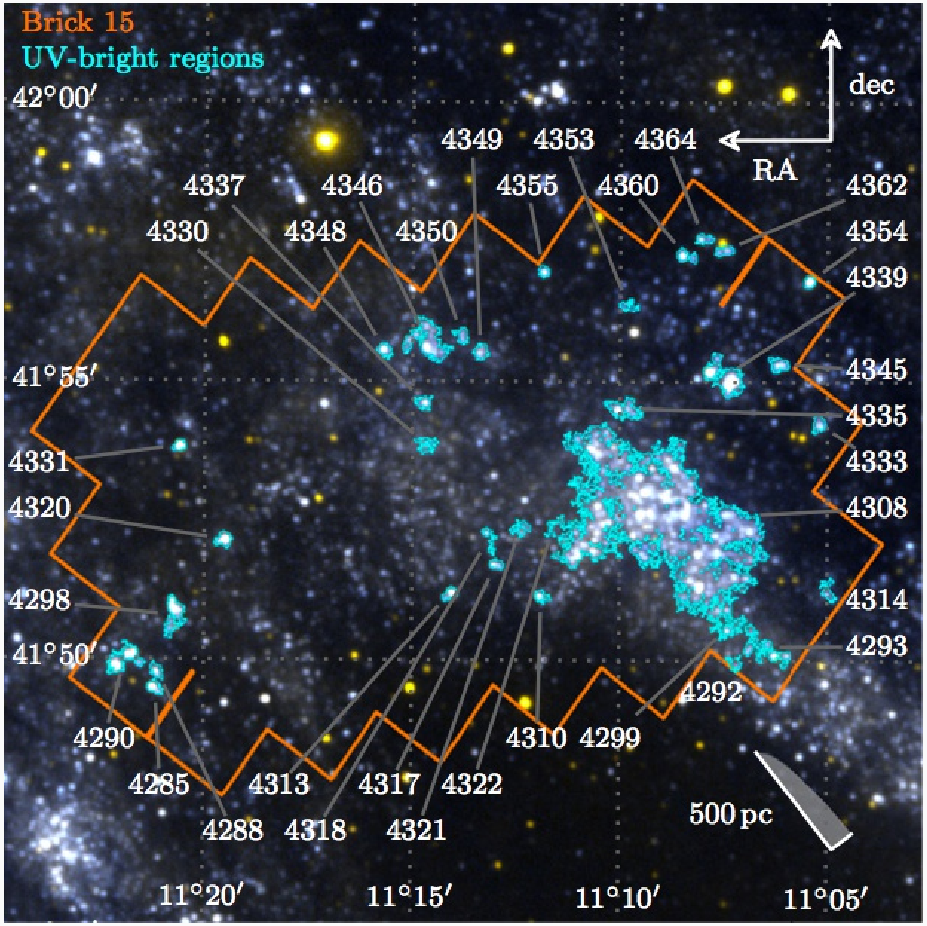
II. Synthetic flux maps - SFHs

Pilot study — UV-bright regions

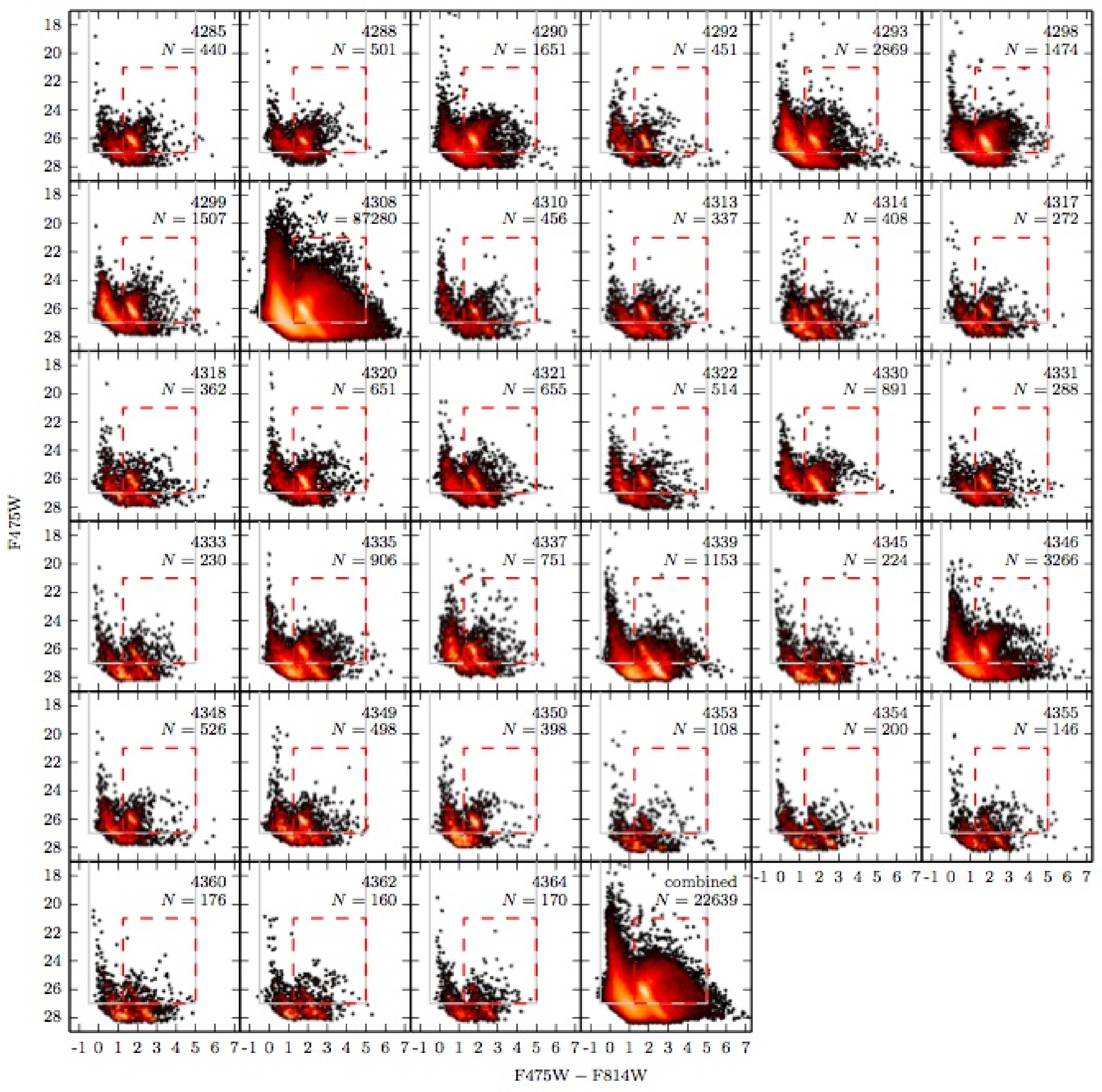
33 UV-bright regions in brick 15 (Kang+, 2009)

$10^4 <$ Area $< 10^6$ pc^2

~100 to 1000 pc in scale



II. Synthetic flux maps - SFHs



II. Synthetic flux maps - SFHs

SFHs from CMD fitting

MATCH: Kroupa (2001) IMF, Padova isochrones

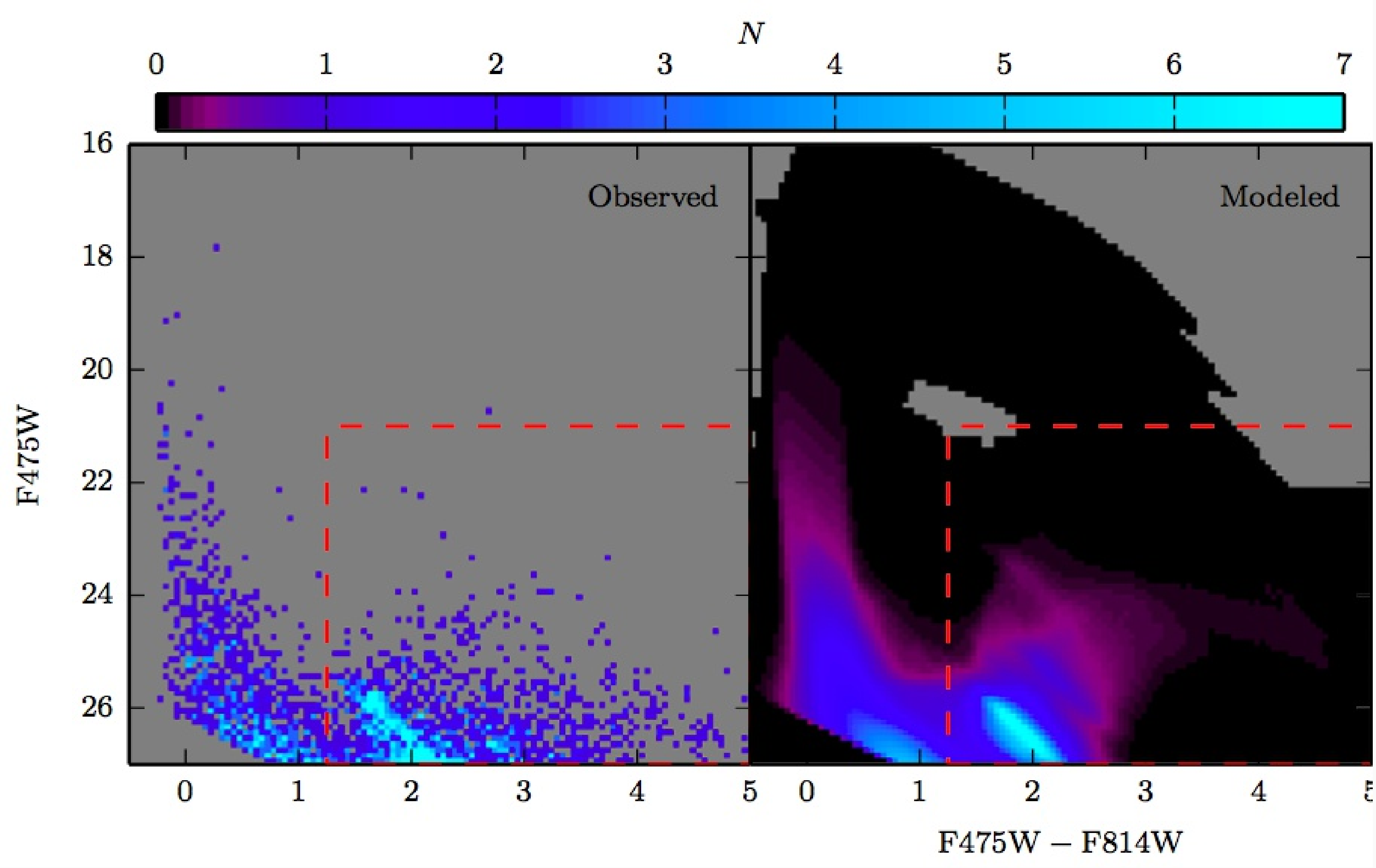
Models a series of CMDs for various linear combinations of SSP models.

Finds best-fit to the observed CMD.

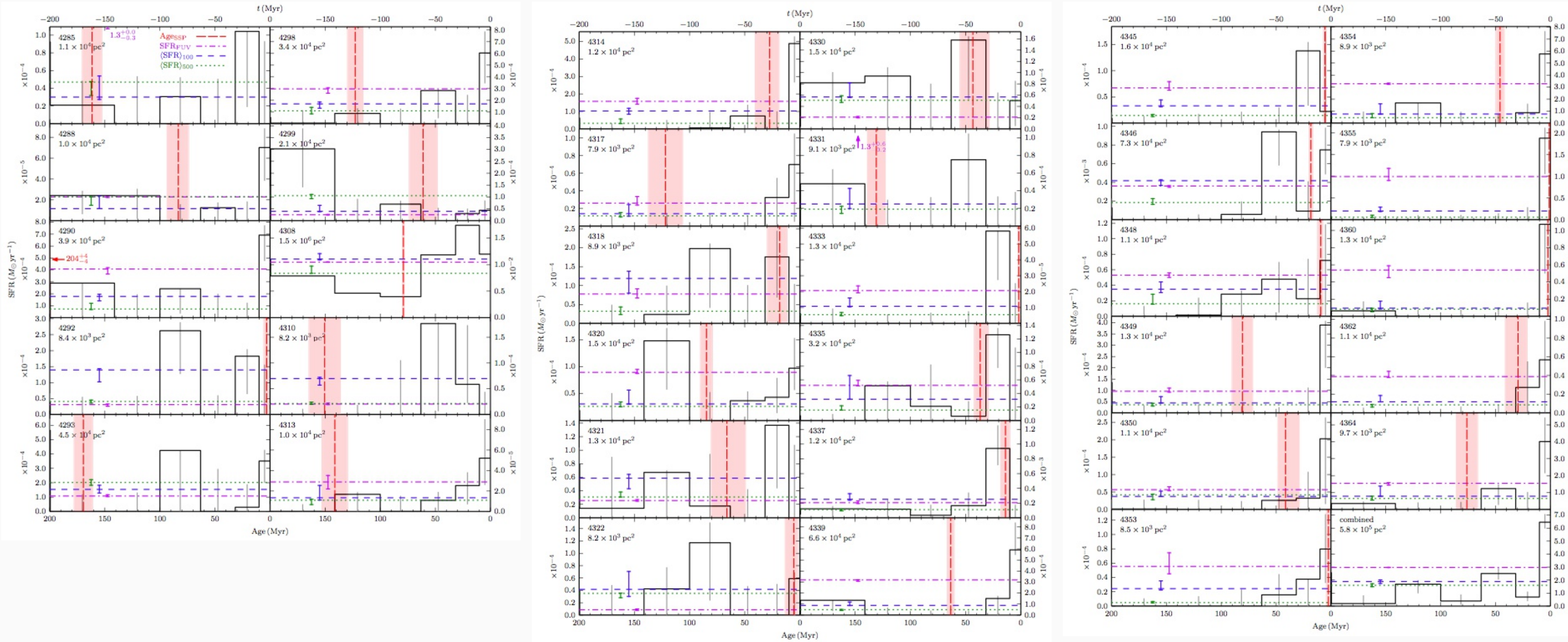
The SFH of the best-fit CMD is the most likely SFH of the stellar population.

II. Synthetic flux maps - SFHs

Example modeled CMD



II. Synthetic flux maps - SFHs

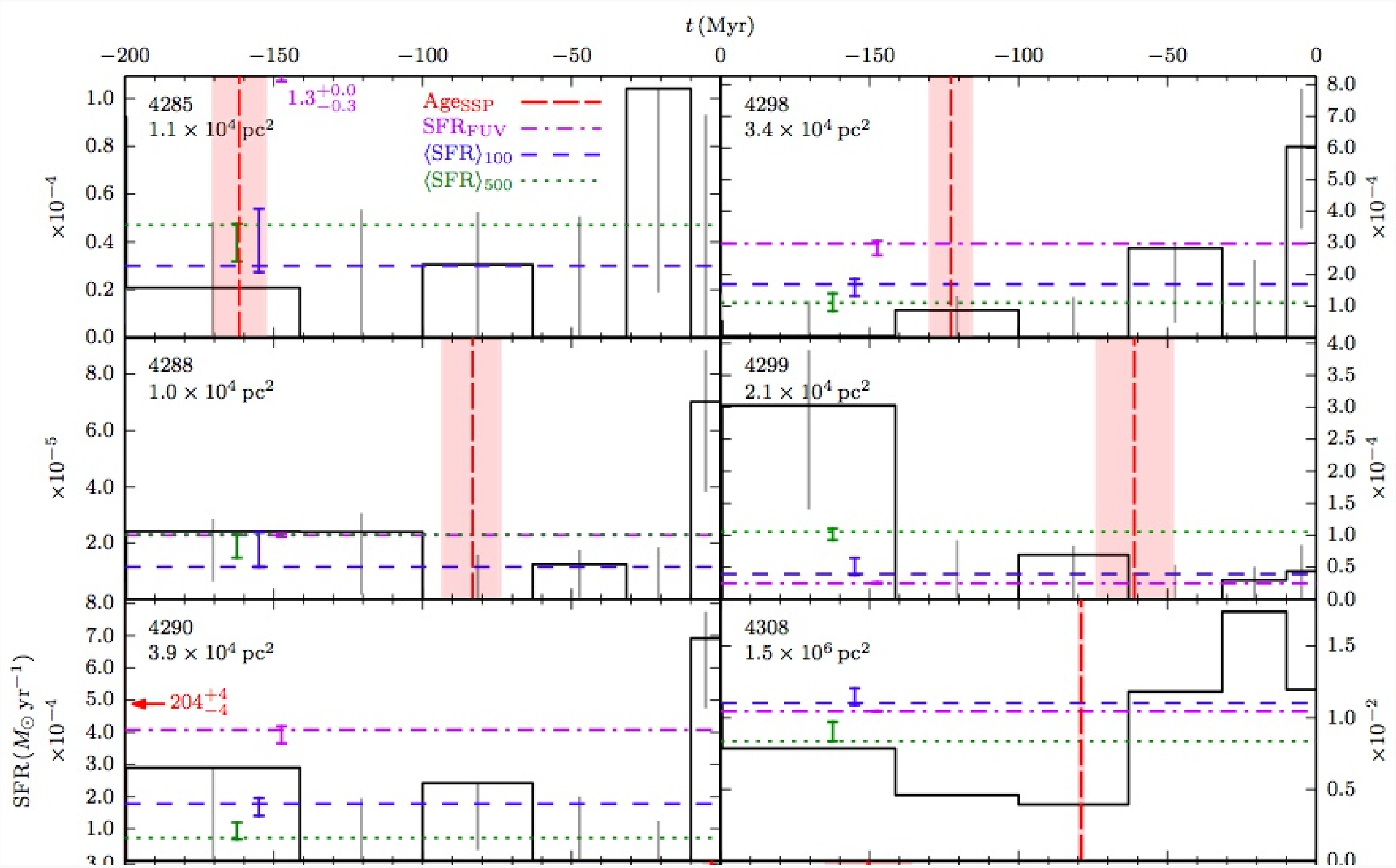


II. Synthetic flux maps - SFHs

SFHs of UV-bright regions

Wide variety of SFHs.

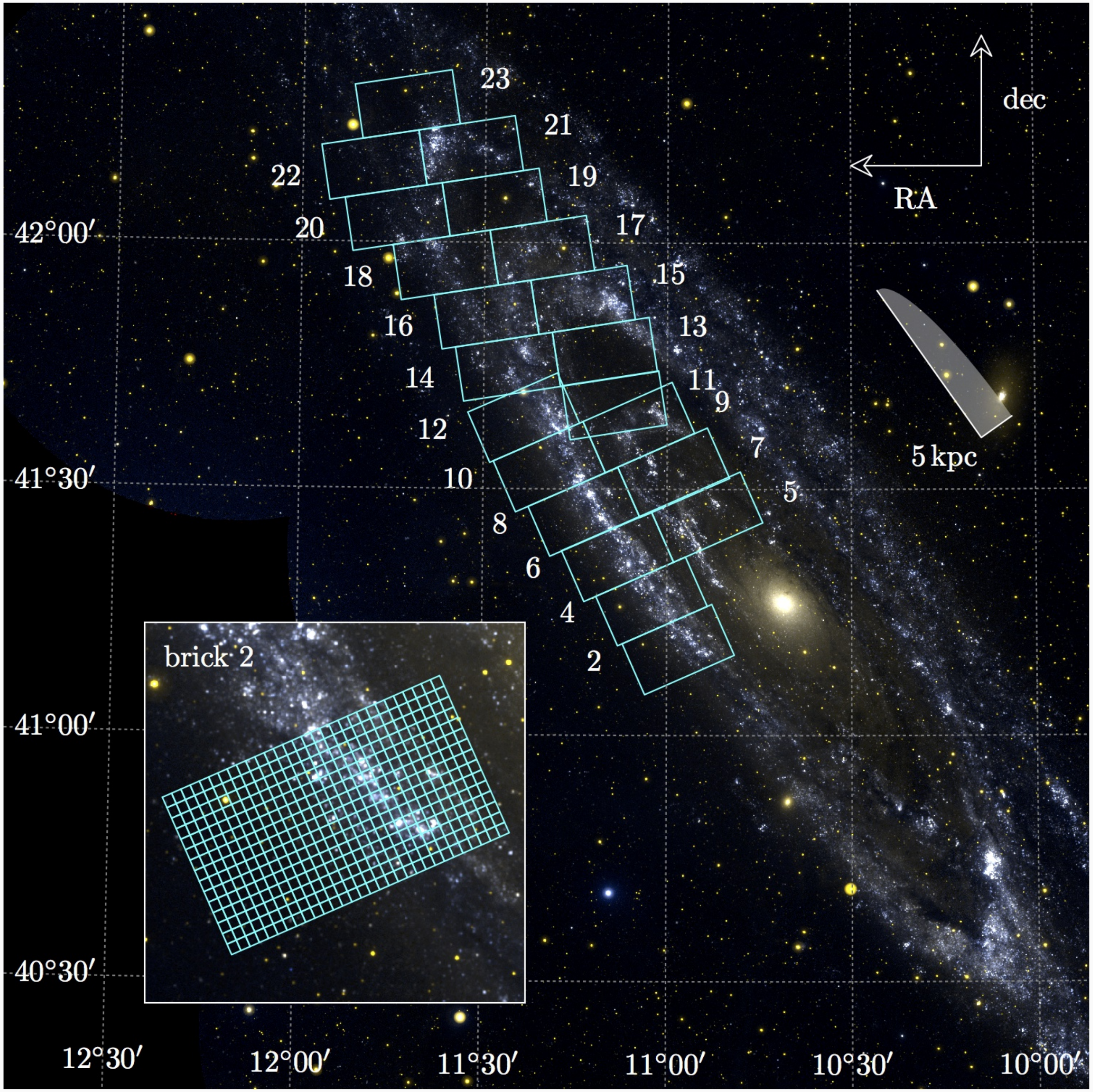
Not SSPs, not constant.



II. Synthetic flux maps - SFHs

Survey-wide SFHs

SFHs for 9000+ regions using the same method.



II. Synthetic flux maps - SPS

Deriving synthetic FUV and NUV flux maps

SPS (FSPS) with the measured SFHs to derive synthetic spectra.

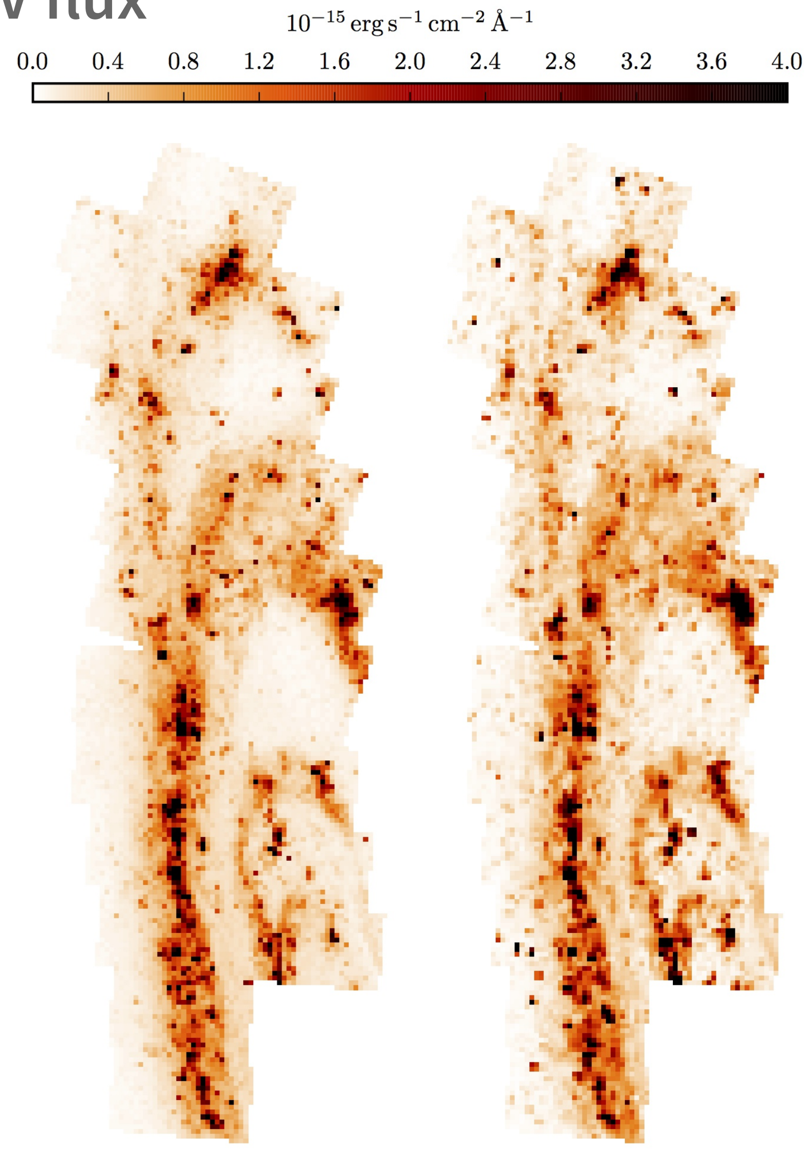
Convolve spectra with the FUV and NUV filters to derive FUV and NUV flux.

Arrange all 9000+ flux values into mosaics.

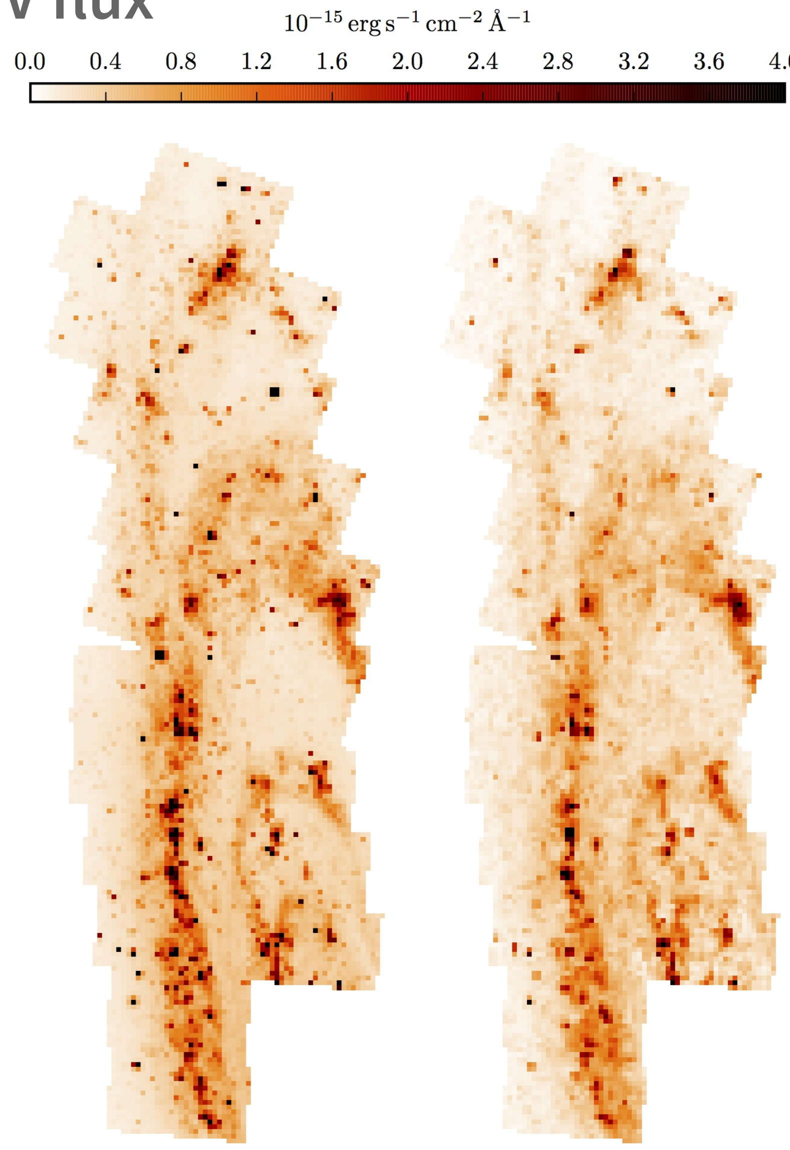
Pixel area = 4×10^4 pc^2

II. Syn. flux maps - comparison

FUV flux

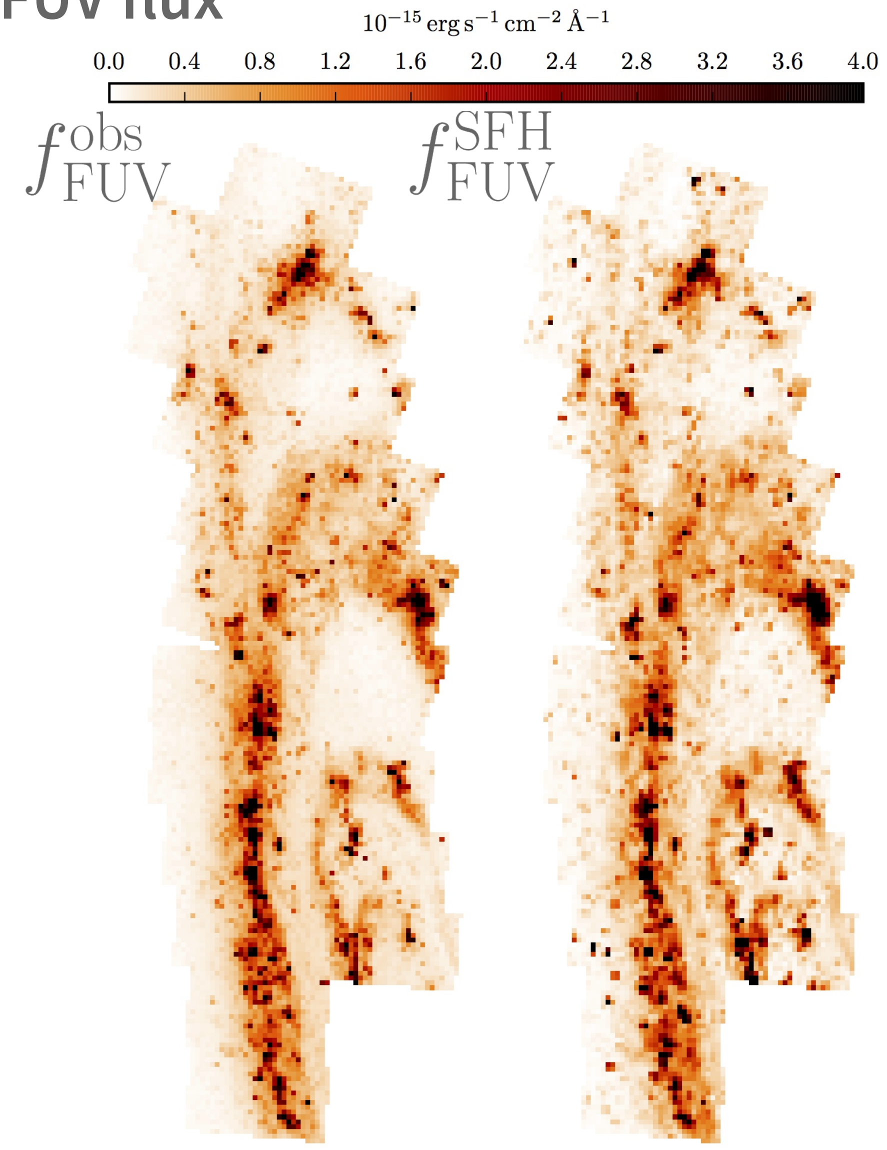


NUV flux

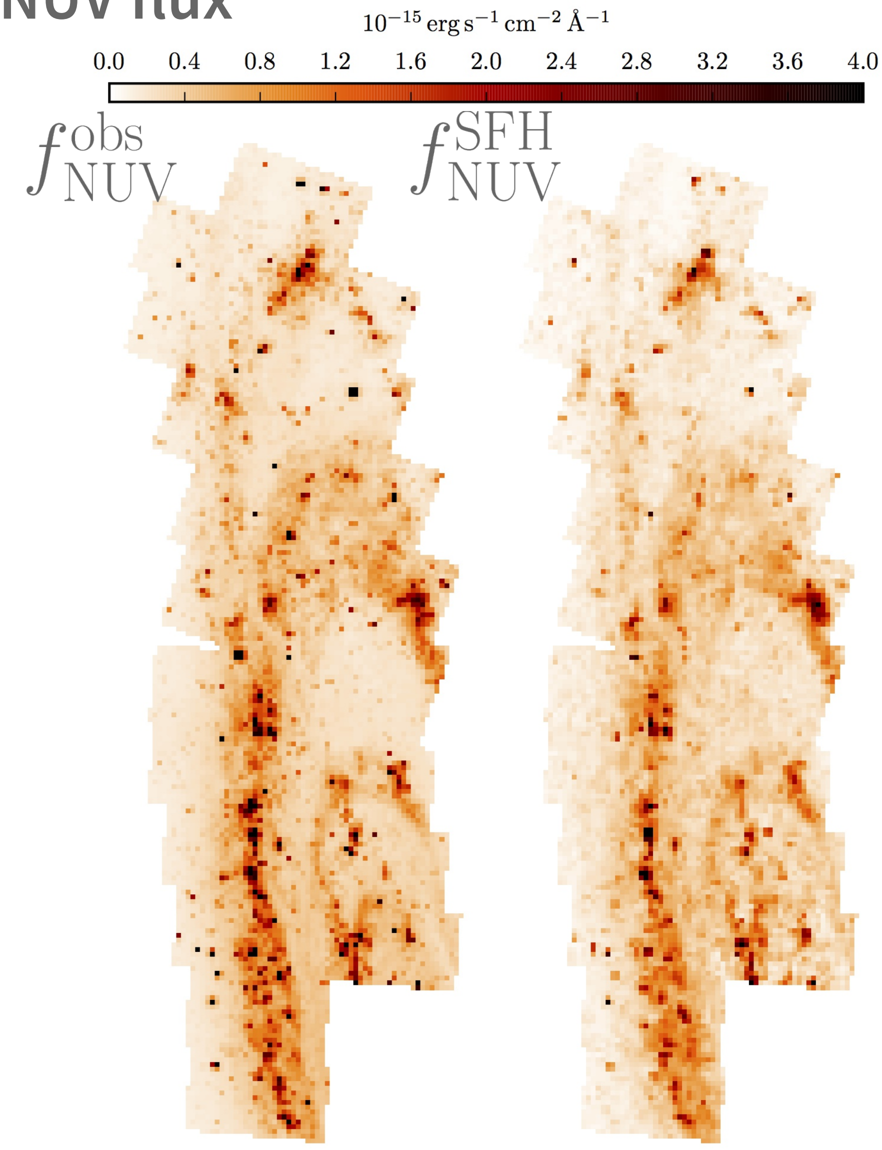


II. Syn. flux maps - comparison

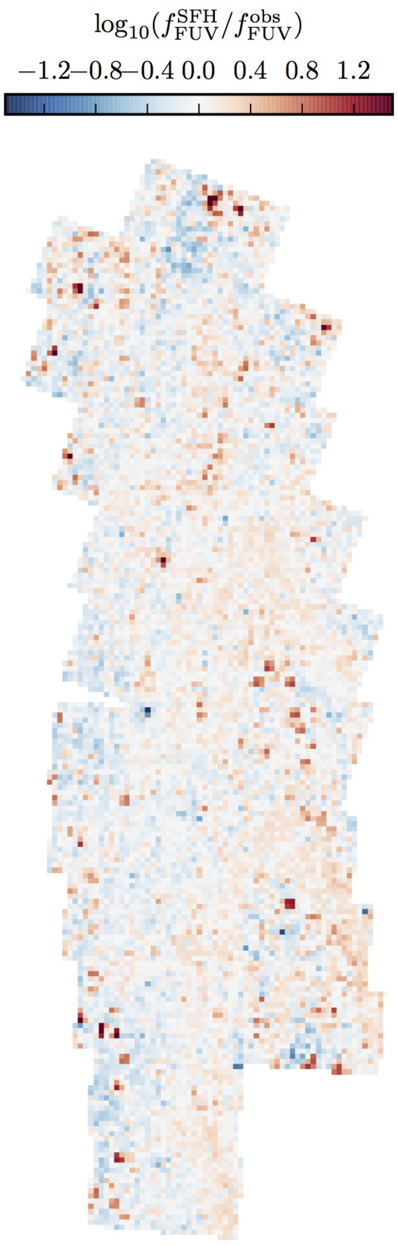
FUV flux



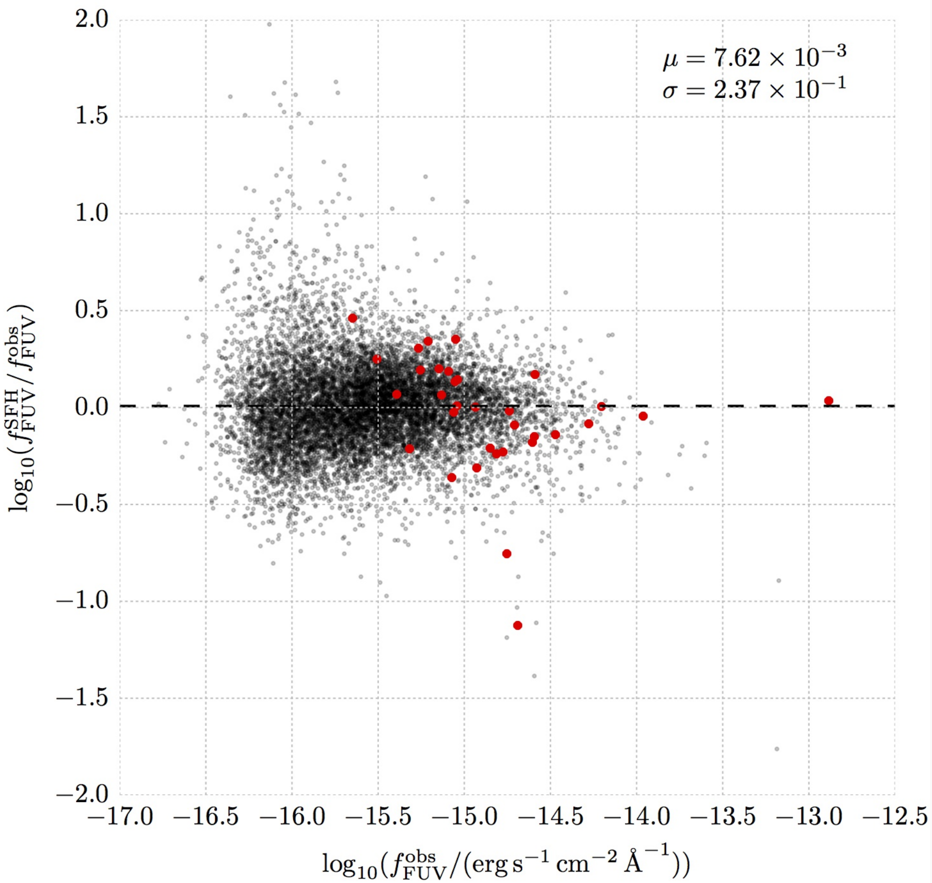
NUV flux



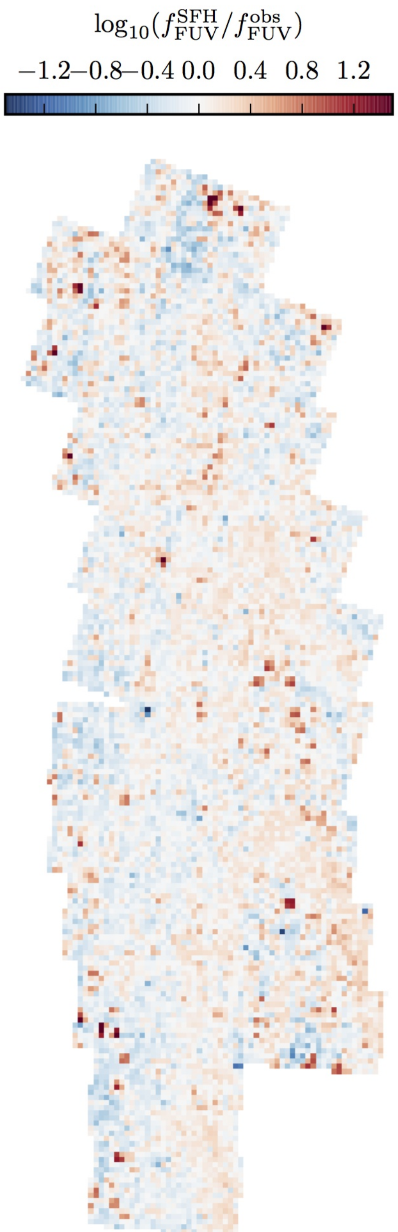
II. Syn. flux maps - comparison

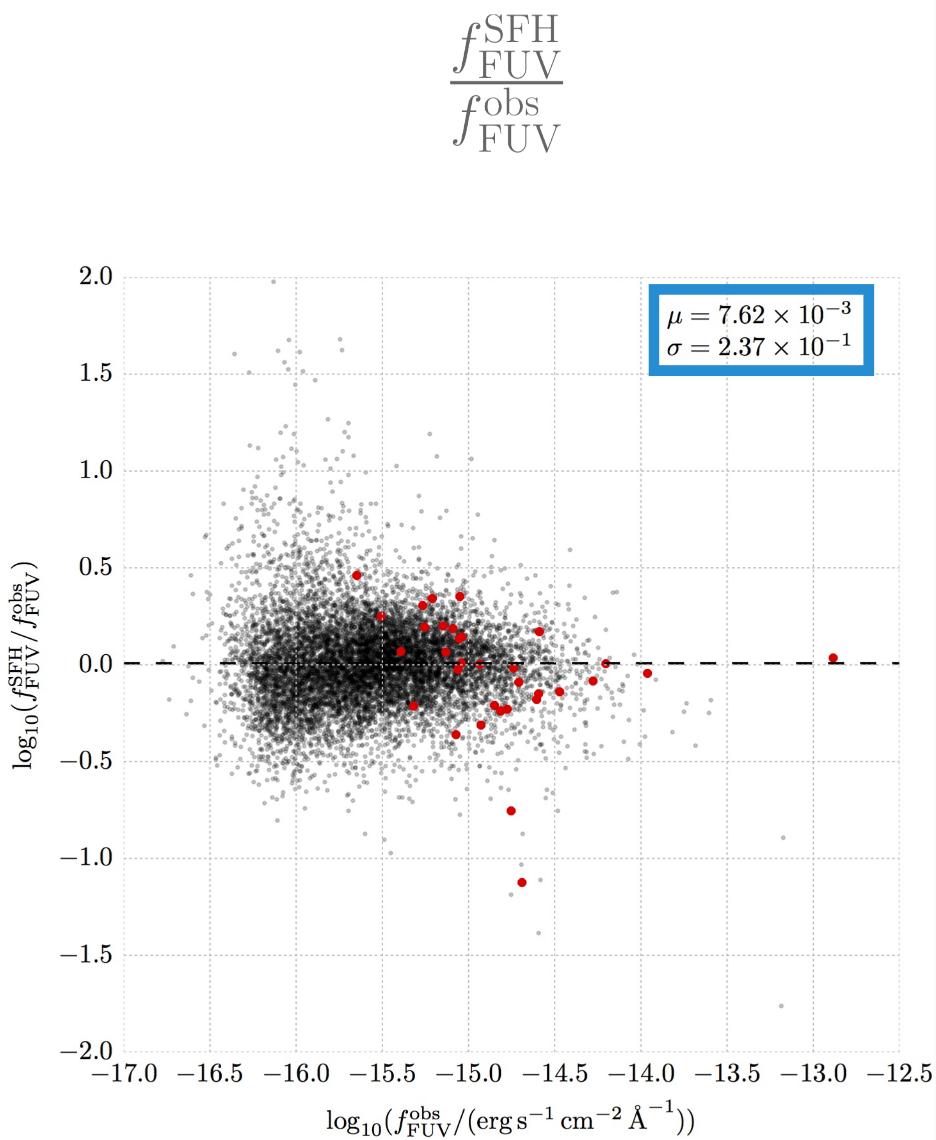


$\frac{f_{\mathrm{FUV}}^{\mathrm{SFH}}}{f_{\mathrm{FUV}}^{\mathrm{obs}}}$



II. Syn. flux maps - comparison



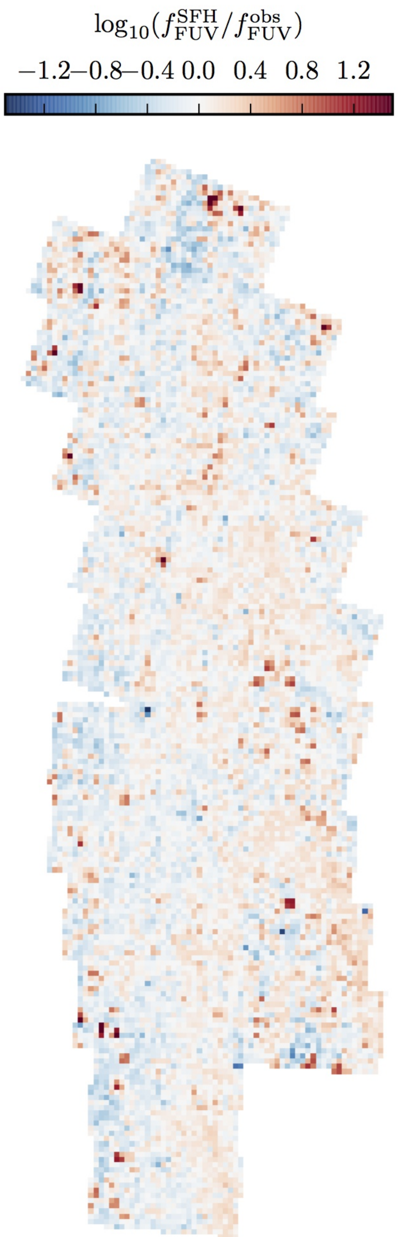


FUV flux ratios

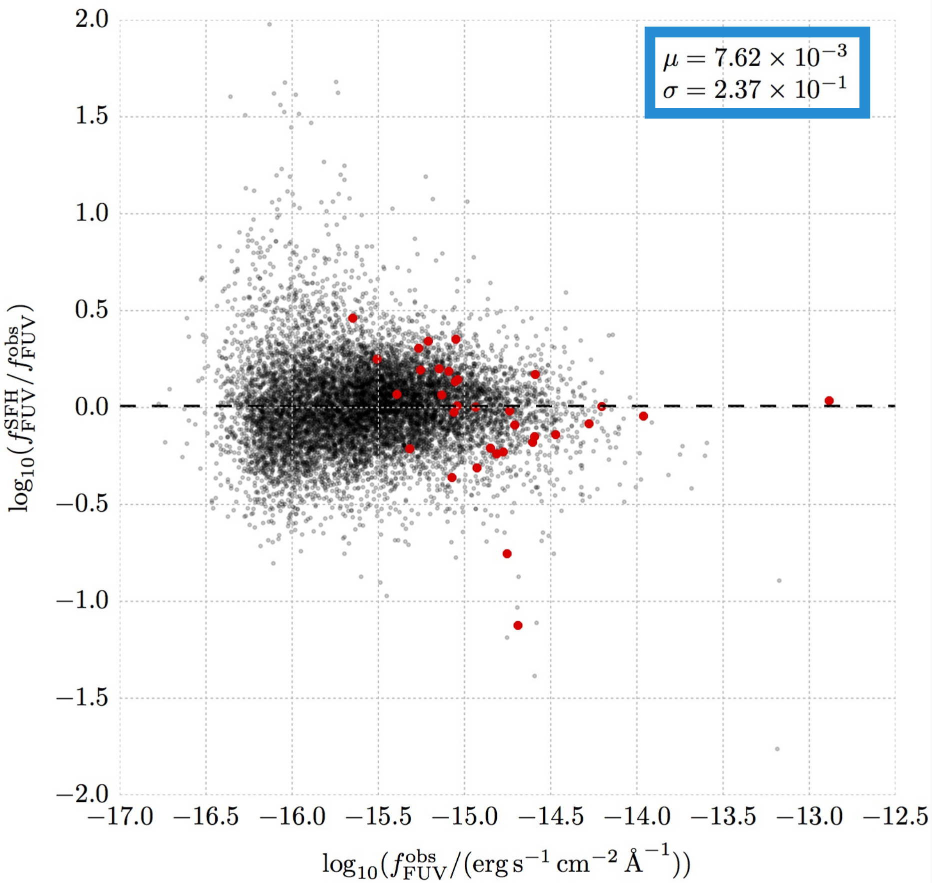
Median ratio: 1.02

(0.59 to 1.76)

II. Syn. flux maps - comparison



$$\frac{f_{\rm FUV}^{\rm SFH}}{f_{\rm FUV}^{\rm obs}}$$



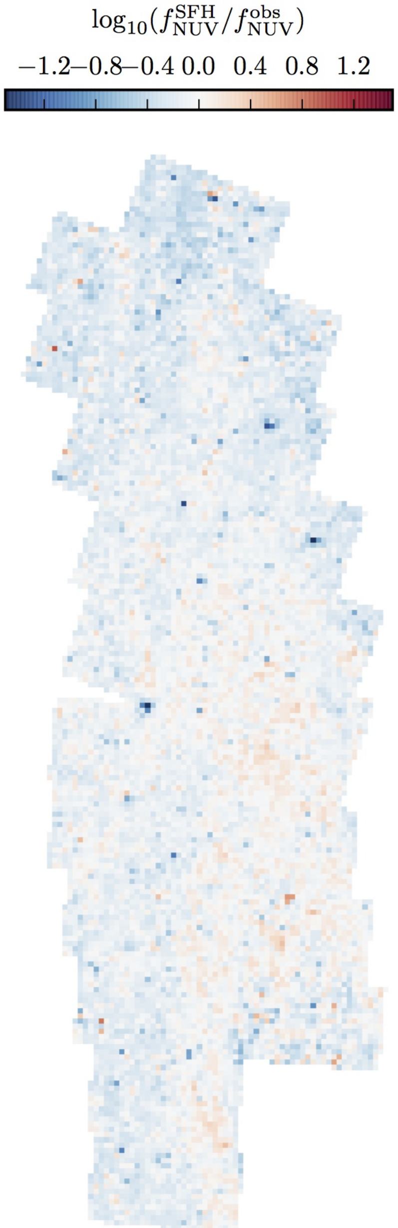
FUV flux ratios

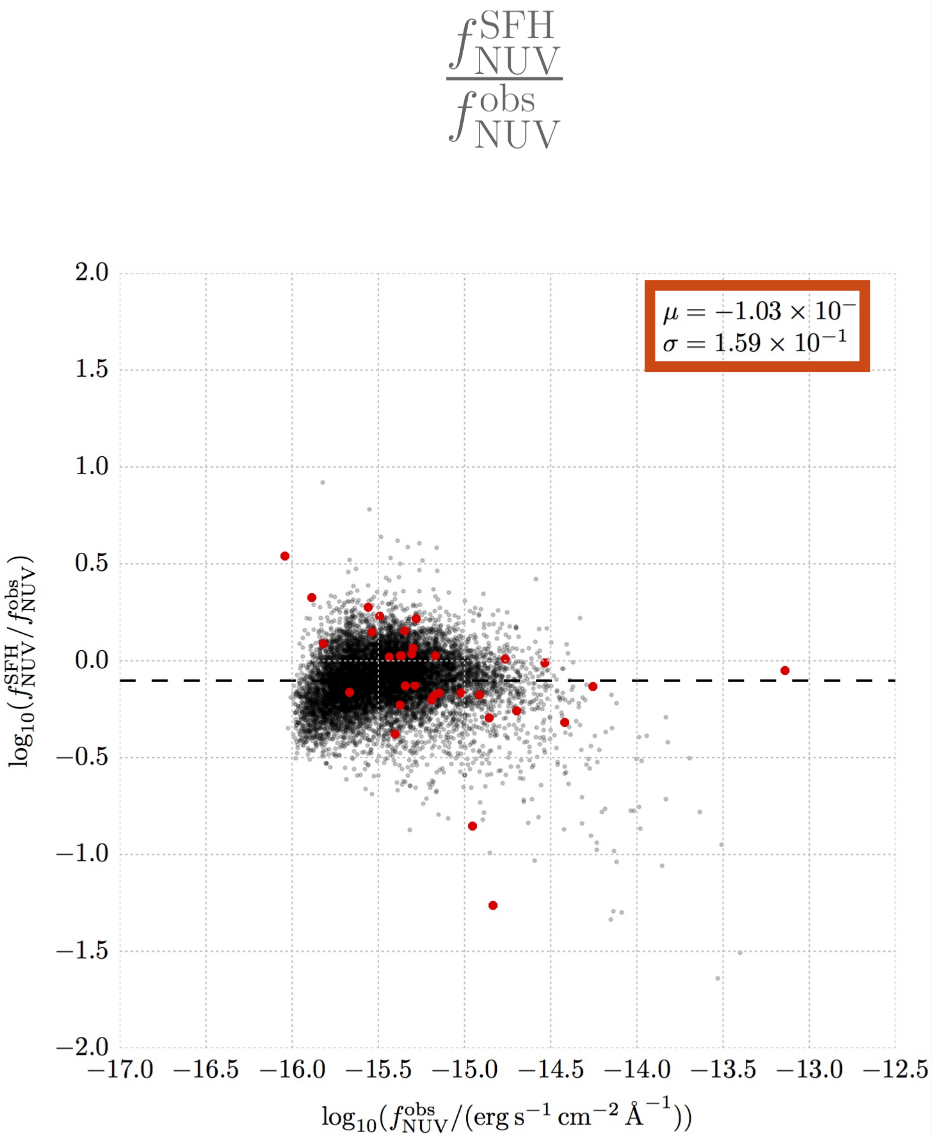
Median ratio: 1.02 (0.59 to 1.76)

» Consistent on average.

» Modeling is robust!

II. Syn. flux maps - comparison





NUV flux ratios

Median ratio: 0.79 (0.55 to 1.14)

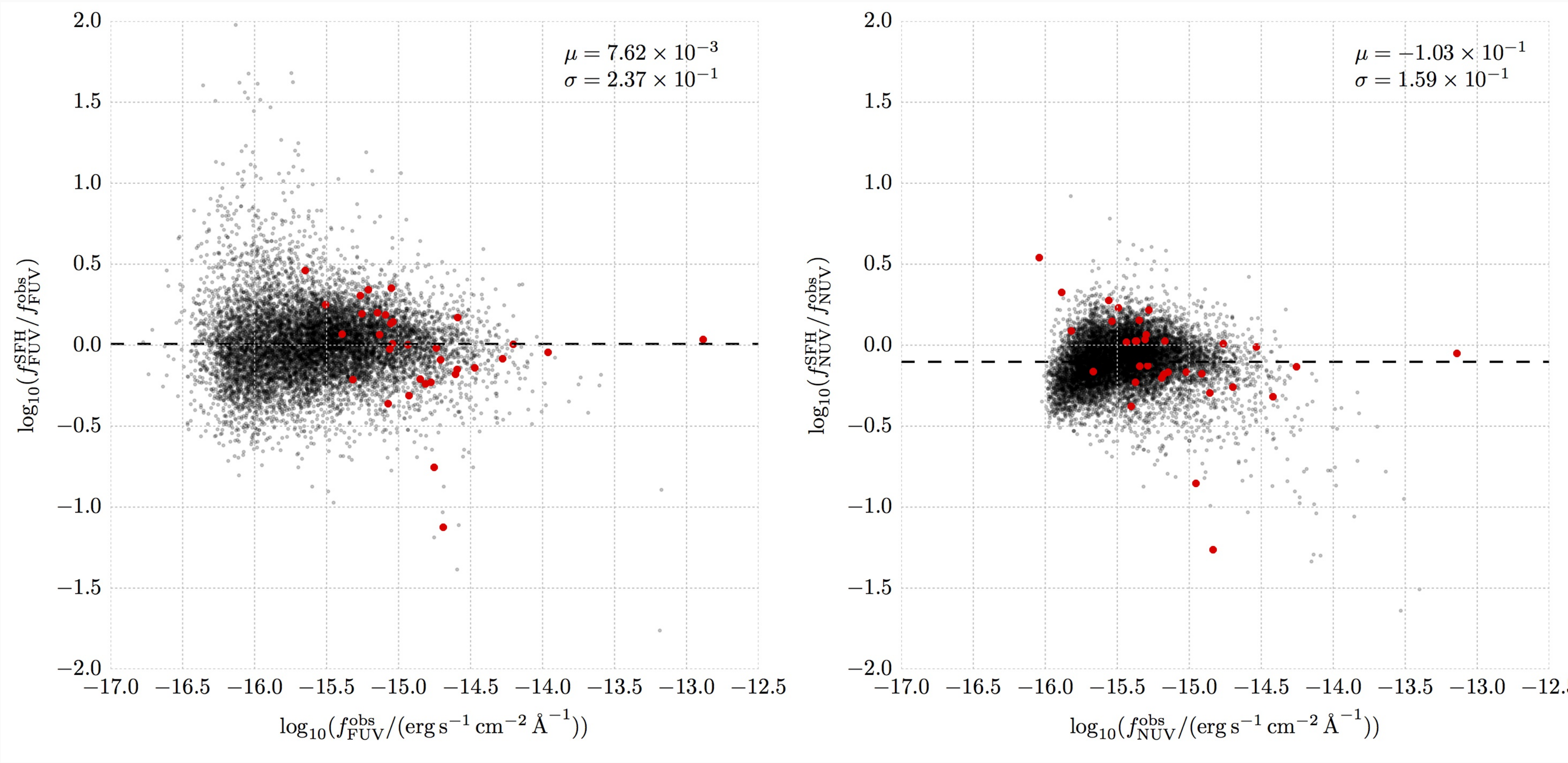
» Consistent on average.

» Modeling is robust!

Similarly for NUV

II. Syn. flux maps - comparison

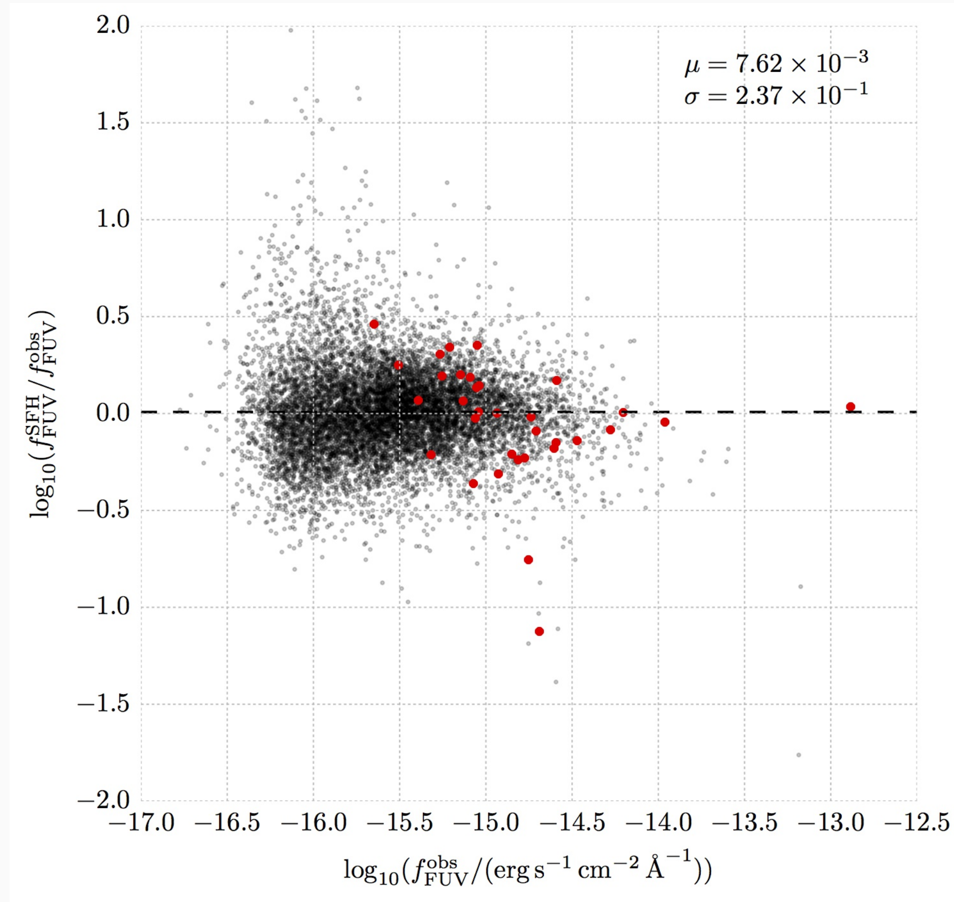
Source of dispersion?



II. Syn. flux maps - comparison

Source of dispersion?

Dispersion is larger among faint pixels.

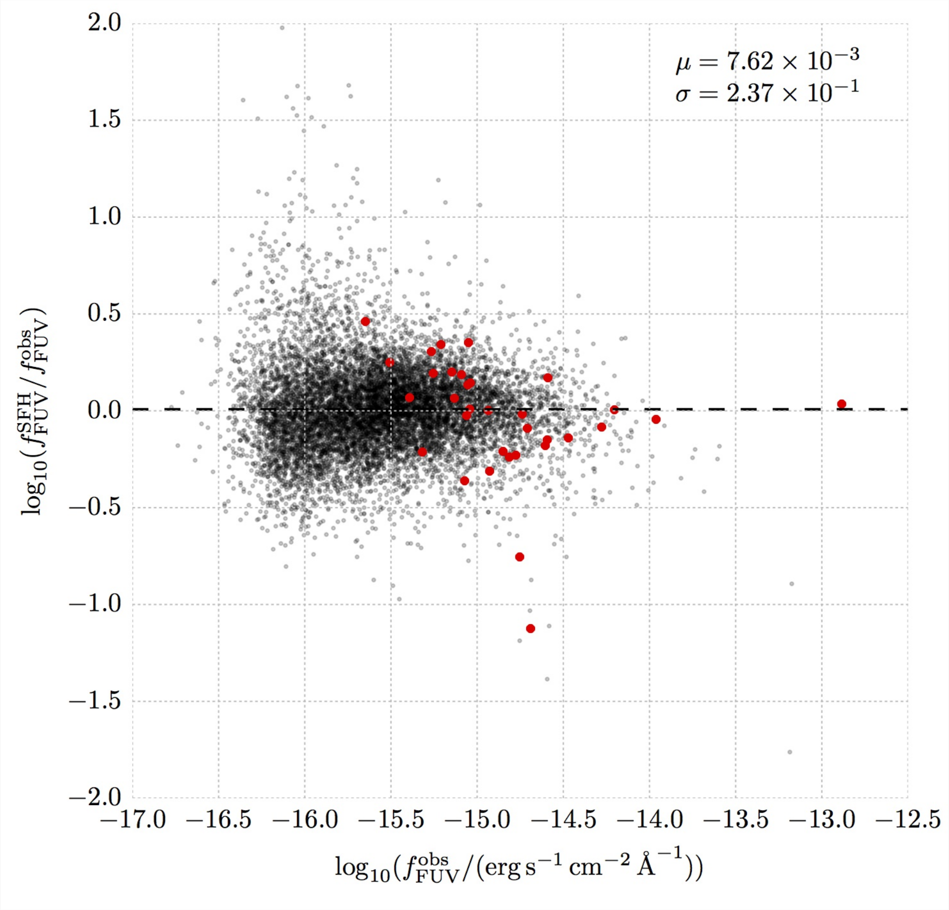


II. Syn. flux maps - comparison

Source of dispersion?

Dispersion is larger among faint pixels.

Faint pixels have fewer stars.



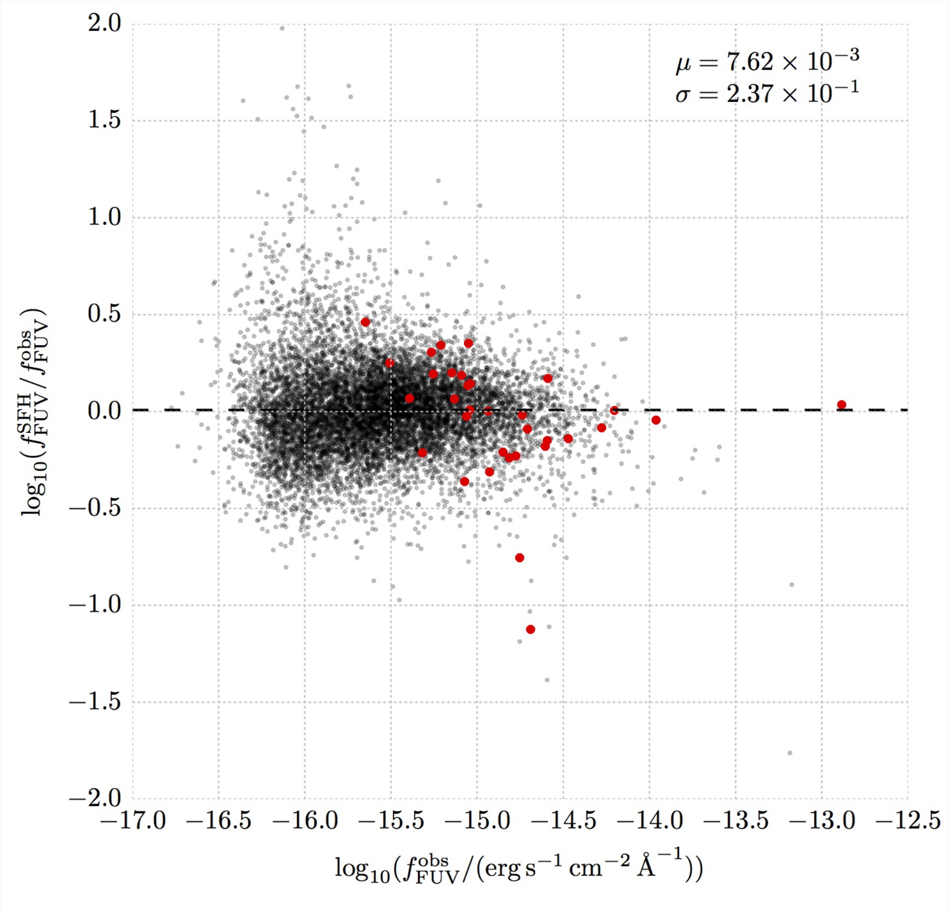
II. Syn. flux maps - comparison

Source of dispersion?

Dispersion is larger among faint pixels.

Faint pixels have fewer stars.

» Violation of the full-IMF assumption.



II. Syn. flux maps - comparison

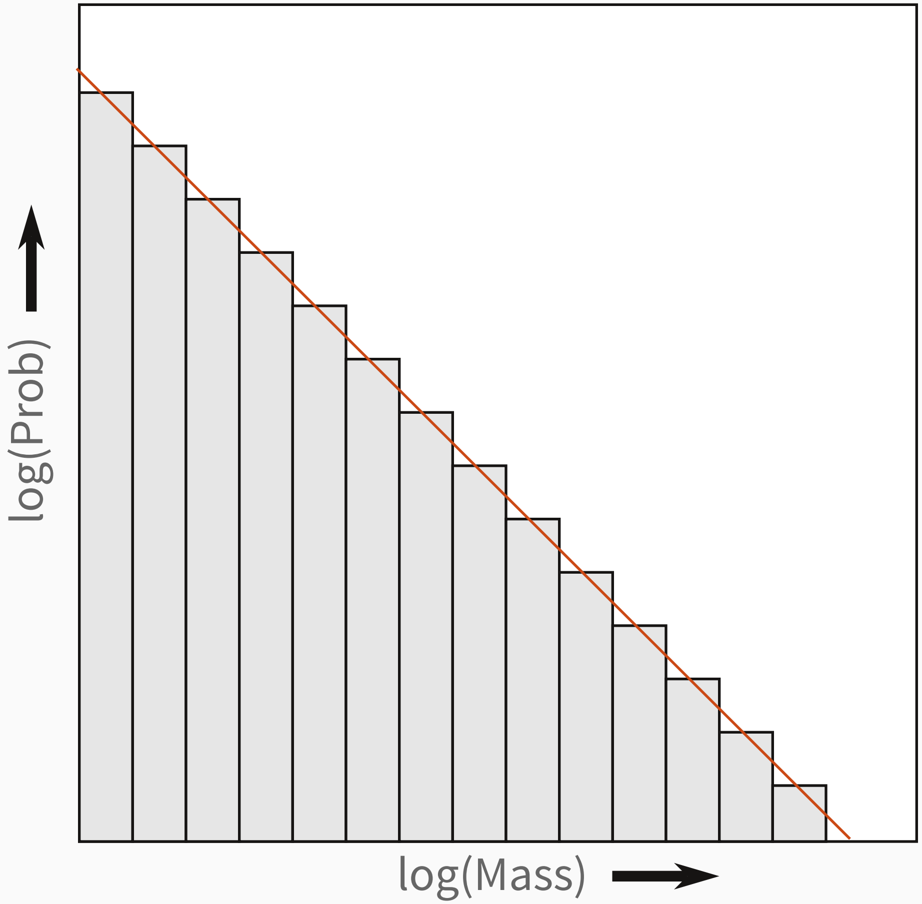
Full-IMF assumption

Stellar population has a smooth mass distribution.

All masses are represented.

Requires a large number of stars (high total mass).

Assumed by SPS.

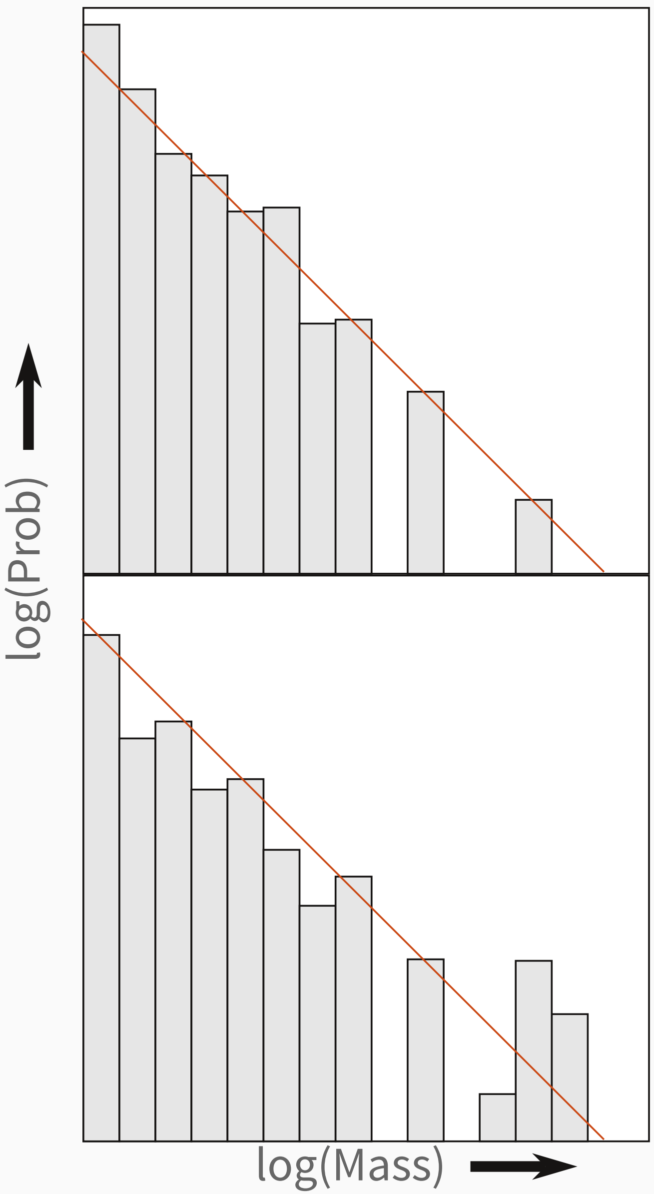


II. Syn. flux maps - comparison

Full-IMF assumption

Not all masses represented when number of stars is small (low total mass).

Any two samplings of the IMF can be very different; different fluxes.



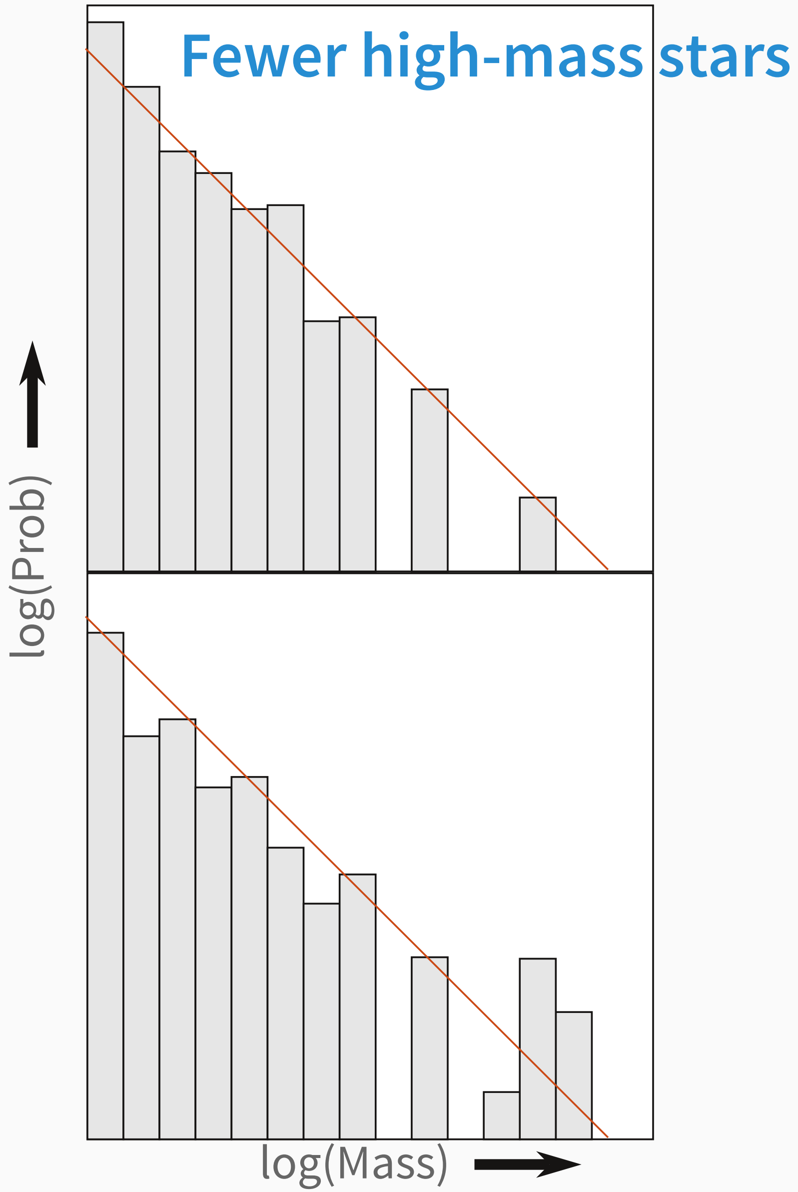
II. Syn. flux maps - comparison

Full-IMF assumption

Not all masses represented when number of stars is small (low total mass).

Any two samplings of the IMF can be very different; different fluxes.

Fewer high-mass MS stars
» SPS overestimates UV flux.



II. Syn. flux maps - comparison

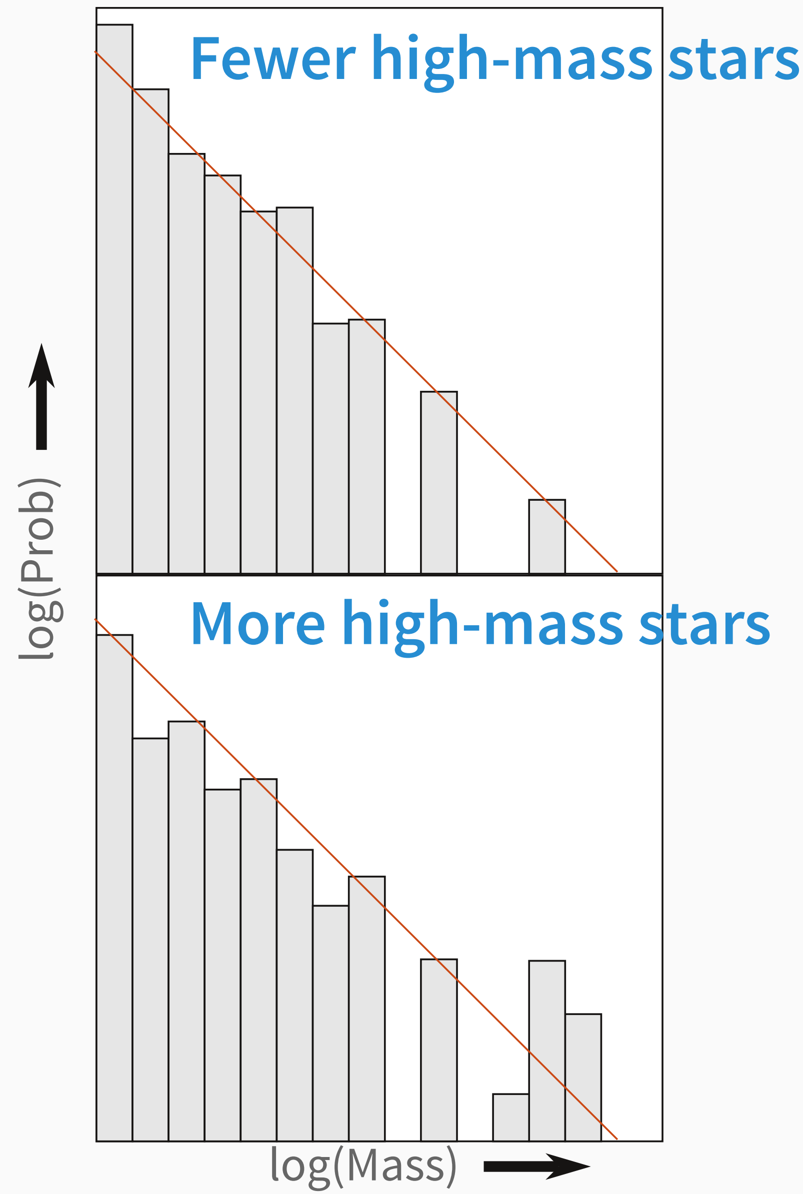
Full-IMF assumption

Not all masses represented when number of stars is small (low total mass).

Any two samplings of the IMF can be very different; different fluxes.

Fewer high-mass MS stars
» SPS overestimates UV flux.

More high-mass MS stars
» SPS underestimates UV flux.



II. Syn. flux maps - comparison

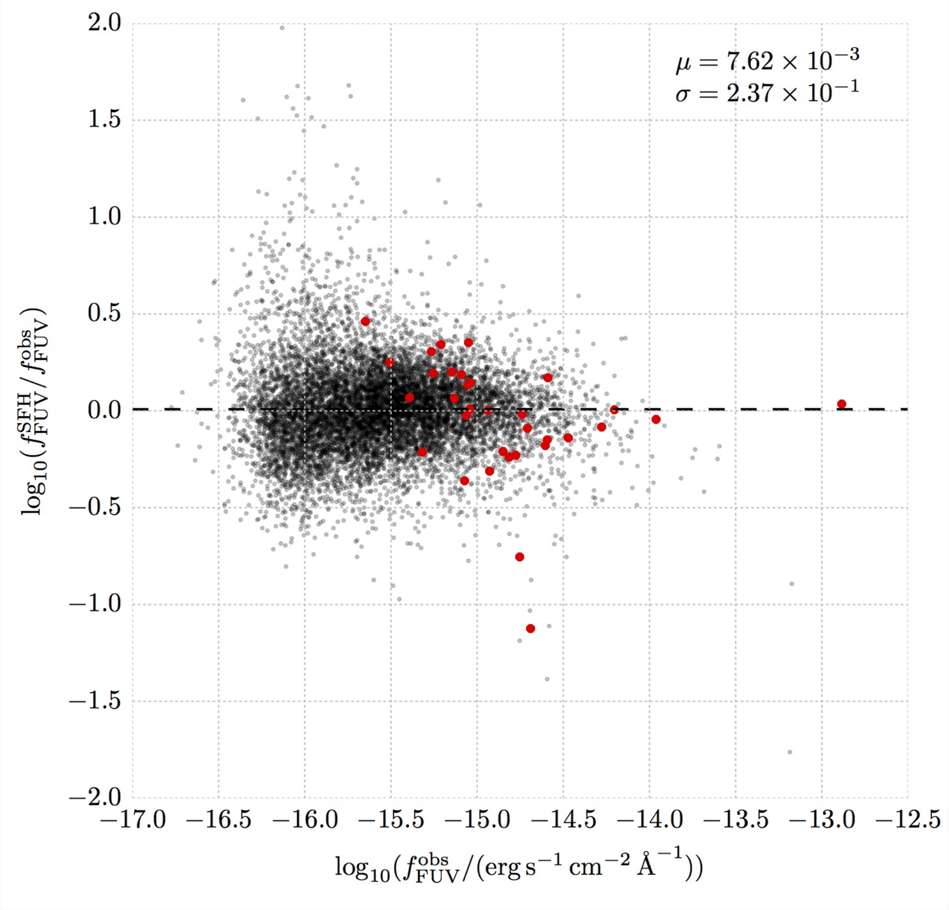
Source of dispersion?

Dispersion is larger among faint pixels.

Faint pixels have fewer stars.

» Violation of the full-IMF assumption.

Result of small pixel areas.



II. Synthetic flux maps of M31

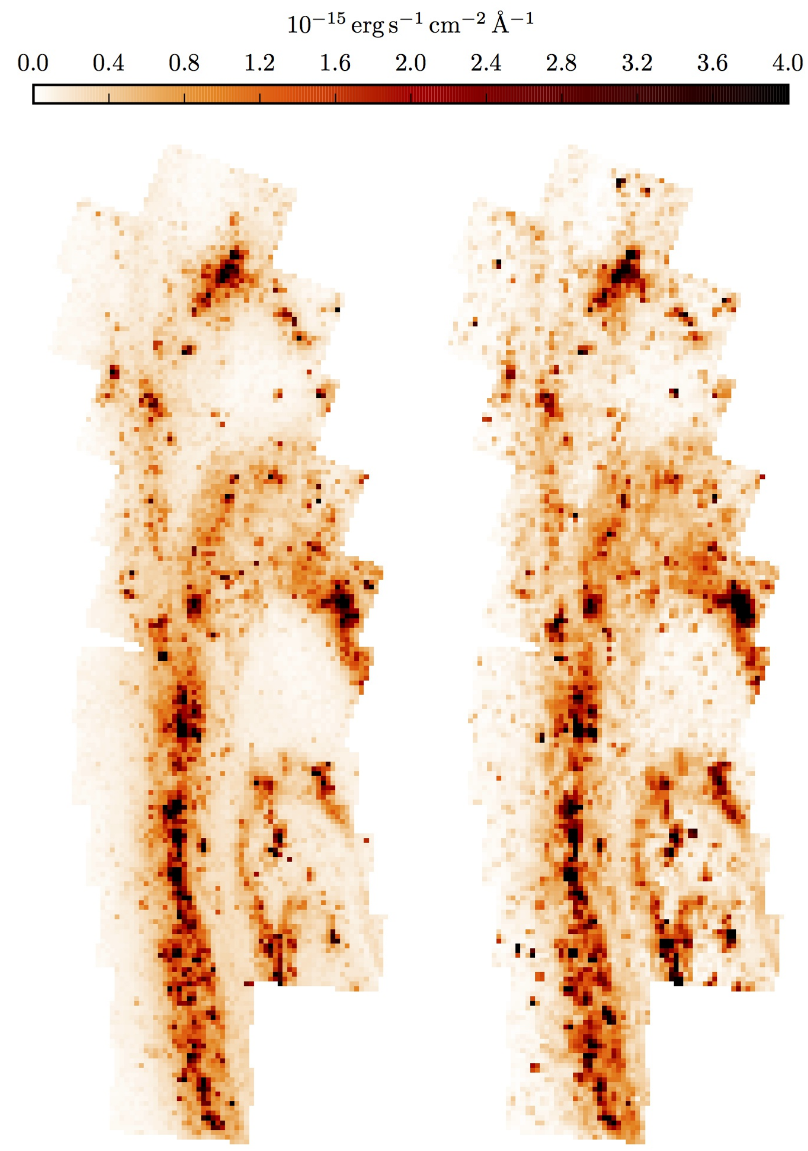
Conclusion

Confident in our ability to model fluxes.

We understand SPS ingredients at least fairly well:

- Stellar evolution
- Stellar spectra
- IMF
- Reconstructing SFHs

SPS can be used (in principle) to estimate quantities based on integrated flux.



III. SFR maps of M31

Maps of UV flux-based SFR

Convert UV flux into SFR using calibrations from Kennicutt & Evans (2012).

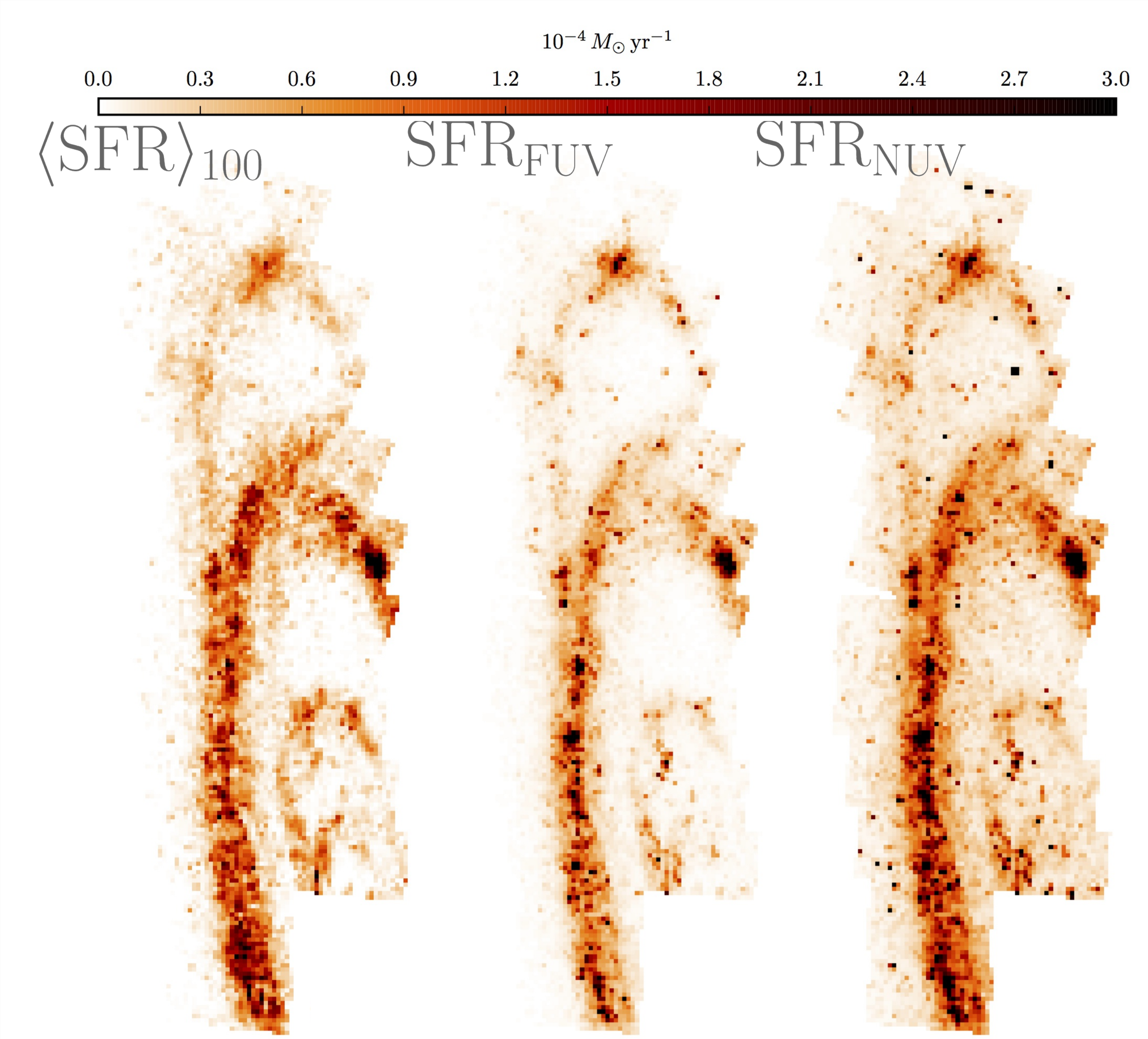
Calibrations derived from SPS assuming,

- Full IMF
- Constant SFR over the past 100 Myr
- Solar metallicity

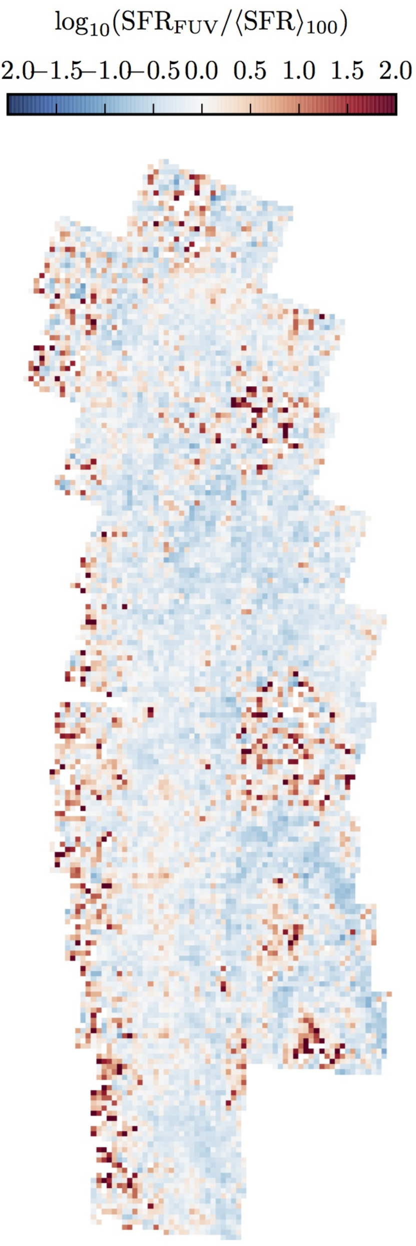
Maps of SFH-based SFR

Calculate the 100-Myr mean SFR from the SFHs.

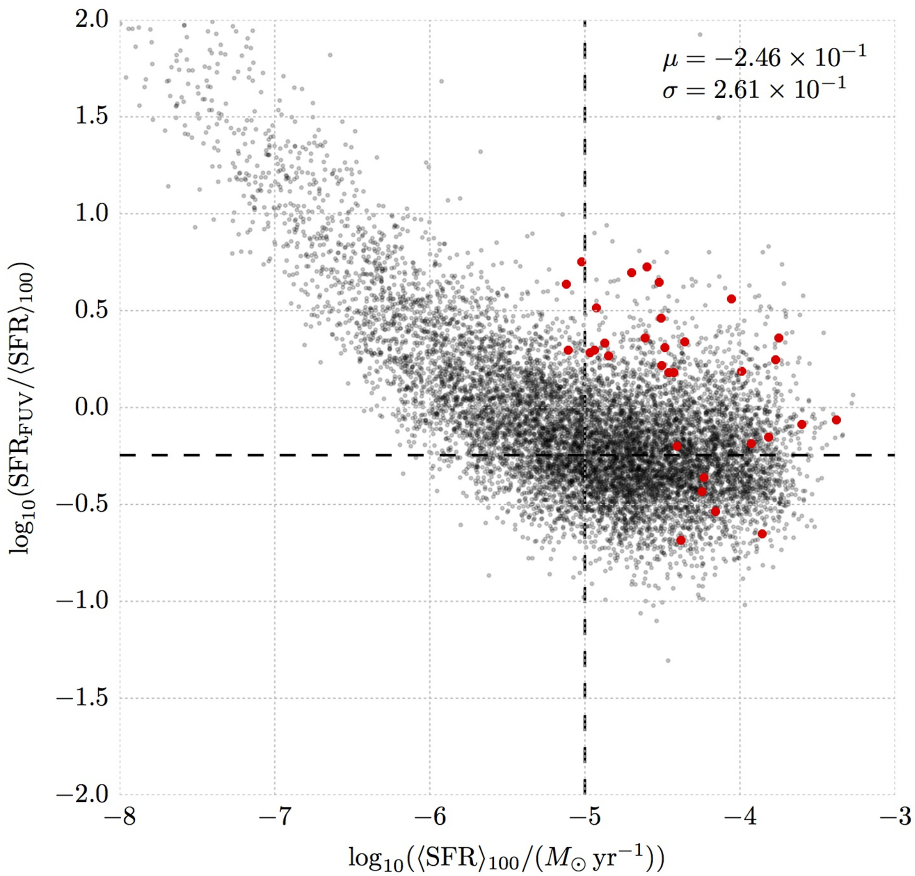
III. SFR maps - comparison



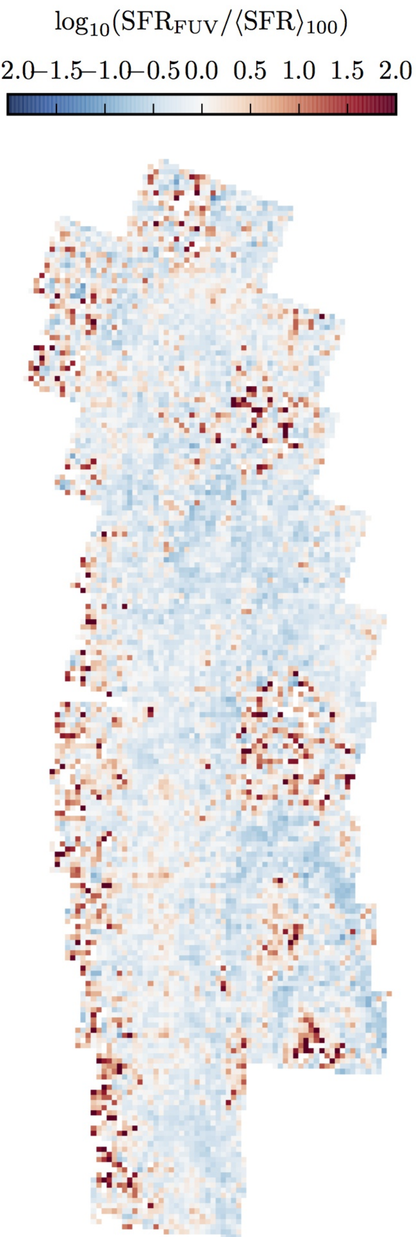
III. SFR maps - comparison



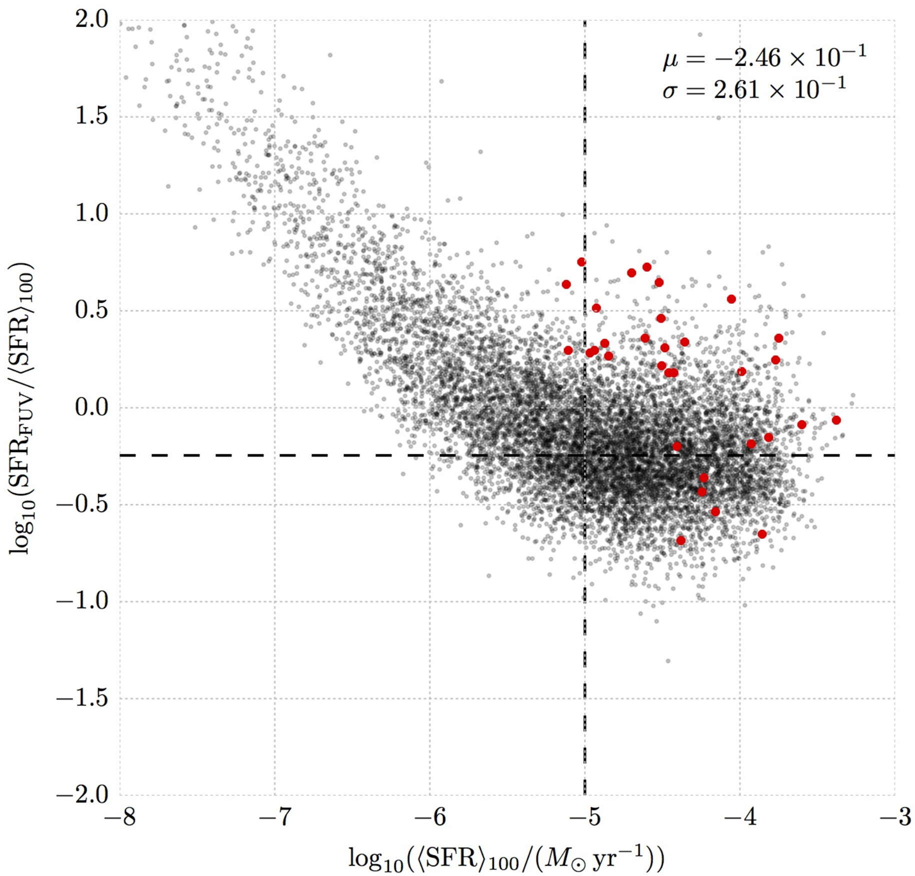
$$\frac{\mathrm{SFR_{FUV}}}{\langle \mathrm{SFR} \rangle_{100}}$$



III. SFR maps - comparison



$$\frac{\mathrm{SFR_{FUV}}}{\langle\mathrm{SFR}\rangle_{100}}$$

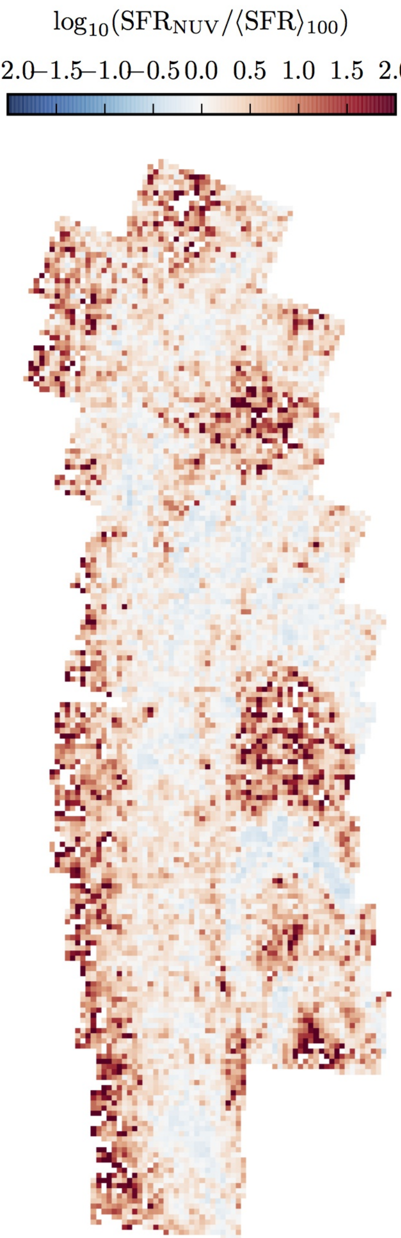


SFR ratios

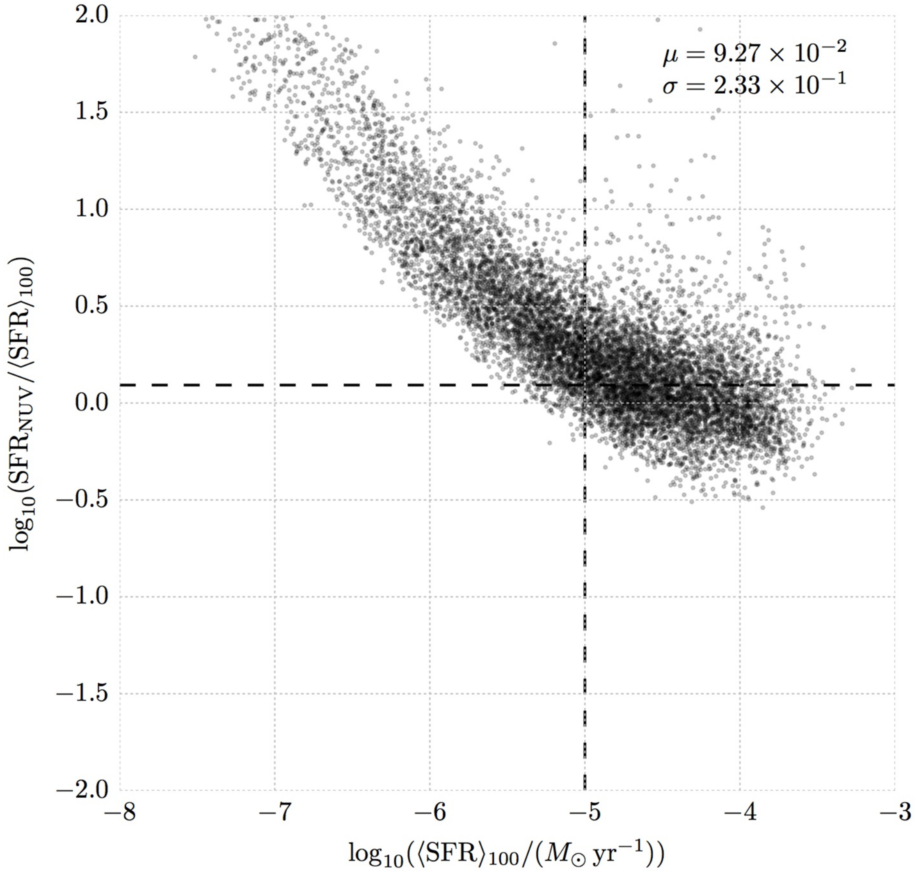
Large ratios in background areas.

» “Tail” feature

III. SFR maps - comparison



$$\frac{\mathrm{SFR_{NUV}}}{\langle\mathrm{SFR}\rangle_{100}}$$



SFR ratios

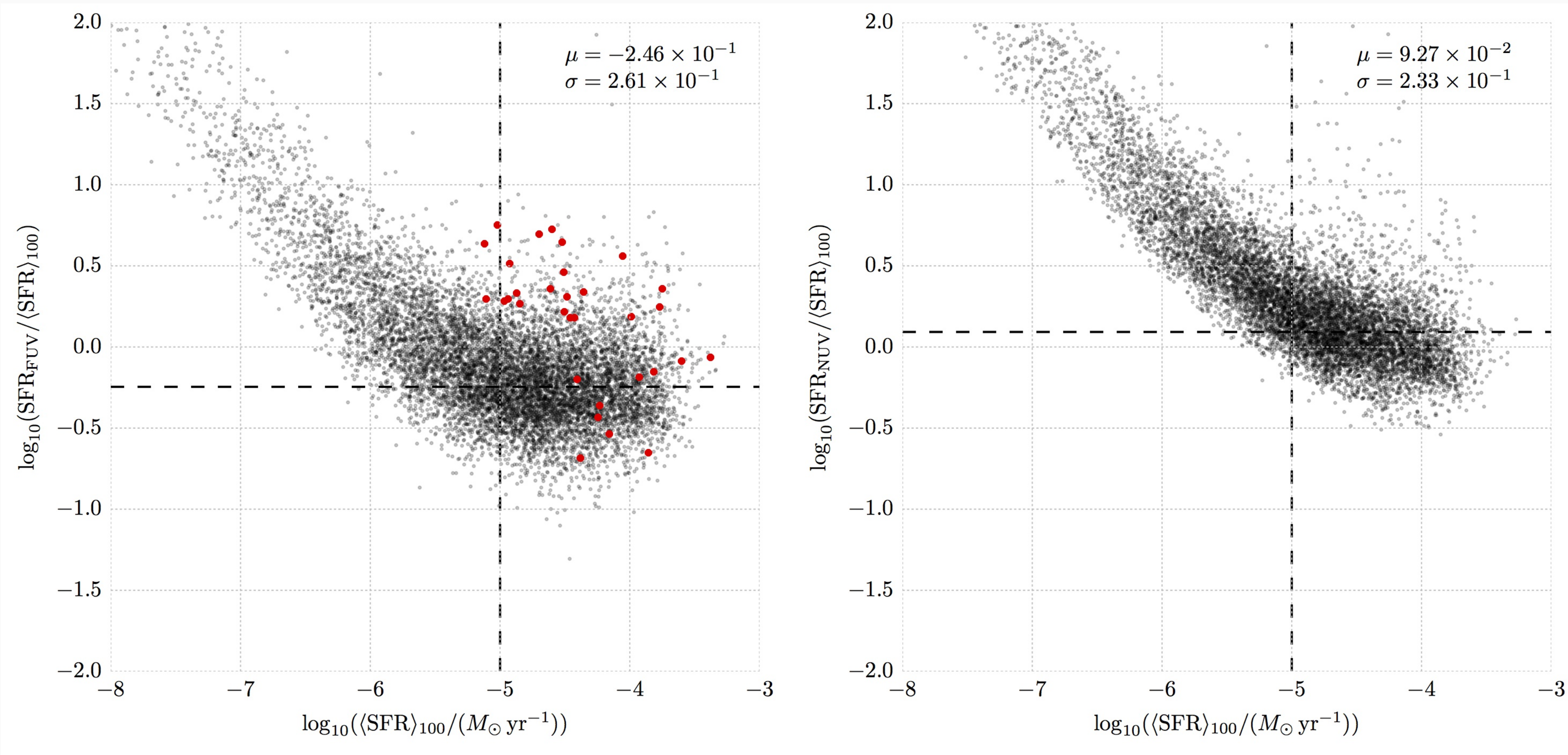
Large ratios in background areas.

» "Tail" feature

Present in both FUV and NUV.

III. SFR maps - comparison

Source of the tails?



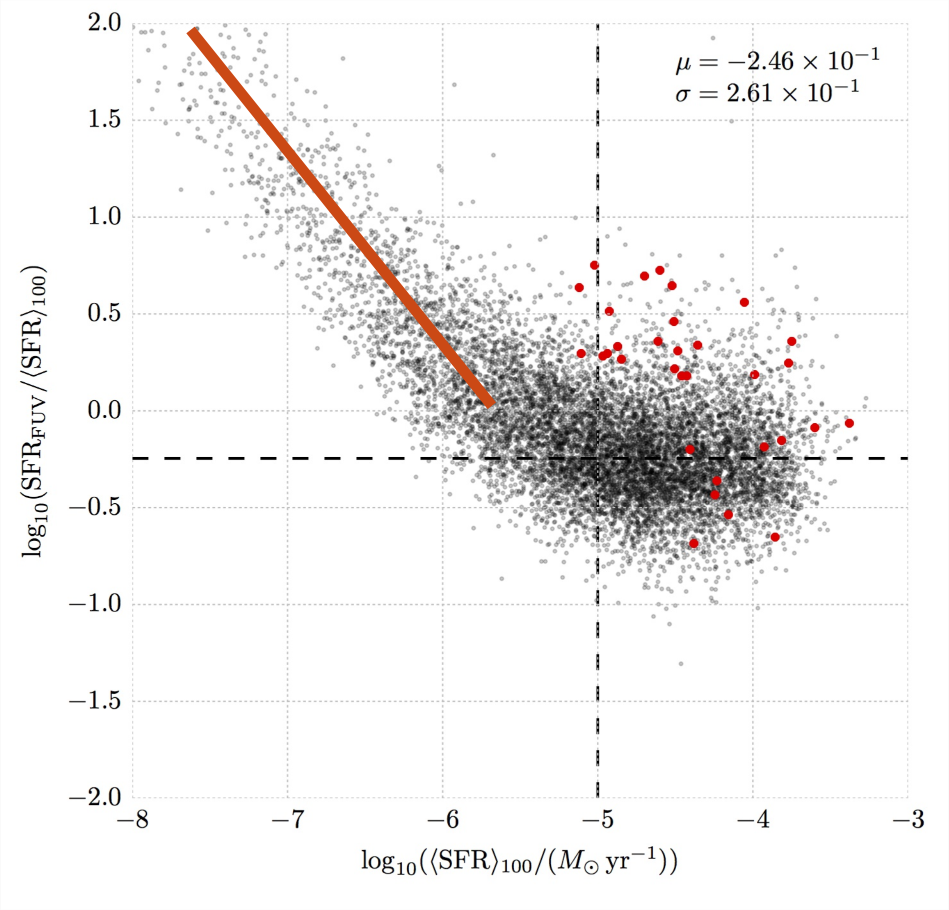
III. SFR maps - comparison

Source of tails?

Distinctly linear:

slope = -1

intercept ~ -6

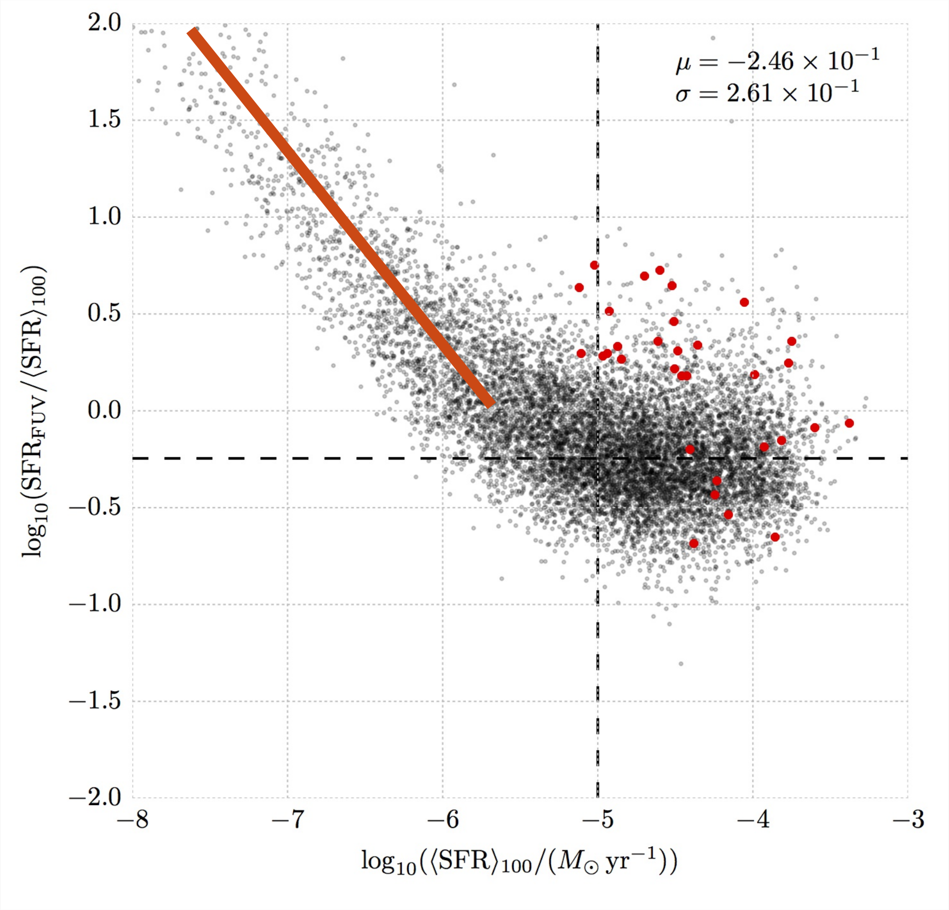


III. SFR maps - comparison

Source of tails?

Distinctly linear:
slope = -1
intercept ~ -6

Flux-based SFR becomes constant below ~ 10^{-6} M_{sun} yr^{-1}.



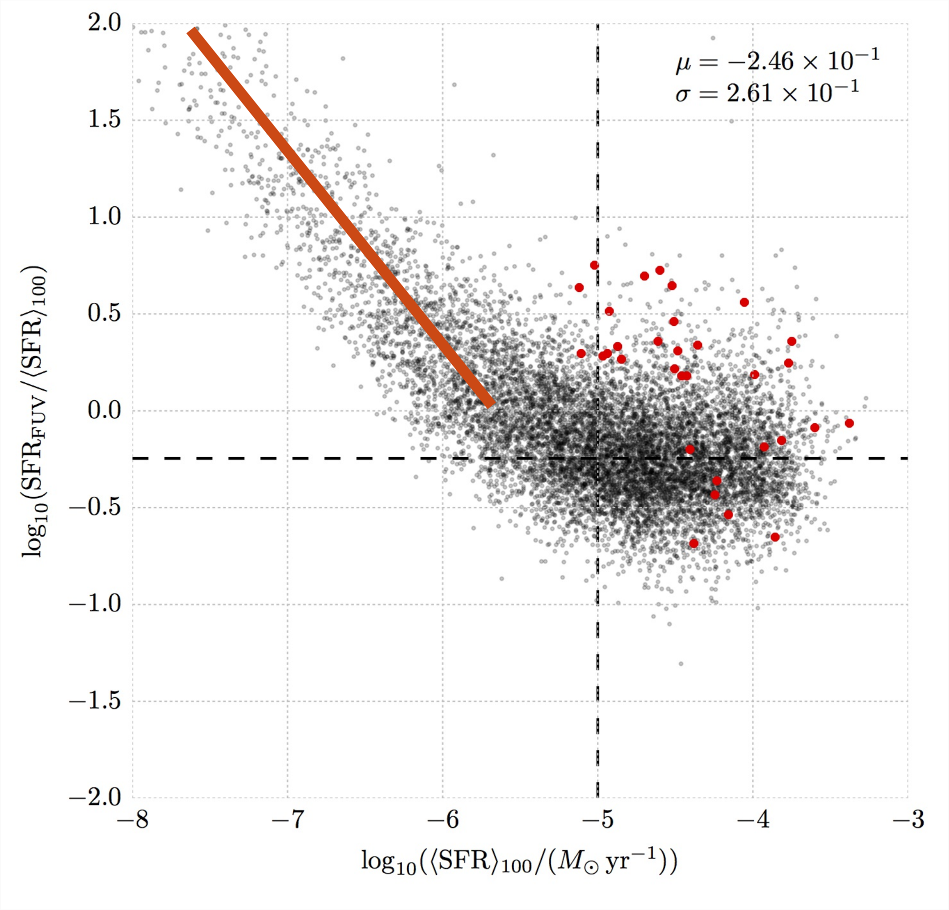
III. SFR maps - comparison

Source of tails?

Distinctly linear:
slope = -1
intercept ~ -6

Flux-based SFR becomes constant below ~ 10^{-6} M_{sun} yr^{-1}.

Linear relationship between flux and SFR breaks down at this limit.



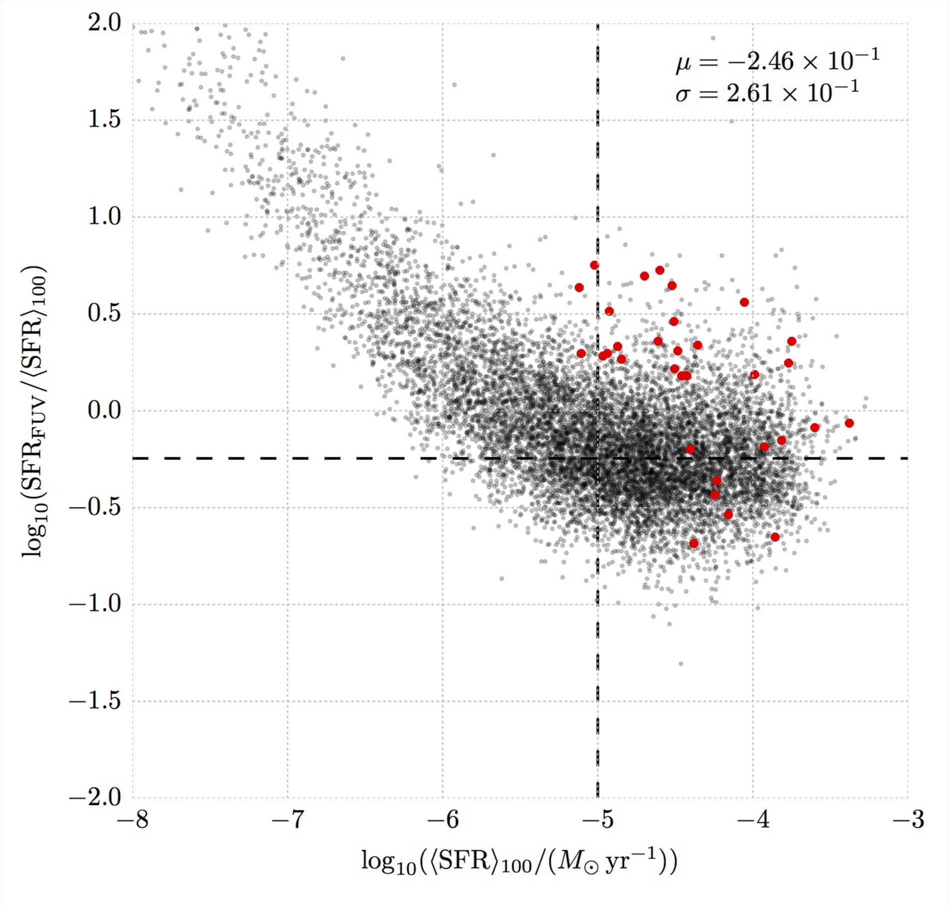
III. SFR maps - comparison

Source of tails?

SFR limit ~ 10^{-6} M_{sun} yr^{-1}

Flux limit ~ 10^{-16} erg s^{-1} cm^{-2} A^{-1}

» Background regions.



III. SFR maps - comparison

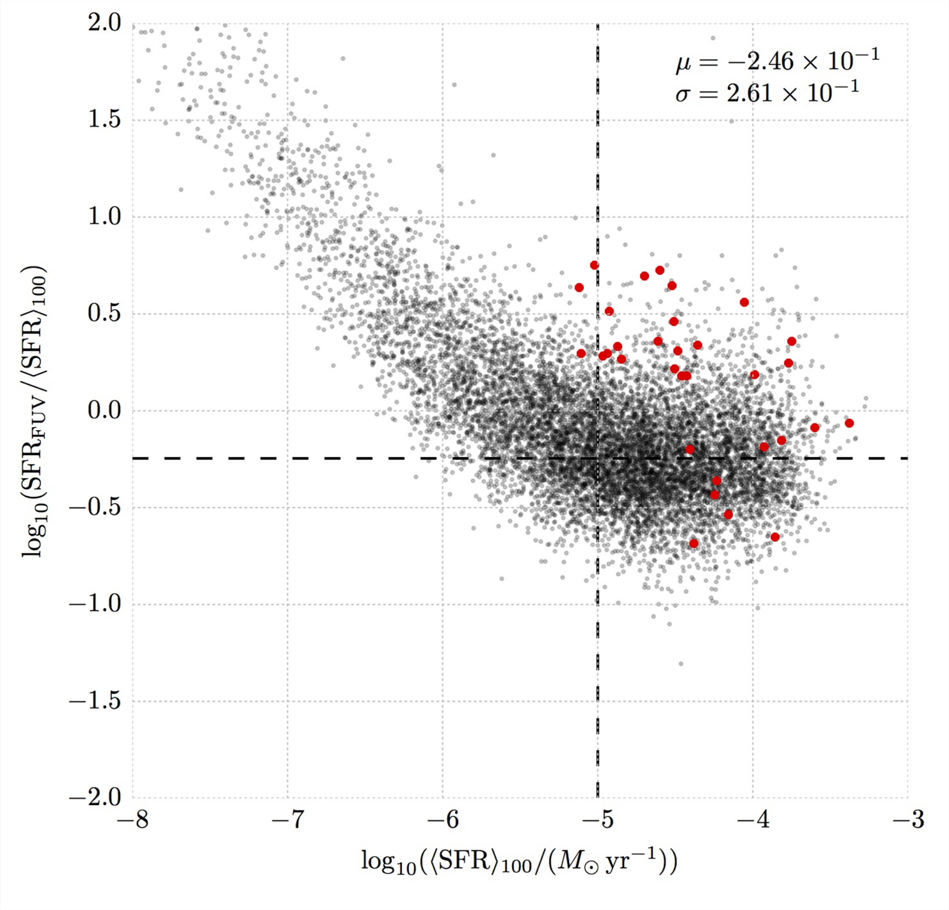
Source of tails?

SFR limit ~ 10^{-6} M_{sun} yr^{-1}

Flux limit ~ 10^{-16} erg s^{-1} cm^{-2} A^{-1}

» Background regions.

~half of sample is affected.



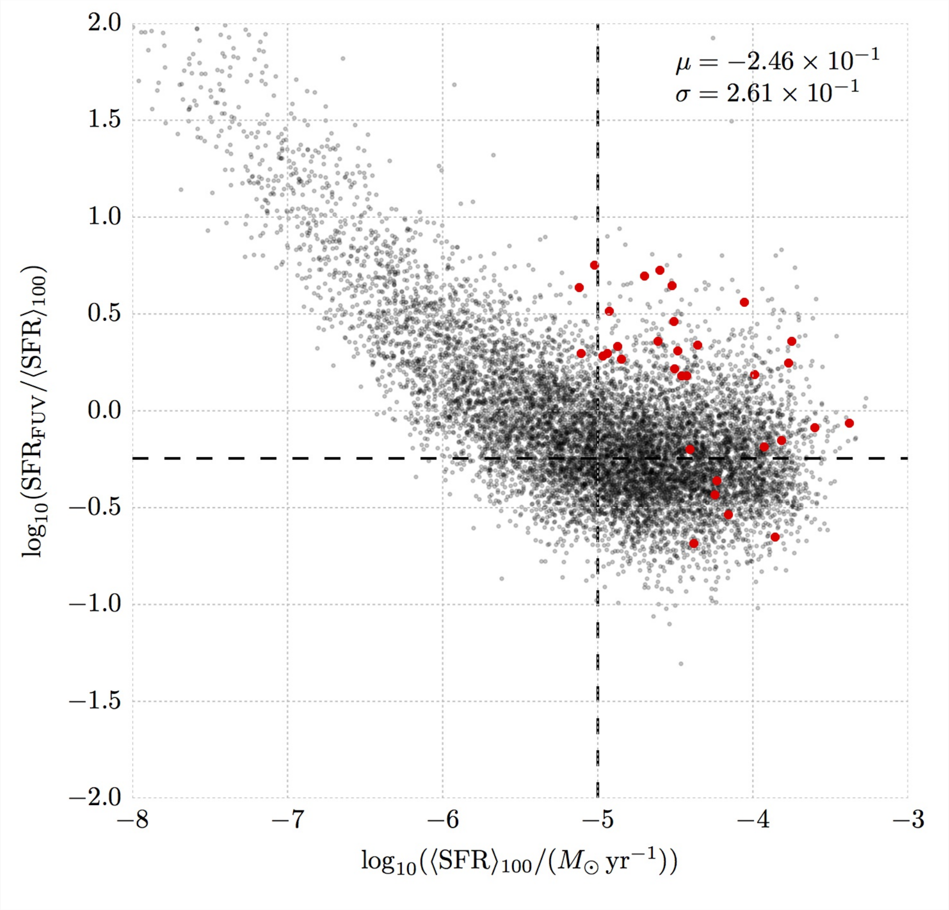
III. SFR maps - comparison

Source of tails?

SFR limit ~ 10^{-6} M_{sun} yr^{-1}
Flux limit ~ 10^{-16} erg s^{-1} cm^{-2} A^{-1}
» Background regions.

~half of sample is affected.

Flux calibrations are completely unreliable in faint, sub-kpc regions (extreme case).



III. SFR maps - comparison

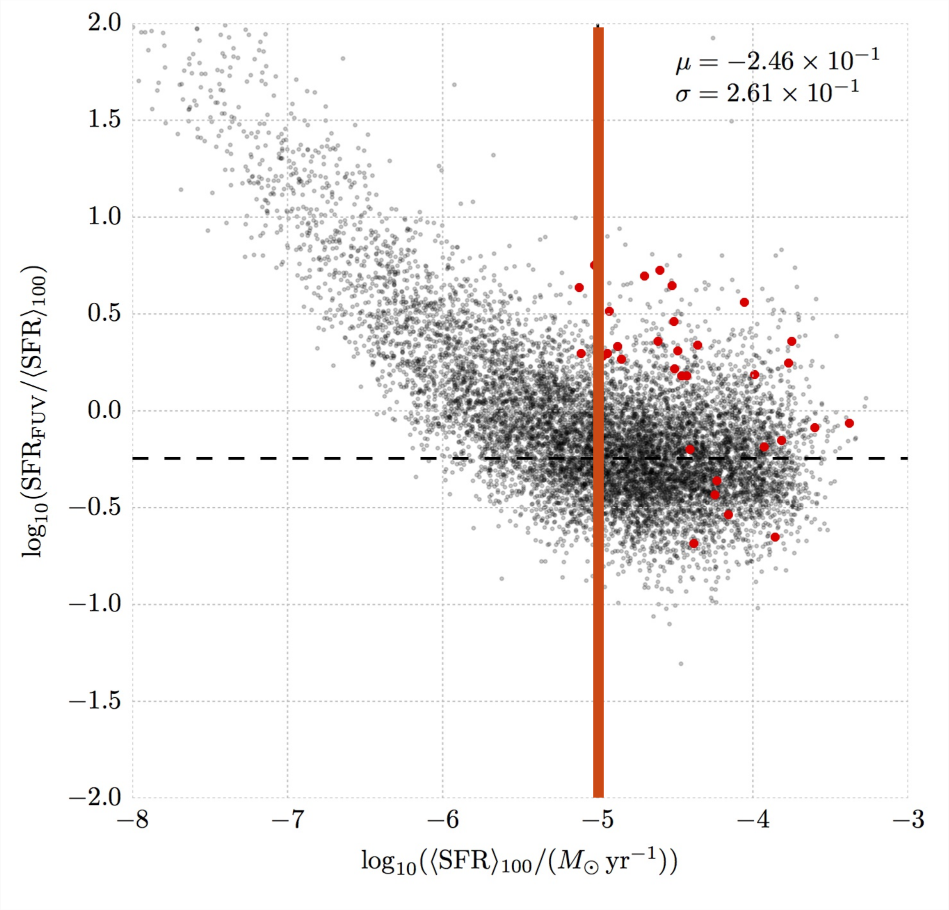
Source of tails?

SFR limit ~ 10^{-6} M_{sun} yr^{-1}
Flux limit ~ 10^{-16} erg s^{-1} cm^{-2} A^{-1}
» Background regions.

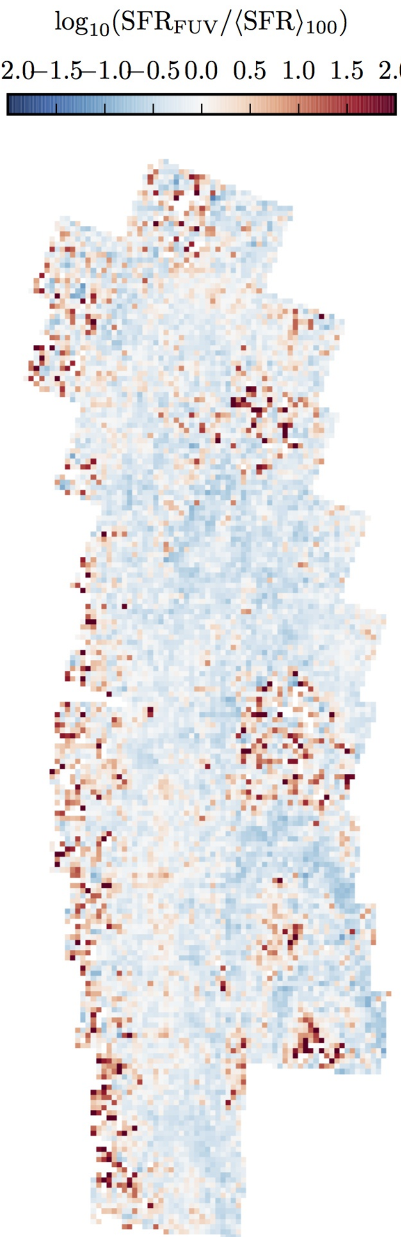
~half of sample is affected.

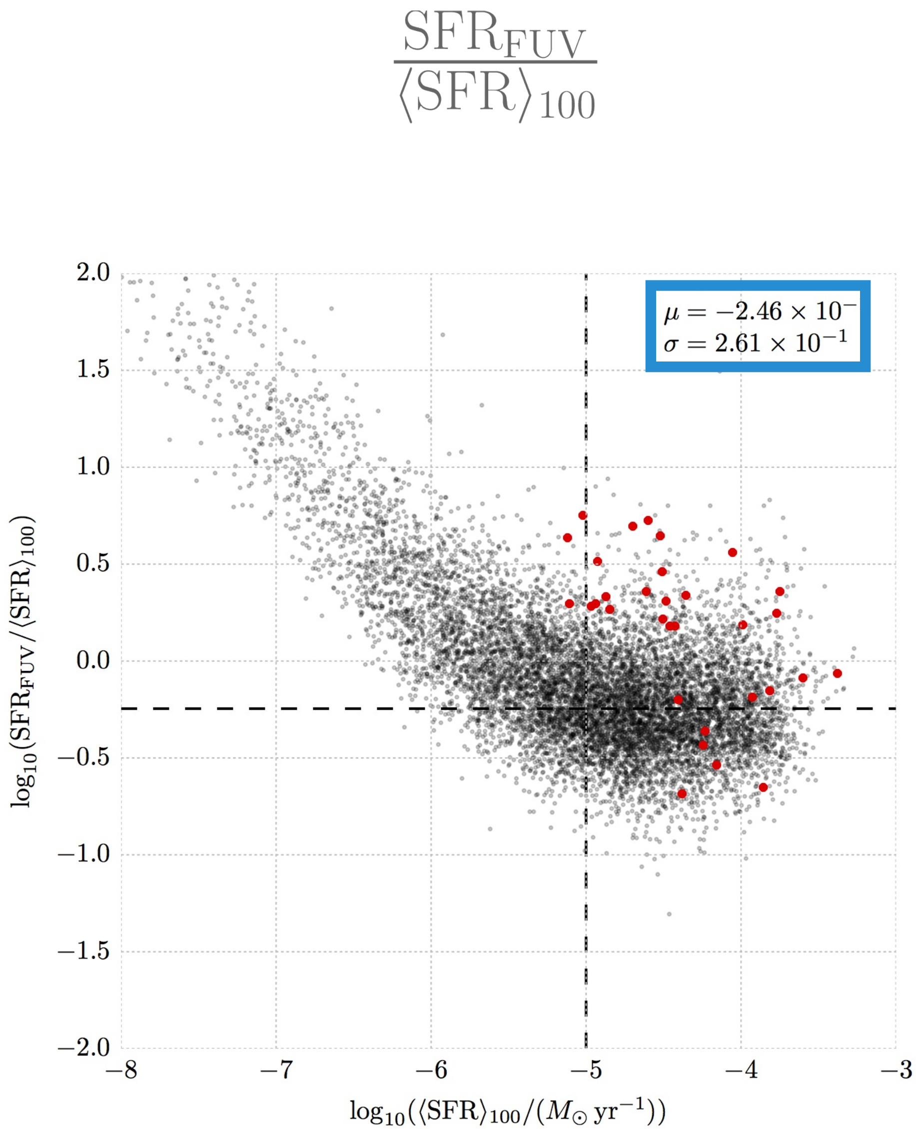
Flux calibrations are completely unreliable in faint, sub-kpc regions (extreme case).

Threshold = 10^{-5} M_{sun} yr^{-1}



III. SFR maps - comparison



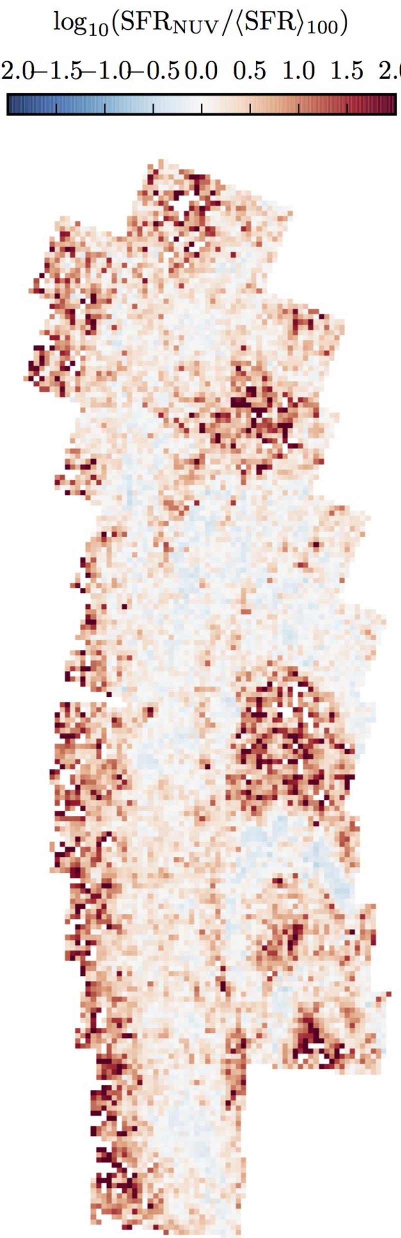


SFR ratios

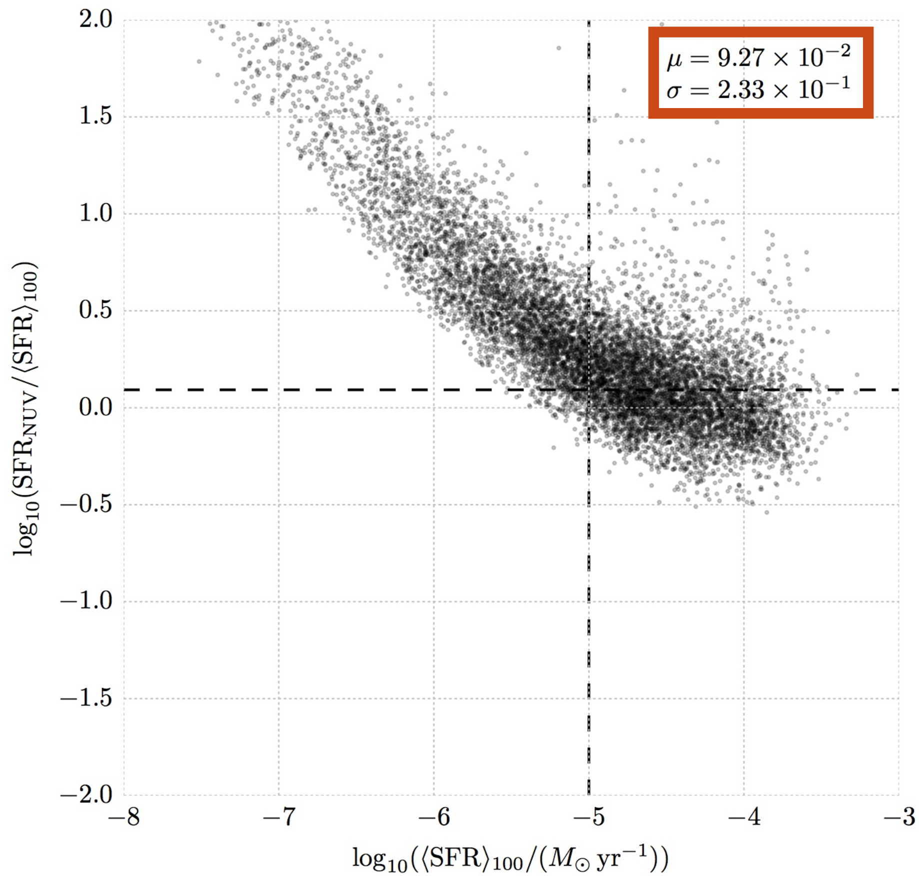
Median ratio: 0.57
(0.31 to 1.04)

» Consistent on average (barely).

III. SFR maps - comparison



$$\frac{\mathrm{SFR_{NUV}}}{\langle\mathrm{SFR}\rangle_{100}}$$



SFR ratios

Median ratio: 1.24 (0.72 to 2.12)

» Consistent on average (barely).

Similarly for NUV

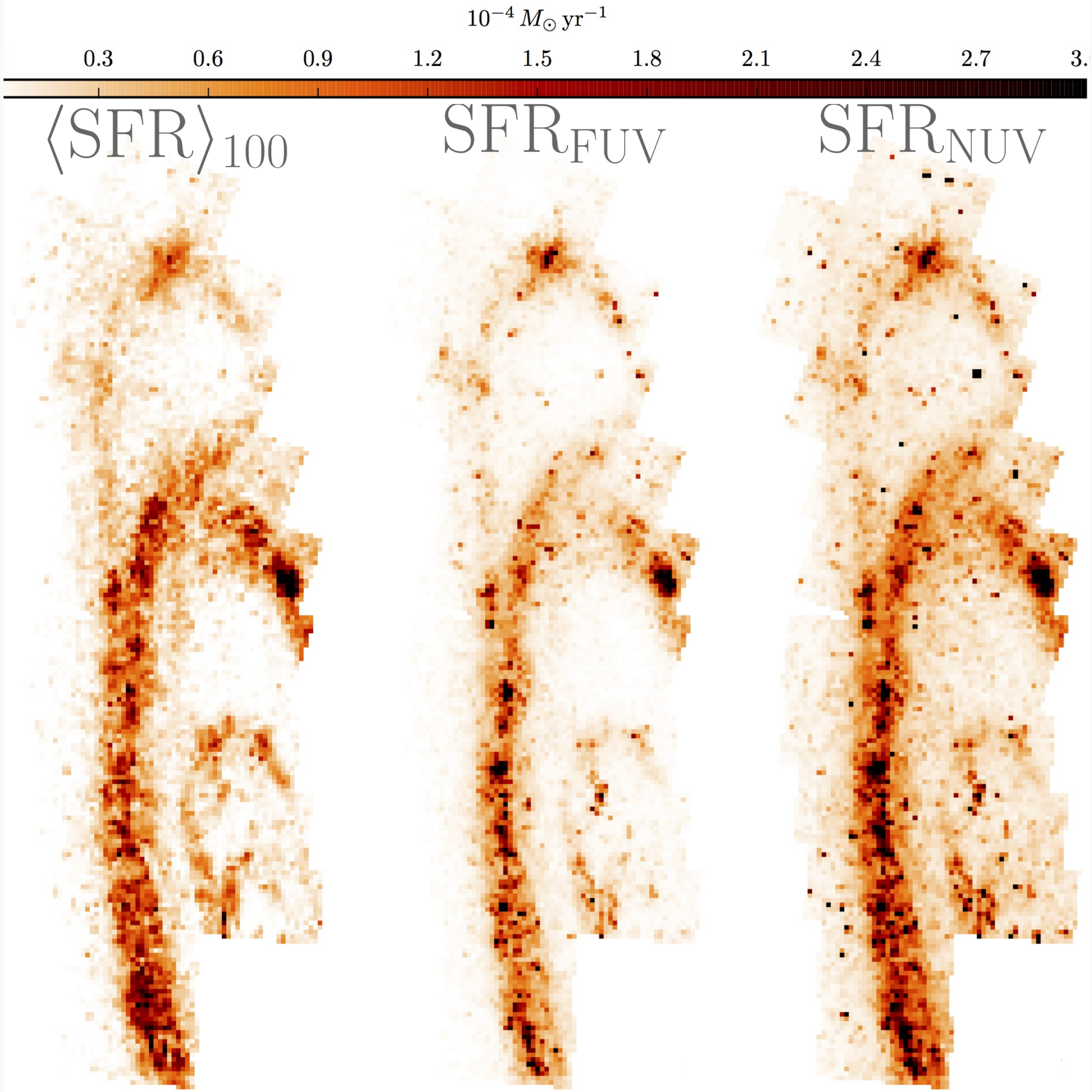
III. SFR maps - comparison

Global SFRs

SFH-based: 0.30 M_{sun} yr^{-1}

FUV-based: 0.22 M_{sun} yr^{-1}

NUV-based: 0.43 M_{sun} yr^{-1}



III. SFR maps - comparison

Global SFRs

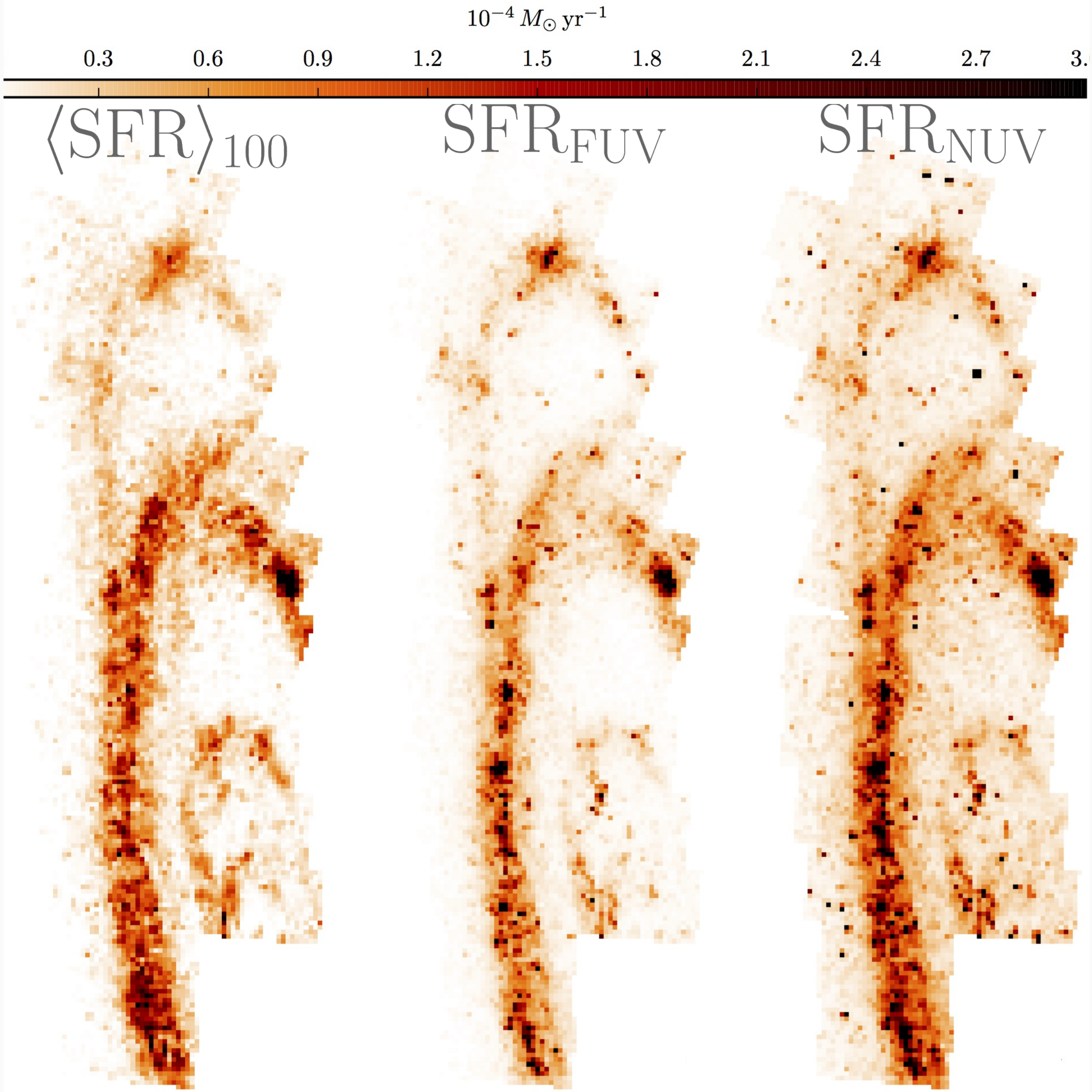
SFH-based: 0.30 M_{sun} yr^{-1}

FUV-based: 0.22 M_{sun} yr^{-1}

NUV-based: 0.43 M_{sun} yr^{-1}

FUV ratio: 0.73

(0.31 to 1.04)



III. SFR maps - comparison

Global SFRs

SFH-based: 0.30 $M_{sun}\ yr^{-1}$

FUV-based: 0.22 $M_{sun}\ yr^{-1}$

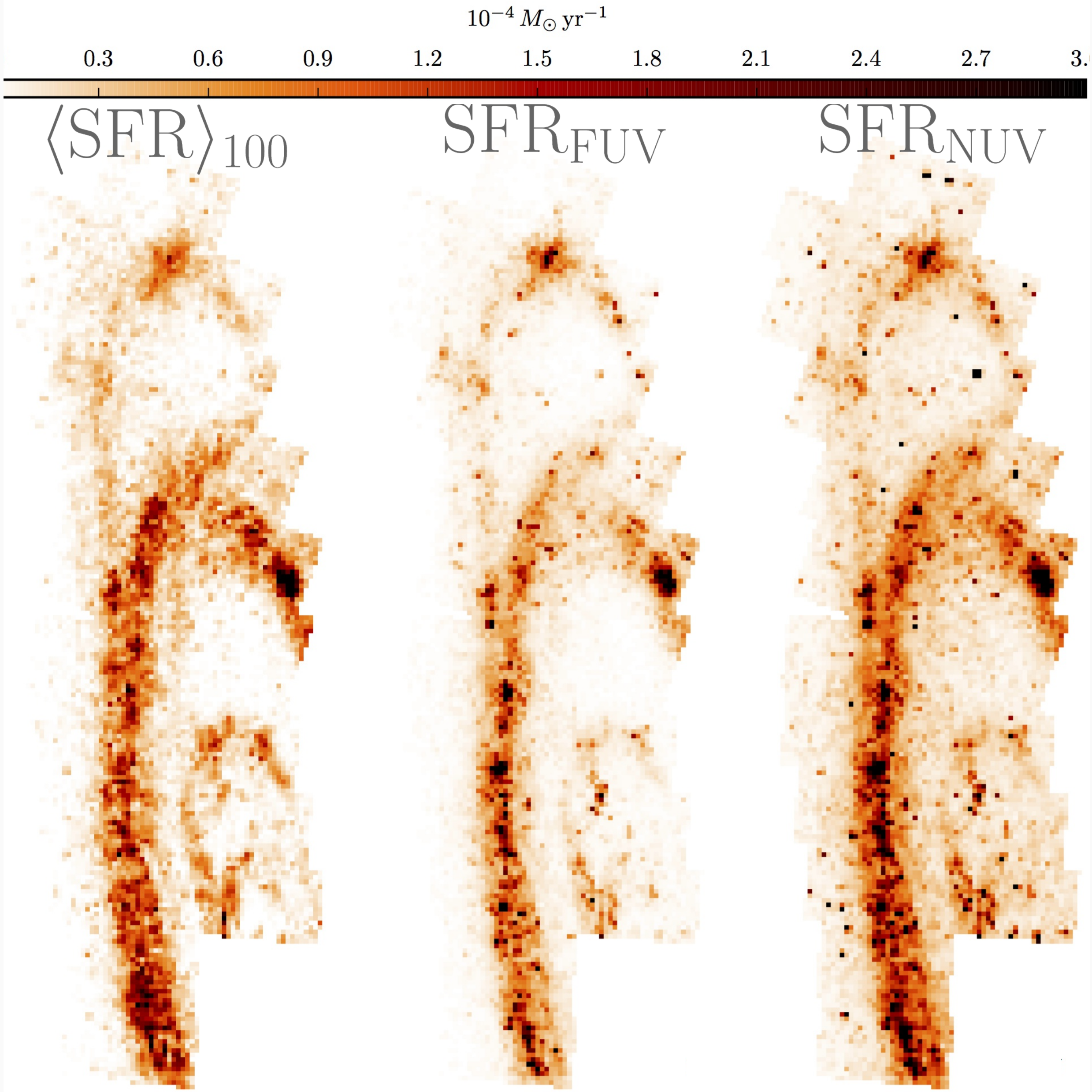
NUV-based: 0.43 $M_{sun}\ yr^{-1}$

FUV ratio: 0.73

(0.31 to 1.04)

NUV ratio: 1.43

(0.72 to 2.12)



III. SFR maps - comparison

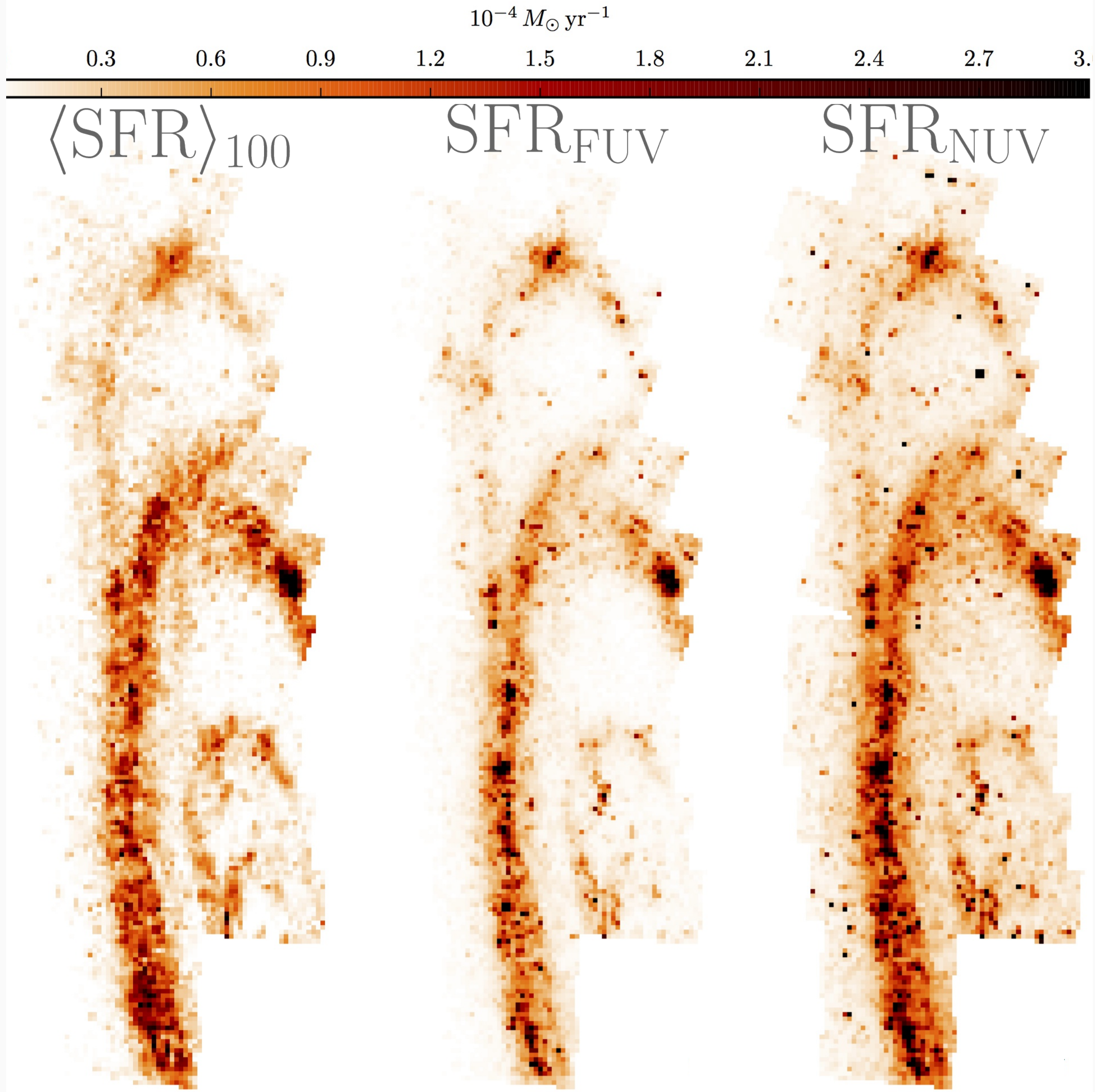
Global SFRs

SFH-based: 0.30 M_{sun} yr^{-1}
FUV-based: 0.22 M_{sun} yr^{-1}
NUV-based: 0.43 M_{sun} yr^{-1}

FUV ratio: 0.73
(0.31 to 1.04)

NUV ratio: 1.43
(0.72 to 2.12)

Well within confidence limits. Flux calibrations are safe.



IV. Summary

- Measured SFHs at sub-kpc resolution (4×10^4 pc^2) over the entire PHAT survey area.
- Used SPS to model FUV and NUV fluxes in M31.
  - Excellent overall morphological agreement.
  - Synthetic fluxes were consistent with observations (median ratio +/- 68% conf.):

    FUV ratio: 1.02 +0.74/-0.43

    NUV ratio: 0.79 +0.35/-0.24
  - Confirmation of stellar evolution models, stellar spectra models, IMF, SFH recovery.

IV. Summary

- Used standard flux calibrations to convert observed UV flux into SFRs.
  - Calibration is unreliable for SFR below ~ 10^{-5} M_{sun} yr^{-1} (background regions).
  - Flux calibrations are safely applicable above this limit.
  - Flux-based SFRs were consistent with the SFHs (median ratio +/- 68% conf.):
    FUV ratio: 0.57 +0.47/-0.26
    NUV ratio: 1.24 +0.88/-0.52
  - Global SFRs also agreed; well within uncertainties.

Thank you

Questions?