Getting ready for JWST: new-generation spectral models and interpretation tools

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the NIRSpec GTO team

and

the NEOGAL team

Outline

I) Context: first stars and galaxies, cosmic reionization, and galaxy evolution

II) Tools: observations

III) Tools: models

IV) Current science: local "analogues" of high-z galaxies

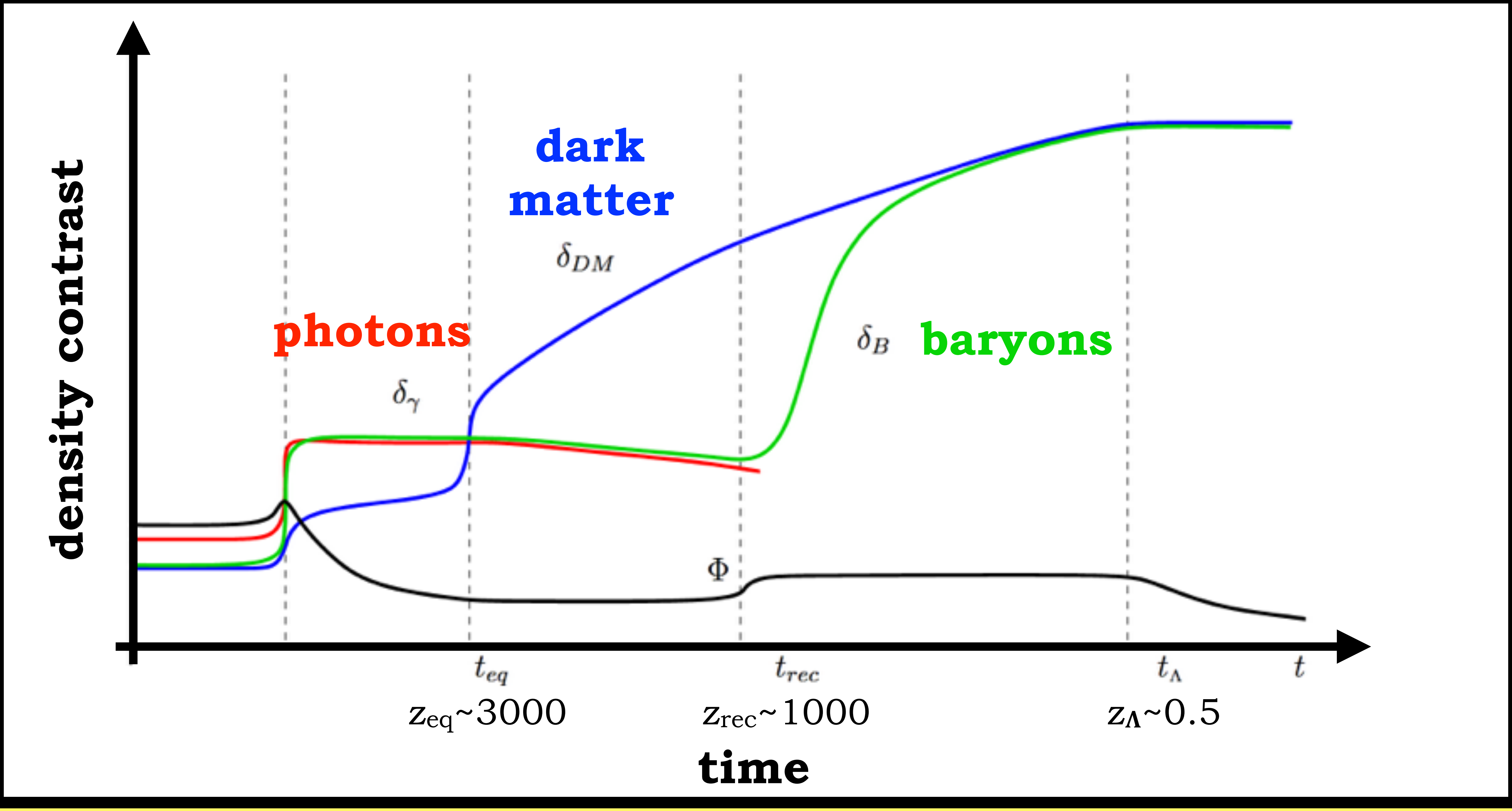
V) Future science: preparing early JWST/NIRSpec observations

Chap. I

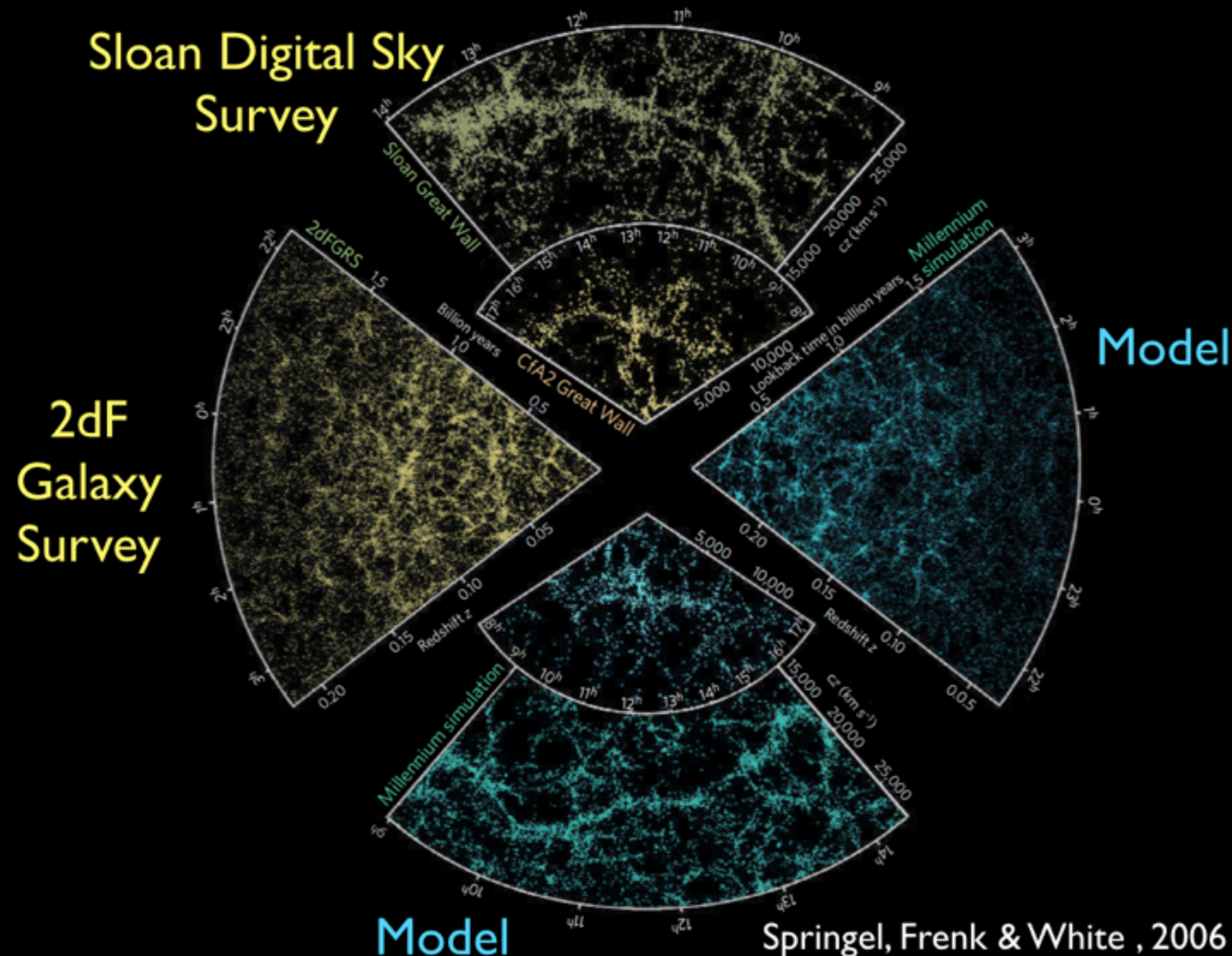
Context

(very) Brief history of the Universe

- Universe becomes matter-dominated at $z_{eq} \sim 3{\cdot}10^3$
- After z_{eq}, dark matter (DM) density perturbations start growing
- Baryons follow DM potential after decoupling

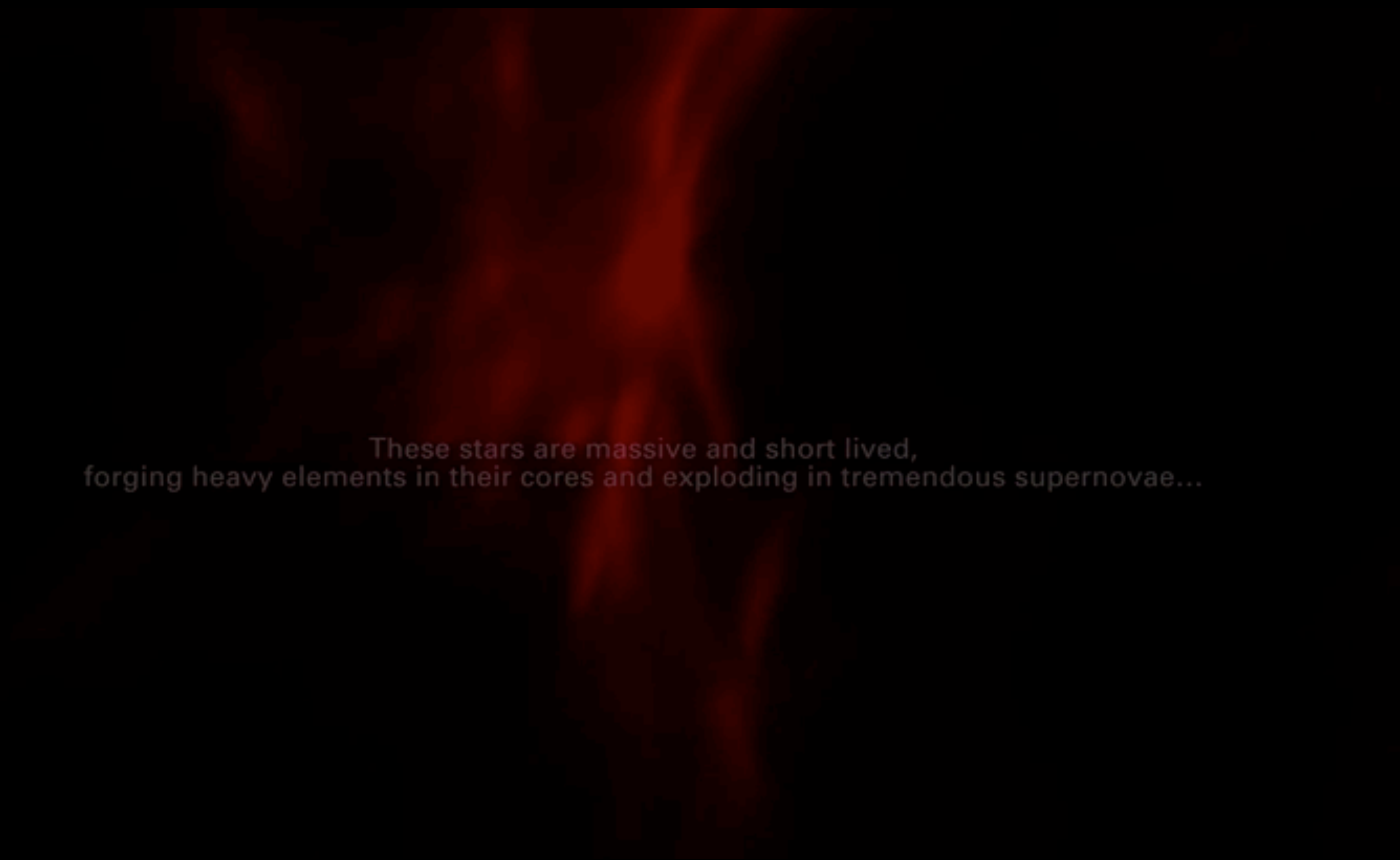


Successes of DM theory

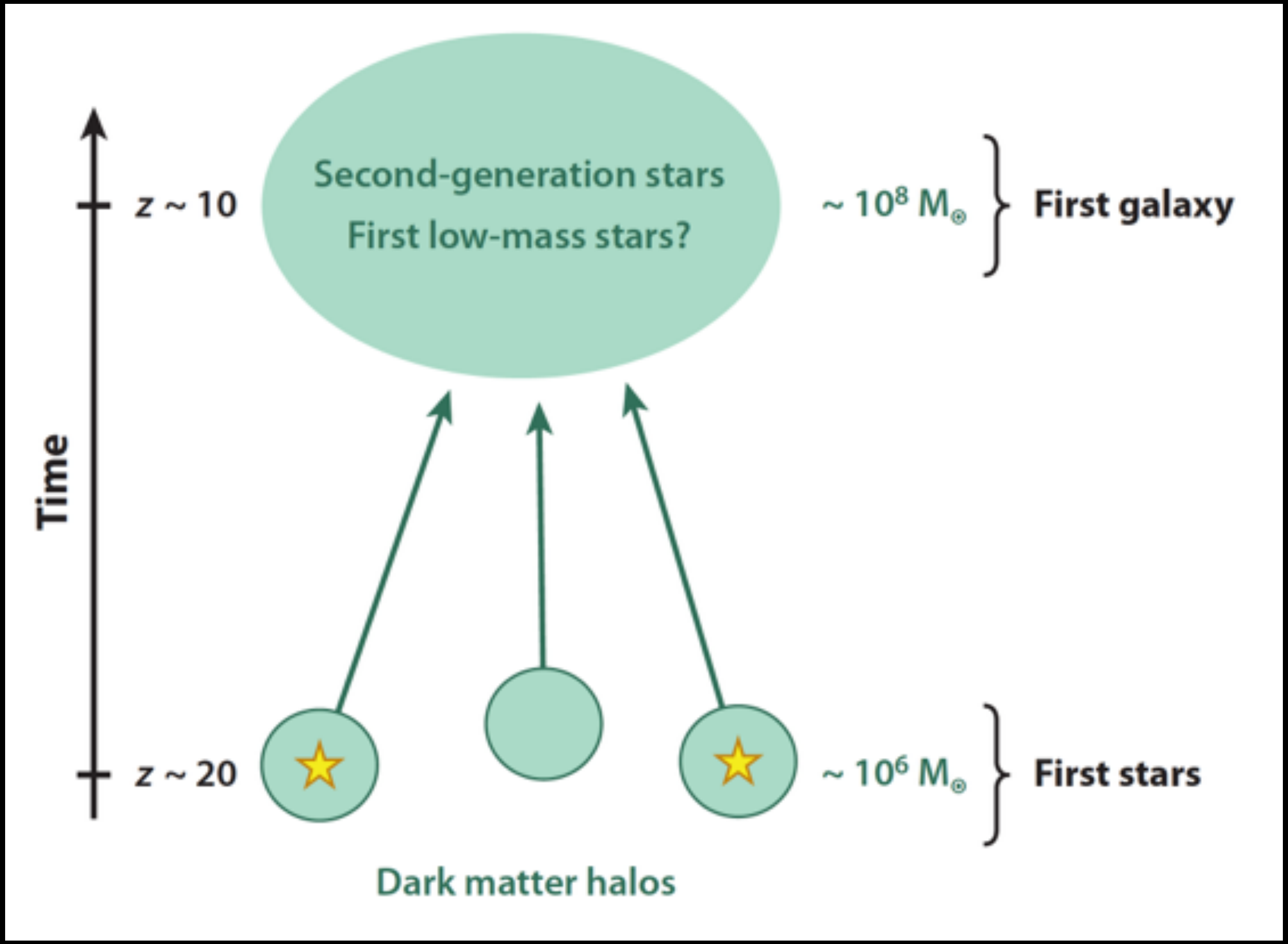


Formation of first stars

- Formation of first stars can only be studied theoretically
- Expected to be very massive (> 100 $M_{\odot}$) and short-lived
- Enrich intergalactic medium (IGM) with metals



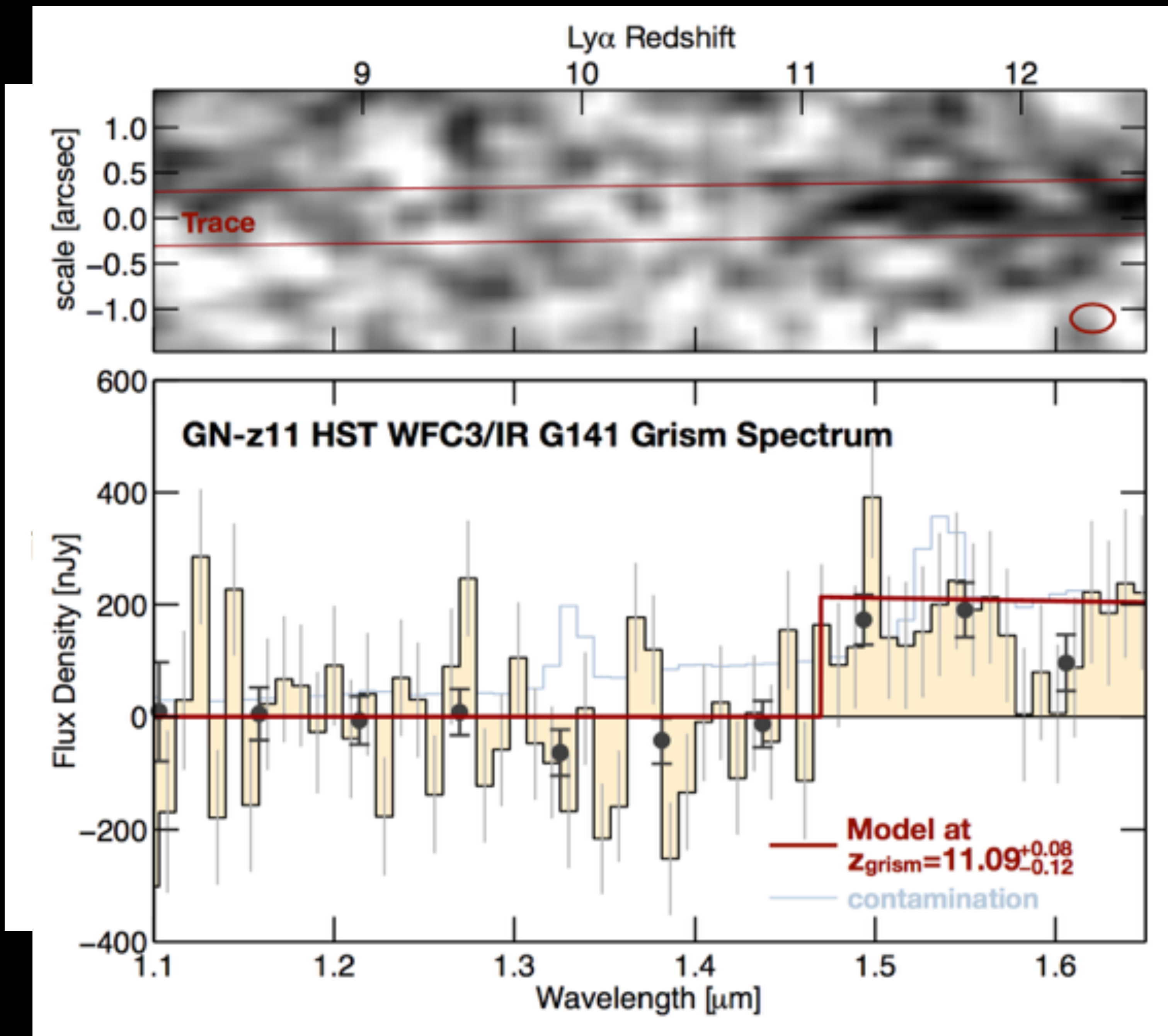
Early galaxies and cosmic reionization



Bromm & Yoshida, ARAA (2011)

- First galaxies form in low-mass DM haloes
- Most distant galaxy spectroscopically confirmed (?): z~11
- Far more massive than predicted by models !!

Early galaxies and cosmic reionization



Oesch+2016

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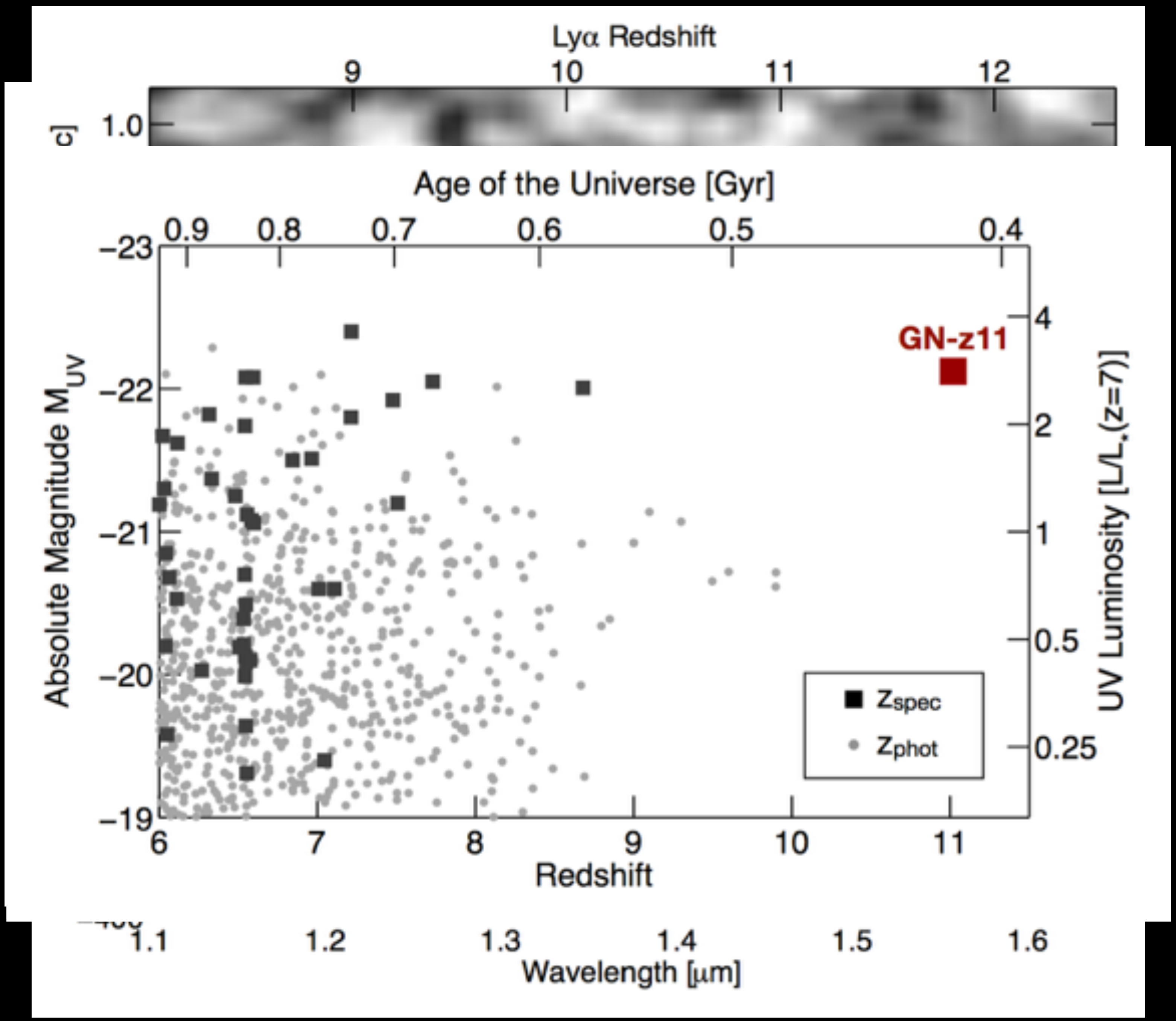
Early galaxies and cosmic reionization

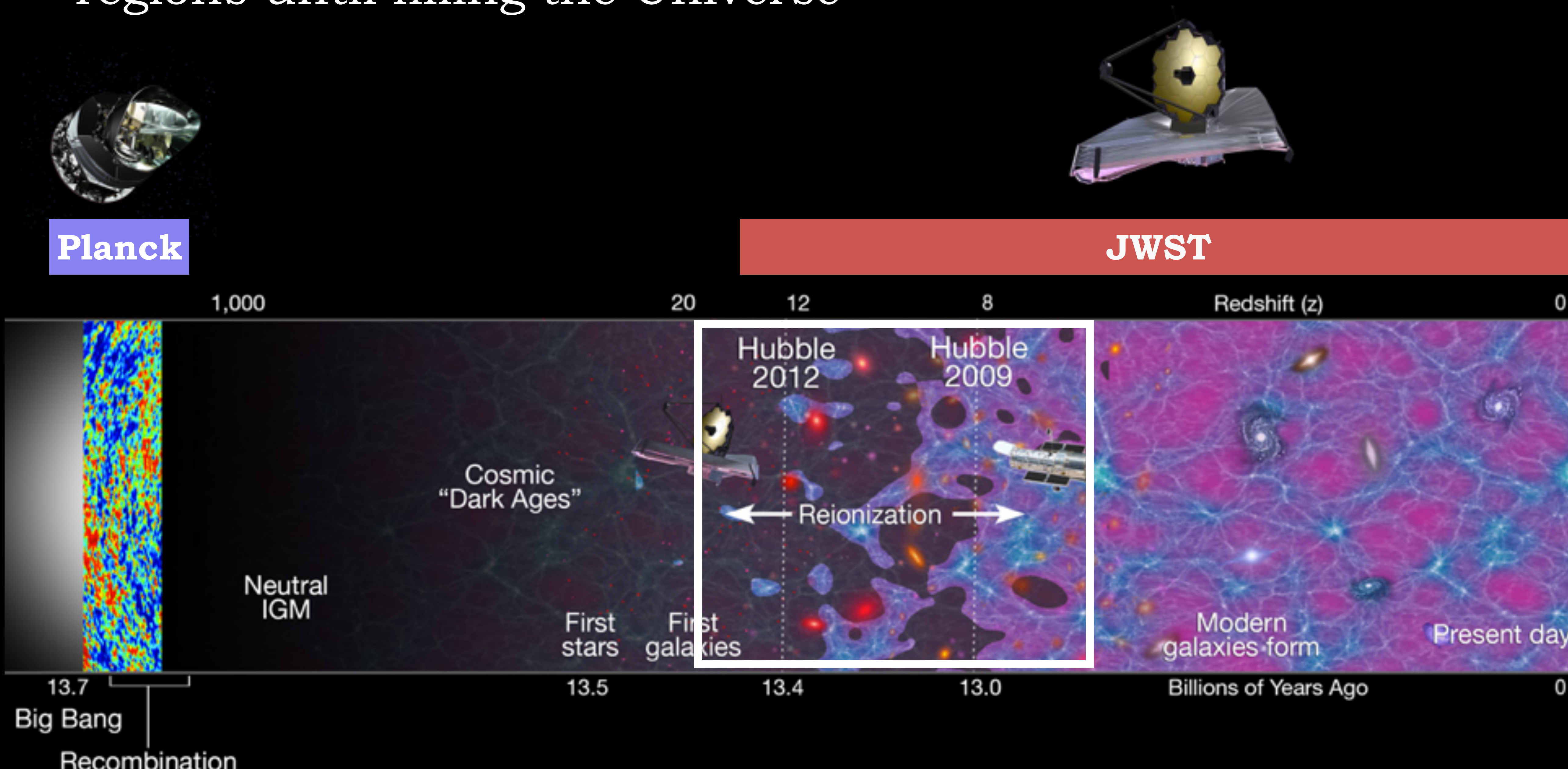


Oesch+2016

- First galaxies form in low-mass DM haloes
- Most distant galaxy spectroscopically confirmed (?): z~11
- Far more massive than predicted by models !!

Early galaxies and cosmic reionization

- First stars and galaxies produce of H-ionizing photons
- “Bubbles” of ionised Hydrogen grow around over-dense regions until filling the Universe



Several open questions…

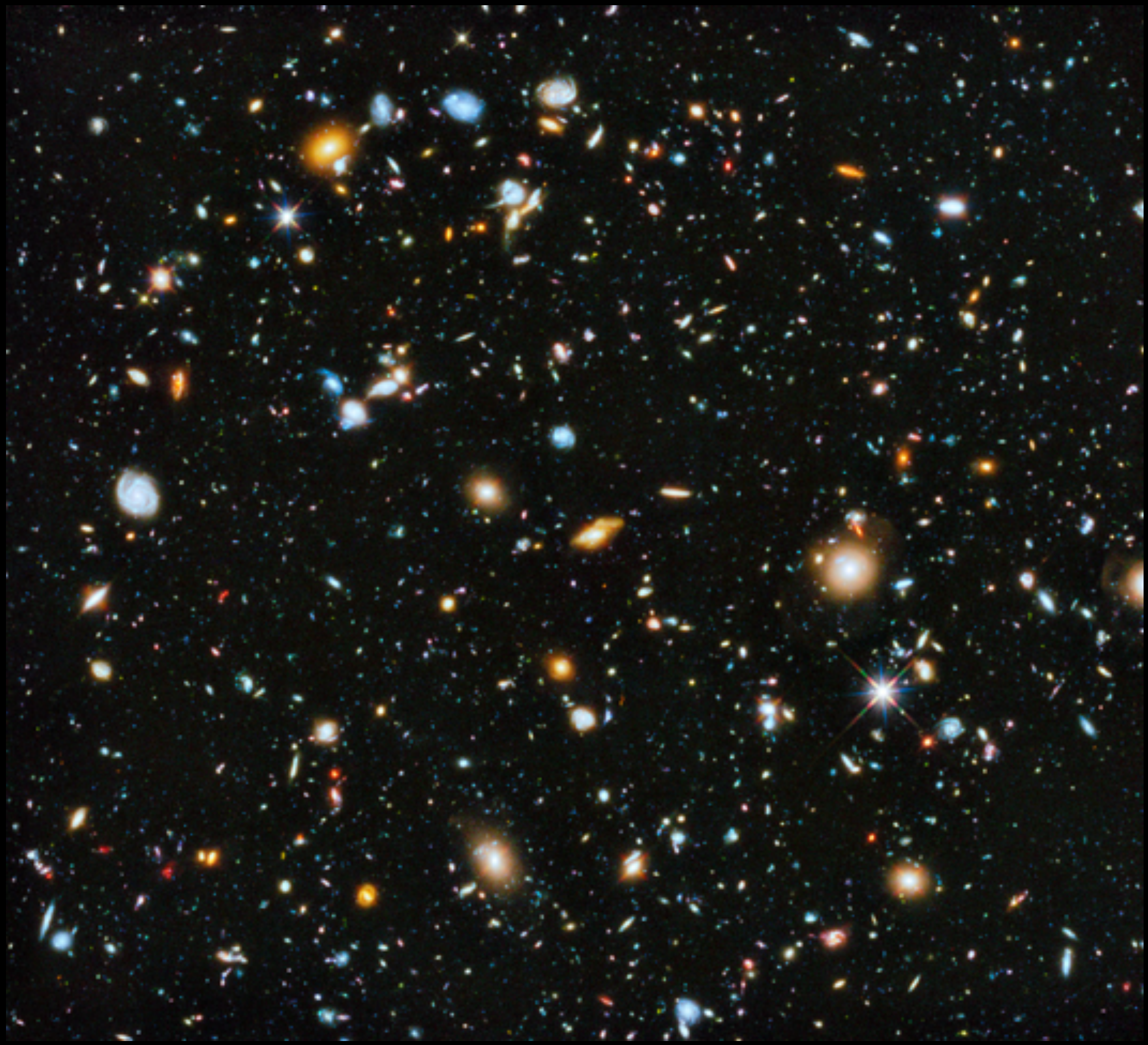
- First stars and galaxies:
  - physics of **Pop. III** stars
  - **early chemical enrichment**: from primordial abundances to metal-enriched gas
- Cosmic reionization:
  - dominant **source**(s) of **H-ionizing** photons (galaxies *vs* AGN *vs* Pop. III stars *vs* X-ray binaries)
  - **escape fraction** of H-ionizing photons
  - space- and time-evolution of H-ionized bubbles
- Galaxy evolution:
  - role of stellar and AGN **feedback** in regulating SF
  - **co-evolution** of galaxies and AGNs
  - **SF efficiency,** relation with hierarchical DM haloes assembly
  - separation of galaxies into different **morphological** types

Chap. II

Tools

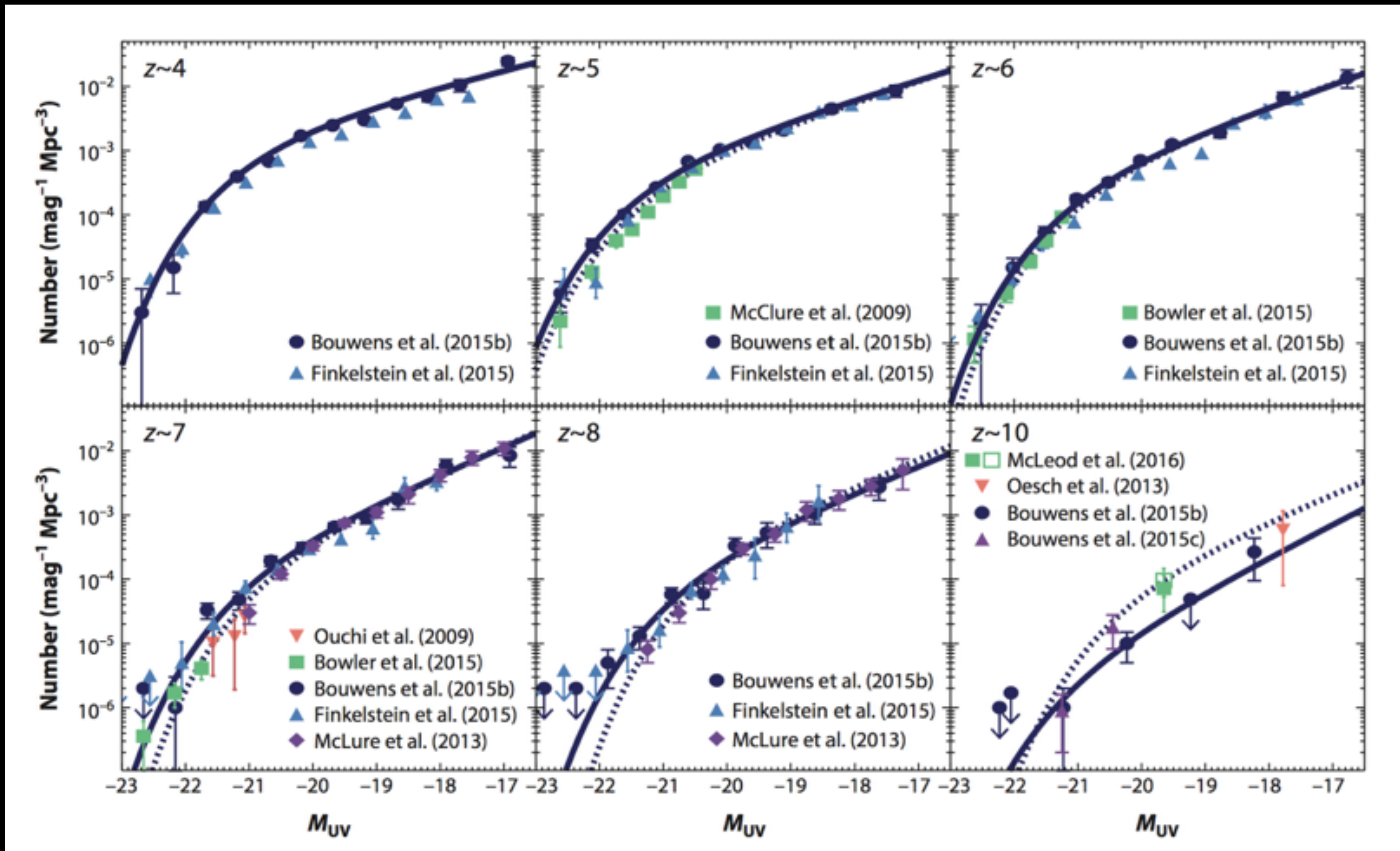
Part I: observations

Deep imaging of high-z galaxies



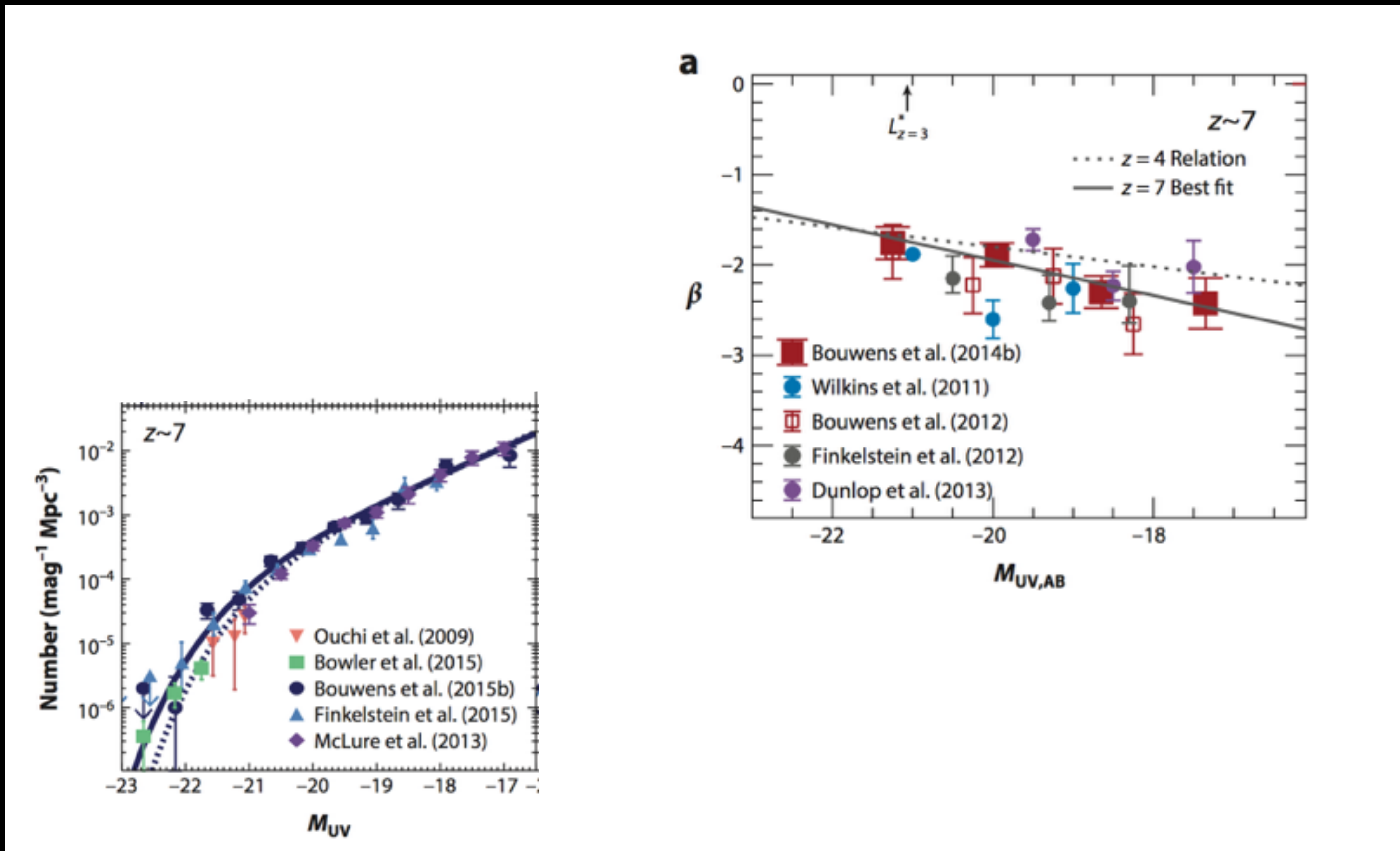
- High-z Universe mainly probed through **Hubble deep imaging**, e.g. HUDF, CANDELS, COSMOS
- Only possible over small areas, and limited to $\lambda <$ **1.8 μm**
- constrain **number density** evolution of galaxies
- little contraints on galaxy **physical properties**

Evolution of UV luminosity function



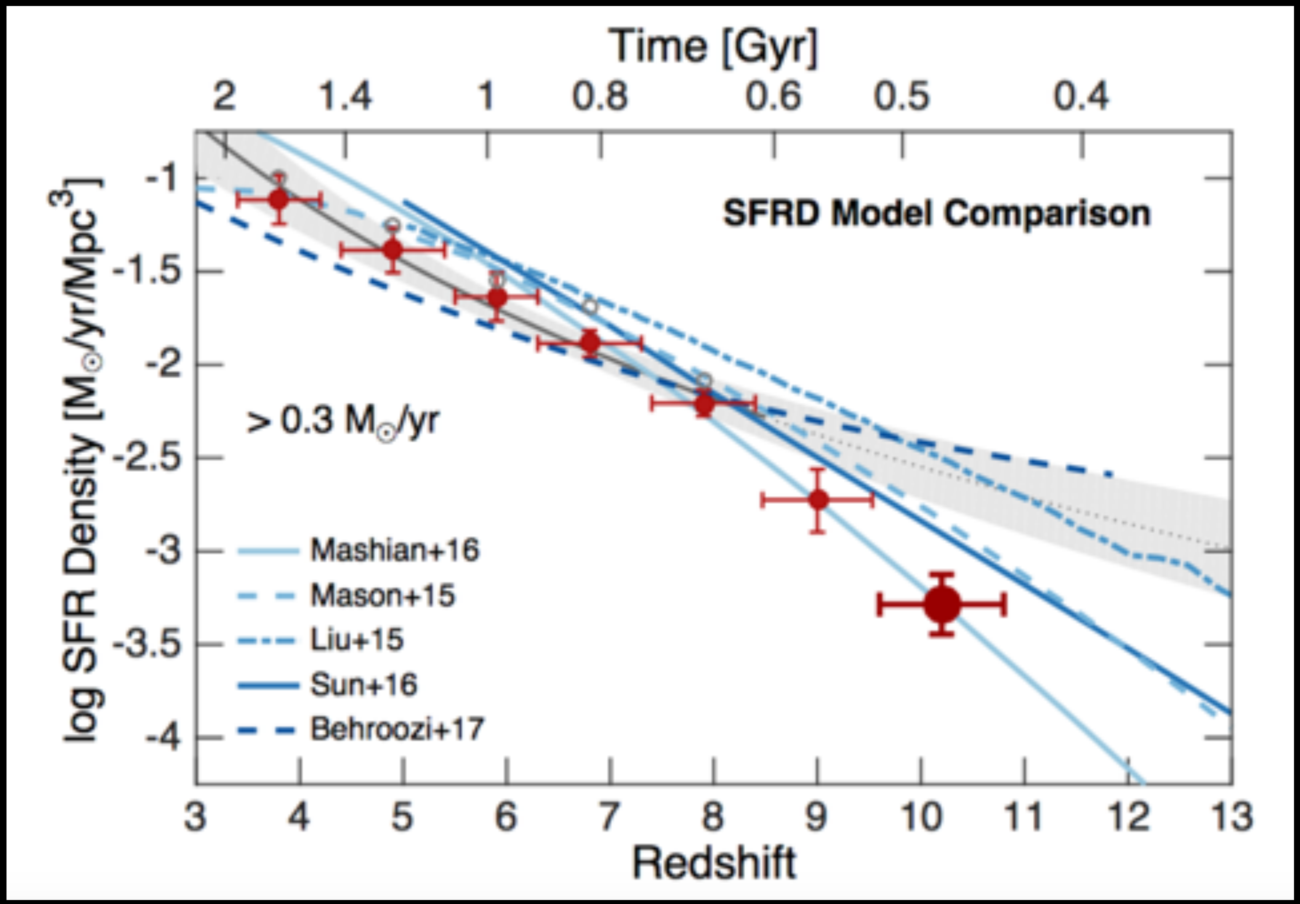
Stark, ARAA, 2016

Evolution of UV luminosity function



Stark, ARAA, 2016

Comparison with galaxy formation models

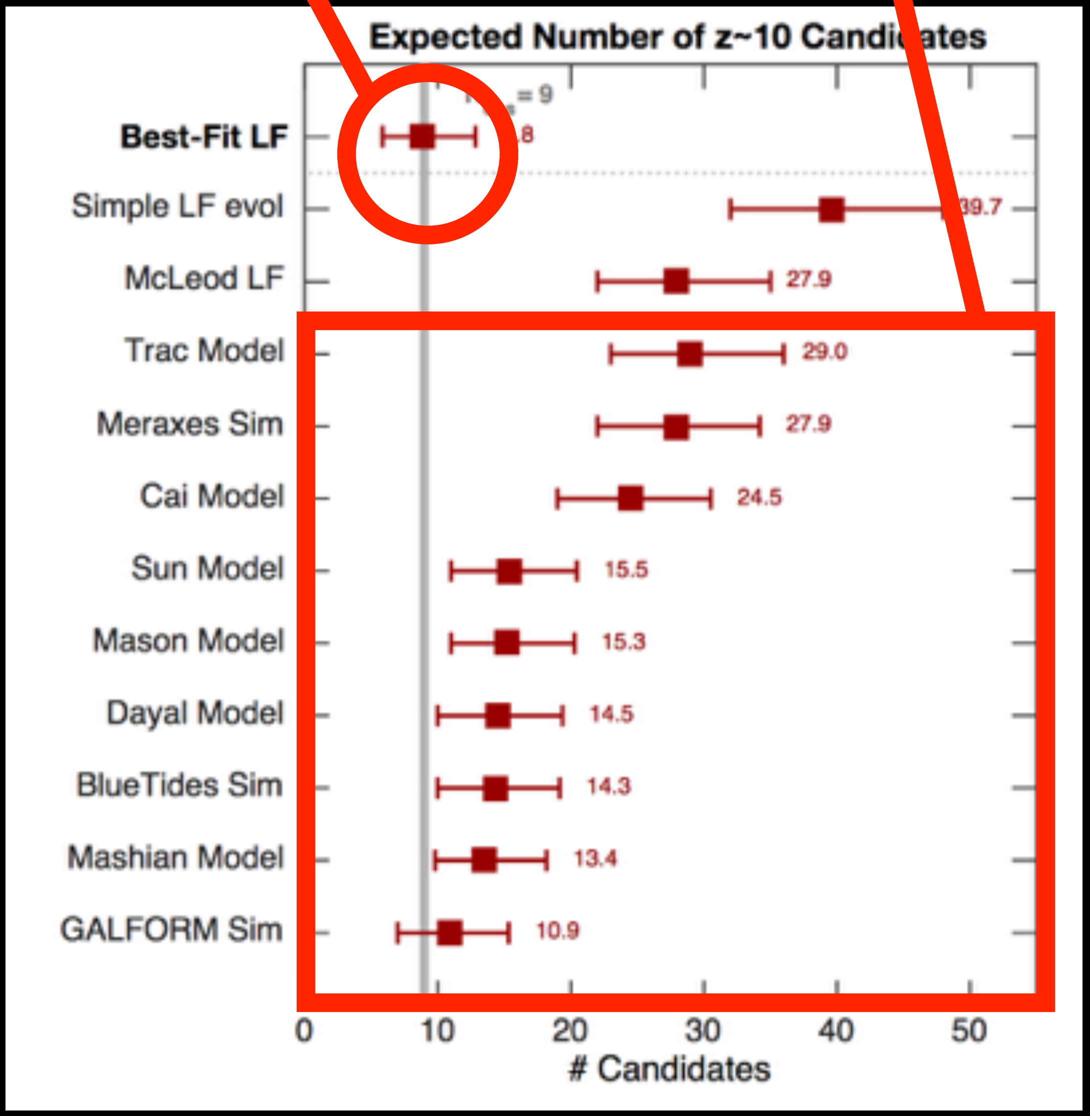


Oesch+17

- UV number counts provide some constraints on galaxy formation models
- But alone cannot determine role of physical processes (e.g. outflows, infall, SF efficiency) shaping galaxy evolution

model predictions

observations



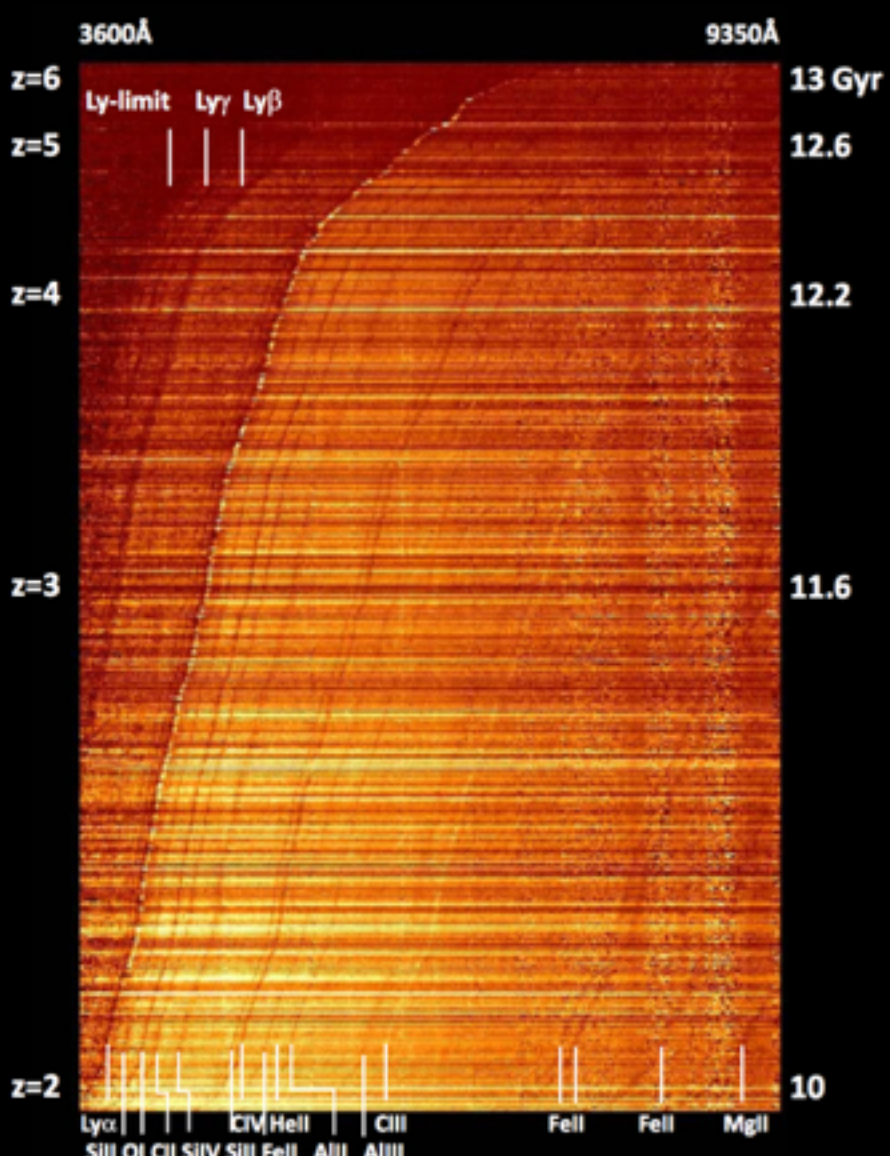
Oesch+17

Spectroscopy of high-z galaxies

- **Limited constraints** on galaxy physical properties (SFR, metallicity, dust) from UV-to-near infrared (broad-band) **photometry**
- **Emission lines** from ionised gas enable **characterisation of physical properties** of galaxies over large range of masses and redshifts
- Can use **HST/grism** spectra (up to 1.6 μm): e.g. WISP (Atek+10), 3D-HST (Brammer+12), GLASS (Treu+15), FIGS (Pirzkal+17)
- **Optical MOS** (e.g. VIMOS @ VLT): e.g. VVDS (Le Fevre+05), zCOSMOS (Lilly+07), **VUDS** (Le Fevre+15), VANDALS (McLure+17), **MUSE** 'deep' (Bacon +17) and 'wide' (Herenz+17)
- **Near-infrared MOS** (e.g. MOSFIRE @ Keck, KMOS @ VLT): e.g. **MOSDEF** (Kriek+15), **KBSS** (Stediel+14), **KMOS^{3D}**(Wisnioski+15), KROSS (Stott+16), KLASS (Mason+17)

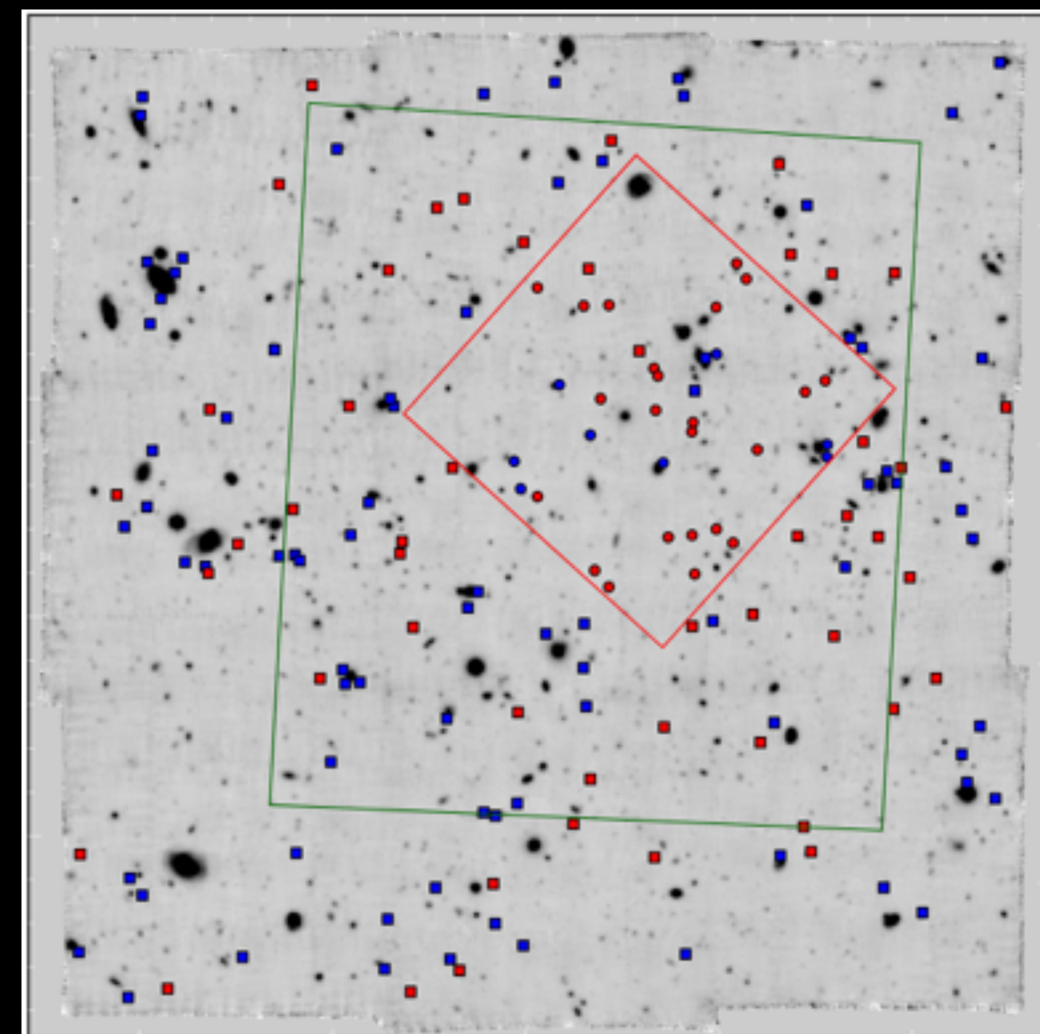
Rest-UV spectroscopy of 2<z<6 galaxies

- VUDS:
  - 10000 galaxies
  - i_{AB} < 25
  - λ= 3650 to 9350 Å
  - R~230



Le Fevre+2015

- MUSE deep/wide:
  - λ= 4750 to 9350 Å
  - R~3000



Bacon+2017

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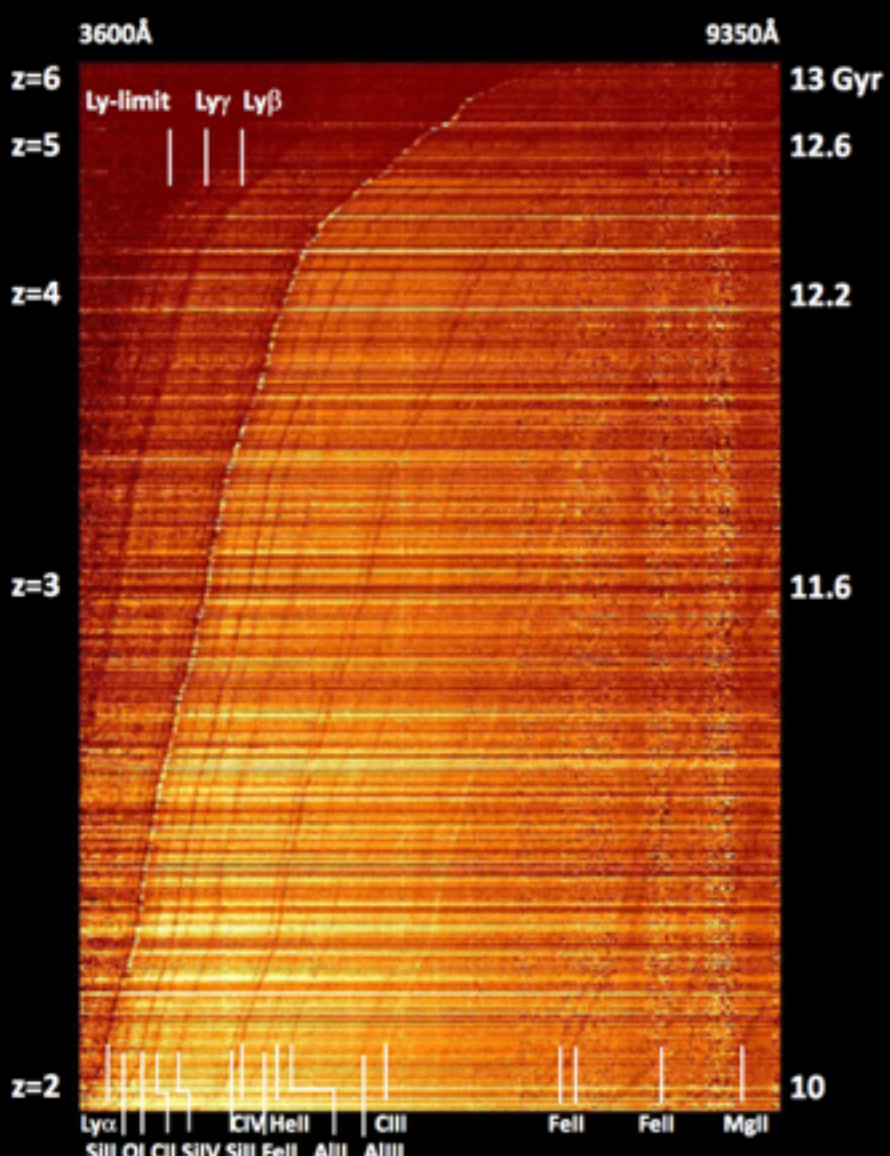

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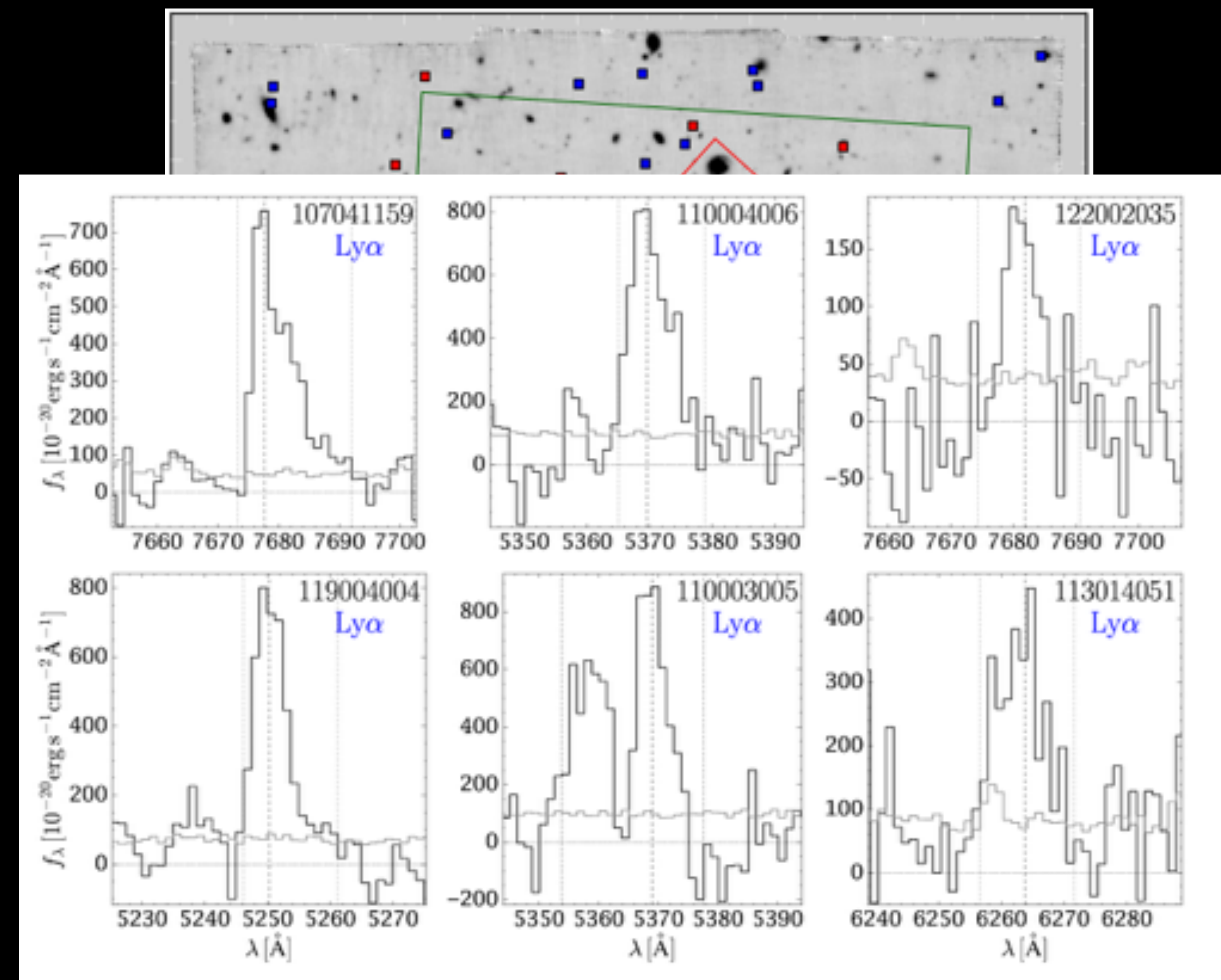
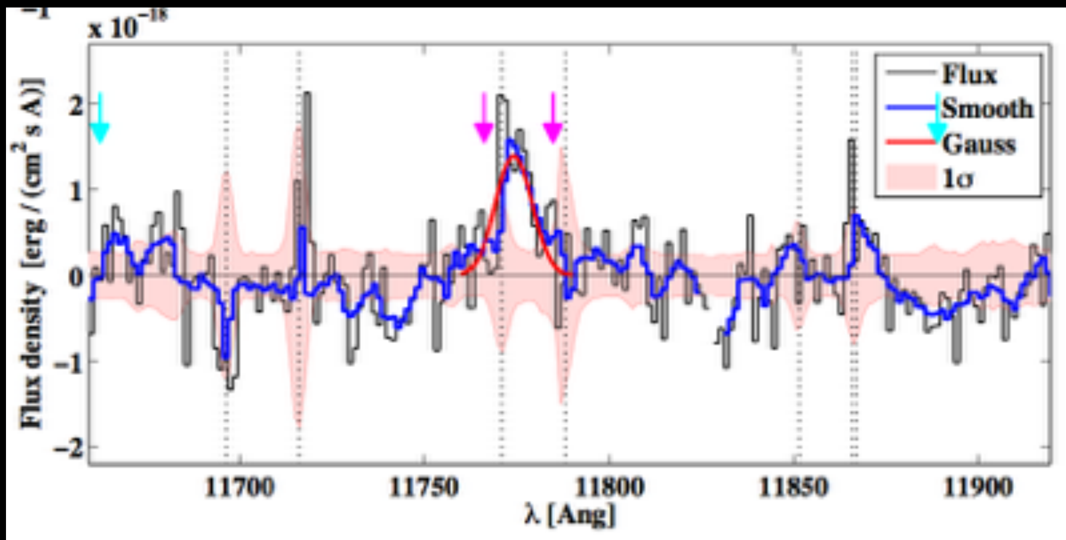


Herenz+2017

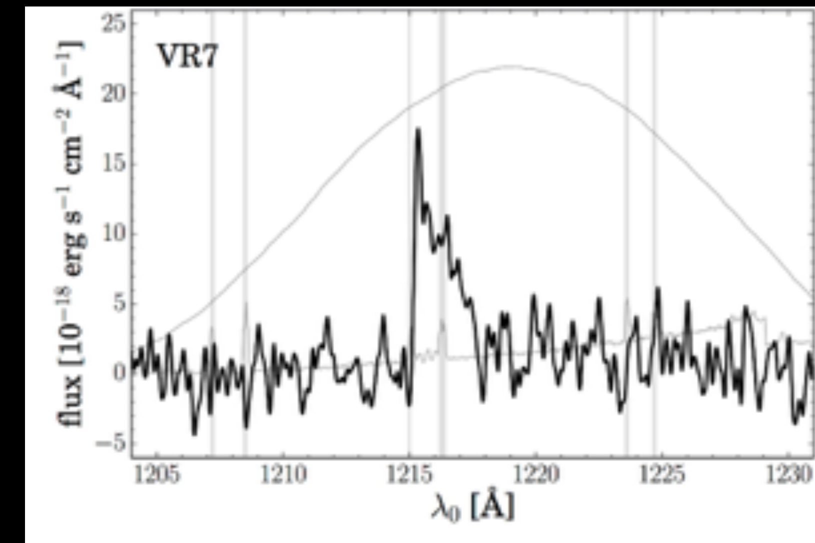
Rest-UV spectroscopy of $z>6$ galaxies

$z \sim 8.5$, $H_{160} \sim 25$



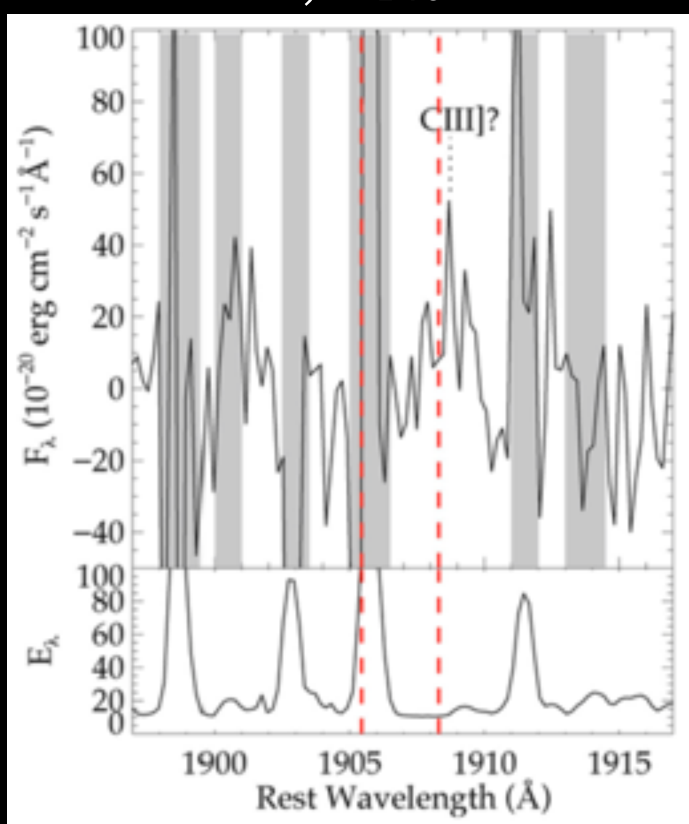
Zitrin+15

$z \sim 6.5$, $J_{140} \sim 24.2$



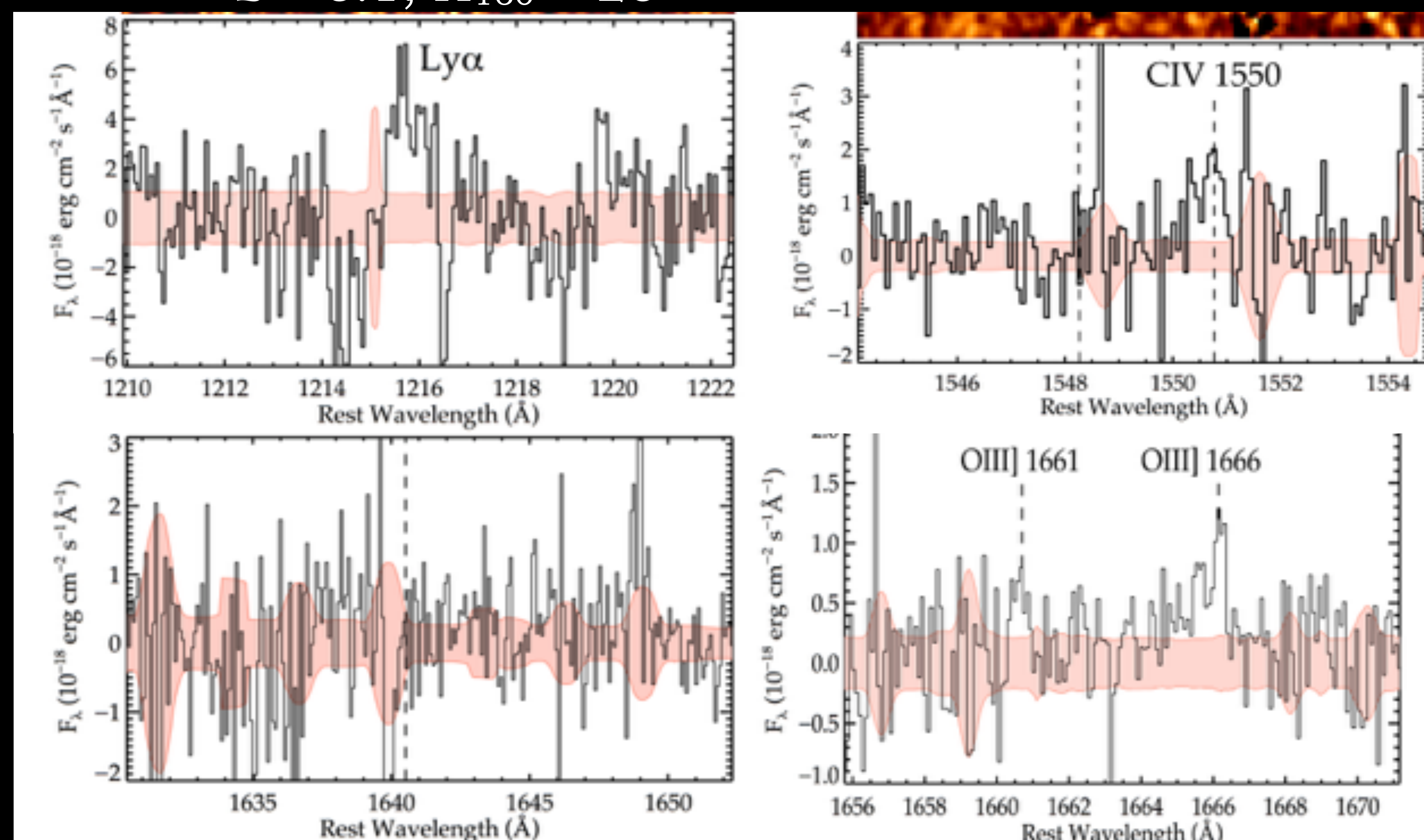
Matthee+17

$z \sim 7.2$, $J_{140} \sim 25$



Stark+15

$z \sim 6.1$, $H_{160} \sim 25$



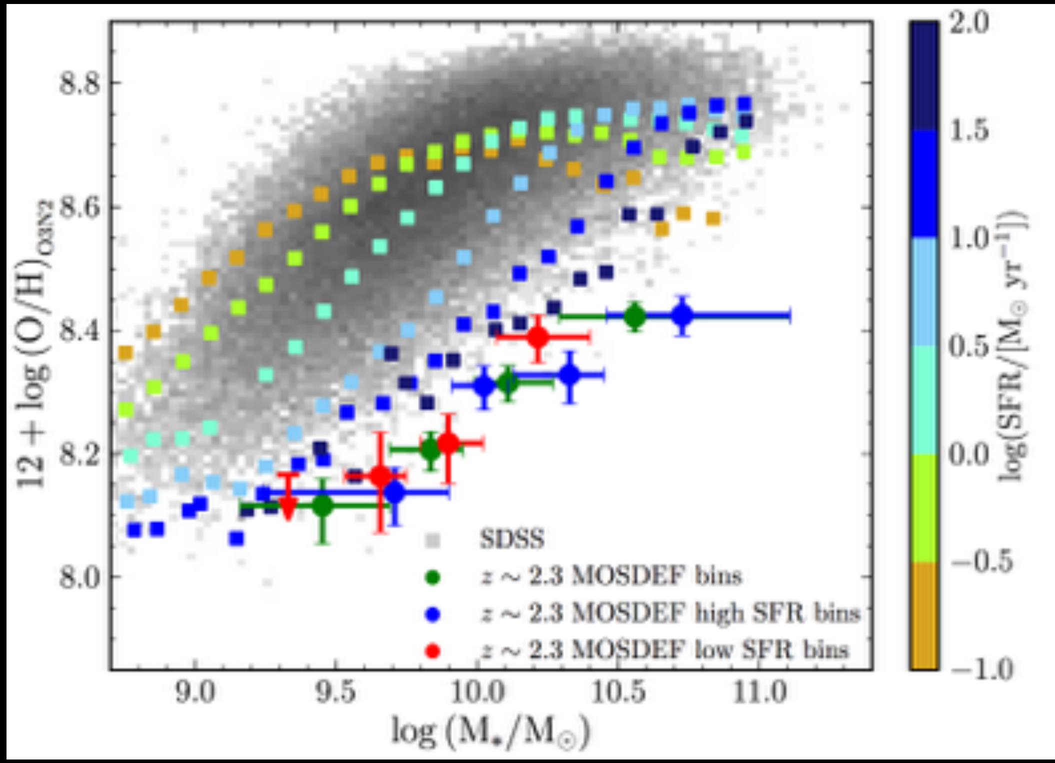
Mainali+17

Rest-UV spectroscopy

- **UV emission lines** provide constraints on galaxy properties, but:
  - Lyα resonant line, loosely related to **SFR** (need H-Balmer lines)
  - UV metal lines (CIV1548,1551; CIII]1907,1909; OIII]1661,1666) are weak → challenging to measure **abundances**
  - need (poorly understood) HeII to distinguish **AGN *vs* SF**

Rest-optical spectroscopy of $z < 4$ galaxies

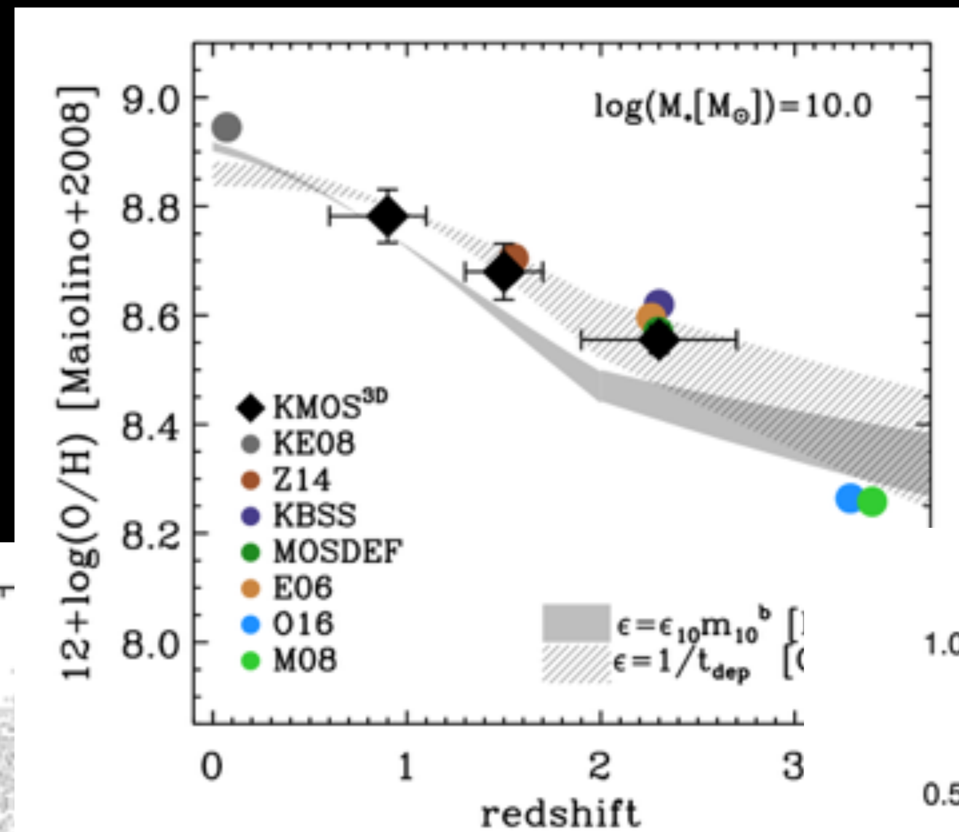
- MOSDEF:
  - 1500 galaxies
  - $H_{AB} < 25$
  - R~3000



Sanders+15

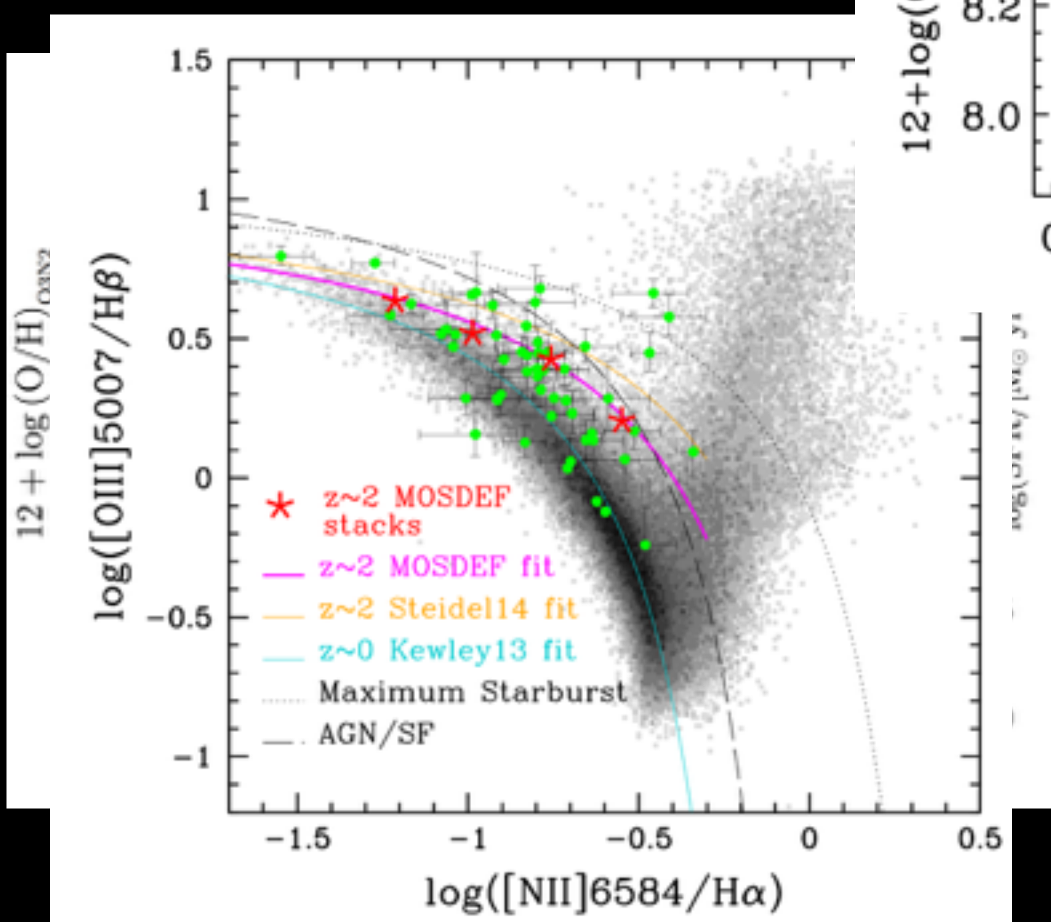
Rest-optical spectroscopy of $z < 4$ galaxies

E. Wuyts+16



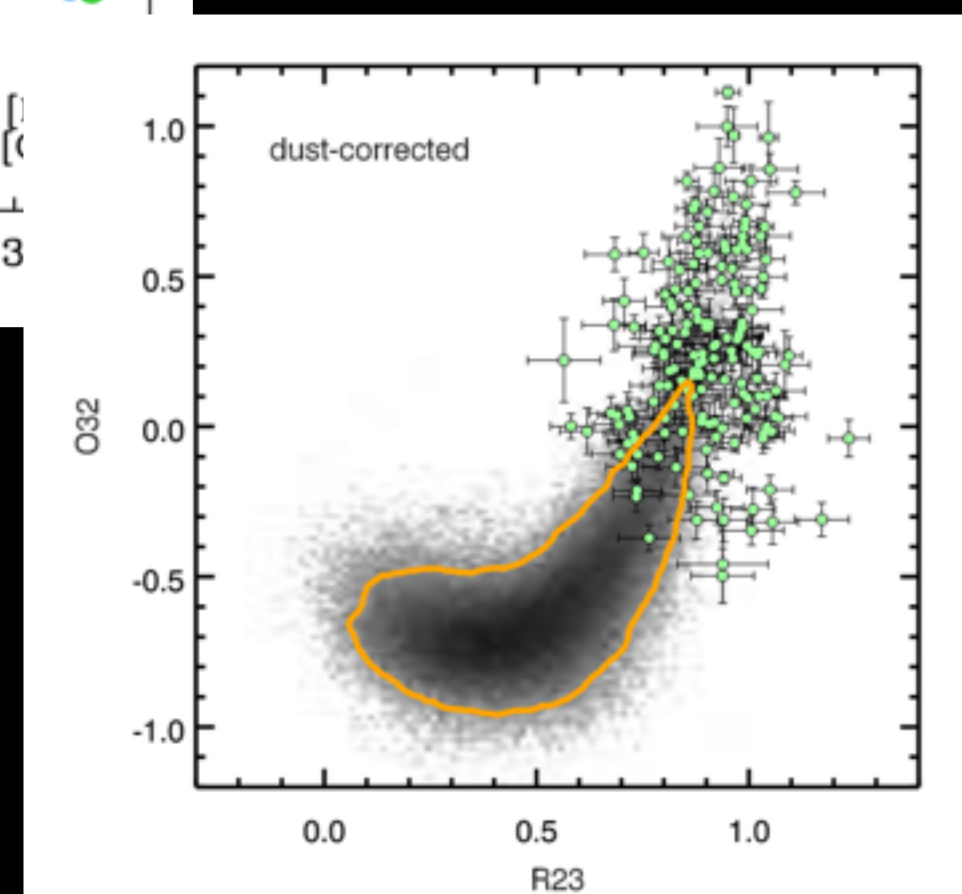
- MOSDEF:
  - 1500 galaxies
  - $H_{AB} < 25$
  - R~3000

- KBSS:
  - ~1000 galaxies
  - $R_{AB} < 25.5$
  - R~3000



Shapley+15

- KMOS^{3D}:
  - 600 galaxies
  - $M/M_{sun} > 10^{10}$
  - R~4000



Strom+17

Rest-optical spectroscopy

- **Optical lines** are stronger and contain tracers of
  - **SFR** (H-Balmer)
  - gas **density** ([OII]3726,3729; [SII]6718,6732)
  - **abundances** (O^+, O^{2+}, N^+, S^+)
  - **dust** attenuation (H-Balmer)
  - **SF** *vs* **AGN** *vs* **shocks** (BPT diagrams)
  - **ionization** parameter (O^+, O^{2+}, H-Balmer) and ionization spectrum (O^+, O^{2+})
- but… NIR spectroscopy **from ground** extremely challenging (telescopes sensitivity, atmosphere absorption/emission) and currently **limited to $\lambda < 2.5\ \mu$m** (optical lines only at ***z*<4**)

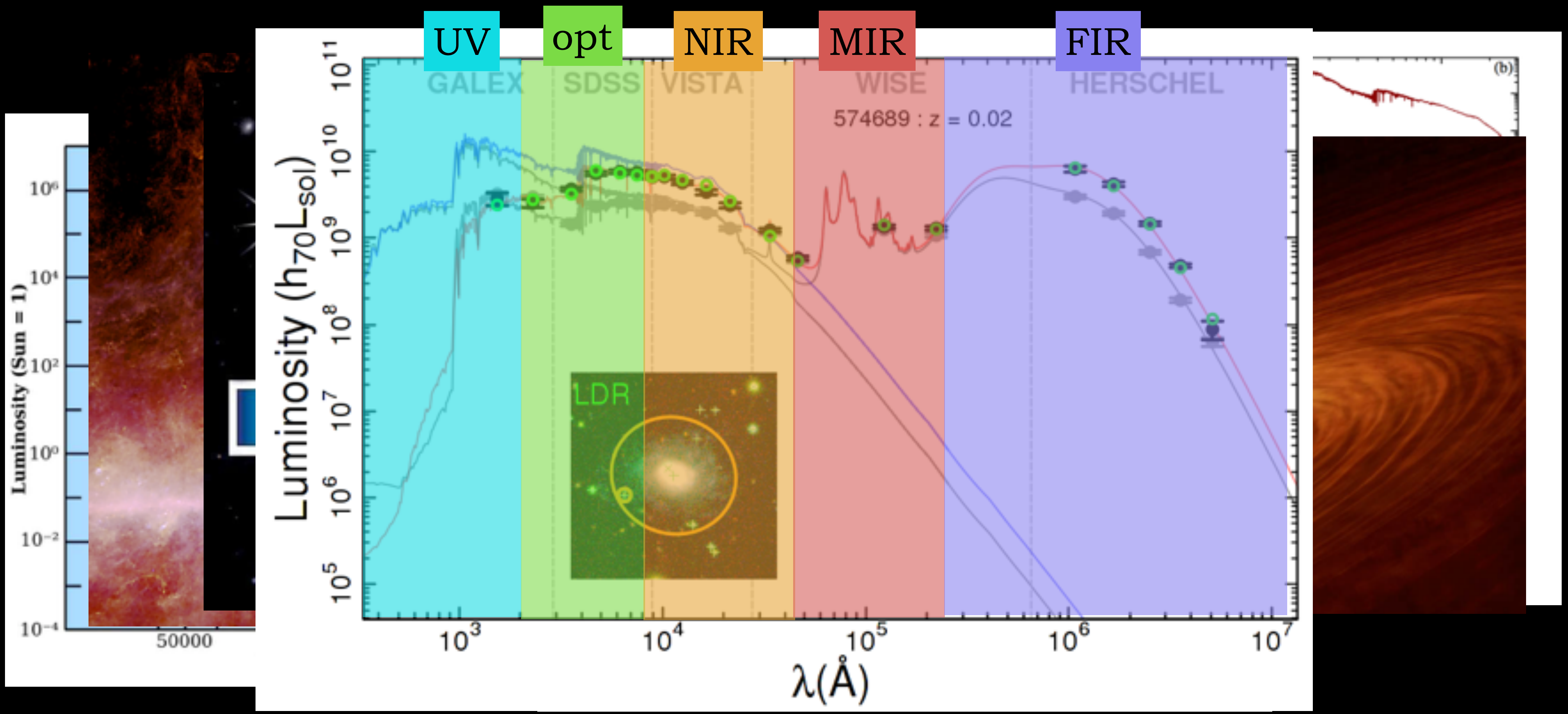
Chap. III

Tools

part II: models

Spectral evolution models

- Spectral evolution models allows us to measure galaxy physical properties
- Typically combine **stellar population synthesis** (e.g. *Pegase*, Fioc & Rocca-Volmerange 1997; *GALAXEV*, Bruzual & Charlot 2003; Maraston 2005; *FSPS*, Conroy & Gunn 2010) and **photoionization** models (e.g. Kewley+2011; Schaerer & de Barros 2009; Gutkin+16)



Spectral evolution models

- Models widely used to describe spectro-photometric observations at UV-to-NIR wavelengths (e.g. stellar masses of galaxies)
- Several existing tools: e.g. *LePhare* (Arnouts+99), *HyperZ* (Bolzonella+00), *CIGALE* (Burgarella+05), *FAST* (Kriek+09), *MAGPHYS* (da Cunha+08), *Prospector* (Leja+16)
- Typical **limitations** of existing modelling approaches:
  - use of **idealised** physical models
  - **no self-consistent treatment** of different galaxy components (i.e. stellar emission, dust attenuation, ionised and neutral gas, AGN)
  - use of **simplified statistical techniques**, unable to deal with complex multi-parameters models
- Motivation to develop **new-generation**, “general purpose” **tool** for modelling and interpretation of galaxy SEDs

The BEAGLE tool

BEAGLE - BAYESIAN ANALYSIS OF GALAXY SEDS

physically-coherent framework for modelling and interpretation of spectro-photometric galaxy observations

Astrophysics

- stellar emission
- nebular emission
- AGN NLR emission
- dust attenuation
- hydro-simulations
- (neutral ISM)
- (shocks)

beagle

Chevallard+16
Gutkin+16
Feltre+16
Vidal-Garcia+17
Curtis-Lake in prep.

Statistics

- high-dimensional models
- characterise degeneracies
- nuisance parameters
- rigorous uncertainties
- adopt informative priors
- (multi-level modelling)

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“light” version of BEAGLE available at https://gazpar.lam.fr/

Modelling galaxy SEDs with BEAGLE

Several past/ongoing applications of BEAGLE to modelling spectro-photometric data:

- **Local "analogues" of high-*z* galaxies (Senchyna+2017, Chevallard +2017a)**
- **JWST/NIRSpec simulations (Chevallard+2017b to be submitted)**
- z>6 galaxies spectra-photometric modelling (Stark+2017)
- Photo-*z* of MUSE 'deep' sources (Brinchmann+2017)
- Lyα emitters from Subaru/HSC (Harikane+2017)
- MUSE spectra + HST photometry of MgII emitters (Feltre+ in prep)
- z<2 galaxy SFR and log(O/H) from HST grism spectra (Pirzkal+in prep)
- JWST/NIRCam simulations (Williams+ in prep)
- ….

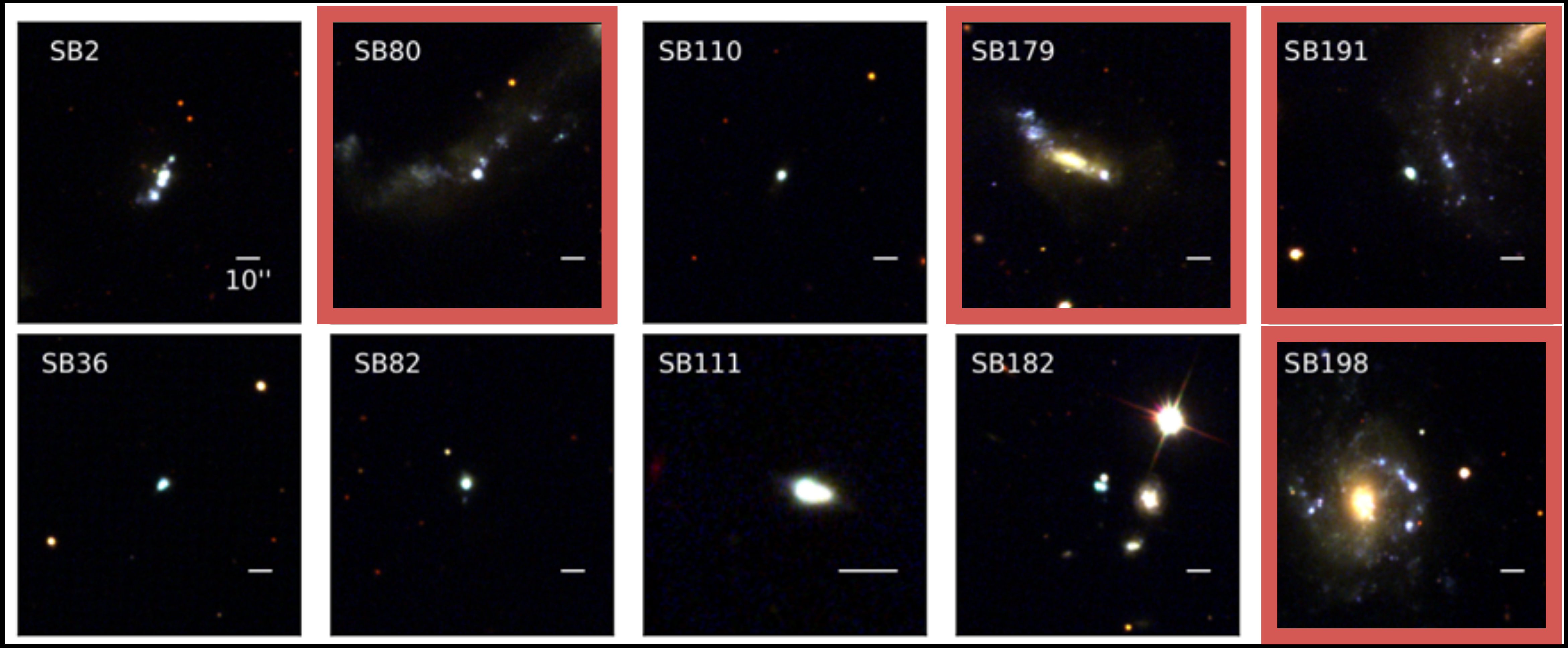
Chap. IV

Current Science:

modelling local "analogues" of high-z galaxies

Local "analogues" of high-z galaxies

- Cannot characterise properties of z>4 galaxies with existing data
- Can we learn about high-z galaxies by studying nearby objects?
- HST/COS observations of 10 galaxies, selected from SDSS to show HeII λ4686 emission



Senchyna, JC+, 2017, MNRAS 472

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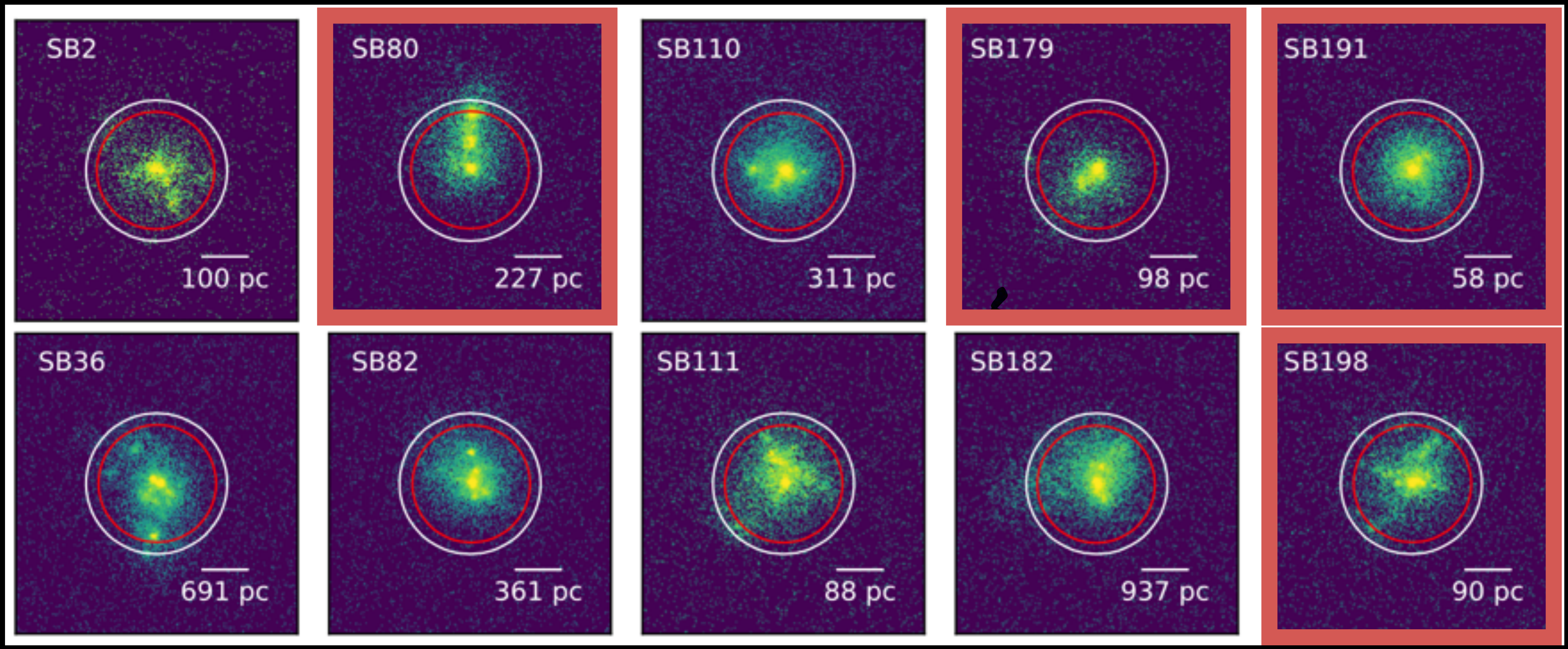
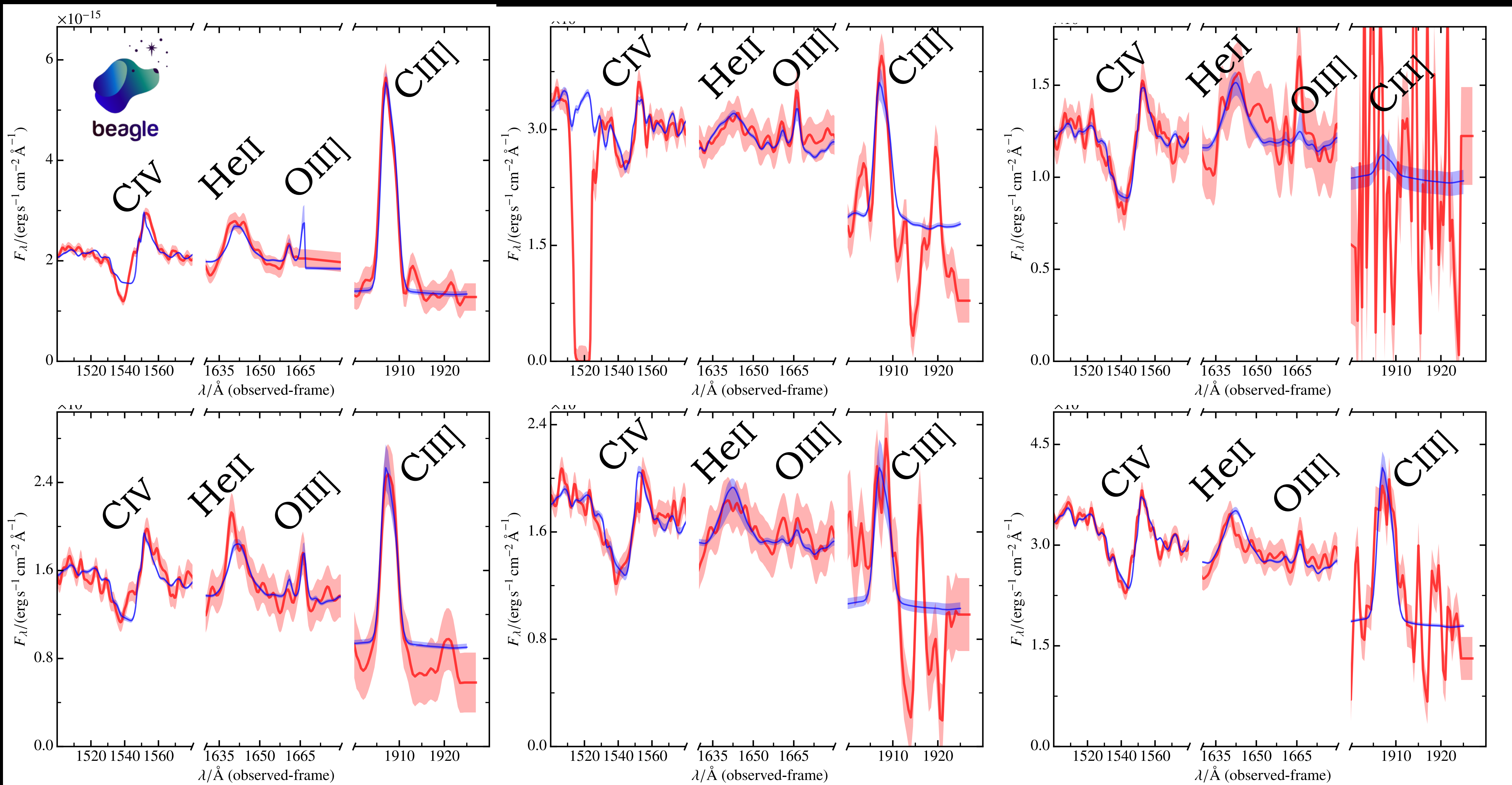


Senchyna, JC+, 2017, MNRAS 472

UV spectra of local “analogues”

- Large variety of UV features (similar to high-z galaxies)
- Ideal sample to test our models and learn about physical properties of these objects: **necessary steps to pave the way for JWST data**



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- Large variety of UV features (similar to high-z galaxies)
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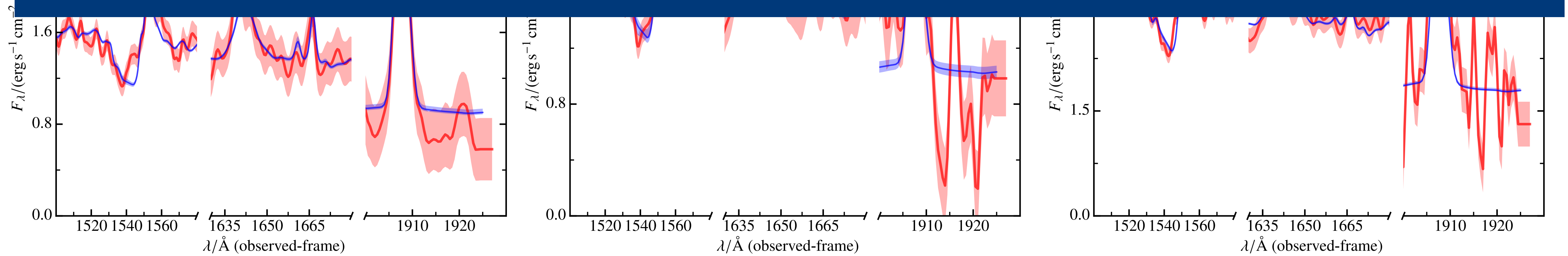
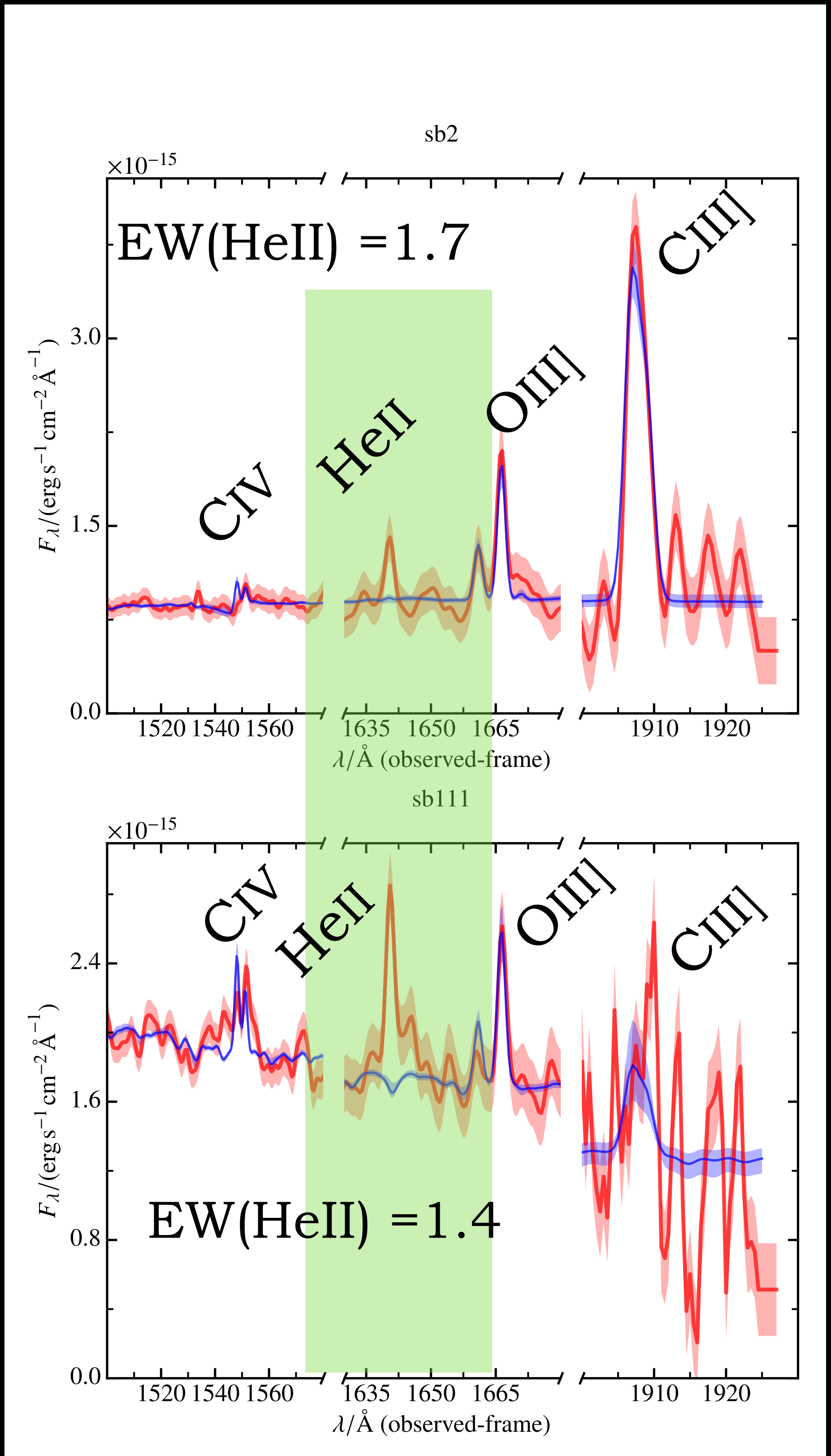
Can match with a **self-consistent physical model**:

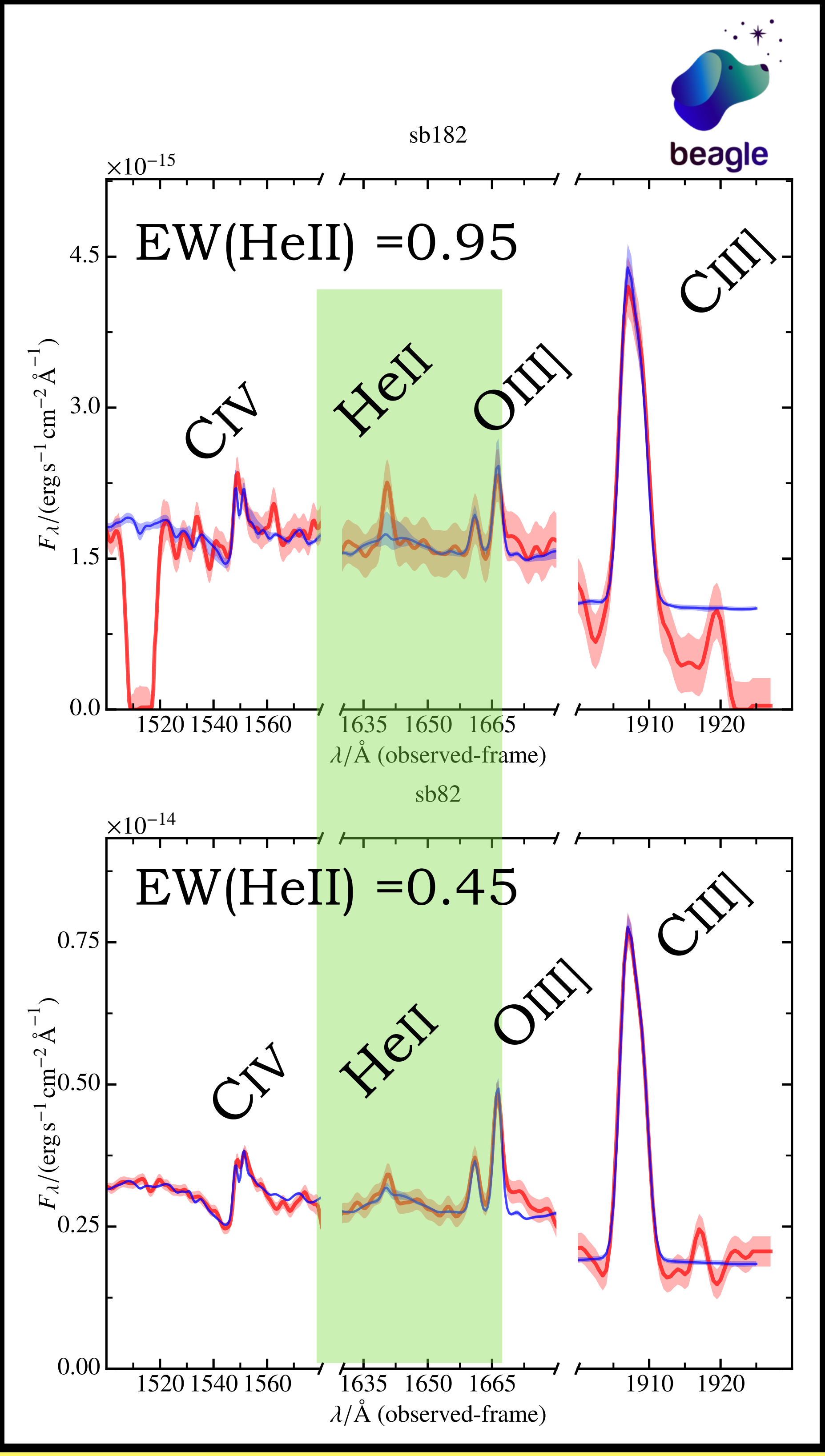
- **stellar continuum** emission/photospheric absorptions
- **stellar winds** emission/absorption
- **nebular** emission
- (soon also low and high-ionization **ISM absorption** lines from Vidal-Garcia+2017)



Modelling UV spectra: HeII emission

$m_{\rm up} = 100\ M_\odot$

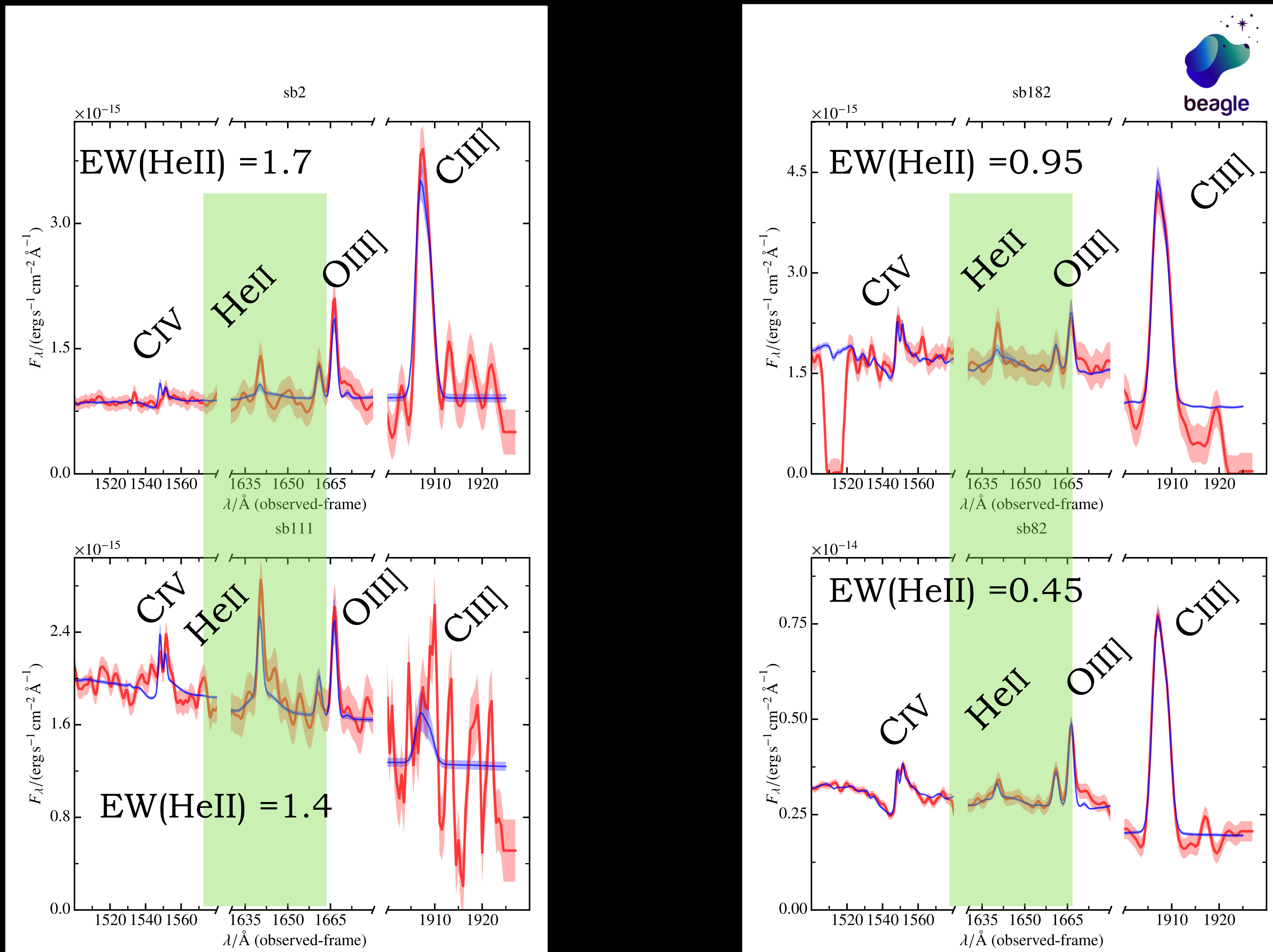




JC+in prep

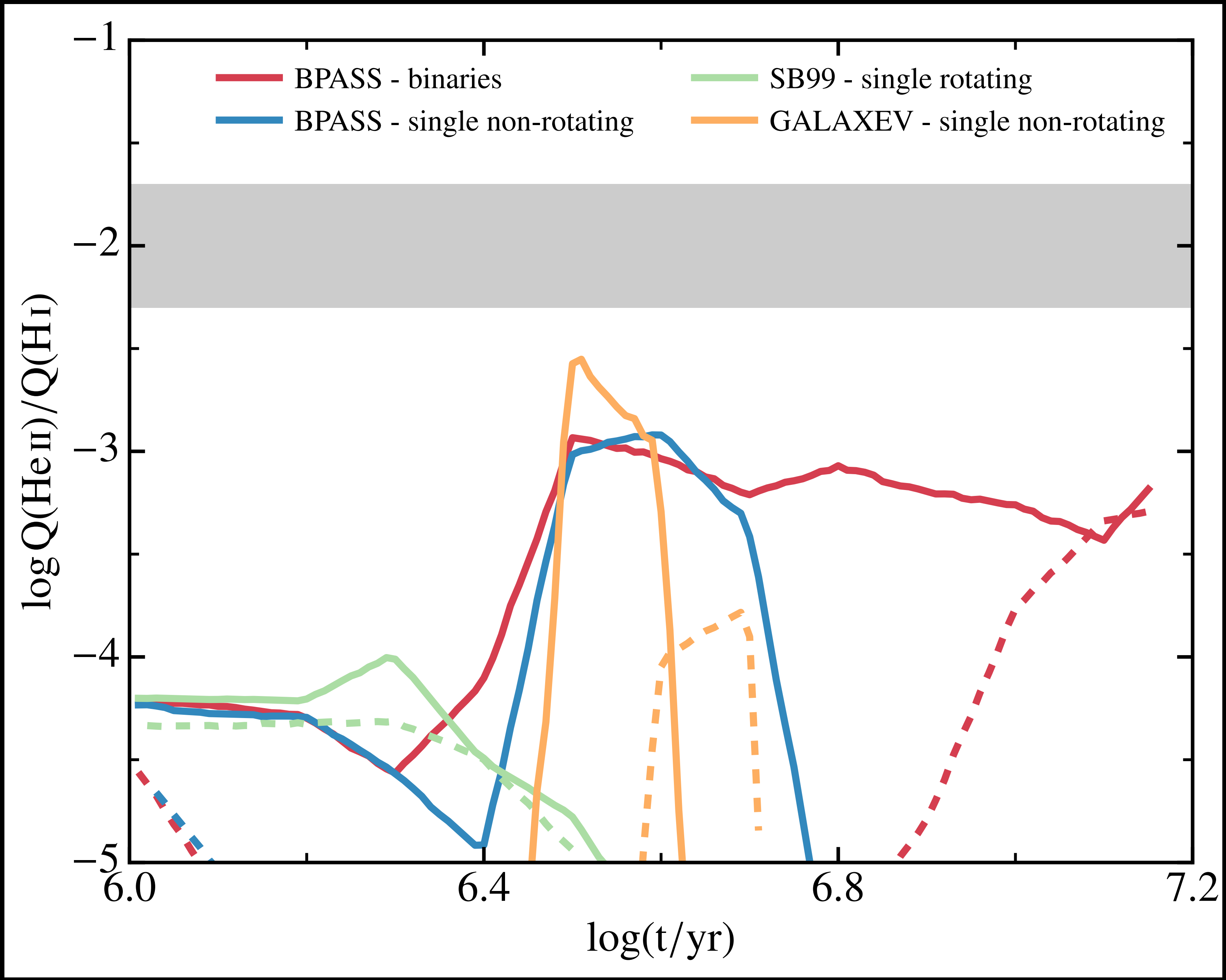
Modelling UV spectra: HeII emission

$m_{\rm up} = 300\ M_\odot$



JC+in prep

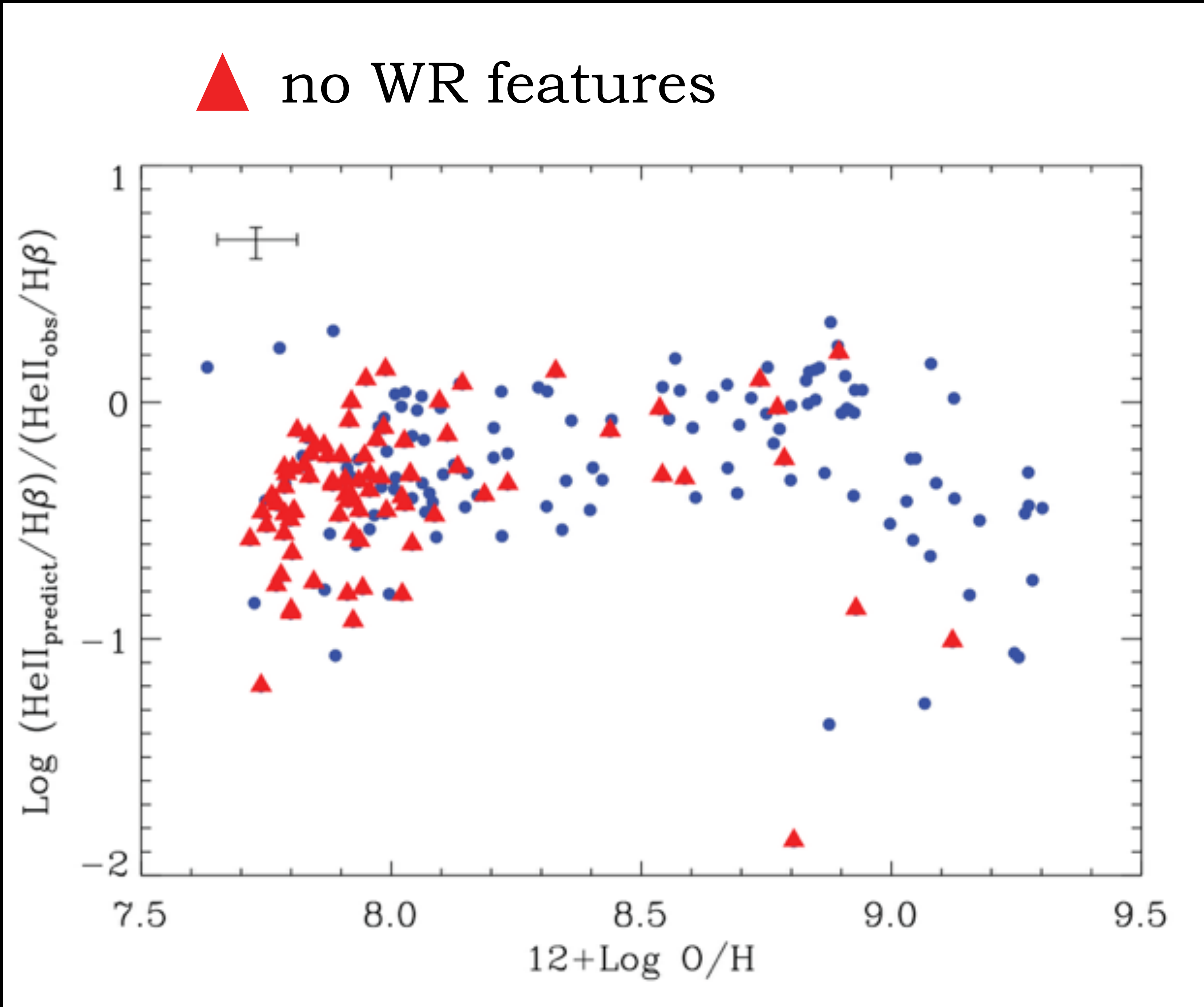
He^{+}-ionizing photons production



Adapted from Wofford+2016, MNRAS 457

- two metallicities
  - solid line: $Z = 0.3\, Z_{\odot}$
  - dashed line: $Z = Z_{\odot}$
- SSPs (lower ratios for constant SF)
- Newer versions of models predict larger Q(HeII)/Q(HI) ratios
- See Charlot & Bruzual (2017, in prep.) for an in depth model comparison

He$^+$-ionizing photons production



Shirazi & Brinchmann, 2012, MNRAS 421
(see also Brinchmann+2008, Kehrig+2015)

- two metallicities

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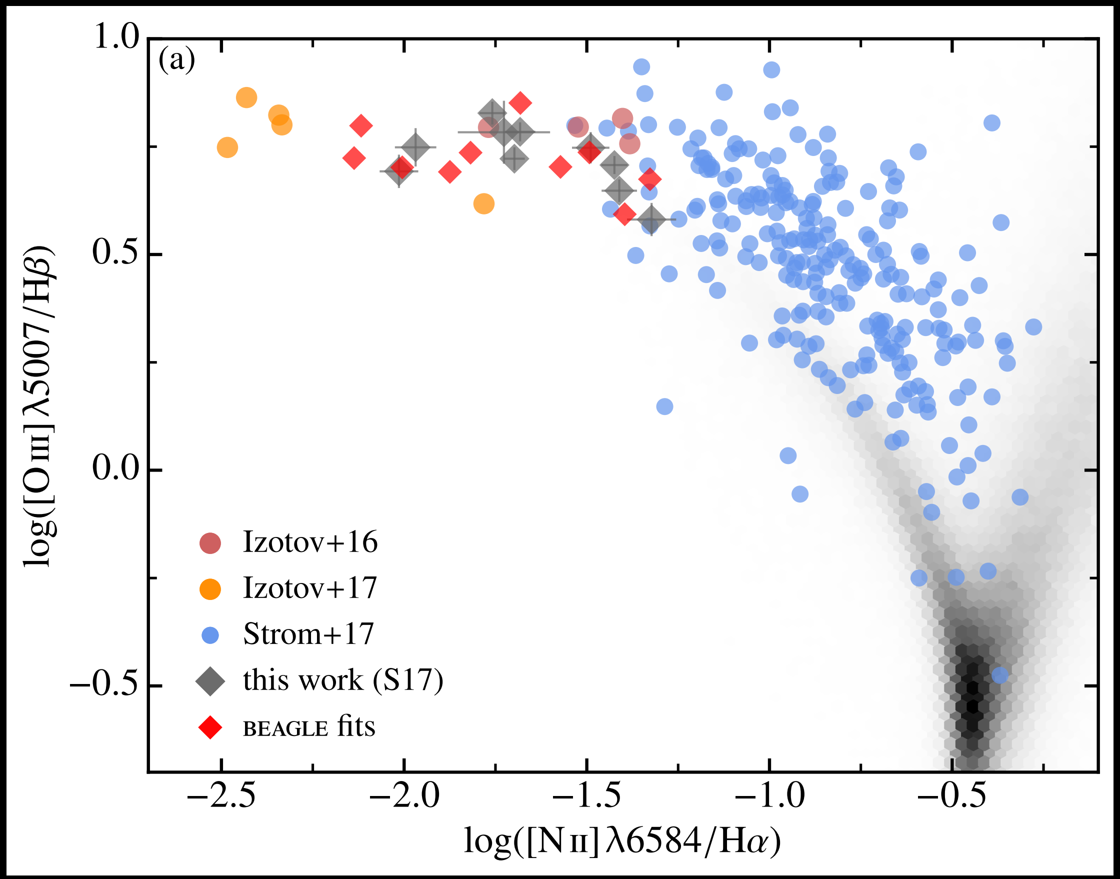
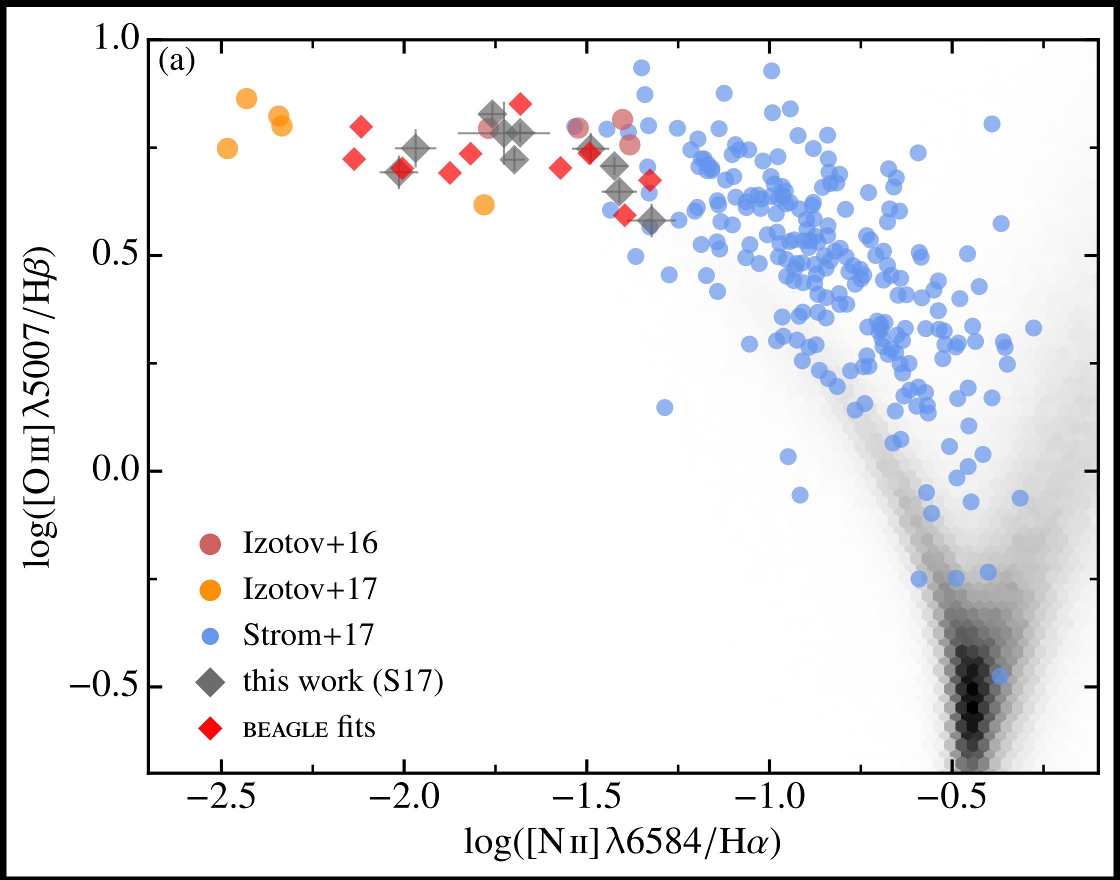
Optical spectra of local "analogues"



Chevallard+17a

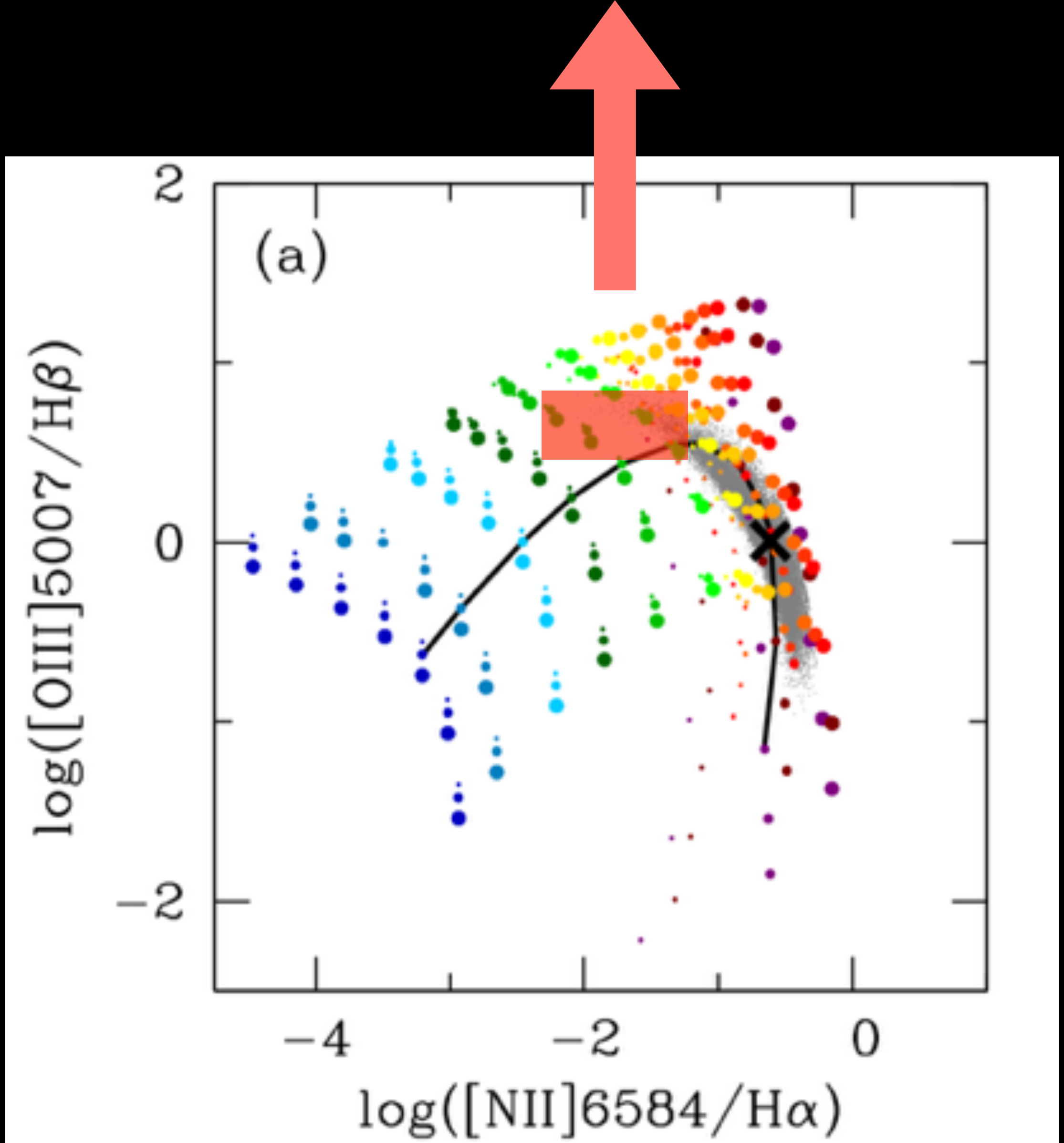
- similar location in NII BPT to z~3 galaxies

Optical spectra of local "analogues"



Chevallard+17a

- similar location in NII BPT to z~3 galaxies
- metallicity Z/Z_{sun} ~ 0.1 to 0.7
- ionization parameter logU > -3



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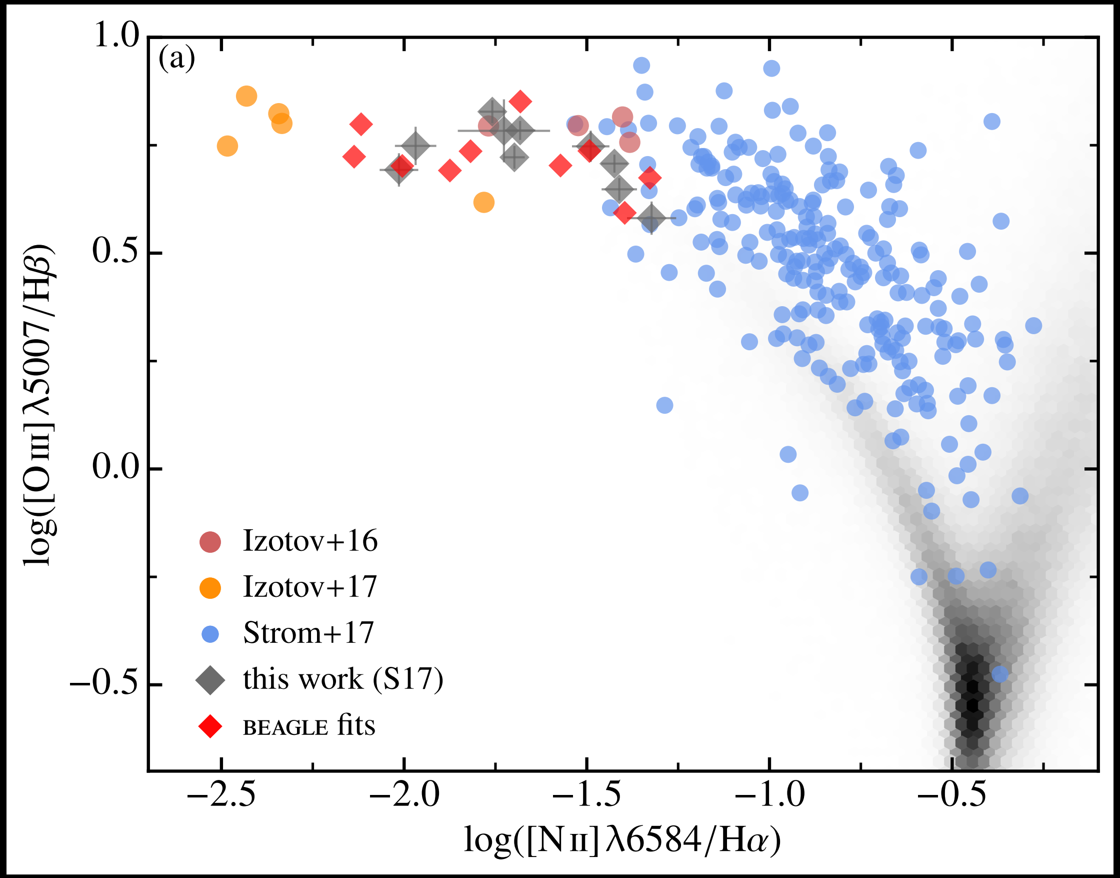

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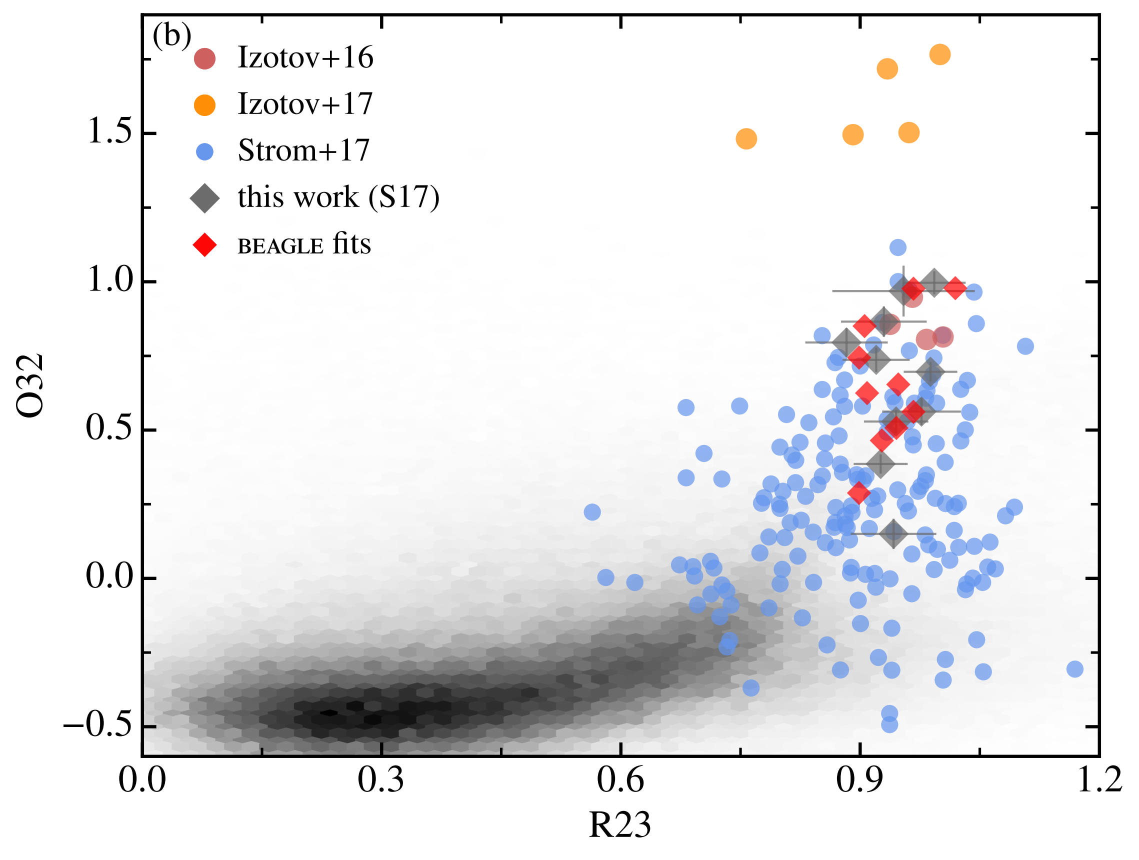
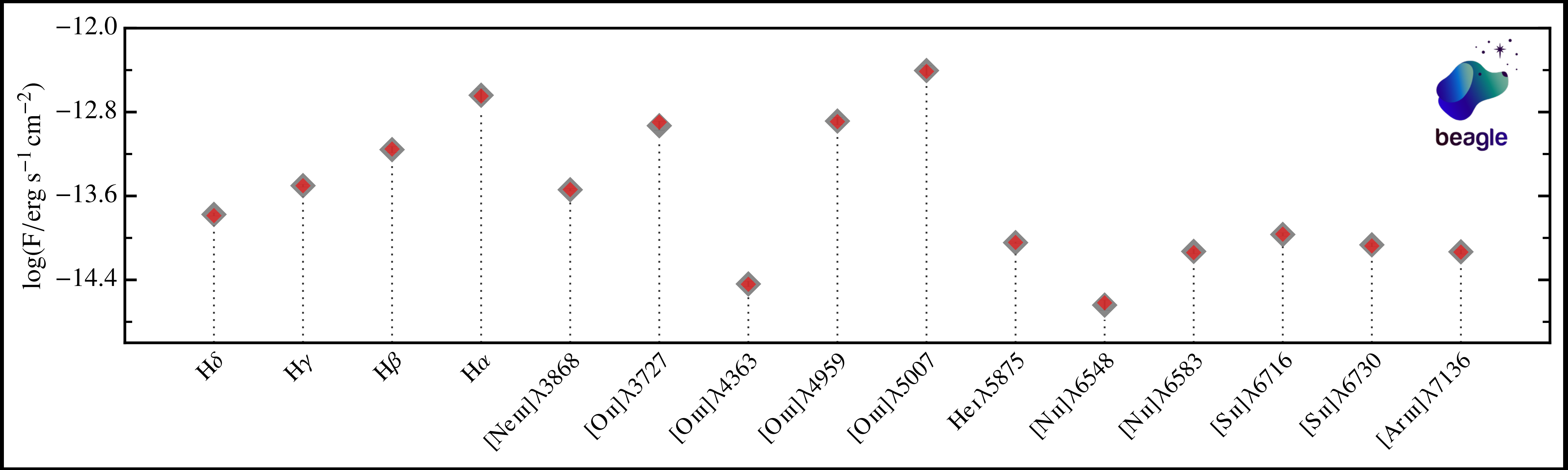


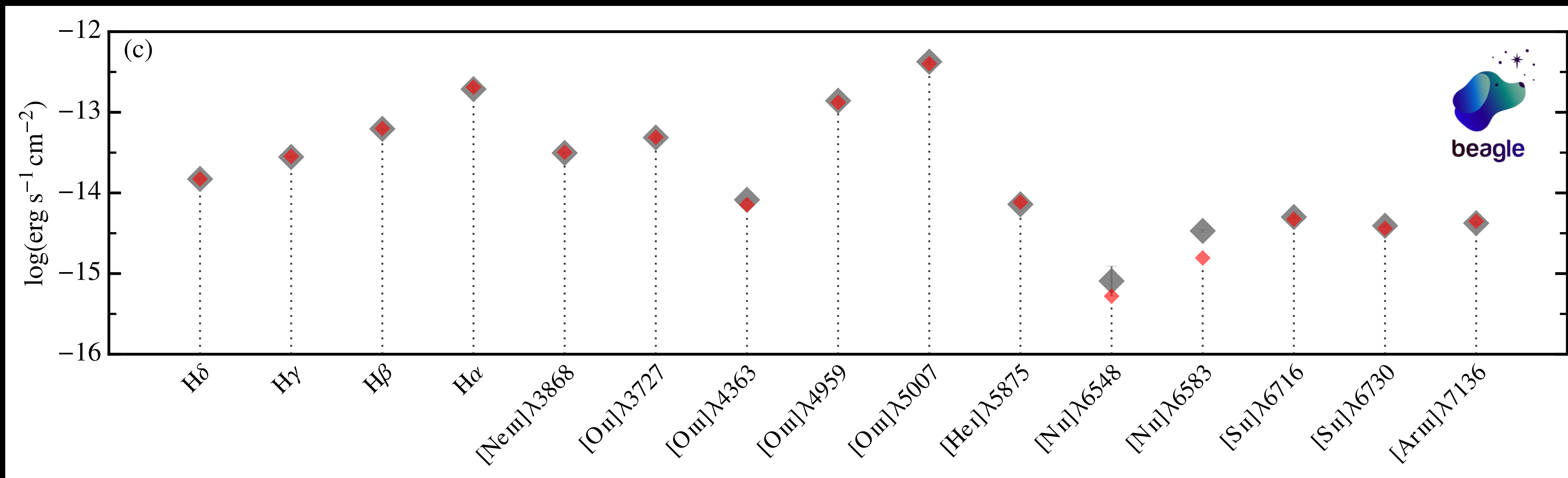
- large [OIII]/[OII] at fixed [NII]/Hα ➞ hard ionising spectrum

Modelling optical emission lines



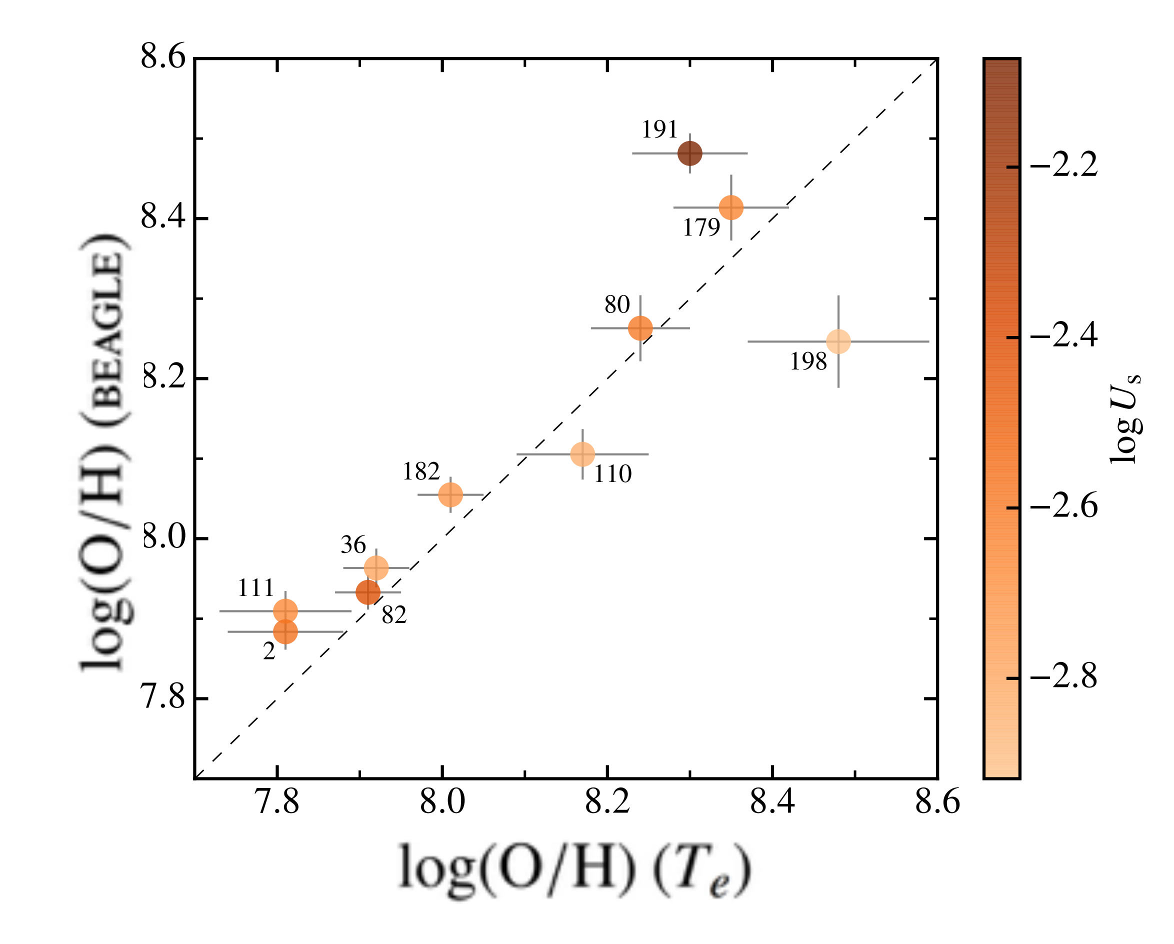
- **BEAGLE fitting** with a self-consistent physical model
- Able to simultaneously reproduce 15 emission lines sensitive to **dust attenuation** (H-Balmer), **ionization parameter** (O^+, O^{2+}, H-Balmer) and **ionization spectrum** (O^+, O^{2+}), gas **density** ([SII]6718,6732), and several **abundances** (oxygen, nitrogen, sulphur, neon; O^+, O^{2+}, N^+, S^+, Ne^{2+})
- Perhaps **nitrogen-abundance** too low for some objects?

Modelling optical emission lines

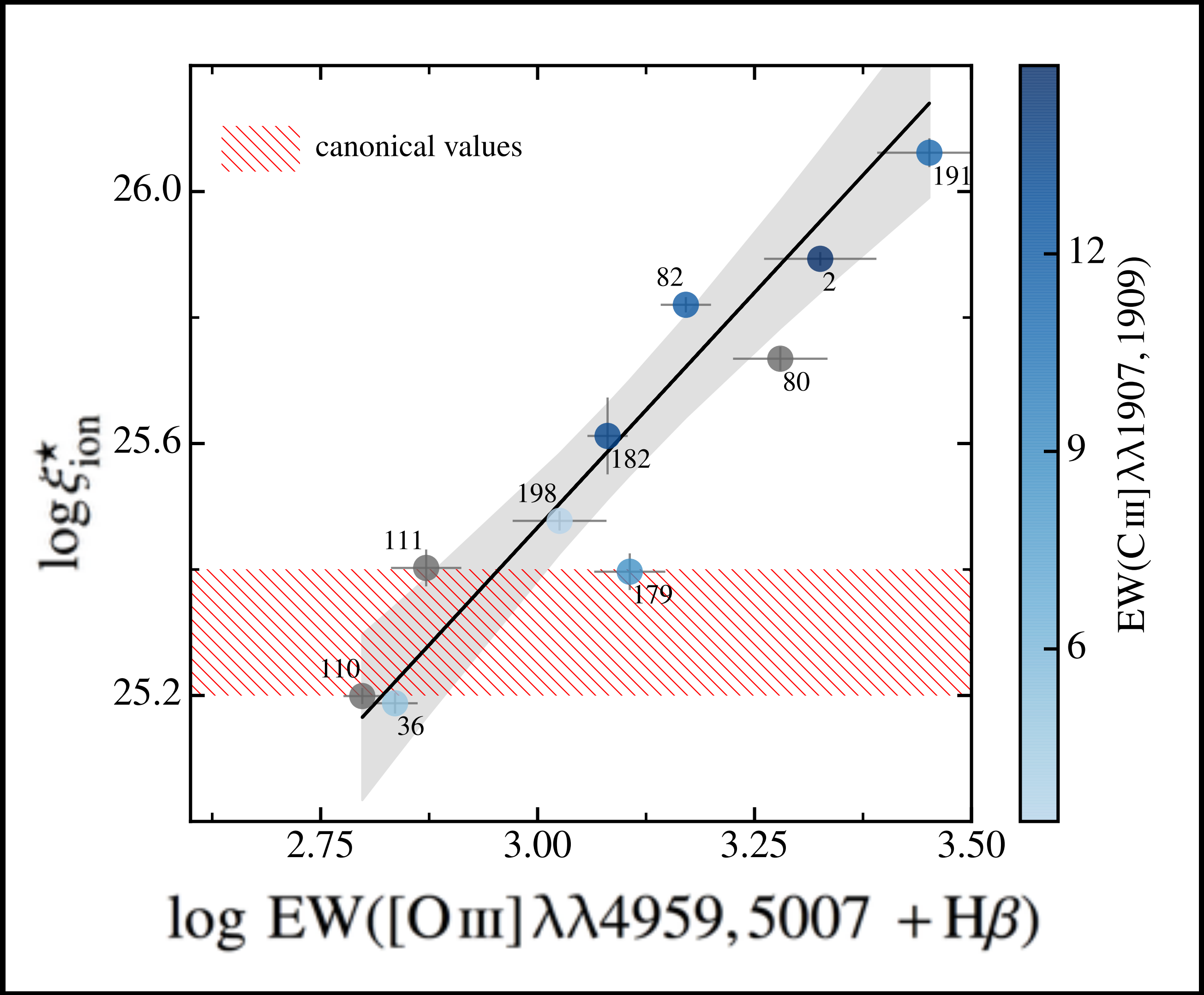


- **BEAGLE fitting** with a self-consistent physical model
- Able to simultaneously reproduce 15 emission lines sensitive to **dust attenuation** (H-Balmer), **ionization parameter** (O^+, O^{2+}, H-Balmer) and **ionization spectrum** (O^+, O^{2+}), gas **density** ([SII]6718,6732), and several **abundances** (oxygen, nitrogen, sulphur, neon; O^+, O^{2+}, N^+, S^+, Ne^{2+})
- Perhaps **nitrogen-abundance** too low for some objects?

H-ionizing photons production efficiency



- Excellent agreement between BEAGLE-based and T_e-based metallicities



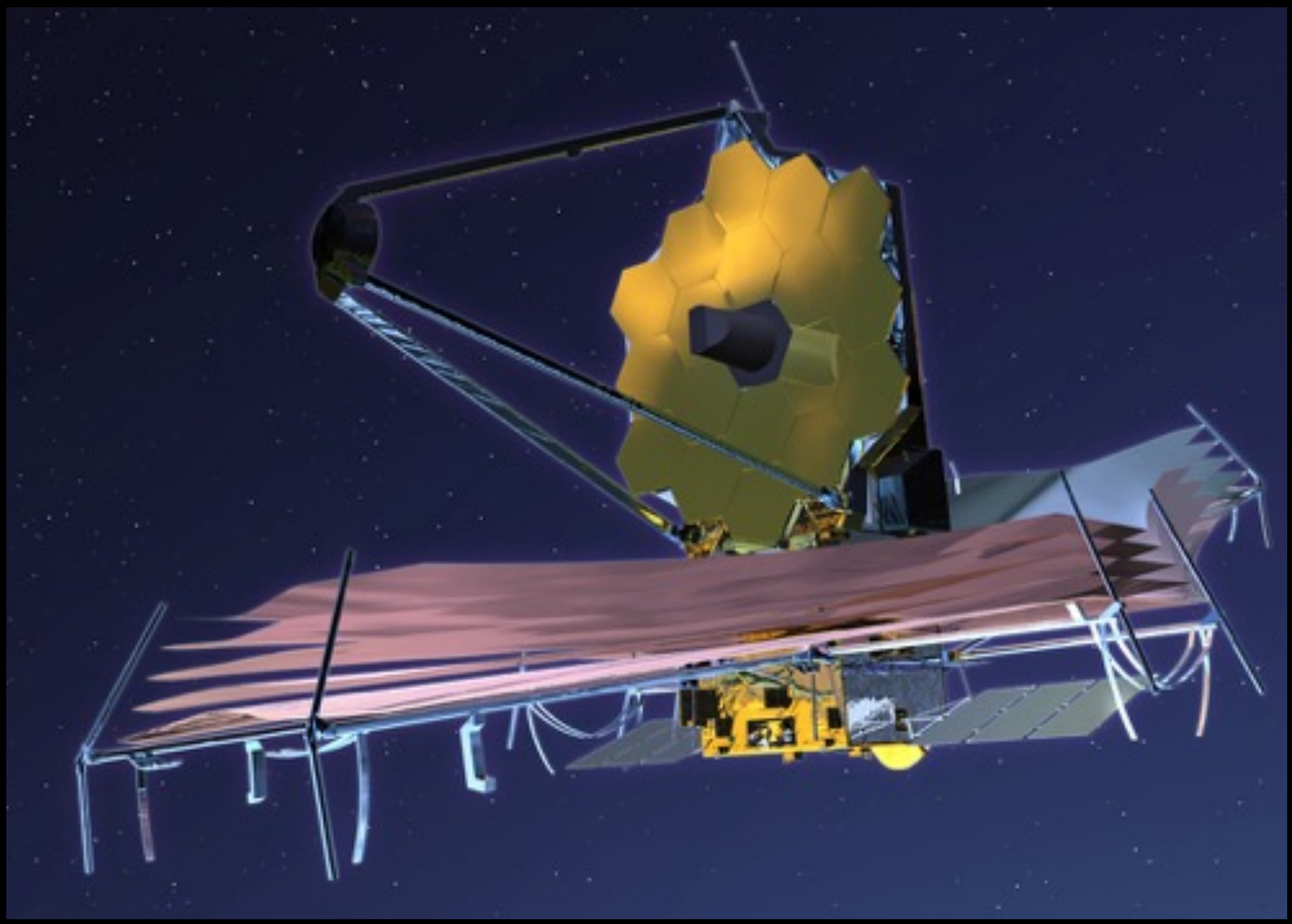
Chevallard+17a

- Relation between EW of [OIII]+Hβ and $\xi_{\rm ion}$
- Can be used to estimate $\xi_{\rm ion}$ from contamination to photometry

Chap. V

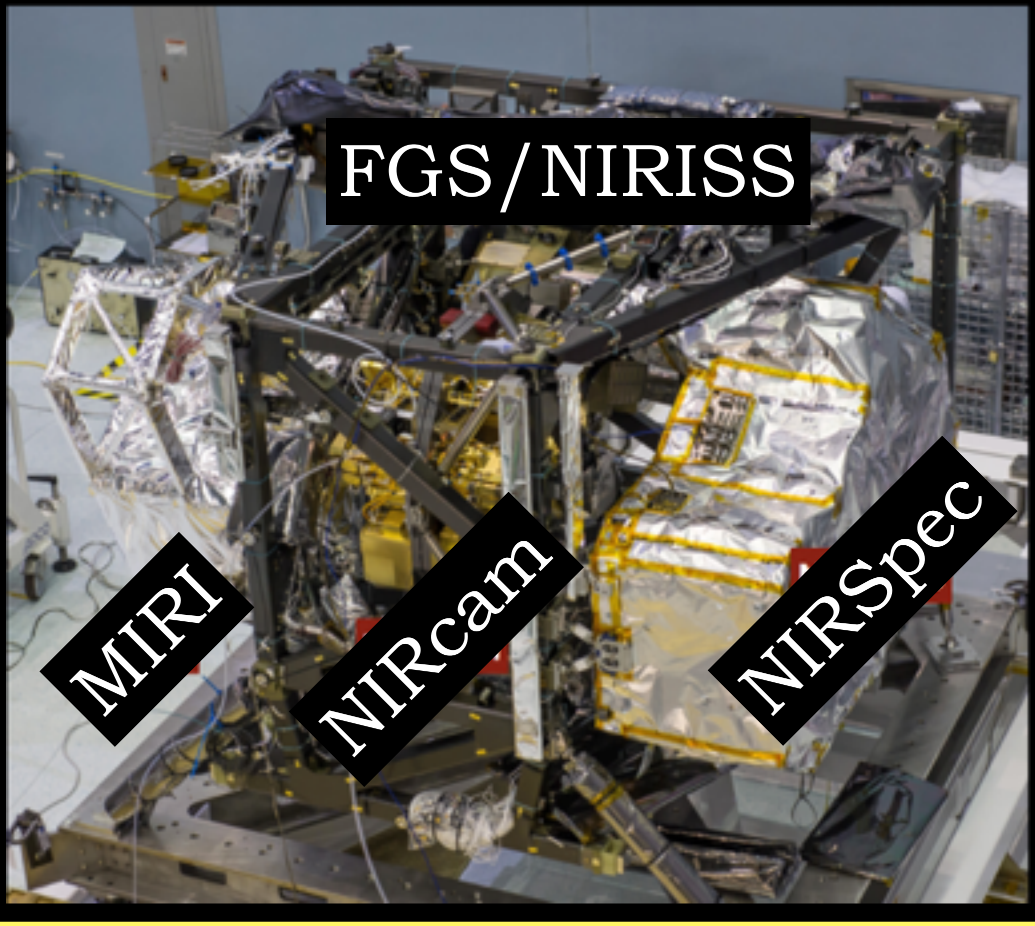
Future Science: preparing early JWST/NIRSpec observations

The James Webb Space Telescope



4 **instruments**:

- **N**ear **I**nfra**R**ed **Cam**era
- **N**ear **I**nfra**R**ed **Spec**trograph
- **M**id **I**nfra**R**ed **I**maging
- **F**ine **G**uidance **S**ensor + **N**ear-**I**nfra**R**ed **I**mager and **S**litless **S**pectrograph



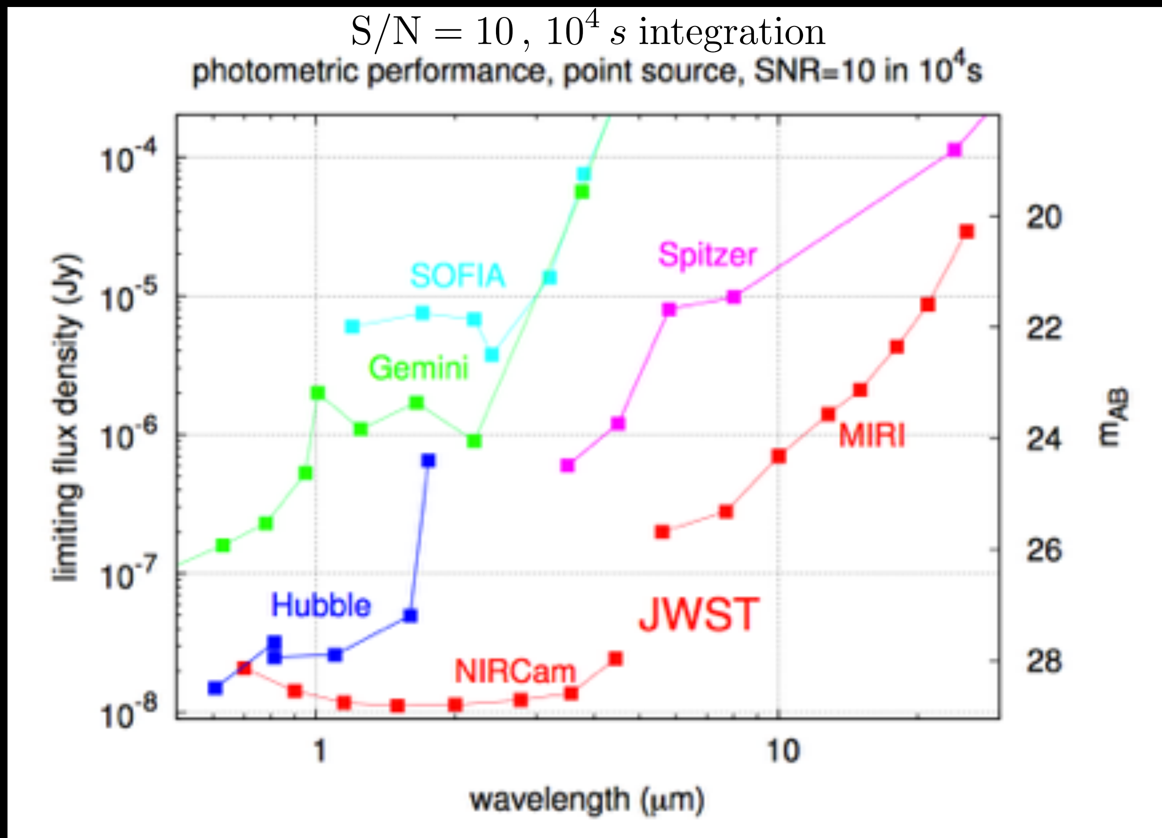
★ 6.5 m primary mirror

★ **7x HST** collecting **area**

★ imaging + spectroscopy in **0.6-28 micron** range

★ launch April - June 2019

JWST: unique sensitivity and wl coverage

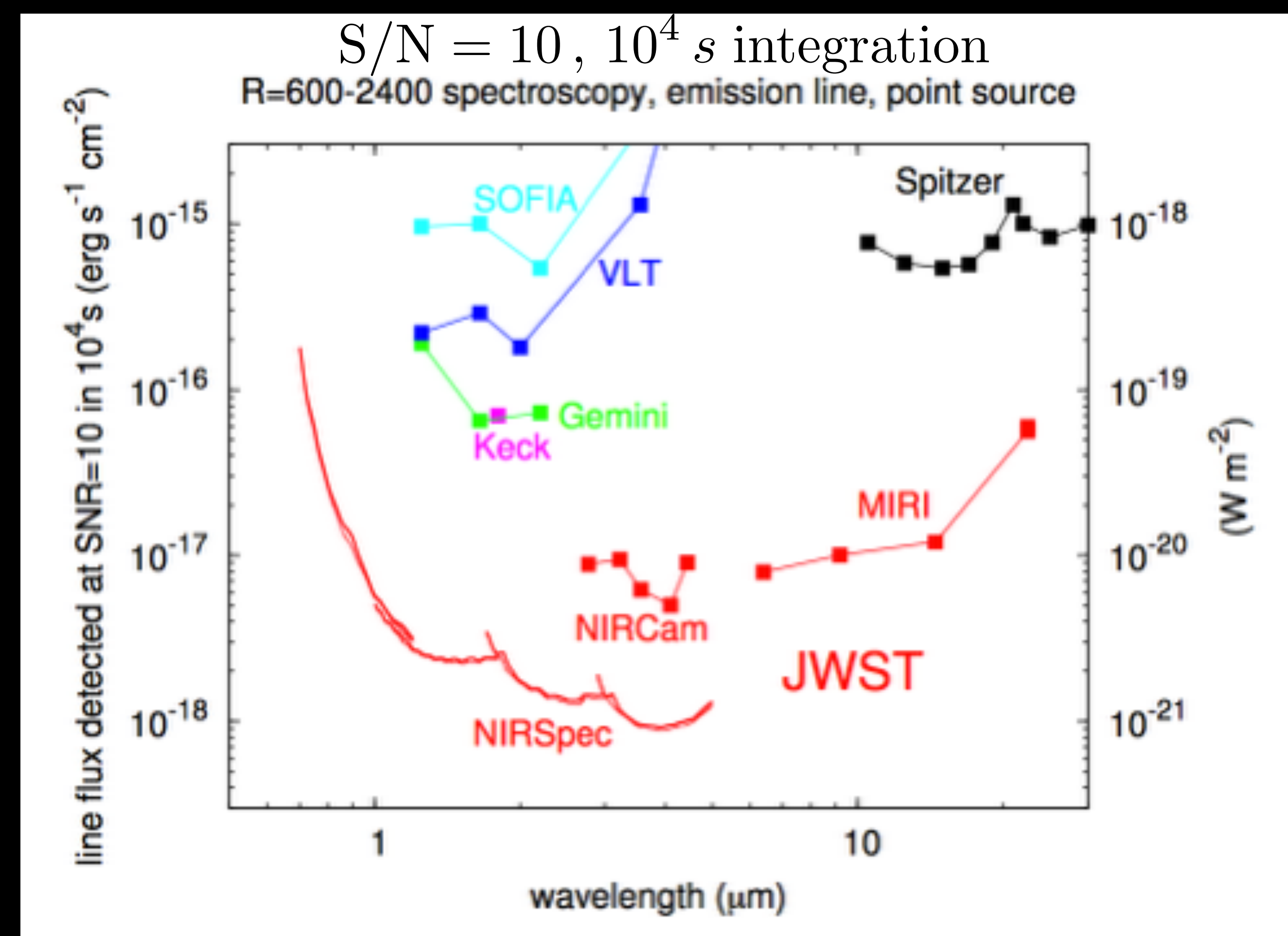


Imaging

- 100x improvement at 2 μm
- 30x improvement at 10 μm

(emission-line) **spectroscopy**:

- 30x improvement at 2 μm
- even greater sensitivity at λ = 2 to 5 μm
- 80x improvement at 10 μm



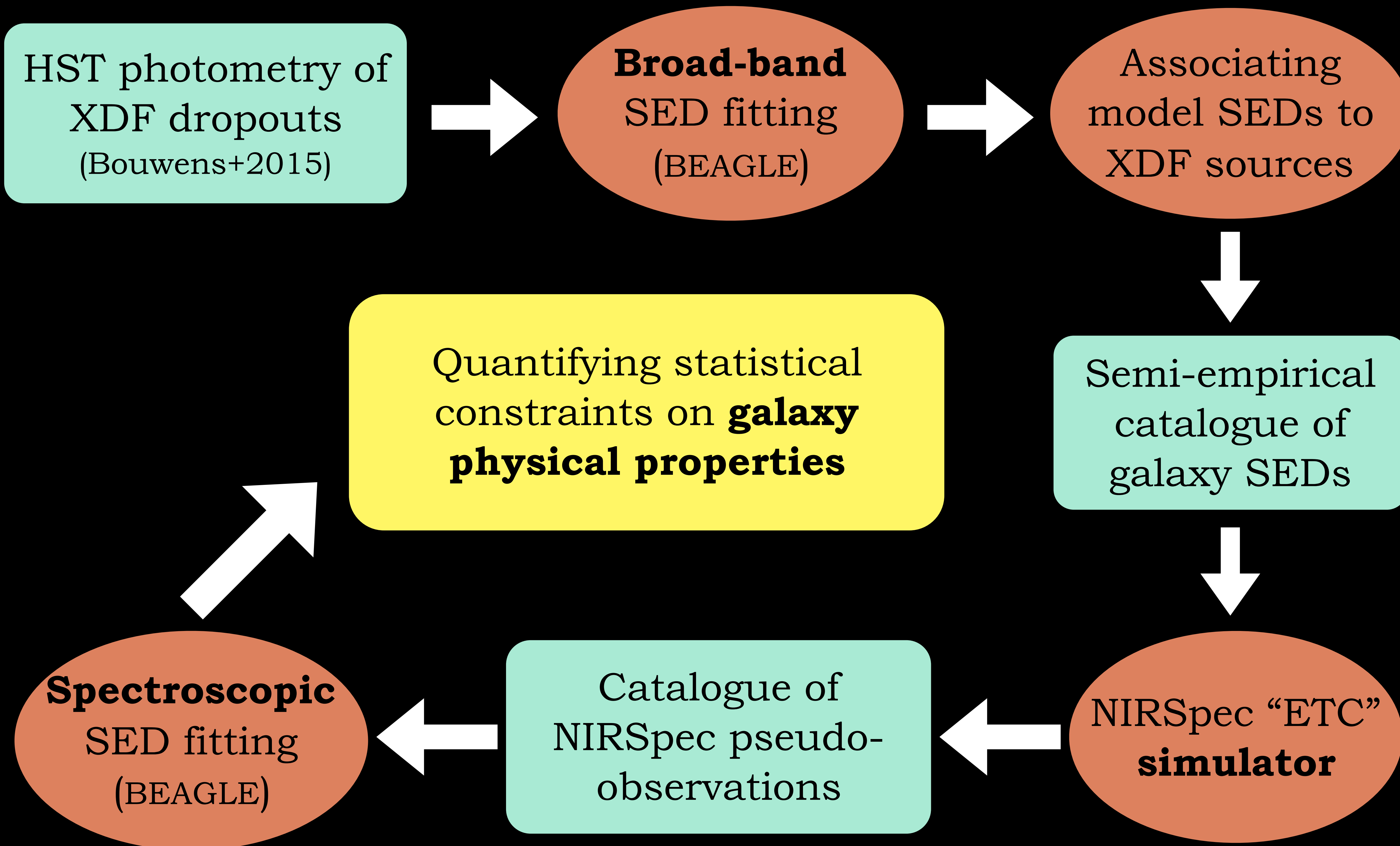
JWST view on galaxy evolution

- JWST: unique combination of **sensitivity** + **wavelength coverage** + **multiplexing**
- **Cycle 1 GO call: 30th November 2017**
- Ideal observatory to study:
  - formation of **first galaxies** at $z > 10$ (and Pop. III stars?)
  - contribution of galaxies *vs* AGNs (*vs* …) to **cosmic reionization**
  - space- and time-evolution of H-ionised fraction (LAE LF, LAE clustering)
  - co-evolution of galaxies and AGNs at $z > 4$
  - properties of **ionised gas** and **stellar populations** at $z > 4$

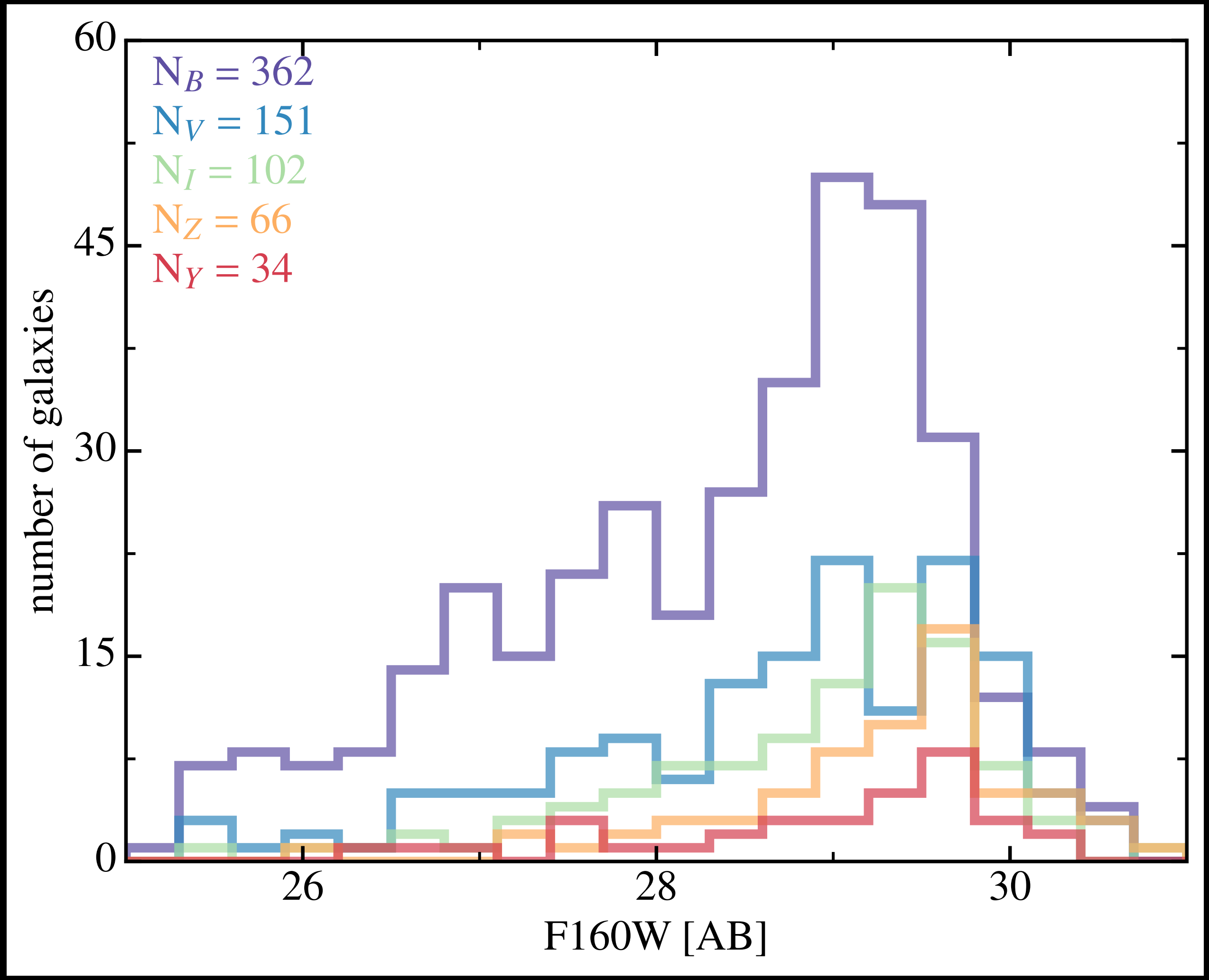
NIRSpec observations of HST sources

- Deep HST observations unveiled **>10^4 galaxies at z > 4**
- z > 4 with **NIRSpec** unique measurements of **optical EL**
- Can measure mass-SFR, mass-metallicity, ionization sources, dust attenuation, …, out to **z~10**
- We face several questions/choices:
  - Which NIRSpec mode (low vs medium resol.) and exposure time?
  - What S/N do we expect for different sources?
  - How do we select/prioritise our targets?
  - Shall we allow spectral overlap?
  - Nodding / dithering strategies?
  - …

Simulations and analysis of NIRSpec data

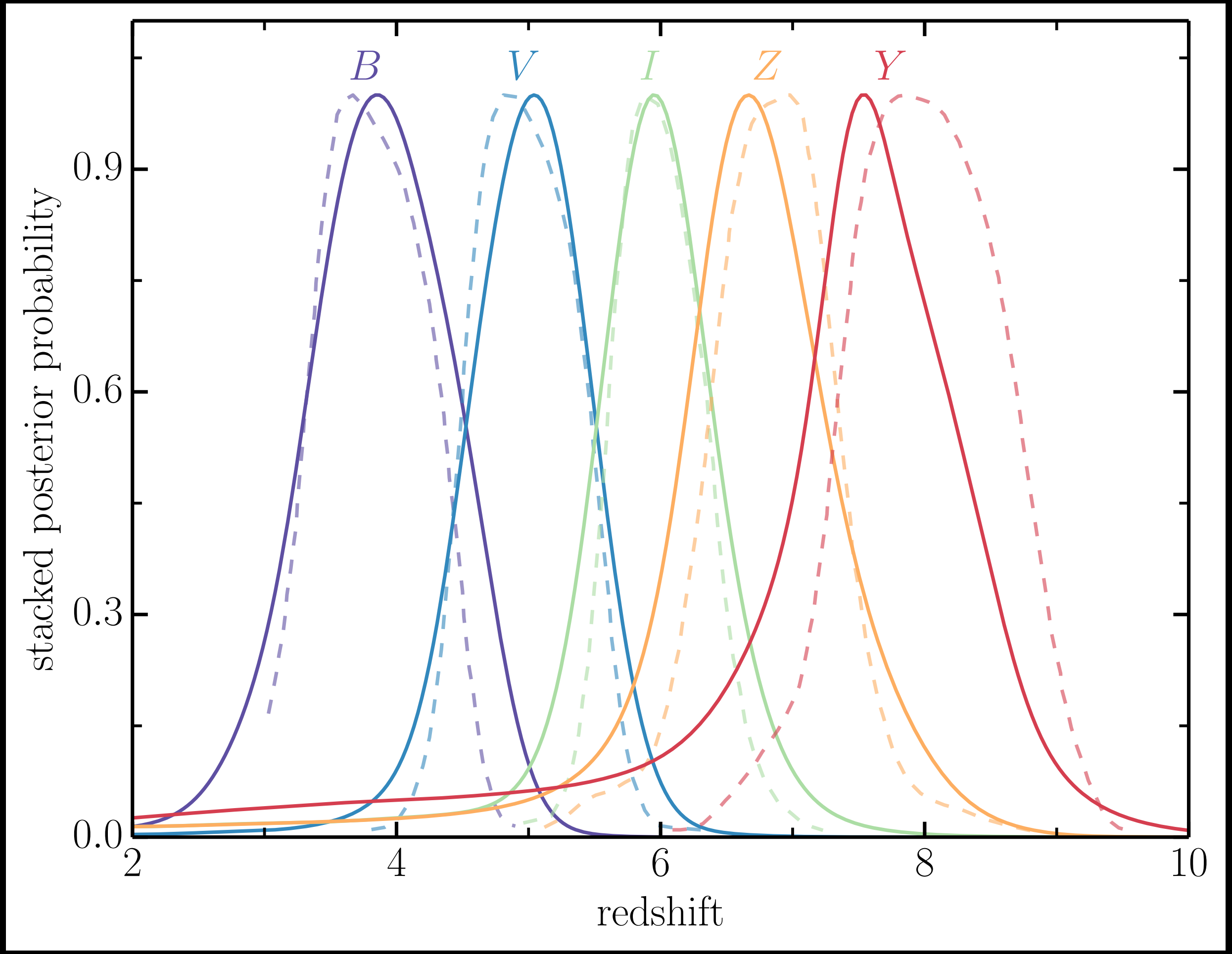


(*B*, V, *I*, *Z*, *Y*) XDF dropouts



Chevallard+17b

- 50 % completeness magnitude between ~ 29.3 (F105W filter, I dropouts) to ~ 29.7 (F160W filter, Y dropouts)

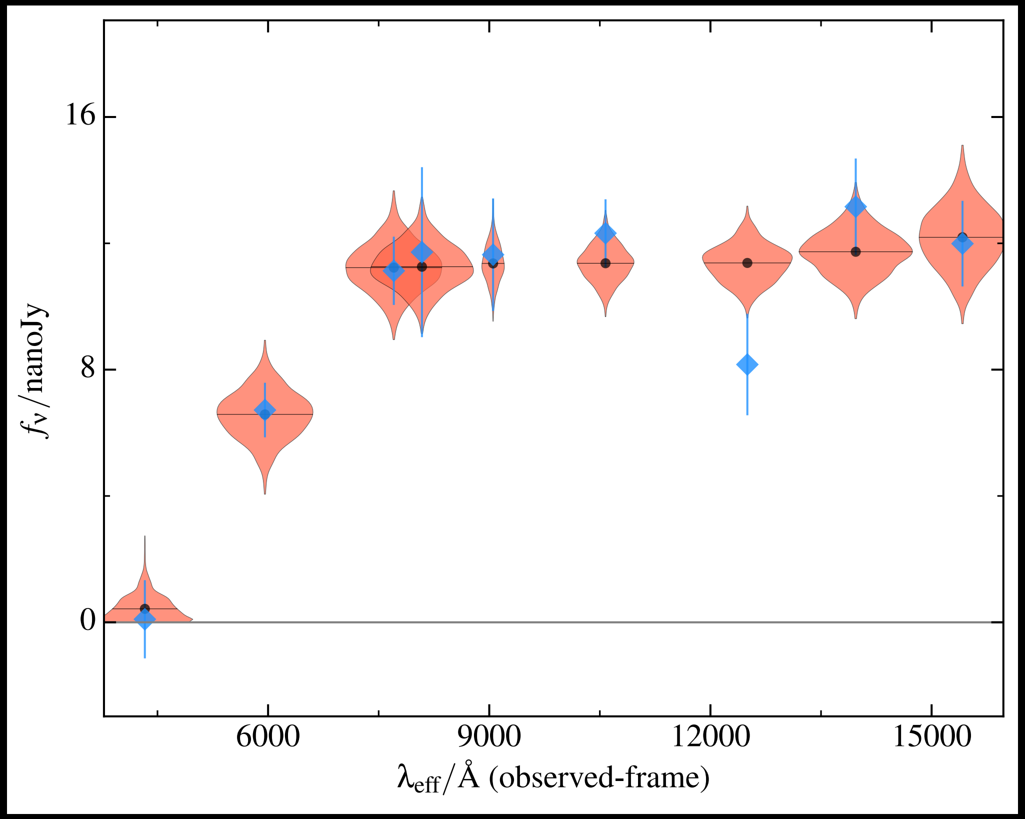


— stacked *pdf* (BEAGLE analysis)

- - - Bouwens+2015 redshift distribution

(BEAGLE) SED fitting to XDF dropouts

- Want to explore a wide range of intrinsic galaxy SEDs
- Adopting a flexible, 9-parameters model to fit HST photometry with BEAGLE
  - **stellar + nebular** (continuum and lines) emission
  - **2-component SFH** (delated exponential + 10 Myr burst)
  - tot. stellar mass and mass in “current” SF burst are degenerate
  - parameters controlling emission lines are largely unconstrained



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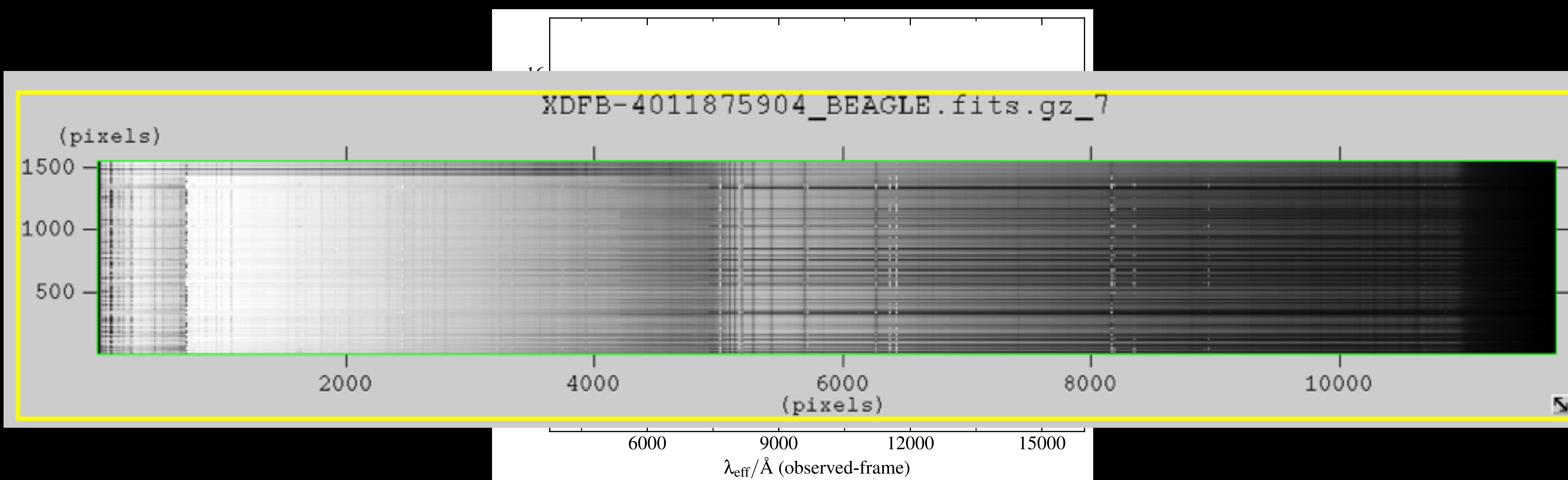
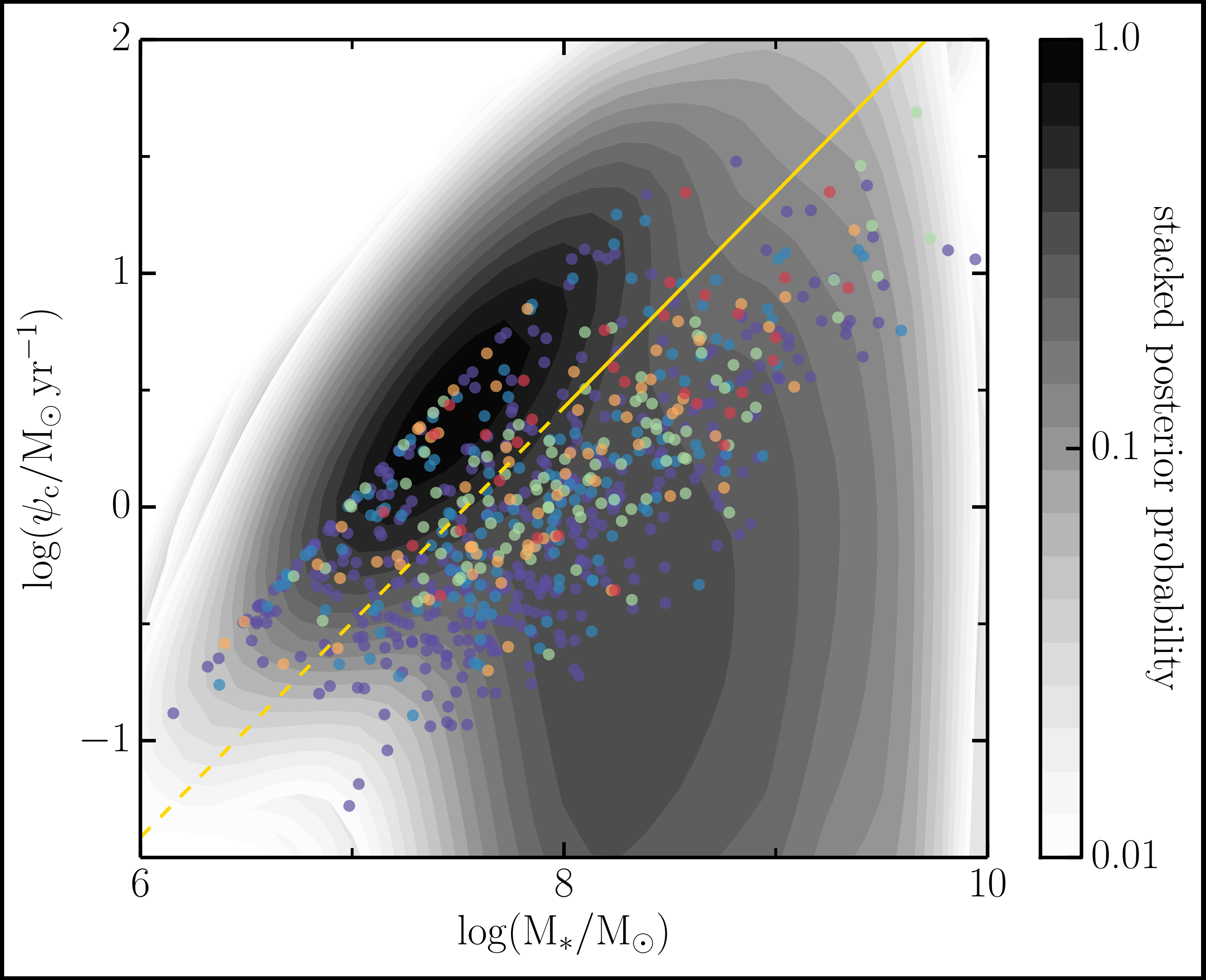


Associating model SED to XDF sources

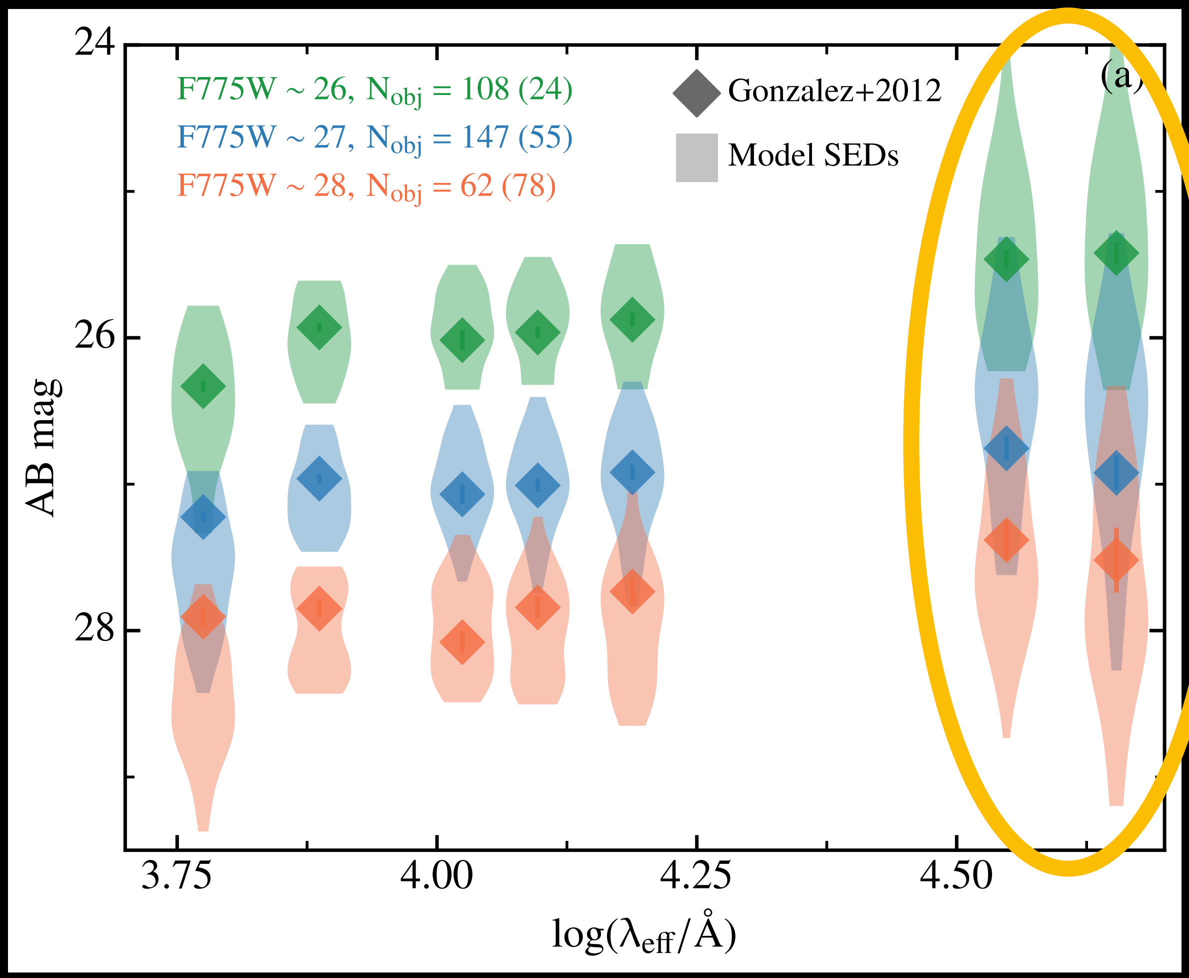
Santini+2017 HST Frontier Fields

Santini+2017 extrapolation

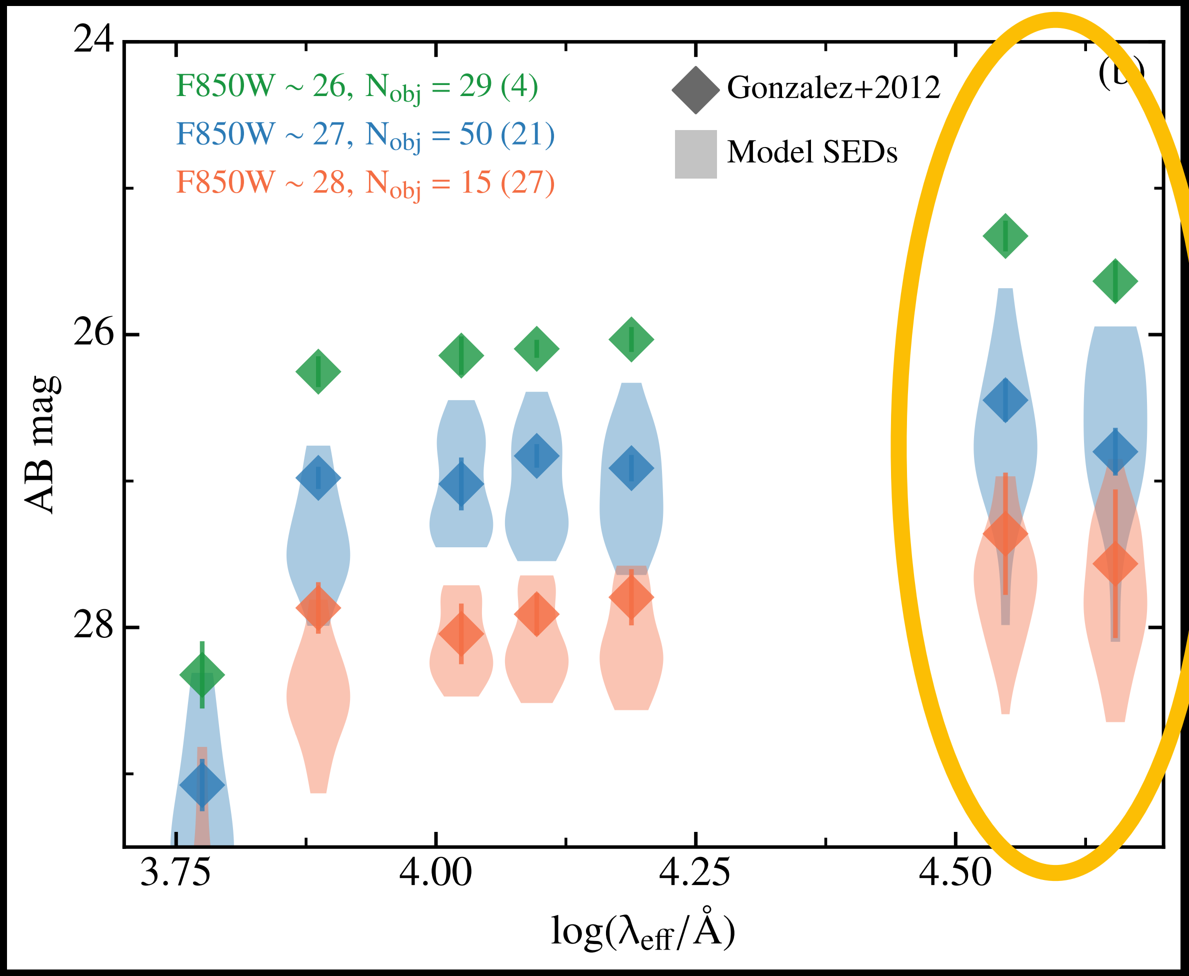
- Stacked *pdf* shows degeneracy between stellar mass and burst mass
- Burst mass (i.e., SFR) sets relative strength of continuum vs EL
- Impose model SEDs to follow mass-SFR relation (with scatter) from Speagle+2014



Comparing model SEDs with indep. data

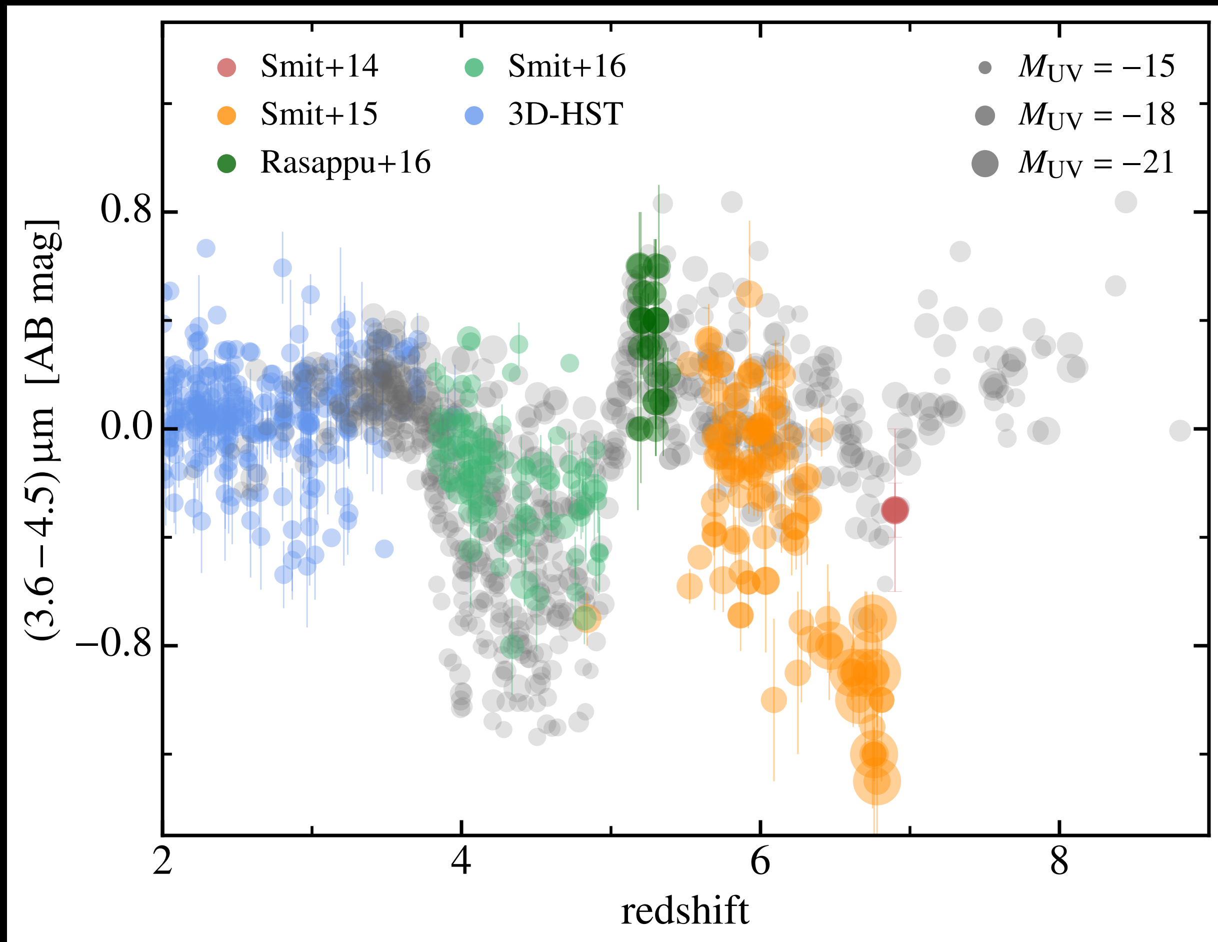


- Stacked SEDs from Gonzalez +2012
- HST + IRAC photometry of sources in GOODS-S



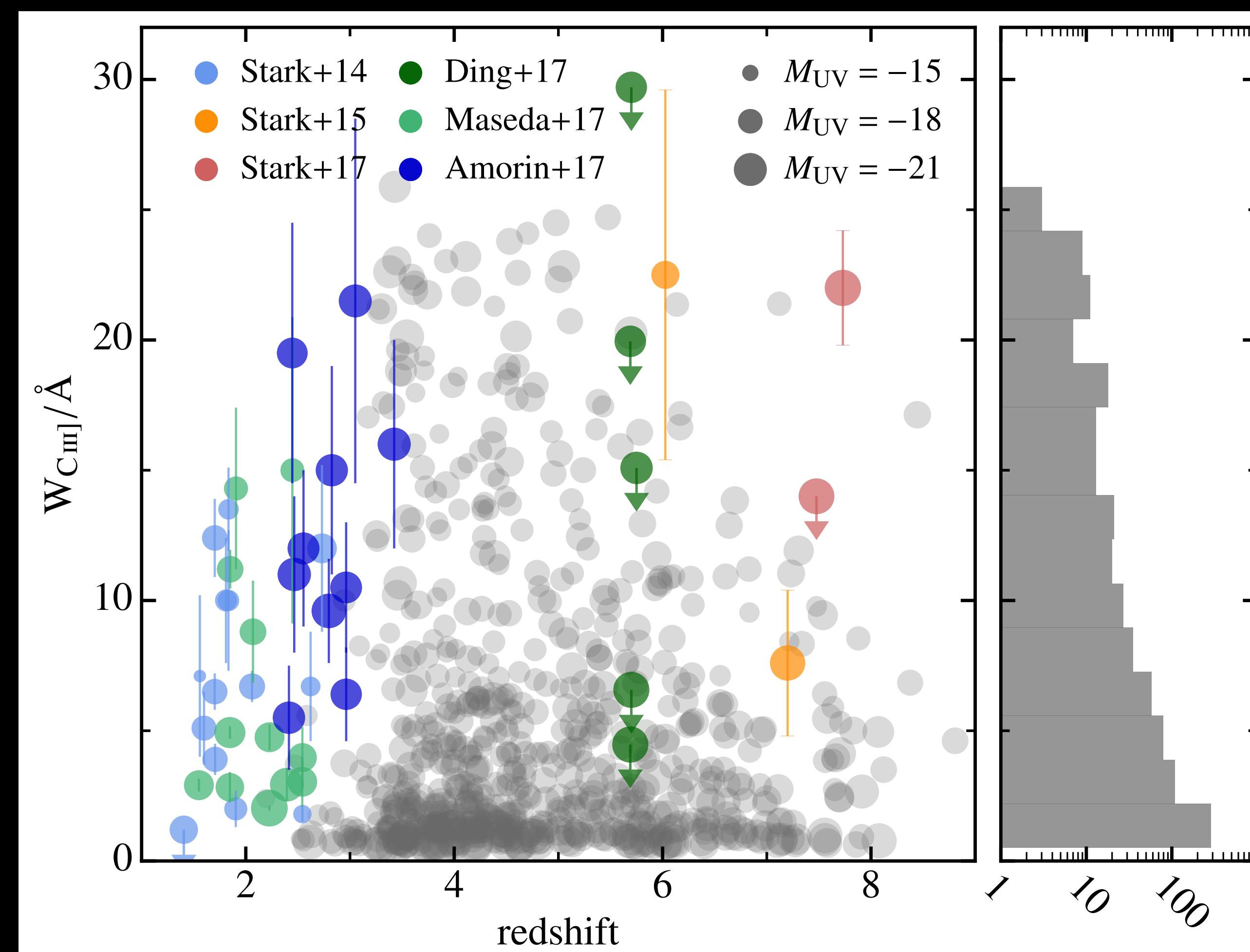
- IRAC fluxes predicted with our approach in good agreement with stacked SEDs

Comparing model SEDs with EL constraints



Chevallard+17b

- Redshift evolution of 3.6-4.5 micron colours related to EL EWs
- Model can match extreme IRAC colours, except for bluest (massive, rare) objects at z~7



- Model SEDs cover wide range of CIII] 1907,1909 EWs, including extreme (EW~20) CIII] emitters observed

Simulating NIRSpec observations

- Assume "prototypical" deep observation of high-*z* galaxies
- Low-resolution (R~100) prism, 100 ks exposure time
- Account for aperture losses of extended source from MSA array

Simulating NIRSpec observations

- Assume “protot galaxies
- Low-resolution me
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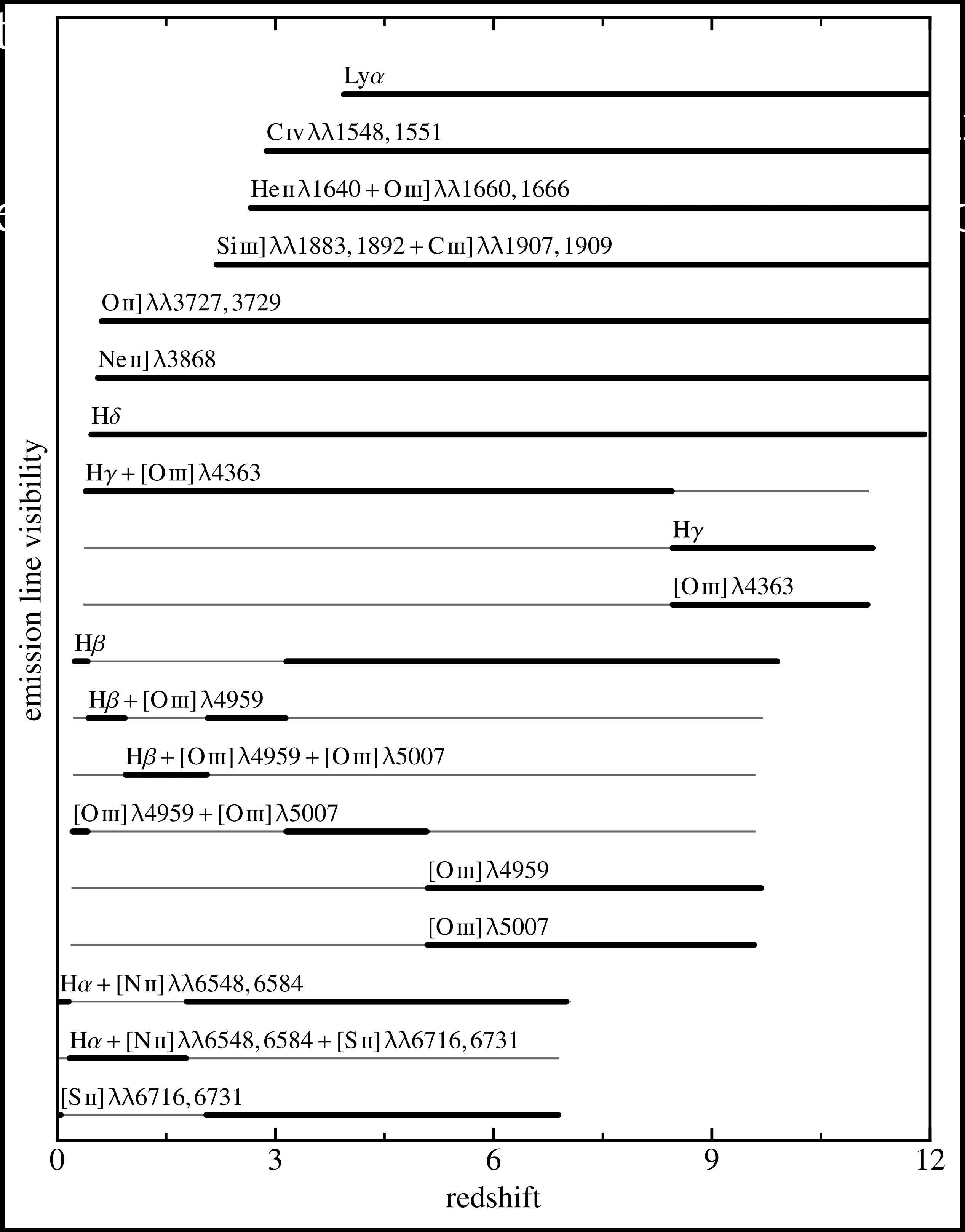
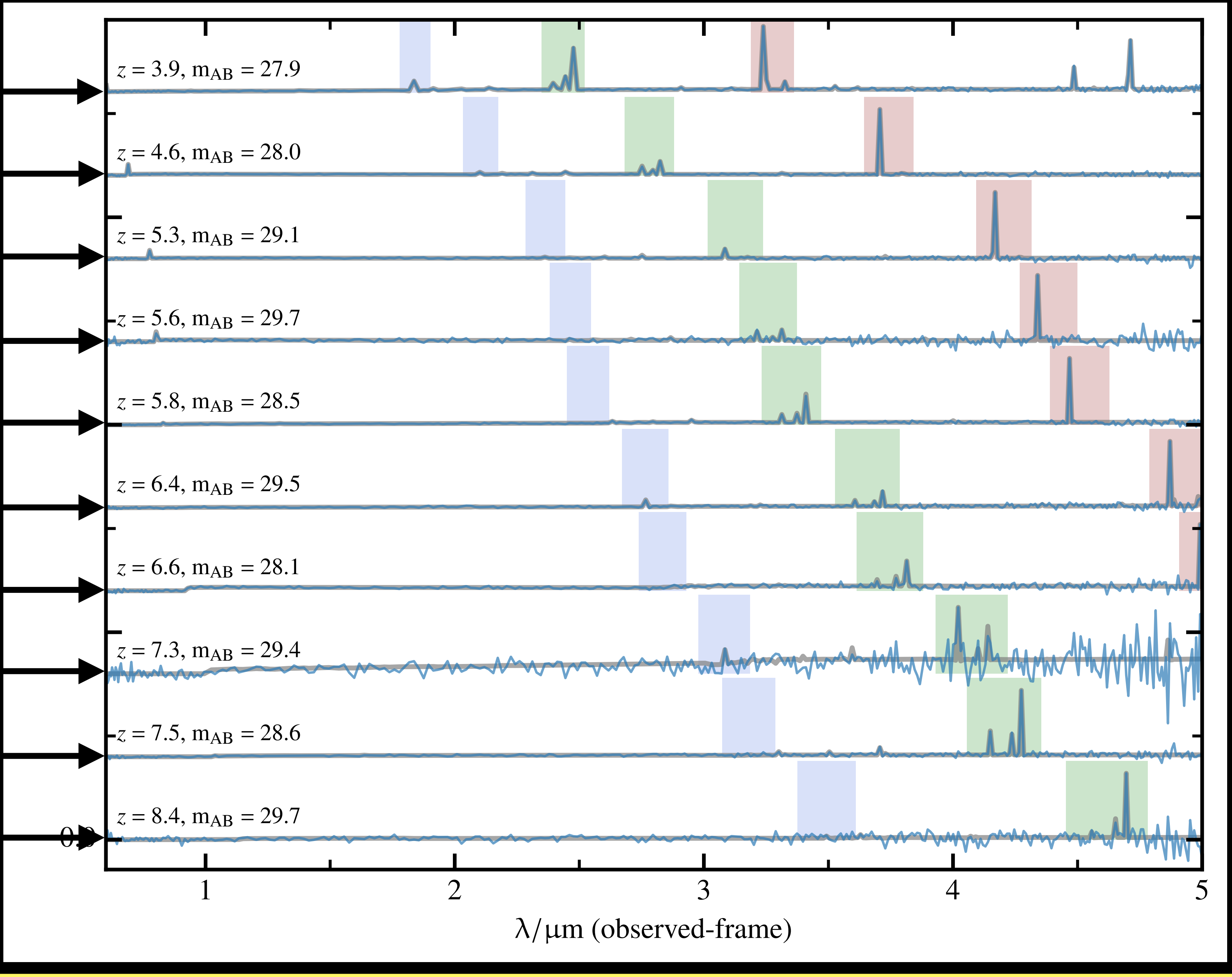


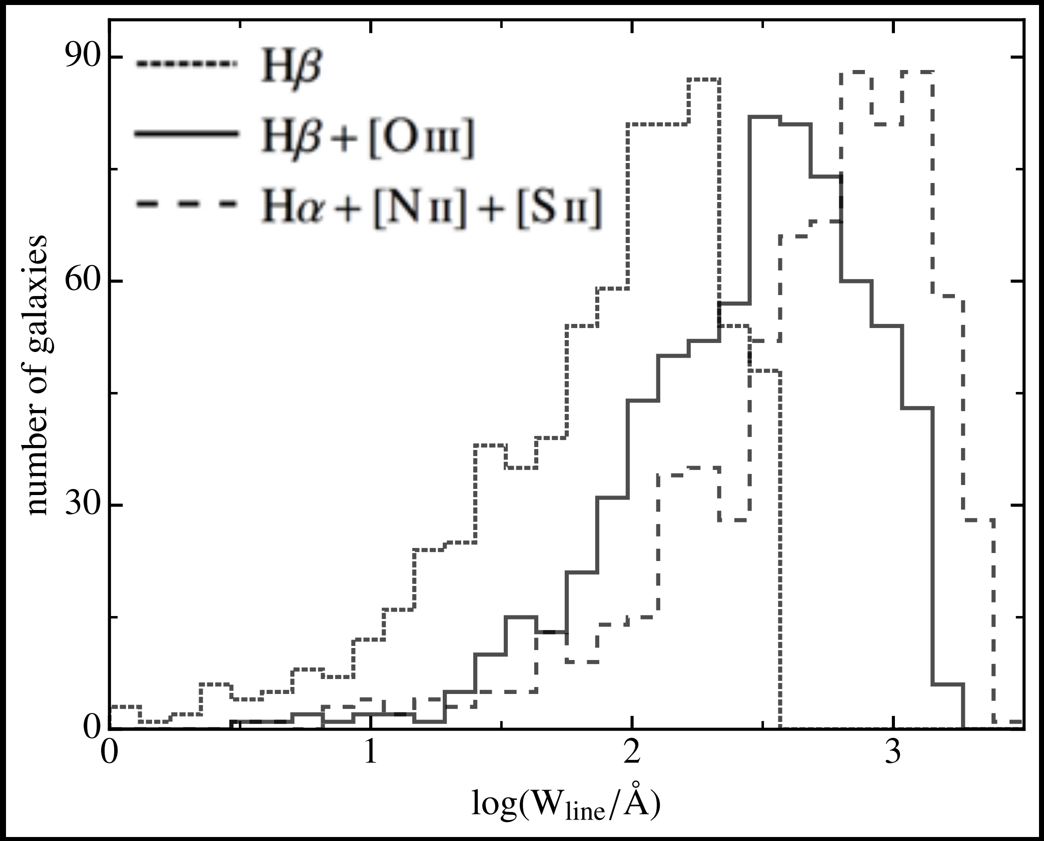
Simulating NIRSpec observations

- Assume "prototypical" deep observation of high-*z* galaxies
- Low-resolution (R~100) prism, 100 ks exposure time
- Account for aperture losses of extended source from MSA array

z=3.9, m_{AB}=27.9
z=4.6, m_{AB}=28.0
z=5.3, m_{AB}=29.1
z=5.6, m_{AB}=29.7
z=5.8, m_{AB}=28.5
z=6.4, m_{AB}=29.5
z=6.6, m_{AB}=28.1
z=7.3, m_{AB}=29.4
z=7.5, m_{AB}=28.6
z=8.4, m_{AB}=29.7

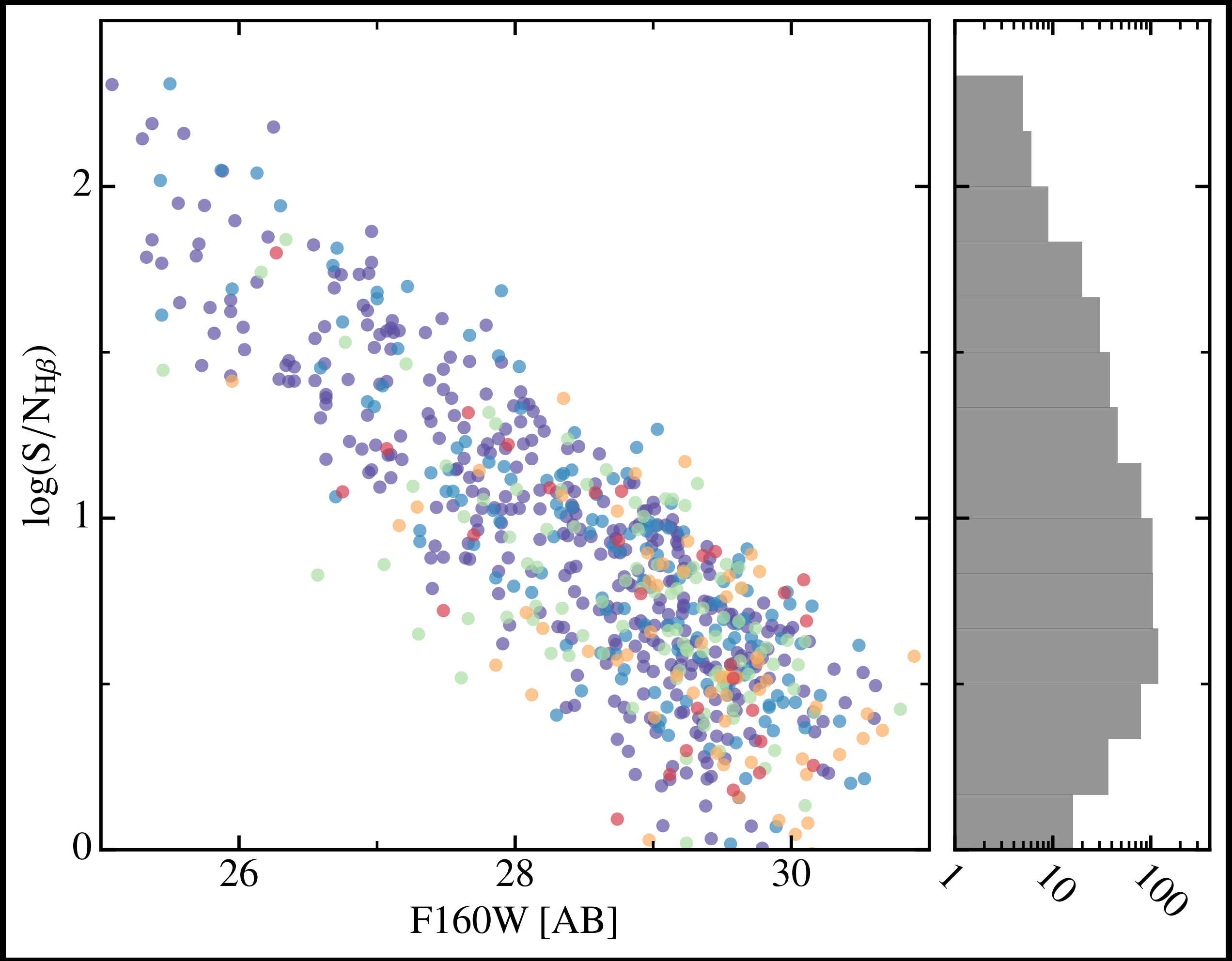


Characteristics of simulated observations



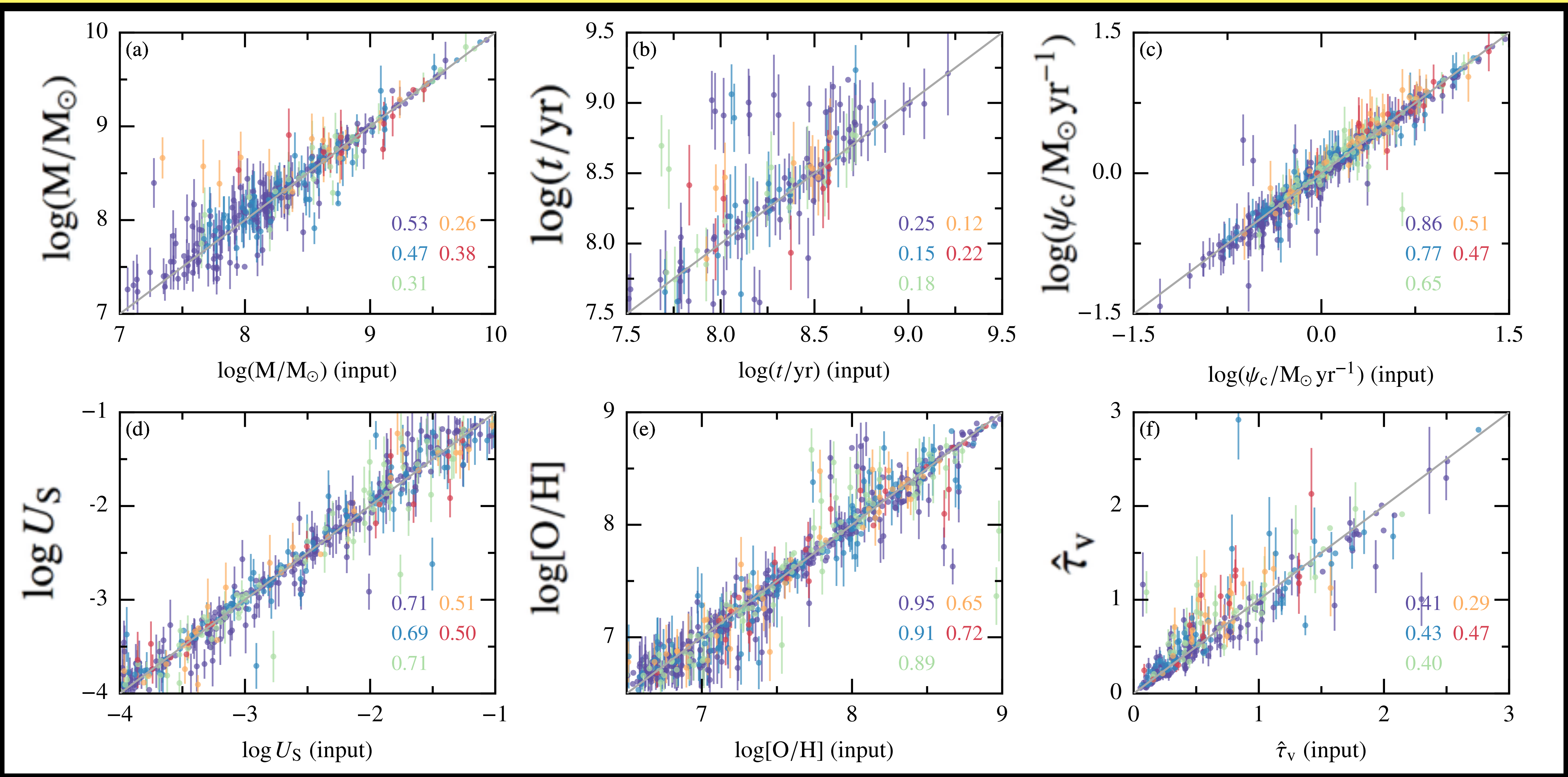
- Mean (median) EW of Hα+[NII]+[SII] ~450 Å (~600 Å)
- Smit+2016 find ~ 400 Å at z ~ 3.8 - 5.0
- Rasappu+2016 ~ 550 Å at z ~ 5.1 - 5.4

- >50 % of galaxies with m_{AB}<29.5 should show S/N
  - Hβ > 5
  - Hα > 20
  - [OIII]5007 > 22
- ~30 % of m_{AB}>30 sources should exhibit S/N(Hβ)>3



Chevallard+17b

Constraining galaxy physical parameters

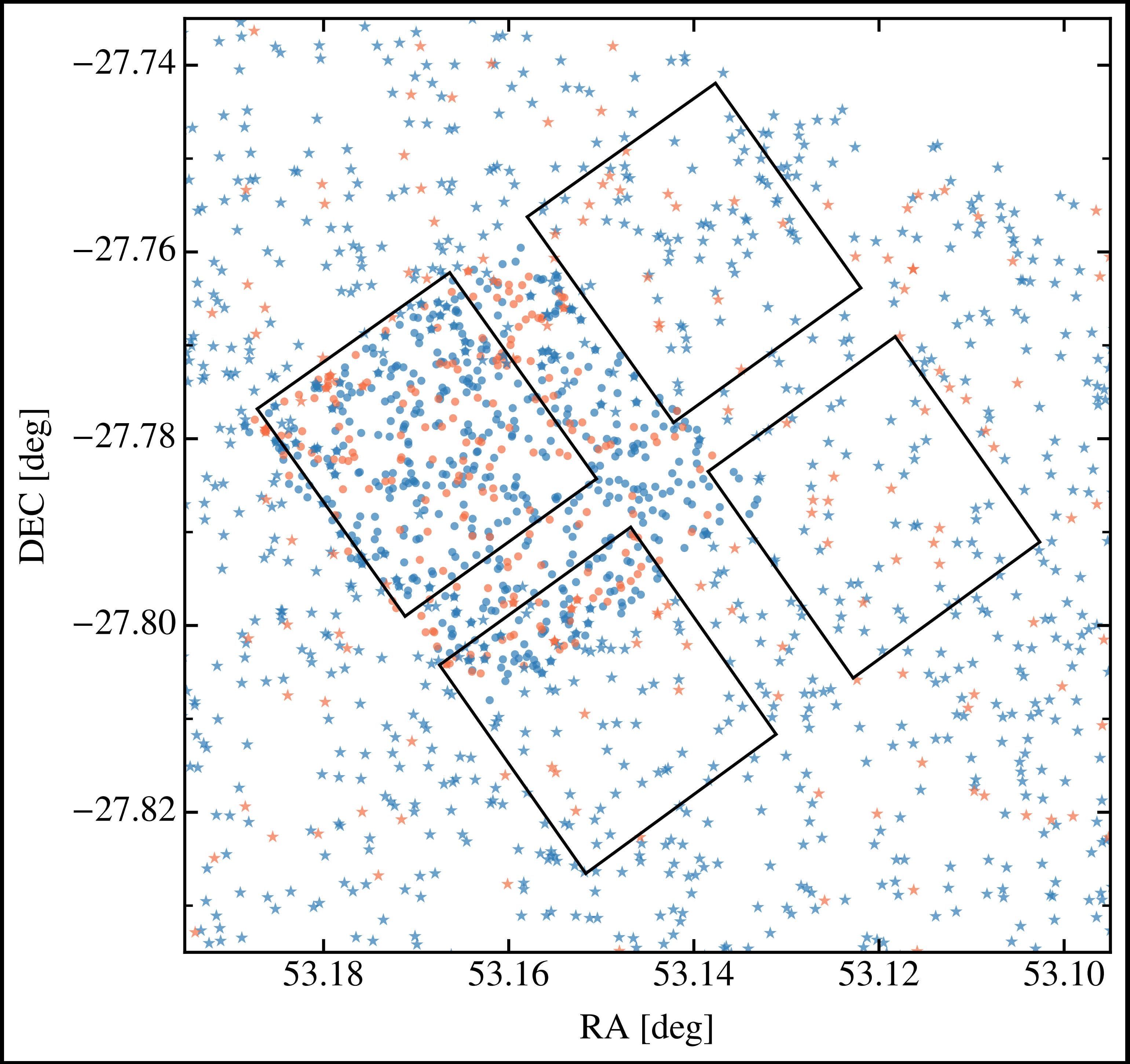


- $\log \psi_c$, $\log U_s$, $\log[O/H]$ constrained within a factor of ~ 1.5
- $\log M/L$ within a factor of ~ 2,
- $\log t$ within a factor of ~ 3
- $\hat{\tau}_V$ with a precision of ~ 0.3

A NIRSpec pointing in the XDF

★ z ~ 4-6
★ z > 6
★ CANDELS GOODS-S
● XDF

- Number of high-z targets in single pointing mainly depends on their on-sky density
- Within XDF, we expect
  - ~20 galaxies at $z > 6$
  - ~15 at z=4-6
- Within GOODS-S
  - ~10 at $z > 6$
  - ~50 at z=4-6
- ~100 slitlet used for lower z targets



Summary

- UV and optical **emission lines +** state-of-the-art **models** and tools to probe **physical properties** of galaxies across widest range of redshift and masses
- Measuring SFRs, abundances, gas properties enables tight constraints on **physical processes** acting in galaxies
- Crucial to test/**calibrate** our models with **low redshift** data
- UV lines sub-optimal to measure galaxy properties, but **currently** limited to **optical lines at** $z<4$ (for bright galaxies)
- JWST/**NIRSpec** to probe optical lines out to $z > 10$
- A **deep** (100 ks) NIRSpec/prism **pointing** to measure SFR, dust, log(O/H), ionized-gas properties for **~100 galaxies at** $z>4$