Modeling and interpreting the SEDs of galaxies with BEAGLE in the era of NIRSpec-JWST

Jacopo Chevallard

Postdoctoral Research Fellow @ ESA-ESTEC

http://www.jacopochevallard.org/beagle/

arXiv 1603.03037

Collaborators

- S. Charlot
- J. Gutkin (PhD)
- A. Vidal (PhD)
- A. Feltre
- E. Curtis-Lake
- M. Hirschmann
- A. Wofford
- D. Stenning

- P. Ferruit
- G. Giardino

- P. Coelho

- M. Franx

- J. Blaizot
- L. Michel-Dansac

- C. Pacifici

Outline

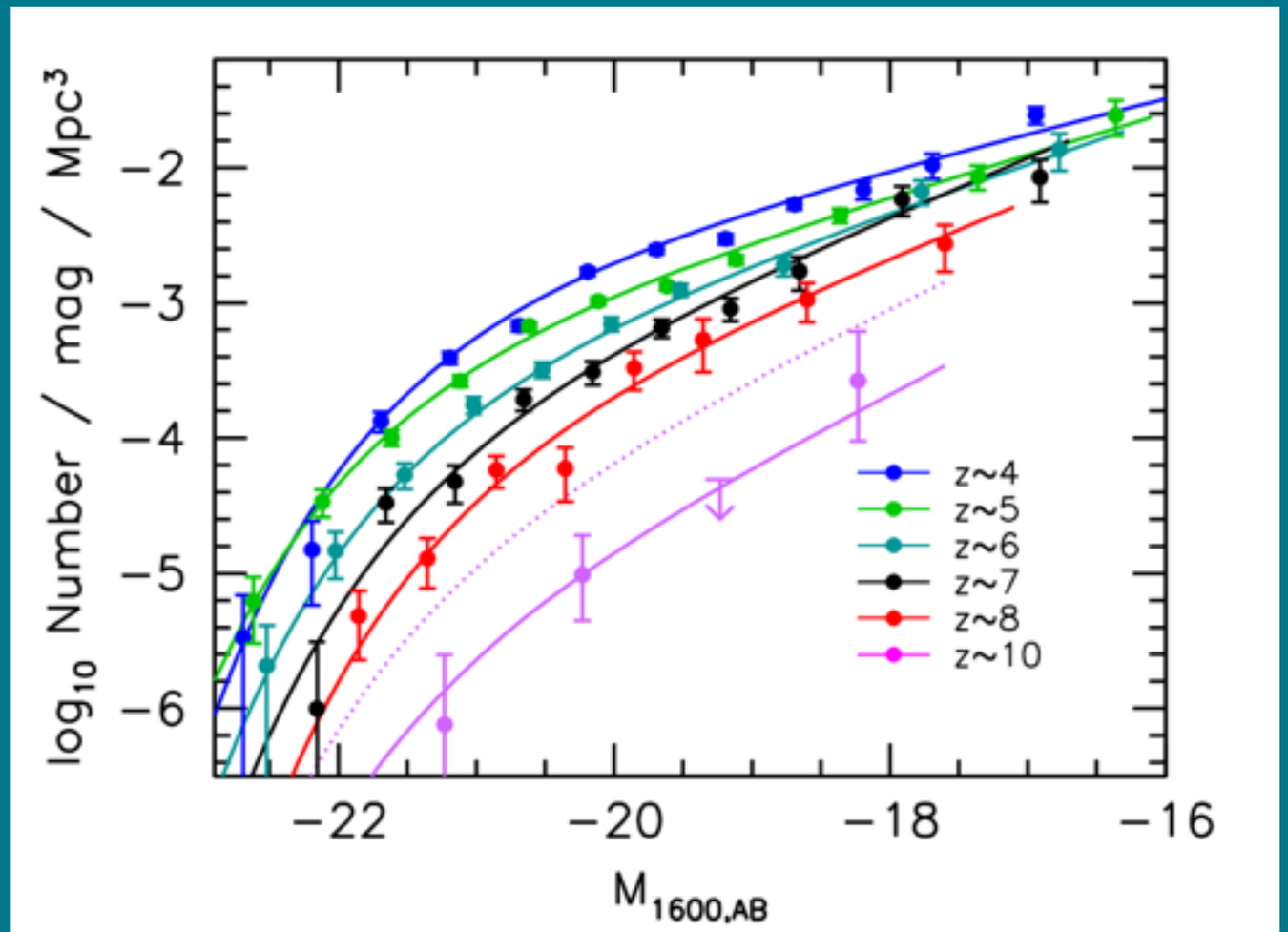
1) JWST, early galaxies and cosmic reionization

2) BEAGLE: a new analysis framework for galaxy SEDs

3) Broad-band SED fitting with BEAGLE

4) Simulating JWST/NIRSpec observations

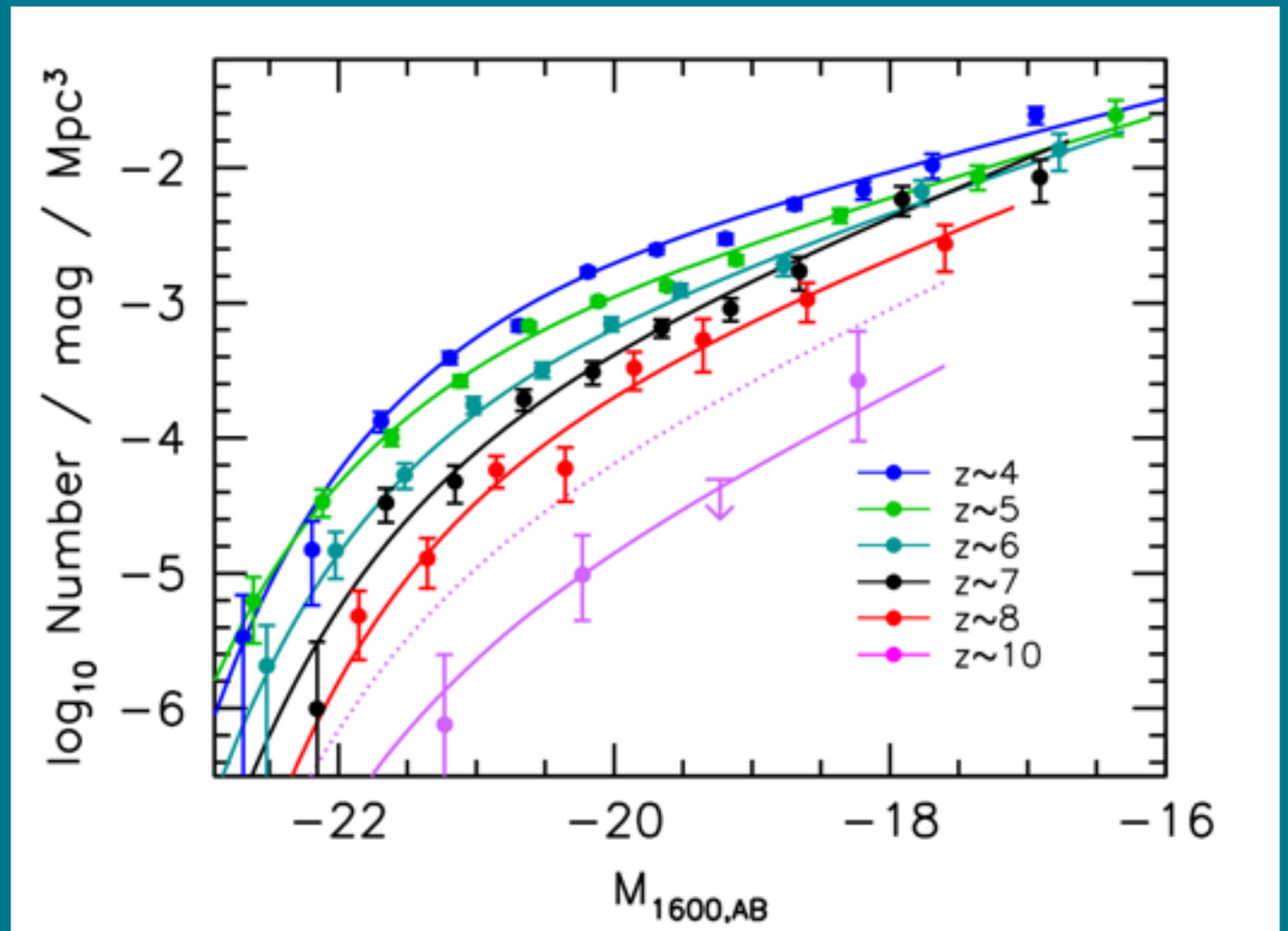
Observational constraints on high-z galaxies



Bouwens+15

Observational constraints on high-z galaxies

- Large samples of high-z galaxy **candidates** assembled by means of deep **photometric surveys** (e.g. Oesch+14, Bouwens+15, Atek+15, Finkelstein+15, McLeod+15, Livermore+16)



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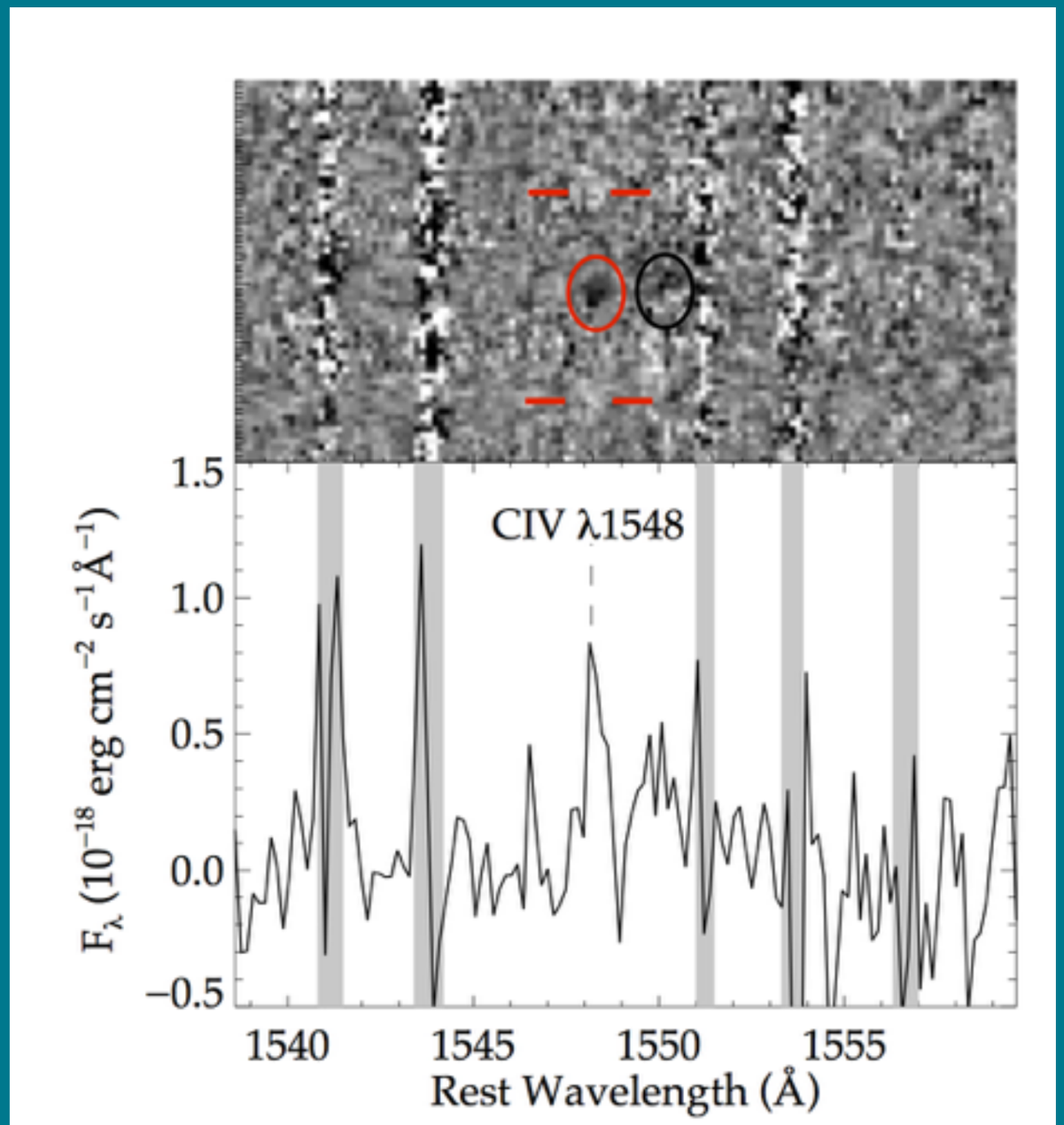
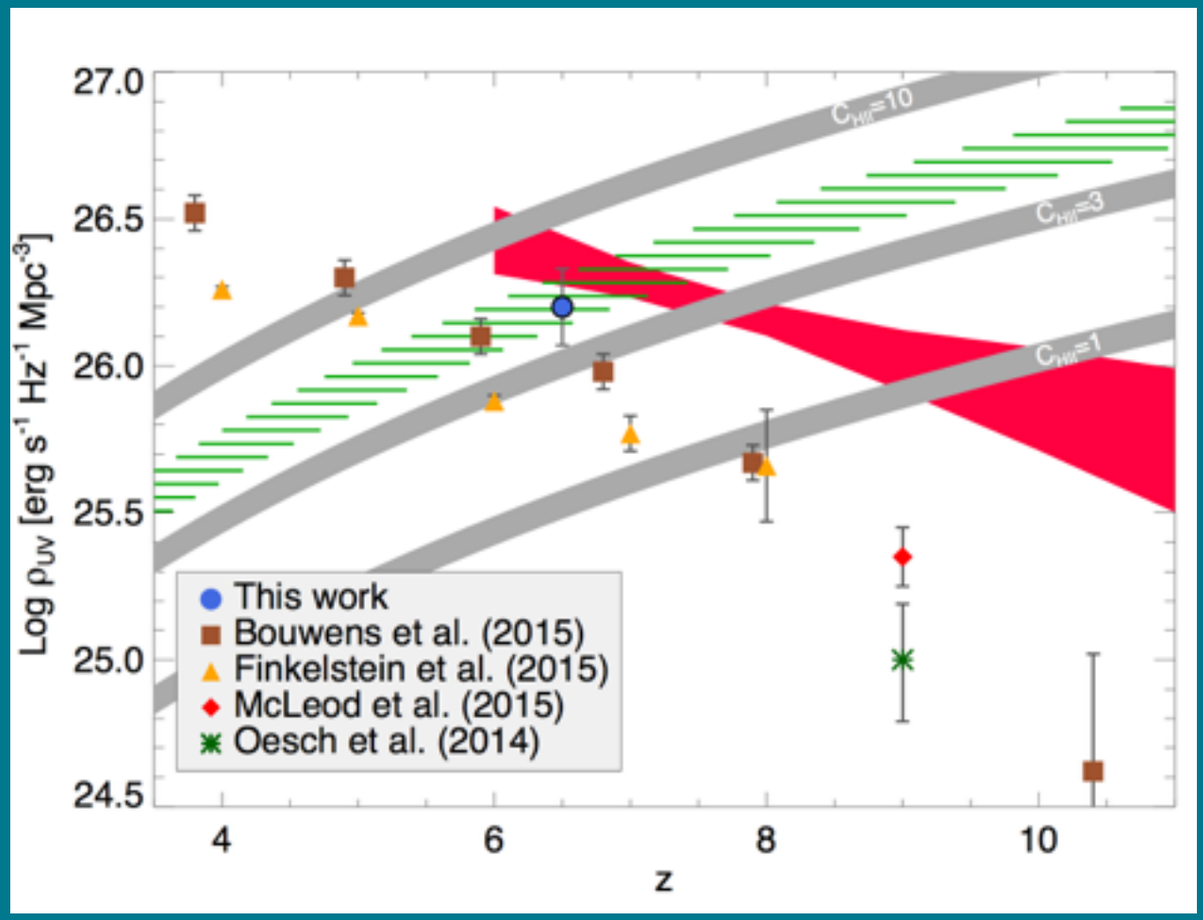
- **Spectroscopic characterisation** of these galaxies still limited (e.g. Pentericci+11, Roberts-Borsani +15, Stark+15;16, Zitrin+15, Oesch+16), because of **challenges** of ground-based NIR spectroscopy



Stark+15

Cosmic reionization and high-z galaxies

- Faint end of high-z UV LF: low-mass **SF galaxies** can provide **enough H-ionizing** photons (e.g. Robertson+15, Atek+15, Bouwens+15)
- This depends on several **assumptions**:
  - **minimum UV magnitude** of high-z galaxies,
  - and their **ionizing emissivity**;
  - **escape fraction** of ionizing photons into ISM;
  - temperature, density and ioniz. fields of IGM ("**clumping factor**").



Atek+15

JWST: a new window to high-z Universe

Large samples of UV-to-optical spectra of high-z galaxies required to understand **cosmic reionization**, but also early **chemical evolution** of galaxies, role of **feedback** processes (AGN, SNe), …

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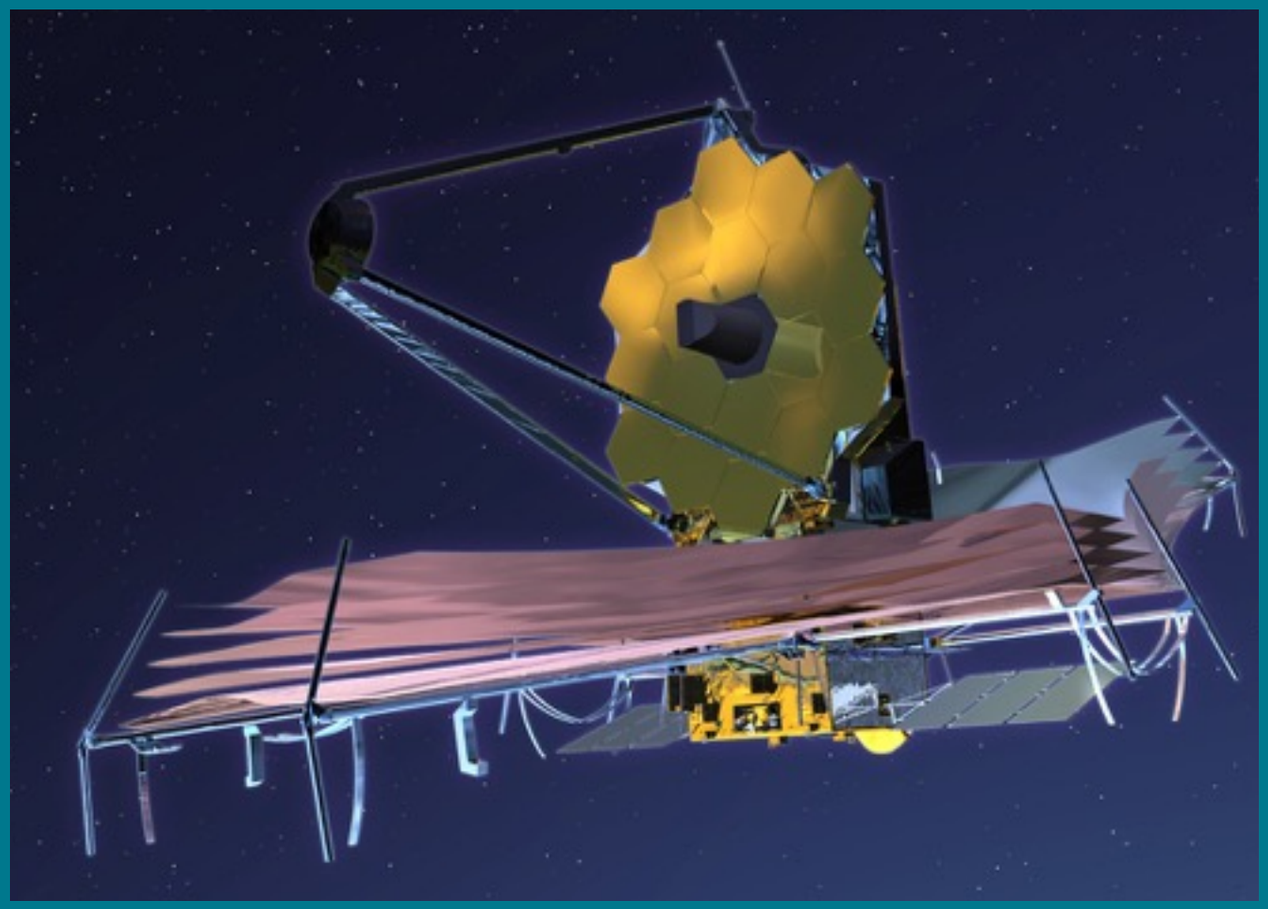
- 6.5 m primary mirror
- **7x HST** collecting **area**
- imaging + spectroscopy in **0.6-28 micron** range



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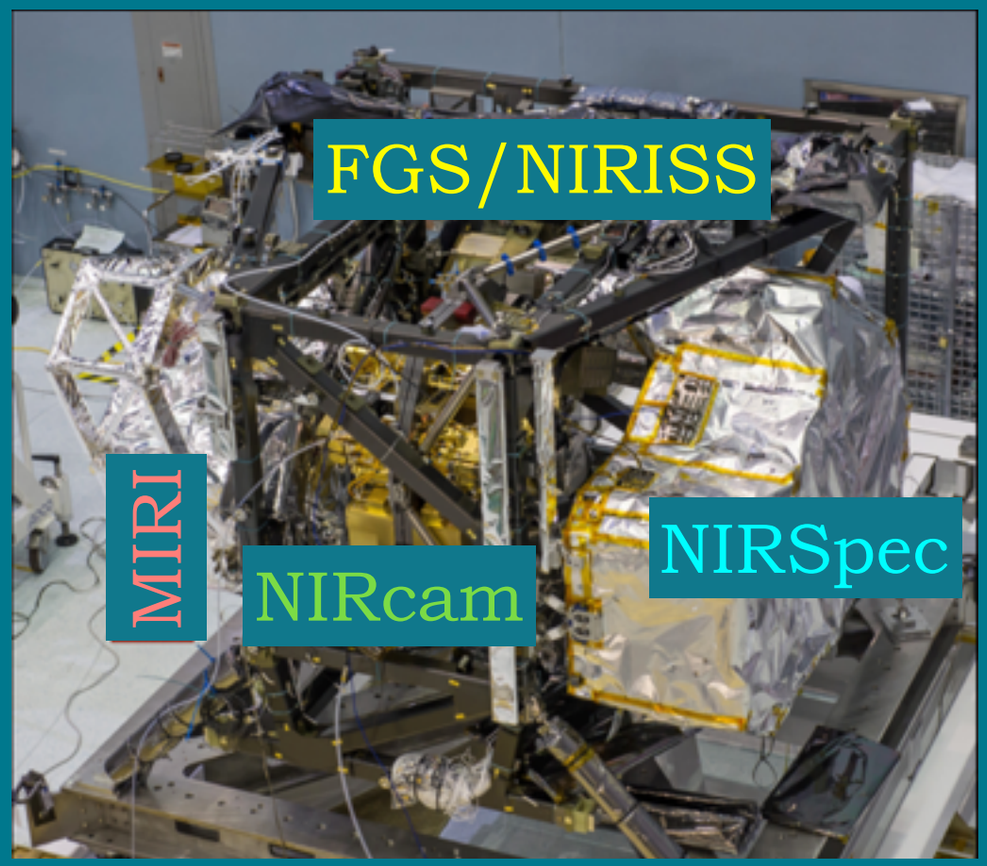
★ wide range of spectroscopic capabilities

★ **low** to **medium** resolution

★ **MOS, IFU** and **single-slit**



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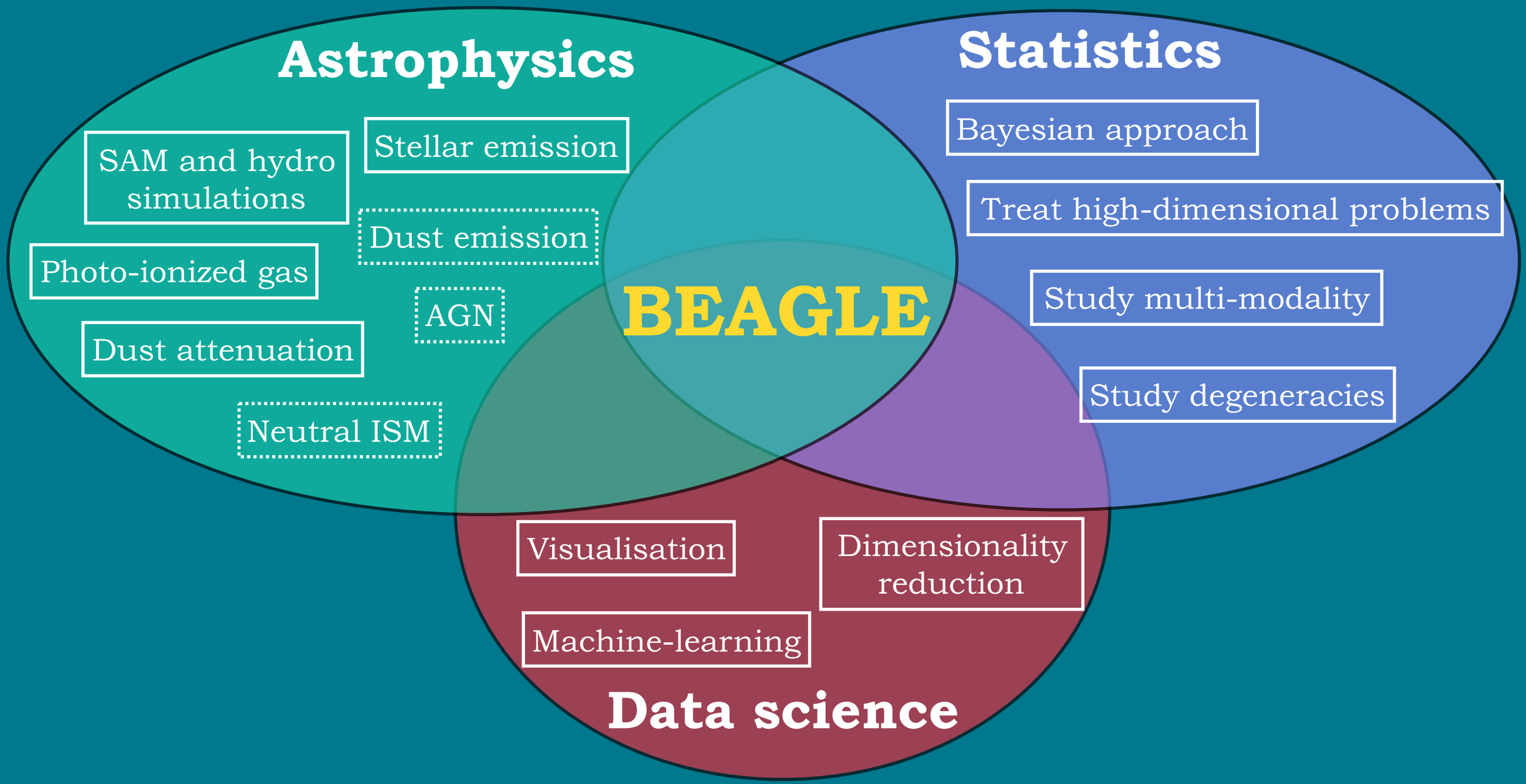
JWST: "**game changer**" for spectroscopic characterization of distant galaxies

Modelling (high-z) galaxies SEDs

- JWST (and ELTs) will provide us with **unique data**
- Need **models** able to cope with these data
- (But our **general approach** can be applied to any spectro-photometric data-set)
- This requires improving SED modelling approaches:
  - include predictions from **galaxy formation models**
  - **treat in a consistent way** different galaxy components (i.e. star, dust, gas, AGN)
  - use of **statistical techniques** able to deal with complex multi-parameters models

The BEAGLE tool



Bay**E**sian **A**nalysis of **G**a**L**axy **sE**ds

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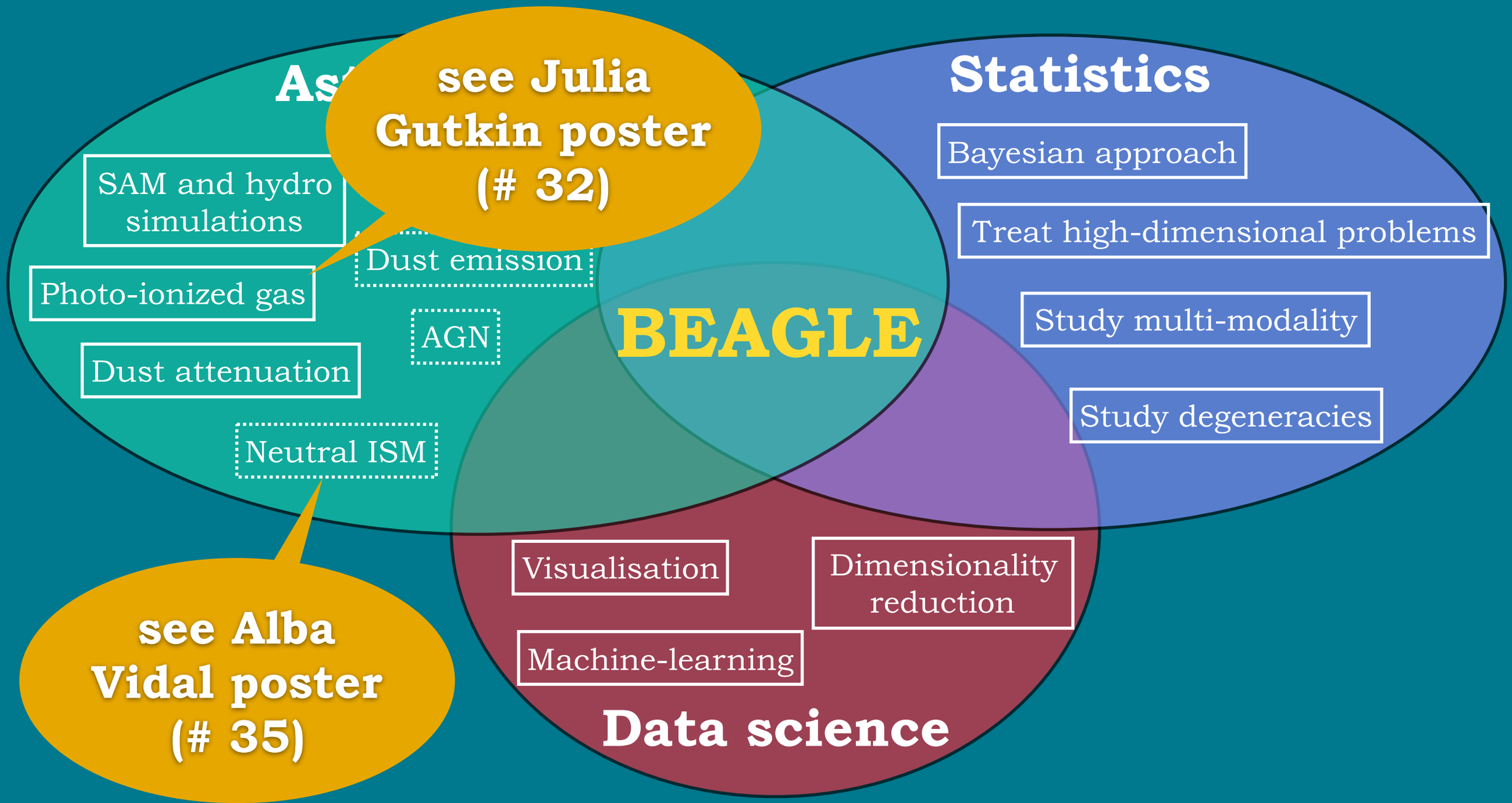

BayEsian Analysis of GaLaxy sEds

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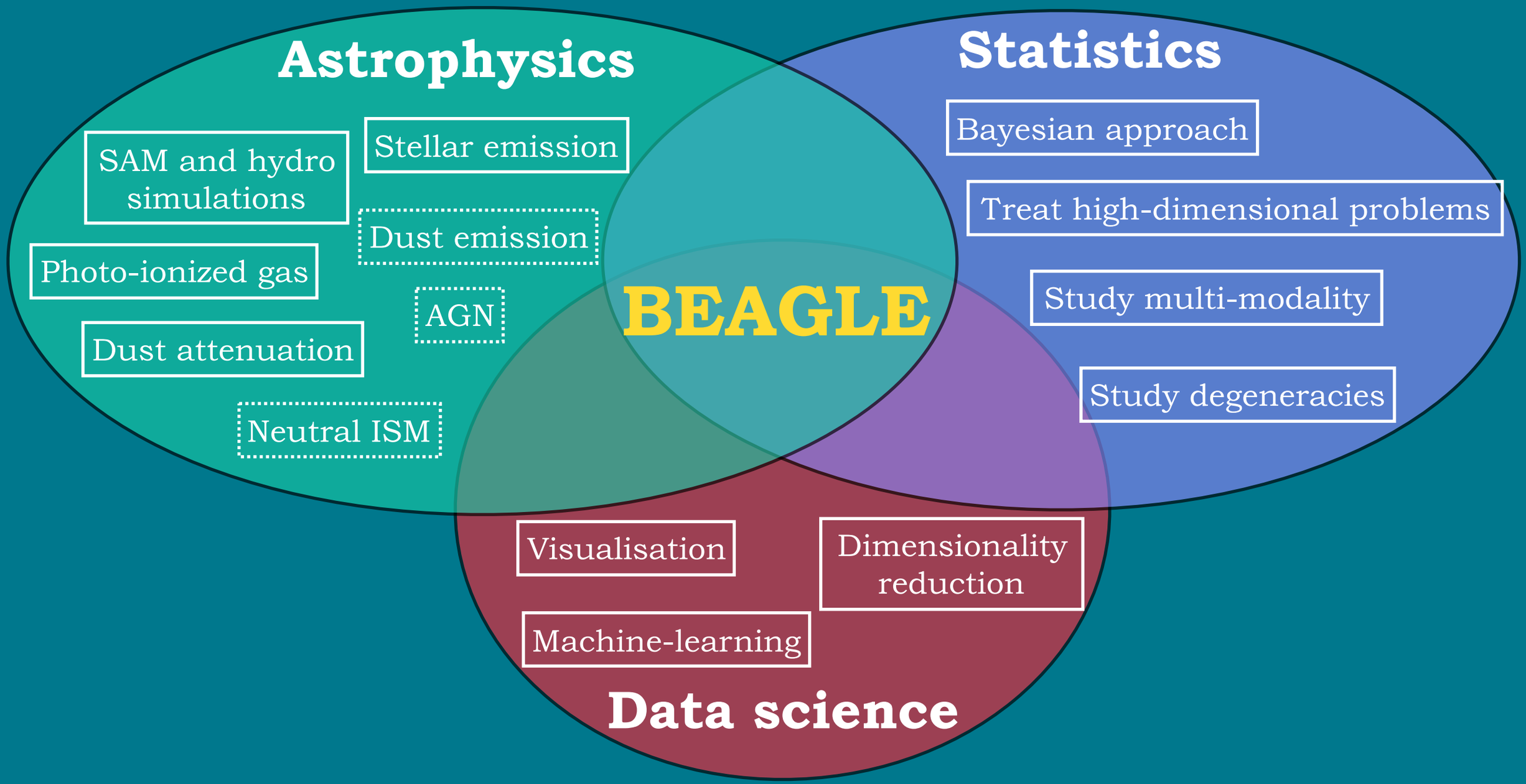

Bay**E**sian **A**nalysis of **G**a**L**axy **sE**ds

Fitting UVUDF photometry

- Used BEAGLE to fit (up to) **12 HST** photometric bands in the **UDF** ("UVUDF" catalogue, Rafelski+2015)
- Physical model adopted:
  - stellar + nebular emission from Gutkin+2016
  - exp. delayed SFH + 10 Myr burst
  - two-components dust attenuation (Chevallard+2013)
  - IGM absorption from Inoue+2014 (similar to Madau+1995)
  - total of 7 free parameters
- Statistical approach (Nested Sampling) can deal with parameter **degeneracies** and **multi-modal solutions**

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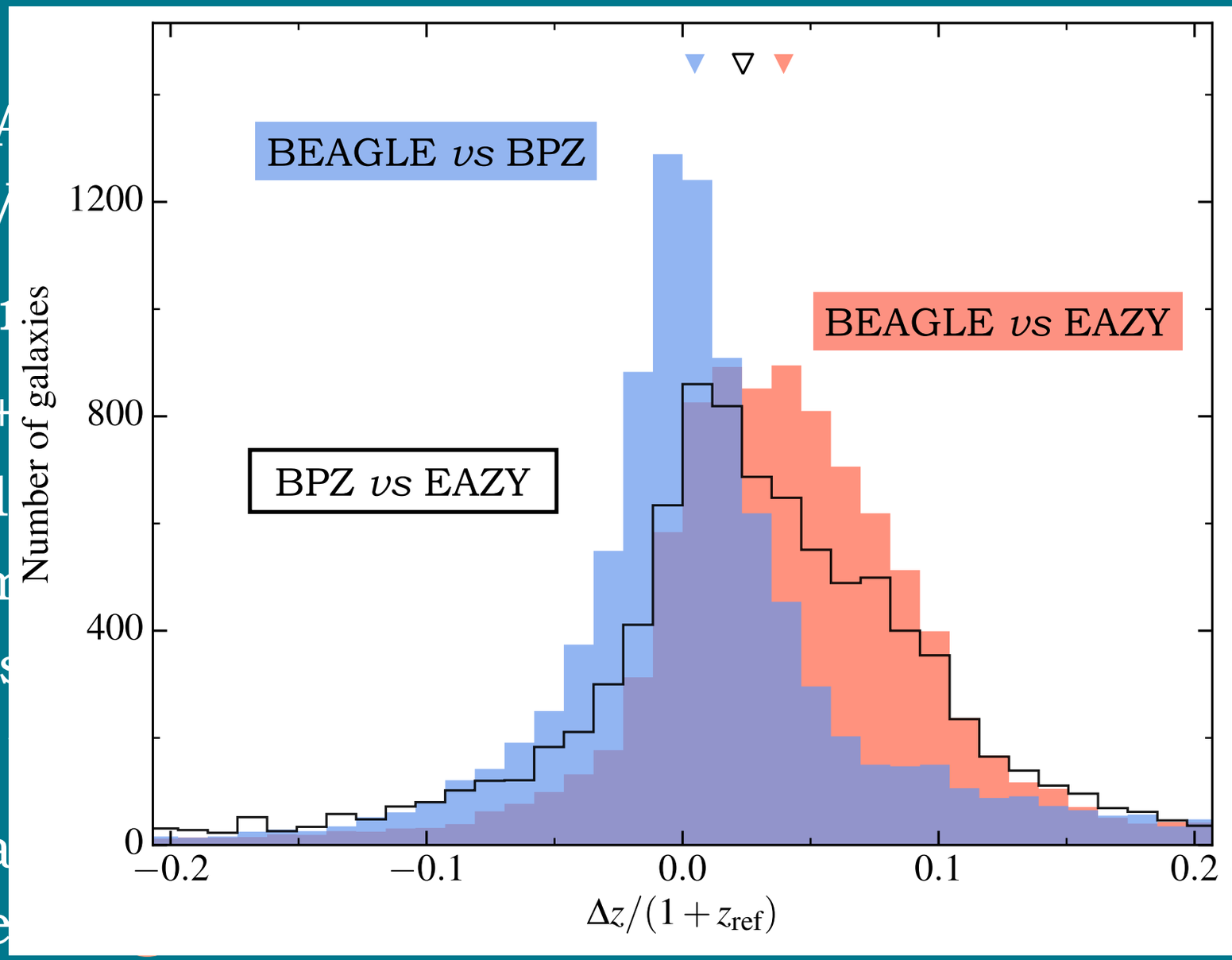
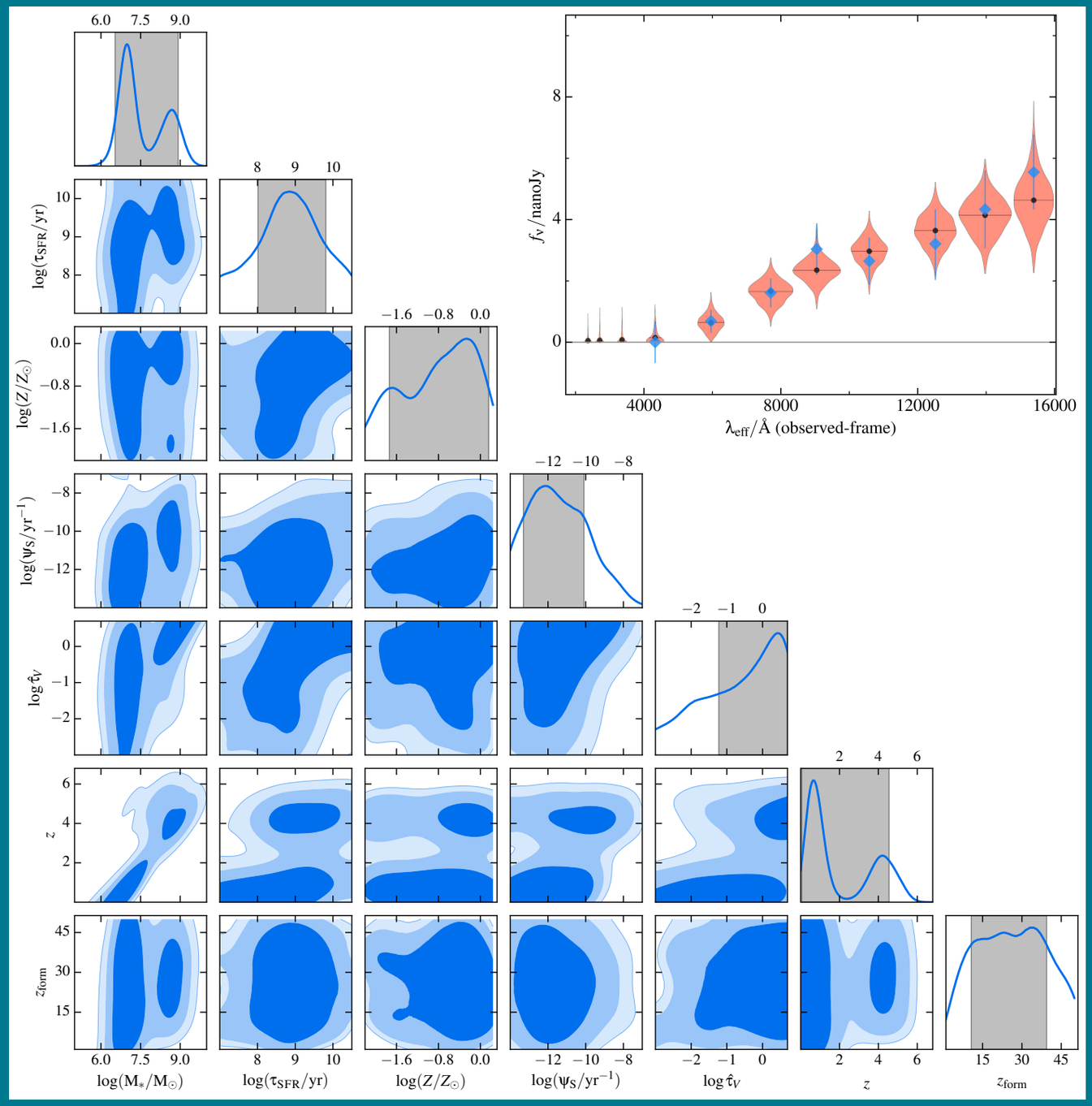


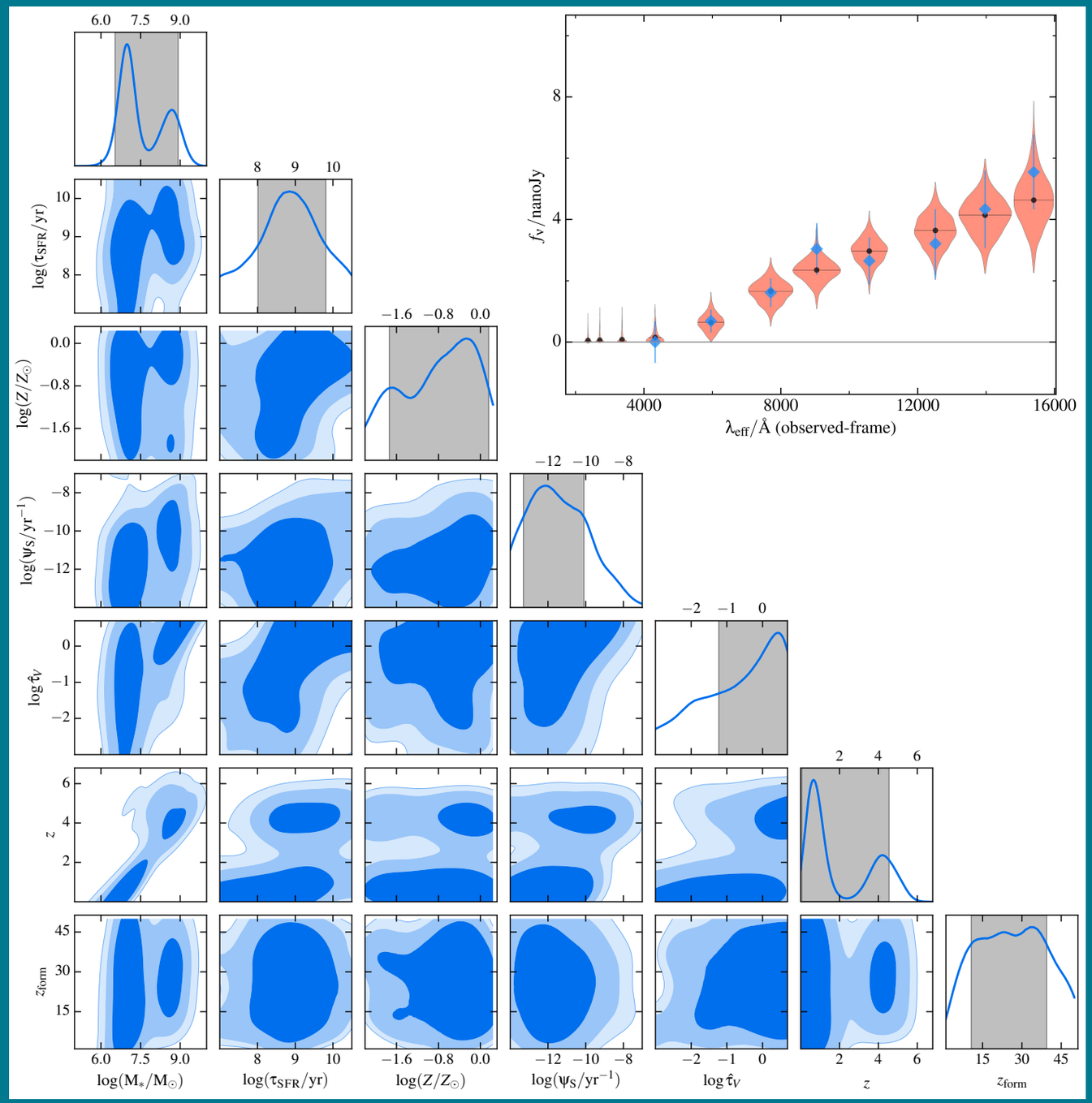
Photo-z estimates statistically consistent

Multiple redshift solutions



Multiple redshift solutions

- BEAGLE provides **posterior PDF** of model parameters
- Allows study of **correlations** between redshift and galaxy physical parameters
- Adopted Bayesian algorithm (**MultiNest**) provides identification of **multiple modes** in the posterior PDF



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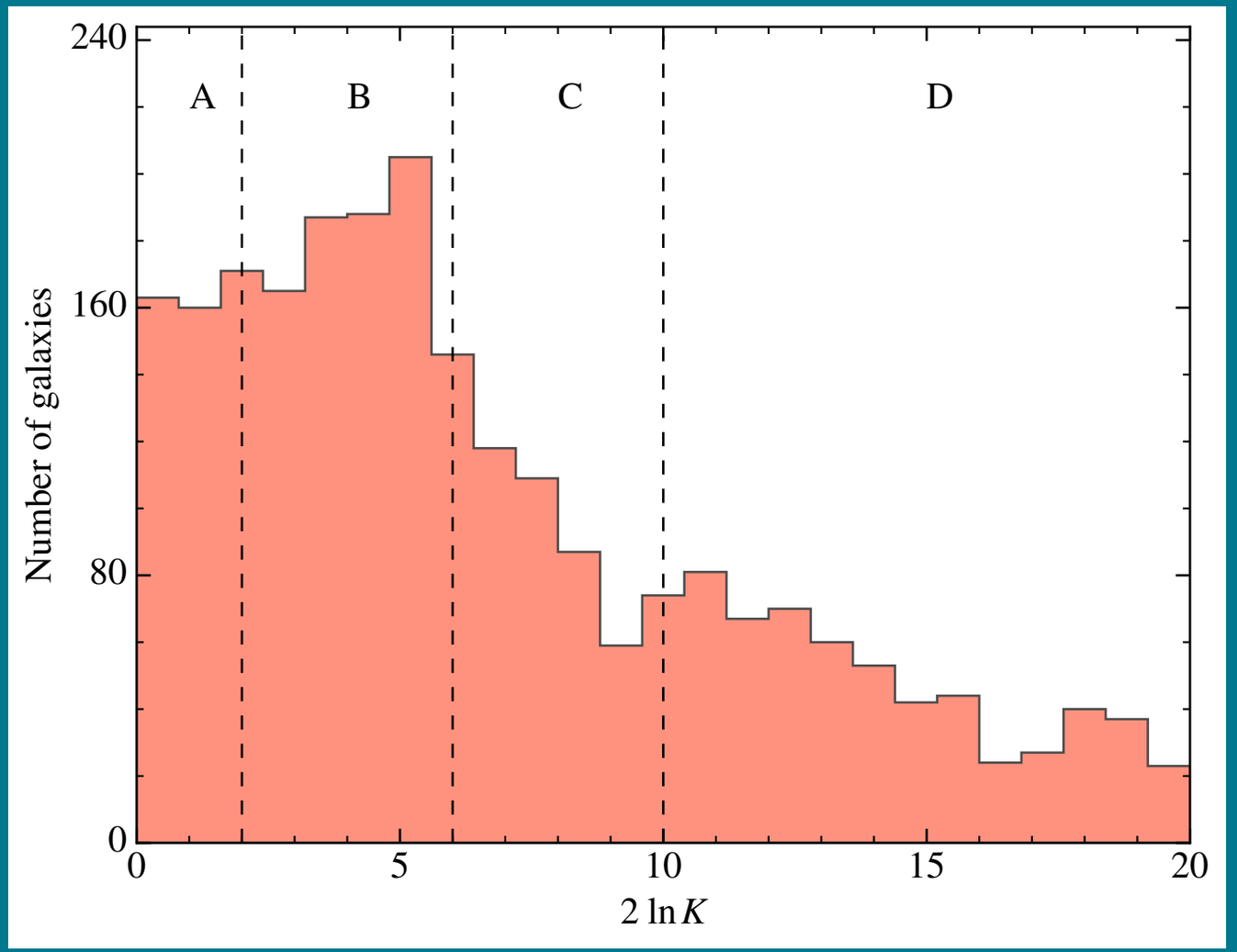

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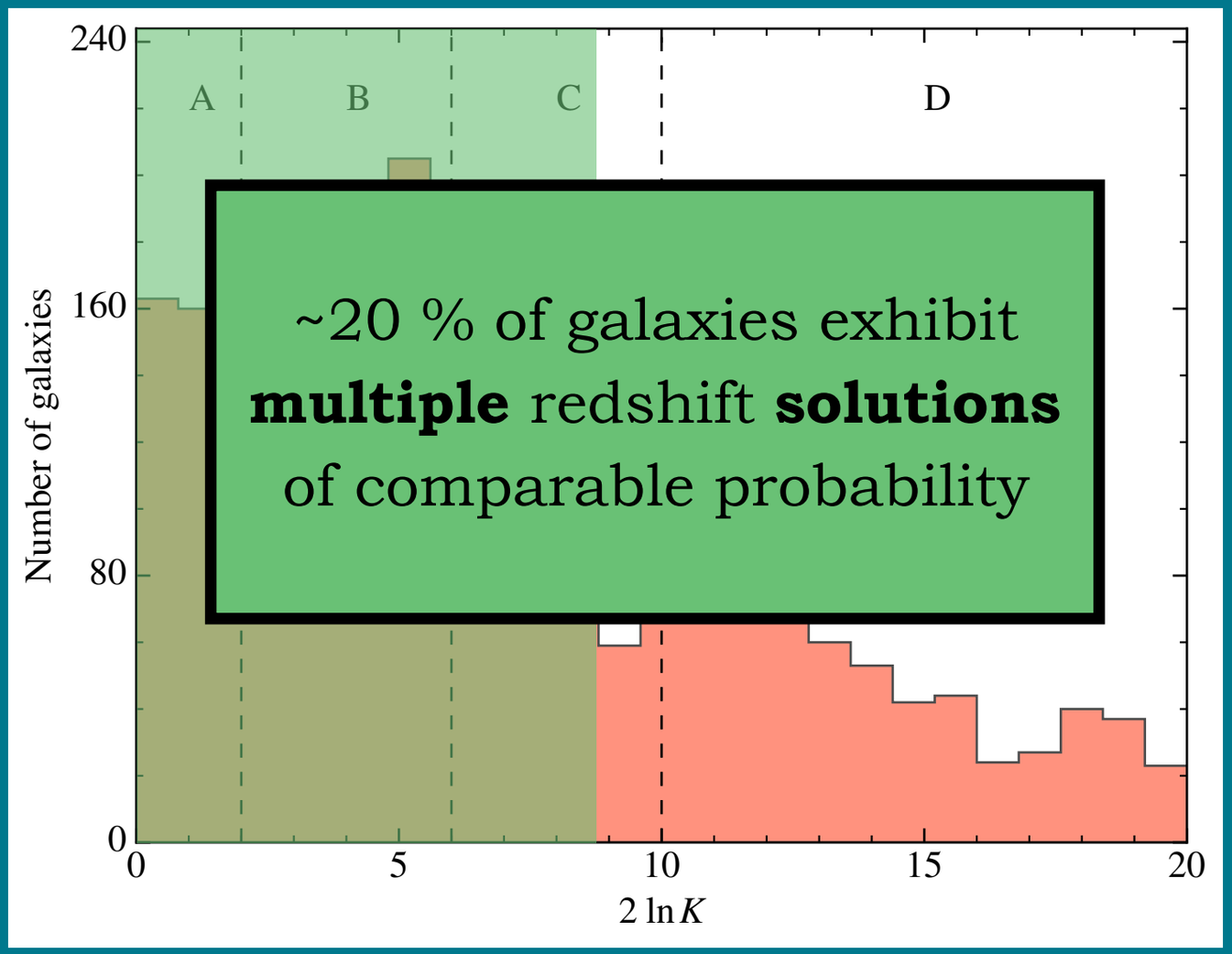
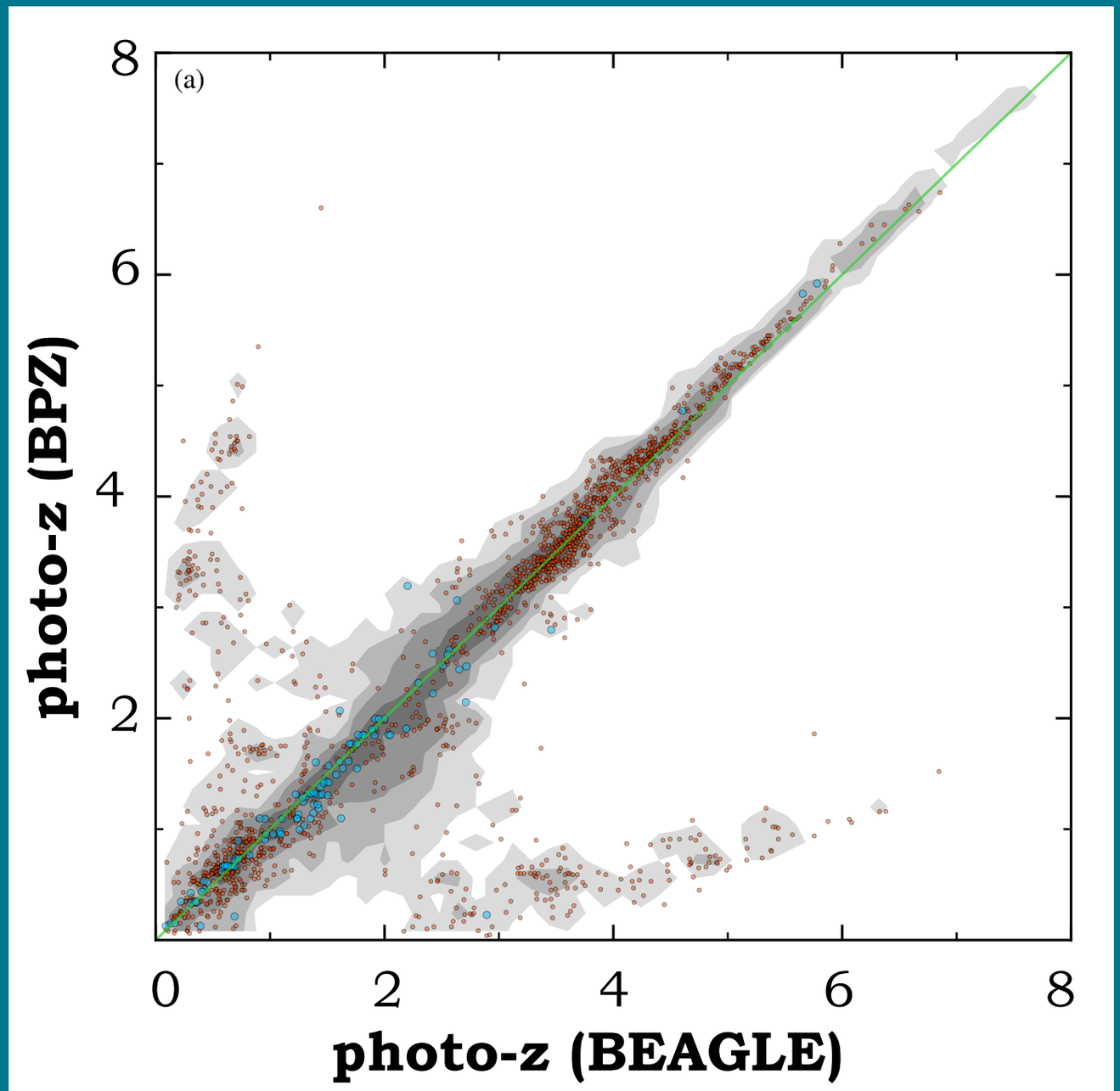


Photo-z *vs* photo-z

- Regions of “outliers” occupied by galaxies exhibiting **multiple** redshift **solutions** of comparable probability (see also Ilbert+06, Brammer+08)

- ~50 % of **outliers** in BEAGLE *vs* BPZ and BEAGLE *vs* EAZY comparisons can be **explained by** these **multiple solutions**



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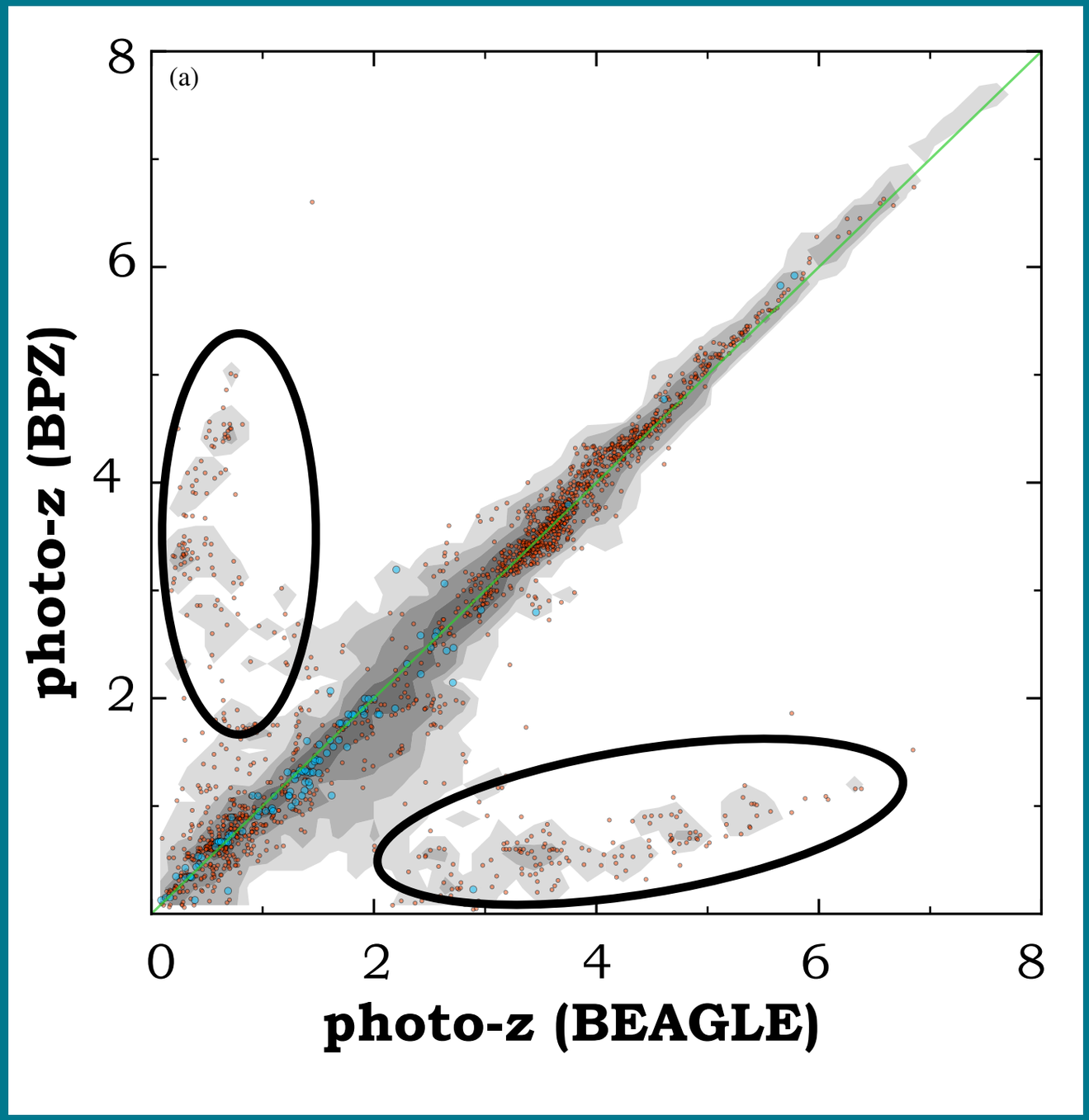


BEAGLE and JWST/NIRSpec

- NIRSpec will provide us with unprecedented data
- Need to search for **best strategy** to study high-z galaxies w. NIRSpec
  - Which **features** in galaxies SED can better constrain different physical parameters, at **different redshifts**?
  - Which **mode**, or combination of modes, is best? E.g. low **resolution** *vs* high resolution, **S/N** thresholds?
  - Which **instrumental effects** can hamper our measurements?

Simulations workflow

Input catalogue
(XDF, Bouwens+15)

Simulations workflow

Input catalogue (XDF, Bouwens+15)

broad-band SED fitting (BEAGLE)

Catalogue of (noiseless) model SEDs

NIRSpec "ETC" simulator

Catalogue of NIRSpec pseudo-observations

spectroscopic SED fitting (BEAGLE)

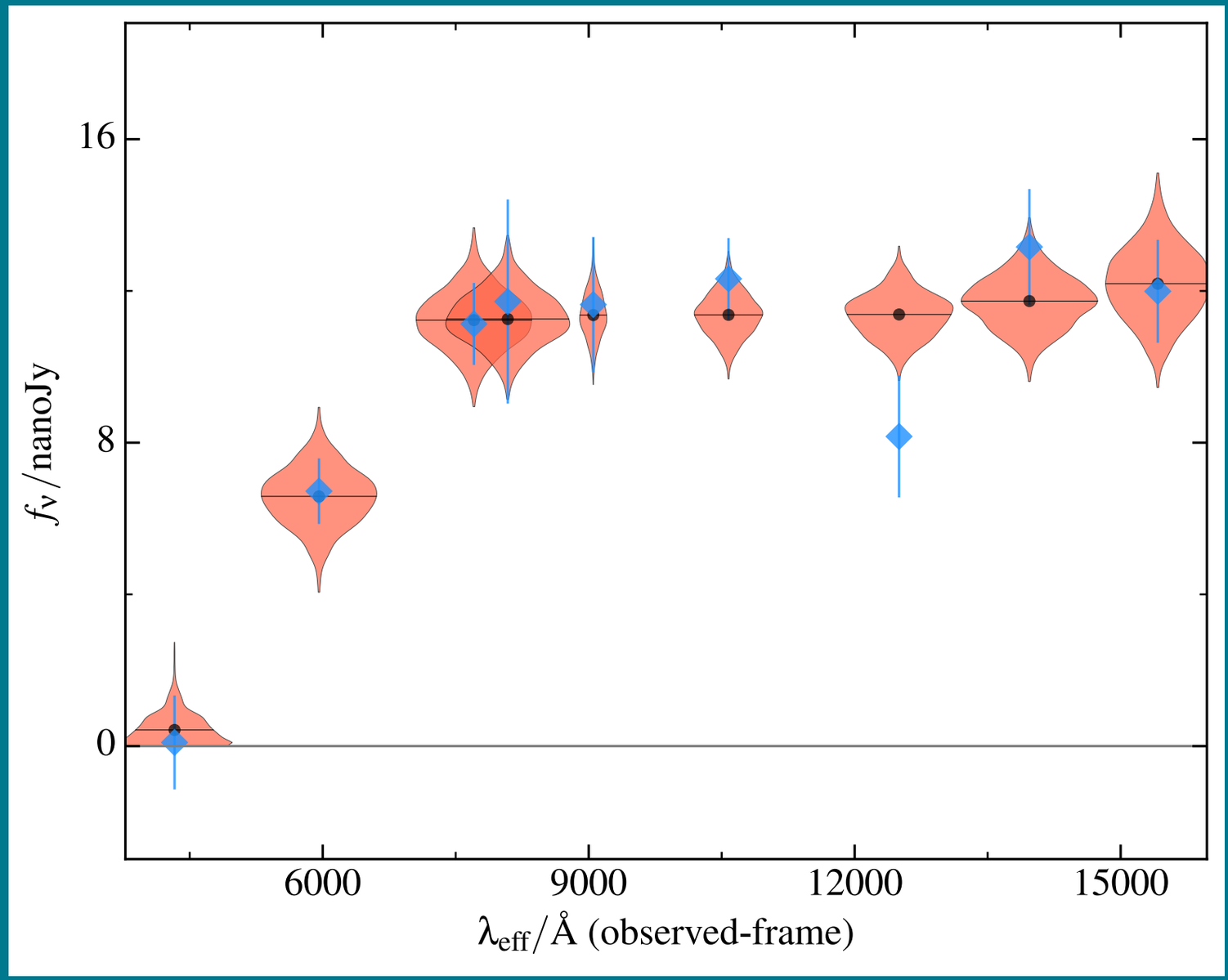
Comparison of input *vs* retrieved physical parameters

Input catalogue: Hubble XDF

- eXtreme Deep Field (**XDF**)
  (Illingworth+2013; Bouwens+2015)
- **4.7 arcmin²** in HUDF with ultra-deep near-IR observations
- HST **F160W** (5σ) = **29.8** AB
- IRAC **3.6** and **4.5 μm** (5σ) = **26.5** AB
- Fit (~700) Bouwens+15 *B*- to *Y*-band dropouts with same **model** adopted for UVUDF (stellar + nebular emission, 2-component SFH, IGM, dust, photo-*z*)

SED fitting of XDF sources: *B*-dropout

B-dropout, ID #4011875904, F160W=28.74 AB



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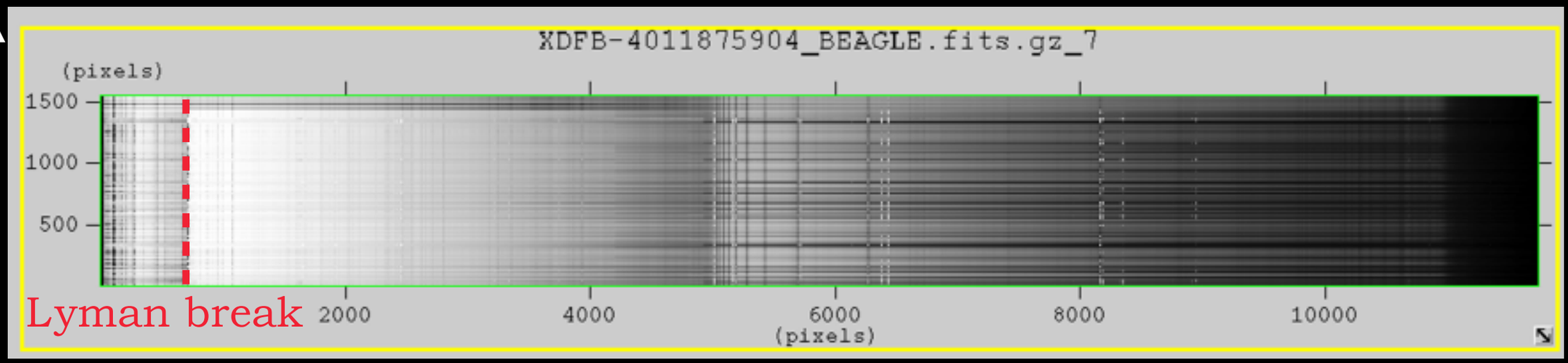
SEDs of increasing probability



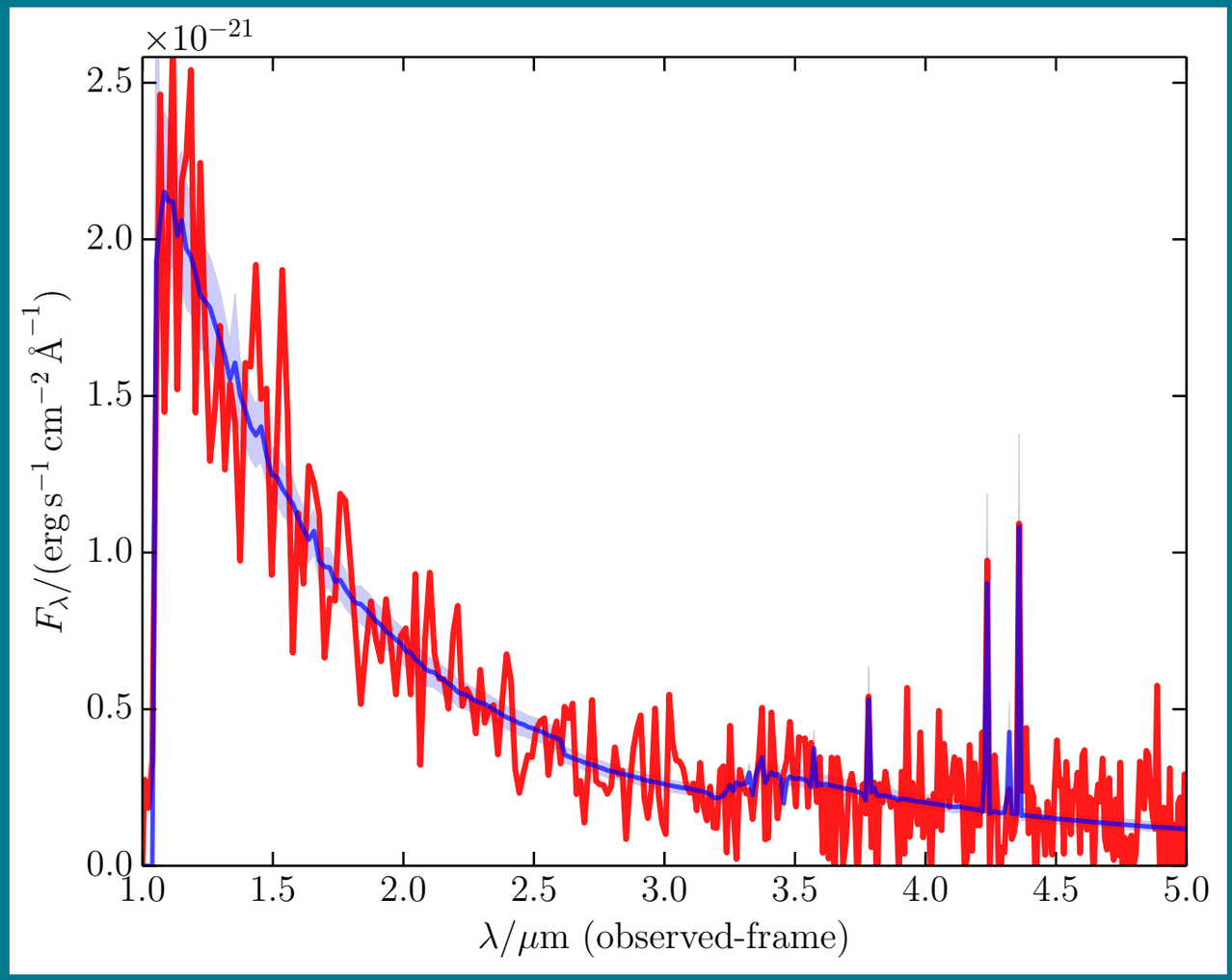
wavelength

XDF sources compatible with a wide variety of SEDs

Important to model different “realisations” of high-z SEDs

Fitting of NIRSpec simulations: *Y*-dropout

- Select **maximum-a-posteriori SED** among ~10^3 SEDs provided by BEAGLE for each XDF source
- Simulate "**deep**" NIRSpec observation (**PRISM, 10^5 s**)
- Split galaxies in two sub-samples: **star forming** (sSFR > -9.5) and **passive** (sSFR < -9.5)
- Study **retrieval** of parameters as a function of dropout band and F160W magnitude



Y-dropout, ID #3920463221,
F160W=28.75, z = 8.648

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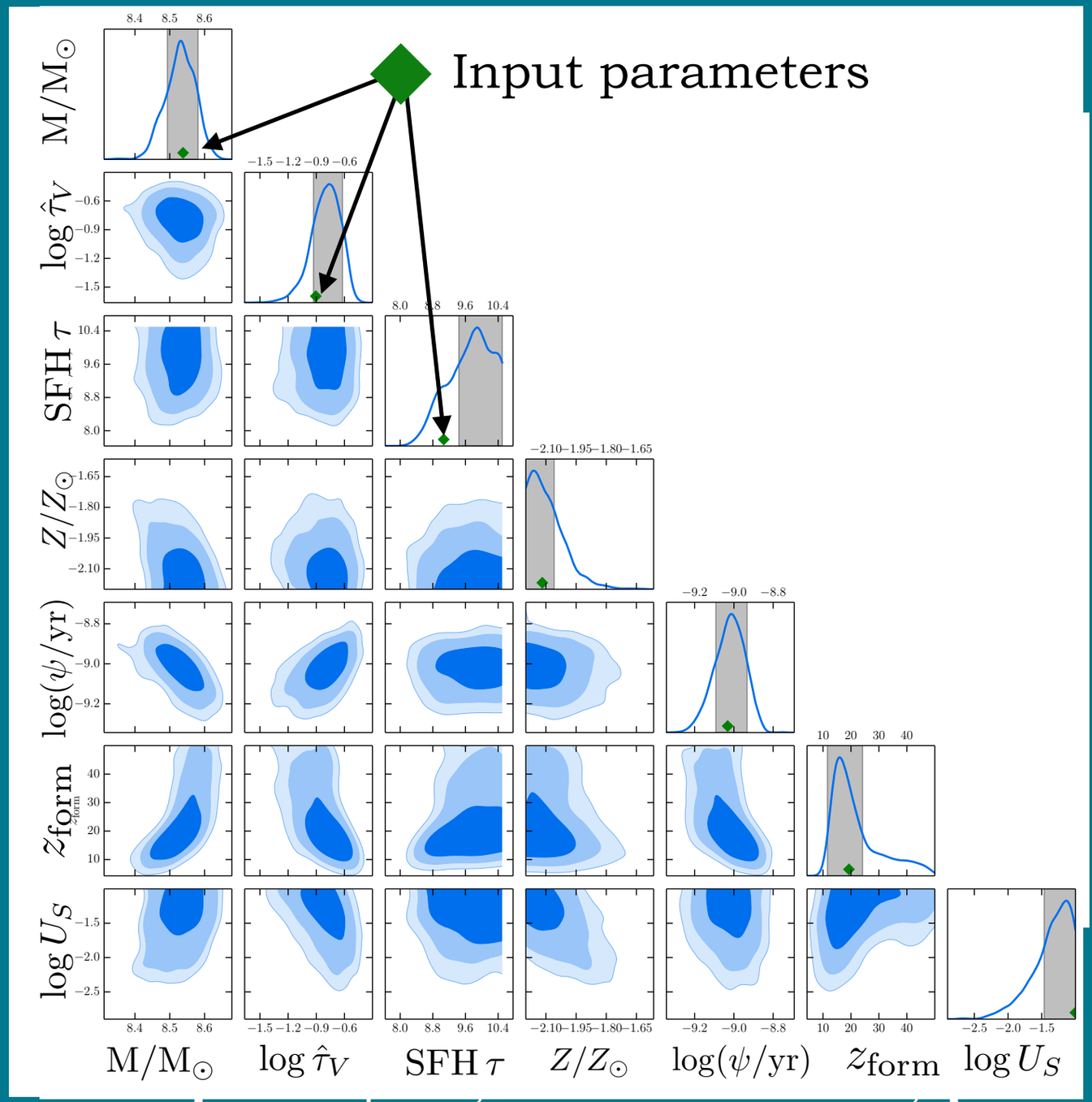

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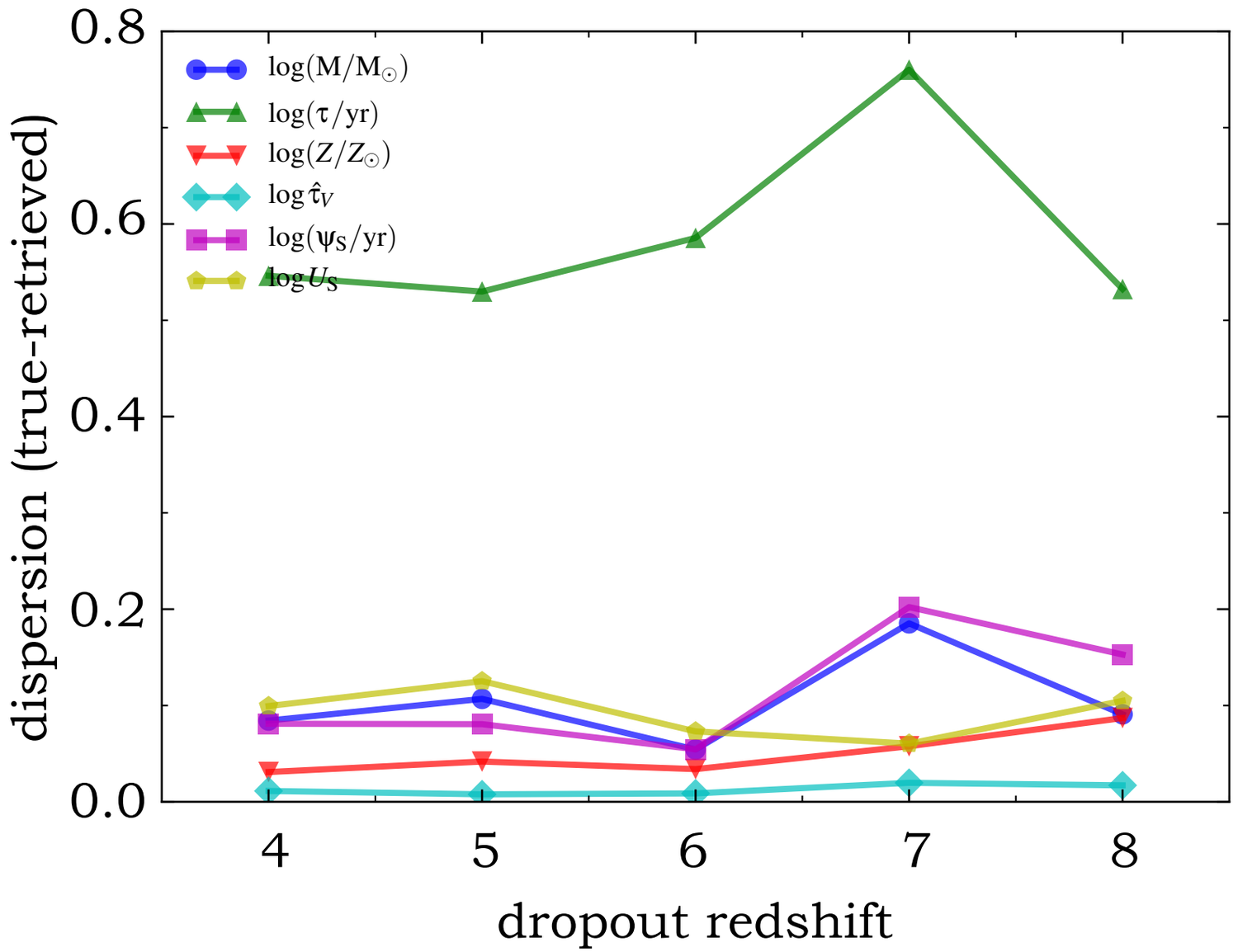
Retrieval as a function of dropout redshift

star forming

- **Ionization parameter** and (**interstellar) metallicity** constrained within 0.1 dex for SF, while **specific SFR** within 0.2 dex
- **SFH** and **stellar mass** better retrieved in passive galaxies
- **Metallicity** better retrieved in SF, for which almost no dependence on redshift



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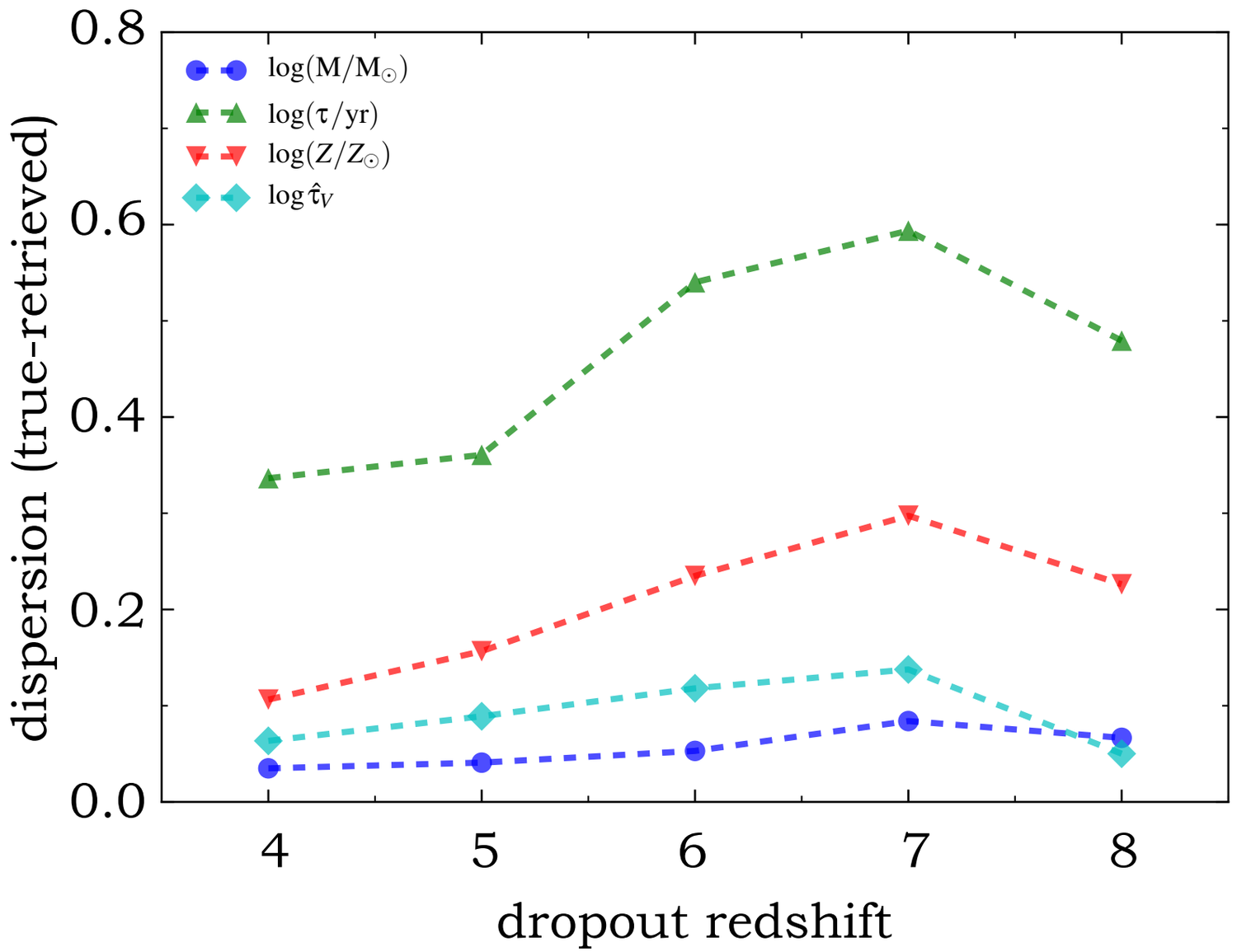

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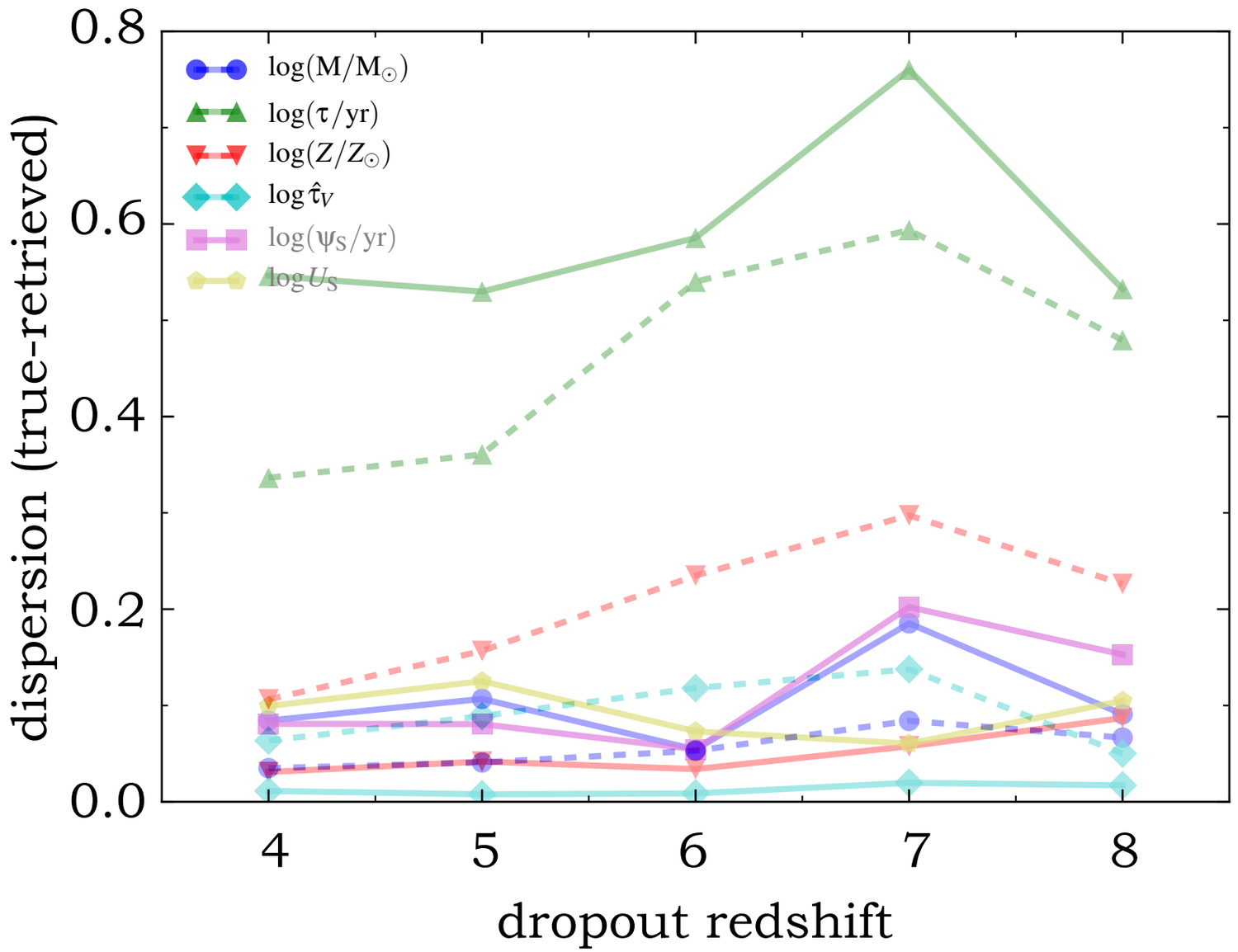
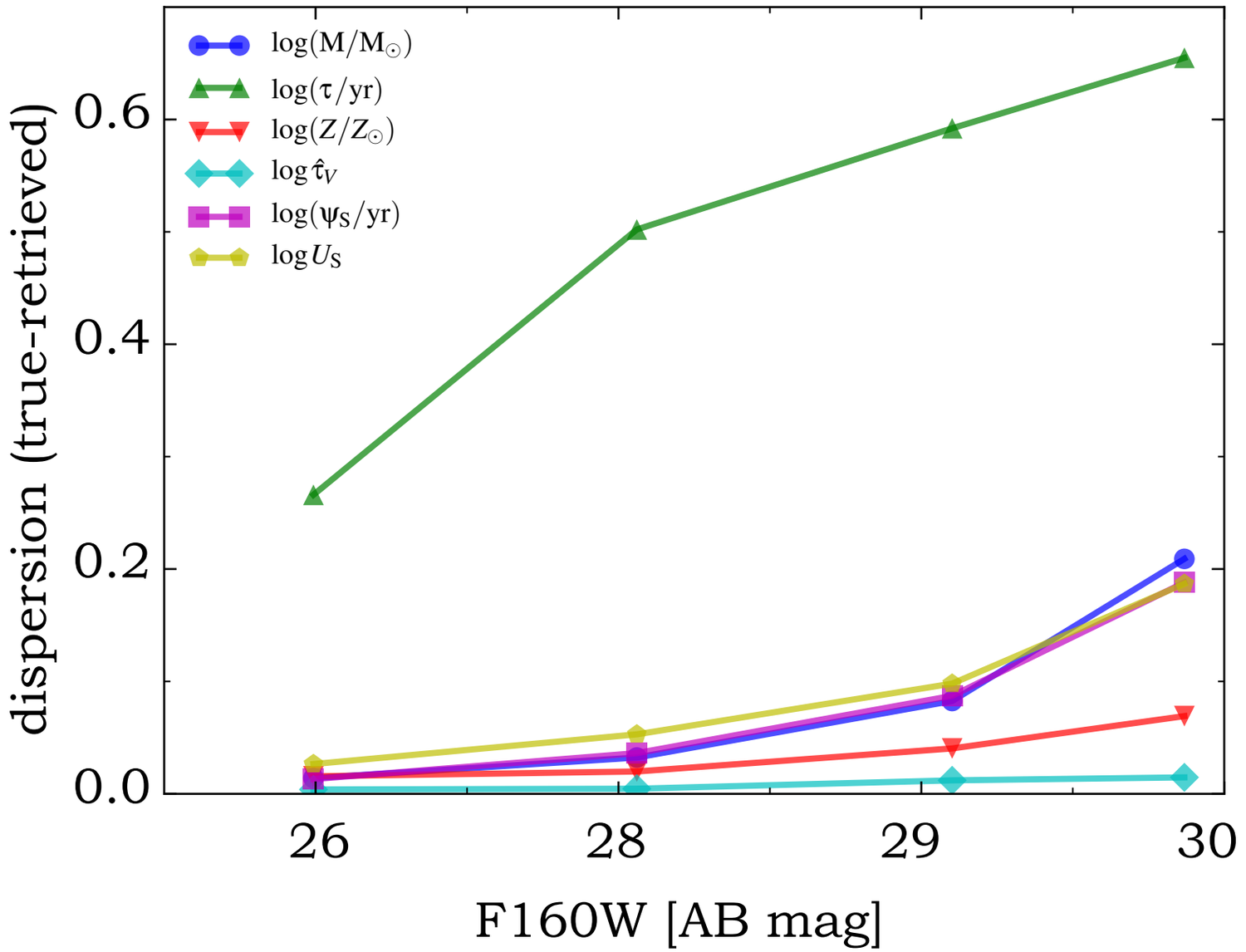


Retrieval as a function of F160W mag

star forming

- Strong dependence of dispersion of retrieved parameters with F160W mag
- For SF galaxies, **ionization parameter**, **specific SFR** and **stellar mass** from 0.05 dex to ~0.2 dex
- For passive ones, **metallicity** and **dust** from 0.05 dex to ~0.2 dex, **stellar mass** from 0.05 to 0.1
- Stronger dependence of **metallicity** on F160W mag for passive galaxies



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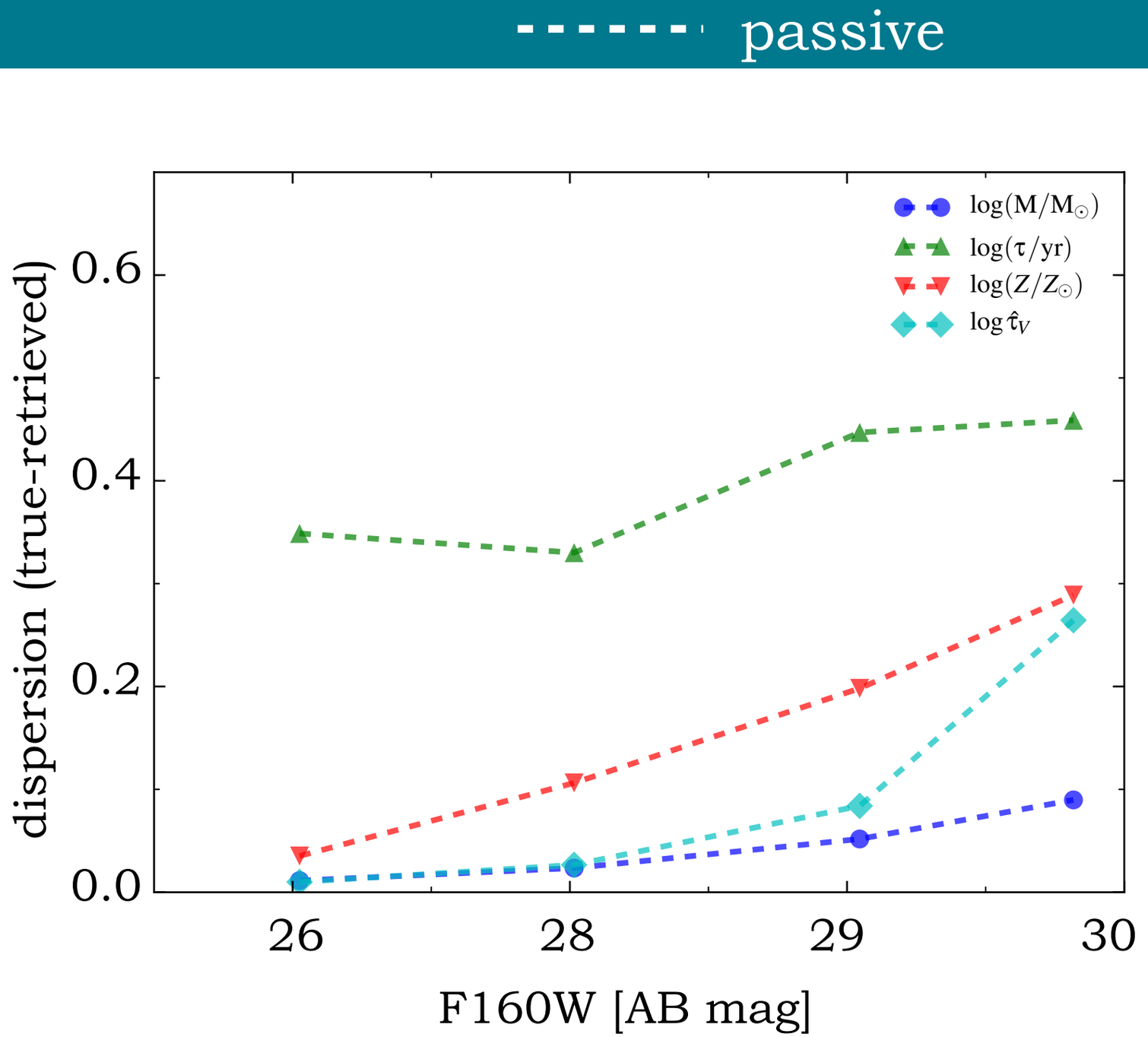

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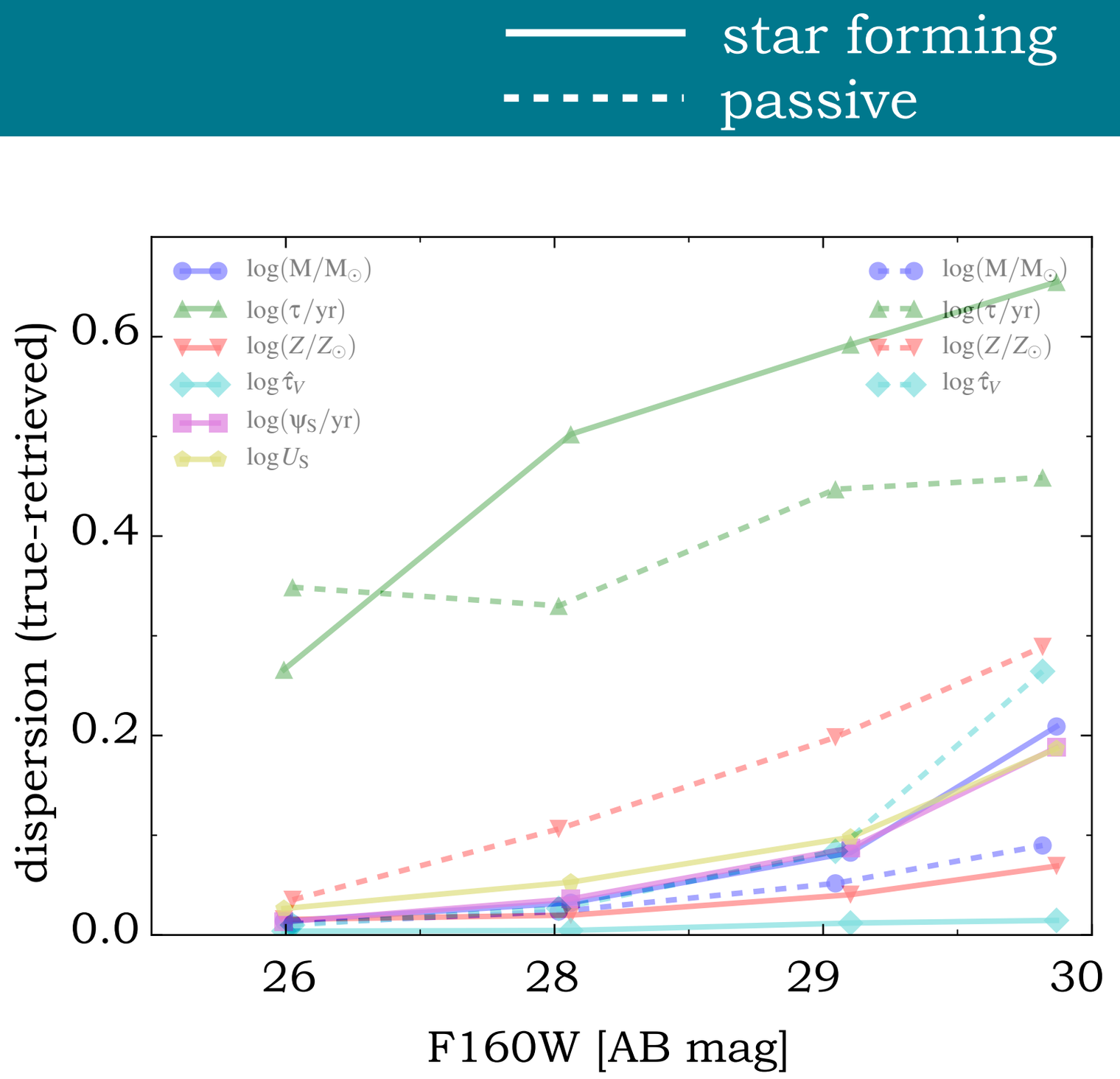

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Conclusions and future developments (1)

- **JWST** will provide us with unprecedented **high quality data** on high-z galaxies
- Need sophisticated models + advanced statistical tools to **maximize information extracted** from galaxy SEDs
- New framework for (high-z) SED analyses
  - **flexible** physical model with **coherent** treatment of different galaxy components
  - can **build** mock **catalogues** of galaxies and **fit** (pseudo) observations
- Approach validated on 10K galaxies at $0 < z < 8$
- Combination of BEAGLE + other tools to simulate JWST/NIRSpec observations and **optimize** future planning of **GTO/GO** campaigns

Conclusions and future developments (2)

- Coherent implementation of physical recipes tailored at reproducing SEDs of **high-*z* galaxies**:
  - **AGN** emission (A. Feltre)
  - emission from **HII regions** with variable chemical abundances (J. Gutkin)
  - emission from **shock-ionized gas** (A. Wofford)
  - new prescription for **high resolution UV** (A. Vidal)
- "**Data science**": development of combined data- and model-driven approaches to SED analyses (D. Stenning)

Thanks

Early galaxies and cosmic reionization

NIRcam NIRSpec MIRI FGS/NIRISS

Early galaxies

- UV LF at high-z and faint mag
- Early chemical enrichment from nebular lines
- Dust content
- Stellar masses and SFH
- AGN-SF connection
- AGN and stellar feedback

Cosmic reionization

- Prod. rate of H-ioniz. photons from stellar pop. analyses
- LyC f_{esc} from UV slope + Balmer lines (need SFH too)
- LyC f_{esc} from Lyα profiles
- Lyα emitters LF evolution (and clustering)
- Lyα f_{esc} (dust, gas geom., kinem.,)
- (QSOs and GRBs spectra probing intervening IGM)

Photo-z *vs* spec-z outliers

3 main **sources of outliers**

A

Contamination of photometry from nearby objects

Should be tackled at **data reduction** level

B

Observed SED compatible with **multiple template SEDs** at different z

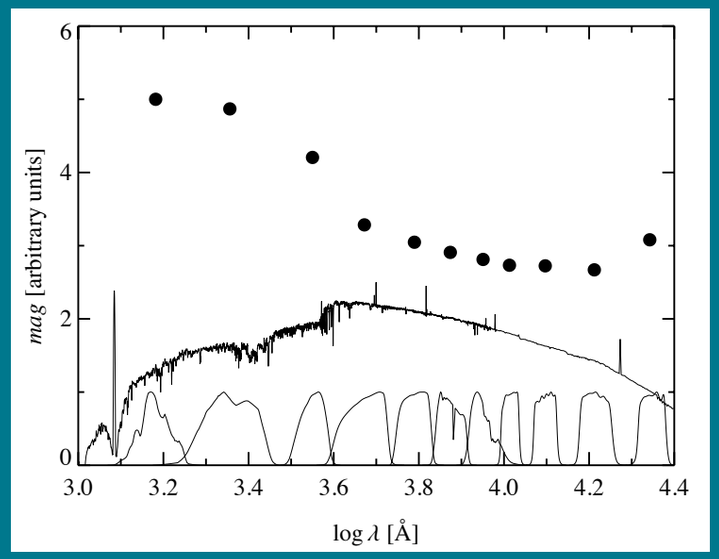
Can **identify** such cases, by adopting a **comprehensive model** for galaxy SEDs + tailored **statistical** approaches

C

No matching template SED to the observed SED

Must **modify** the adopted **model** for galaxy SEDs (or data calibration)

BANGS workflow



Spectral evolution model

Model predictions

Noise addition

Input data

(spectra and photometry)

Pseudo-observations

Observations

Data fitting (Bayesian statistics)

Output

(spectro-photometric) Mock catalogues

Output

Galaxy physical parameters

Dust content

Gas-phase metallicity

Star formation rate

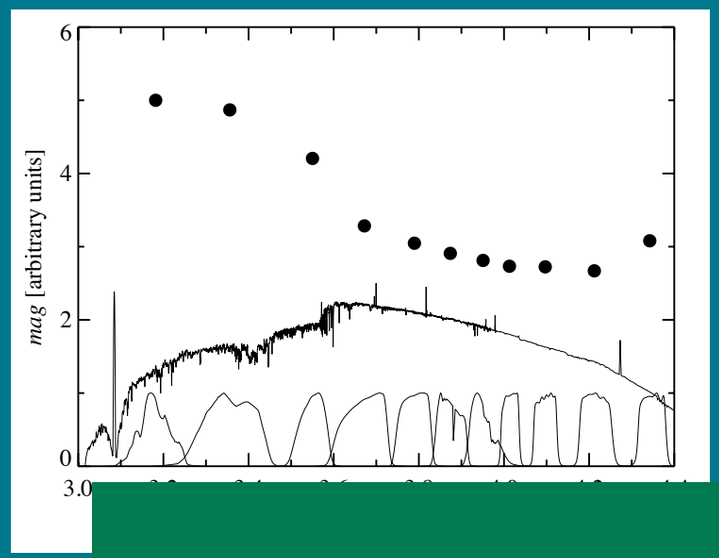
Stellar mass

LOSVD

α-elements abundance

Star formation and chemical enrichment history

BANGS workflow



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Crucial testing on low-z "analogues" of high-z galaxies !

(See Aida Wofford poster)

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BANGS and JWST/NIRSpec

Science preparation

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Catalogue of galaxy properties and SEDs

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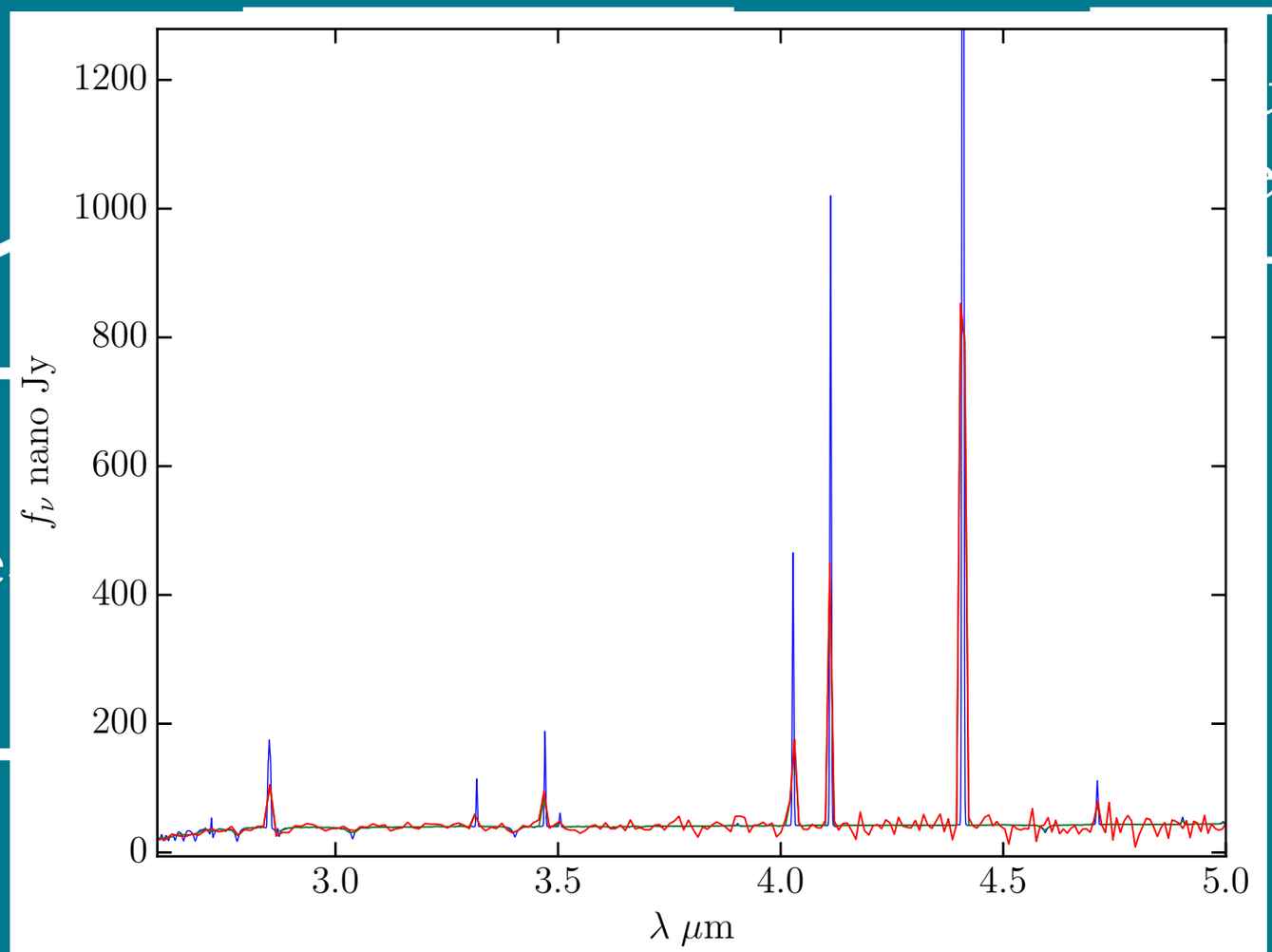

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