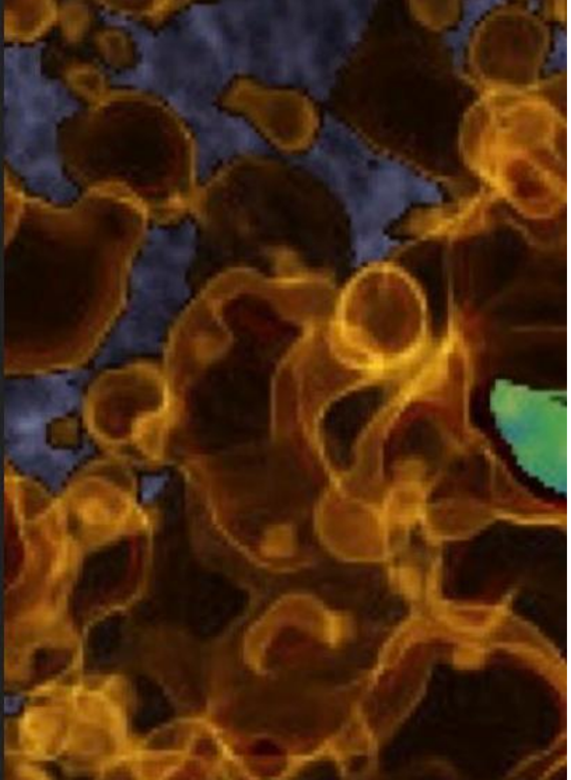
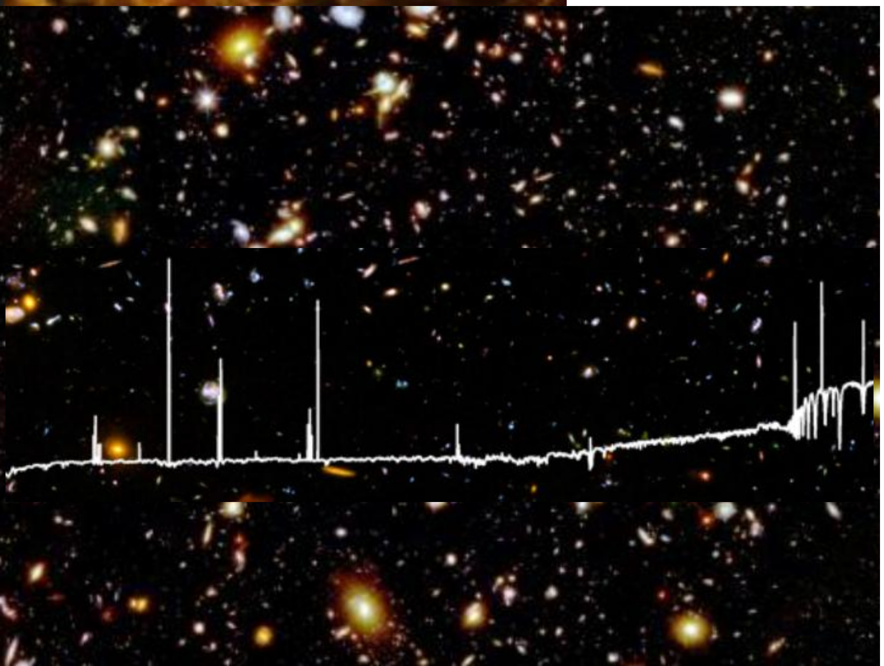
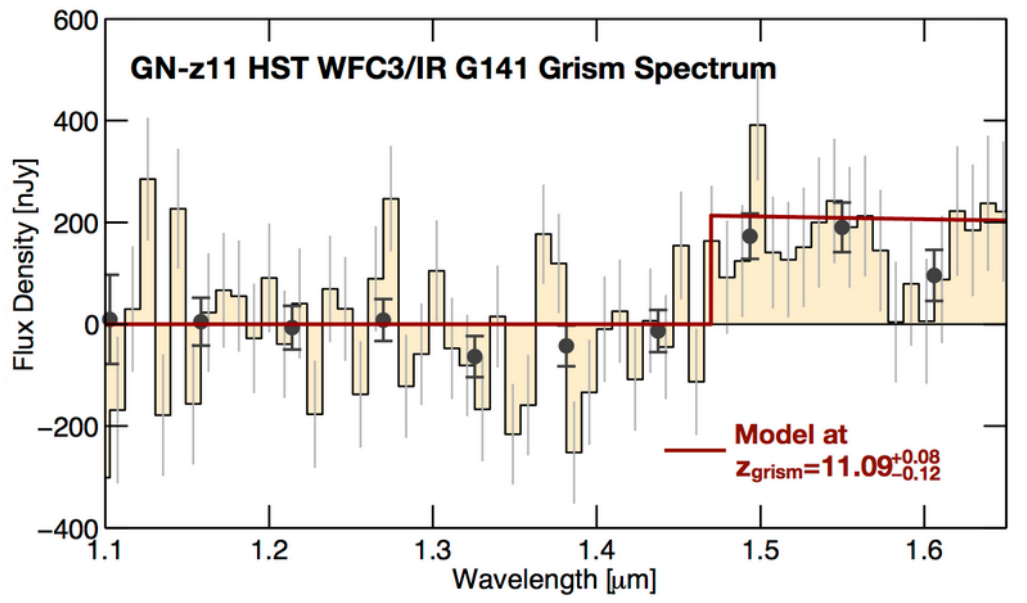
Françoise Combes
24 June, 2016



Cosmic dawn of galaxy formation: a summary





Outline

1- Observations of first stars, galaxies and black holes

2- Simulations of first galaxies and reionization

3- Physical parameters from SED, ionizing sources

4- Low-z analogs

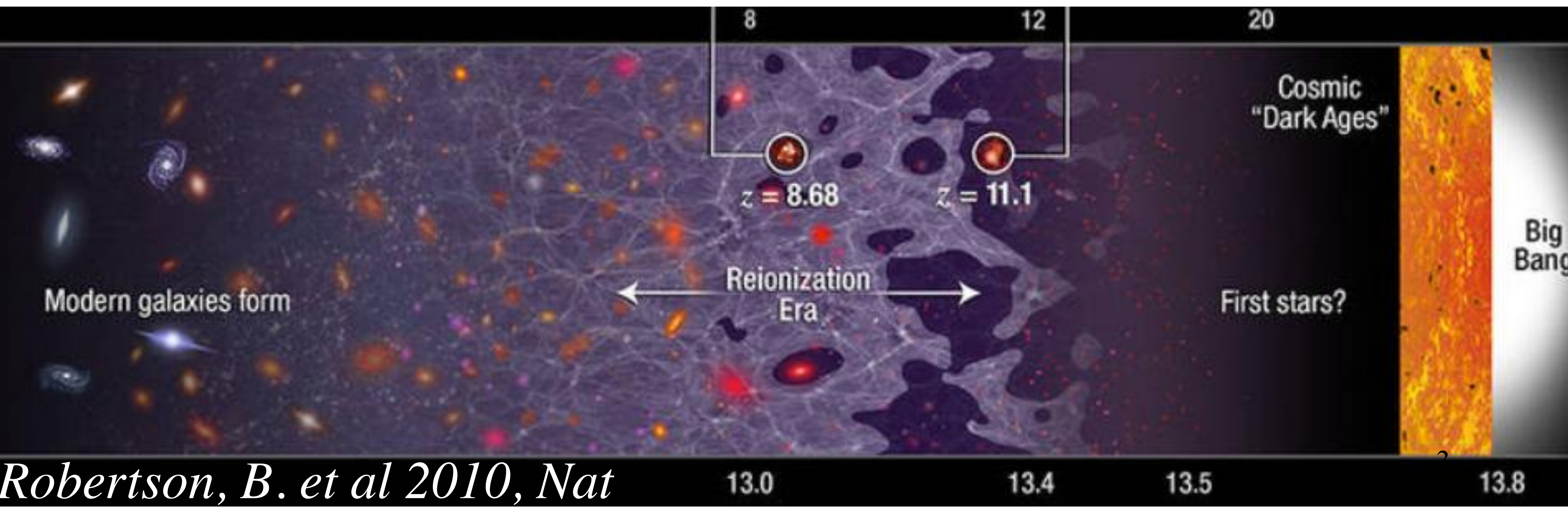
5- Feedback processes, Metal enrichment

History of the universe: dark age, cosmic dawn

How, and at which pace is the universe re-ionized?

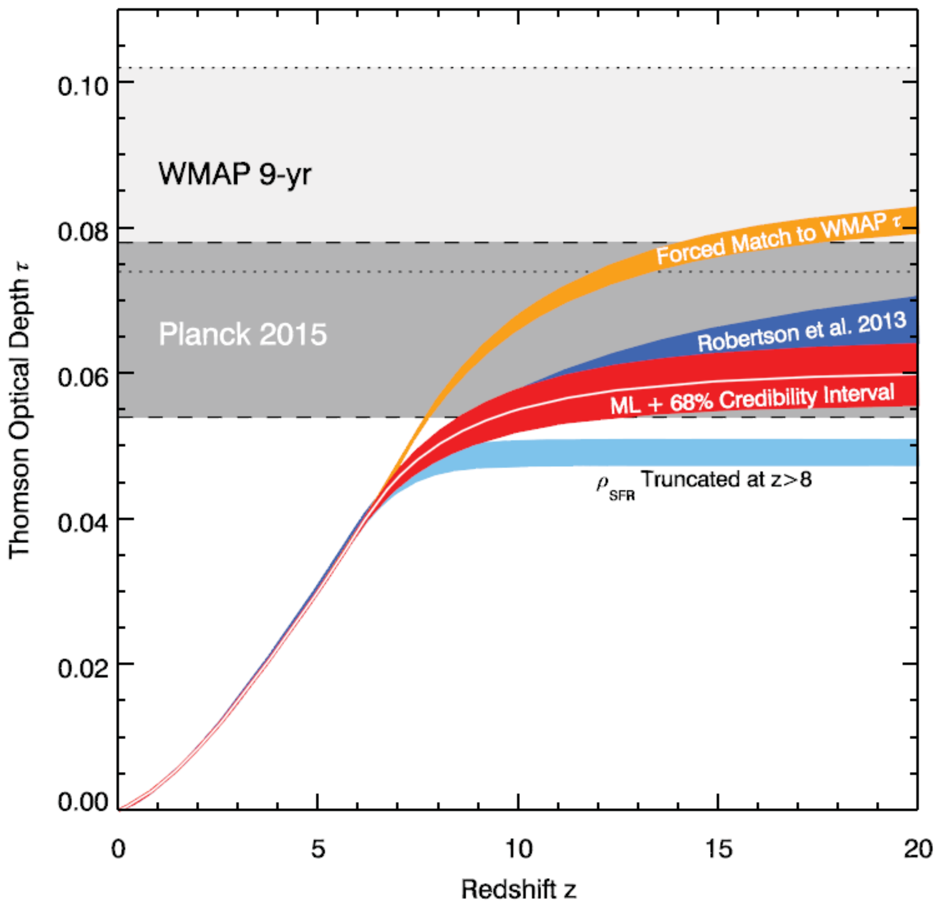
What are the main actors: galaxies, quasars?

z



Robertson, B. et al 2010, Nat

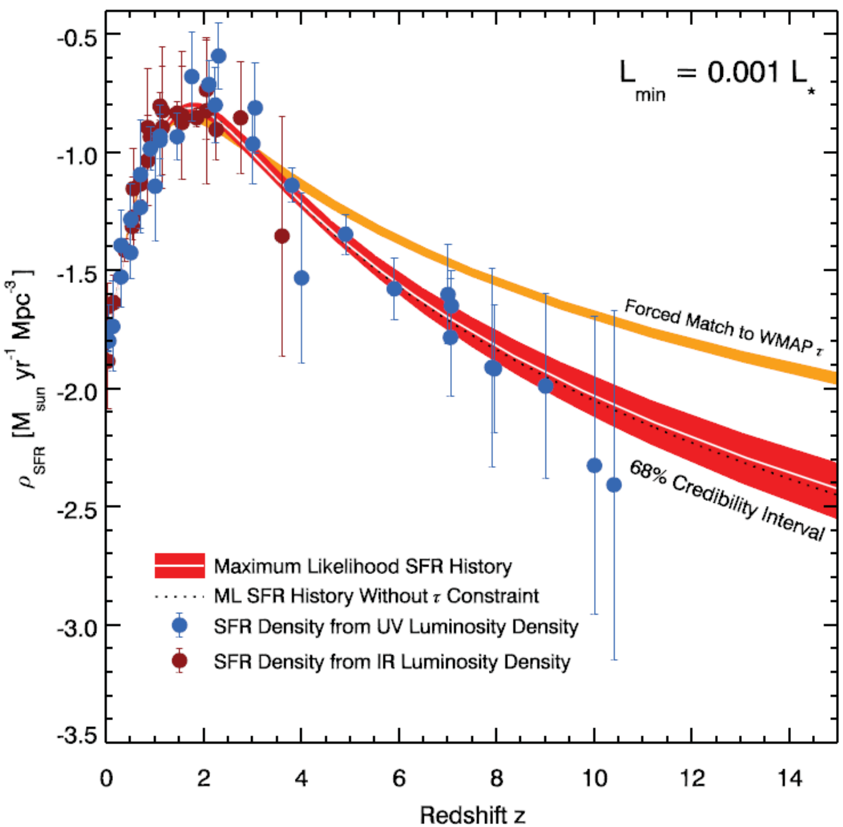
New opacity from Planck



τ= 0.058±012

Planck Collaboration (2016)

Requires less galaxies at z>8



Robertson et al 2015

1- First stars, galaxies and black holes: obs

Dan Stark,
Laura Pentericci

Out of the dark age

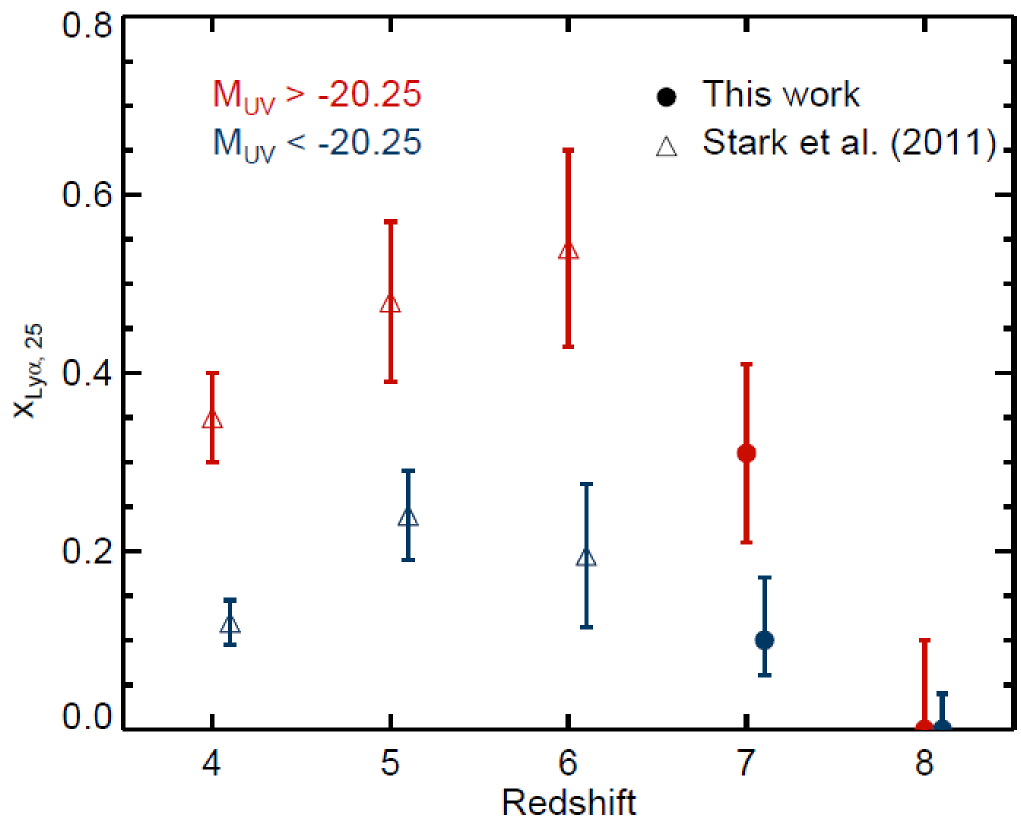
Universe progressively transparent at UV light

Large-statistics required, to beat the variance
Patchy re-ionisation
(Pentericci 2014)

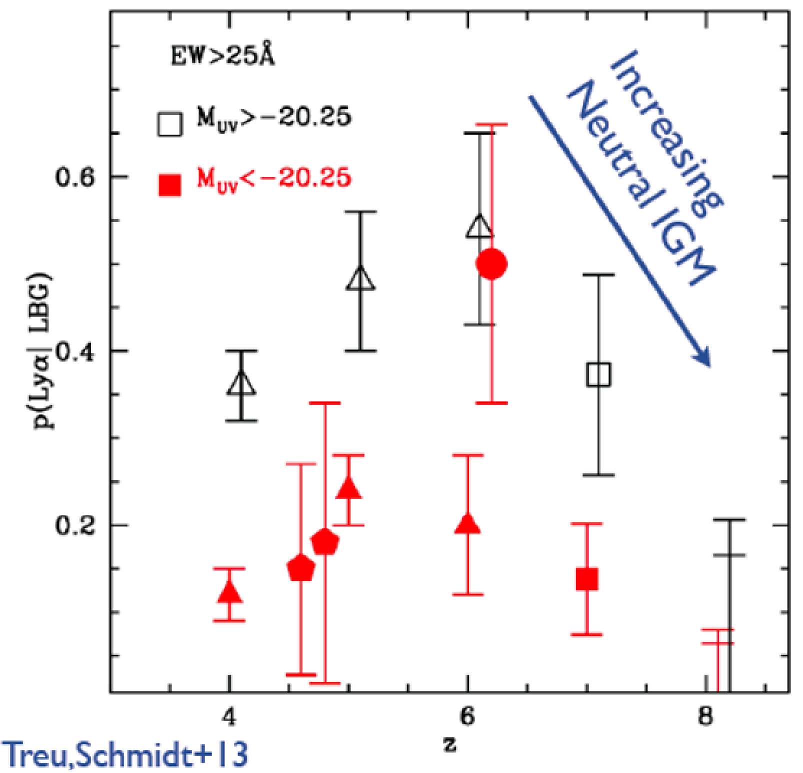
UV slope method: determine dust content and stellar pop

➔ Improved Ly-α fraction

Lyman-α decline



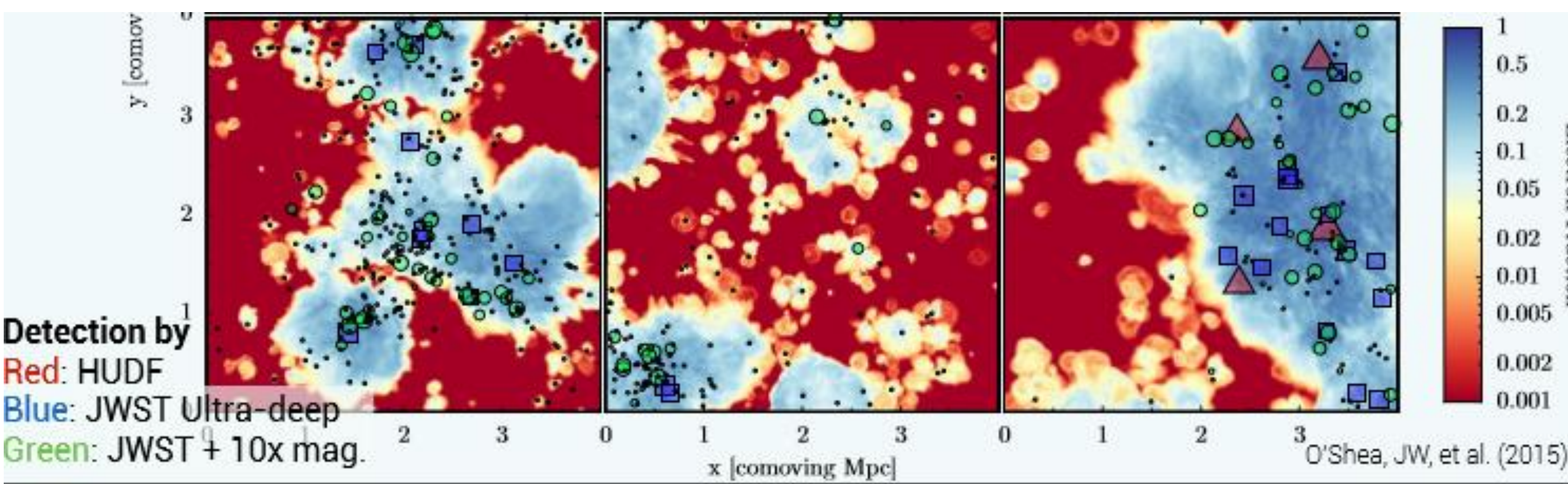
Schenker et al 2014



Diagnostic from Lyα

Less decline for massive galaxies, with a redshifted Ly-α line

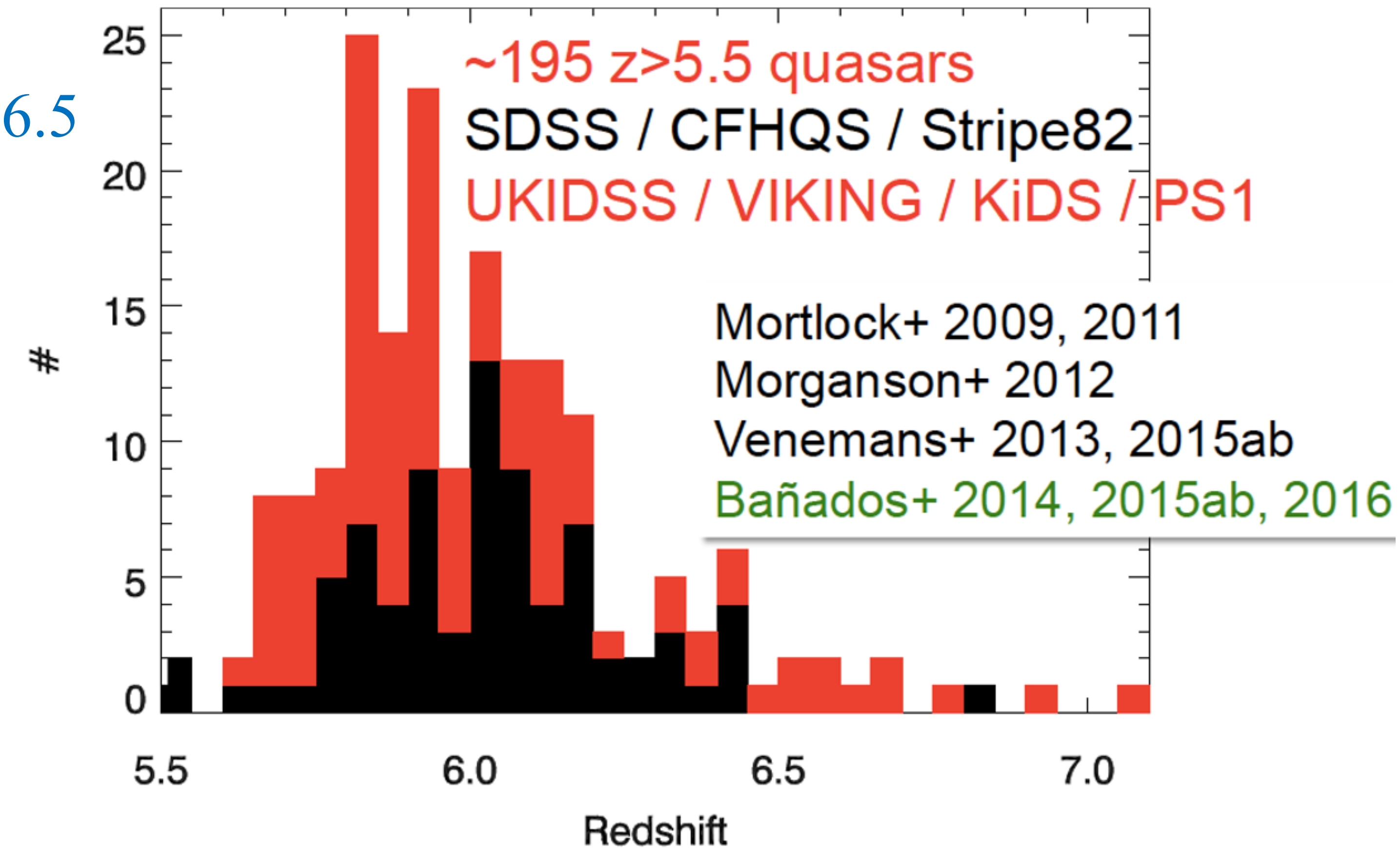
Voids are reionized last



Recent progress

550 galaxies at z>6.5   SFR from 0.5 to 300 Mo/yr
Drop by 15-20 from z=4 to 8
Faint end slope steepens

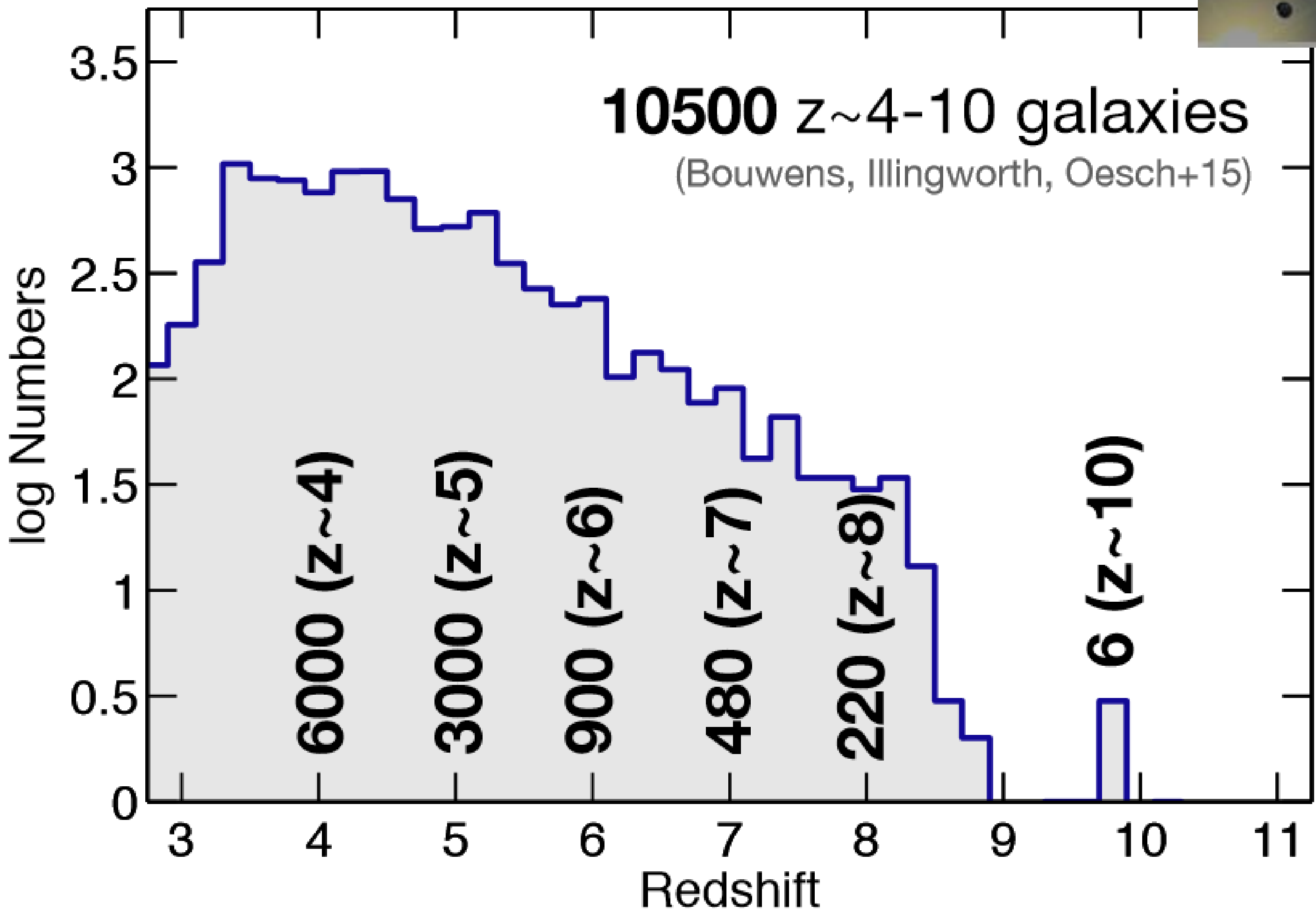
QSO 195 at
z>5.5, 7 at z > 6.5



histogram from Bram Venemans

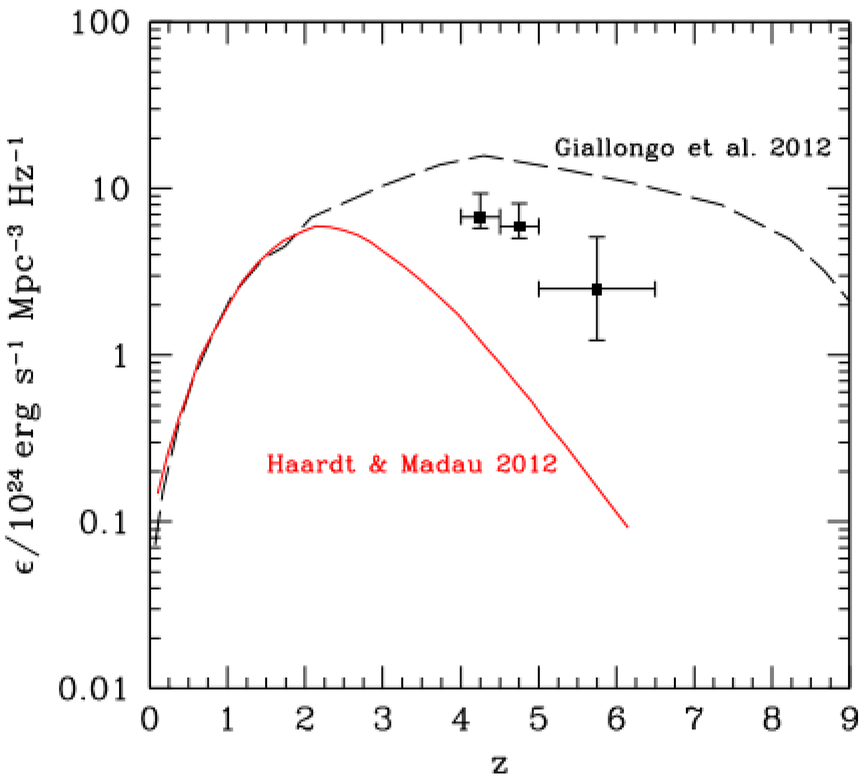
Where do we stand?

HST deep fields, difficult to go further ➔ JWST



Pascal Oesch

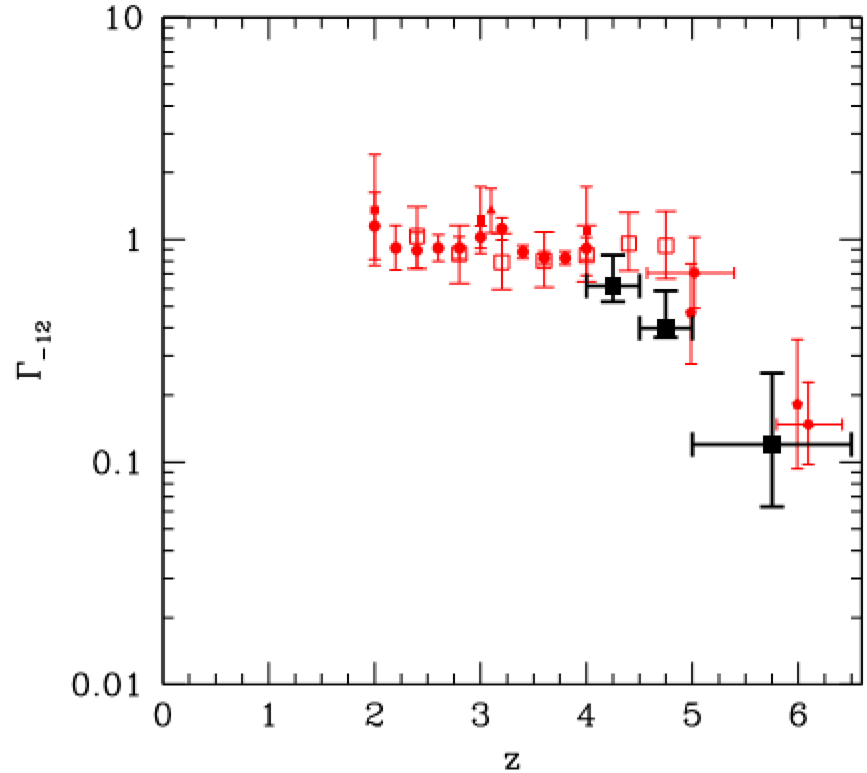
Are AGN out in the re-ionization?



GOODS

Giallongo et al 2015

Ionizing rate of AGN (black)



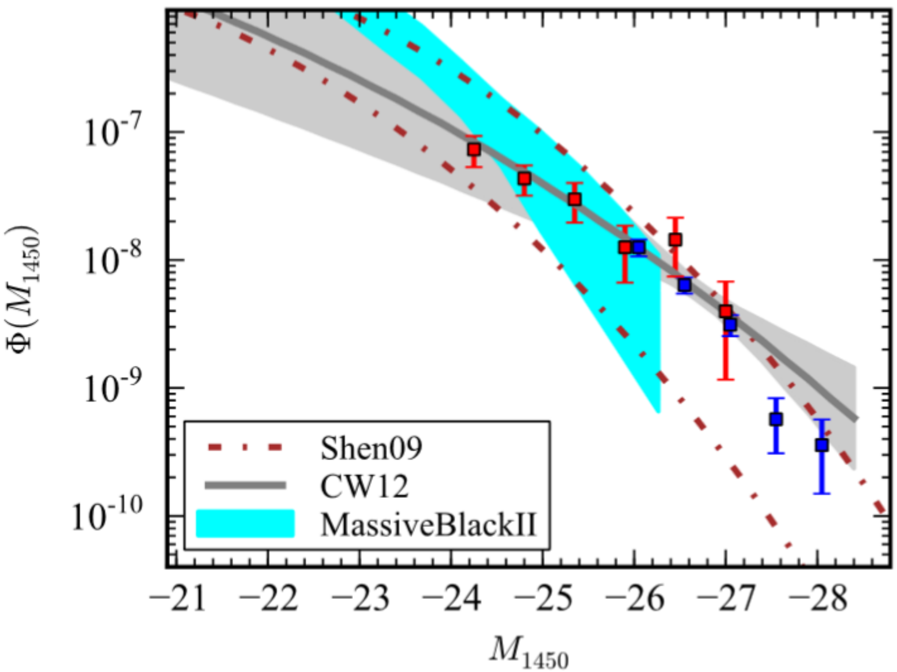
In red: inferred from the Lyα forest in high-z QSO

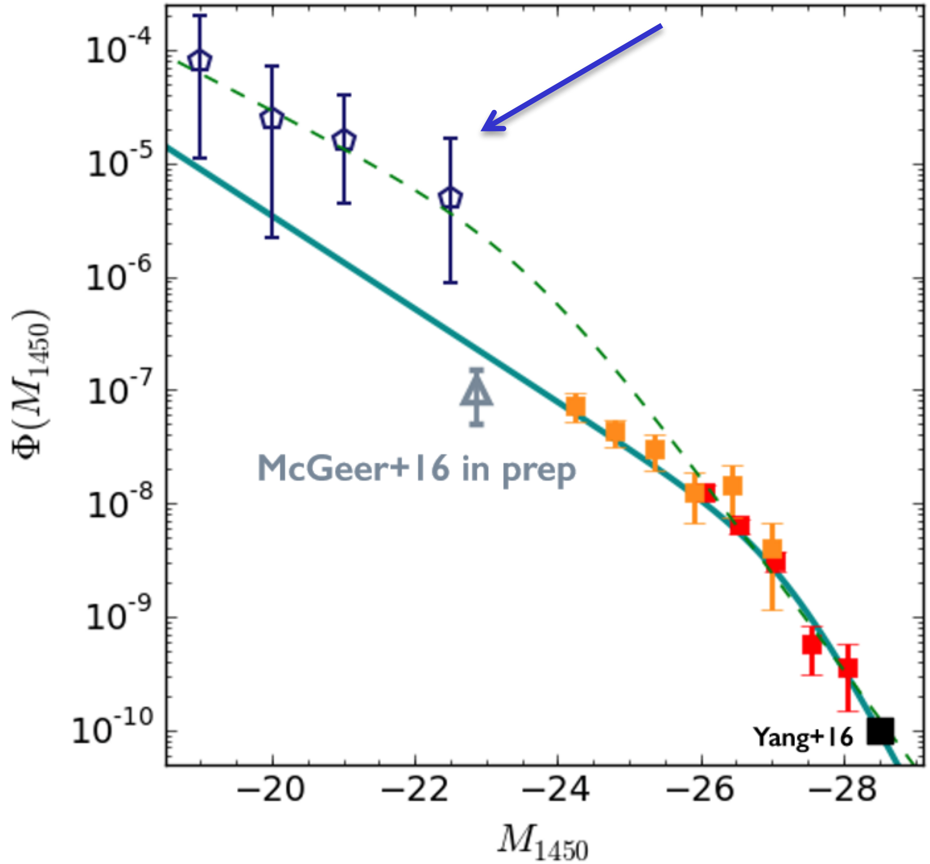
Luminosity function of Quasars

Incompatibility of results at z~5

Giallongo et al 2015

McGreer et al 2013



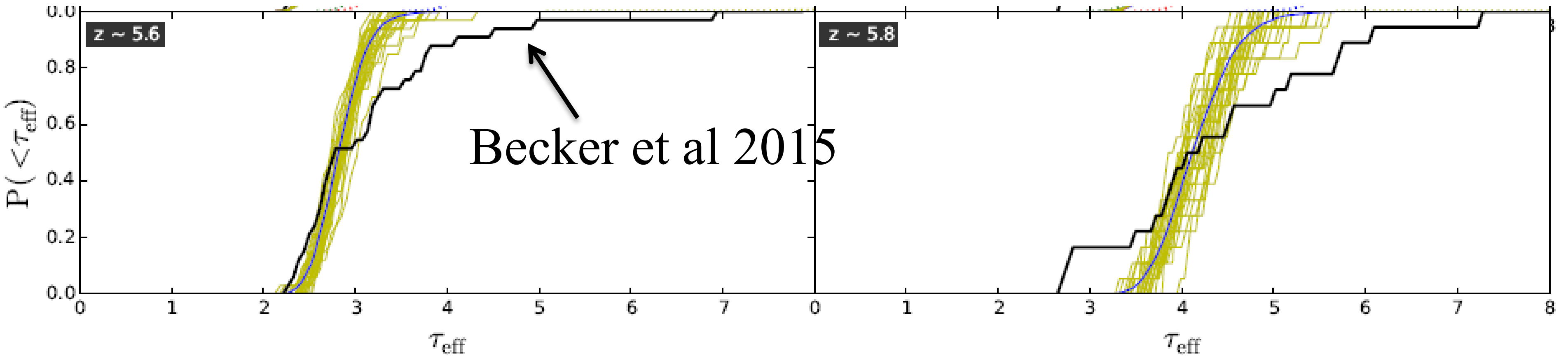


Comparison with model predictions

Dan Stark

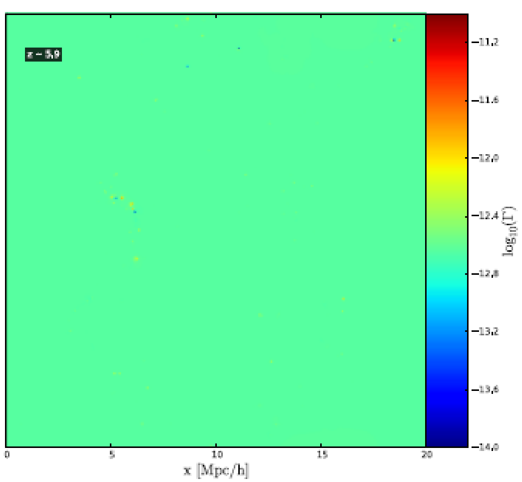
Patchiness of the reionization

Jonathan Chardin

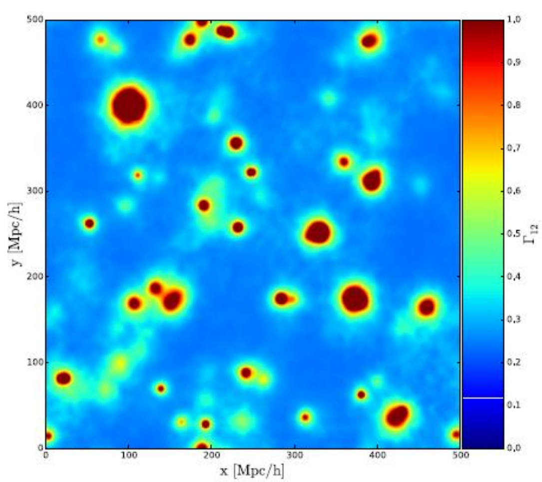


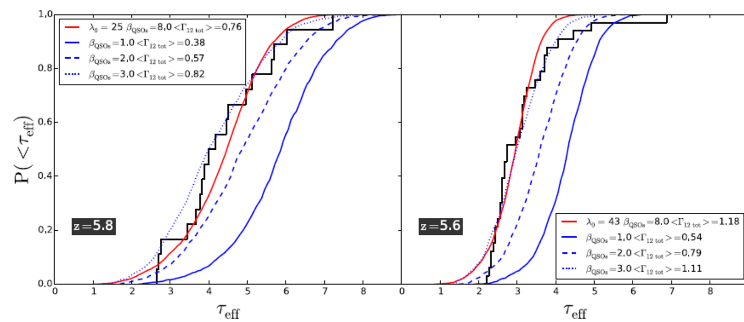
Lyα forest at z=5-6: very irregular, suggesting patchy ionisation

Galaxies



Quasars

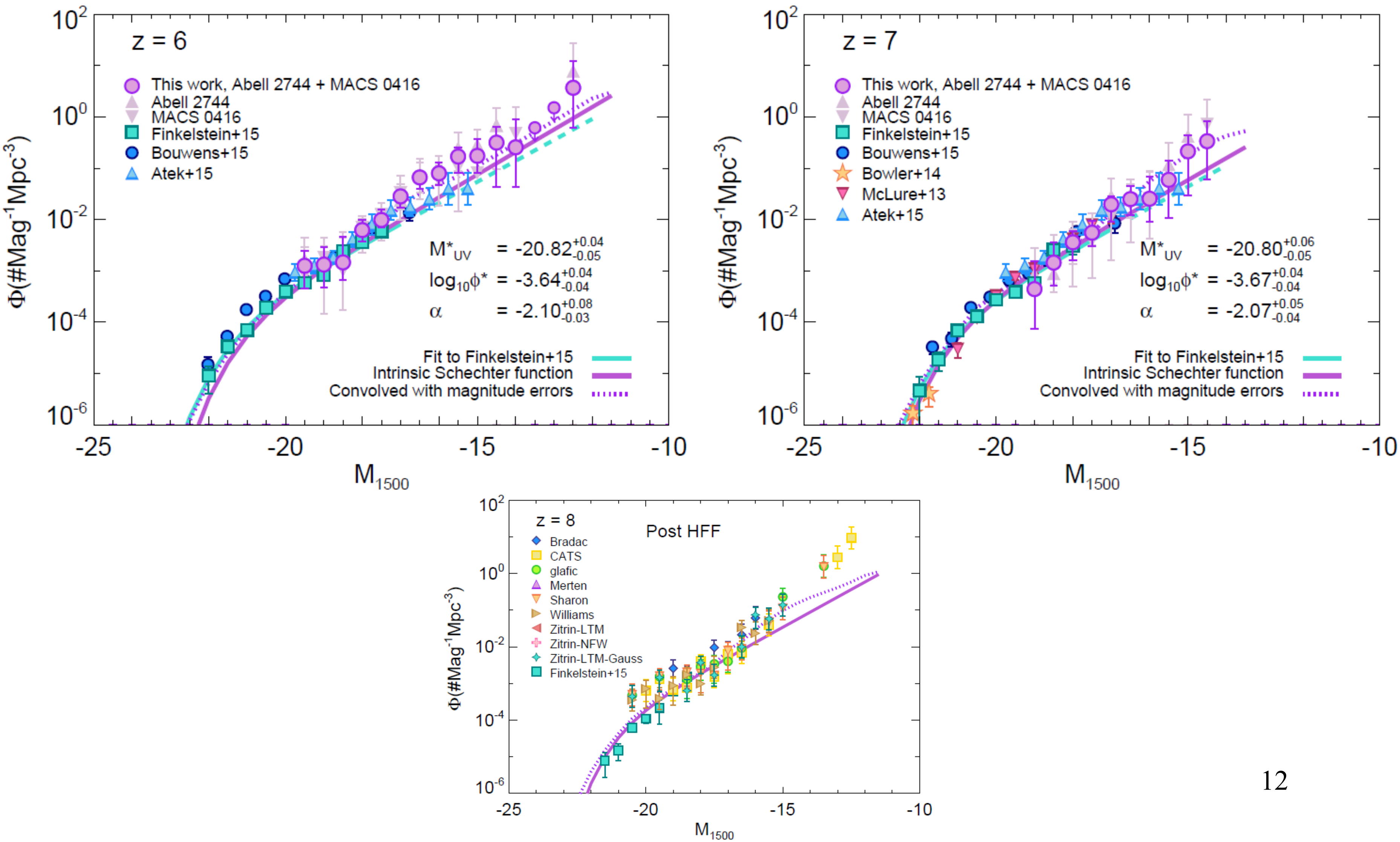




Faint end slope

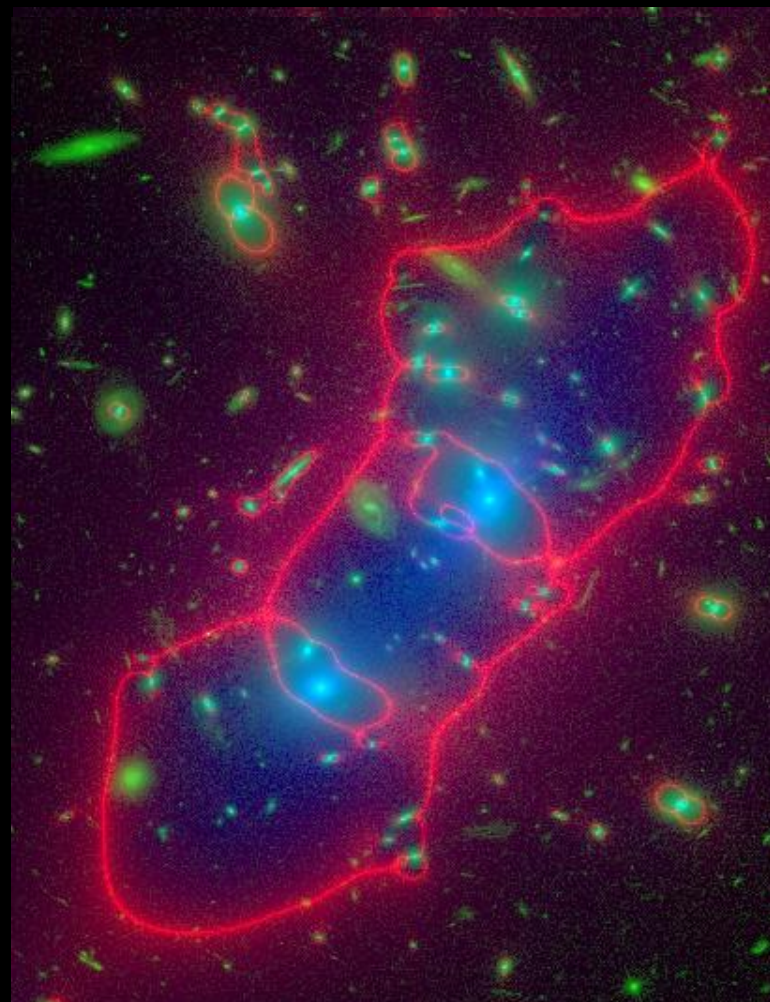
Using amplification, A2744, MACS 0416, Frontier Fields

Livermore et al 2016



Gravitational lensing – the full “horror….”

Ross McLure



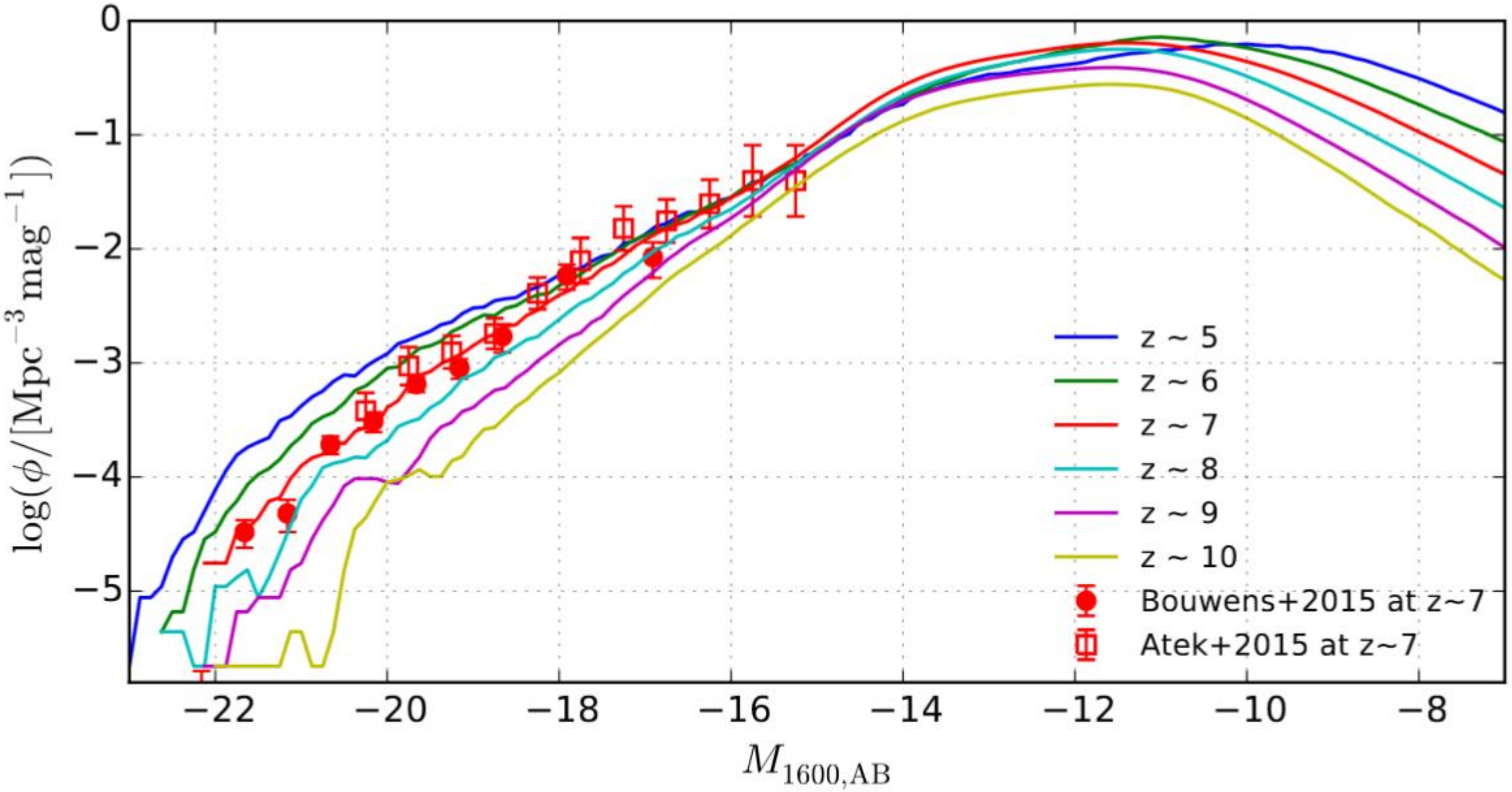
Grey data-points
show the z=8 LF

Alternative published magnification maps for Abell 2477

Predictions from simulations (DRAGONS)

Liu, Mutch et al 2015

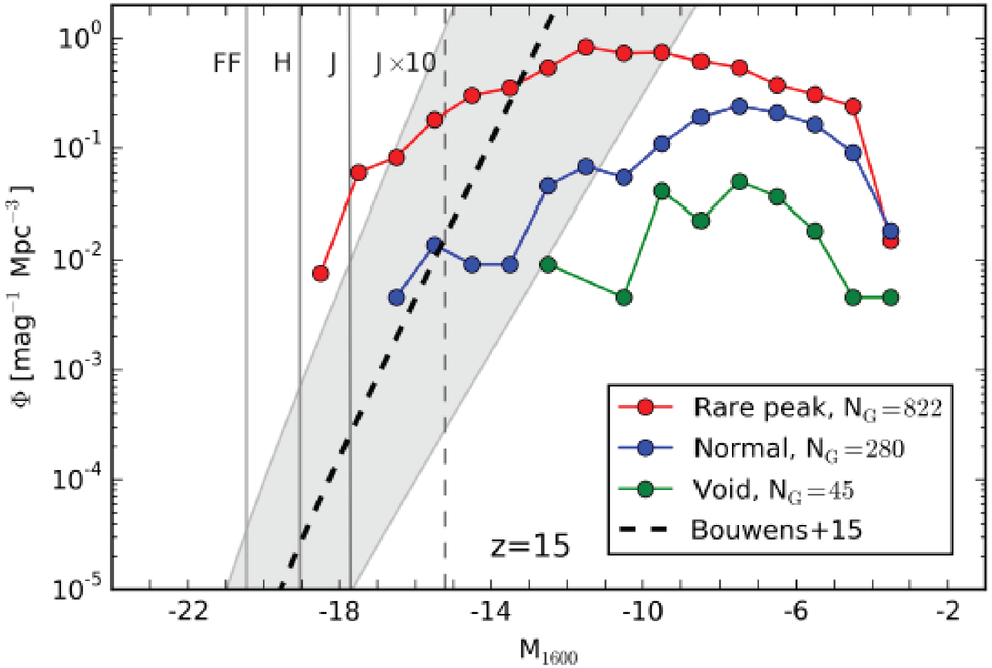
Galaxies fainter than M UV~ -17 are the main source of ionizing photons for reionization.



Inefficient cooling in haloes < 10^8 M_o

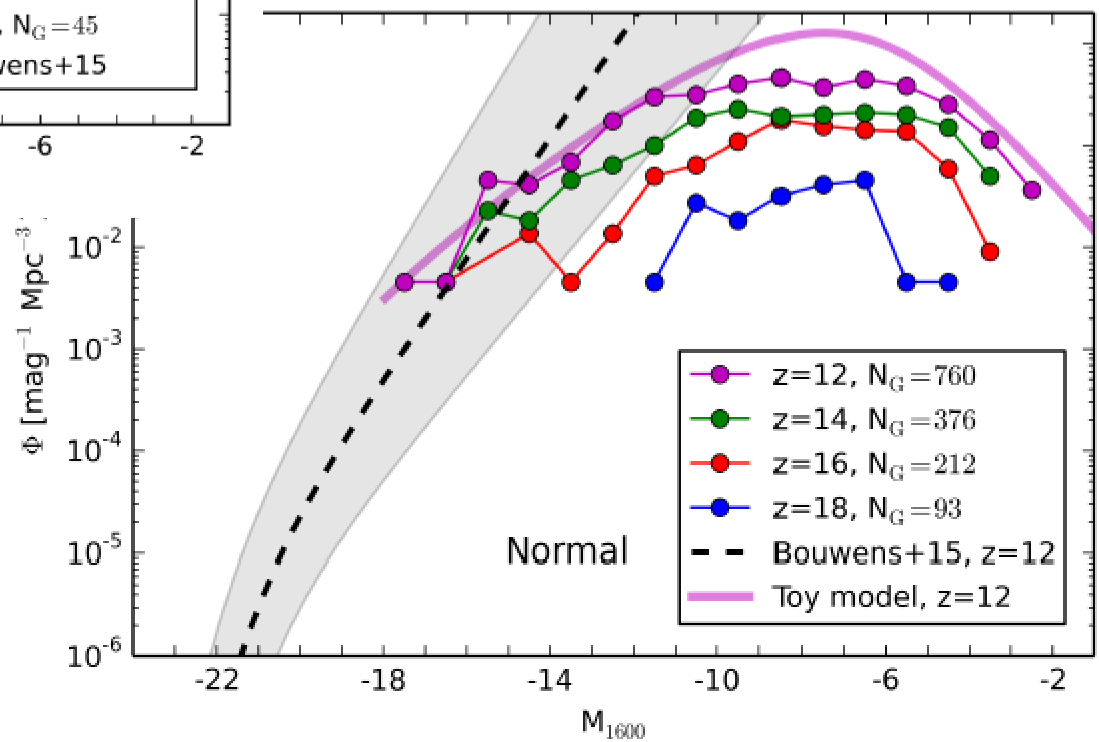
Renaissance simulation

O'Shea, Wise et al 2015

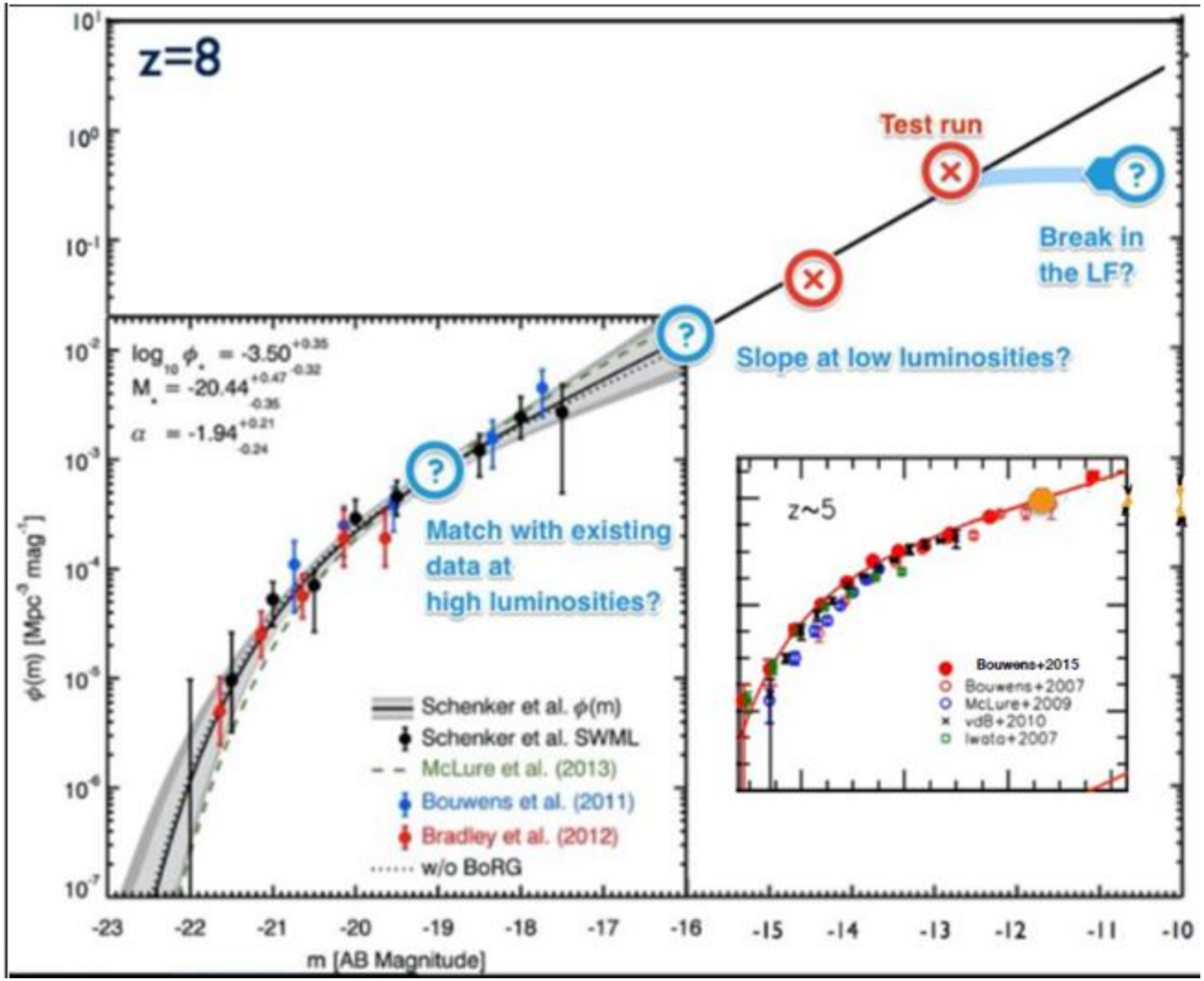


z=15

Normal



FirstLight simulations



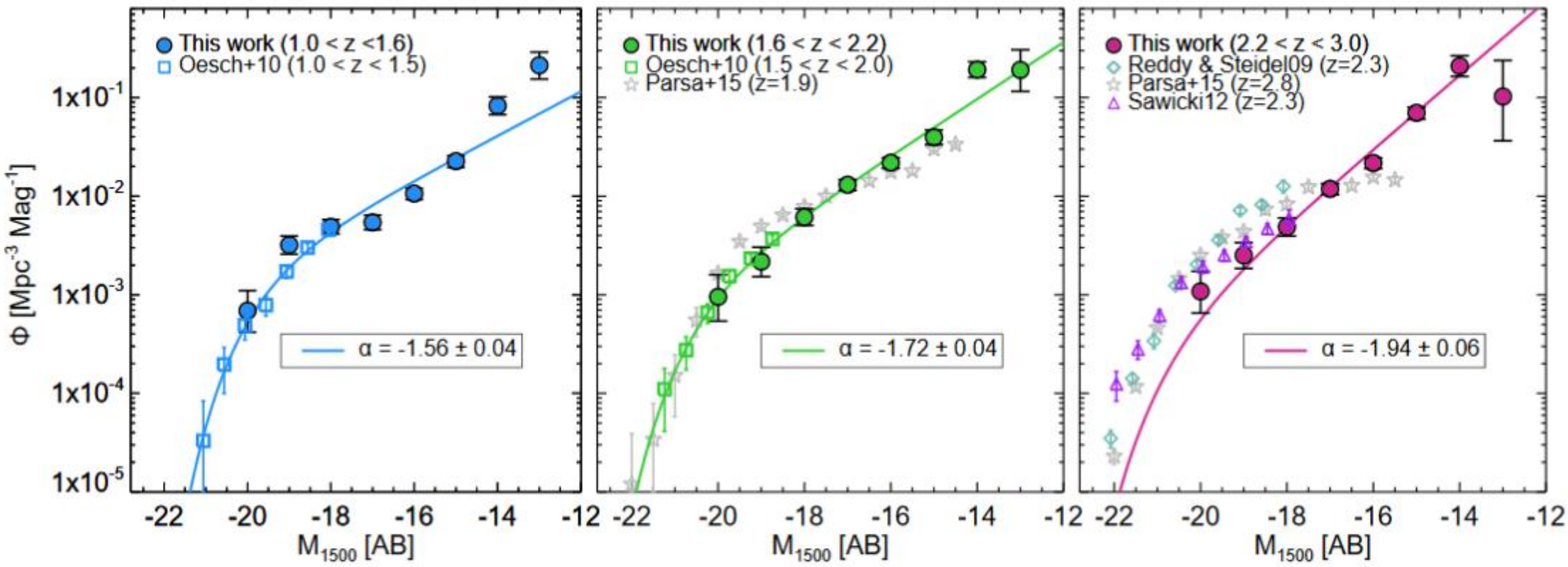
Daniel Ceverino

1000 simulations

Re-ionization done by intermediate mass galaxies

For low-z analogs

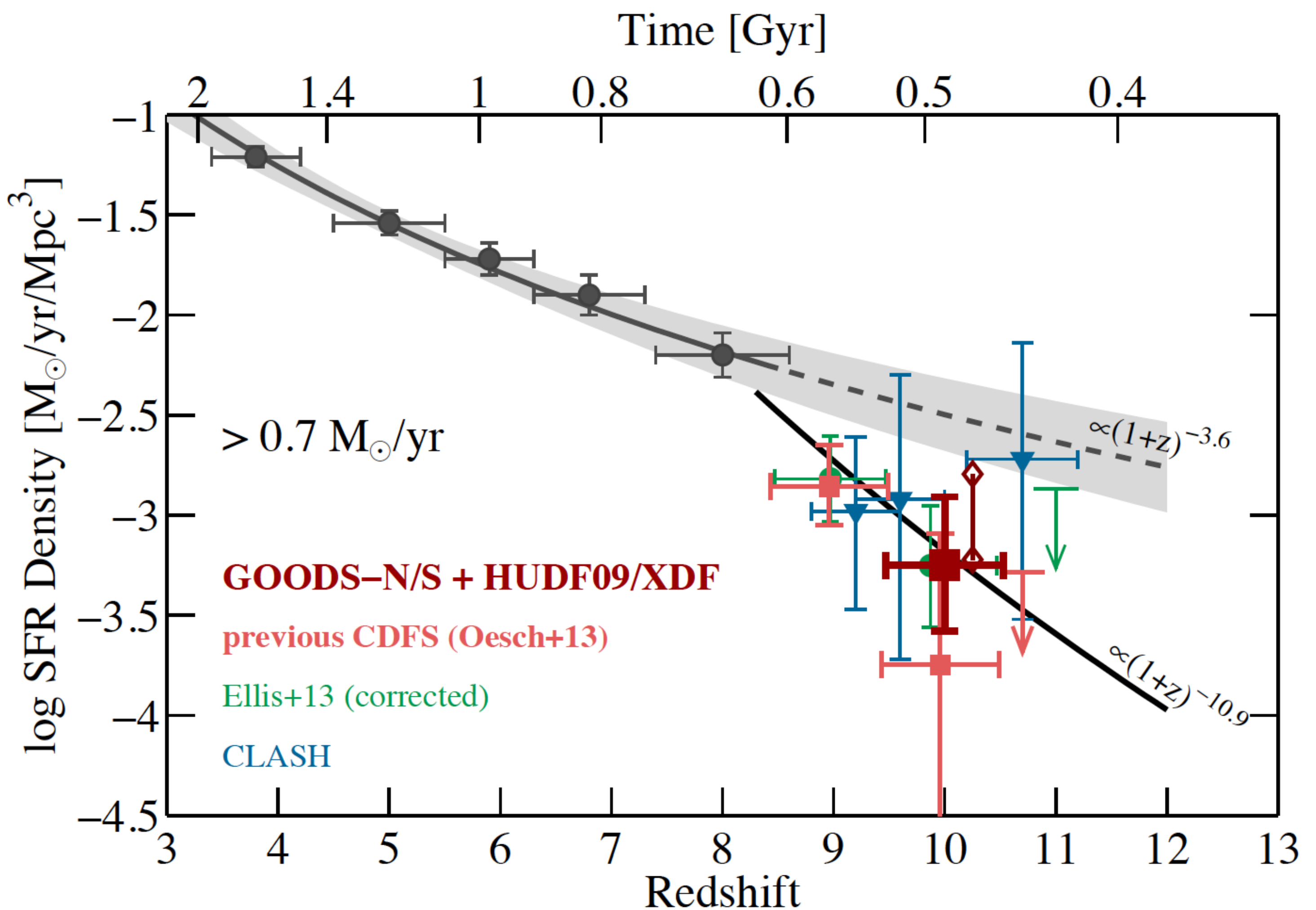
Anahita Alavi



Luminosity density evolution

Oesch et al 2014

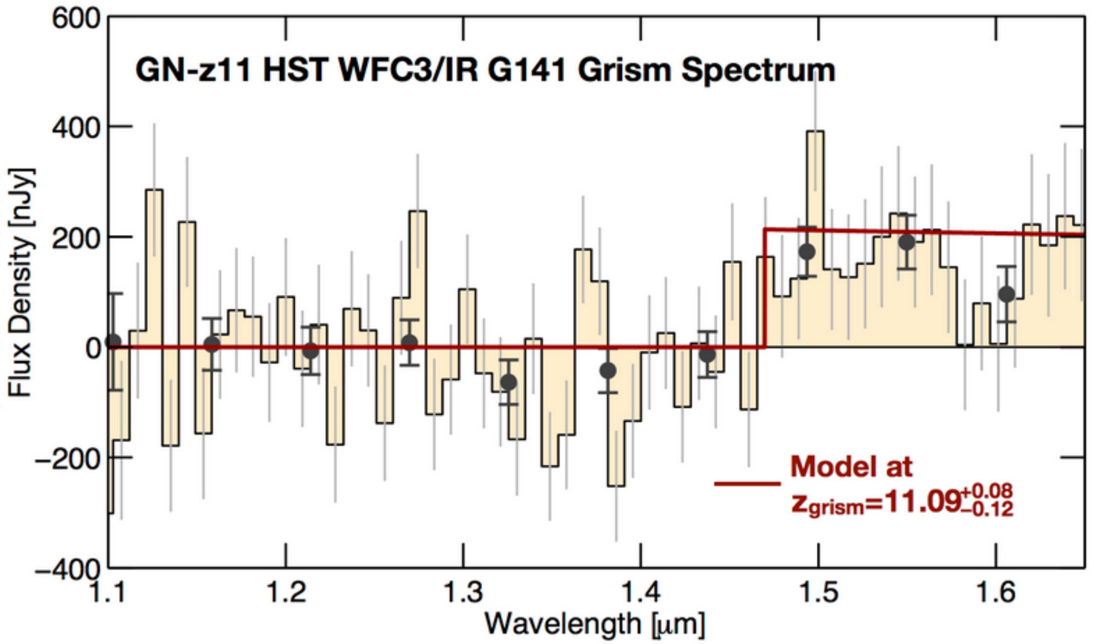
More rapid evolution after z=8



There exist models to explain this (but large uncertainty)

Surprising z=11.1 object

Oesch et al 2016



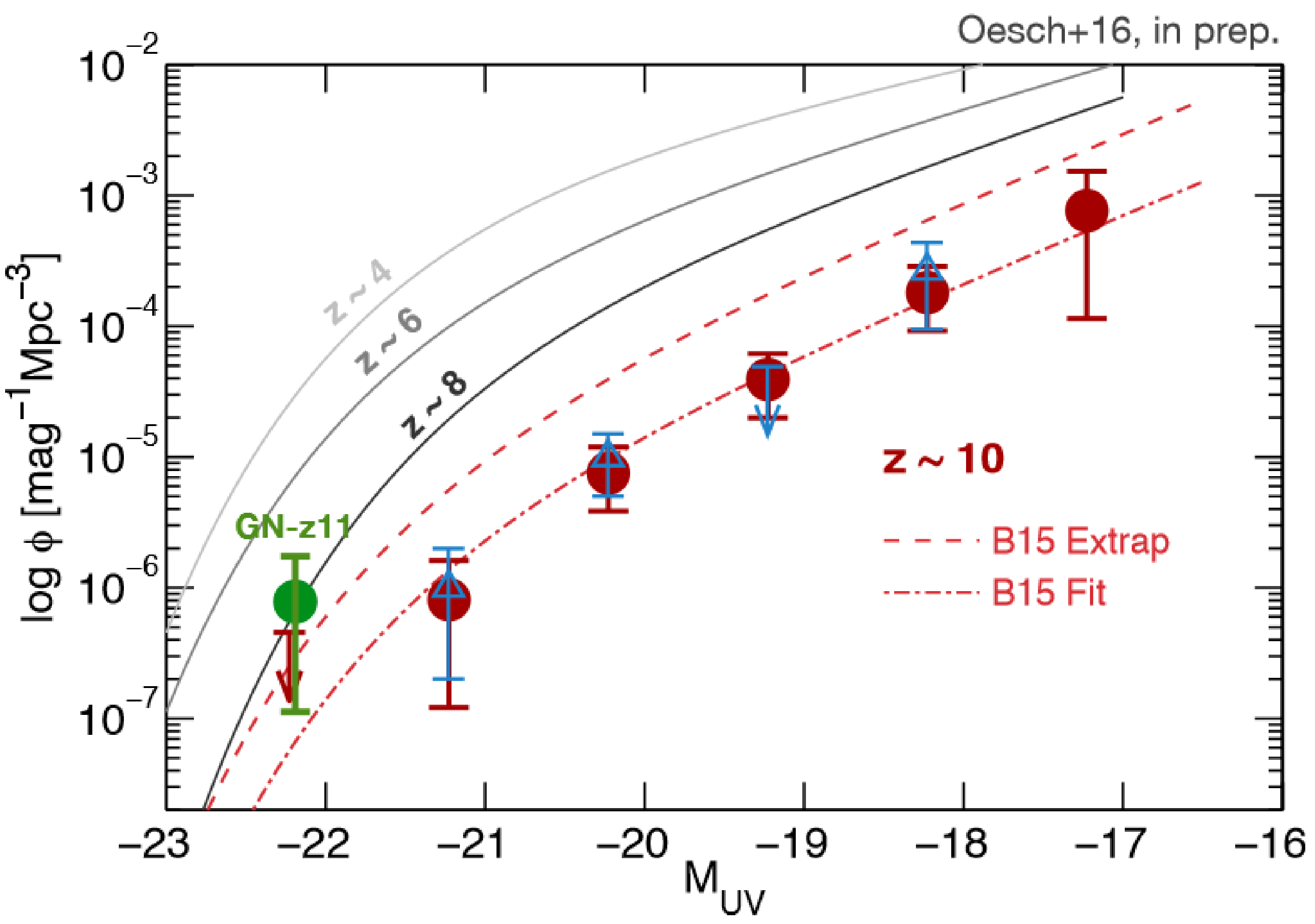
Mass 10^9 M_o

Should require 10-100 more area to detect such a bright object

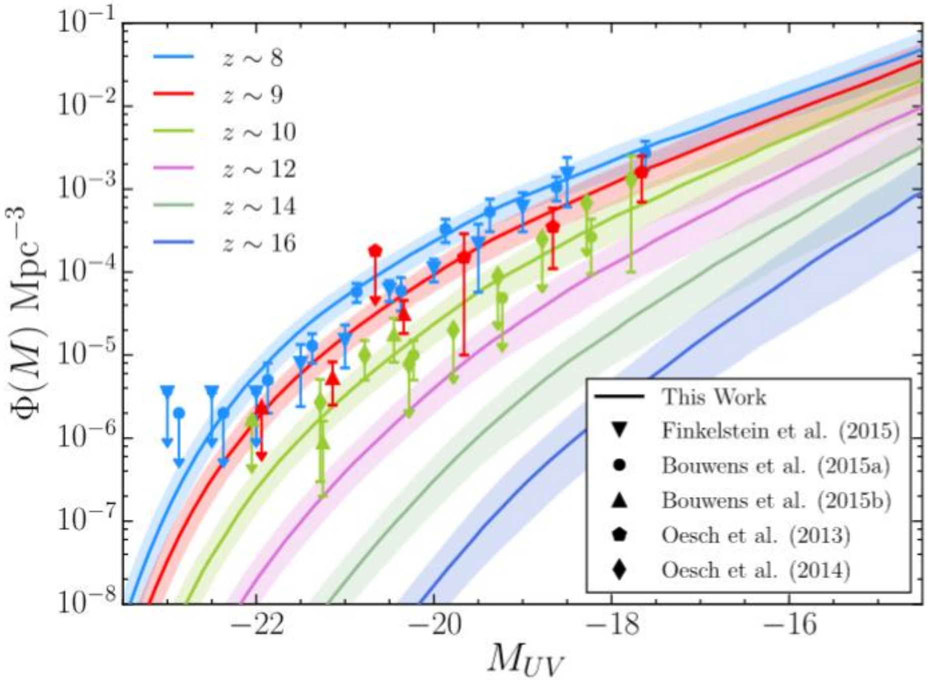
The z-phot was derived at 10.2 (Labbe 2008)

The brightest object at z> 6
Detected in a survey of only 0.2°^{2}

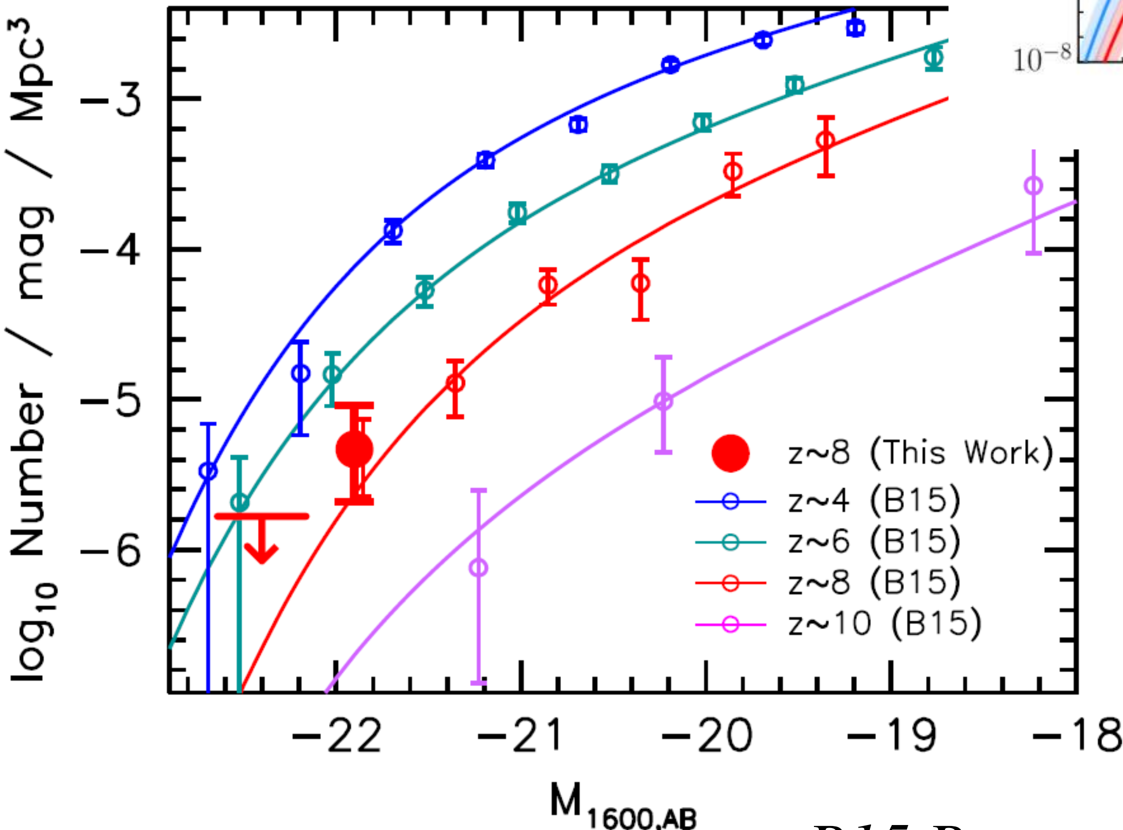
Makes a distortion in LF



Luminosity function at high-z



Roberts-Borsani et al 2016



Mason, Trenti, Treu 2015

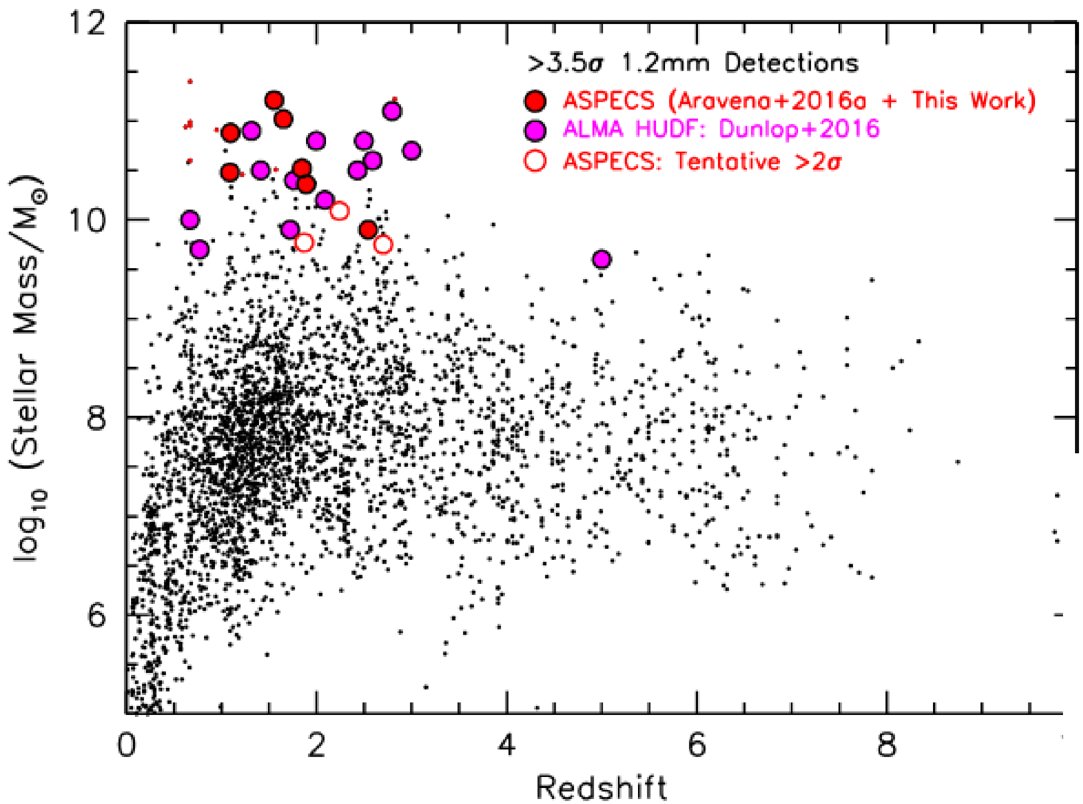
α = -1.68 z=0

α = -2.10 z=8

α = -3.51 z=16

B15 Bouwens et al 2015

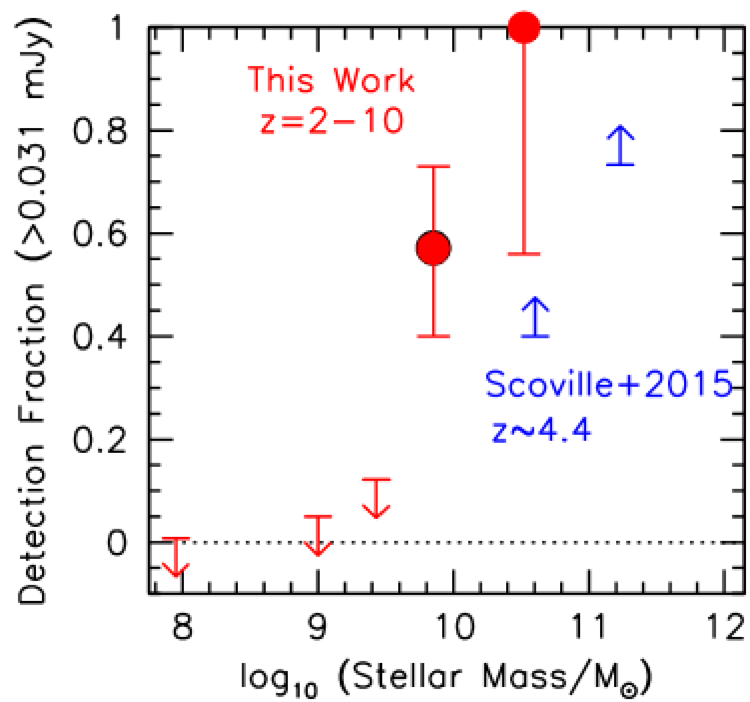
ALMA high-z surveys



Bouwens, Dunlop

Only massive galaxies detected (more dust, Z)

Bouwens et al 2016



HUDF covered by wide and shallow survey *(Dunlop et al 2016)* and smaller deeper ones *(Aravena et al 2016, Bouwens et al 2016)*

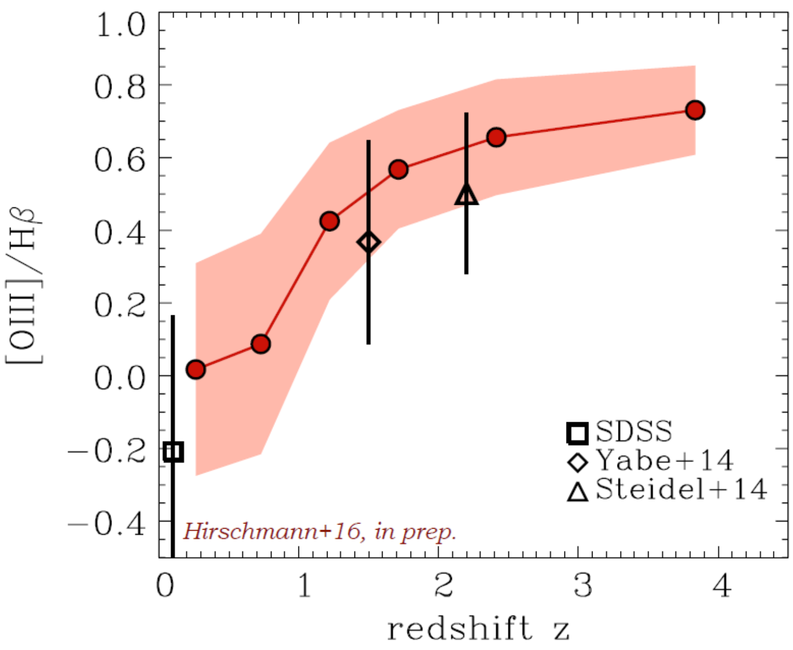
Excitation diagnostics

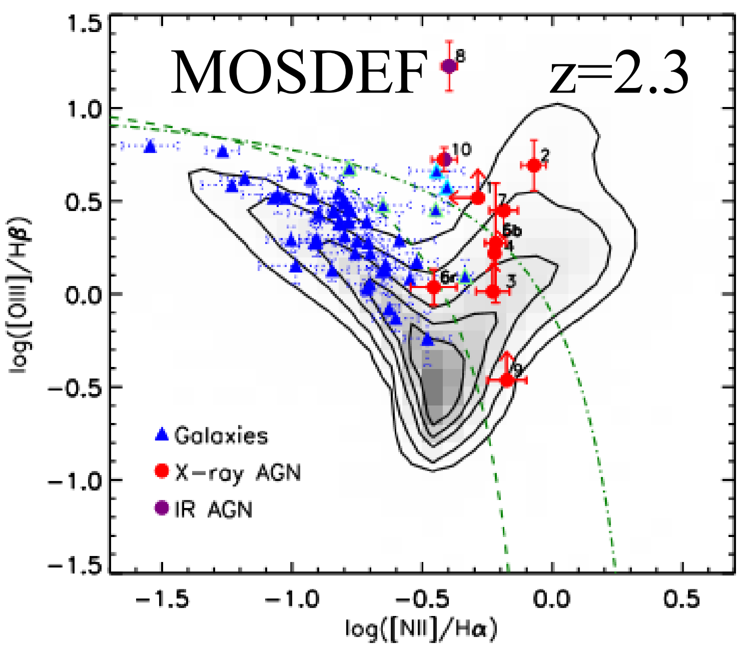
At high z, high radiation fields, compactness, higher ne, pressure
low metallicities Z=0.1 solar, N/O abundance

Different BPT diagram ([SII] instead of [NII])

Take into account the higher excitation [OIII]/Hβ
Michaela Hirschmann

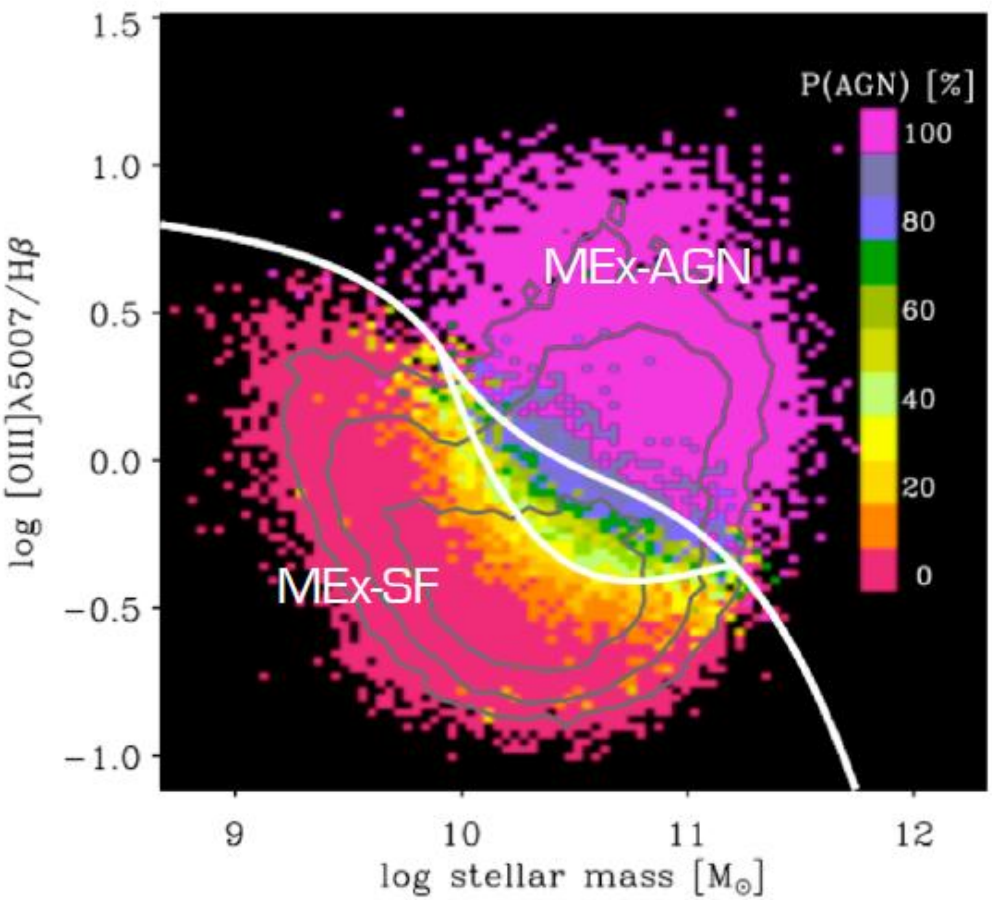
Coil et al 2015



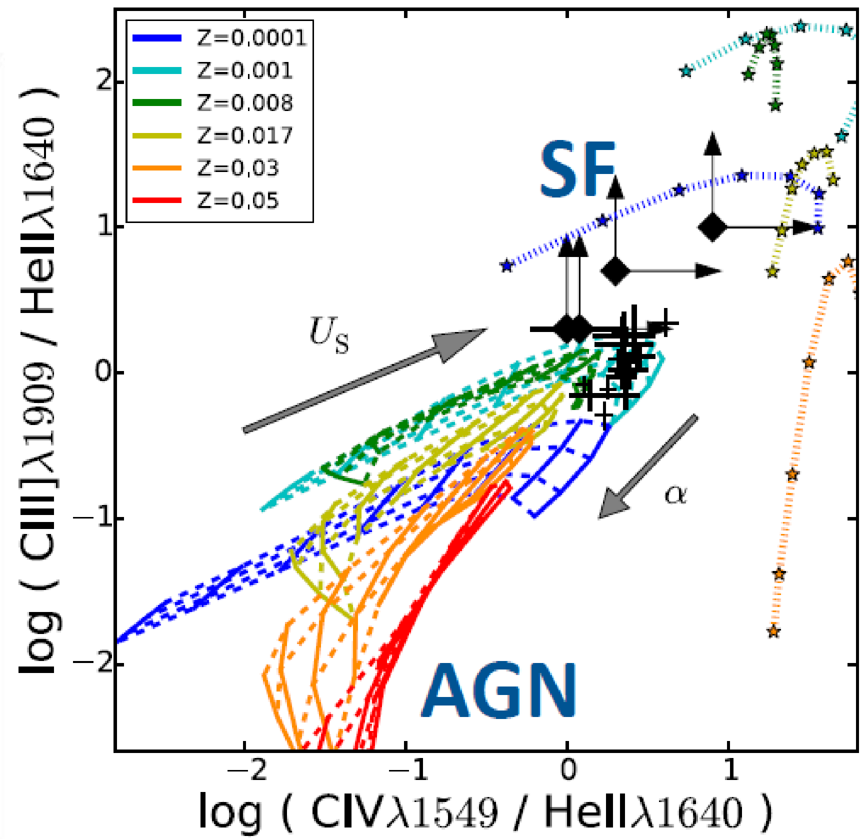


Other diagnostics

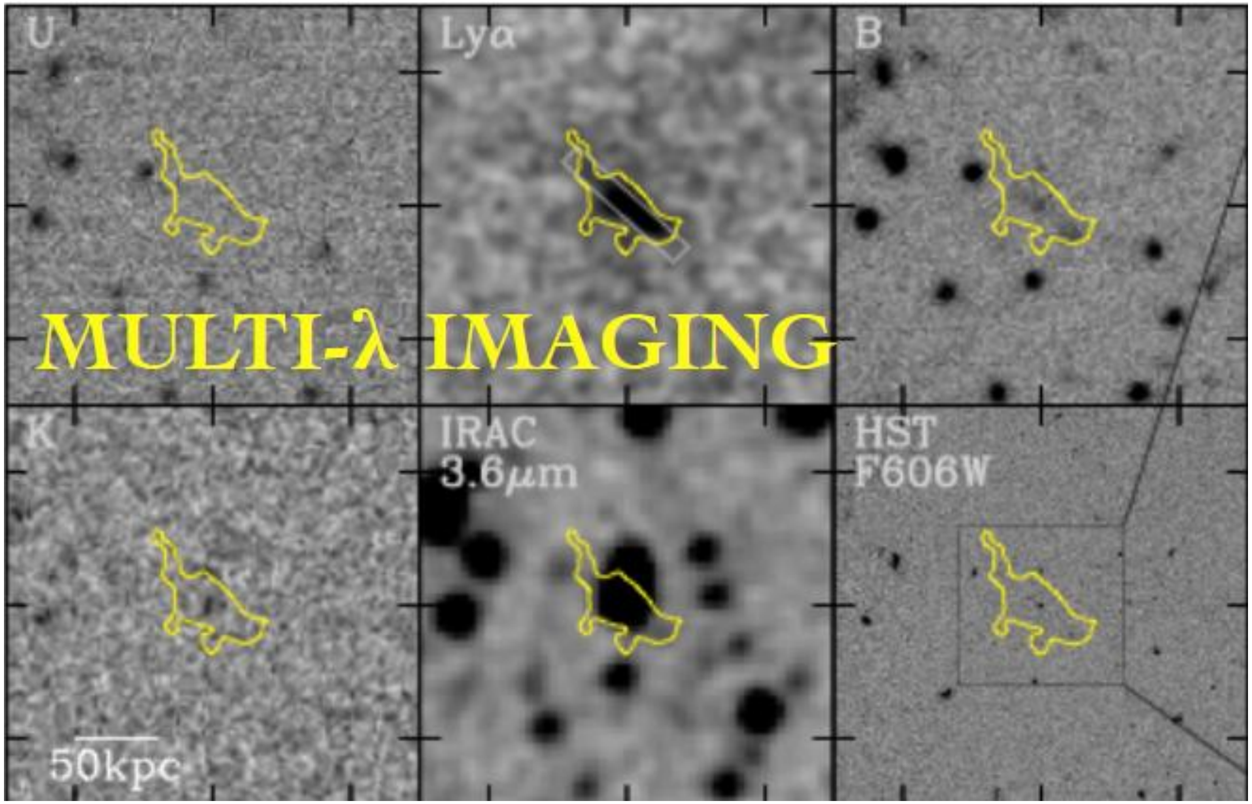
Mass-Excitation (MEx) S. Juneau



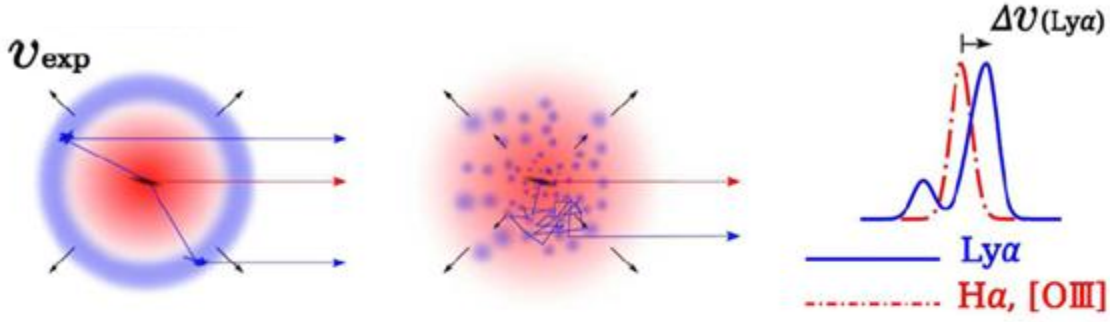
UV lines Anna Feltre



Ly-α blobs: dynosaurs !



Ann Zabludoff

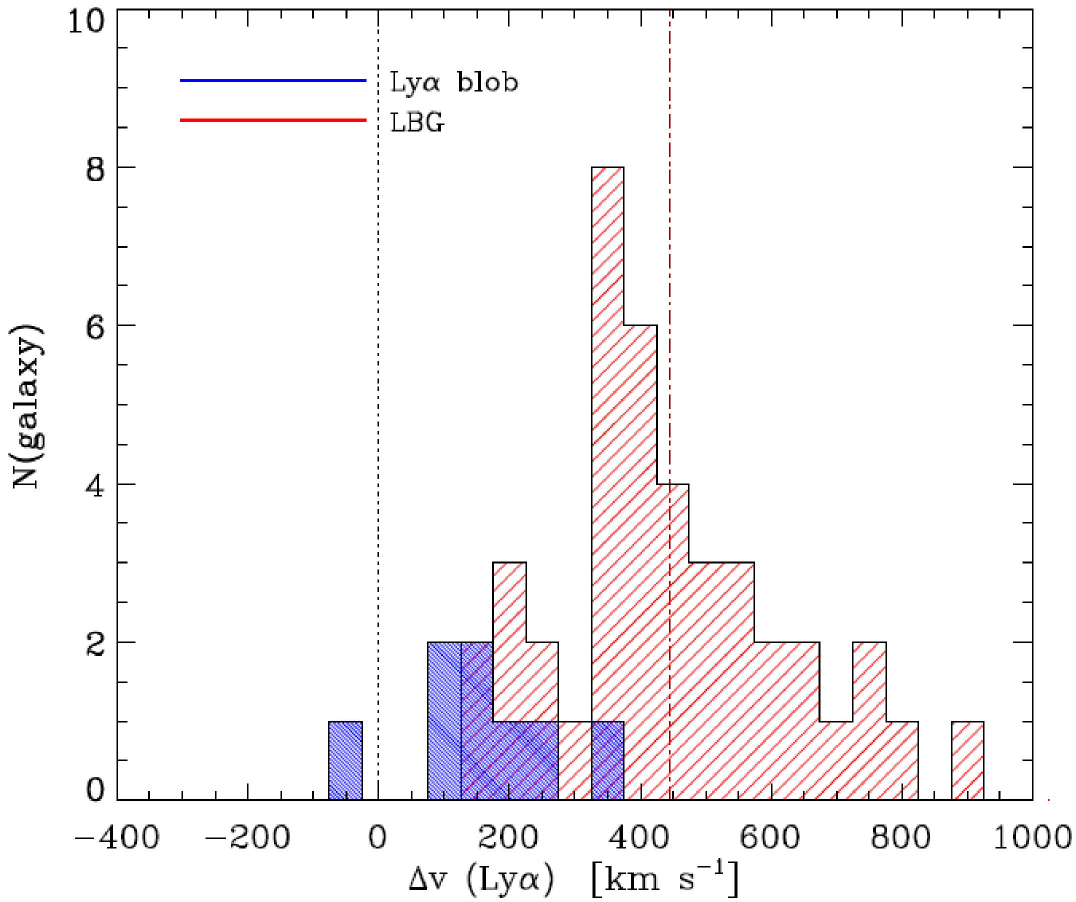


Outflow
Blue-absorption
$\Delta V > 0$

Ly-α blobs vs LBG

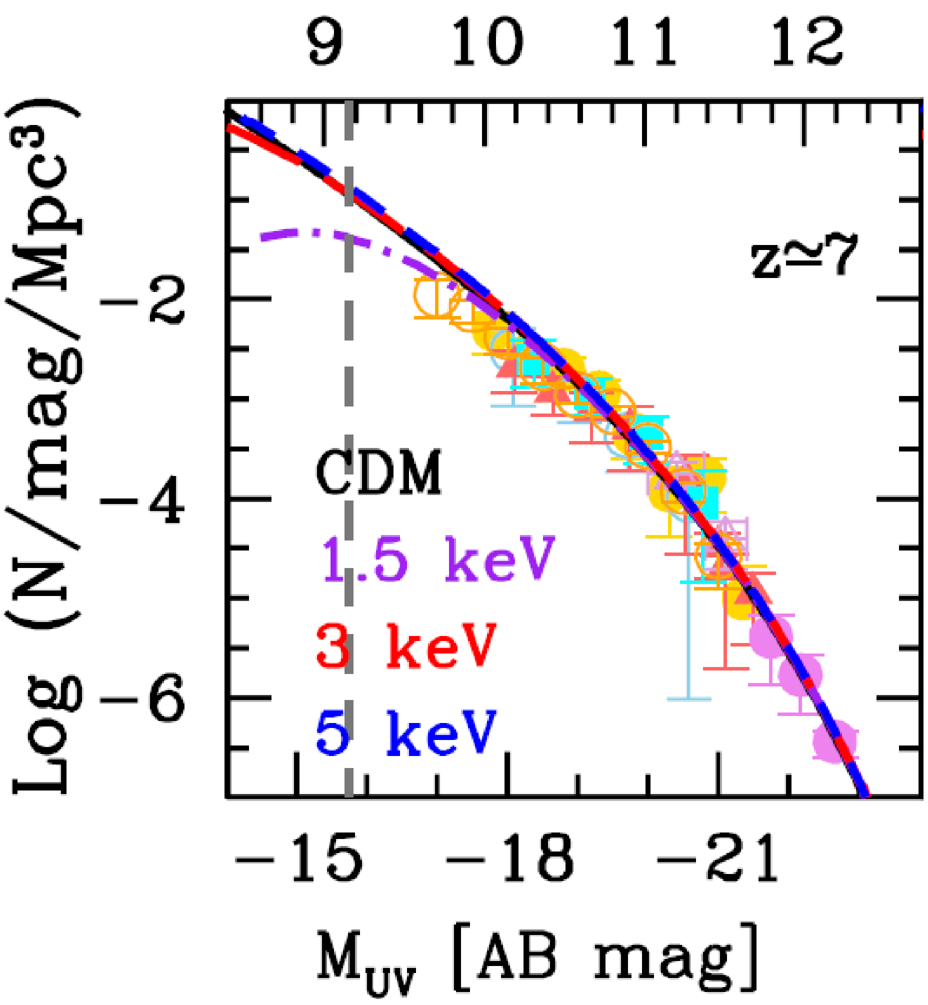
No blue-dominated Ly-α
Always outflowing
No evidence of inflow

Or very rarely
(not likely to be powered
by gravitational cooling)



Velocities observed a few 100km/s (less then LBG)
Not strongly outflowing *(Yang, Zabludoff et al 2014)*

High-z galaxies: diagnostics of DM?



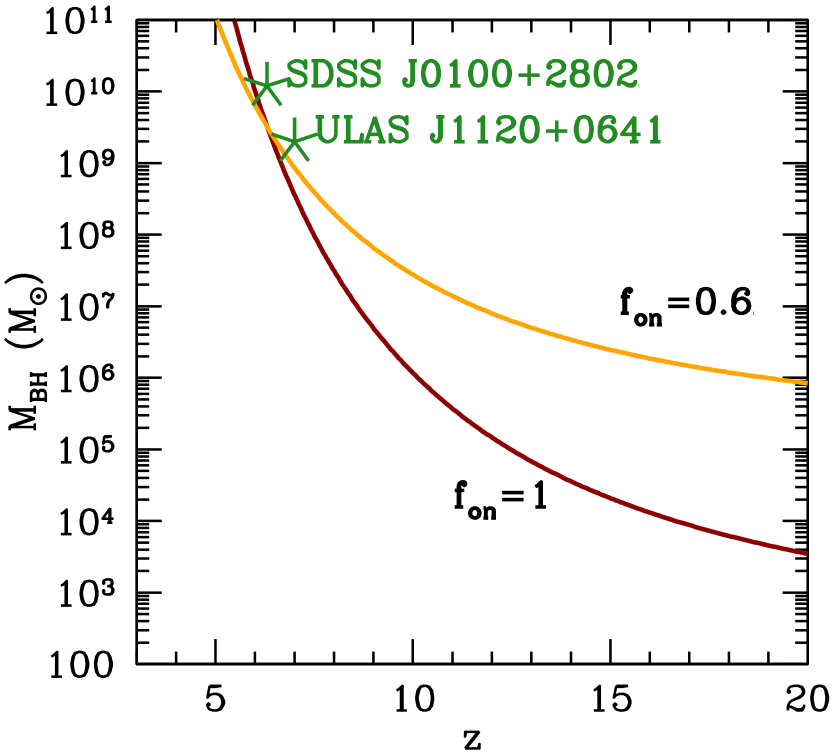
Pratika Dayal

Including baryons (and SF) decreases the difference between CDM and 1.5 keV WDM models

(Dayal et al 2015)

The puzzle of high-z quasars

Detection of a $2\times10^9\ M_o$ BH at z=7 and a $10^{10}\ M_o$ BH at z=6.3 (Mortlock et al., 2011, Wu et al. 2015)



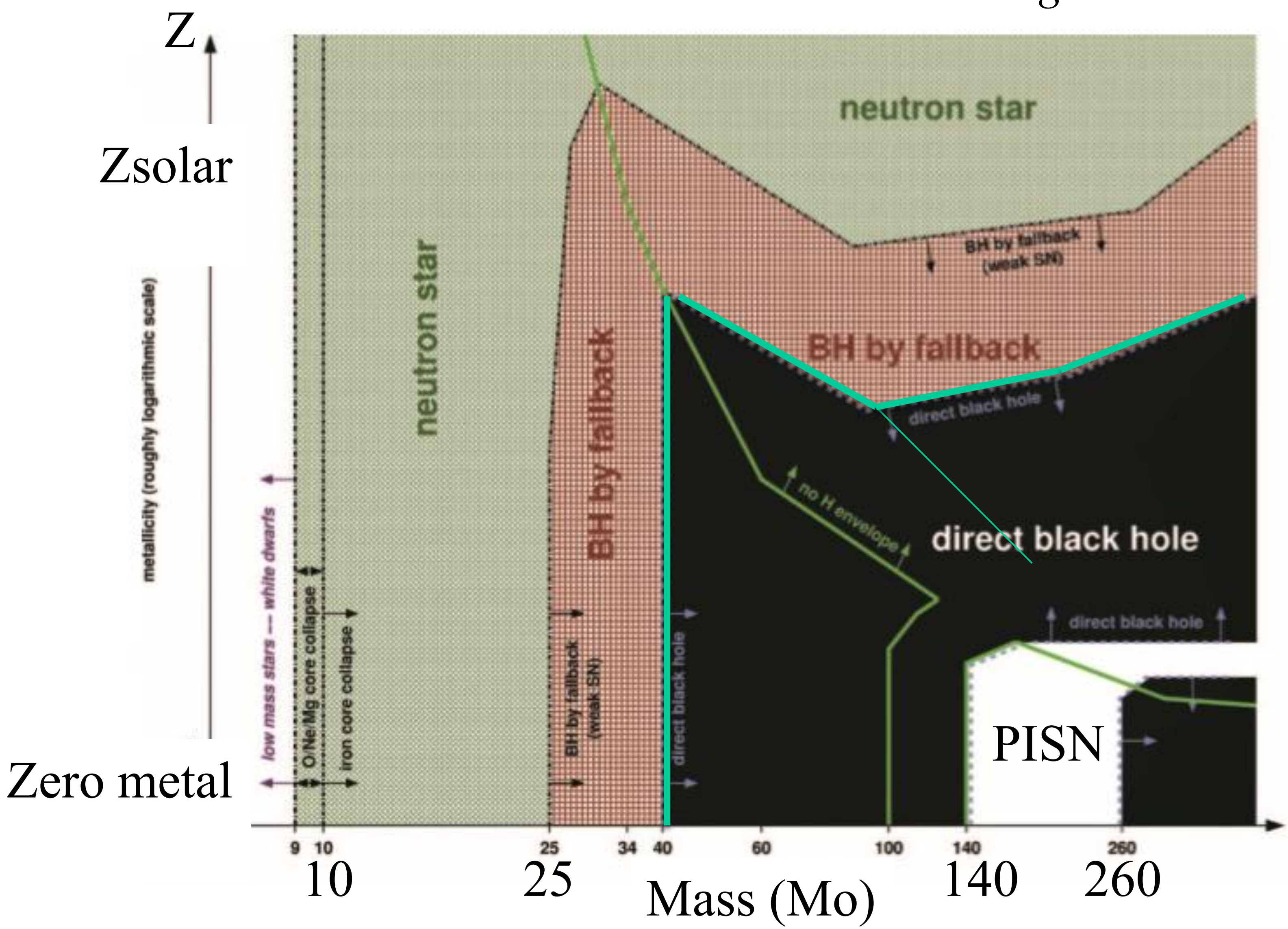
Requirement:

- Need to grow at the Eddington limit for the whole time (M_0~300 M_{sun}) or 60% of the time (M_0~$10^5 M_{sun}$)

Direct black hole formation

Low metallicity is essential

Heger et al 2003



Growth of BH at high redshift

Marta Volonteri

Seeds: could be very massive stars (low metallicity)

Direct collapse BH, if H_2 formation is suppressed by nearby UV flux

Eddington limit can be passed

Super-critical growth, faster, emitting less light (sub-Eddington Lum)
Slim-disk accretion, compared to standard
Less ionizing photons?

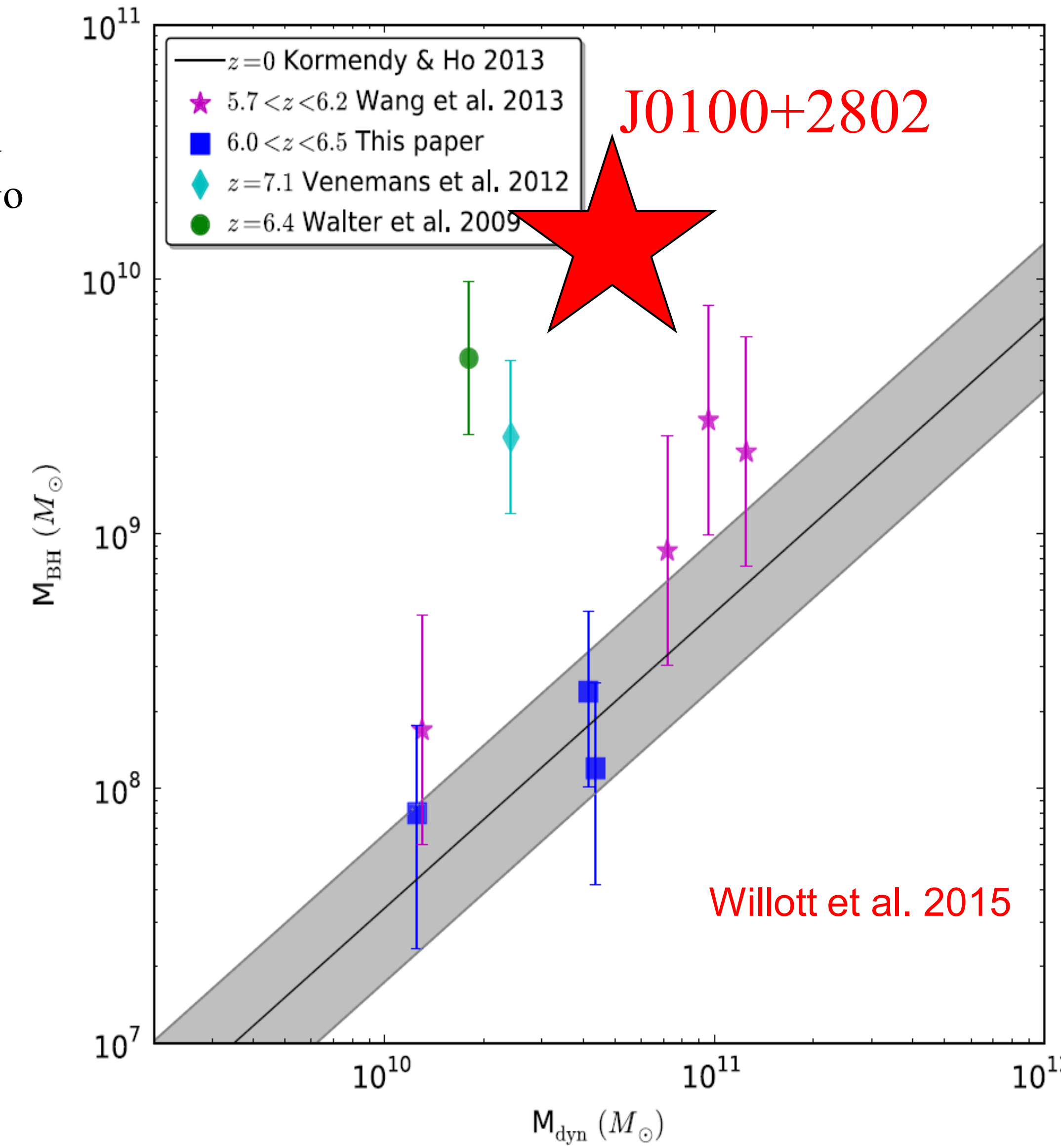
BH predicted to produce 20-50% of the reionization
(Volonteri & Gnedin 2009)

Over-massive SMBH at high-z

The most massive 1.2 $10^{10} M_o$
J0100+2802 z=6.3
Wu et al 2015, Nature

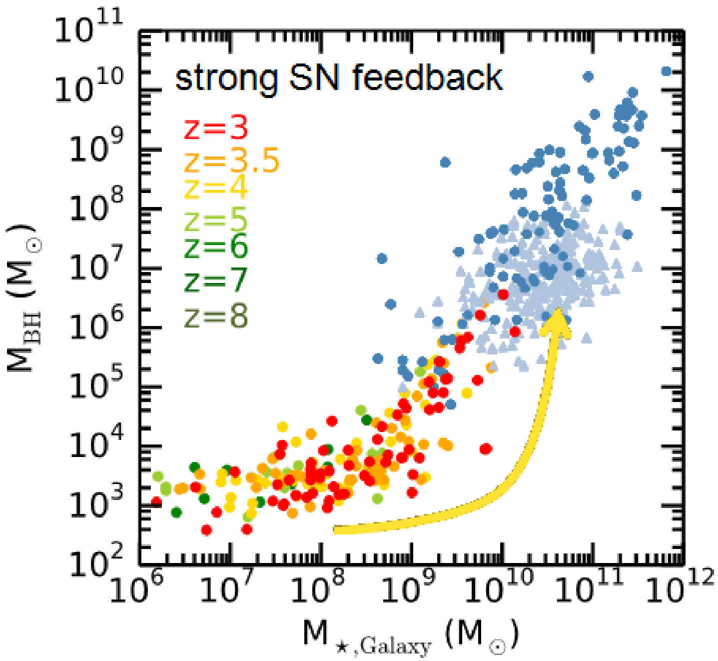
Also the highest Lum
Eddington

Could that be only a
selection bias?

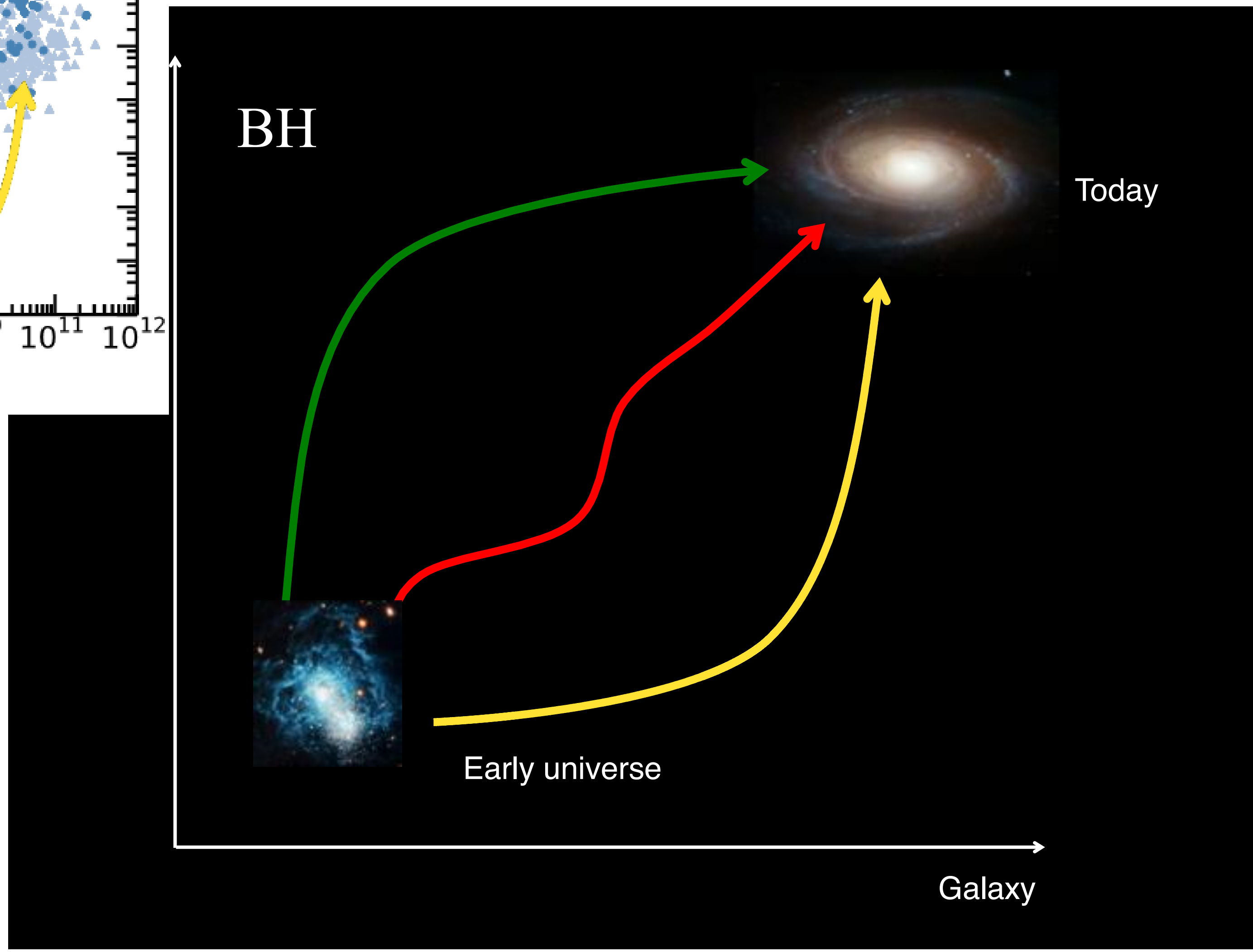


How do BH grow?

Marta Volonteri

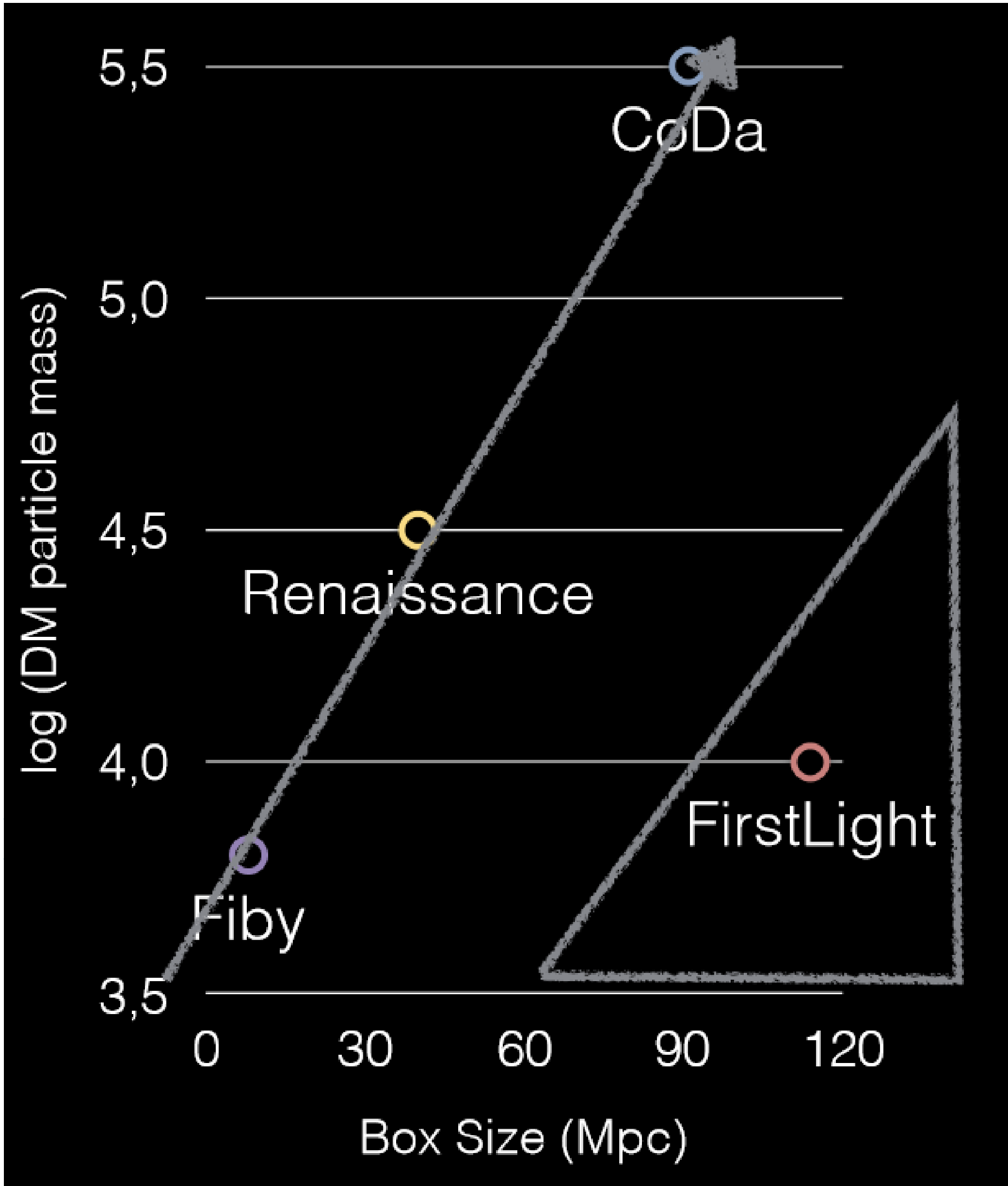


Habouzit et al 2016



2- Simulations: first galaxies, mass assembly

CoDA (P. Ocvirk)
Renaissance (J. Wise)
FirstLight (D. Ceverino)
FiBy (S. Khochfar)



Quasars at z=6?

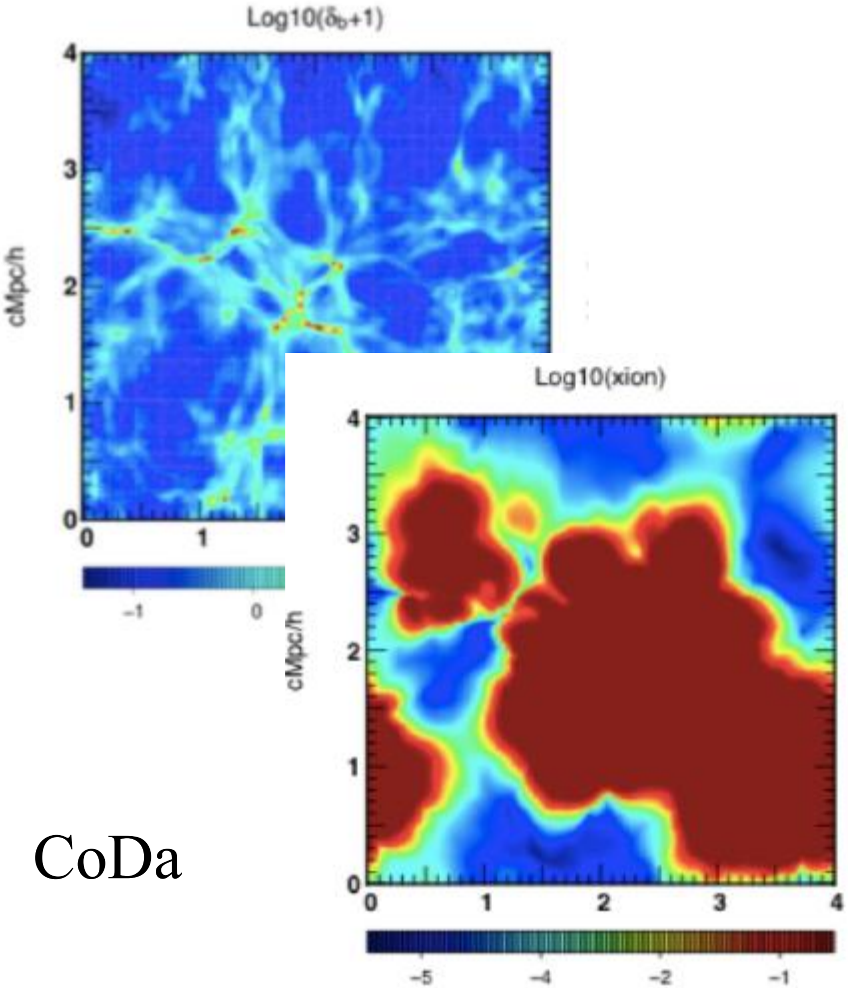
Requires that seeds of $M_{BH} = 10^5$ are there at z=10

Then Bondi-Hoyle accretion
Eddington rate in simulations

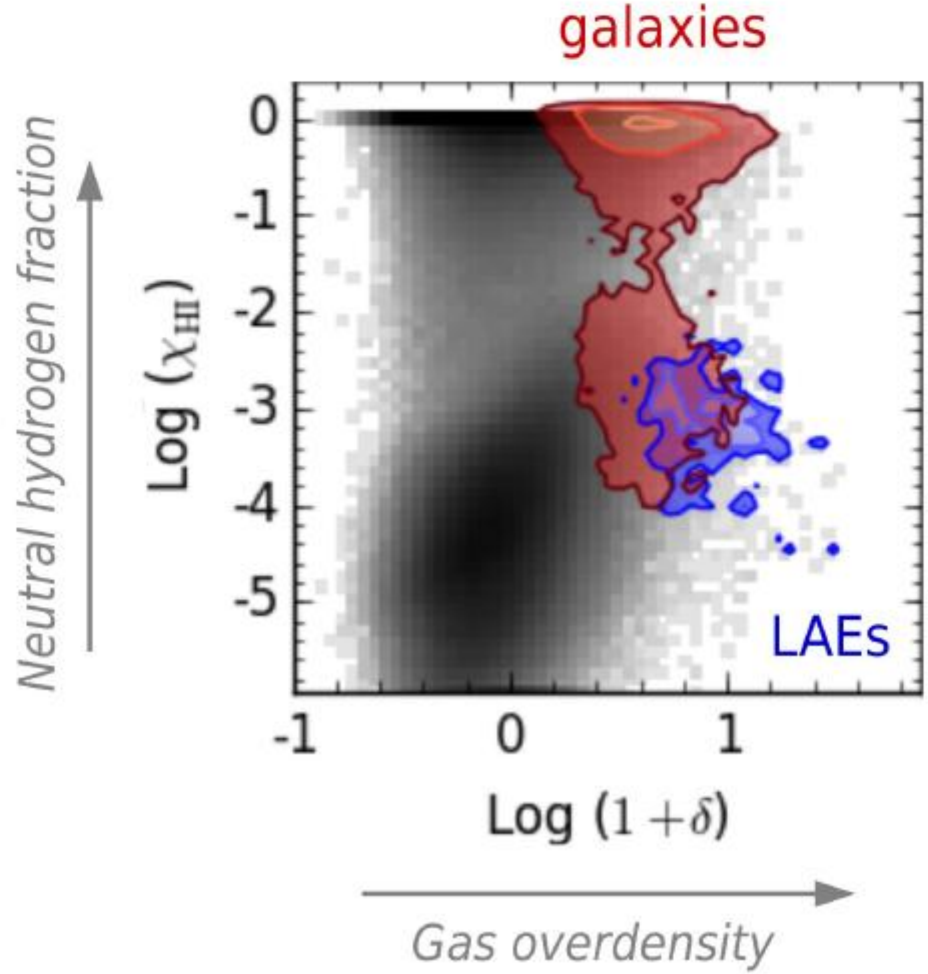
Correlation 21cm - LAE

A Future tool for the EoR
The 21cm surveys
LOFAR - SKA

Anne Hutter



CoDa

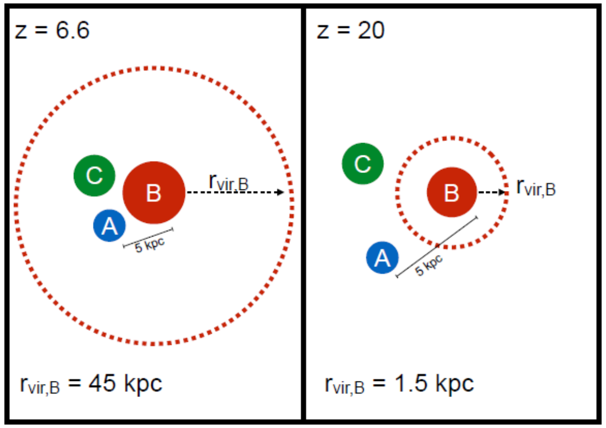


Black hole formation

Volker Bromm

DCBH: Direct collapse of super-massive stars: external UV field prevents H_2 formation: gas cannot fragment ($10^5 M_o$ star)

During galaxy mergers, gas can flow to a high nuclear concentration
➔Direct collapse to a BH (Mayer et al 2010)
If the gas can cool, formation of a dense nuclear cluster, which then undergoes star collisions into a BH
Formation of VMS of 1000 M_o, then a BH of the same mass (no SN), plus stellar relaxation processes *(Yajima & Khochfar 2016)*



CR7 LAE Agarwal et al 2016

Jcrit in the UV depends on the SED

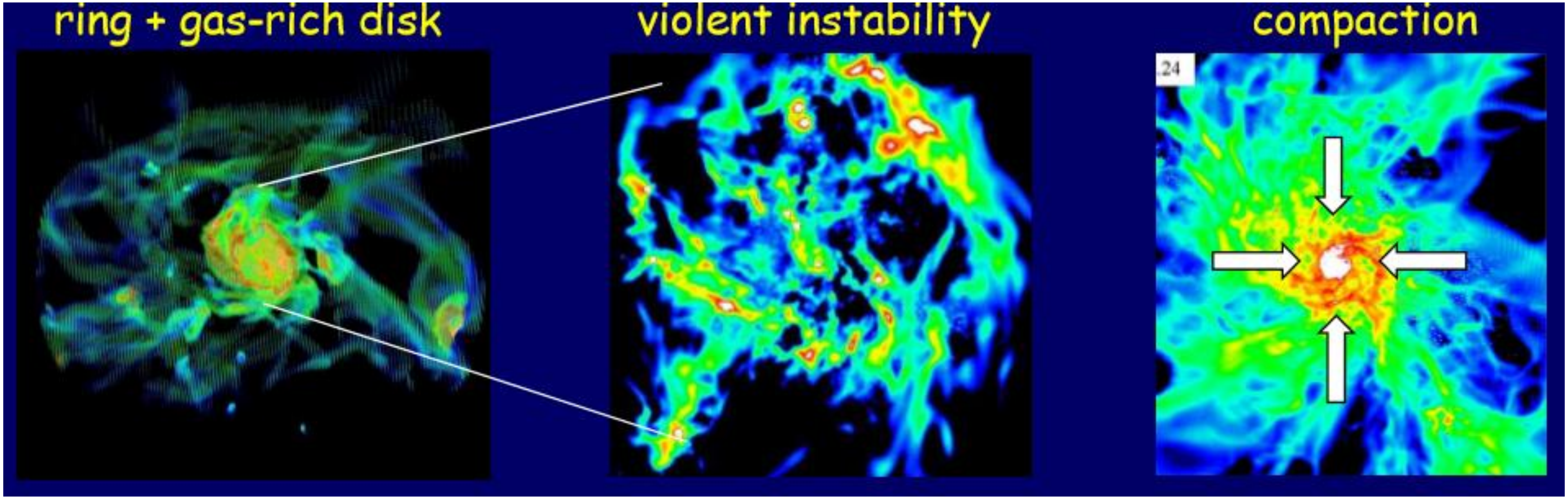
Mass assembly z=10-3

Avishai Dekel

Accretion and SFR time-scales

z>3 tacc < t_{SFR}, gas accumulates, explains high fgas in galaxies

At z<3 gas accretes in a few orbital times ➔ VDI



3- Physics from SED, ionizing sources

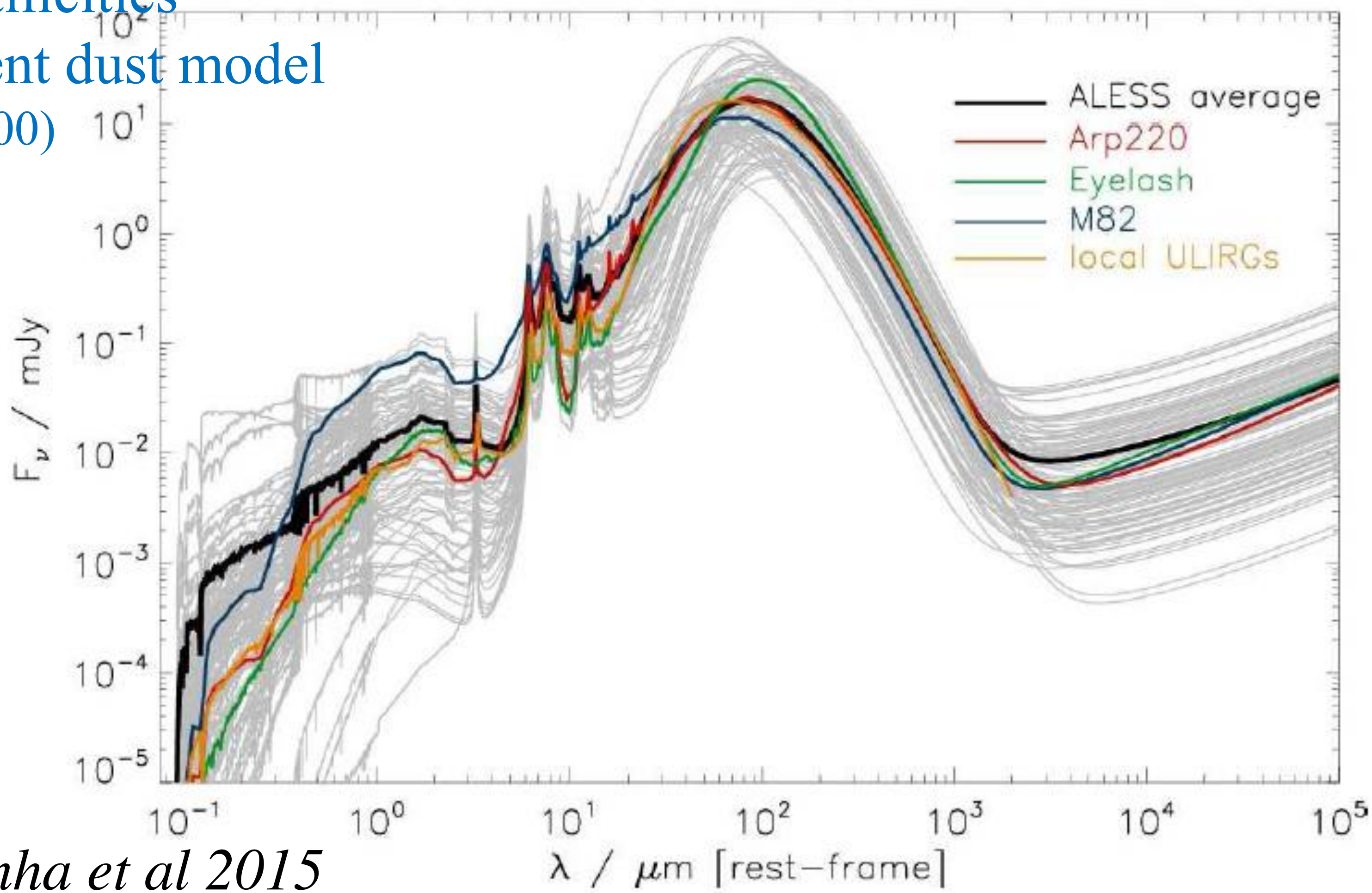
How to measure SFR at high z? (assuming Zsol, IMF, ..)
--UV emission: problem of dust
--Recomb and forbidden lines (again dust, or leakage from AGN..)
--Infrared dust emission: global, however, dust could be heated by old stars or an AGN (torus)
--FIR fine-scructure lines (CII, etc..) calibrations uncertain

➔Multi-wavelength hybrid method, with SED
Break degeneracies, dust, age metallicity, depends on stellar pop but can obtain many physical parameters (stellar mass, SFH..)

Optimization, statistics: χ^2 or Bayes?

SED fitting for SMG

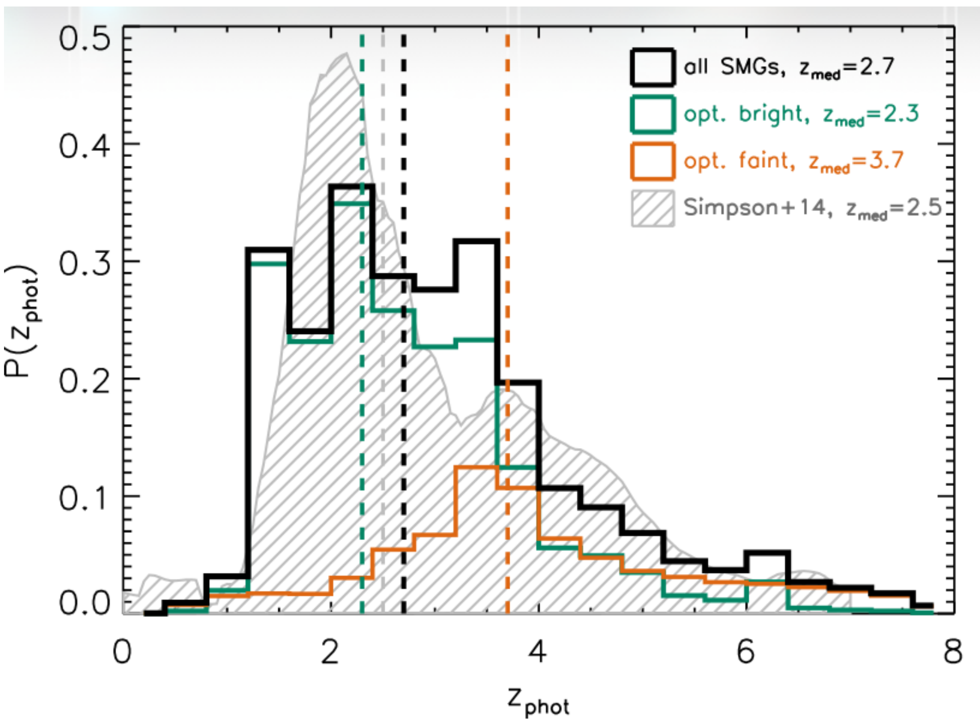
MAGPHYS, extended to high-z
--Bruzual & Charlot models, fixed Chabrier IMF
--range of star formation histories
-- range of metallicities
-- two-component dust model
(Charlot & Fall 2000)

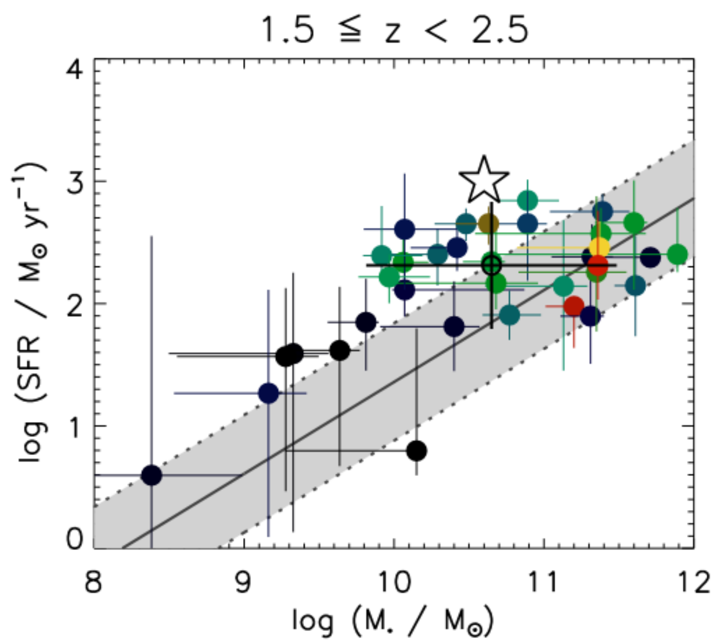


Da Cunha et al 2015

Application to SMG in LESS

126 SMG detected with LABOCA (APEX)
Now with ALMA: 30-50% of sources resolved into multiple SMGs





BEAGLE: New Bayesian tool

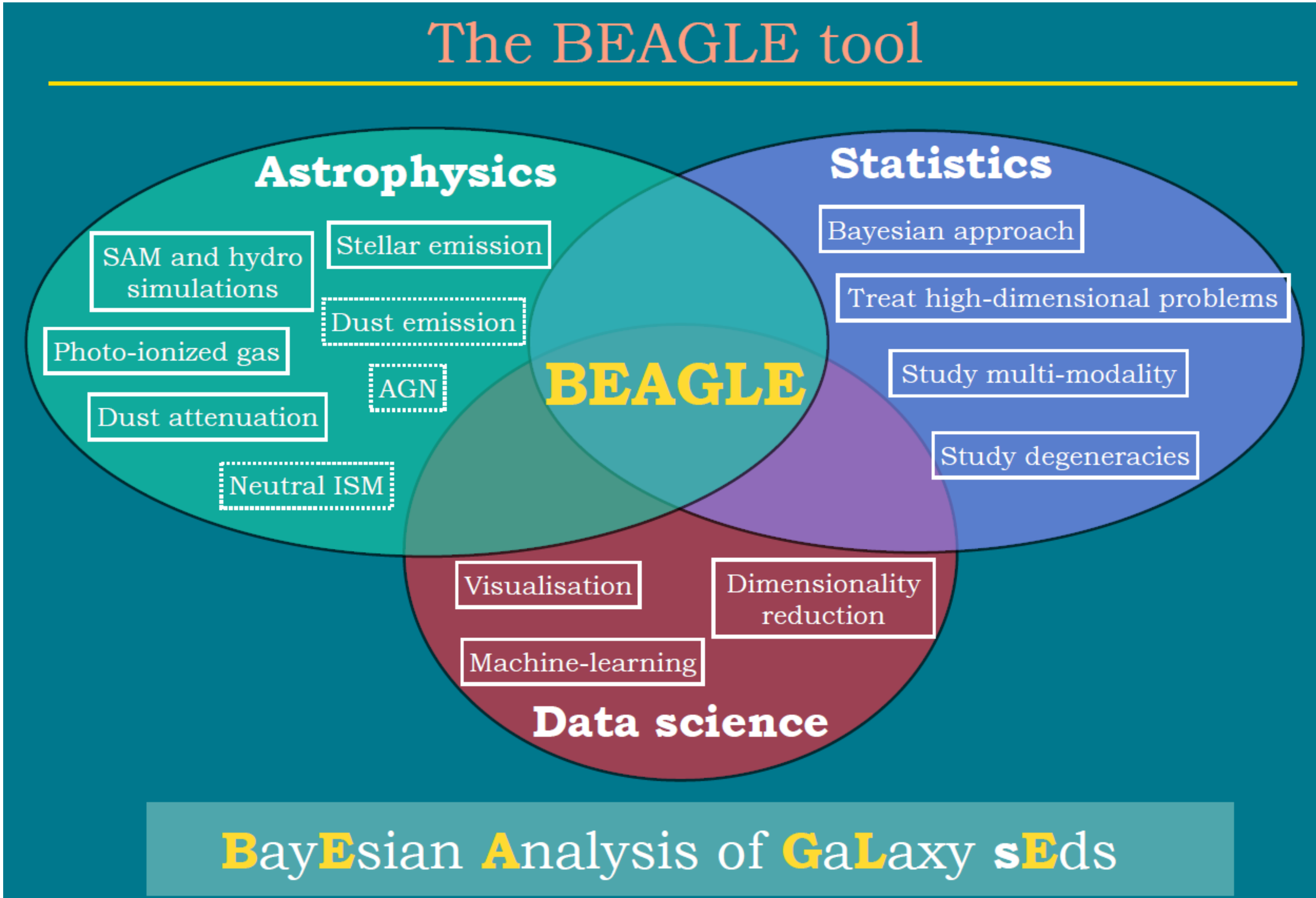
Jacopo Chevallard

*Stell*ar pop+ nebular emission
Radiation tranfer, dust extinction, metallicity
α/Fe ratios, AGN properties

Fit the SED of 10^4 galaxies
Photo-z, SFR history

- 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 modeldriven approaches to SED analyses (D. Stenning)

Chevallard & Charlot 2016



SFR-M_*, M_*-Z at high-z

BEAGLE allows to both produce mock photometry
with selfconsistent SF and chemical enrichment histories and nebular emission as well as performing full Bayesian SED fitting (Jacopo Chevallard, Emma Curtis-Lake, Julia Gutkin)

The Bayesian hierarchical modelling can recover and provide the full uncertainties in slope, intercept and intrinsic scatter of the M*-SFR relation.

- No assumption of shape of joint uncertainties in M*-SFR for individual objects.
- Allows us to assess and compare different selection and SED fitting strategies.

The Bayes Church: new methodology

David Hogg, Jarle Brinchman

Are we going to interpret modern rich data like 40 yrs ago?

$$\text{Posterior} = \frac{\text{Likelihood} \times \text{Prior}}{\text{Model evidence}}$$

Data d, Model M, and parameters θ

$$P(\boldsymbol{\theta}|\boldsymbol{d}, M) = \frac{P(\boldsymbol{d}|\boldsymbol{\theta}, M)P(\boldsymbol{\theta}|M)}{P(\boldsymbol{d}|M)}$$

Inversion problem

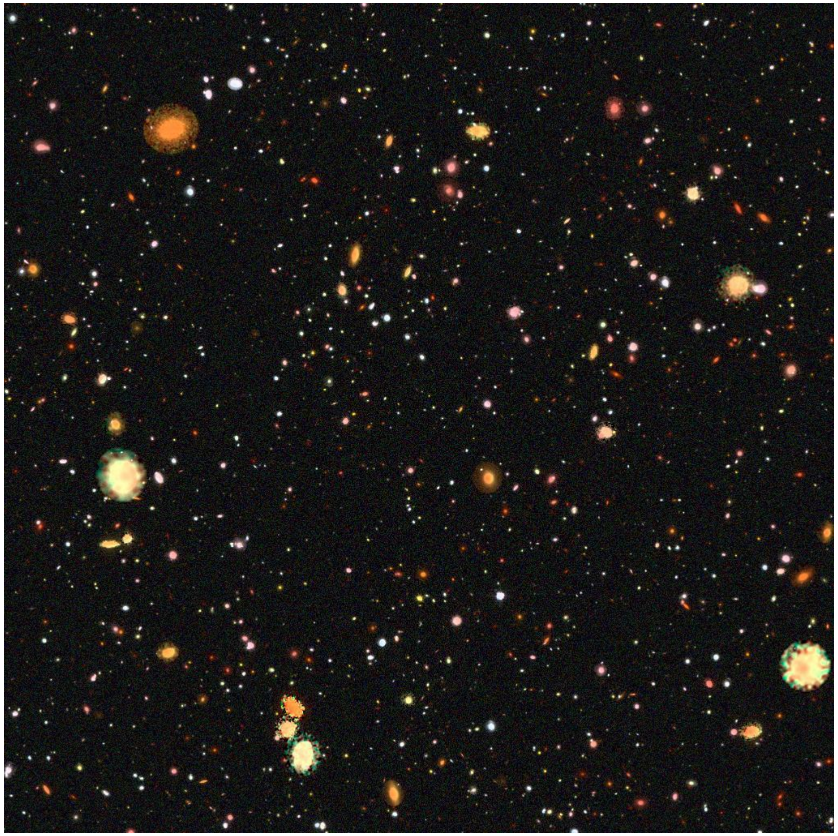
Make your assumptions explicit!
Classification of galaxies through computer, deep learning
➔Use artifical intelligence, machine-learning with big data

Forward modelling

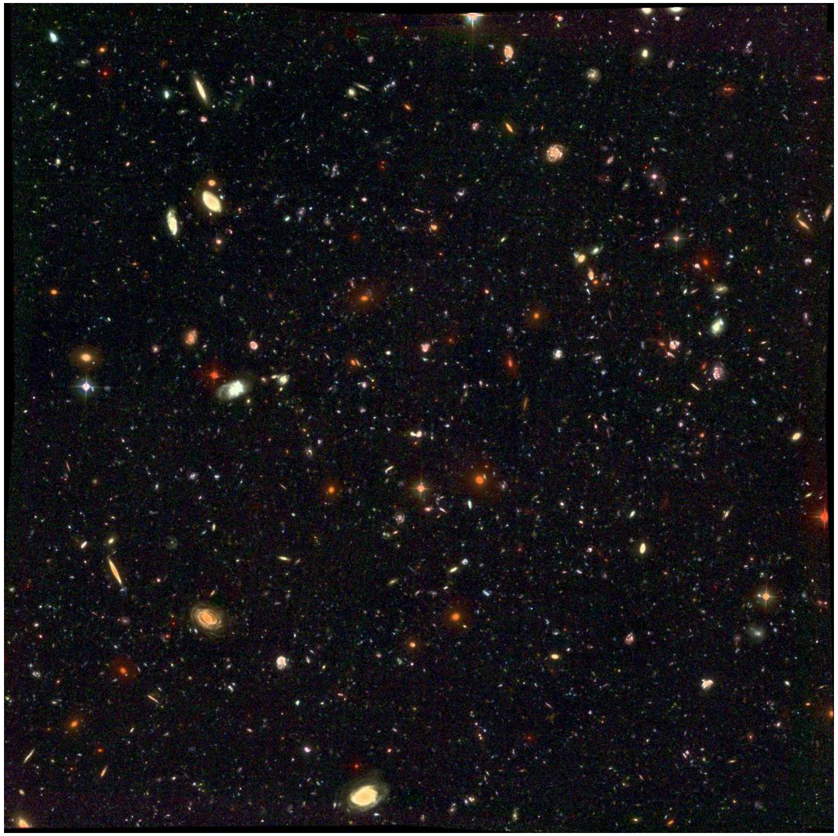
Mike Fall

See the difference by eye!

HUDF image: f850lp, f606w, f435w filters



Mock HUDF map



Real HUDF map

For z > 6, be skeptical of any statistical results not derived by forward modeling!.

http://www.sedfitting.org/SED08/Models.html

BayeSED (Yunkun Han)

STELLAR POPULATION MODELS

Note: There exist other webpages with link collections, e.g. at STScI or from th

BASTI
: A bag of Stellar Tracks and Isochrones

BPASS
: Binary Population and Spectral Synthesis

Buzzoni
: SSPs, Template Galaxy Models and more

Coelho
: Spectral models for Solar scaled and α-enhanced stellar popul

FSPS
: Flexible Stellar Population Synthesis by Conroy et al.

Galadriel
: The Padova GALaxies AnD single stellaR populatIon modELs

Galaxev
: The Bruzual and Charlot Stellar Population Synthesis models

Galev
: GALaxy EVolutionary Synthesis models by Kotulla et al., includes the spectral and chemical evolution of galaxies

Gonzalez Delgado
: Models for both evolution of Balmer Absorption lines, and higl spectral resolution stellar libraries

Lee, Worthey et al.
: Lick indices with individual element abundance variations

Maraston
: The Maraston et al. 'fuel-consumption' stellar population synthesis

MILES
: The stellar population synthesis models for old and intermediate age stellar populations by Vazdekis et al.

Pegase
: "Projet d'Etude des GALaxies par Synthese Evolutive" code by Rocca-Volmerange et al., includes high-res SSPs based on ELODIE

PopStar
: Evolutionary Synthesis Models by Garcia-Vargas, Bressan, Molla

SLUG
: Stochastically Lighting Up Galaxies

SPoT
: Stellar Population Tools

Starburst99
: Stellar population code designed to model spectrophotometric and related properties of young galaxies

Yggdrasil
: Spectral models for the first galaxies, including nebular continuum and emission lines

DUST EMISSION MODELS

4- Low-z analogs: Green Peas

Name from citizen science in the Galaxy Zoo!

Lyα sizes 2-5 times larger, widened by resonant scattering

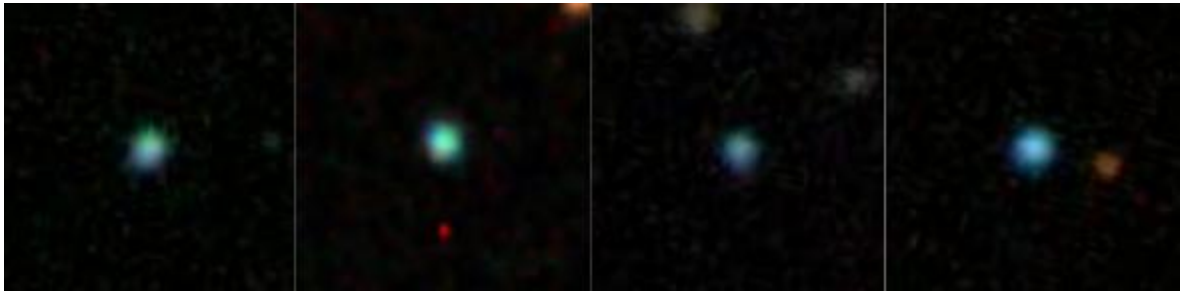
Low M*, low Z, high SFR, high magnetic field

From Lyα/Hα ratio, 5 to 60% of Lyα photons escape

No correlation of escape fraction with velocity of LIS (metal lines)

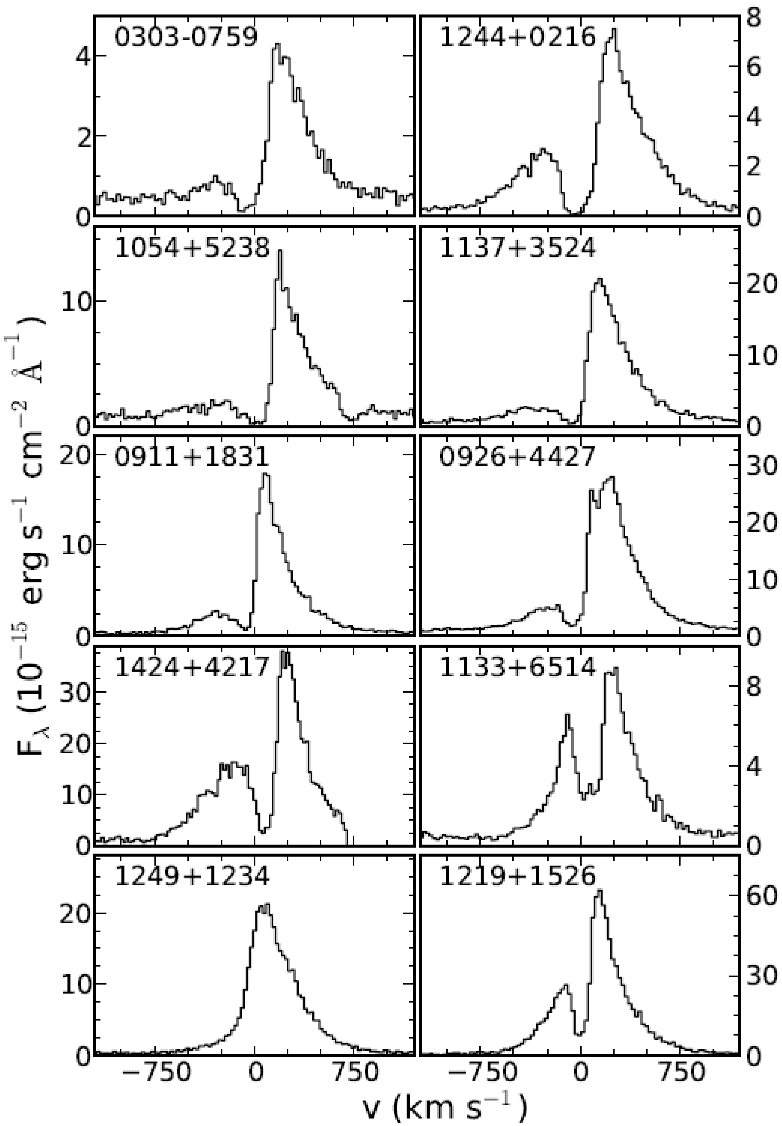
No patchy coverage, but uniform for NHI $>10^{16}$ cm^{-2}

Lyα espace is correlated to HI column density *(Henry et al 2015)*



Escape fraction of Green Peas

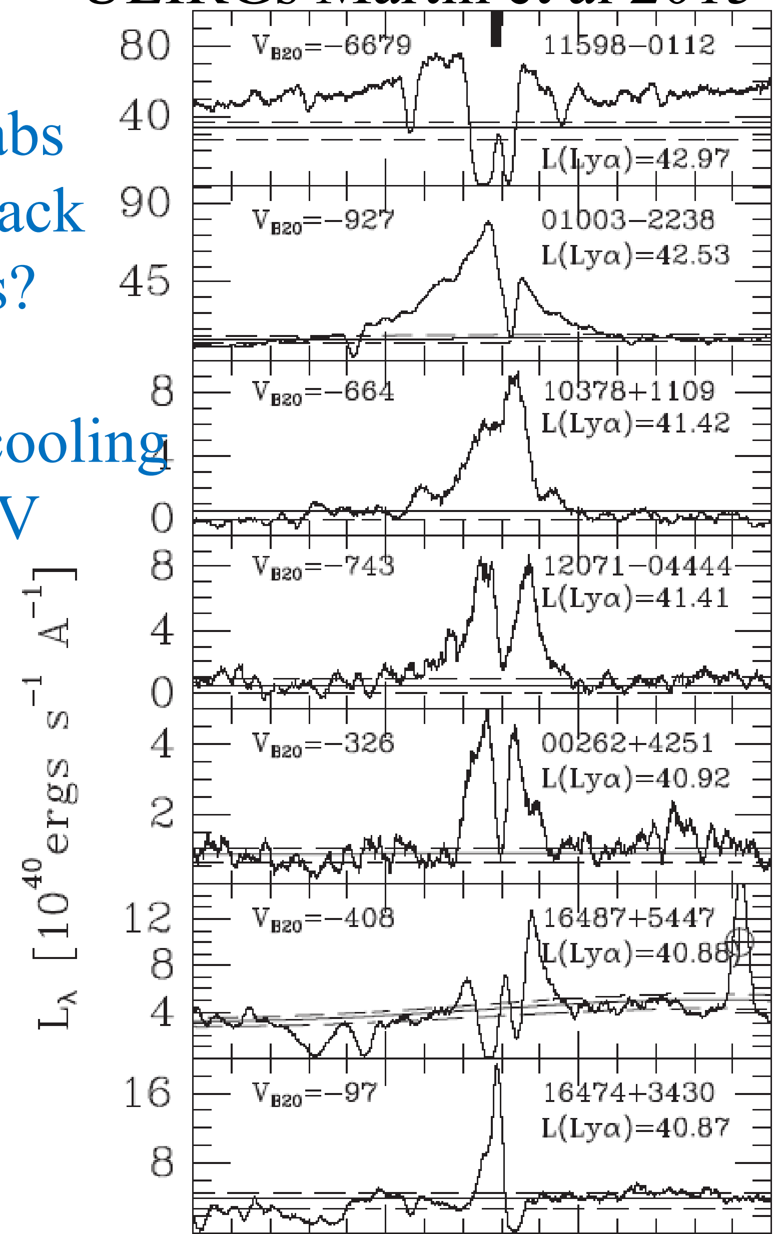
Henry et al 2015



Blue wing abs
AGN feedback
or SF winds?

Dense gas cooling
in the high-V
wind

ULIRGs Martin et al 2015



How does the Lyα escape?

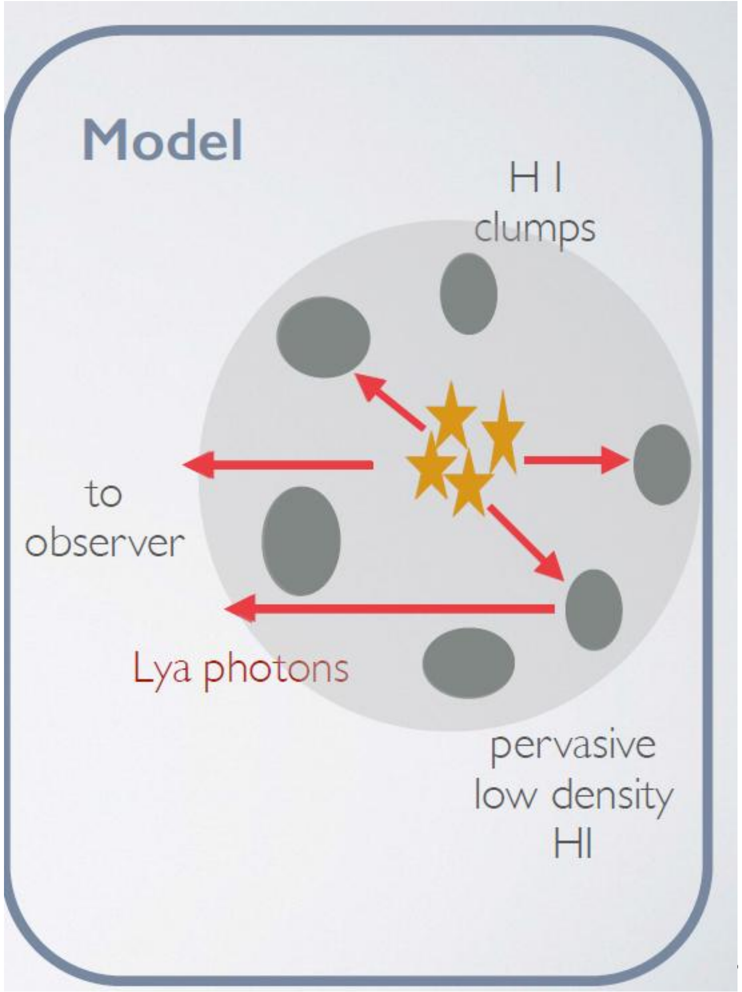
Alaina Henry

The escape is through a diffuse HI medium with full coverage

More than by holes in the clumpy medium

They all show outflows, but not Correlated with the Lyα flux

Can help to understand high-z analogs



Two kinds of low-z analogs

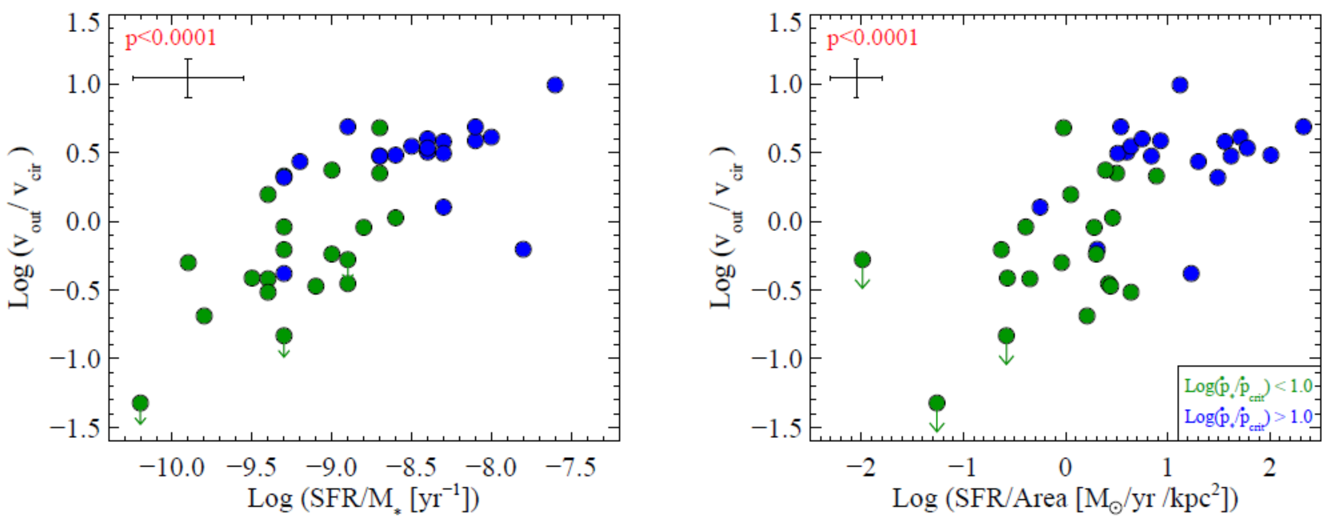
Tim Heckman

LBA Lyman Break Analogs, low-Z, masses 10^9-$10^{10}M_o$

Green Peas: discovered by the Galaxy Zoo, even lower Z, and lower masses 10^8-10^9M_o

These dwarfs are subject to efficient stellar feedback

Weak or **strong** winds



Physics of the outflows

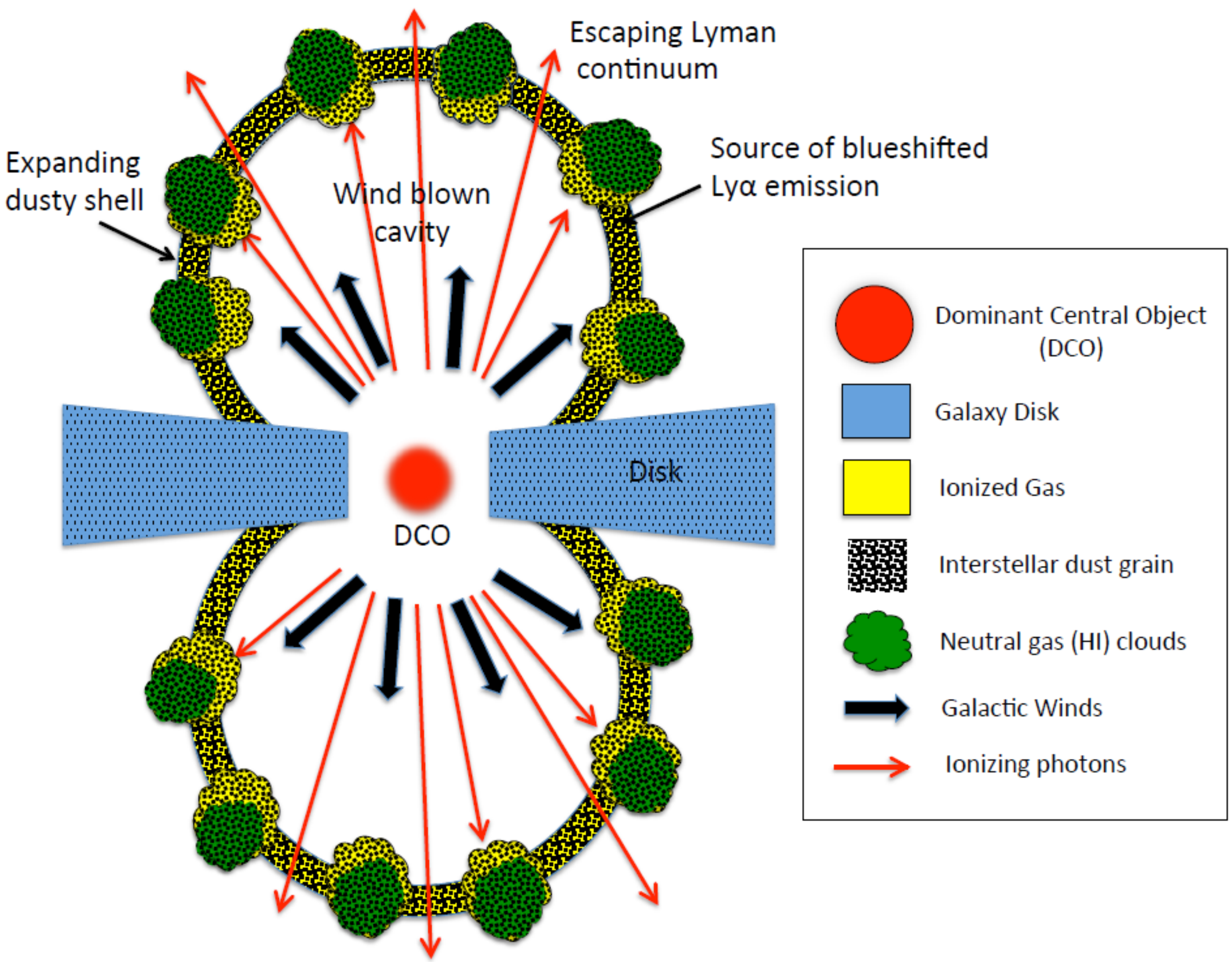
Kinetic Energy ~1% Lbol
Momentum = 3 Lbol/c
Vmax = 3000km/s

Ram and radiation pressure
Compare with the critical momentum flux
required to overcome gravity p_crit
Ratio Rcrit = p /Pcrit

Weak or **strong** winds, according to Rcrit <10 or **Rcrit > 10**

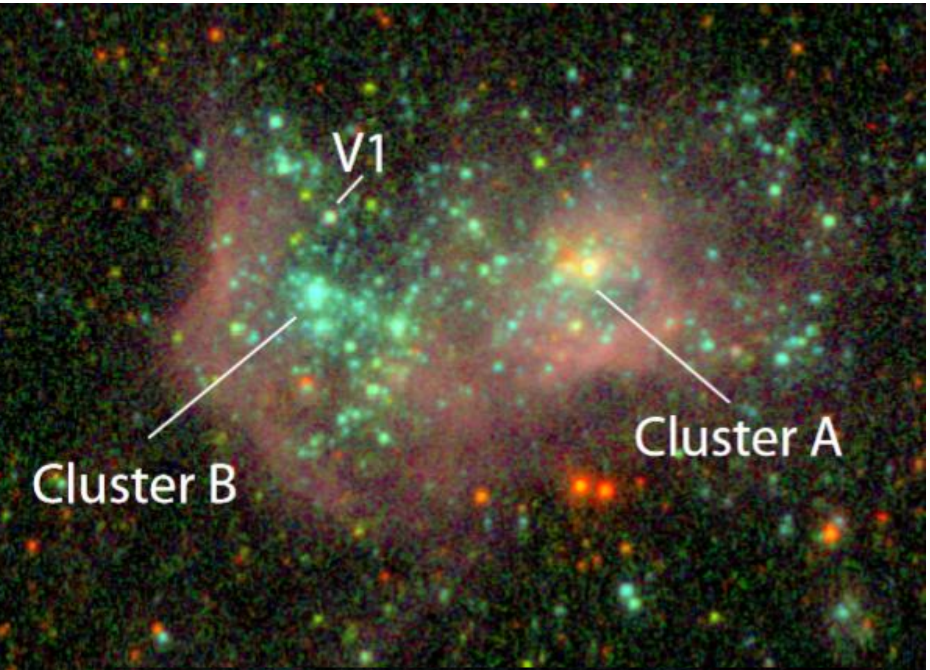
Vout/vcir >1 for strong outflows
Correlates with SFR/area, SFR/M*

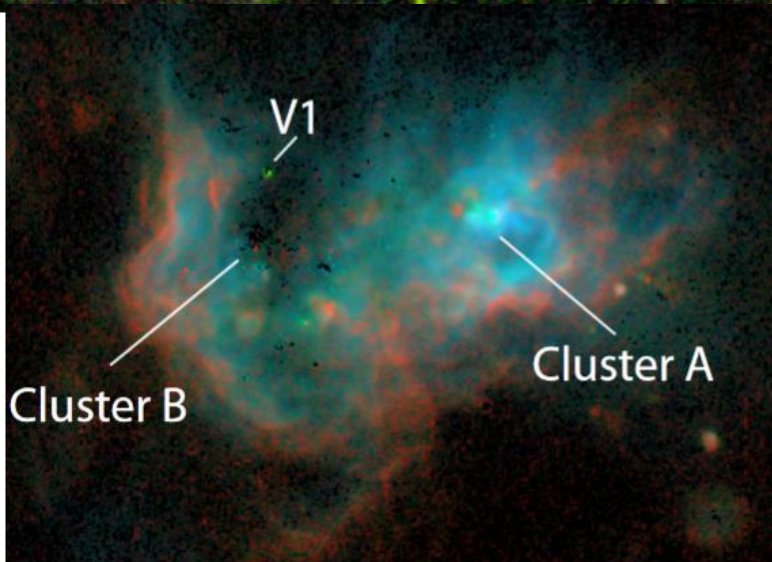
Schematic outflow due to a starburst (or AGN?)



Borthakur 2014

Feedback in analogs (BCD)





Bethan James

Gas photo-ionized, with
no sign of shock-excited emission

Inhomogeneous metallicity
at r< 50pc

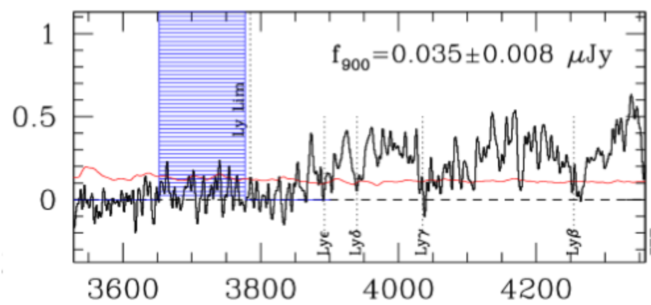
Mrk71

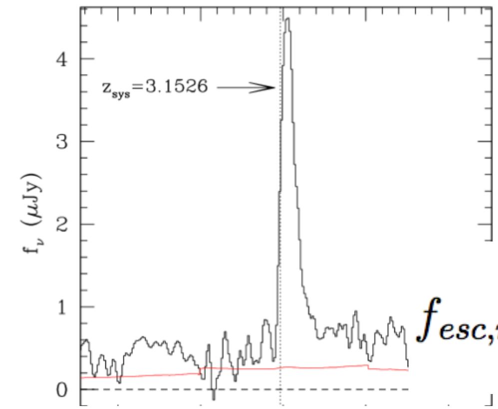
James et al (2016)

Search for f_{esc} at z~3

Alice Shapley

Q1549-C25



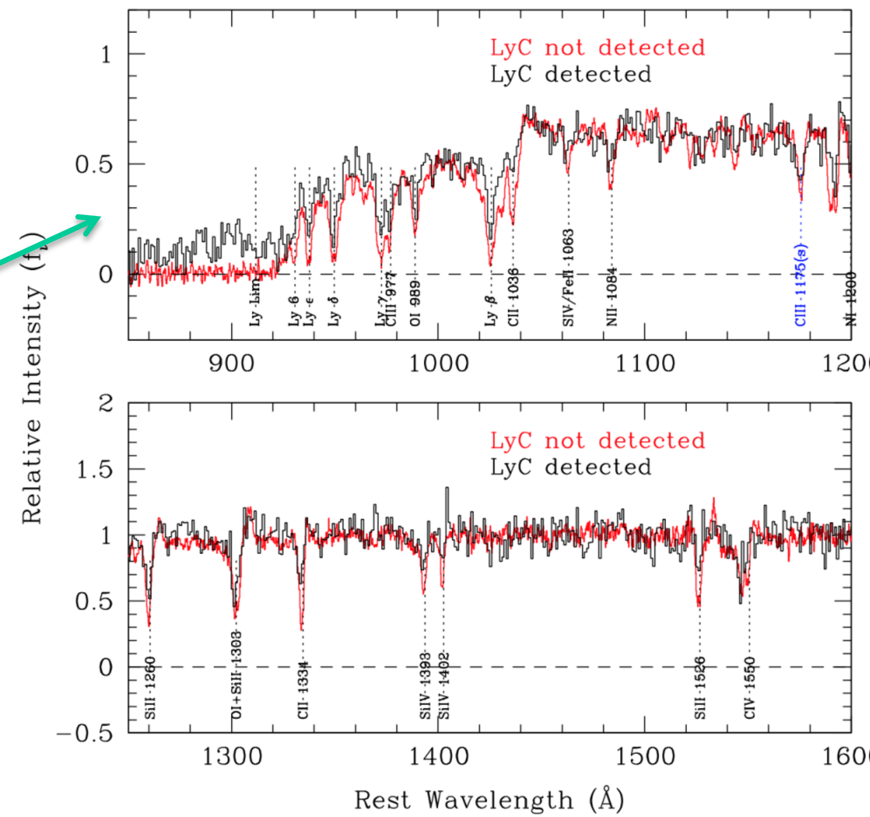


$$f_{esc}(\mathrm{LyC}) = \frac{L_{LyC,out}}{L_{LyC,in}}$$

$$f_{esc,rel}(\mathrm{LyC}) = \frac{f_{900}/f_{1500}}{(L_{900}/L_{1500})t_{IGM}}$$

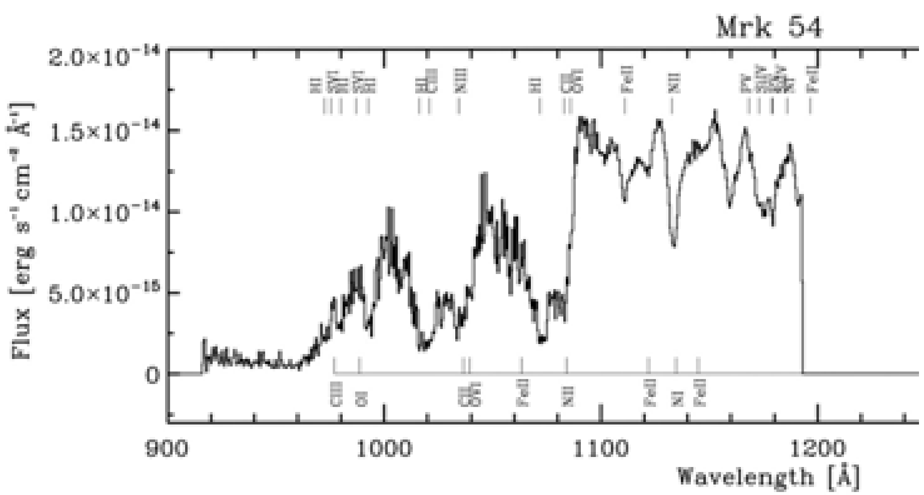
Two detected objects only
Q1549-C25 and Ion2
Vanzella et al 2016

124 LBG
13/124 detected
Follow-up with HST to
Check the contamination
(Steidel et al 2016)



Search for f_{esc}

Why so unsuccessfull at z~3 ?
Does the LBG selection bias against finding LyC? (Cooke 2014)?
No bias of the dropout technique *Vanzella et al 2015*



Claus Leitherer

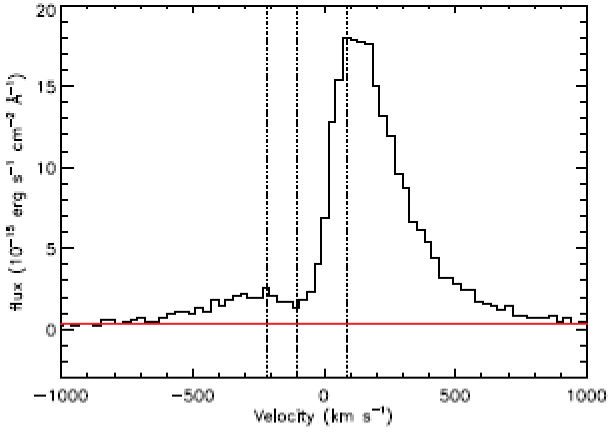
Two systems detected at z~0
Mrk54 and Tol 1247-232

fesc in absolute is a few %

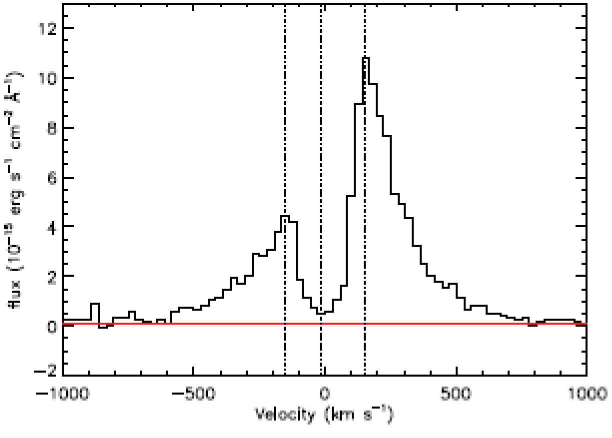
Indirect tracers

Anne Verhamme

fesc(LyC)=0.074



fesc(LyC)=0.072

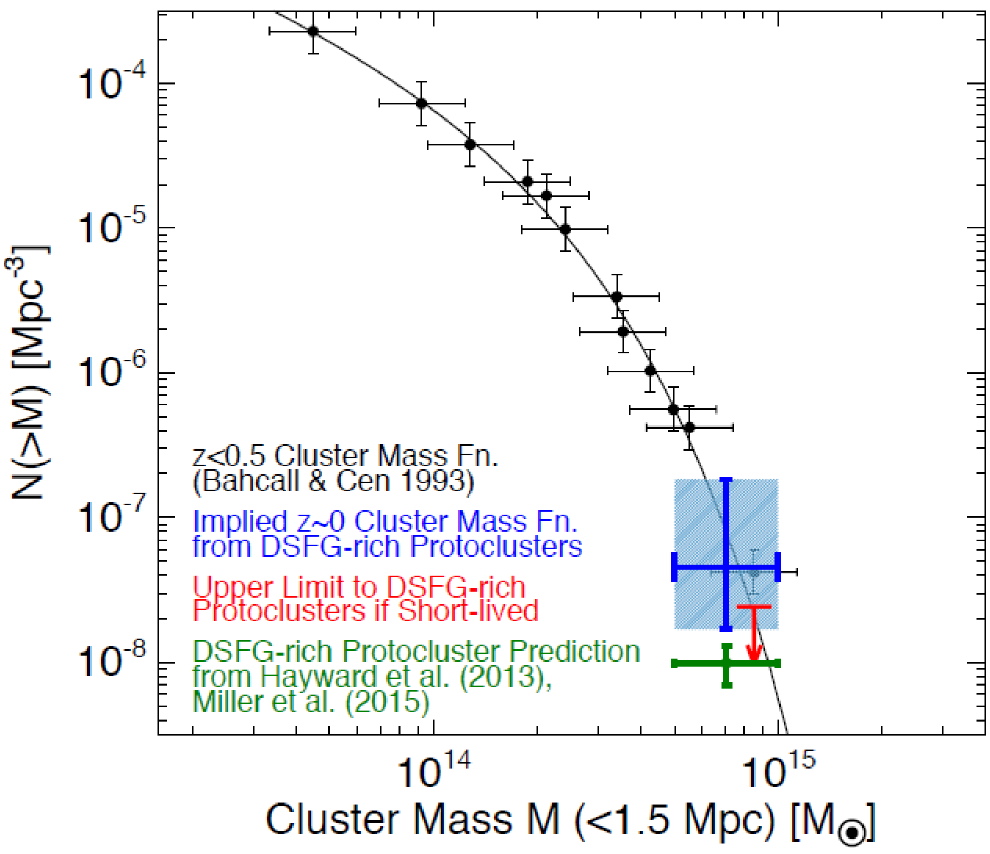


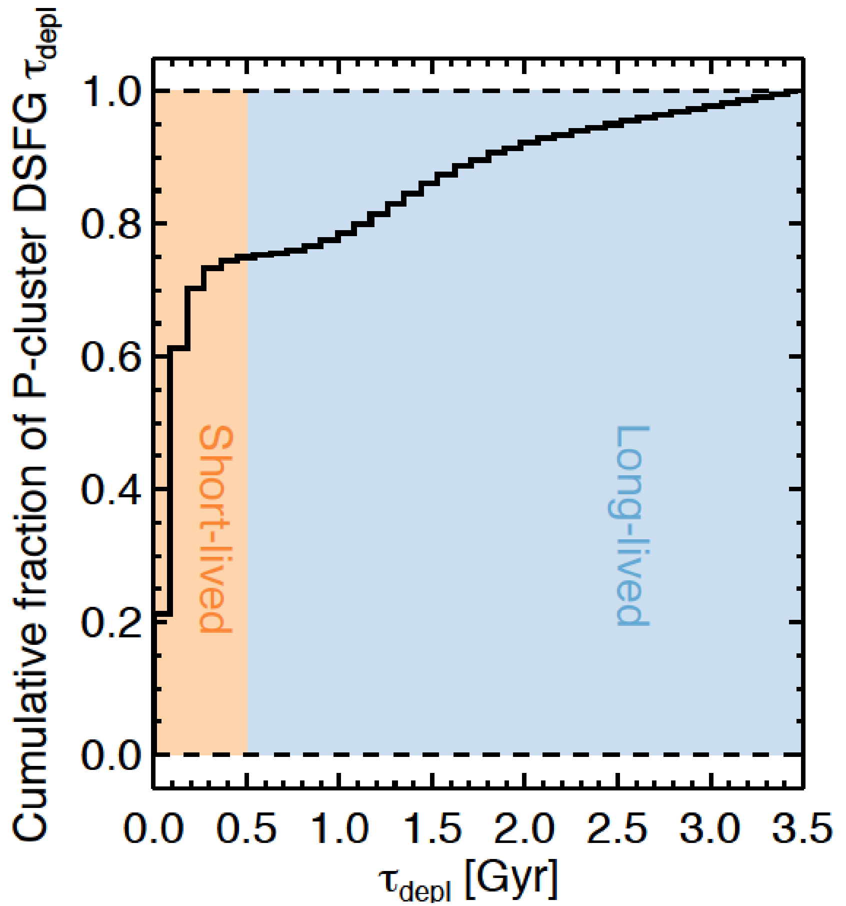
The Lyα profiles can indicate the LyC leakers, and fesc

Clusters triggering DSFG

Caitlin Casey

ULIRGs gathered in 5 proto-cluster at z~3

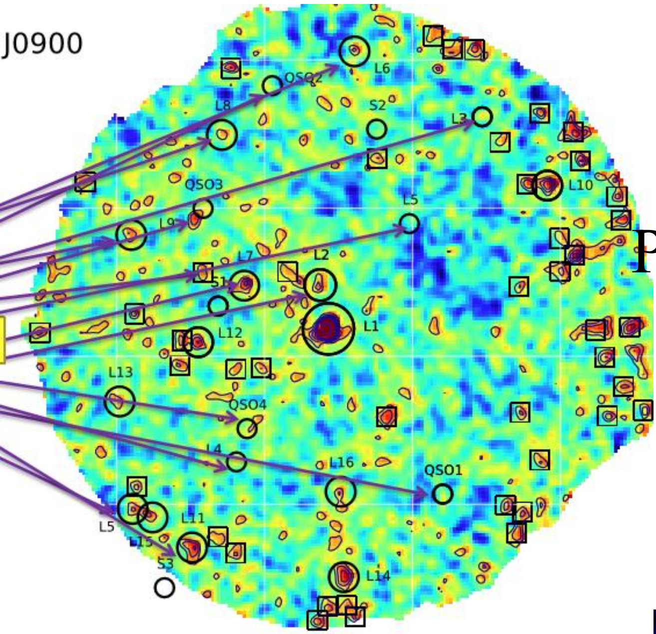




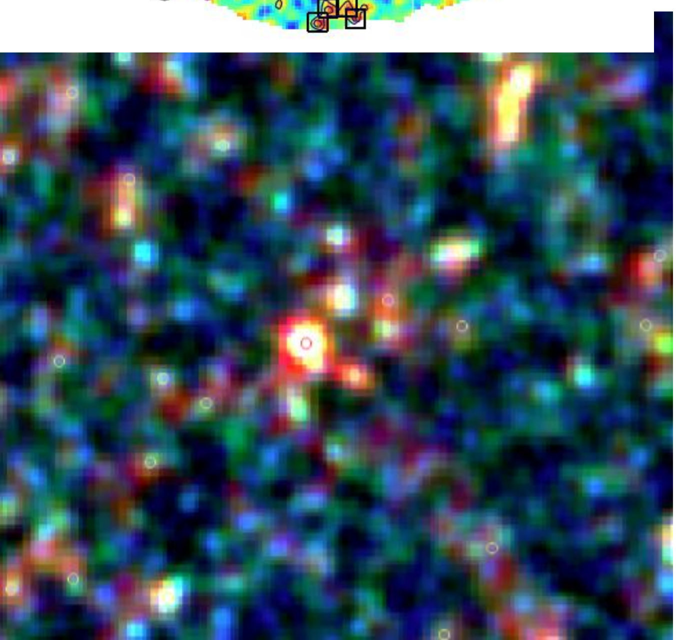
Casey 2016

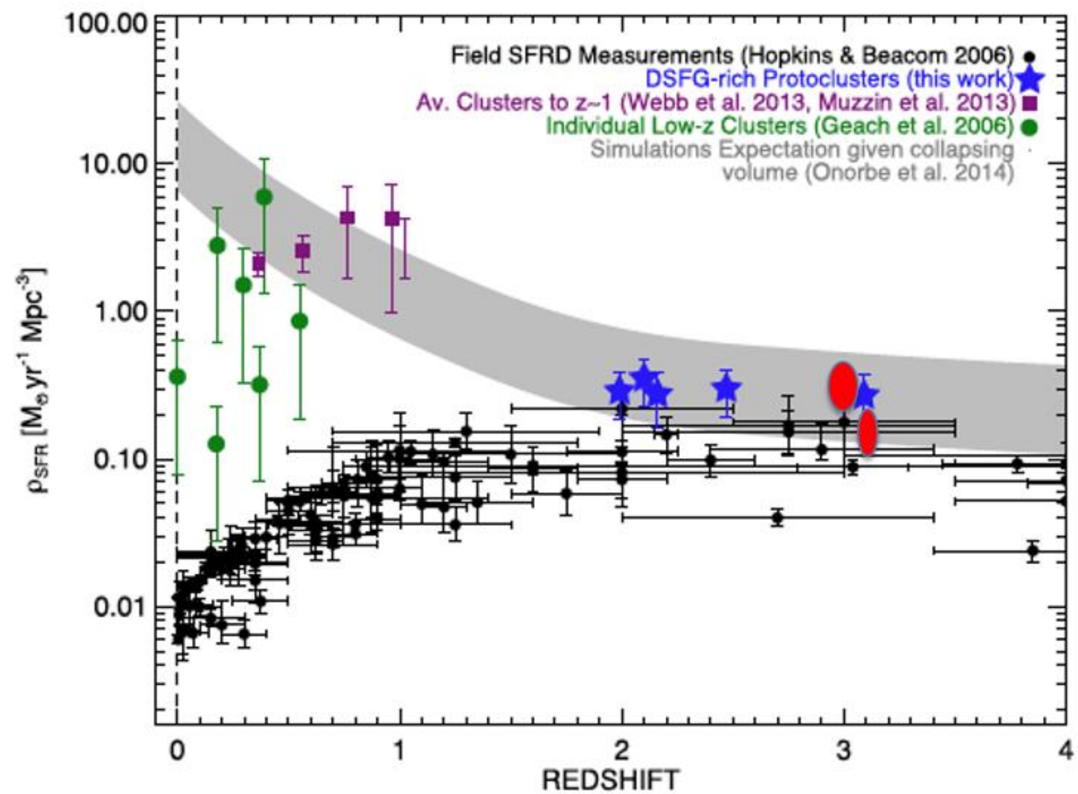
Clusters at high-z with APEX

Paola Andreani



Proto-cluster at z~3





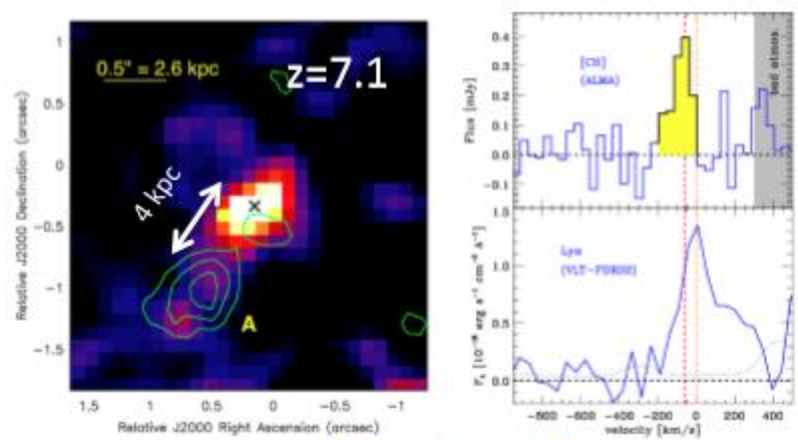
Casey 2016

5- Feedback processes, Metal enrichment

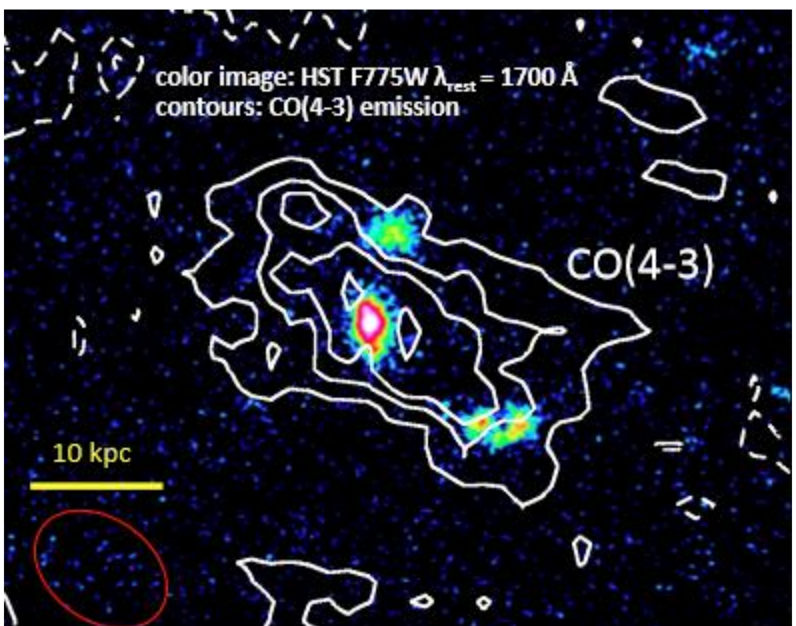
Roberto Maiolino

No problem to enrich the neighborhood of AGN
Positive abundance gradients at hig z (expected)

Surprising: kpc offsets between line detection and optical body
Outflows?



Maiolino+15



Large molecular reservoirs ?

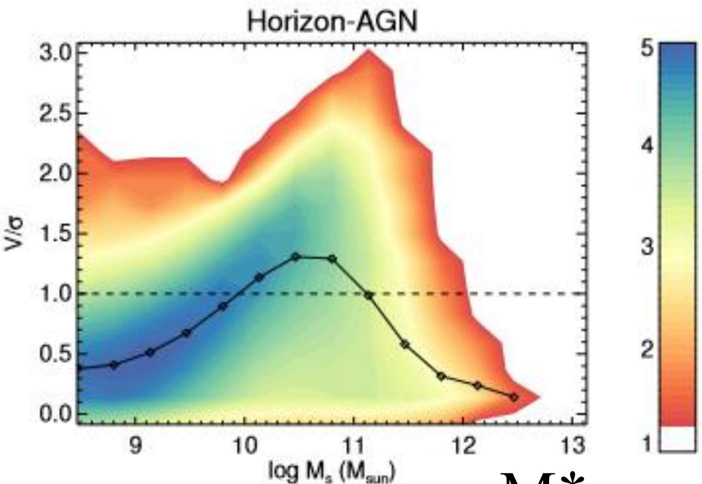
Problem: too much dust at high-z
Even with SN dust

Ginolfi et al 2016

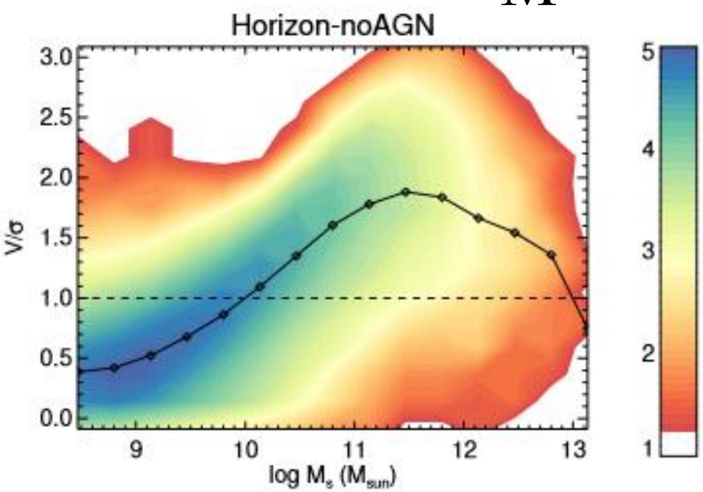
Feedback processes: simulations

Yohan Dubois

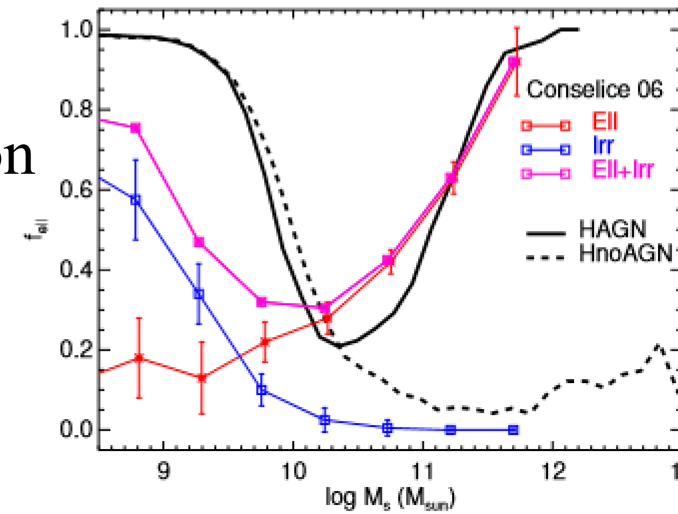
High-M* spirals suppressed



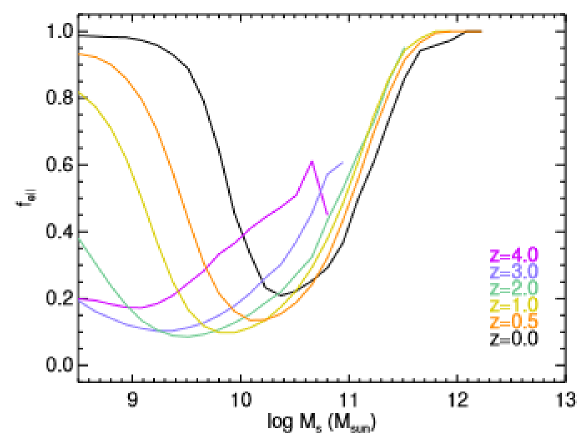
M*



Fraction of Ell



M*



Some Highlights

- ➔ Reionization: essentially galaxies? Or QSO play a role (patchyness)
- ➔ No turnover in galaxy UV LF to MUV~-15?
- ➔ escape fraction fesc? Very low (only 2 detections at z~0, 3), with Lyα

- ➔ Line diagnostics to be reviewed (BPT, SII, MEx,UV lines..)
- ➔ Models updated (EPS, SSP..) Bayesian techniques, priors, likelihood

- ➔ TITANesc simulations, radiative transfer

Calibration of reionization, mass assembly

- ➔ Low-z analogs: green peas and LBA

- ➔ Are Black holes over-massive at high-z ?

- ➔ AGN feedback required: first realistic results in simulations