

Modeling of H α -Emitting Galaxies for Euclid & WFIRST

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With thanks to my collaborators:

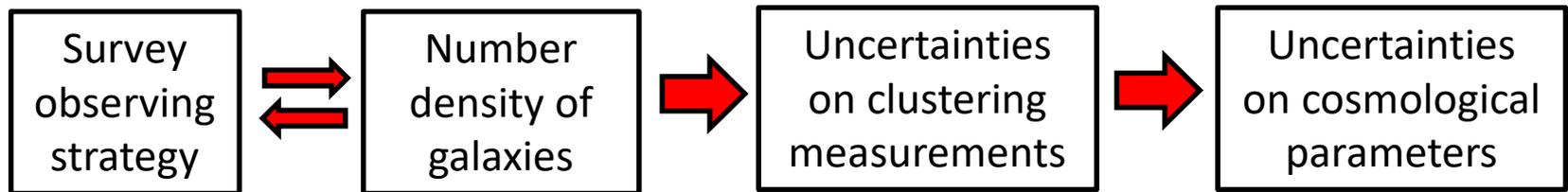
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Why are we interested in H α -emitting galaxies?



- Want to understand what is driving the accelerated expansion of the Universe?
- ESA Euclid and NASA WFIRST missions will **measure clustering of H α -emitting galaxies.**
- Need to know how many we expect to see to optimise survey strategy for these missions.
- So, **how many H α -emitting galaxies do we expect to see?**



Optimise this... .. to maximize this...

...to minimise these!

Existing number counts estimates

Pozzetti et al. (2016):
three empirical models
designed to fit H-alpha
luminosity function.

Fit combinations of
observations from WISP,
HiZELS & HST+NICMOS
grism survey.

Predictions:

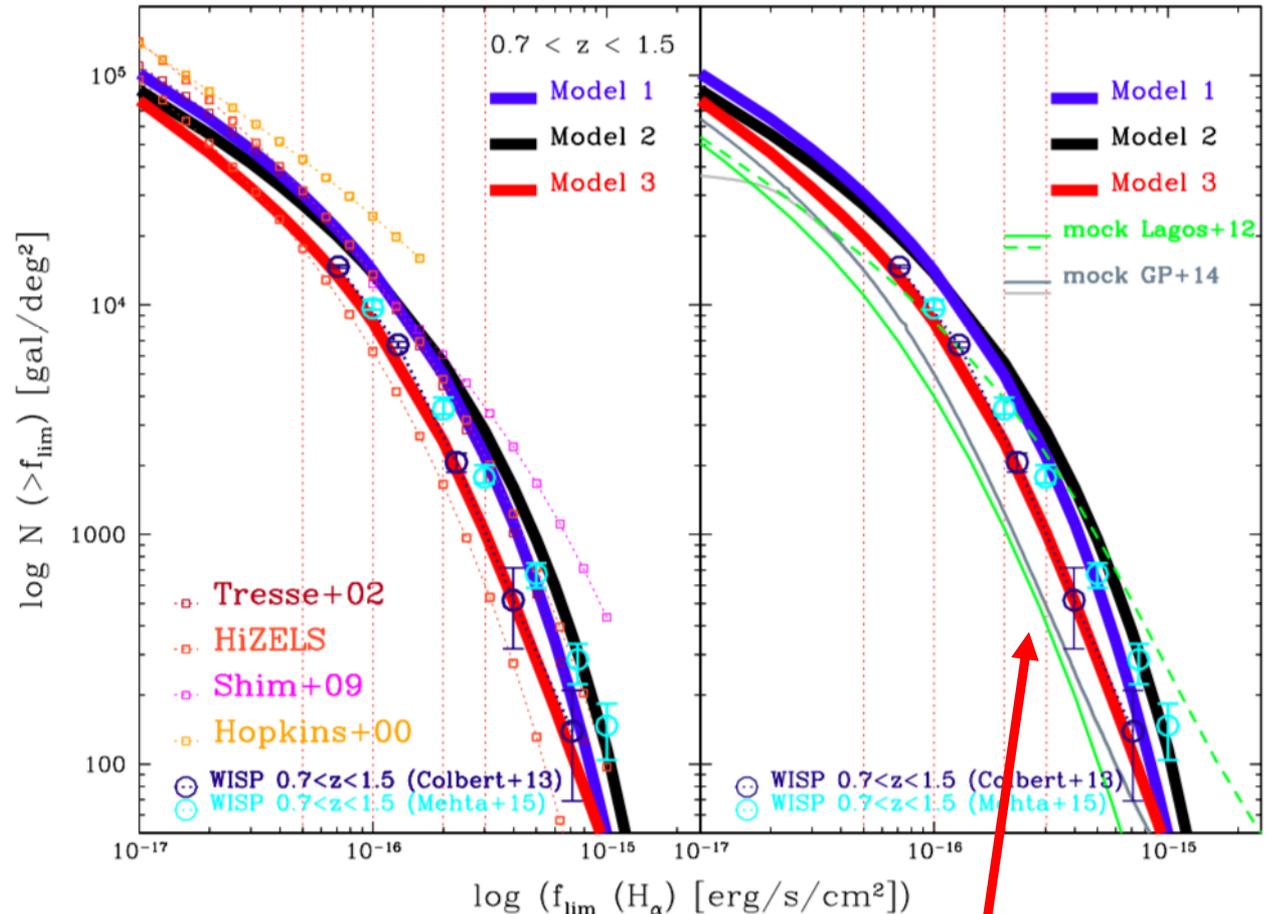
Model 1: 3939 deg⁻²

Model 2: 4819 deg⁻²

Model 3: 2014 deg⁻²

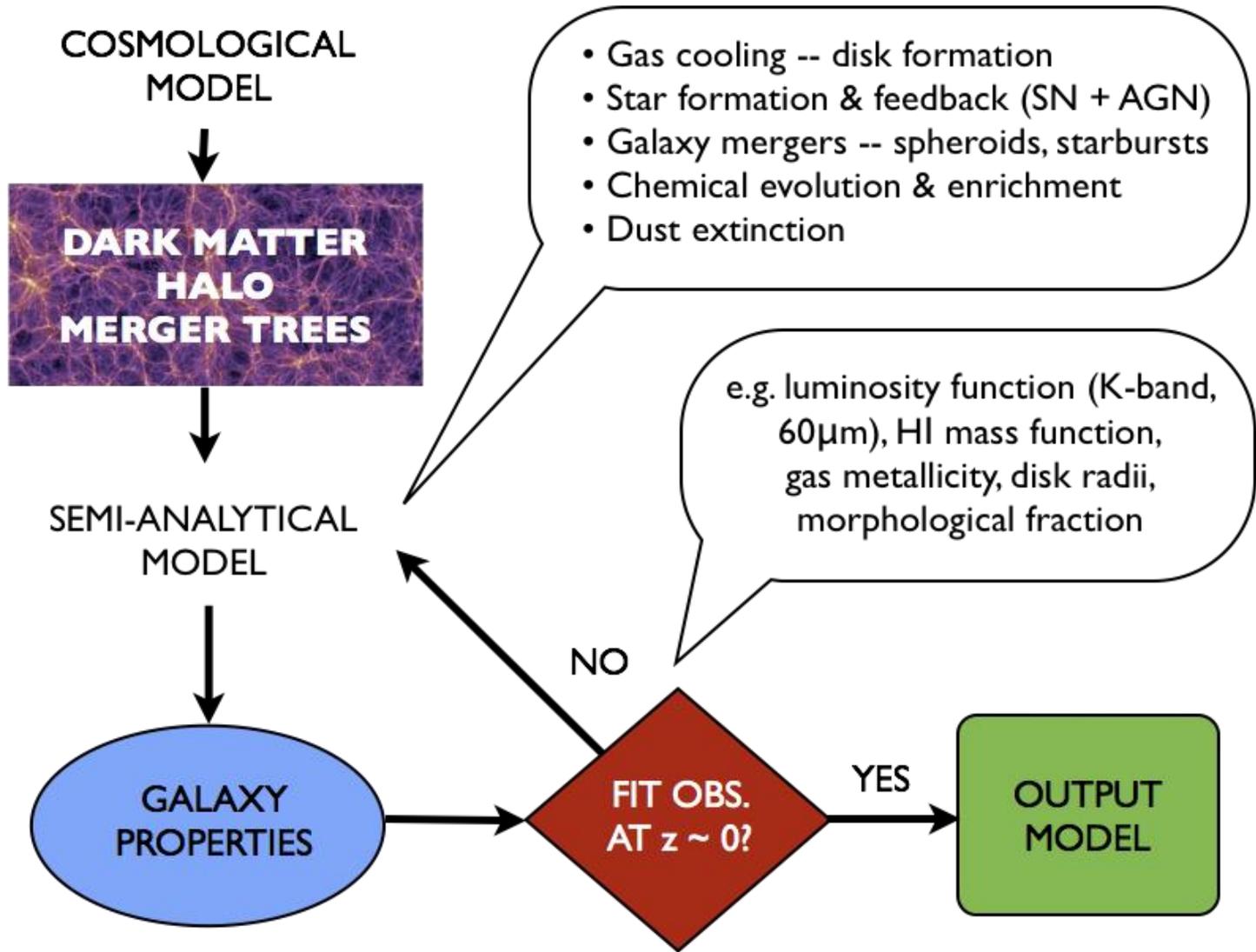
$0.9 < z < 1.8$

2×10^{-16} erg s⁻¹ cm⁻²
de-blended fluxes



Previous H α mocks under-predicted counts

Semi-analytical Galaxy Formation



The Galacticus Galaxy Formation Model

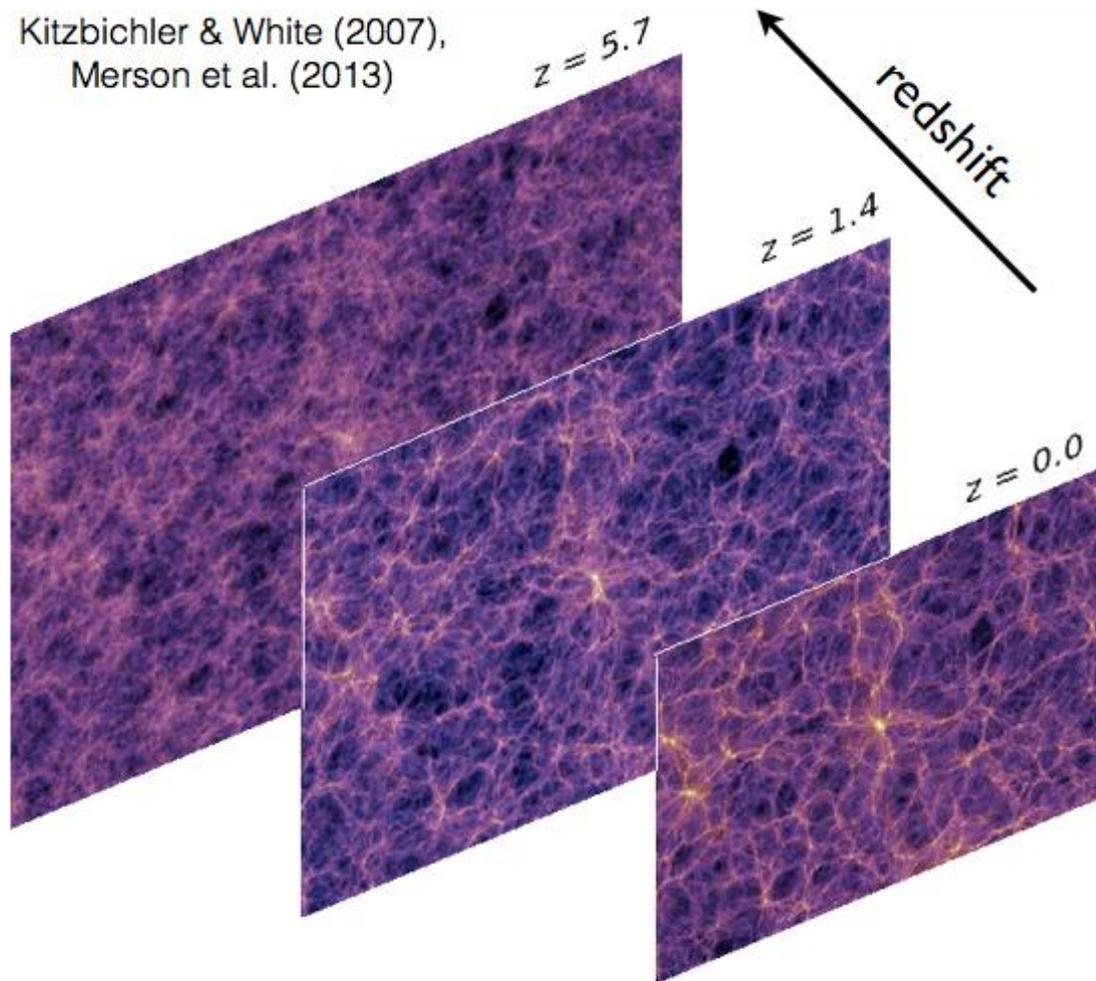
- Open source **semi-analytical model** (Benson 2012)
 - solves coupled sets of differential equations governing astrophysical processes
 - can make multi-wavelength predictions (emission lines + photometry)
 - calibrated against local Universe observations (inc. stellar mass function).

Galacticus source code available from: <https://sites.google.com/site/galacticusmodel/>

- Emission line luminosities computed by interpolation over grid of models from photo-ionization model **CLOUDY** (Ferland et al. 2013)
 - interpolated over hydrogen density, metallicity of ISM, ionizing luminosities of HII regions (Hydrogen, Helium, Oxygen)
 - emission lines consistent with other galaxy properties
- Dust modelling:
 - Ferarra et al. (1999): library of dust curves as function of various galaxy properties
 - Charlot & Fall (2000): optical depth follows power law with wavelength
 - Calzetti et al. (2000): empirical *dust screen* (global rescaling, function of wavelength)

Building a Galacticus Lightcone

Kitzbichler & White (2007),
Merson et al. (2013)



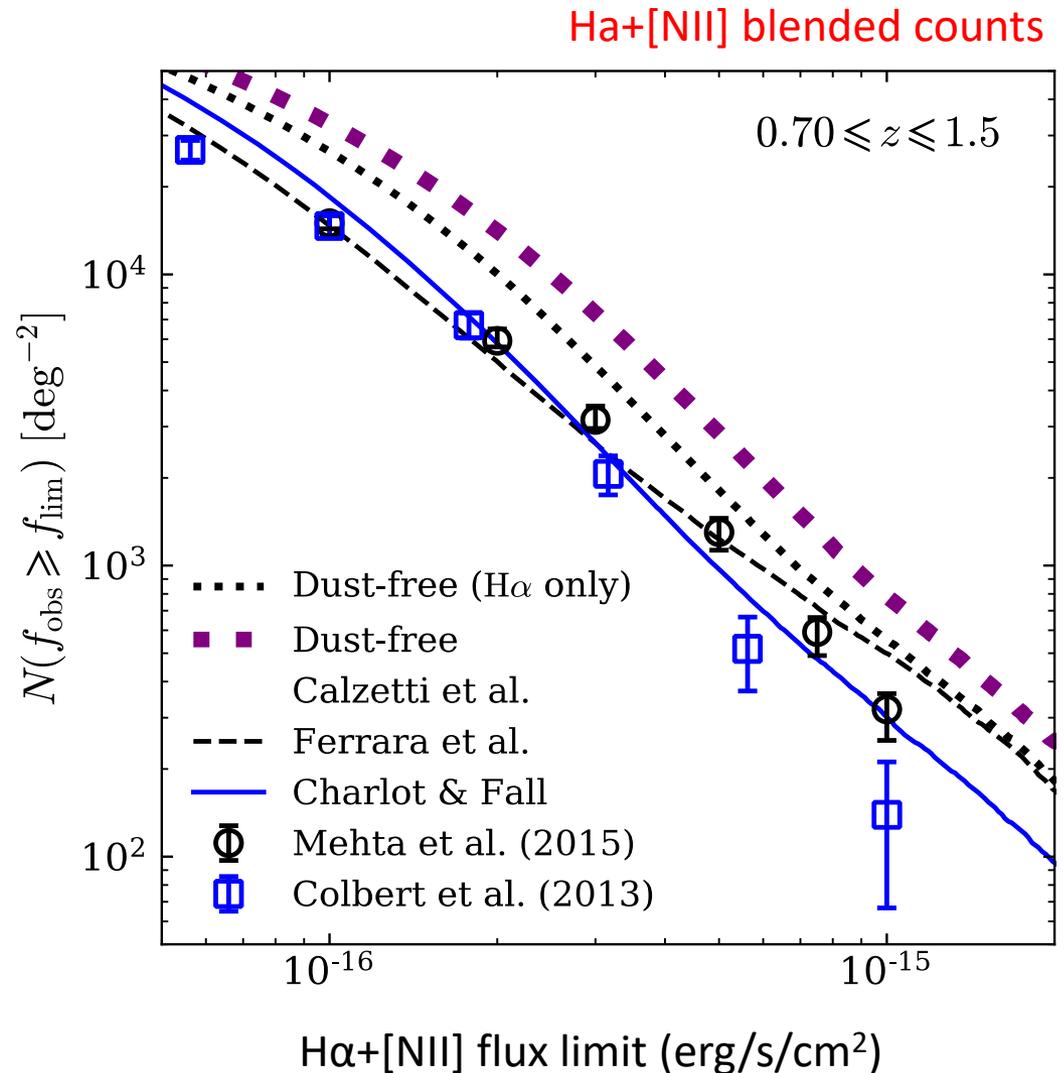
- Run Galacticus on snapshots from Millennium Simulation (Springel et al. 2005).
- Output all galaxies that cross past lightcone of observer in redshift range $0.5 \leq z \leq 2$ within **4 square degrees**
- Compute emission line properties and dust attenuation.
- Apply Euclid or WFIRST selection criteria (flux limit and wavelength cut)



Millennium Simulation visualisations courtesy of The Virgo Consortium.

Comparison with WISP H α counts

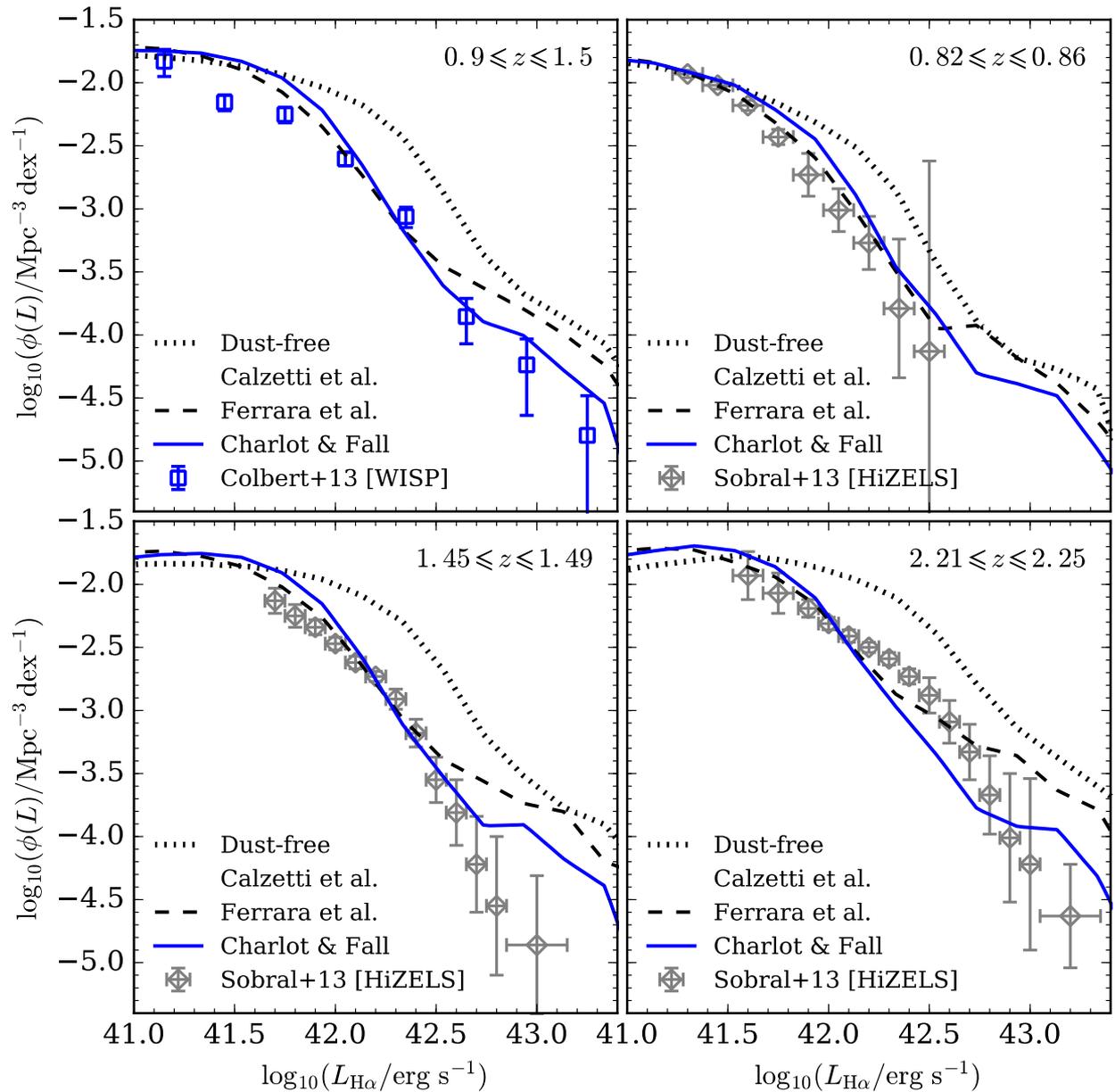
- Compare Galacticus to counts from the **WFC3 Infrared Spectroscopic Parallels Survey (WISP)** -- slitless grism spectroscopy with HST WFC3 (see Colbert et al. 2013; Mehta et al 2015).
- Galacticus able to match WISP counts (previous mocks under-predicted counts).
 - Dust attenuation strength set by χ^2 -minimization.
 - [NII] contamination set by cross matching to SDSS catalogue from Masters et al. 2016 (see also Faisst et al. 2018).
- Calzetti et al. (2000) dust method leads to best match to counts (lowest χ^2).



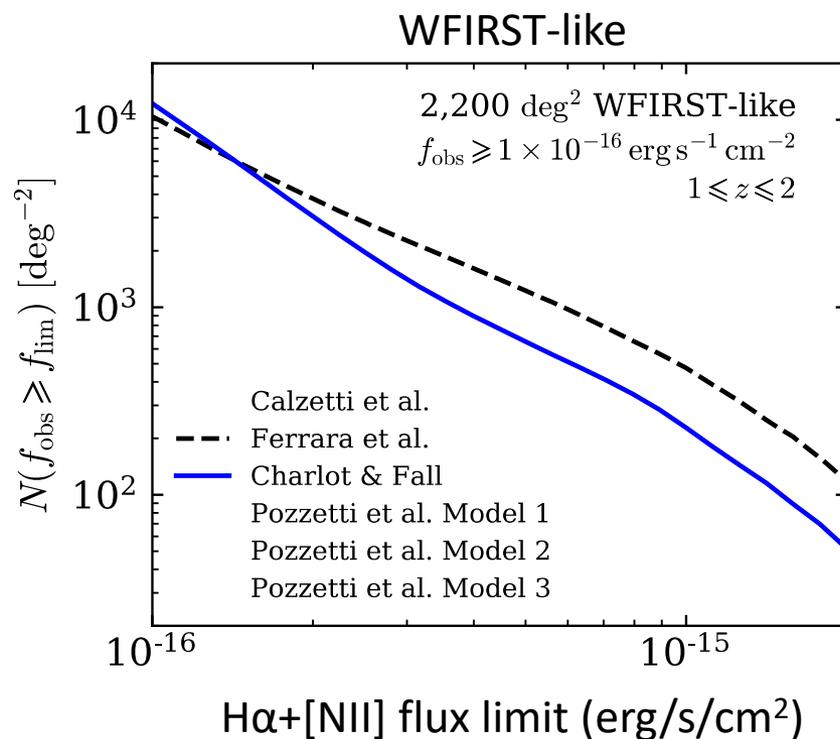
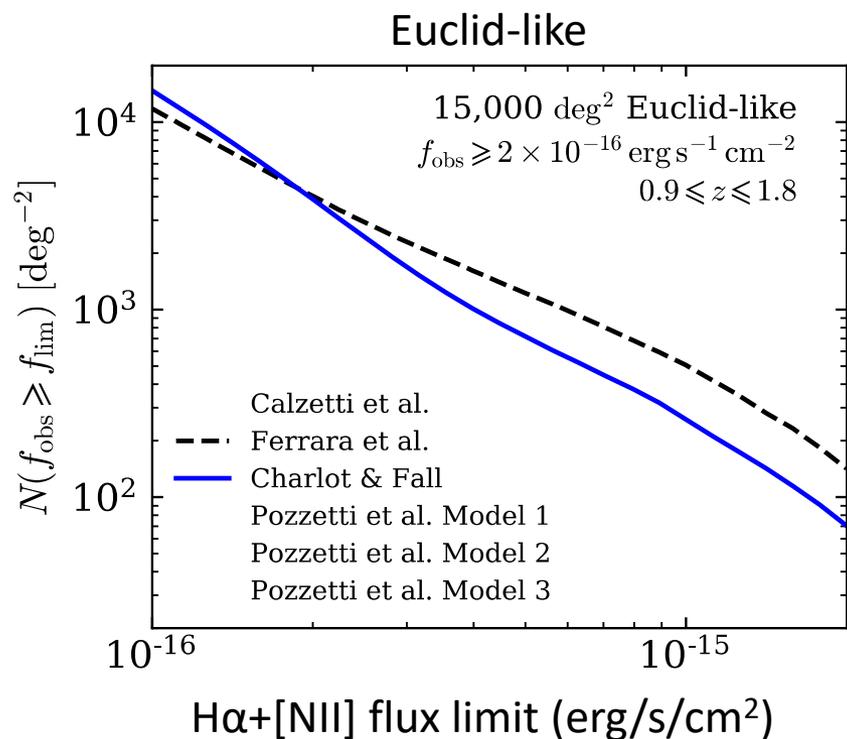
H-alpha Luminosity Function

Dust-attenuated, rest-frame H-alpha luminosity function

- Good agreement with WISP and with HiZELS at low redshift.
- Poorer agreement towards higher redshifts (sample selection difference or further calibration of model needed?).



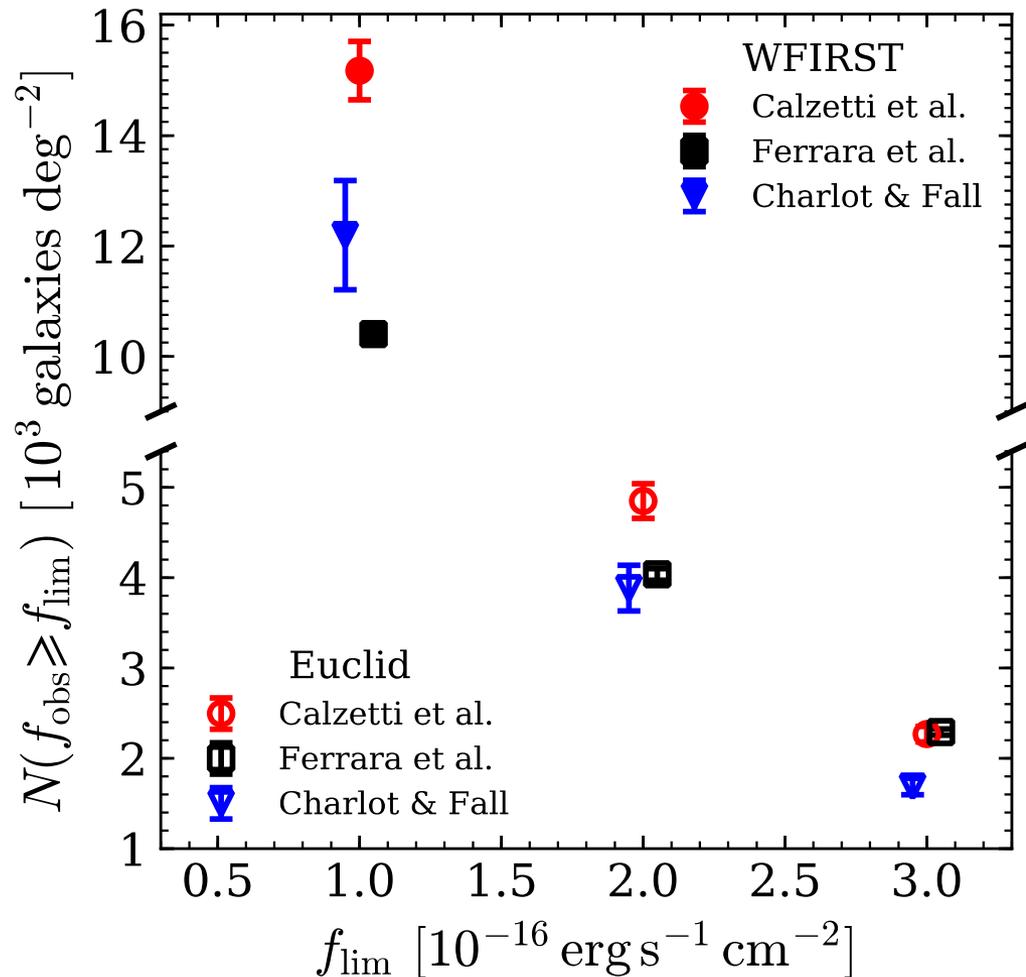
Predicting Euclid & WFIRST H α counts



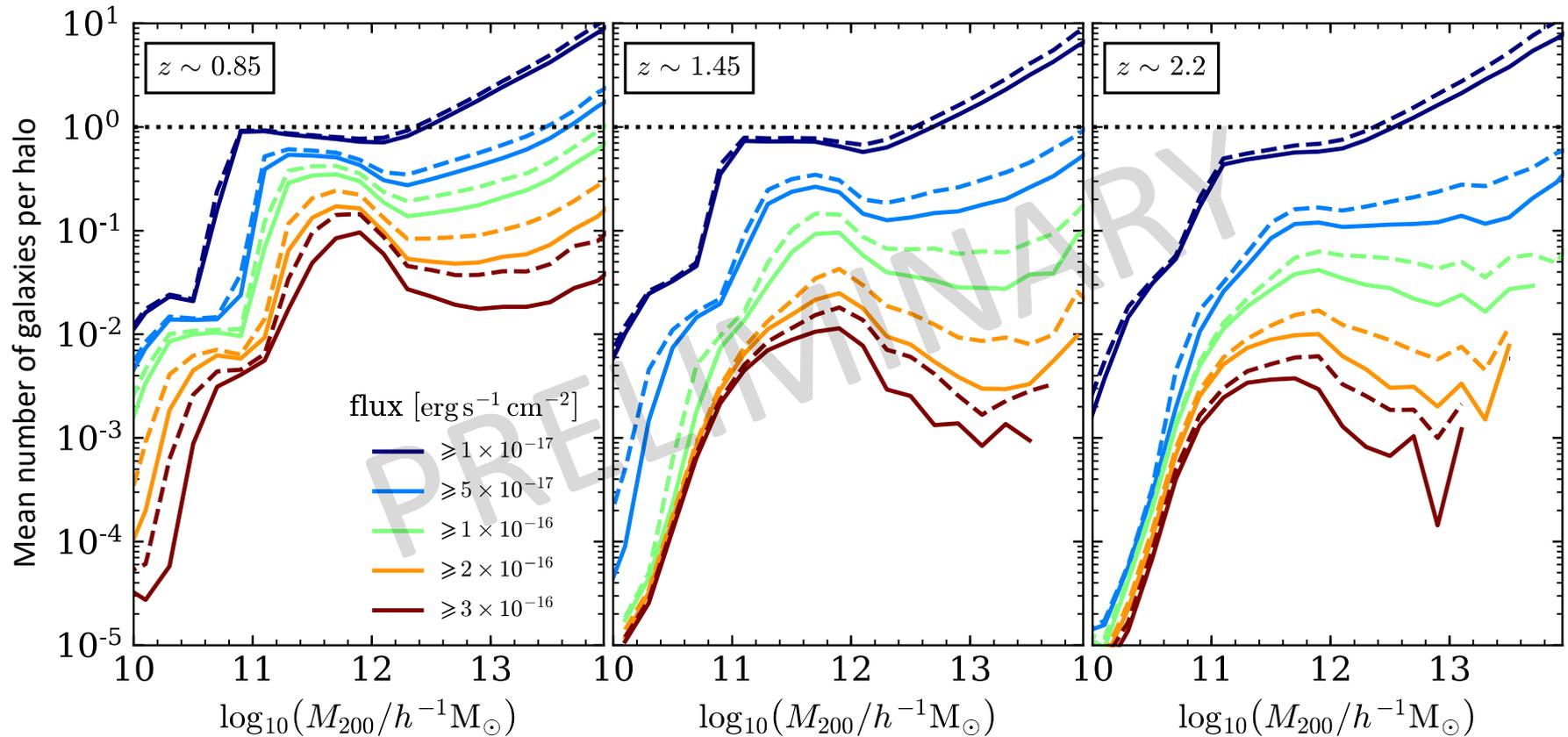
Survey	Flux Limit	Ferrara et al. (1999)	Calzetti et al. (2000)	Charlot & Fall (2000)
Euclid-like	$> 2 \times 10^{-16}$ erg/s/cm 2	$4,036 \pm 62$ (deg $^{-2}$)	$4,849 \pm 192$ (deg $^{-2}$)	$3,884 \pm 252$ (deg $^{-2}$)
WFIRST-like	$> 1 \times 10^{-16}$ erg/s/cm 2	$10,403 \pm 138$ (deg $^{-2}$)	$15,176 \pm 528$ (deg $^{-2}$)	$12,195 \pm 987$ (deg $^{-2}$)

Predicting Euclid & WFIRST H α counts

- Scatter in Galacticus predictions:
→ **5%—30%** for Euclid-like
→ **20%—50%** for WFIRST-like
- Comparable or smaller scatter compared to empirical models.
- Galacticus predictions more **robust** — physical galaxy formation model with properties calculated self-consistently.
- Galacticus counts most consistent with **model 3** from Pozzetti et al. (2016).



Ongoing work: H α galaxy HODs

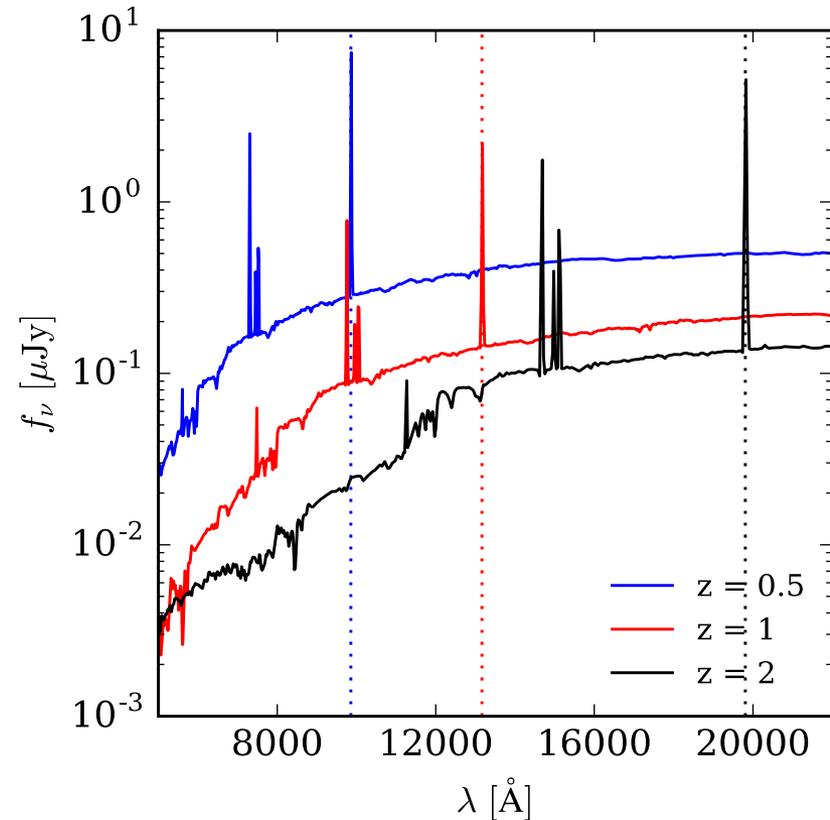
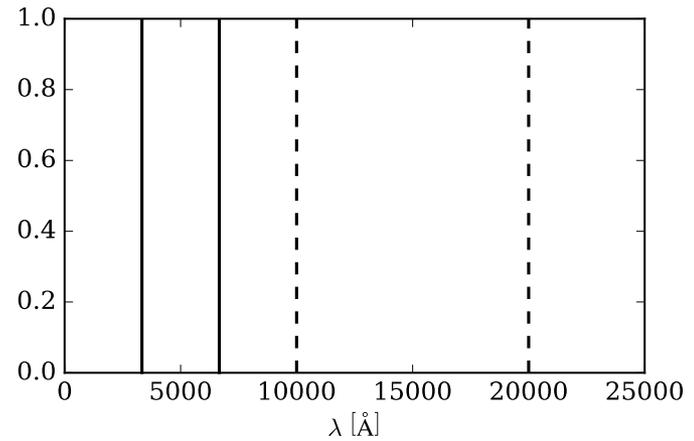


- At $z \sim 1.45$ for $f > 2 \times 10^{-16} \text{ erg/s/cm}^2$ expect one H α -emitting galaxy per ~ 100 DM halos.
- Next step: use HODs and LFs to predict H α galaxy bias as function of redshift and luminosity.

Merson et al. (in prep.)

Ongoing work: Spectral Energy Distributions

- Continuum from array of top-hat filters.
- Resolution limited by resolution of outputs from stellar population synthesis model.
- Emission lines added on top:
 - Gaussian profiles
 - Amplitude set by luminosity
 - Profile width estimated using velocity dispersion (or set to fixed width in km/s).
- Example spectra to test emission line detection for Euclid & WFIRST.



Summary

- Knowledge of number density of H α -emitting galaxies essential for **optimizing survey strategy**.
- Counts of H α -emitting galaxies from **Galacticus lightcone able to reproduce observed counts** from WISP survey.
- Galacticus number densities of:
 - 3,800–4,800 deg⁻² for $f > 2 \times 10^{-16}$ erg/s/cm⁻² over $0.9 < z < 1.8$ (~Euclid)
 - 10,400–15,200 deg⁻² for $f > 1 \times 10^{-16}$ erg/s/cm⁻² over $1 < z < 2$ (~WFIRST)
- Galacticus counts consistent with Model 3 of Pozzetti et al. (2016), but with smaller scatter for a Euclid-like survey. Comparable scatter for deeper WFIRST-like survey.
- Galacticus H α number counts published in **Merson et al. (2018) arXiv:1710.00833**.
- Ongoing work:
 - Extensive calibration of Galacticus using MCMC chains (A. Benson).
 - Examination of bias of H α -emitting galaxies as function of redshift and luminosity.
 - Provision of mocks with SEDs (continuum + emission lines) for testing emission line detection (collaboration with WISP).

EXTRA SLIDES

The WFC3 Infrared Spectroscopic Parallels Survey (WISP)

“There is currently no better laboratory for predicting what these future missions can expect.”

Colbert et al. (2013)

- **Slitless grism spectroscopy with HST WFC3**
(Atek et al. 2010, 2011)
 - G141 (1.2-1.7 μm , $R\sim 130$) + G102 (0.8-1.2 μm , $R\sim 210$)
 - Detects H-alpha emitters out to $z\sim 1.5$
 - Total area ~ 0.3 square degrees over ~ 400 separate fields (not all fields processed yet).

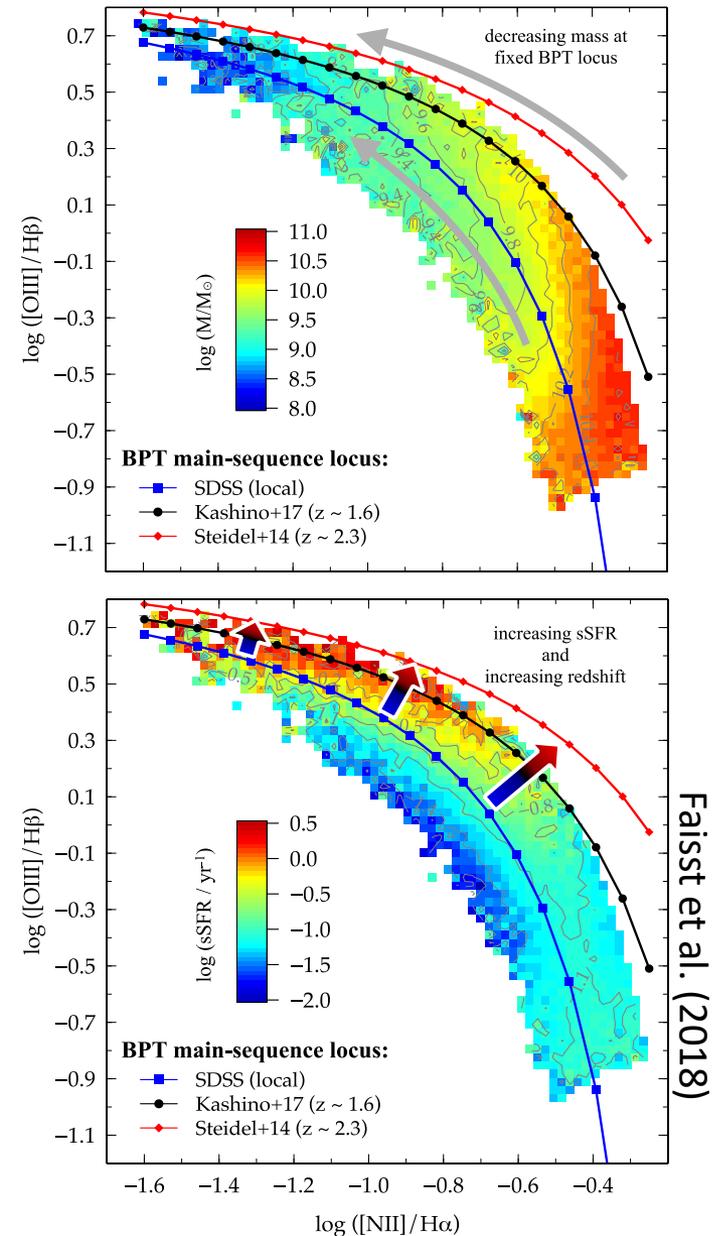
H α detection with Euclid & WFIRST

- Euclid: 1.25 μm – 1.85 μm ($0.9 < z < 1.8$)
 - WFIRST: $\sim 1 \mu\text{m}$ – $2 \mu\text{m}$ ($0.5 < z < 2$)
- Number densities from WISP ($0.7 < z < 1.5$, flux limit of $2 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$):
 - Colbert et al. (2013): $\sim 6700 \text{ deg}^{-2}$ (29 fields over area $\sim 0.037 \text{ deg}^2$)
 - Mehta et al. (2015): $\sim 6000 \text{ deg}^{-2}$ (52 fields over area $\sim 0.051 \text{ deg}^2$)



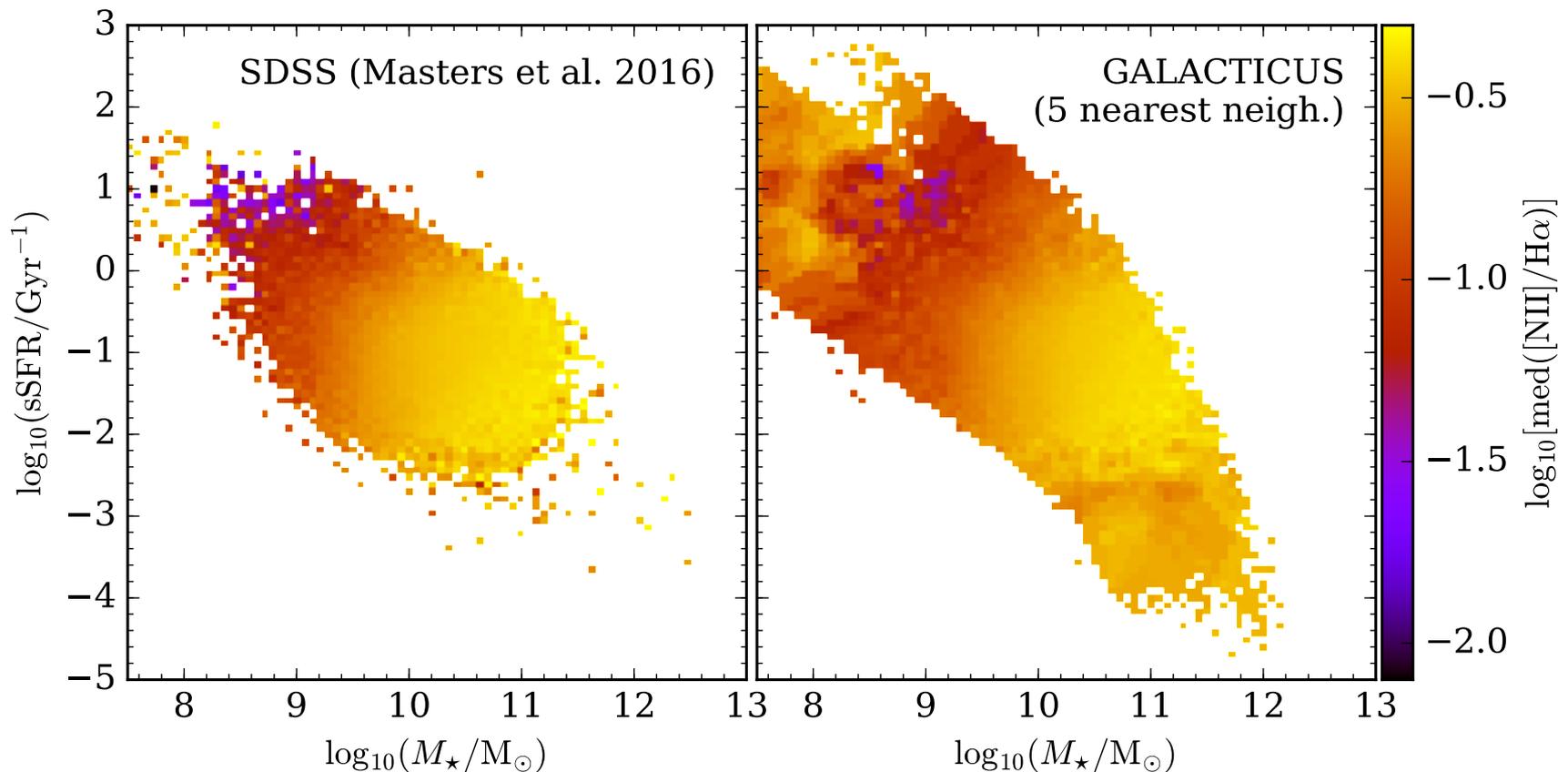
[NII] Contamination

- Masters et al. (2014) find $[NII]/H\alpha \sim 0.1-0.2$.
- $[NII]/H\alpha$ ratios from Galacticus ~ 0.02 .
- Do not calibrate Galacticus ISM gas metallicities so $[NII]$ luminosities likely under-estimated.
- Masters et al. (2016) find strong correlation between stellar mass and sSFR and position in BPT diagram ($[NII]/H\alpha$ vs. $[OIII]/H\beta$)
 - **only weakly dependent on redshift**
 - **stellar mass is dominant influence.**
- Assign $[NII]/H\alpha$ ratio to Galacticus galaxies by cross-matching to SDSS catalogue used by Masters et al. (2016): using 5 nearest neighbours in stellar mass vs. sSFR space.



For further details on the modelling of $[NII]/H\alpha$ ratios see Faisst et al. (2018).

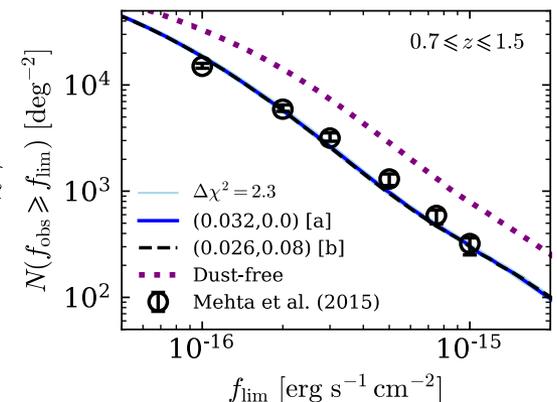
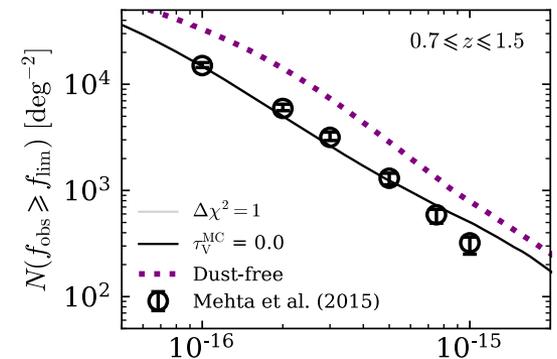
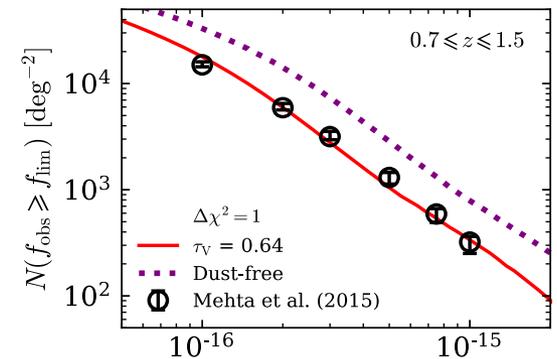
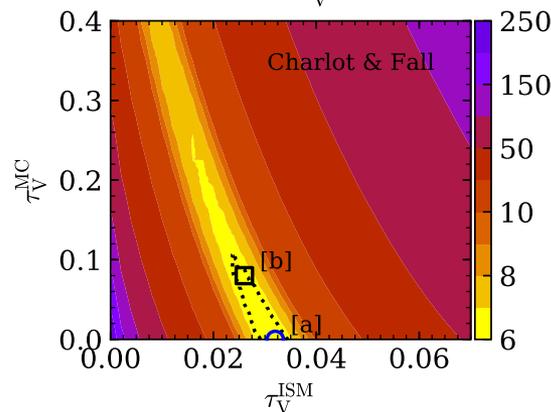
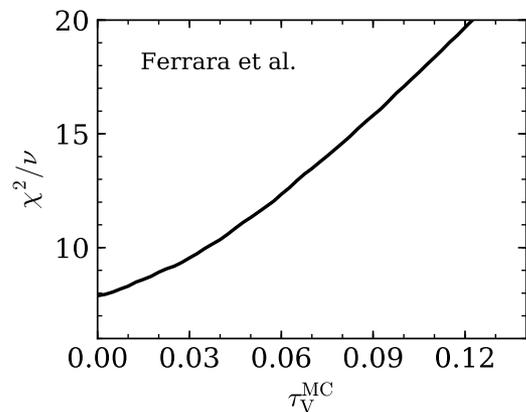
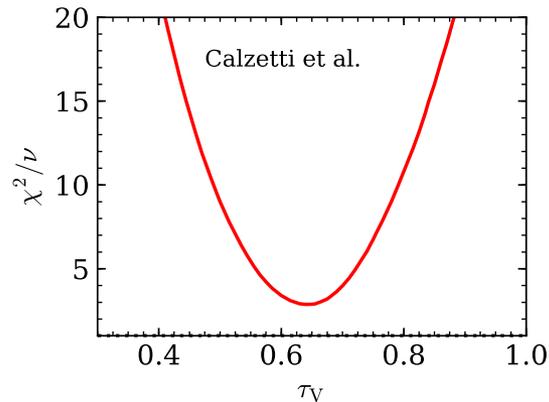
Modelling [NII] Contamination



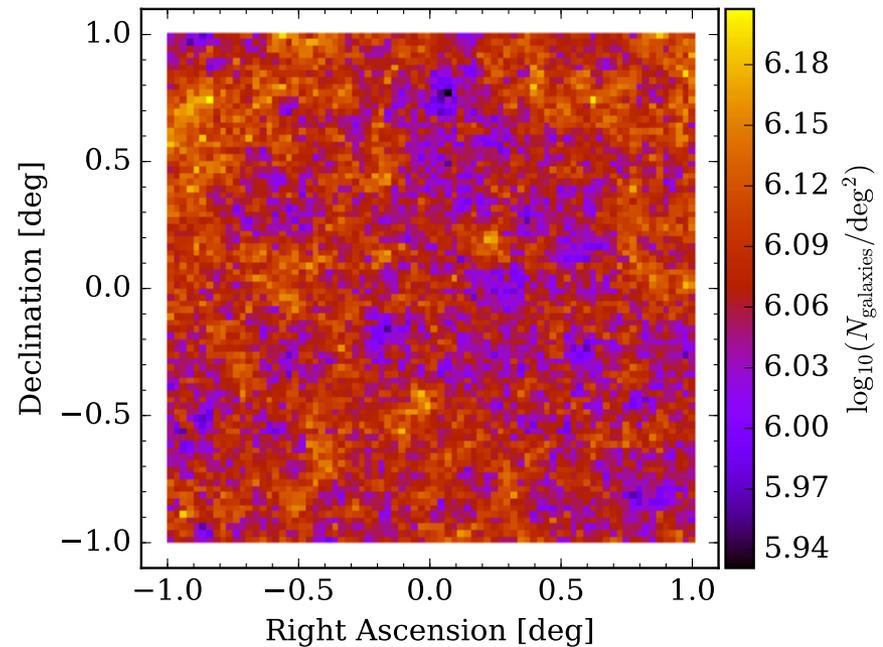
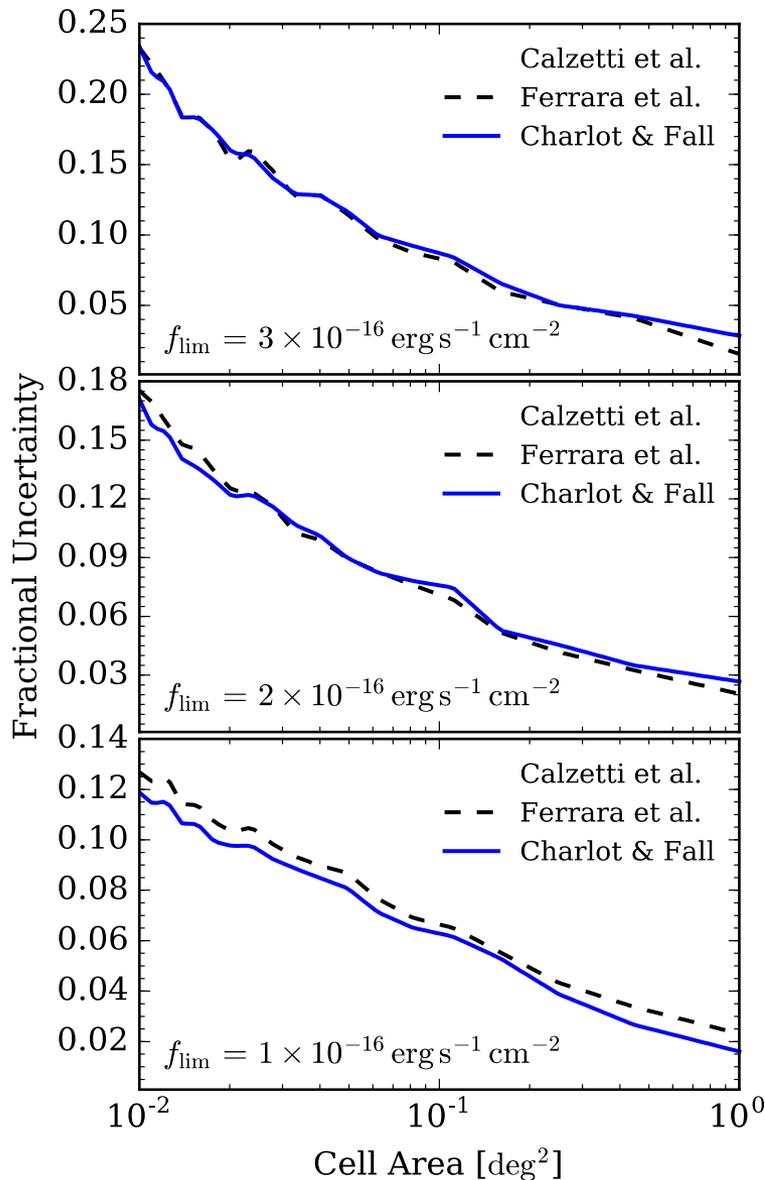
- [NII]/H α value assigned to Galacticus using 5 nearest neighbours from Masters et al. (2016) SDSS catalogue.
- Negligible IMF correction needed: Galacticus uses Chabrier et al. (2003) and Masters et al. (2016) used Kroupa et al. (2001).

Dust Modelling

- Three dust methods:
 - **Ferrara et al. (1999):** library of dust curves as function of various galaxy properties
 - **Charlot & Fall (2000):** optical depth follows power law with wavelength
 - **Calzetti et al. (2000):** empirical *dust screen* (global rescaling, function of wavelength)
- Use χ^2 minimisation technique to determine optical depths to match WISP counts from Mehta et al. (2016).



Impact of Cosmic Variance

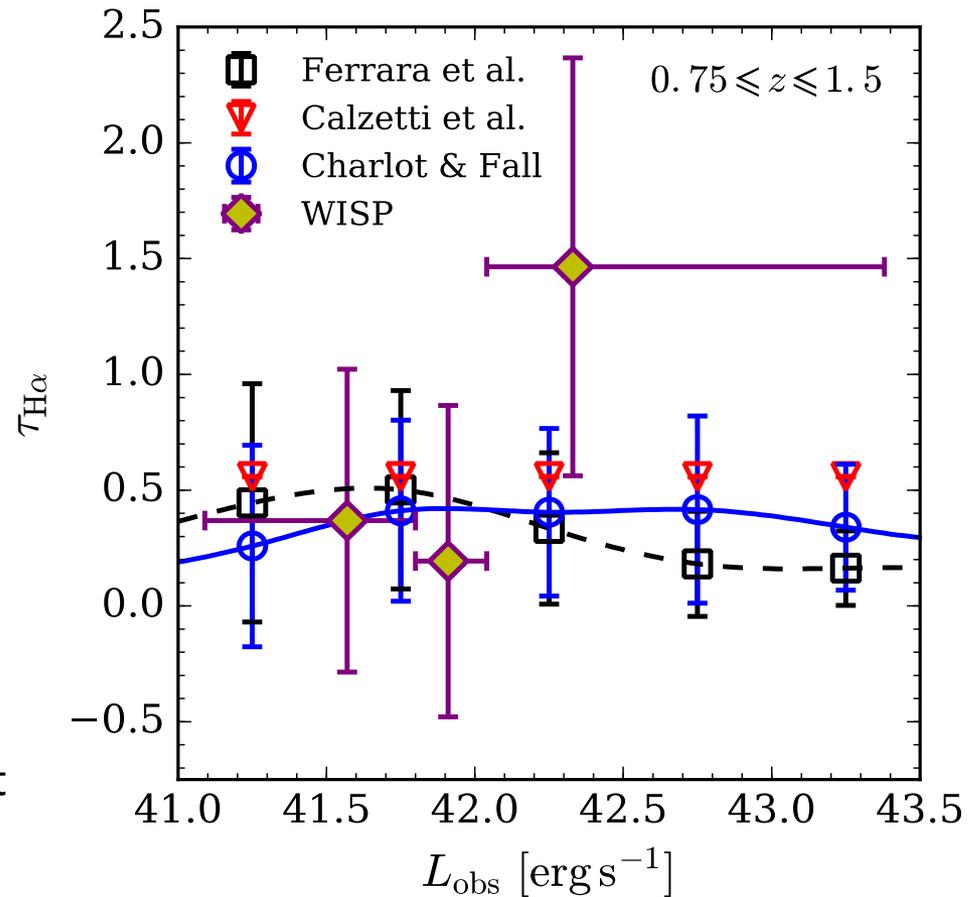


- Split lightcone footprint into $N \times N$ cells and compute counts for each cell.
- Fractional uncertainty = $\text{std.dev.}/\text{mean counts}$ (over $N \times N$ cells) at particular flux limit.
- **For full lightcone, cosmic variance impacts counts at ~2-3% level.**
- For $\sim 0.05 \text{ deg}^2$ (area used by Mehta+2015) cosmic variance impacts at ~8-9% level.

Optical Depth Comparison

$$\tau_{\text{H}\alpha} = -\ln\left(\frac{L_{\text{H}\alpha}^{\text{att}}}{L_{\text{H}\alpha}^0}\right)$$

- WISP optical depths from Domínguez et al. (2013).
- Galacticus optical depths consistent for faint luminosities.
- Increasing optical depth towards bright luminosities not reproduced by in Galacticus.



Predicting Euclid/WFIRST counts

- Use χ^2 minimisation results to construct likelihood for dust parameters.
- Use Monte-Carlo sampling to sample dust likelihoods 1000 times \rightarrow generate 1000 optical depths for each dust method.
- Apply each optical depth \rightarrow generate 1000 realisations for redshift distribution and counts.

