H-alpha emitters number density predictions for the Euclid spectroscopic survey

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Outline

- Motivation
- Current observations
- Empirical models
- The Galacticus semi-analytical model
- Comparison with observations
- Predictions for Euclid

Why are we concerned about galaxy number density?

$$\left[\frac{\sigma_P(k)}{P(k)}\right]^2 \propto \frac{1}{V_{\rm eff}(k)}$$

galaxy number density

$$V_{\rm eff}(k) \propto \int \left[\frac{n(z)P(k)}{1+n(z)P(k)}\right]^2 \frac{{\rm d}V(z)}{{\rm d}z{\rm d}\Omega}{\rm d}z$$

(Feldman, Kaiser & Peacock 1994; Tegmark 1997; Seo & Eisenstein 2003)

- Want sub-percent precision on cosmological parameters
- Fractional error on power spectrum dependent on effective volume
- Need to **maximize effective volume** of survey

Survey strategy → Number density of galaxies → Uncertainties on matter power spectrum → Uncertainties on cosmological parameters

Need to optimise this!

We want this!

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 - 1.7um, R~130) + G102 (0.8 - 1.2 um, R~210)
  - H-alpha detectable for $z < 1.5$
- Total area ~0.3 square degrees over ~400 separate fields (though not all fields processed yet).

- Predicted Euclid number densities from:
  - Colbert et al. (2013): 29 fields over area ~0.037 deg^2
    - $2x10^{-16}$ erg $s^{-1}cm^{-2}$ for $0.7 < z < 1.5$ —> 6700 deg^{-2}
  - Mehta et al. (2015): 52 fields over area ~0.051 deg^2
    - $2x10^{-16}$ erg $s^{-1}cm^{-2}$ for $0.7 < z < 1.5$ —> 6000 deg^{-2}
    - $2x10^{-16}$ erg $s^{-1}cm^{-2}$ for $0.7 < z < 2$ —> 11,000 deg^{-2}

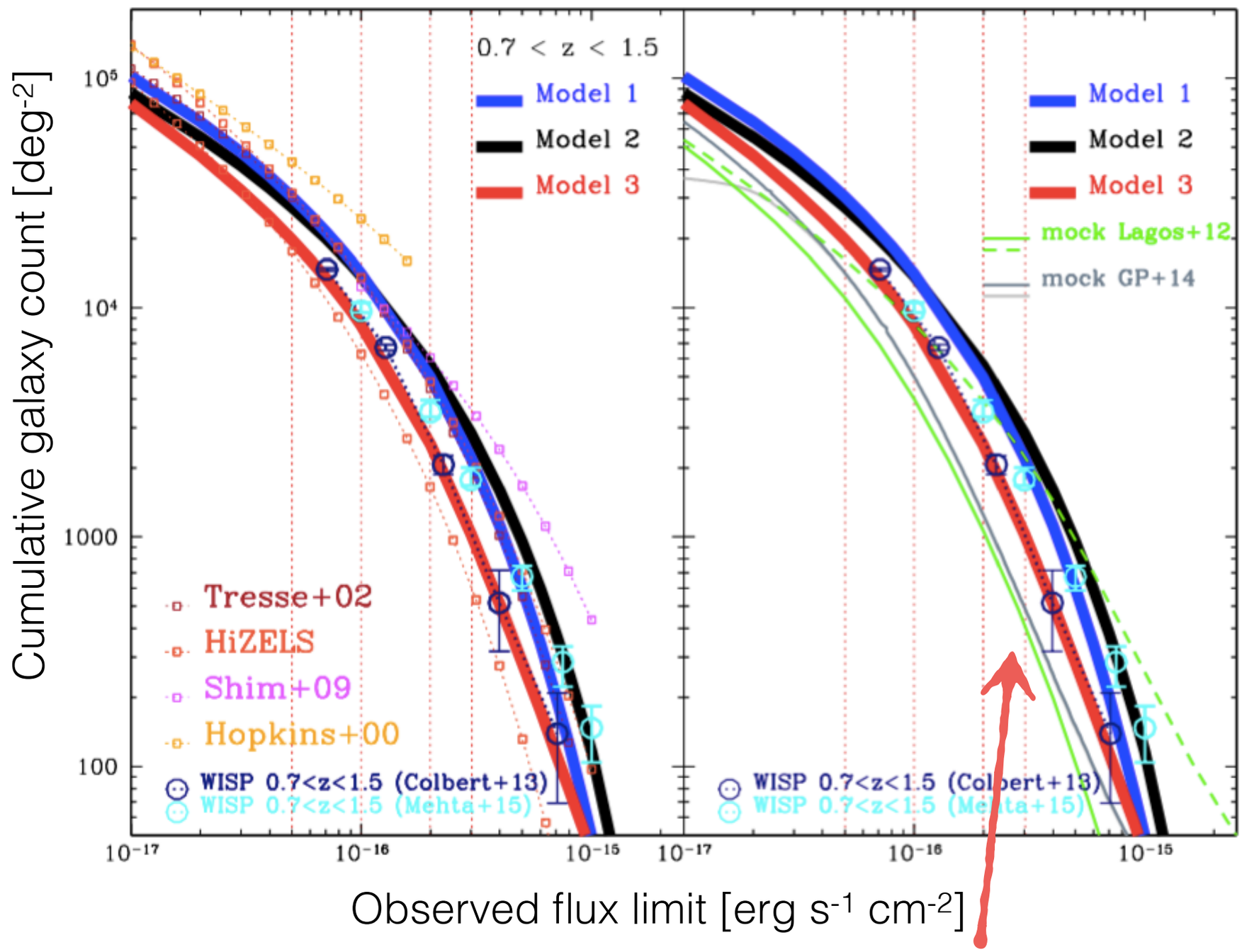
Empirical models

Pozzetti et al. (2016): three empirically motivated models for H-alpha luminosity function.

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

Predictions (no NII):
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}



Previous Euclid galaxy mocks under-predicting counts!

The **Galacticus** galaxy formation model

Available here!
https://sites.google.com/site/galacticusmodel/

- **Semi-analytical model** (Benson 2012)
  - following philosophy of *Galform* model (Cole et al. 2000)
  - solves coupled sets of ODEs governing astrophysical processes
  - galaxy properties extracted by integrating ODEs to desired epoch
  - modular nature — new physics easily incorporated
  - SEDs obtained by convolving star formation histories with stellar population synthesis model (Conroy et al. 2010) and IMF (Chabrier 2003).
  - calibrated against local Universe observations (inc. stellar mass function).
  - **open source**

- 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
  - can output all emission lines provided by CLOUDY.

The **Galacticus** galaxy formation model

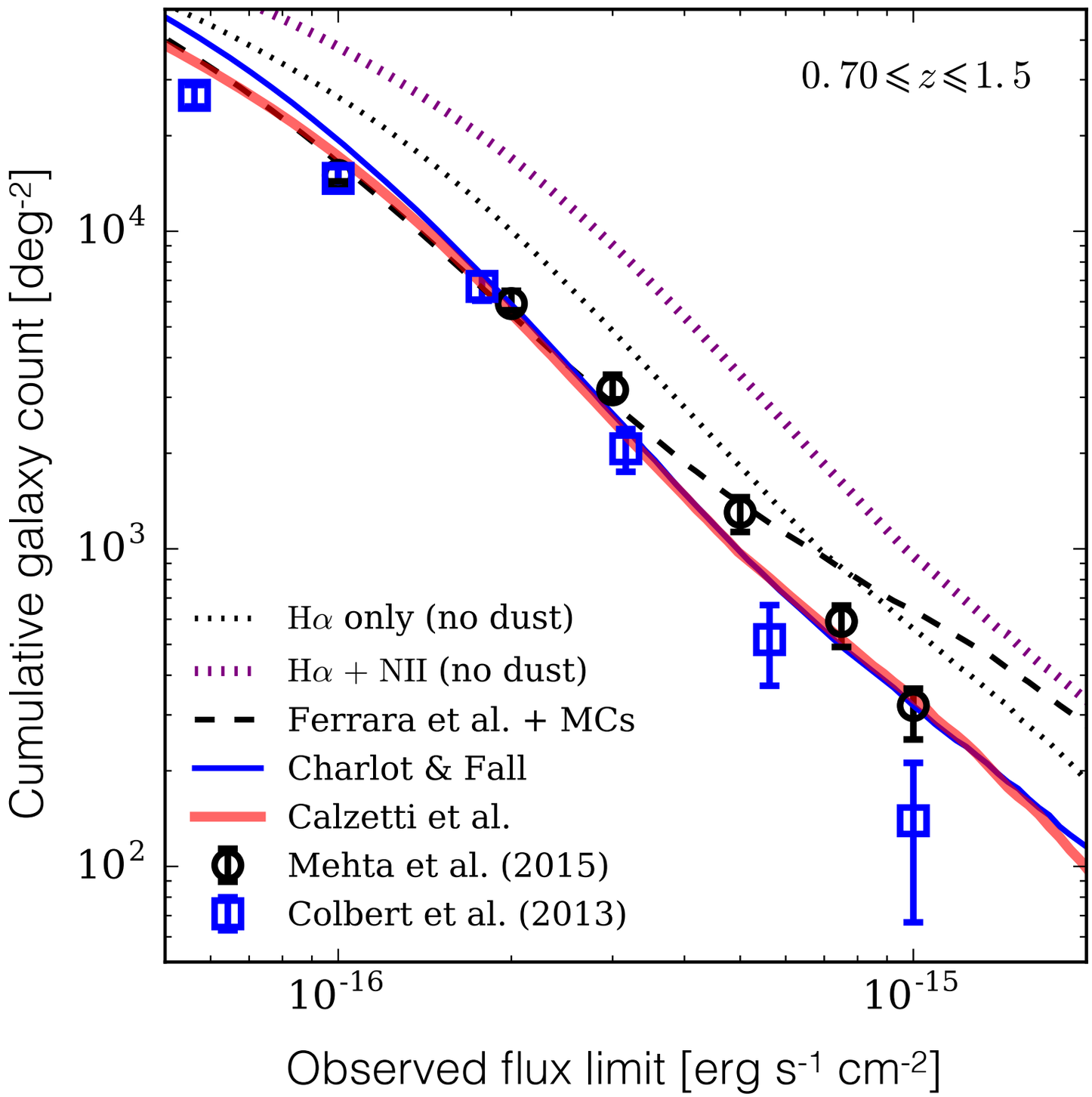
- Dust modelling:
  - **Ferarra et al. (1999)**: library of dust curves as function of various galaxy properties
    - interpolate over library using Galacticus properties
  - **Charlot & Fall (2000)**: optical depth follows power law with wavelength
    - nebula attenuation applied to stellar light from recent (~10 Myr) star formation

$$\tau_\lambda^{\rm ISM} \propto \hat{\tau}_{\rm V}^{\rm ISM} \Sigma_{\rm gas}^{\rm metals} \left(\frac{\lambda}{\lambda_0}\right)^{-n} \qquad \tau_\lambda^{\rm MC} = \hat{\tau}_{\rm V}^{\rm MC} \frac{Z_{\rm gas}}{Z_{\rm ISM}} \left(\frac{\lambda}{\lambda_0}\right)^{-n}$$

  - **Calzetti et al. (2000)**:
    - empirical *dust screen* (global rescaling, function of wavelength)

- Lightcone construction:
  - merger trees from Millennium Simulation (Springel et al. 2005).
  - lightcone methodology from Kitzbichler & White (2007).
  - Galacticus outputs all galaxies that cross past lightcone of observer in redshift range **0.5 ≤ z ≤ 2** within **4 square degrees**
  - compute emission line properties and dust attenuation.
  - apply Euclid flux limit and wavelength cut
  - galaxies re-distributed according to HEALPix cells (Gorski et al. 2005)

Comparison with WISP galaxy counts

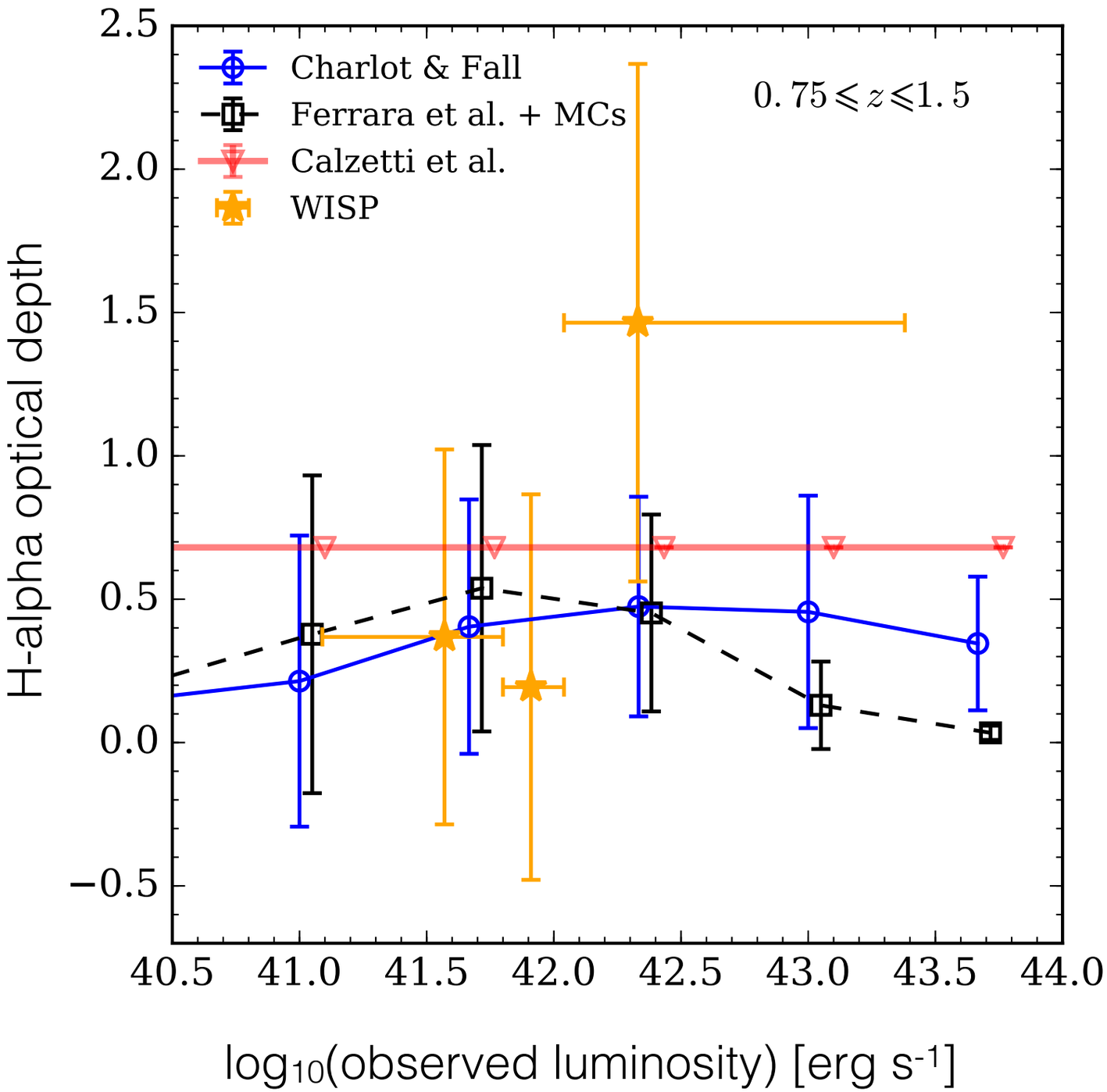


Assume NII contamination 29% (consistent with Colbert et al. 2013)

$$L_{\mathrm{H}\alpha+\mathrm{NII}} = L_{\mathrm{H}\alpha}/0.71$$

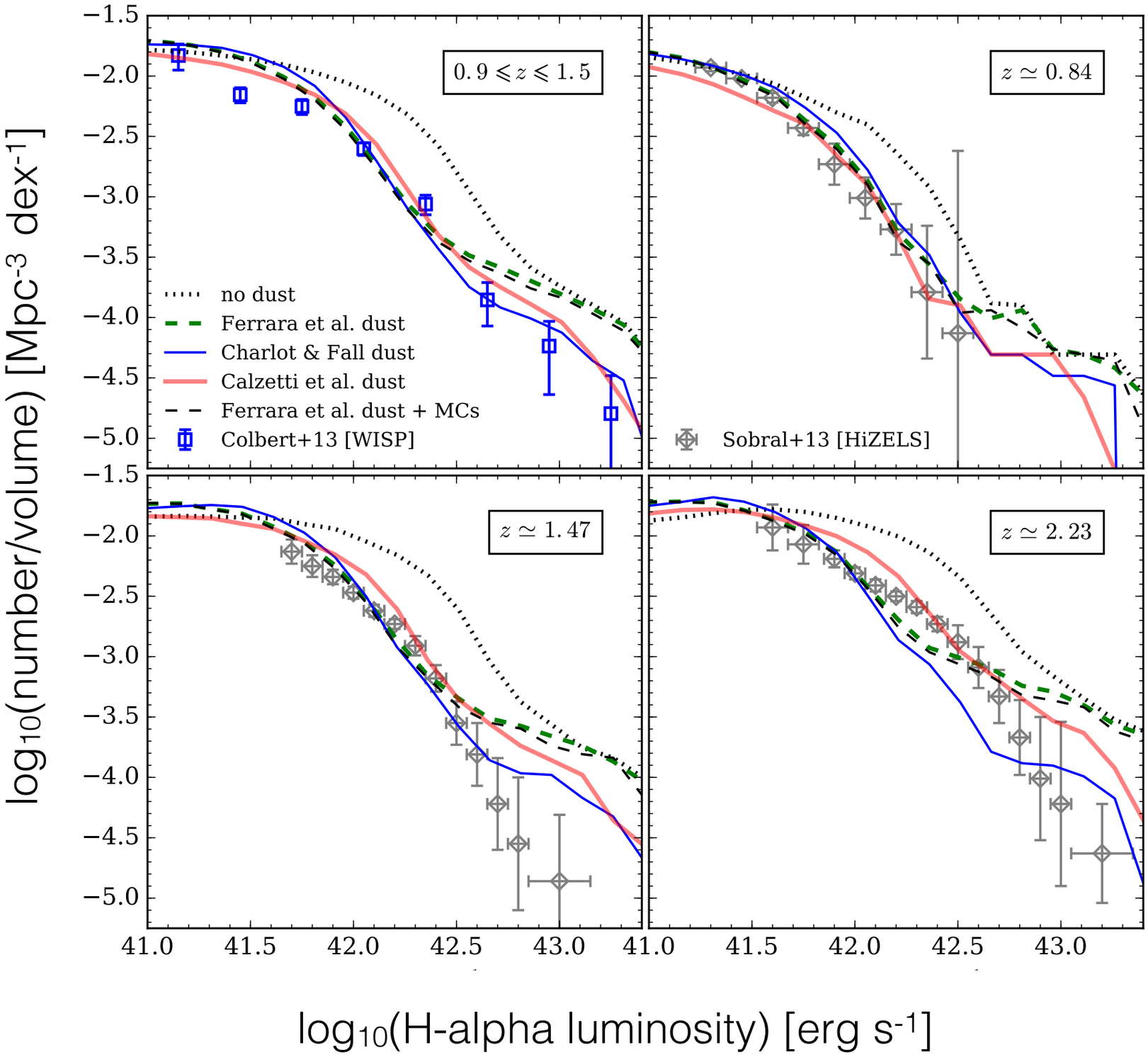
- Adjust dust strength to match WISP counts (Mehta et al. 2015)
- Good agreement for **Calzetti et al.** and **Charlot & Fall**.
- **Ferrara et al.** over predicts bright counts (no adjustment applied)

Consistency checks: optical depth



- Optical depths consistent with WISP estimates.
- Galacticus suggests no clear increase in optical depth with luminosity at brightest luminosities.

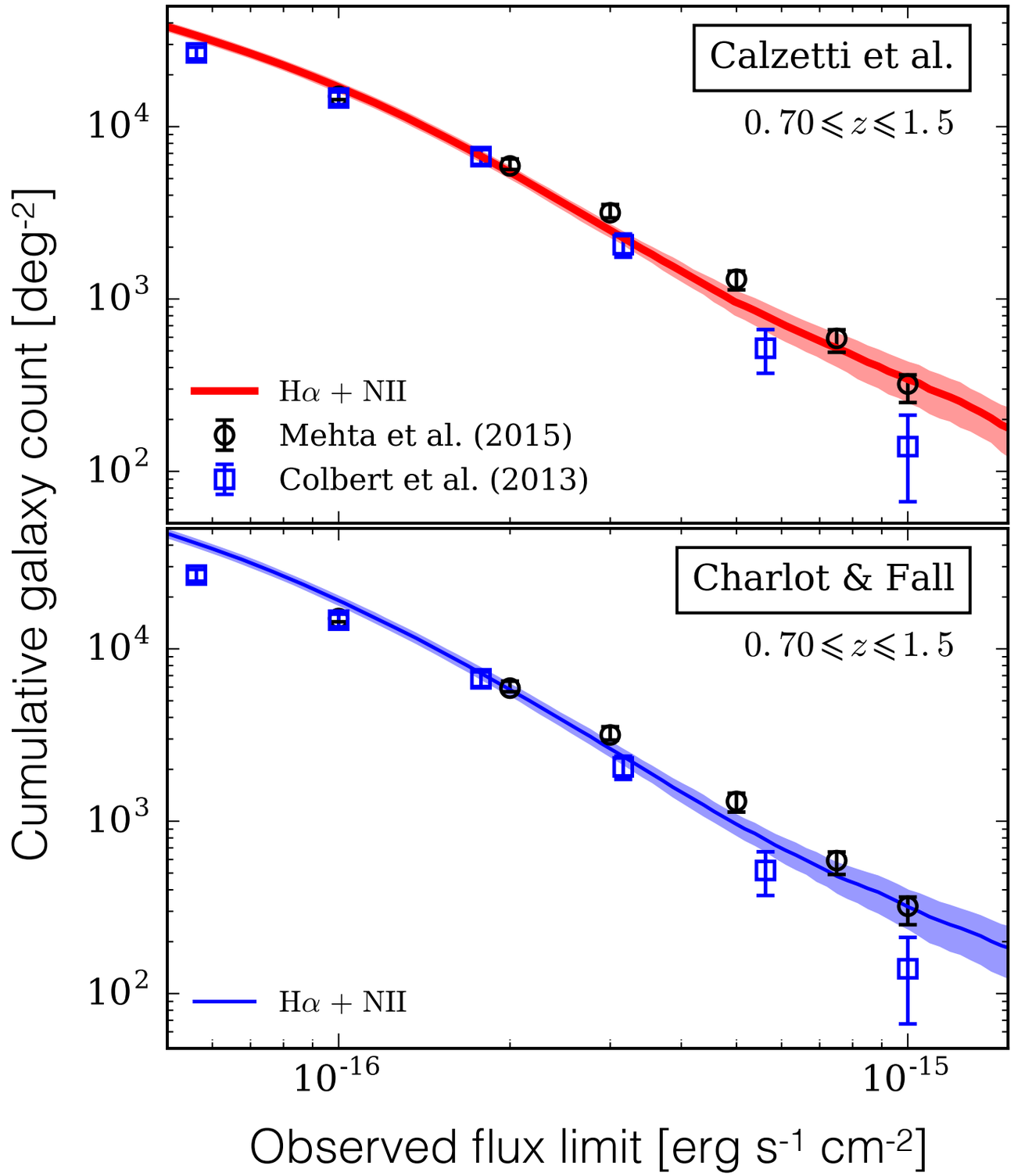
Consistency checks: luminosity function



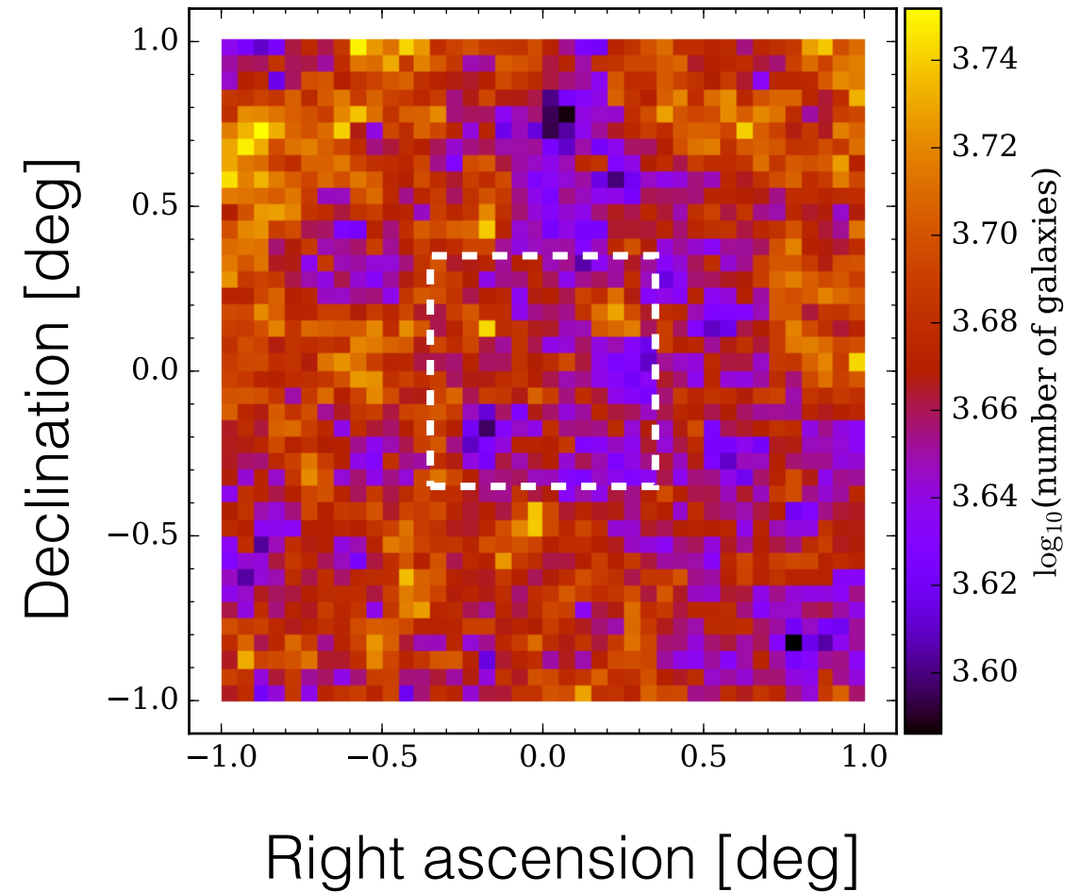
Dust-attenuated rest-frame H-alpha luminosity function

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

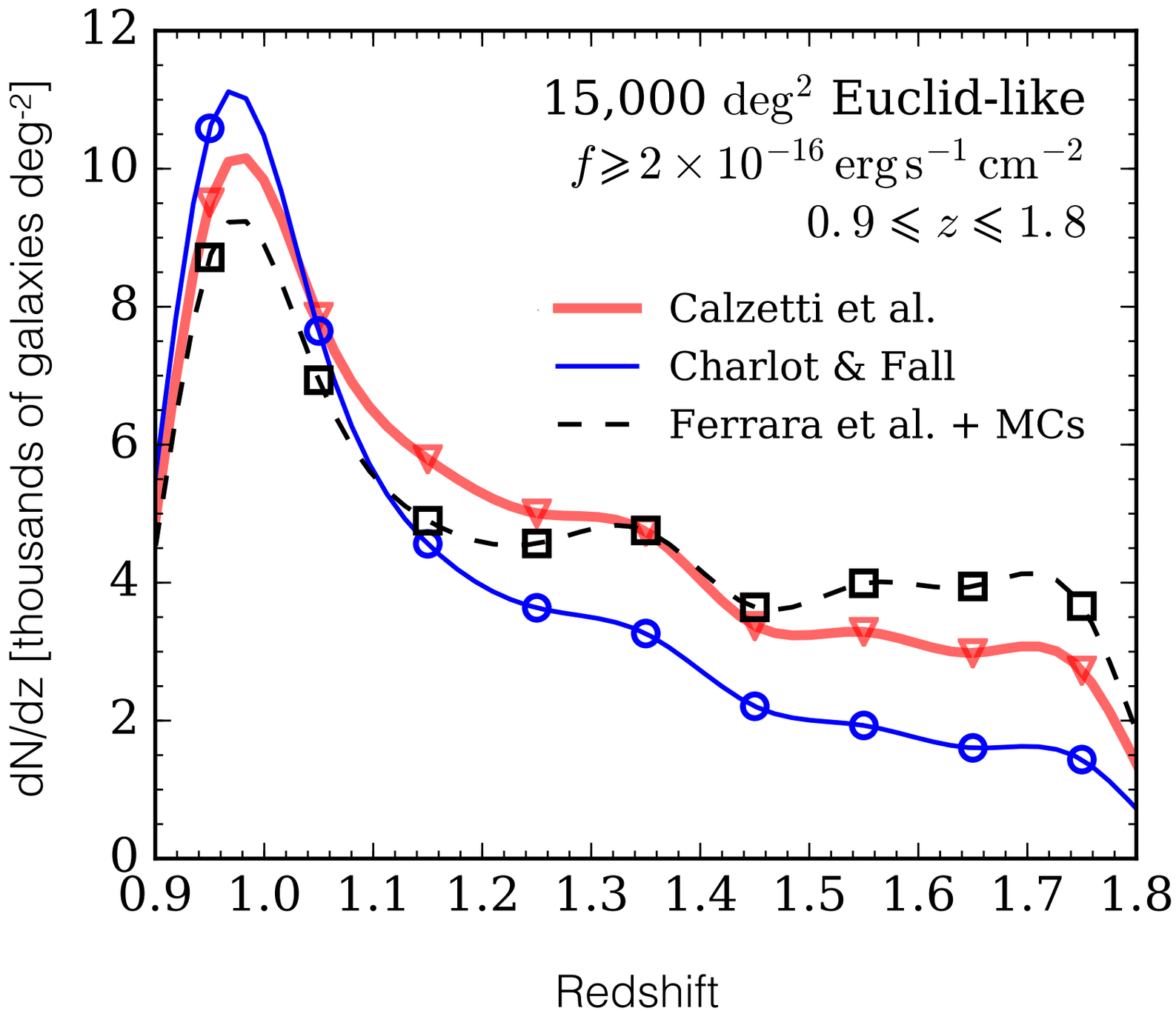
Impact of cosmic variance



- Counts computed for individual HEALPix cells (NSIDE = 256)
- HEALPix cell size ~0.05 deg^2
- one WISP field ~0.001 deg^2 (~4.6 arcmin^2)



Predicted Euclid redshift distributions



- All dust methods show peak at z~1
- Close agreement between methods at z<1.2
- Largest difference at high redshift — difference of factor ~2 at 1.5 < z < 1.7

Predicted Euclid number counts

Cumulative counts per square degree

Flux Limit (erg s^{-1} cm^{-2})	Calzetti et al.	Charlot & Fall	Ferrara et al. (inc. MCs)
2×10^{-16}	4487	3651	4480
3×10^{-16}	2124	1639	2640

Observed luminosity (**H-alpha + NII**), $0.9 \leq z \leq 1.8$

- Galacticus counts between **model 1 and model 3** from Pozzetti et al.
- Galacticus luminosity function slope steeper compared to Pozzetti et al.luminosity functions

- Galacticus predictions vary by **10%—30%** in counts
- Larger variation in predictions from empirical models due to large scatter in observations
- Galacticus predictions more **robust** — physical galaxy formation model with properties calculated self-consistently

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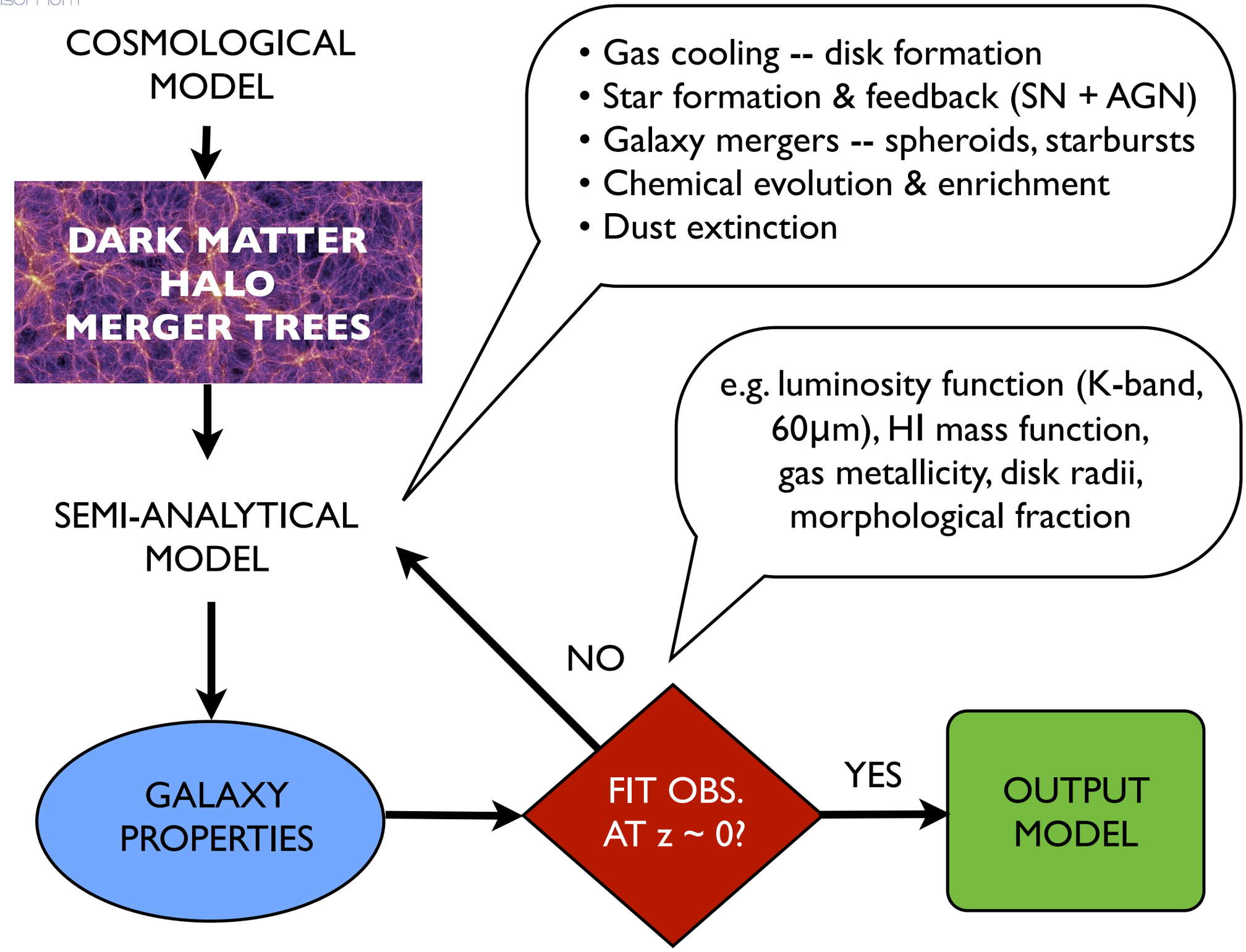
Observed luminosity (**H-alpha + NII**), $0.9 \leq z \leq 1.8$

- Comparison to WISP predictions (Mehta et al 2015):
  - flux limit of 2×10^{-16} erg $s^{-1} cm^{-2}$ over redshift range $0.7 < z < 2$
  - Galacticus finds significantly fewer galaxies
    - require further adjustment of dust for $z > 1.5$?
    - emission lines too weak at $z > 1.5$?
    - incorrect extrapolation from lower-z H-alpha+OIII bivariate luminosity function?

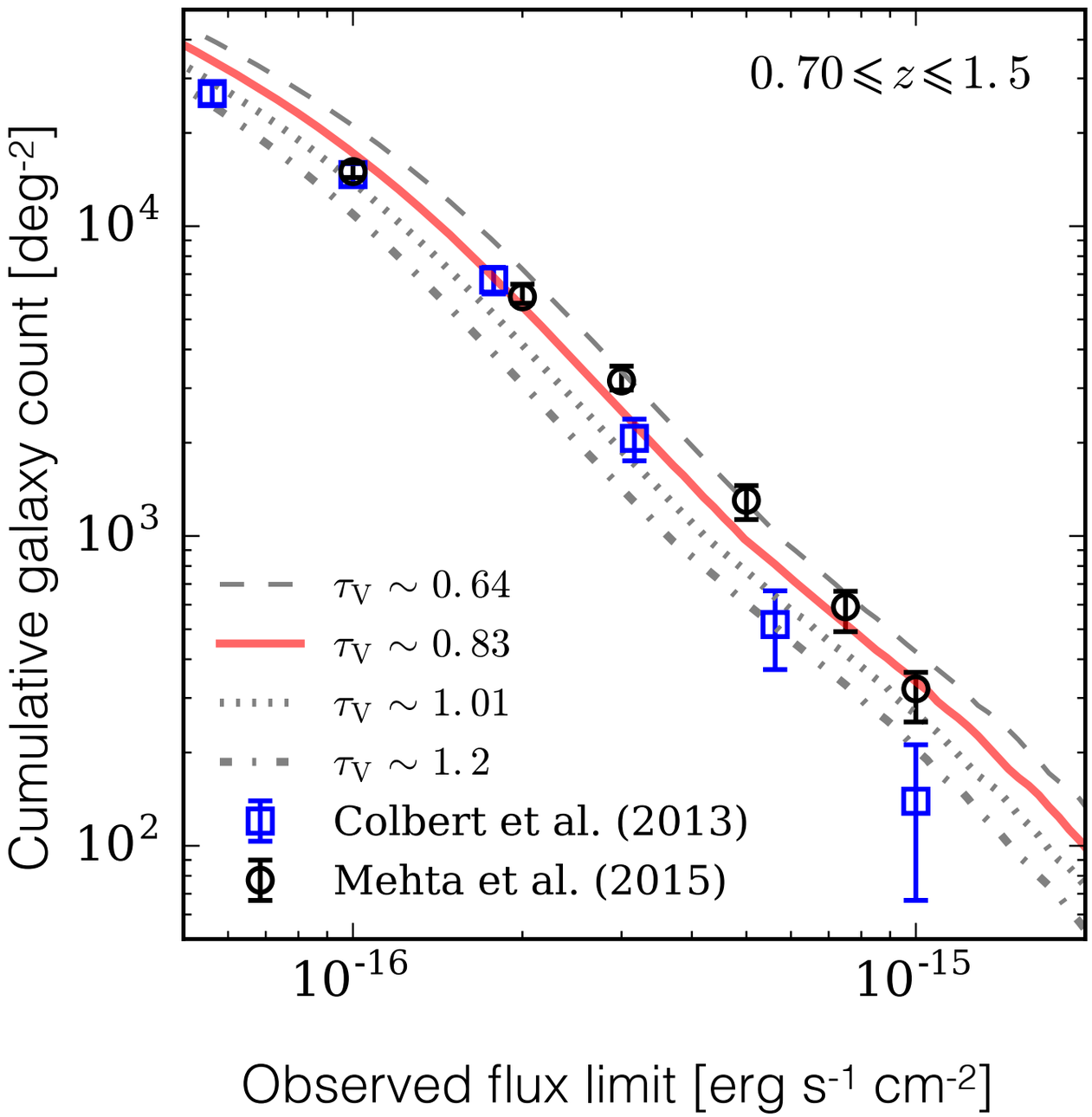
Summary

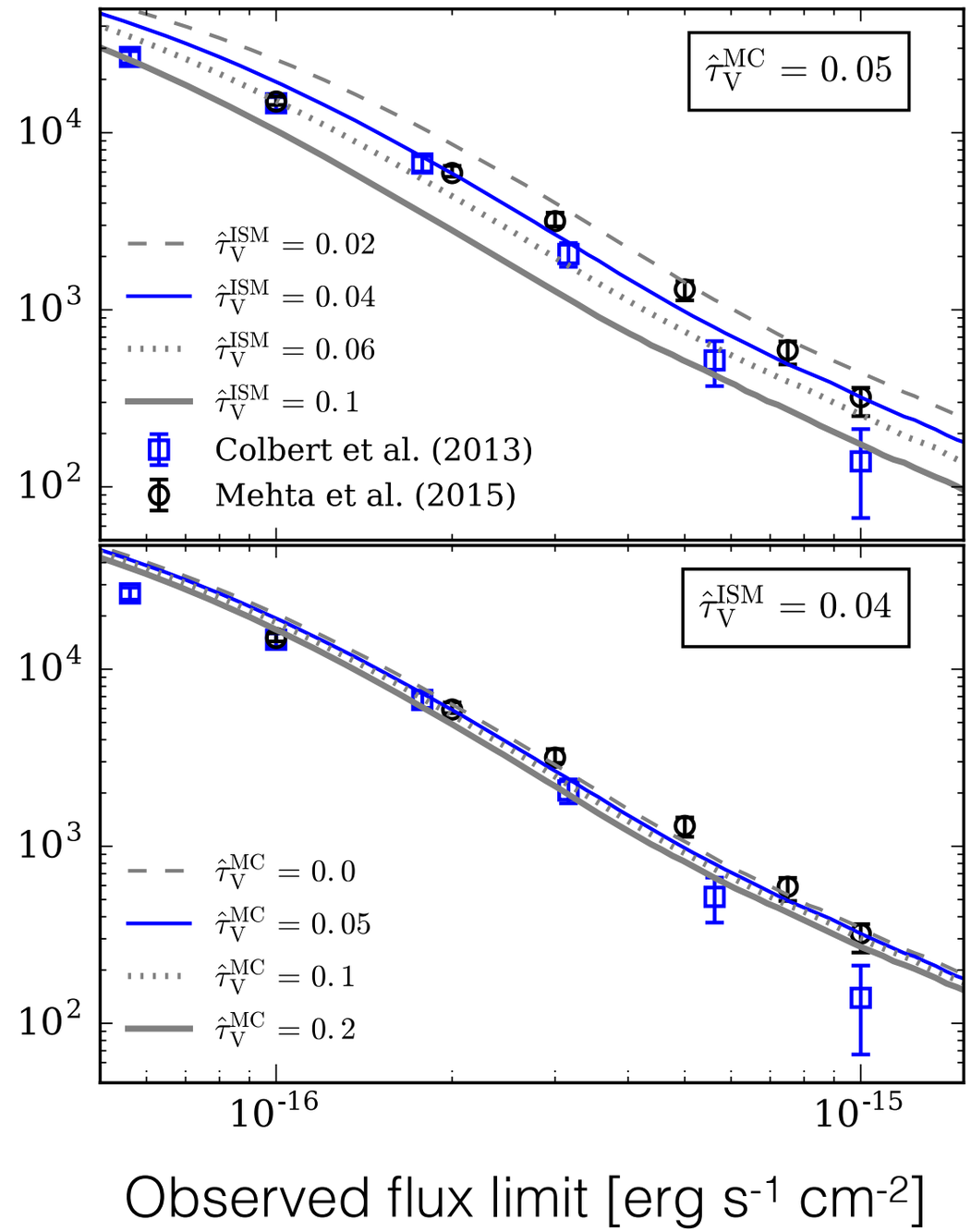
- Knowledge of galaxy number density essential for **optimising survey strategy**
- Galaxy counts from **Galacticus lightcones able to reproduce WISP counts**
  - Galacticus optical depths and luminosity functions consistent with WISP
- Galacticus predicts number densities of:
  - **3600–4500 deg^{-2}** for **$0.9 \leq z \leq 1.8$** and flux limit **2×10^{-16} erg s^{-1}cm^{-2}**
  - **1600–2600 deg^{-2}** for **$0.9 \leq z \leq 1.8$** and flux limit **3×10^{-16} erg s^{-1}cm^{-2}**
- Galacticus counts between Pozzetti et al. **models 1 and 3**, but have **smaller scatter in predicted numbers**.
- <u>Possible future developments</u>:
  - larger volume simulations —> larger area lightcones
  - **application to the Flagship Simulation would require merger trees**
  - investigate other emission lines and properties (NII, OIII, equivalent widths, SEDs,…)
  - predictions for clustering of H-alpha emitters

ADDITIONAL SLIDES

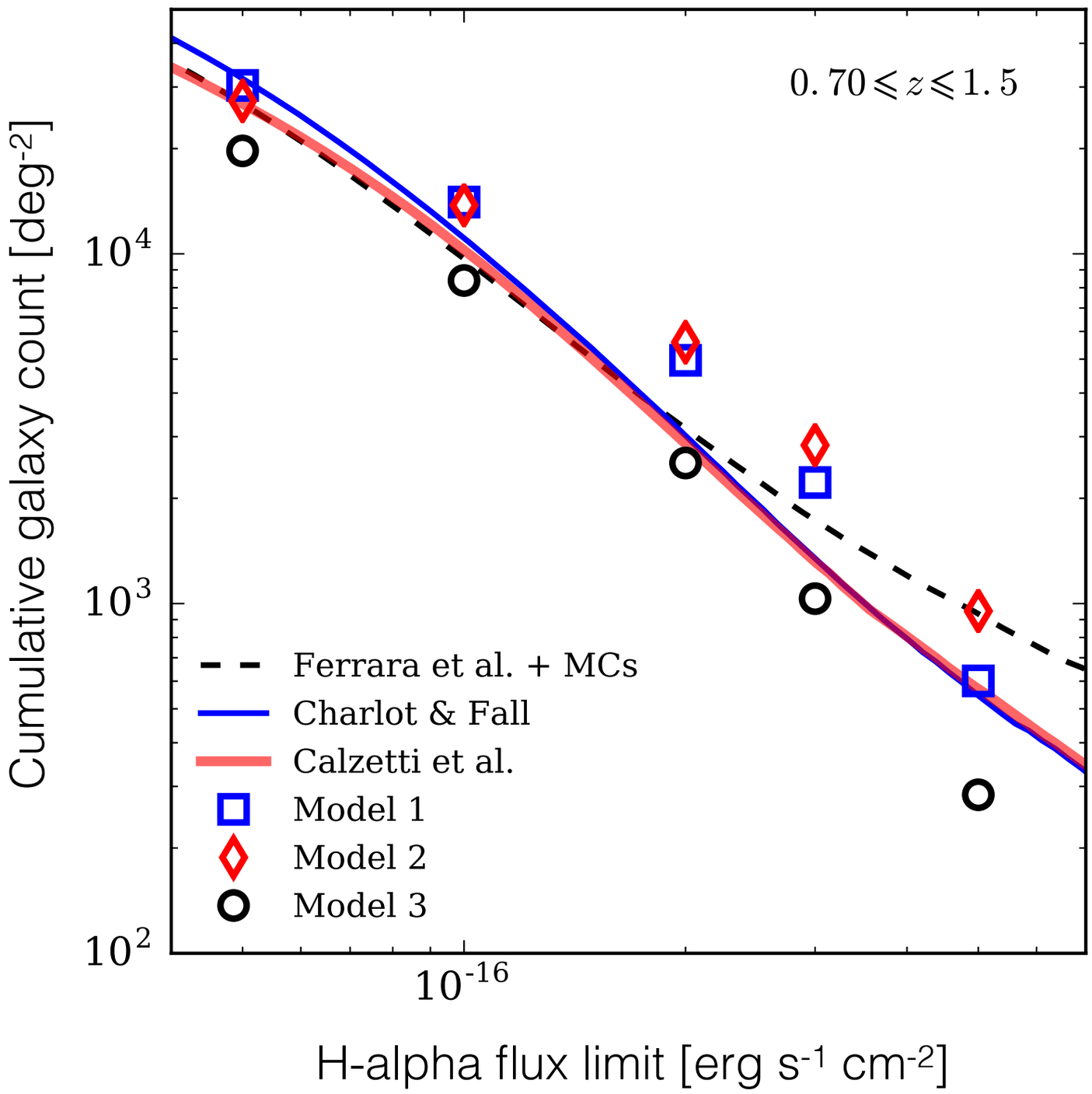

COSMOLOGICAL MODEL
DARK MATTER HALO MERGER TREES
SEMI-ANALYTICAL MODEL
• Gas cooling -- disk formation
• Star formation & feedback (SN + AGN)
• Galaxy mergers -- spheroids, starbursts
• Chemical evolution & enrichment
• Dust extinction
e.g. luminosity function (K-band, 60μm), HI mass function, gas metallicity, disk radii, morphological fraction
NO
GALAXY PROPERTIES
FIT OBS. AT z ~ 0?
YES
OUTPUT MODEL

Adjusting strength of dust attenuation





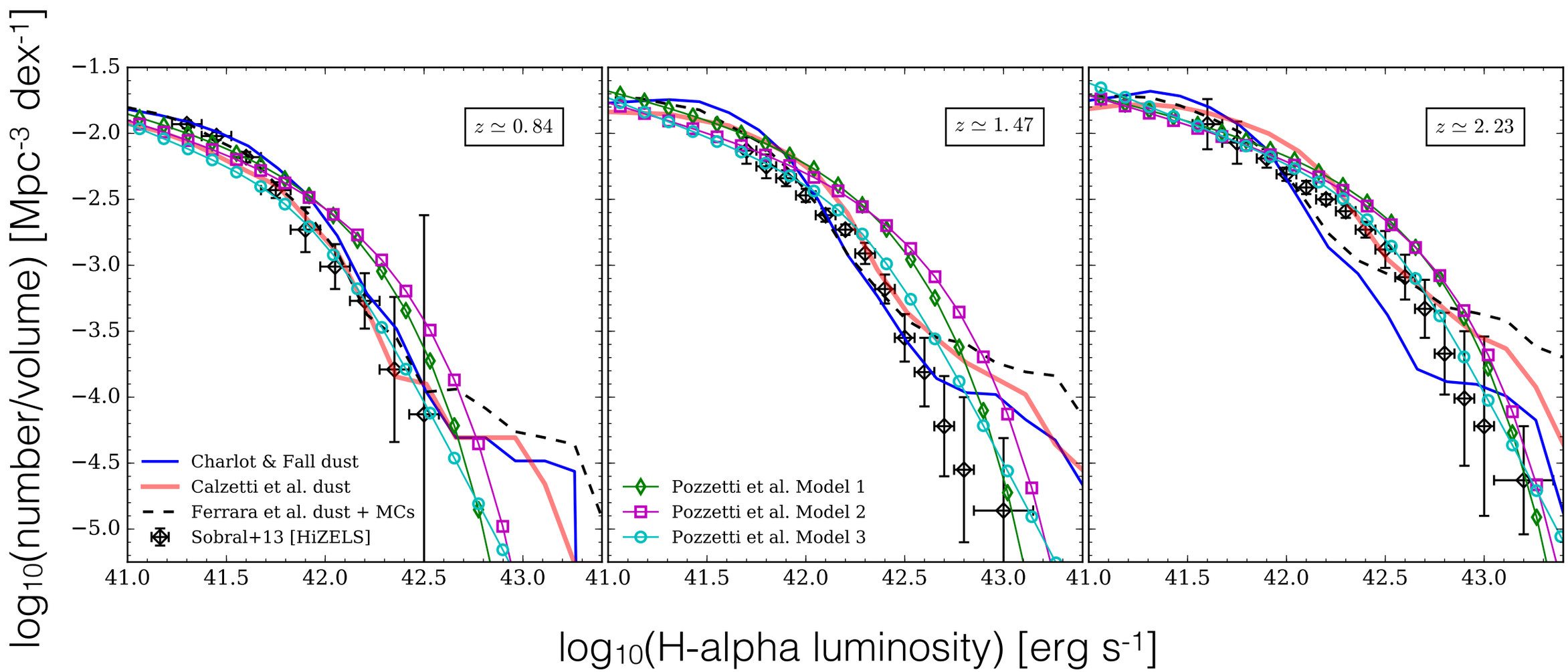
Comparison with empirical models



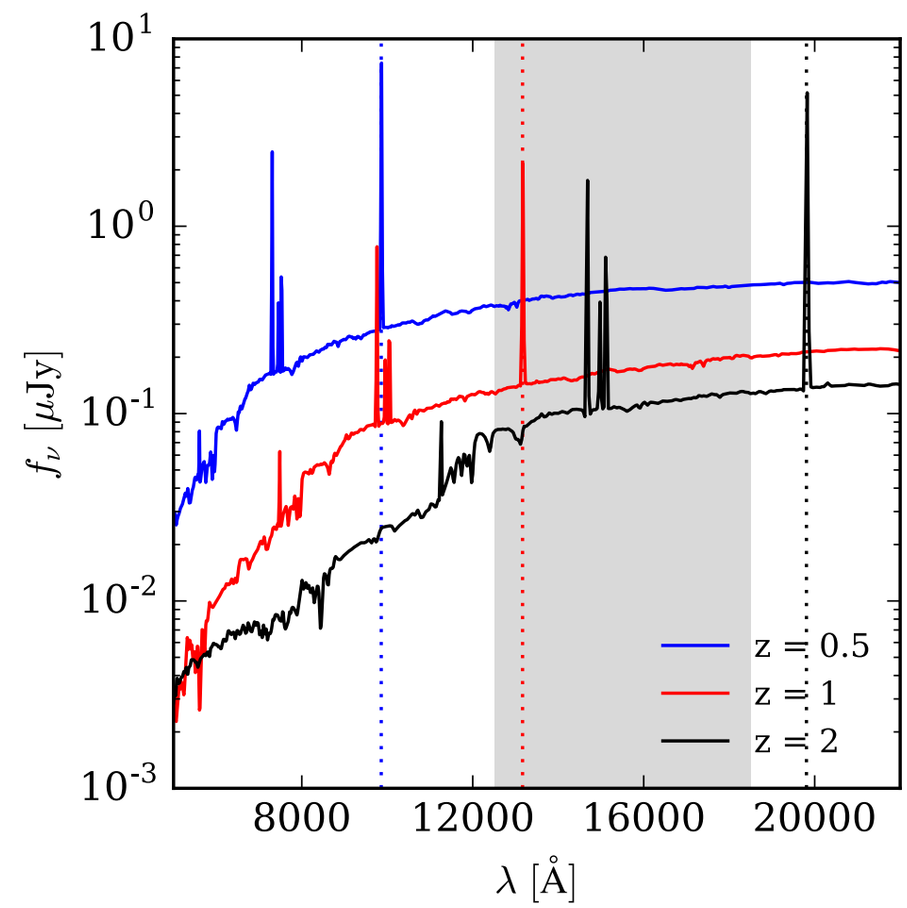
Models 1,2,3 from Pozzetti et al. (2016)

Not including blending of H-alpha + NII

Comparison with empirical models



- Dust attenuated H-alpha luminosity function
- No NII blending

Future developments

- Larger volume simulations (Gpc-sized) available
- Improved calibration (Monte-Carlo sampling)
- Properties of additional emission lines (OIII, NII, …)
- Other observables: equivalent widths, SEDs, …
- Clustering predictions (e.g. galaxy bias)
- More sophisticated dust models (e.g. radiative transfer methods)
- Photometric (YJH) counts predictions
- Connection to (weak) lensing
- Comparison with Flagship simulation