Update on the pathchiness of IGM opacity to Lyman-α radiation

Sarah Bosman

University College London

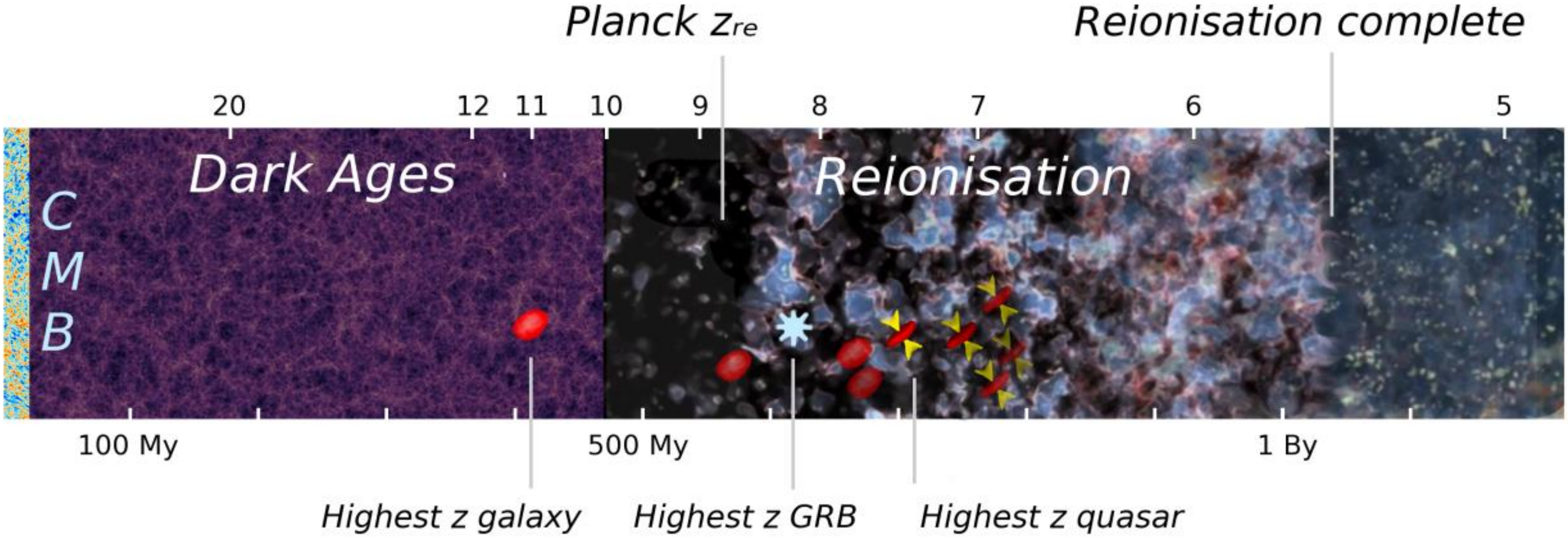
George Becker, Martin Haehnelt, Xiaohui Fan,

Yoshiki Matsuoka (SHELLQs collaboration), Sophie Reed (DES-VHS collaboration), Linhua Jiang (SDSS collaboration)

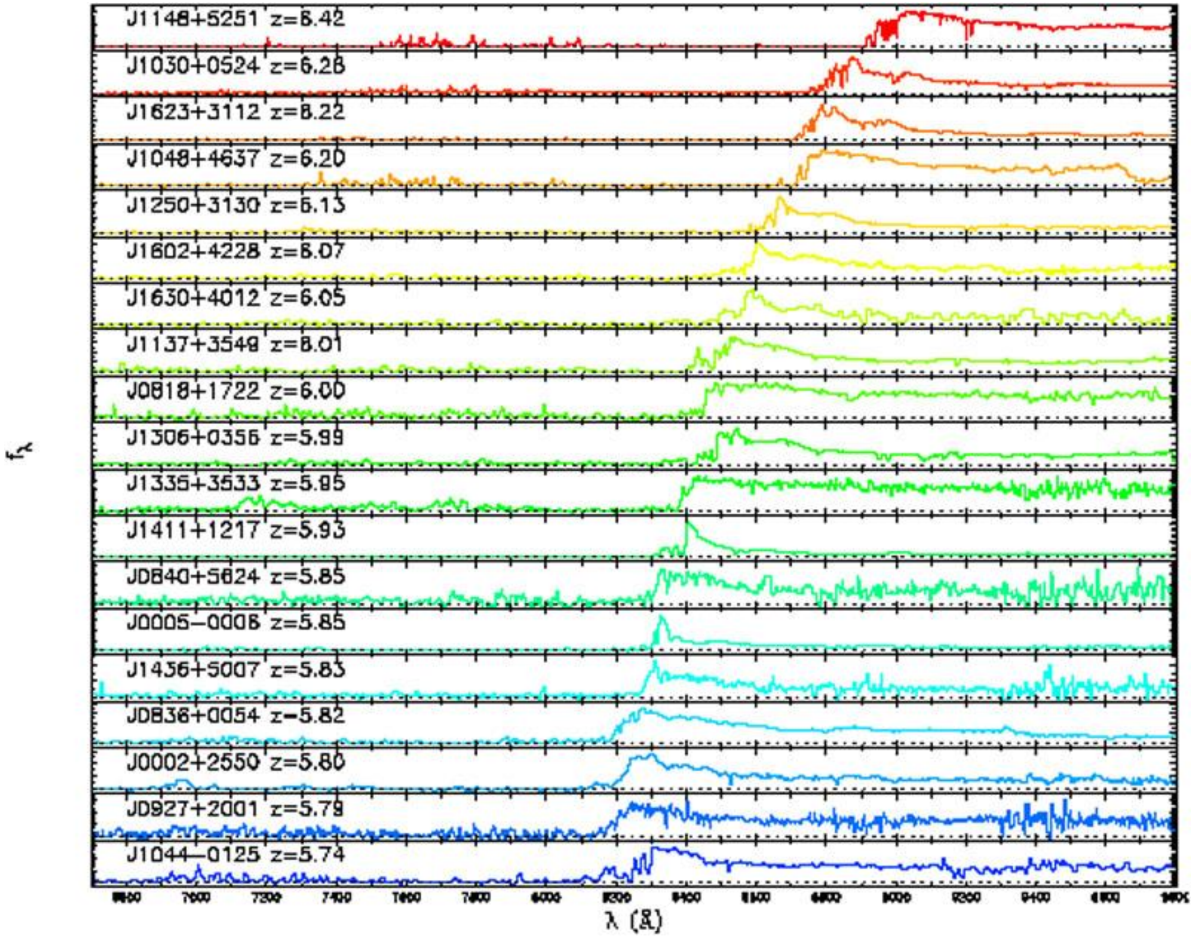
European Research Council

Established by the European Commission

Probing Reionisation using Lyman-α transmission towards AGN



Probing Reionisation using Lyman-α transmission towards AGN

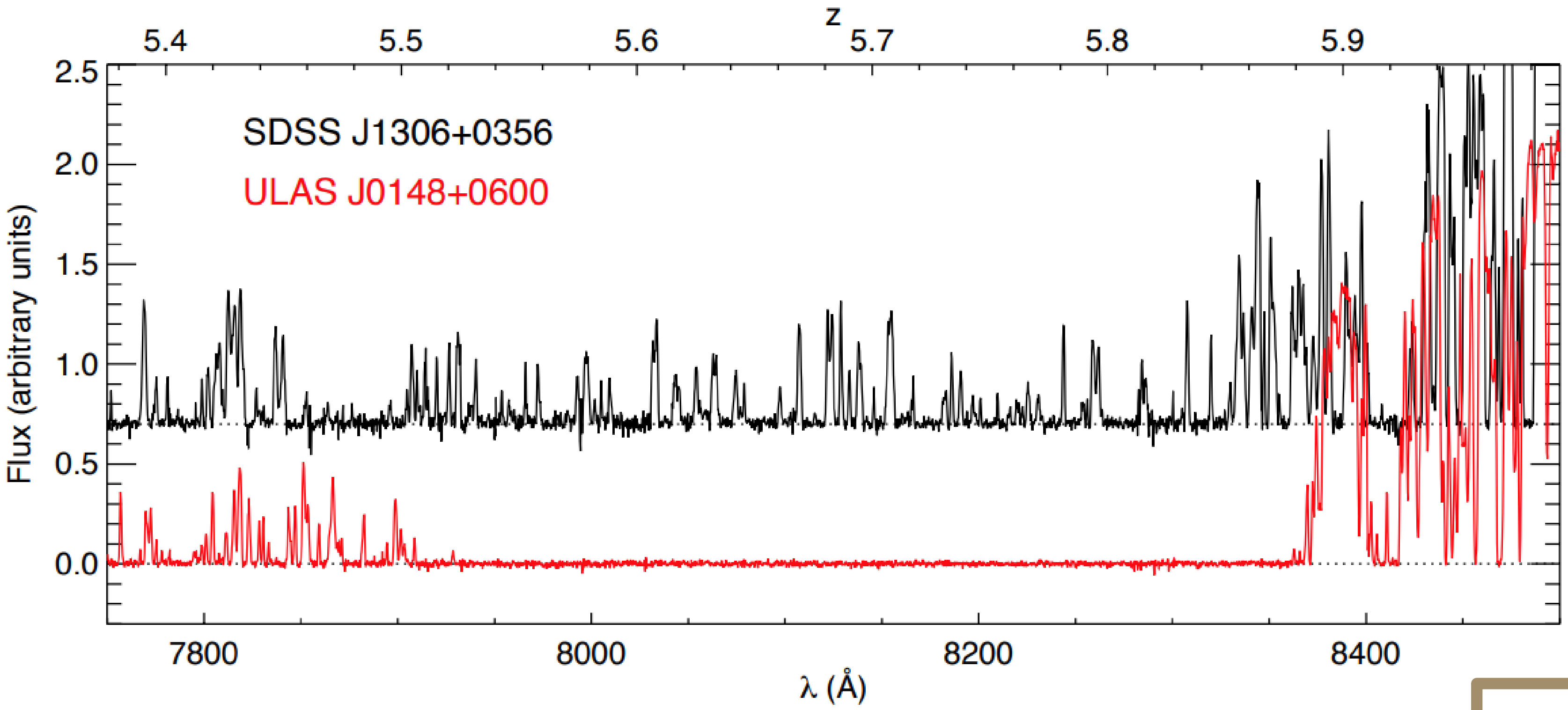


Fan+06

Full Gunn-Peterson absorption kicks in at z=5.9

→ Universe is at least 99.9% ionized at z<5.9 in a global-averaged sense

Probing Reionisation using Lyman-α transmission towards AGN



Credit: George Becker

Becker+15 discovers extremely opaque line of sight spanning *z*=5.5 – 5.85 :

Intrinsic $\Delta\tau_{\mathrm{eff}}$ at the *same redshift* much larger than expected from density fluctuations alone!

$$\tau_{\mathrm{eff}} = -\ln\left(< \boldsymbol{F} >_{50\ cMpc\ h^{-1}} \right)$$

Three families of models proposed:

Rare bright sources
contribute significantly:
AGN, largest galaxies

e.g. Chardin+15, 17

Differential timing
of Re^{o} due to temperature fluctuations:
high ρ regions ionize, cool down and recombine first

e.g. D'Aloisio+15;
Keating+17

Varying mean free path
of Re^{o} photons due to fluctuations of the UV background

e.g. Davies & Furlanetto 16

Our objective: improve measurements of τ_{eff}

- Dramatic increase in number of lines of sight: 62 (96) up from 33

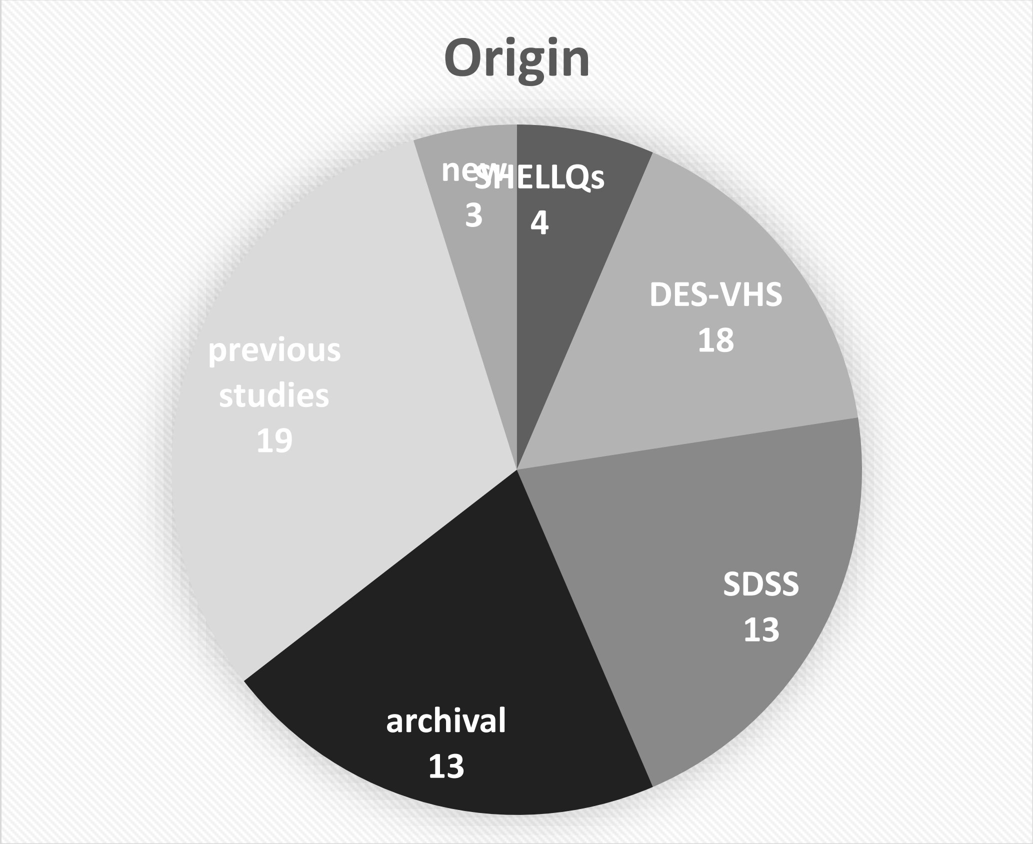
  -> Grasp on cosmic variance, error bars

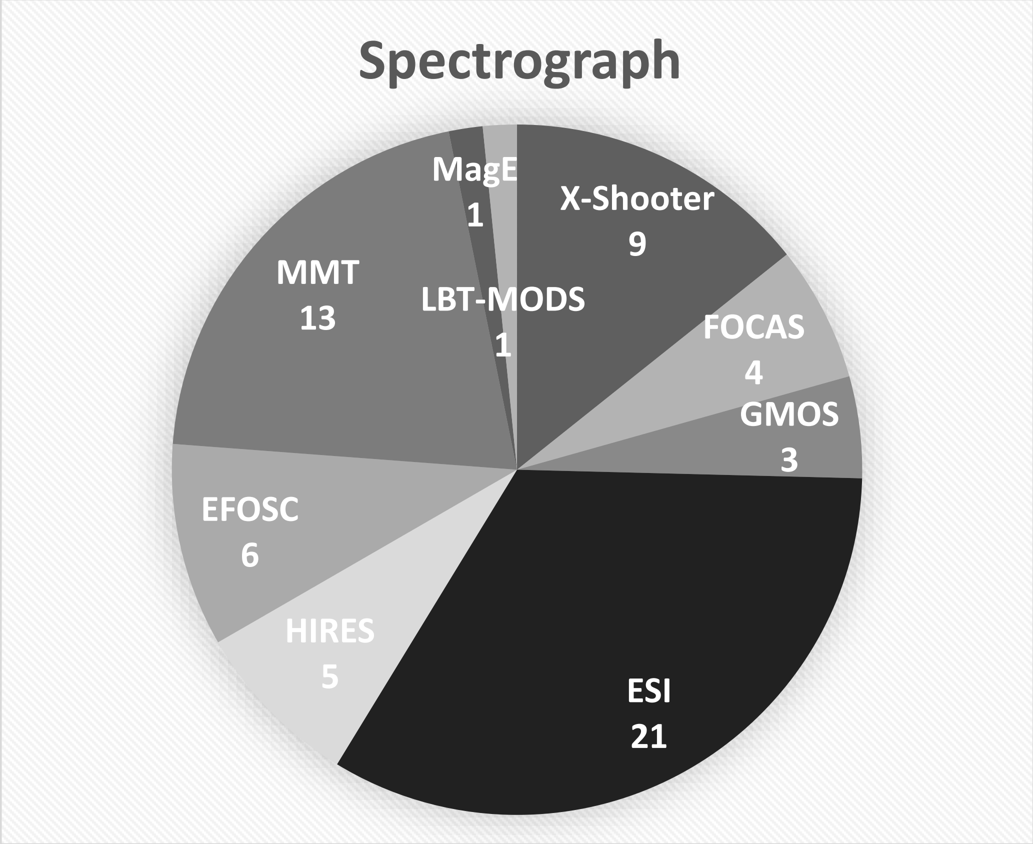
- Consistent measurement of τ_{eff} across all lines of sight

- Push to z=6.1

- Test biases in a statistical sample (e.g. length of proximity zone, data quality, bin size)

The catalogue: 62 QSOs at $z>5.7$



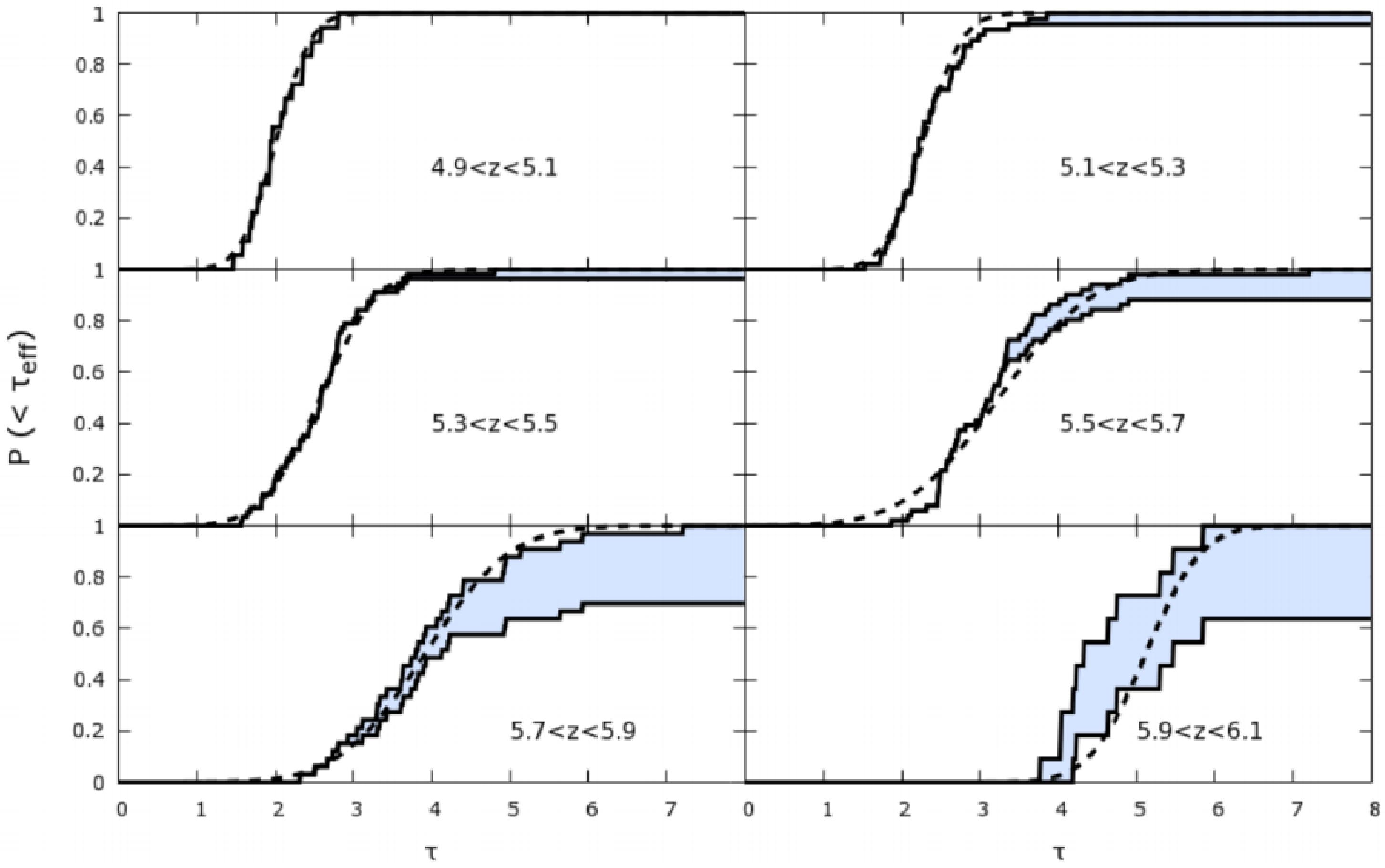


Measurement technique

- Normalize spectrum by power-law fit to continuum
- τ_{eff}= – ln (<*F*>) over fixed comoving window – usually 50 *c*Mpc h^{-1}
- Excludes quasar proximity zone, BALs and DLAs
- Two bounds depending on treatment of non-detections:

take	τ_{eff}	= – ln (2 ε)	"real flux just below detection threshold"
and	τ_{eff}	= ∞	"real *F* = 0"

Results

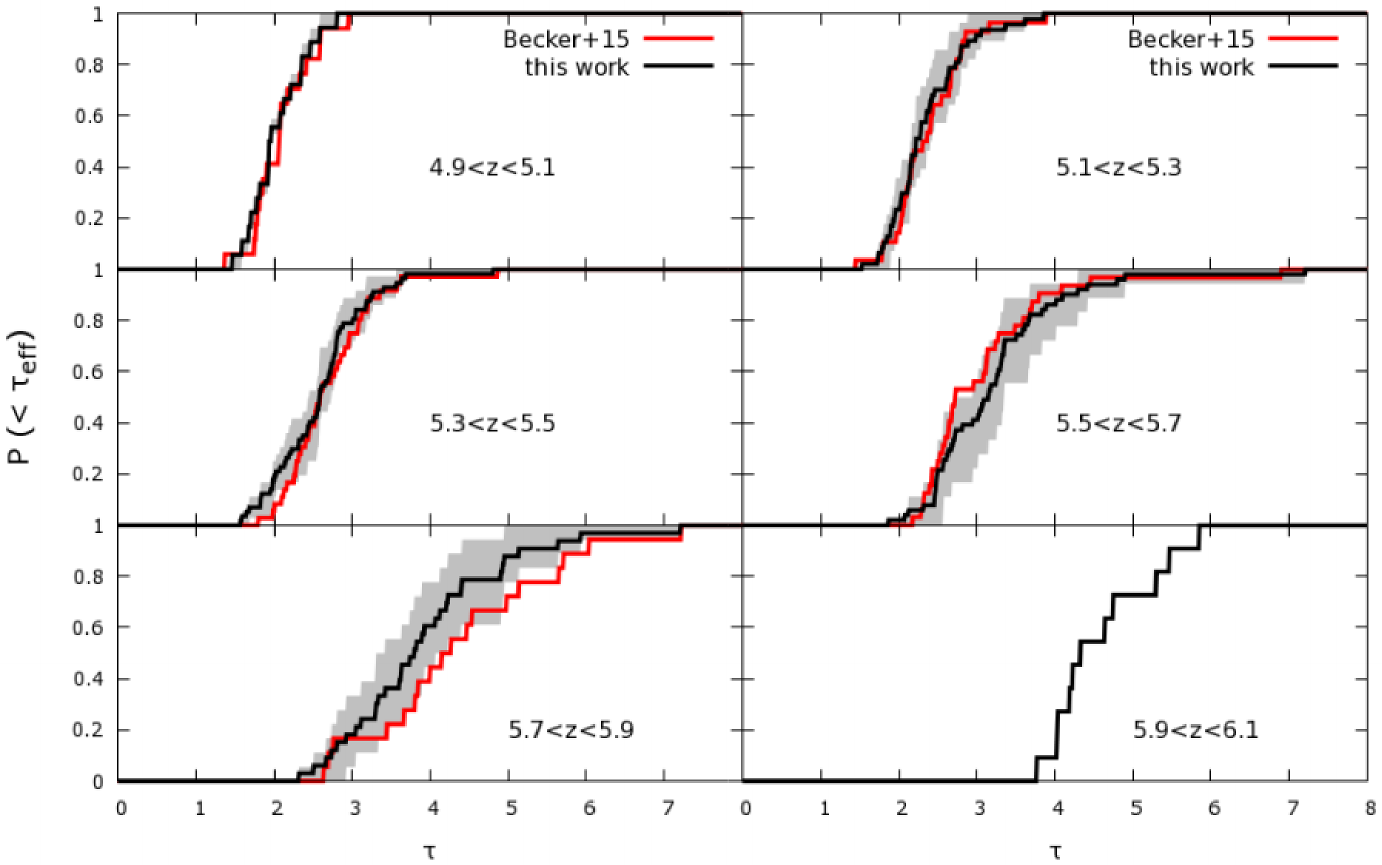


We confirm the huge spread in Lyman-α opacities

Opaque 'tail' already exists at z=5.2 !!

First bounds at z=6.0

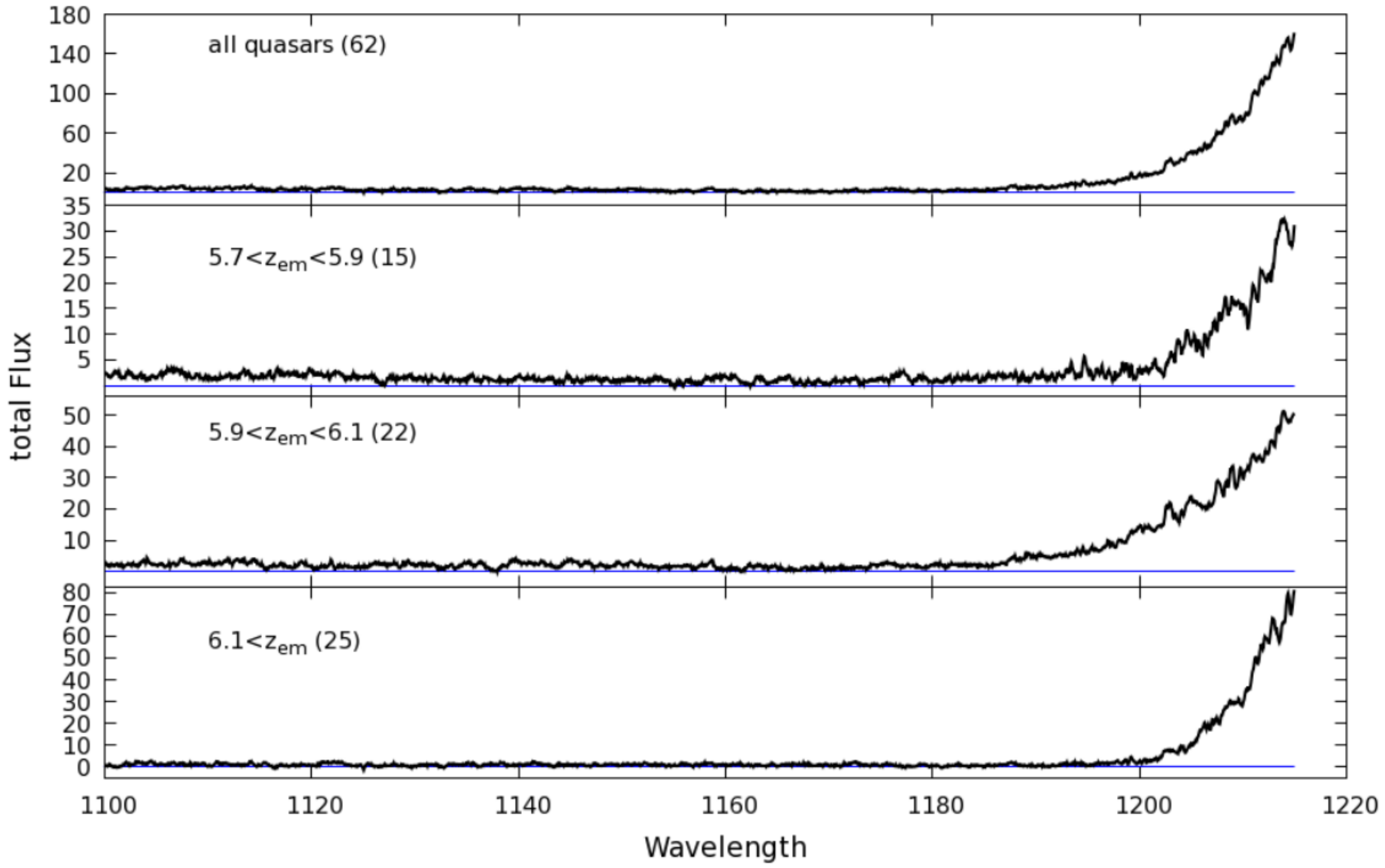
Consistency with previous work



Our sample contains all quasars from previous B15 study: can check we get the same results

All distributions agree with both Fan+06 and Becker+15 within 1σ measured via bootstrap (sub)sampling

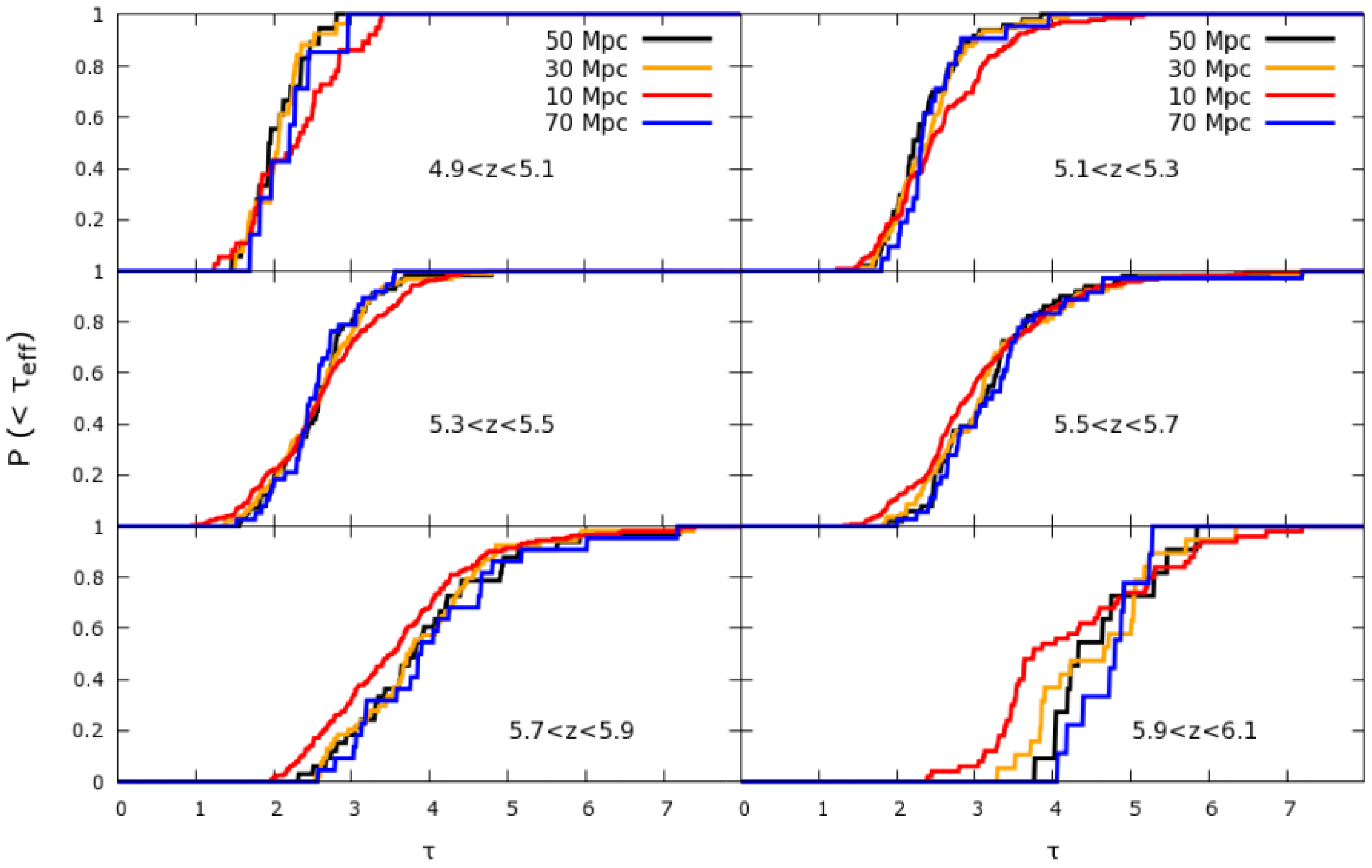
Systematics: proximity zone



Stacks of quasars in redshift bins + individual inspection

→ Choose λ = **1178Å** as fixed end of proximity zone

Systematics: binning size

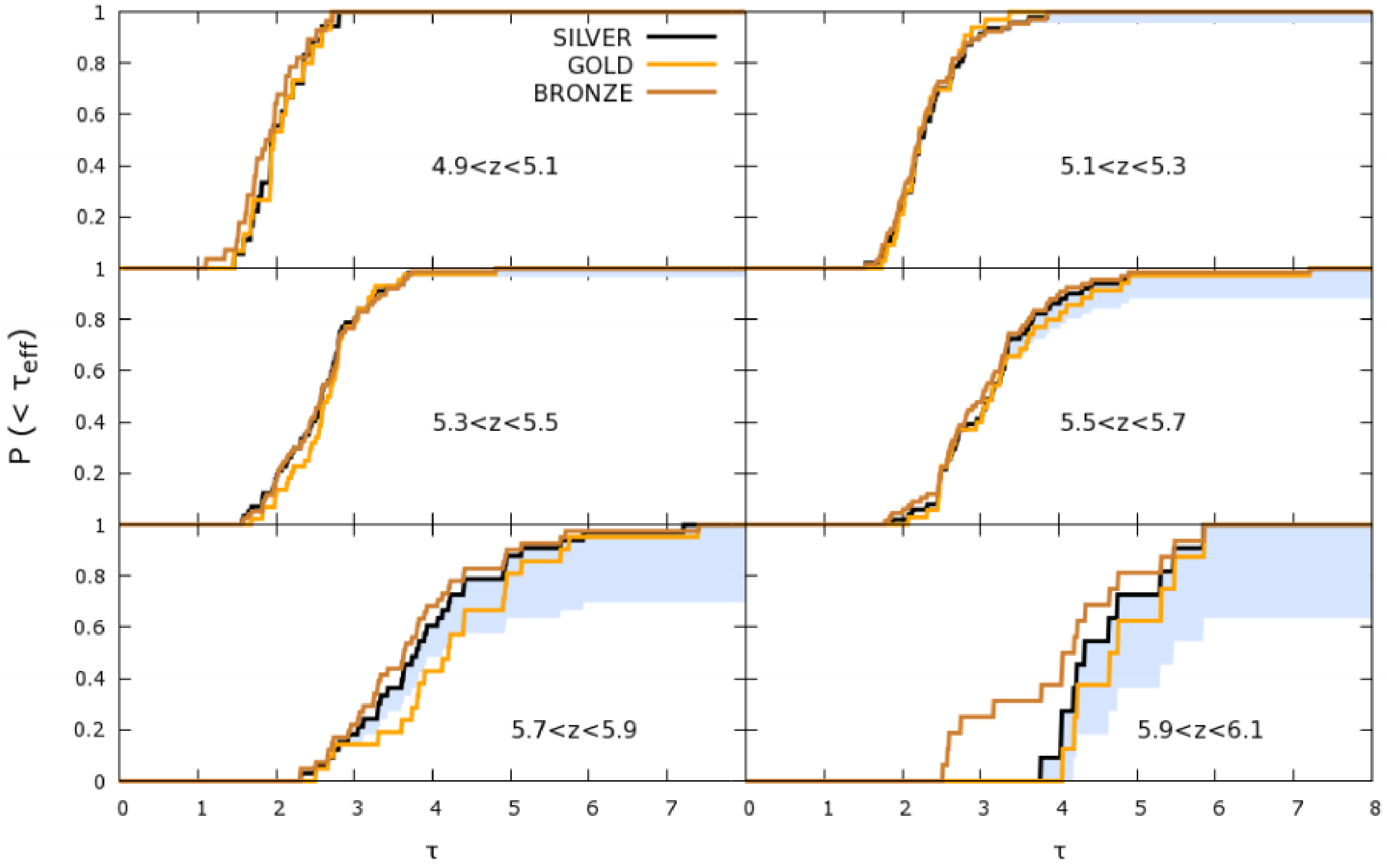


Repeat using l = 10, 30, 50, 70 *c*Mpc h^{-1}

l = 10 *c*Mpc h^{-1} picks up individual peaks and troughs

l > 30 *c*Mpc h^{-1} necessary

Systematics: data quality



Pick SILVER and GOLD samples of objects with SNR > 5.3 and SNR > 11.2 (matching previous studies)

Only few spectrographs can detect τ_{eff} > 4 !

Comparison with numerical models

Rare bright sources
contribute significantly:

Lines of sight from
Chardin+17

Differential timing
of Re^{0} due to temperature
fluctuations:

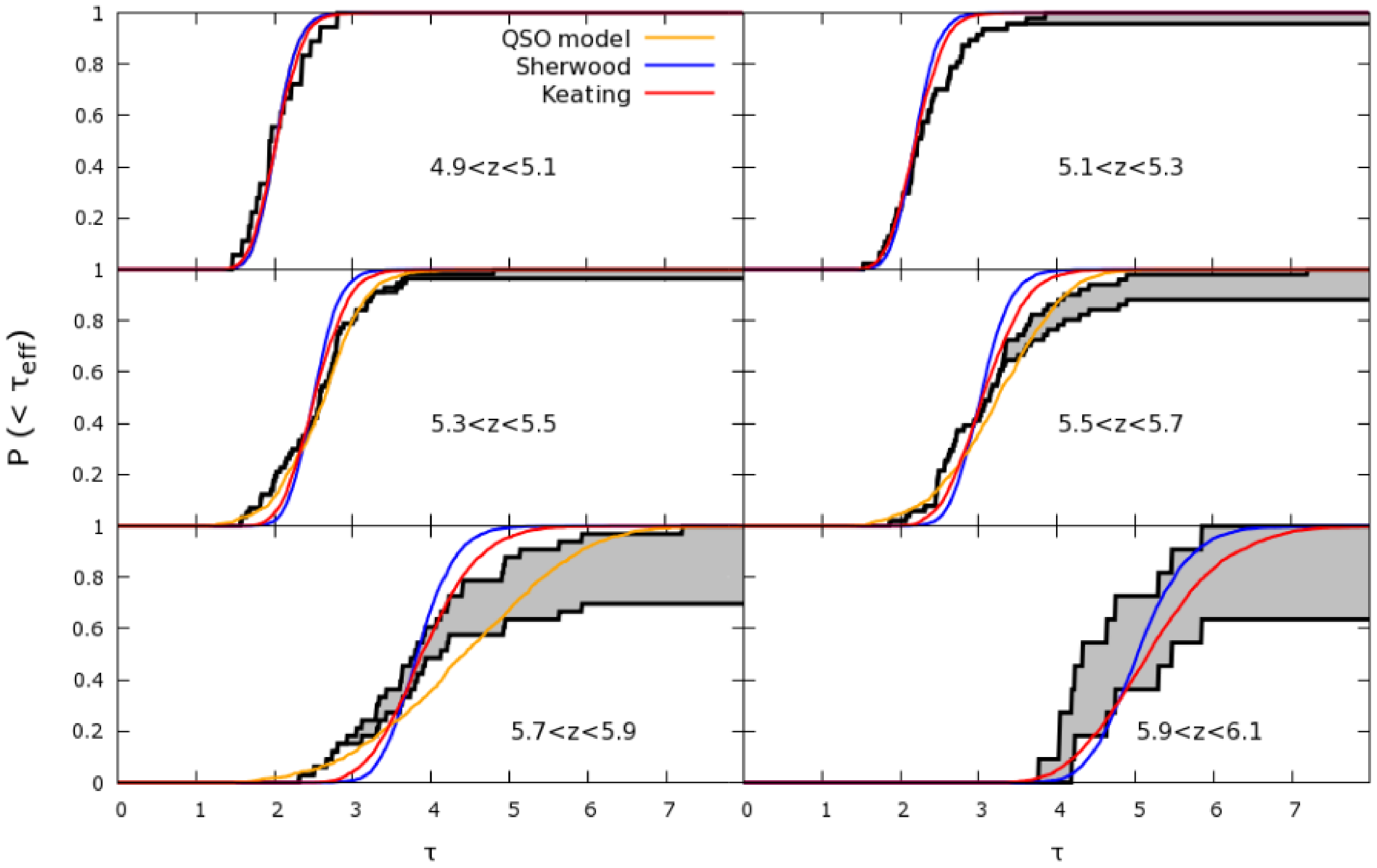
Lines of sight from
Keating+17

‘Null hypothesis’
with constant UV
background:

Lines of sight from the
Sherwood simulation
Bolton+17

The global emissivity in all of these is tuned to match the mean flux !!

Comparison with numerical models

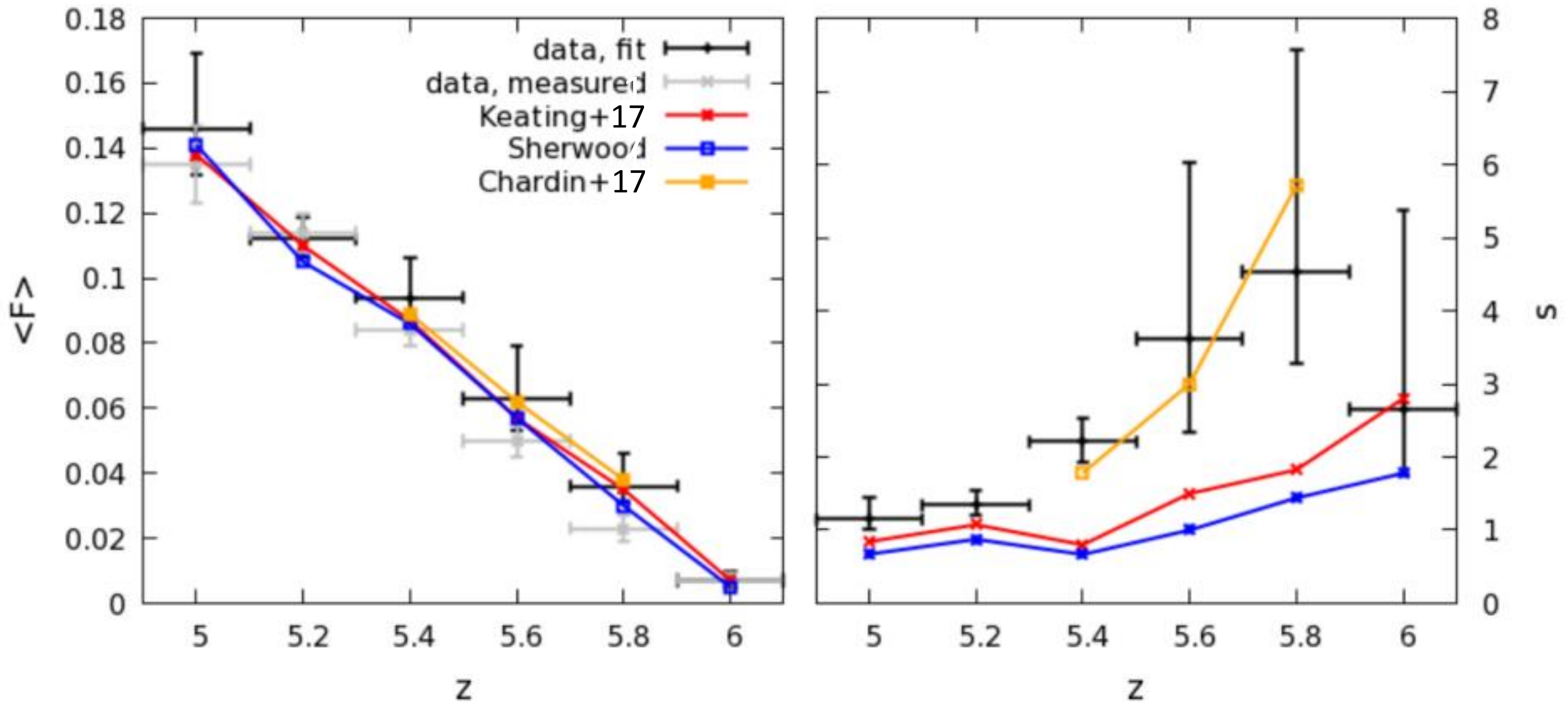


Models don't work

Rare sources model does the best but still mismatches observations

More models being developed…

Comparison with numerical models



Models don’t work

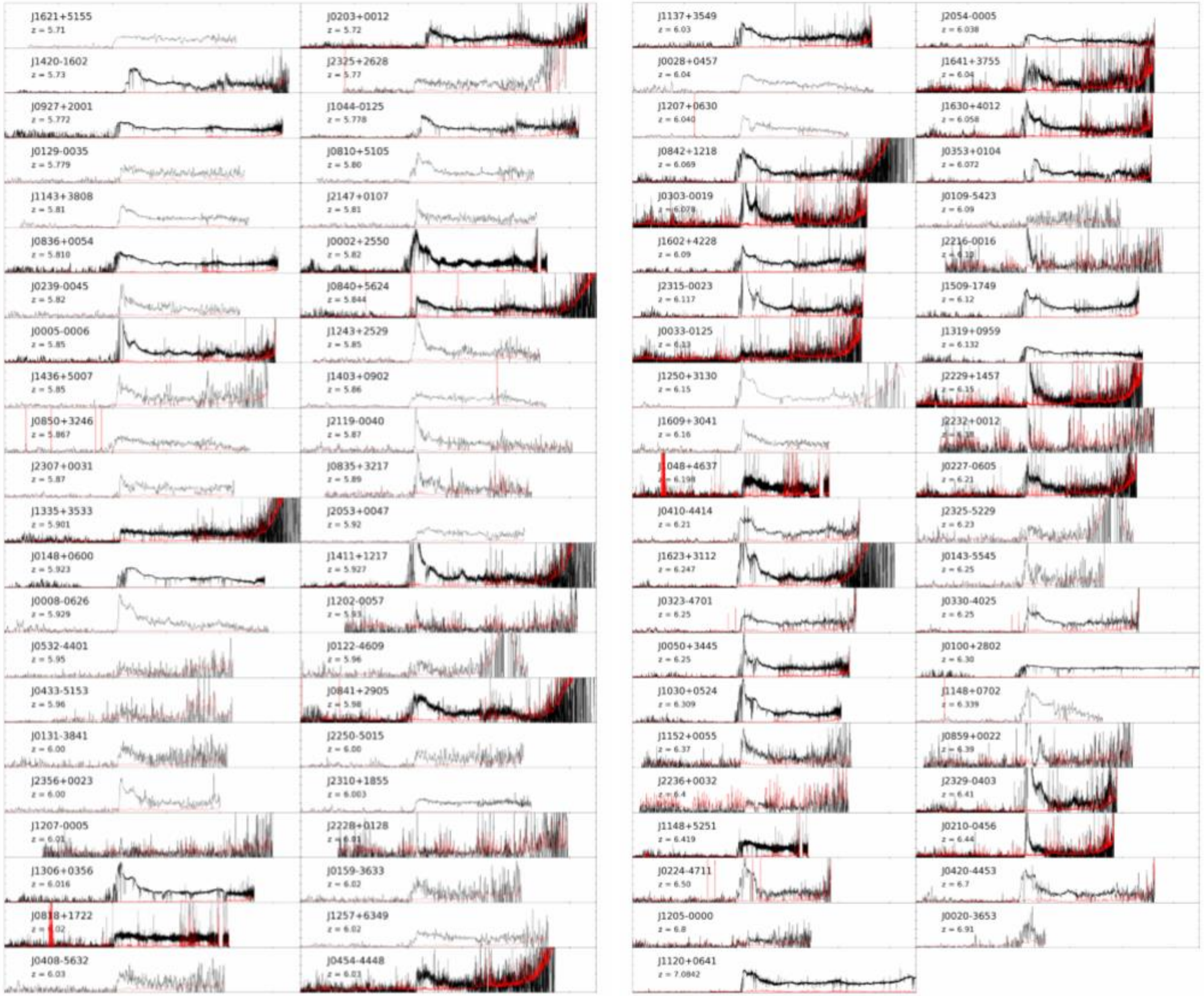
Mean opacity is a ‘forced match’ to simulations

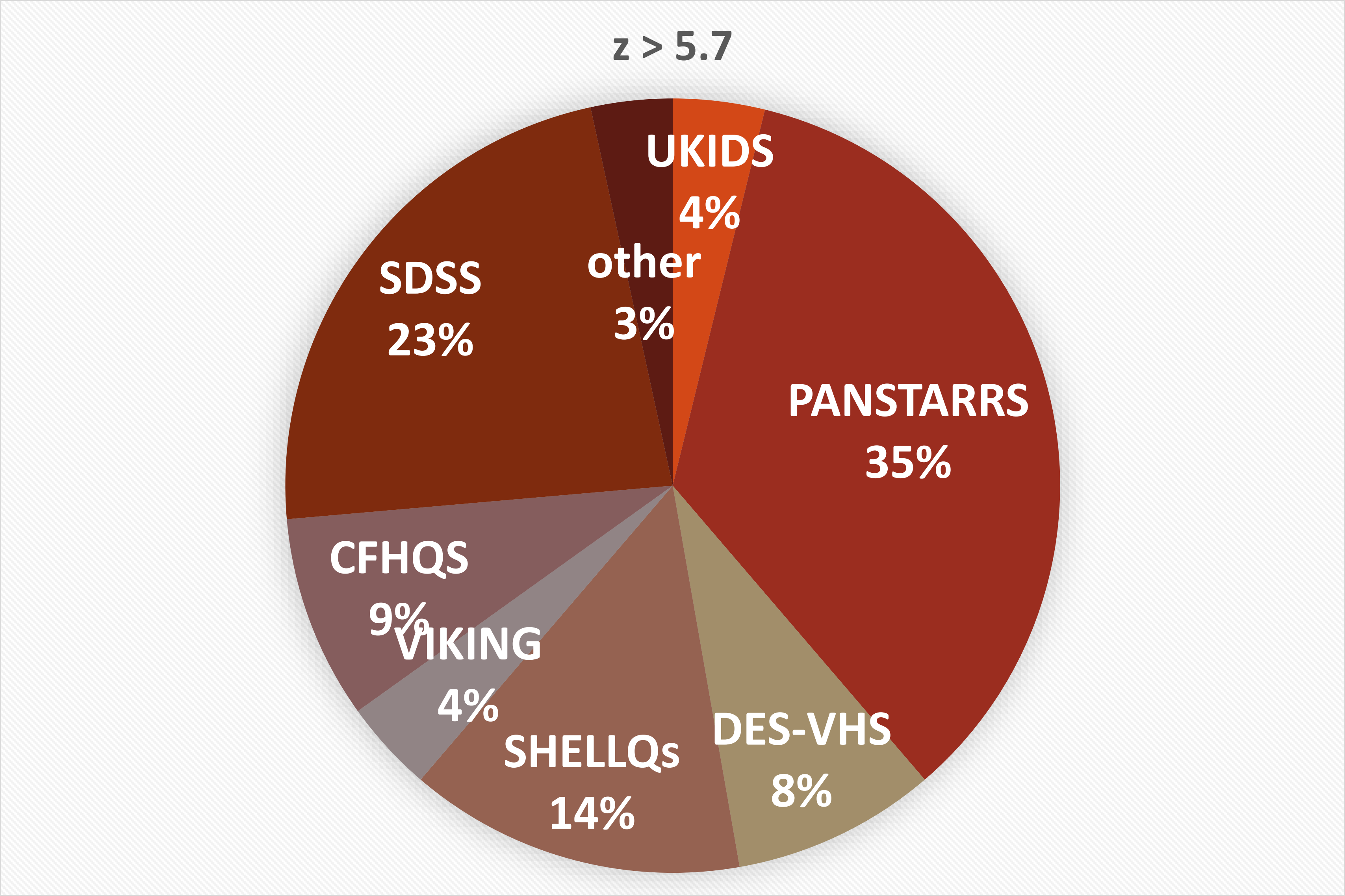
Spread or **skewness** is the issue

Conclusions

- Improved measurements of Lyman-α τ_{eff}
  - Opaque tail still exists are z = 5.2 … which is a problem
  - First bounds at z = 6.1
- Discrepancy with numerical models persists / gets worse when considering non-detection bounds
- A rare-sources-only (toy) model provides the only decent fit to the data so far…
  - Future: better radiative transfer, self-shielding…
  - Implications for observing high-z LAEs ?

Thank you!


J1621+5155 z = 5.71
J1420-1602 z = 5.73
J0927+2001 z = 5.772
J0129-0035 z = 5.779
J1143+3808 z = 5.81
J0836+0054 z = 5.810
J0239-0045 z = 5.82
J0005-0006 z = 5.85
J1436+5007 z = 5.85
J0850+3246 z = 5.867
J2307+0031 z = 5.87
J1335+3533 z = 5.901
J0148+0600 z = 5.923
J0008-0626 z = 5.929
J0532-4401 z = 5.95
J0433-5153 z = 5.96
J0131-3841 z = 6.00
J2356+0023 z = 6.00
J1207-0005 z = 6.01
J1306+0356 z = 6.016
J0818+1722 z = 6.02
J0408-5632 z = 6.03
J0203+0012 z = 5.72
J2325+2628 z = 5.77
J1044-0125 z = 5.778
J0810+5105 z = 5.80
J2147+0107 z = 5.81
J0002+2550 z = 5.82
J0840+5624 z = 5.844
J1243+2529 z = 5.85
J1403+0902 z = 5.86
J2119-0040 z = 5.87
J0835+3217 z = 5.89
J2053+0047 z = 5.92
J1411+1217 z = 5.927
J1202-0057 z = 5.93
J0122-4609 z = 5.96
J0841+2905 z = 5.98
J2250-5015 z = 6.00
J2310+1855 z = 6.003
J2228+0128 z = 6.01
J0159-3633 z = 6.02
J1257+6349 z = 6.02
J0454-4448 z = 6.03
J1137+3549 z = 6.03
J0028+0457 z = 6.04
J1207+0630 z = 6.040
J0842+1218 z = 6.069
J0303-0019 z = 6.078
J1602+4228 z = 6.09
J2315-0023 z = 6.117
J0033-0125 z = 6.13
J1250+3130 z = 6.15
J1609+3041 z = 6.16
048+4637 z = 6.198
J0410-4414 z = 6.21
J1623+3112 z = 6.247
J0323-4701 z = 6.25
J0050+3445 z = 6.25
J1030+0524 z = 6.309
J1152+0055 z = 6.37
J2236+0032 z = 6.4
J1148+5251 z = 6.419
J0224-4711 z = 6.50
J1205-0000 z = 6.8
J1120+0641 z = 7.0842
J2054-0005 z = 6.038
J1641+3755 z = 6.04
J1630+4012 z = 6.058
J0353+0104 z = 6.072
J0109-5423 z = 6.09
J2216-0016
J1509-1749 z = 6.12
J1319+0959 z = 6.132
J2229+1457 z = 6.15
J2232+0012
J0227-0605 z = 6.21
J2325-5229 z = 6.23
J0143-5545 z = 6.25
J0330-4025 z = 6.25
J0100+2802 z = 6.30
J1148+0702 z = 6.339
J0859+0022 z = 6.39
J2329-0403 z = 6.41
J0210-0456 z = 6.44
J0420-4453 z = 6.7
J0020-3653 z = 6.91


z > 5.7
UKIDS
4%
other
3%
PANSTARRS
35%
SDSS
23%
CFHQS
9%
VIKING
4%
SHELLQs
14%
DES-VHS
8%