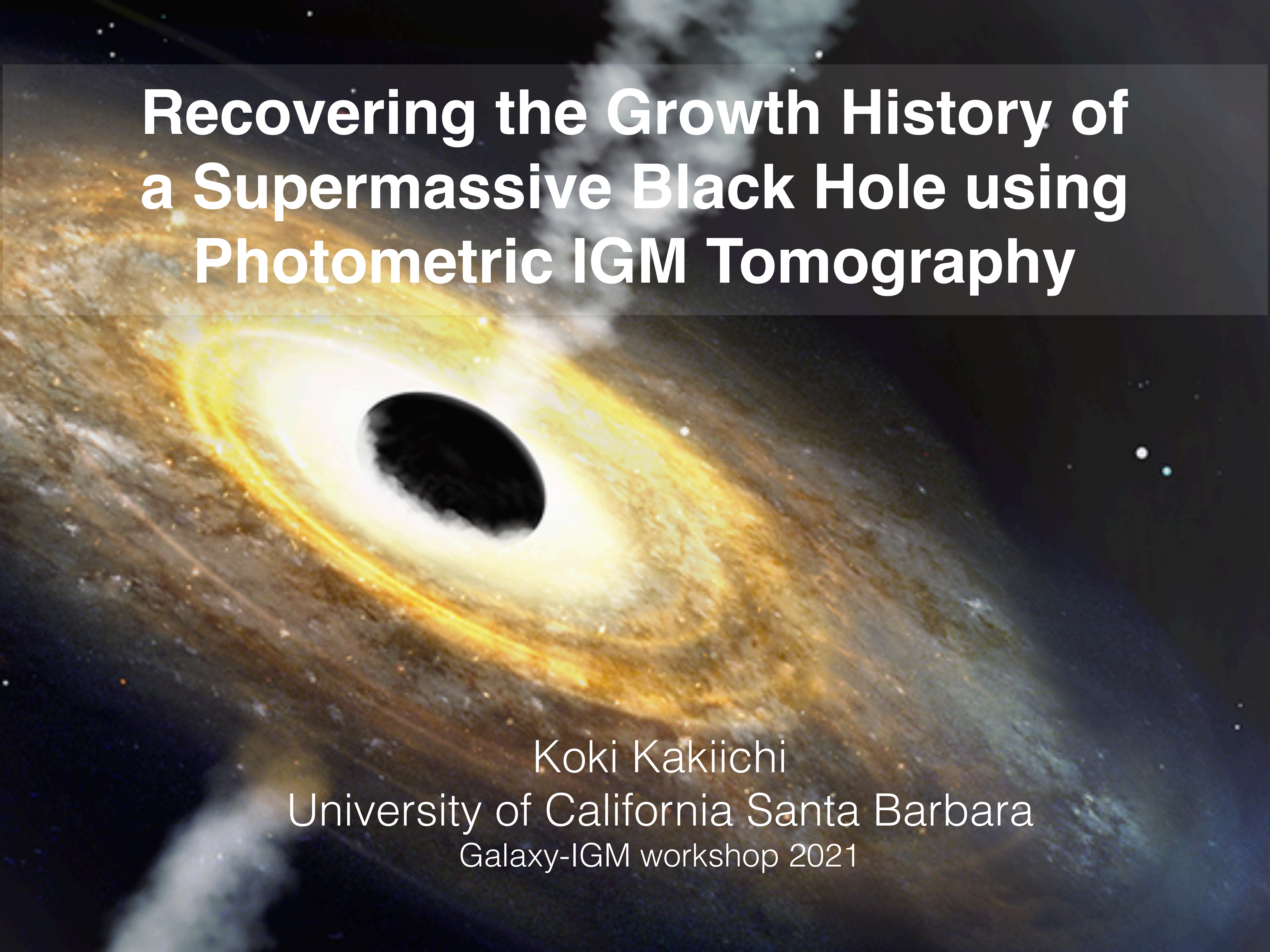
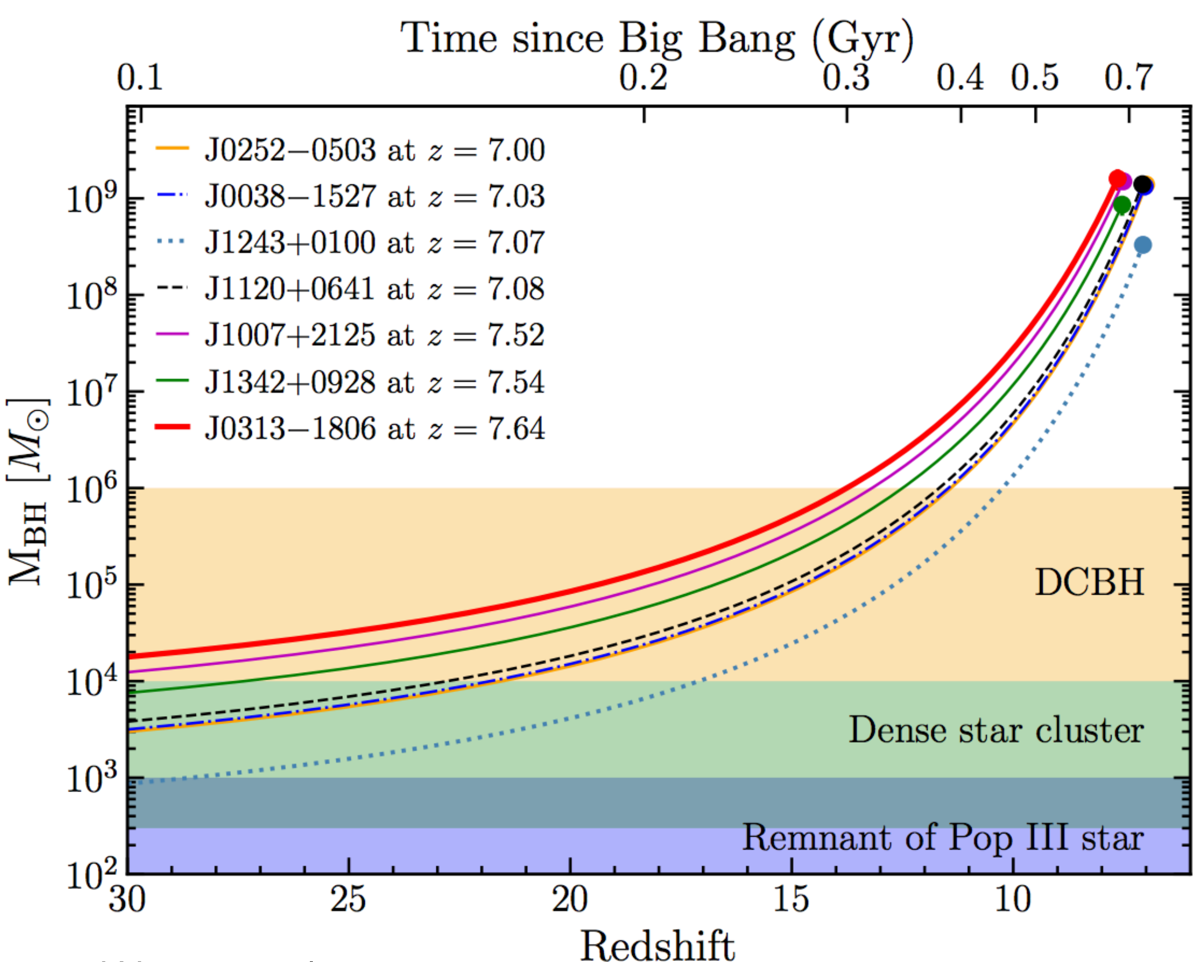


Recovering the Growth History of a Supermassive Black Hole using Photometric IGM Tomography

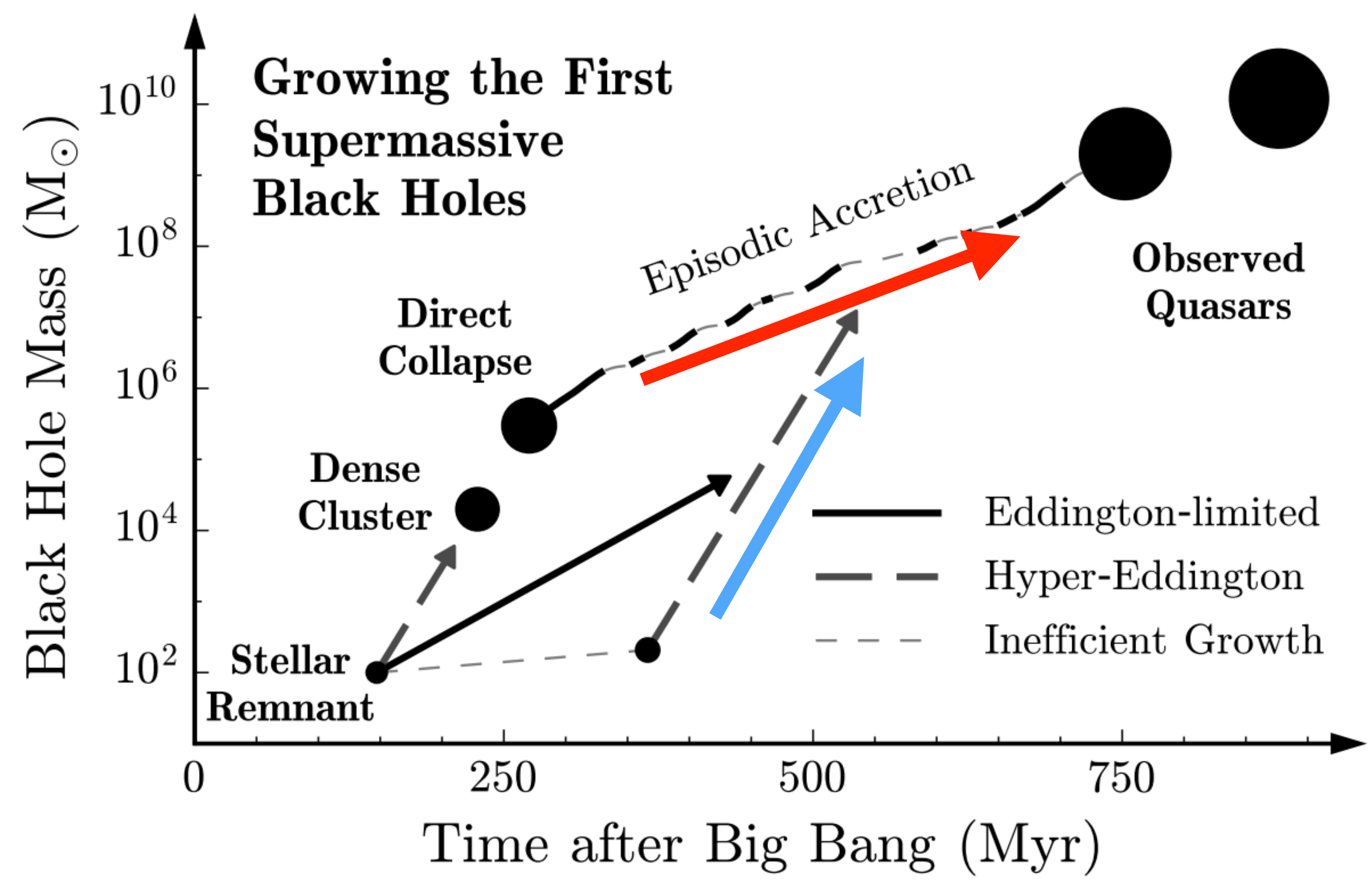
Koki Kakiichi
University of California Santa Barbara

Galaxy-IGM workshop 2021

How to form supermassive black holes at z>6-7?



Wang et al 2021



How did a SMBH acquire its mass?

- ***kick start from a massive seed >10^4 $M_\odot$? (seed formation)***

  e.g. Woods et al 2018, Inayoshi et al 2020

- ***rapid accretion via super-Eddington growth? (growth mechanism)***

  e.g. Madau et al 2014

In the local Universe, we think the most of SMBH mass are acquired through QSO luminous phase

QSO luminosity powered by the accretion onto disk/SMBH

QSO luminosity $$L_{\rm bol} = \epsilon \dot{M} c^2$$

$\dot{M}$: gas accretion rate

ϵ: radiative efficiency ~0.10

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SMBH mass growth rate during QSO phase

QSO luminosity function

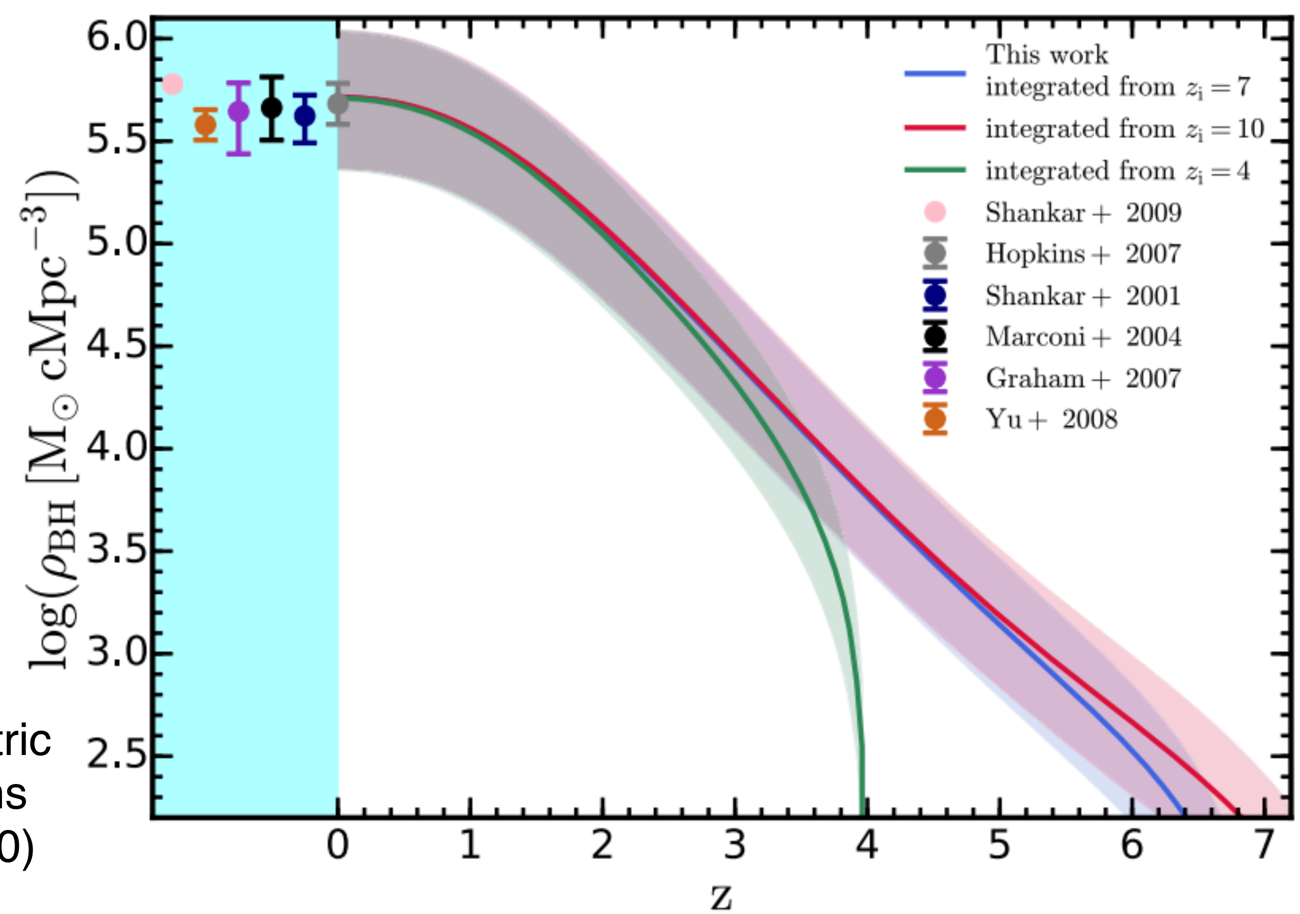
Soltan's argument

$$\rho_{\rm BH}(z=0) \approx \rho^{\rm QSO}_{\rm BH,acc}(z=0) = \int_{z=0}^{\infty} \frac{dt}{dz} dz \int_0^{\infty} \frac{(1-\epsilon)L_{\rm bol}}{\epsilon c^2} \Psi(L_{\rm bol}, z) dL_{\rm bol}$$

local SMBH mass density

SMBH mass density accreted during QSO phases

If most of local SMBH mass are obtained during the QSO phase…



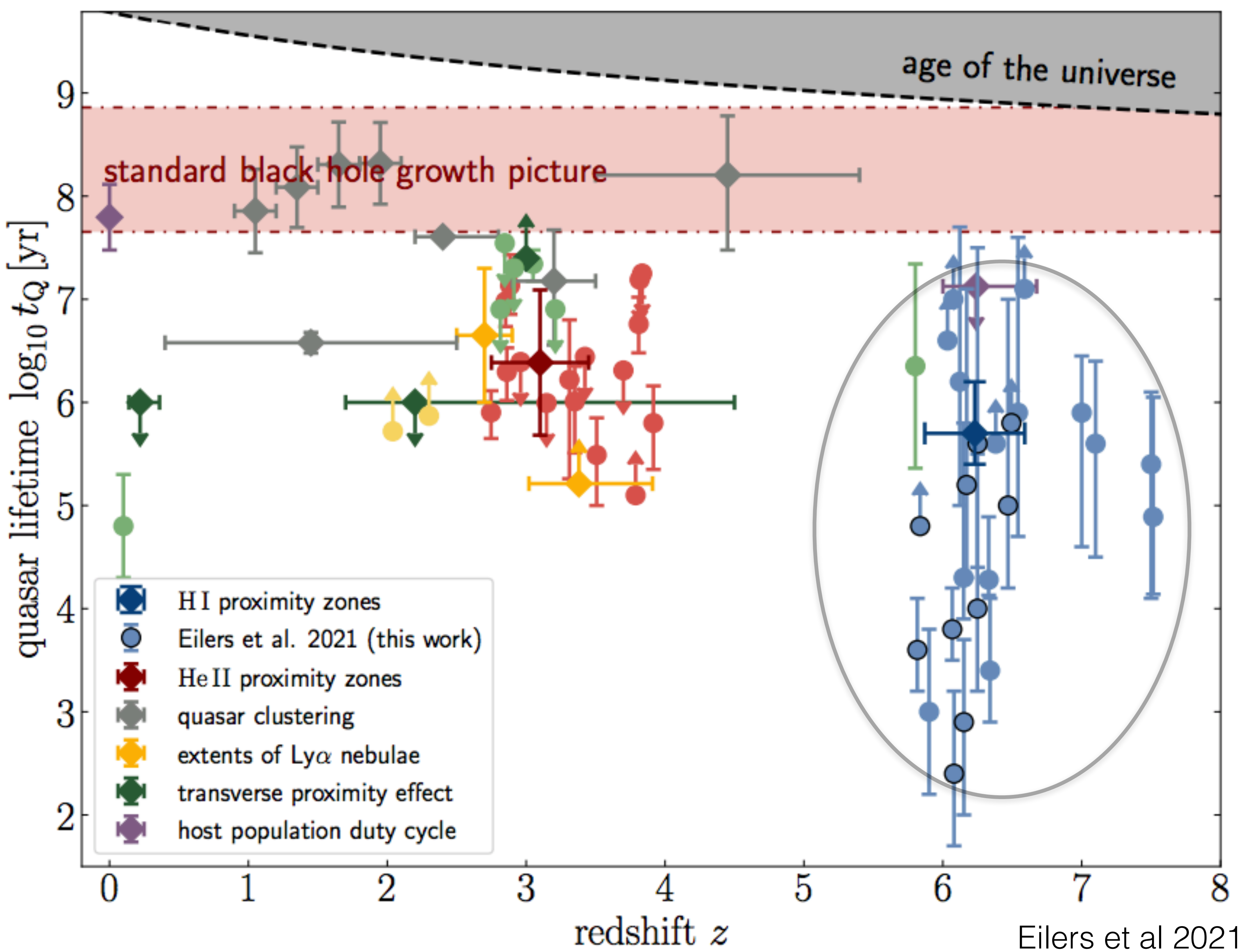
Using up-to-date bolometric QSO luminosity functions at z=0-7 (Shen et al 2020)

See also Yu & Tremaine 2002, Shankar et al 2004, Ueda et al 2014

For High-z QSOs, too short time to grow ~$10^9 M_\odot$ SMBHs through the QSO luminous phases?

SMBH growth timescale (Salpeter or e-folding time)

$$t_S = 4.5 \times 10^7 \left[\frac{\epsilon/(1-\epsilon)}{0.1}\right] \left(\frac{L_{bol}}{L_{Edd}}\right)^{-1} \mathrm{yr}$$



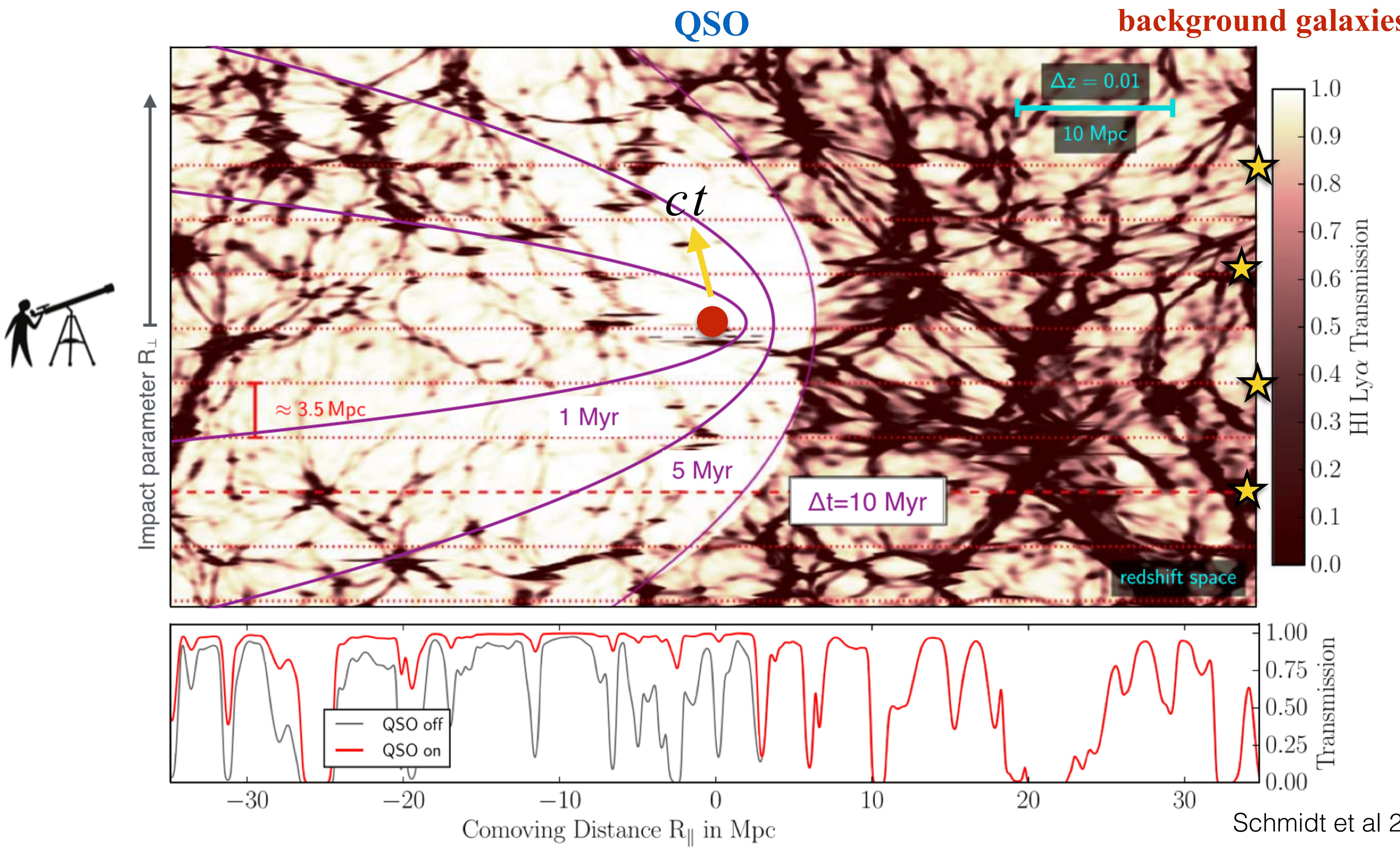
Eilers et al 2021

Too short time compared the SMBH growth timescale?

- *Dusty obscured growth?*
- *Super-Eddington growth?*
- *Eddington-limited growth from massive seeds?*

Need a new observing strategy to probe the SMBH growth history

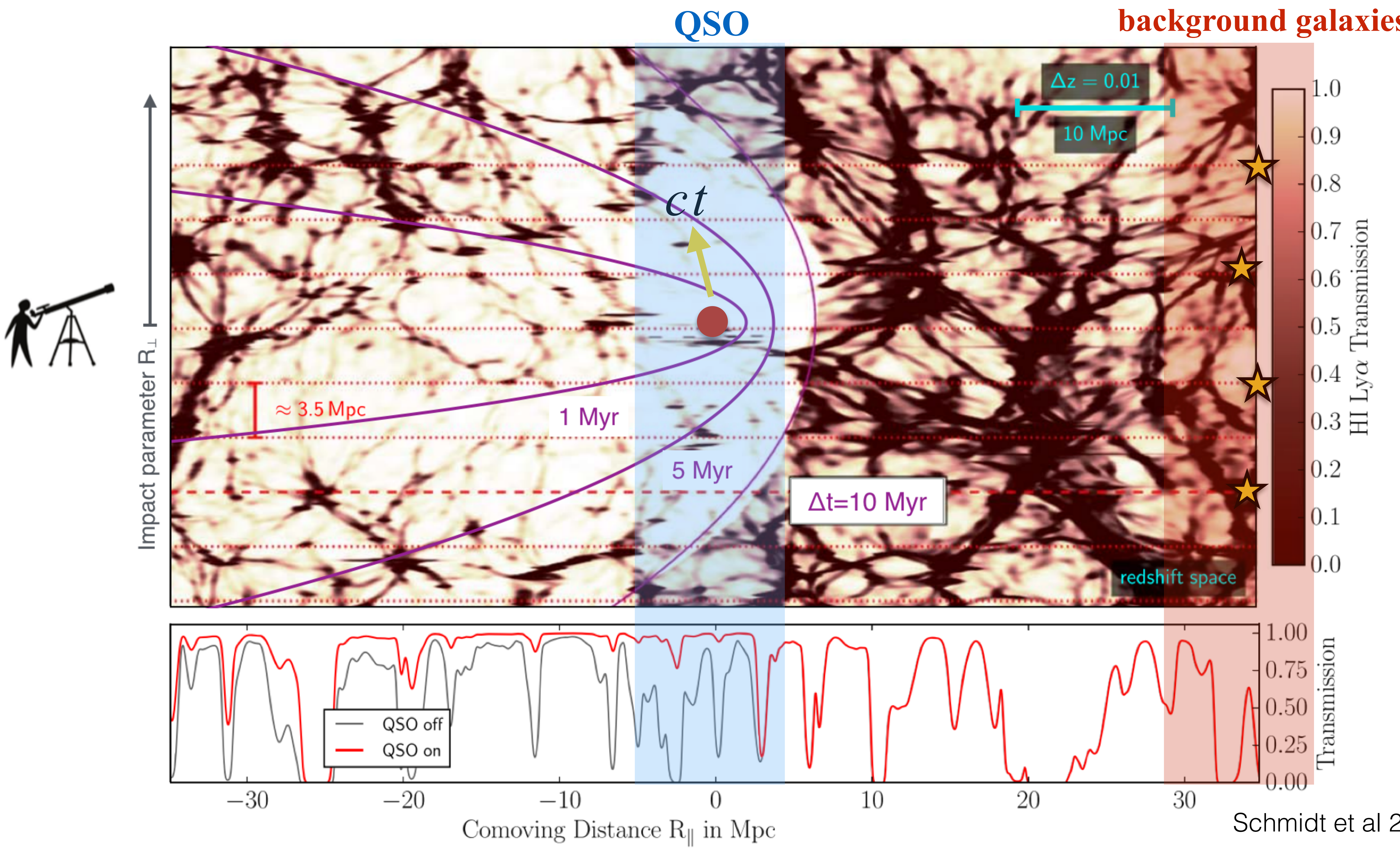
Constraining the QSO-active growth history from "IGM Light-Echo Tomography"



Schmidt et al 2018

See also Adelberger 2004, Visbal & Croft 2008

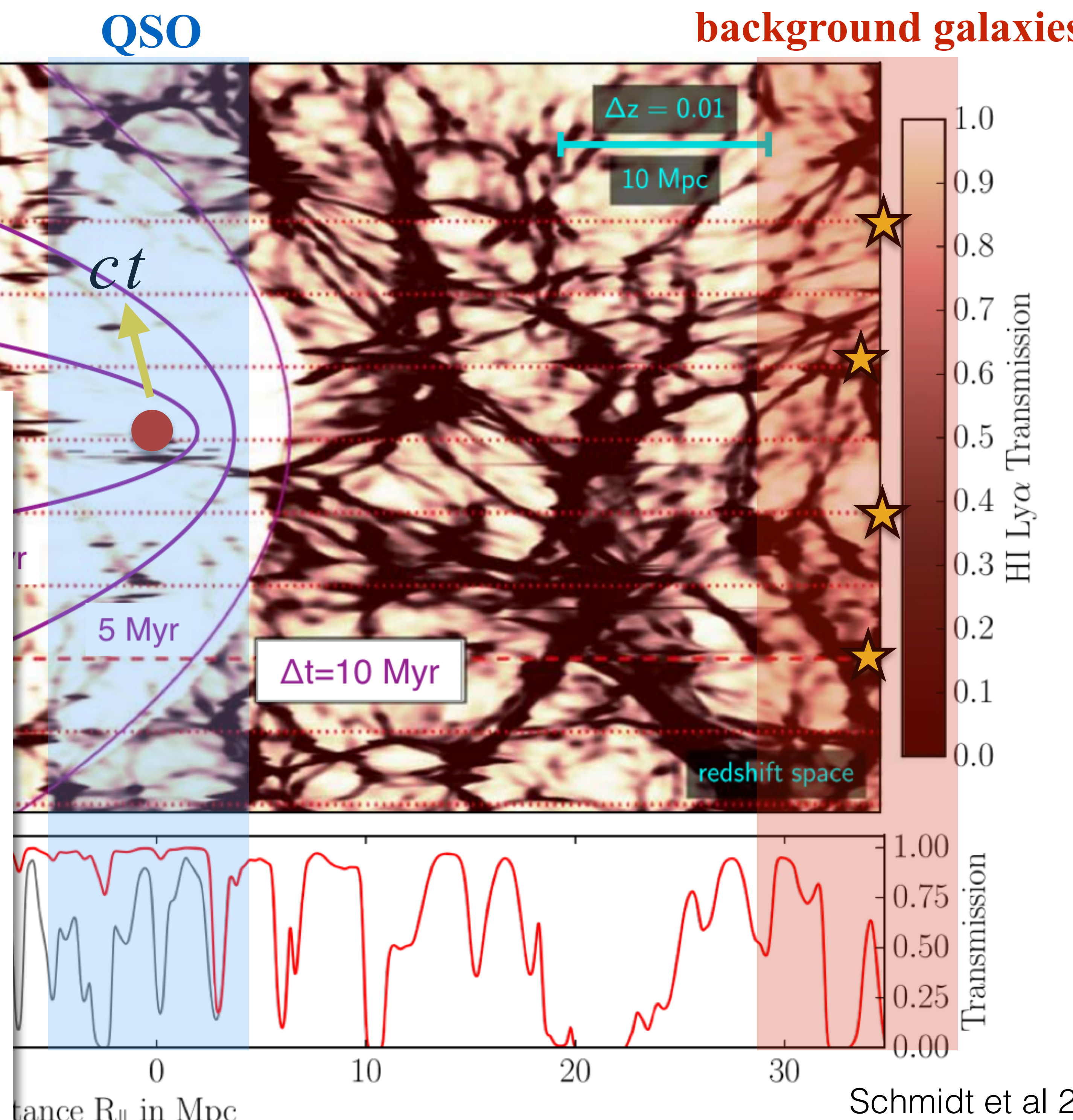
Constraining the QSO-active growth history from "*Photometric* IGM Light-Echo Tomography"



Schmidt et al 2018

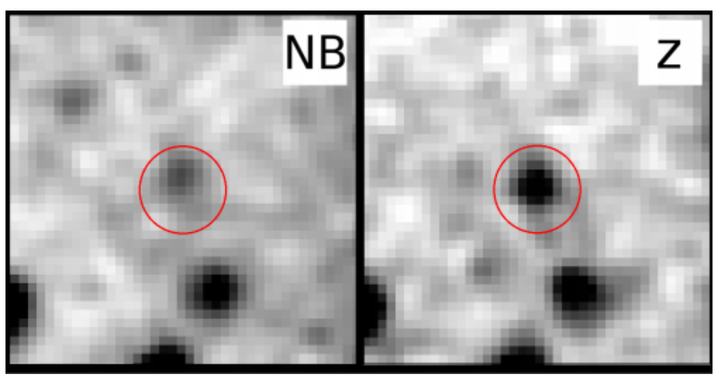
cf. Mawatari et al 2017 for the use of narrow-band for 2D tomography

Constraining the QSO-active growth history from "*Photometric* IGM Light-Echo Tomography"

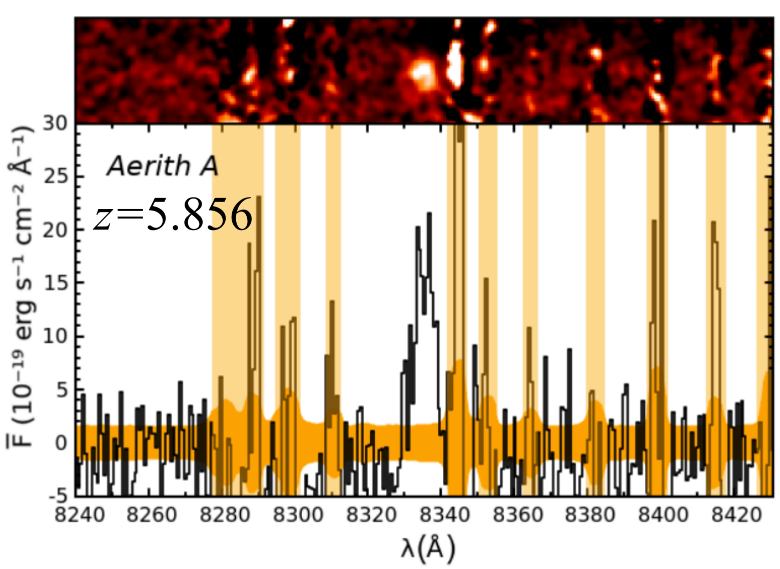


Schmidt et al 2018

Photometric detection of transverse proximity effect around a QSO z=5.802



Depth
NB816=27.2(3σ)
z=26.4(3σ)

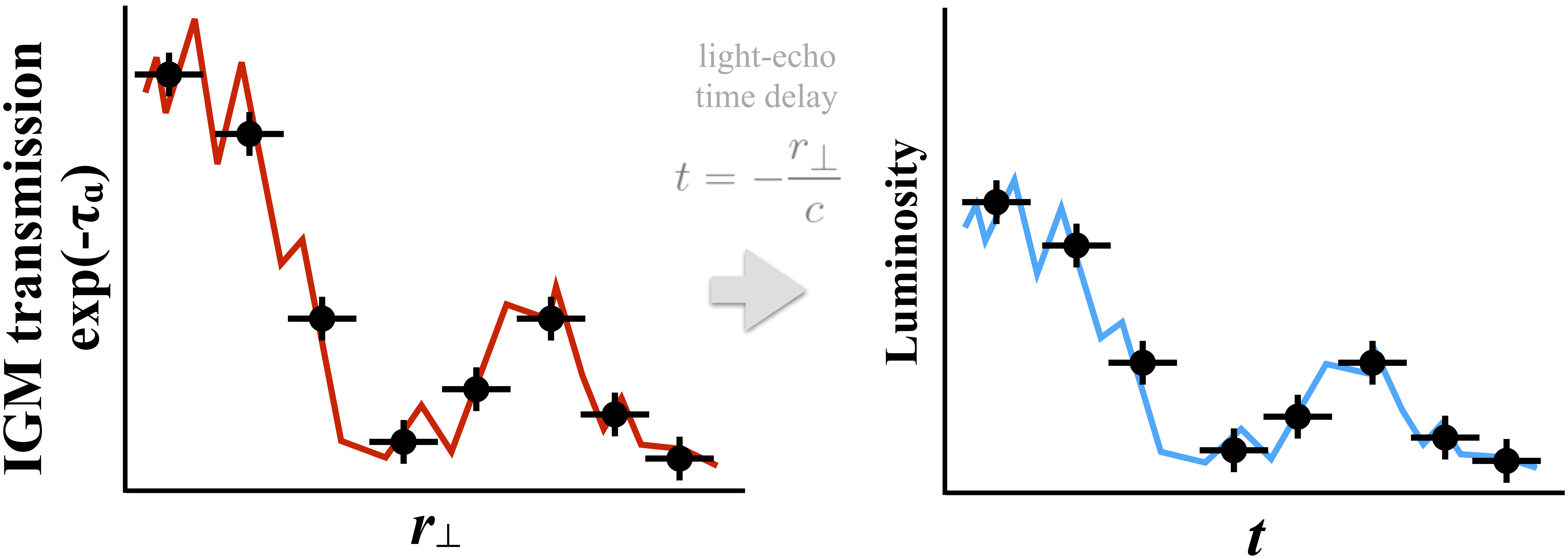


Bosman, KK+2020

cf. Mawatari et al 2017 for the use of narrow-band for 2D tomography

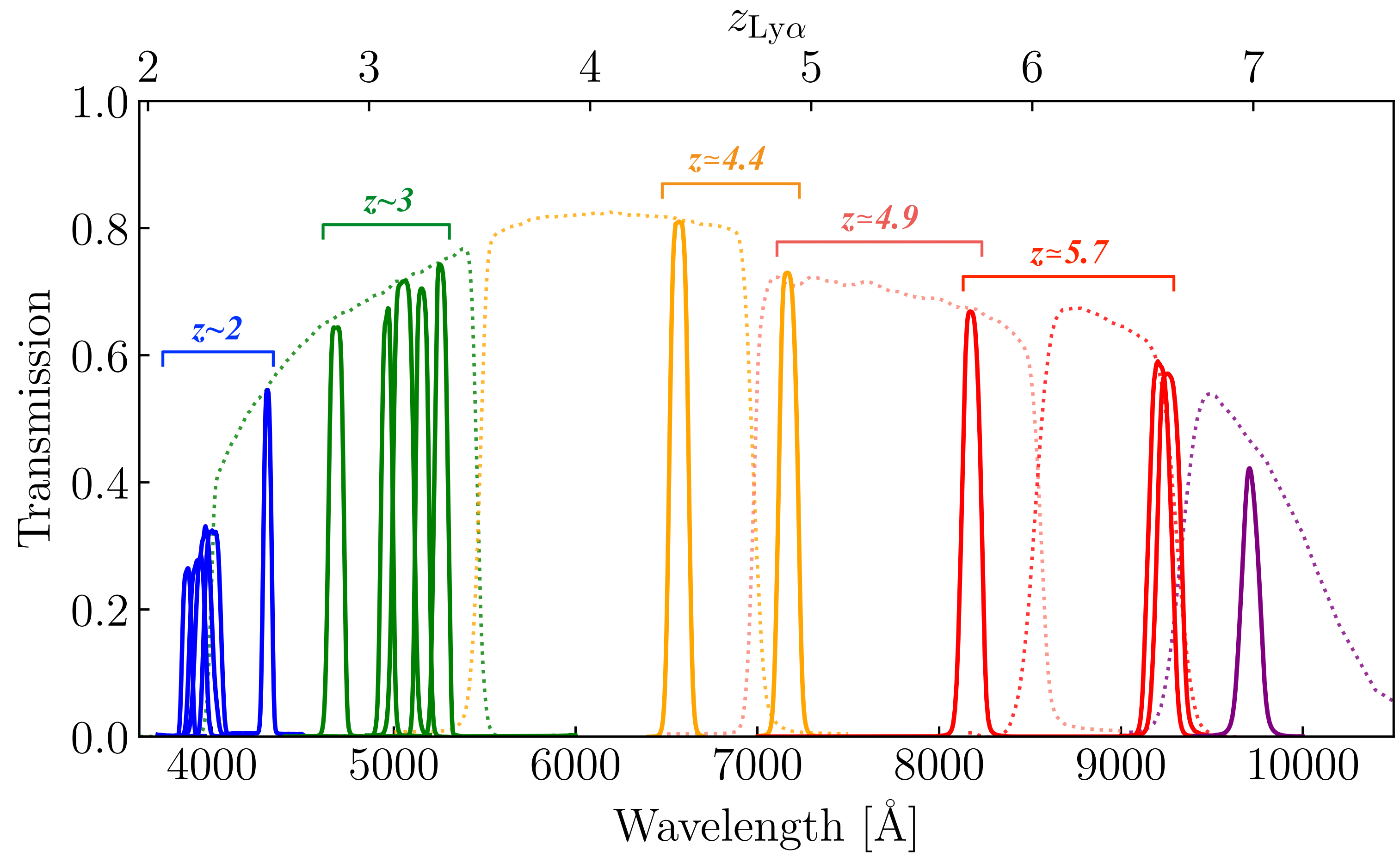
Constraining the QSO-active growth history from "*Photometric* IGM Light-Echo Tomography"

QSO transverse proximity effect → **Lightcurve constraint**



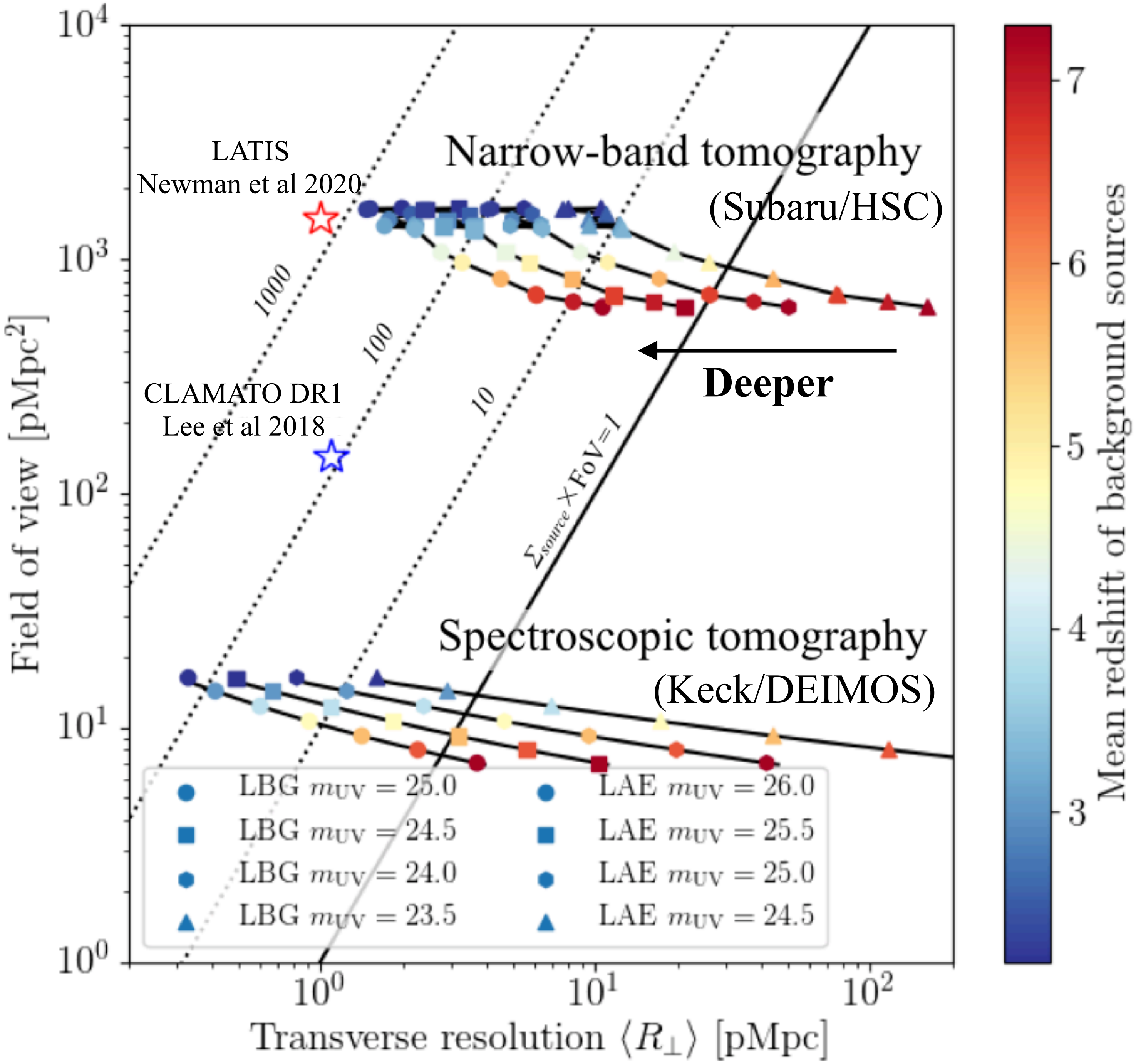
Spatial IGM tomography of QSO light-echo at Mpc-scale* translates into a *Myr-scale time-domain constraint on the quasar lightcurve* of *an individual SMBH over the baseline of ~100 Myr

Available pairs of narrow-band filters: Subaru/HSC



	fg. filter	bg. filter $z_{\mathrm{Ly}\alpha}$	NB391 2.22	NB395 2.25	NB400 2.29	NB430 2.54	NB468 2.85	NB497 3.09	NB506 3.16	NB515 3.24	NB527 3.33	NB656 4.39	NB718 4.90	NB816 5.71	NB921 6.57	NB926 6.62	NB973 7.00	NB1010 7.31
	NB387	2.18	✓	✓	✓	✓												
z~2	NB391	2.22		✓	✓	✓												
	NB395	2.25			✓	✓	✓											
	NB400	2.29				✓	✓											
	NB430	2.54					✓	✓	✓									
	NB468	2.85						✓	✓	✓	✓							
	NB497	3.09							✓	✓	✓							
z~3	NB506	3.16								✓	✓							
	NB515	3.24									✓							
	NB527	3.33																
z~4-5	NB656	4.39											✓					
	NB718	4.90												✓				
z~6	NB816	5.71													✓	✓		
	NB921	6.57														✓	✓	✓
	NB926	6.62															✓	✓
	NB973	7.00																✓

Expected background galaxy counts: Photometric vs Spectroscopic IGM tomography

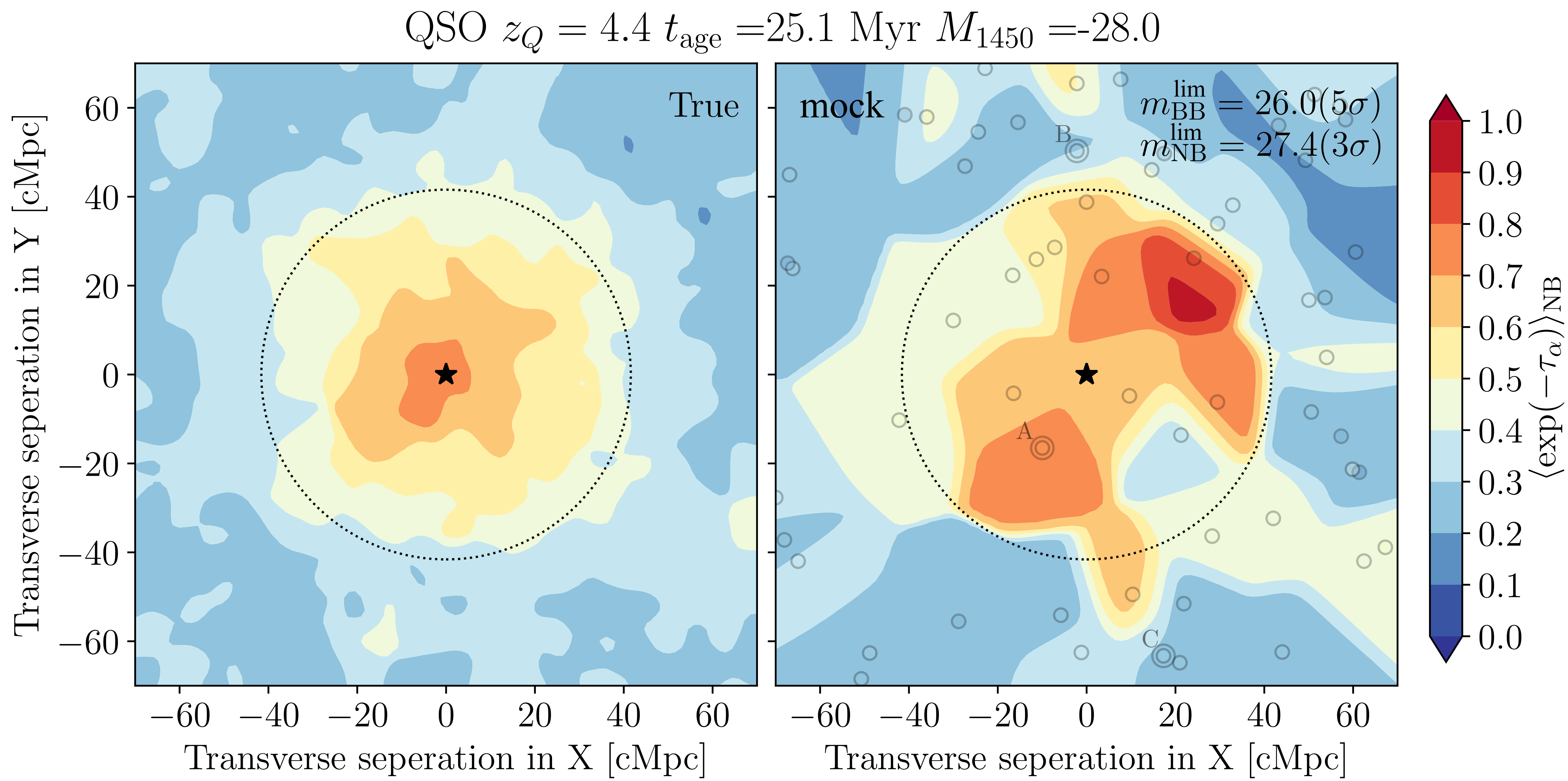


Model:
UV luminosity functions (Bouwens+21)
×
Lyα EW-PDF model (Dijkstra & Wyithe 12)
(EWs of galaxies are assigned to match
with z~2-6 Lyα luminosity functions (Konno+16,18))
=
UV luminosities of
narrow-band (Lyα EW>25A) selected galaxies

<u>Expected UV-bright LAE source counts:</u>

$$\langle R_\perp \rangle = \Sigma_{\rm LAE}^{-1/2} \approx 1.78 \times 10^{[(m_{\rm uv}/26.57)^{-9.78}-1]}\ \rm pMpc,$$

Photometric IGM Tomography around QSO Light Echoes: simulation mock



<u>Simulations:</u>

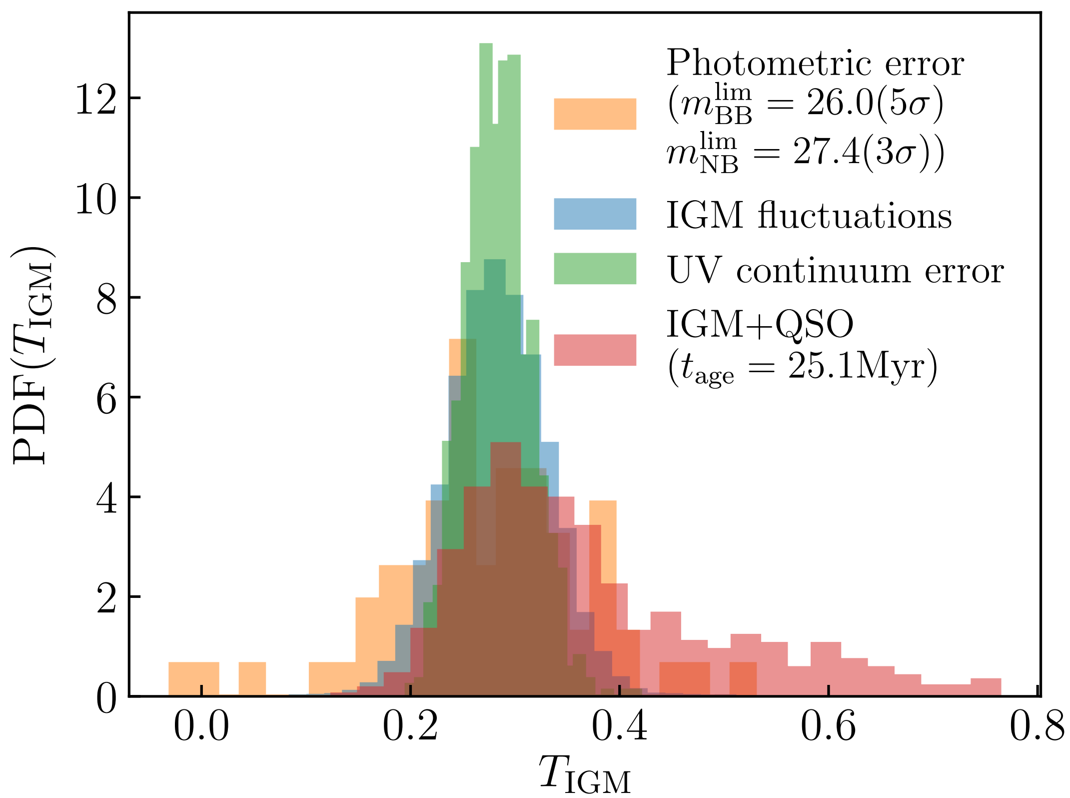
1: cosmological hydrodynamic simulations (>$10^{12}M_\odot$) + simple $\propto r^{-2}$ RT *around QSO*

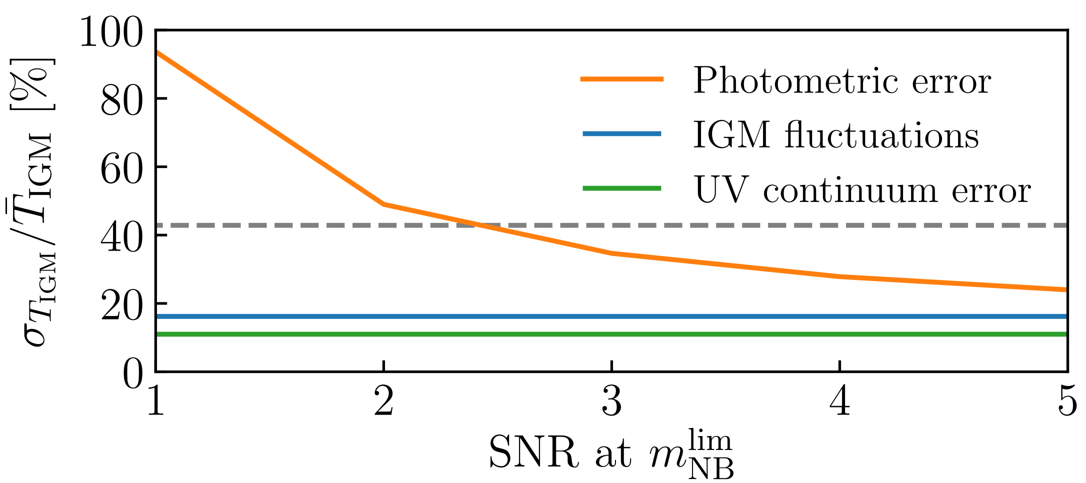
- NyX code, $100h^{-1}$cMpc 4096^3 fixed grid (Lukić et al. 2015))

2: forward modelling of observational systematics

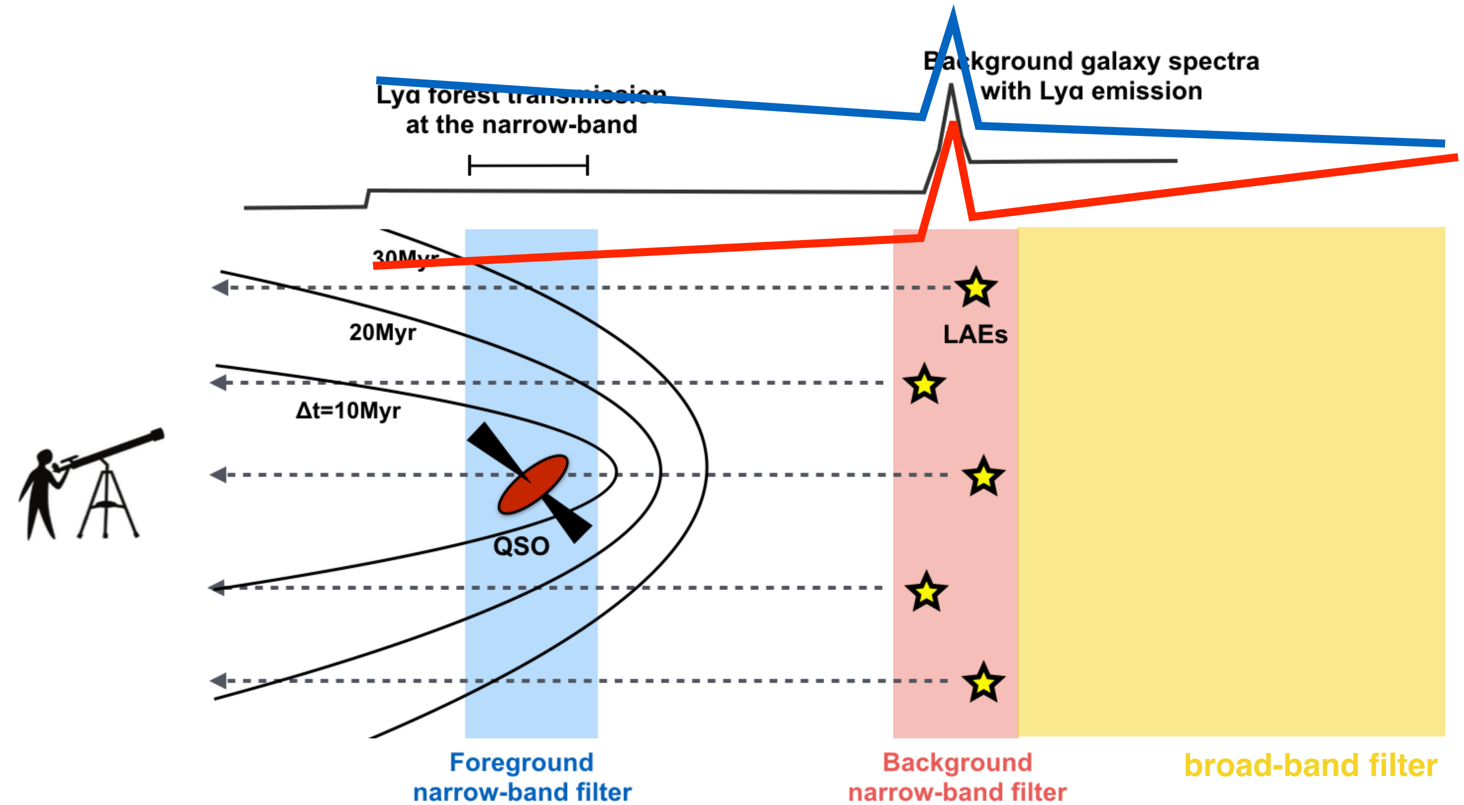
- photometric noises
- continuum slope error of bkg. galaxies
- Poisson sampling of bkg. galaxies

Photometric IGM Tomography around QSO Light Echoes: Observational systematics “error budget”





fluctuations by
QSO transverse proximity effect



- Photometric error is the dominant source of systematic uncertainties
- UV continuum error is sub-dominant (comparable to the IGM density fluctuations)
- 3σ depth for the foreground NB filter to detect the mean IGM transmission is enough

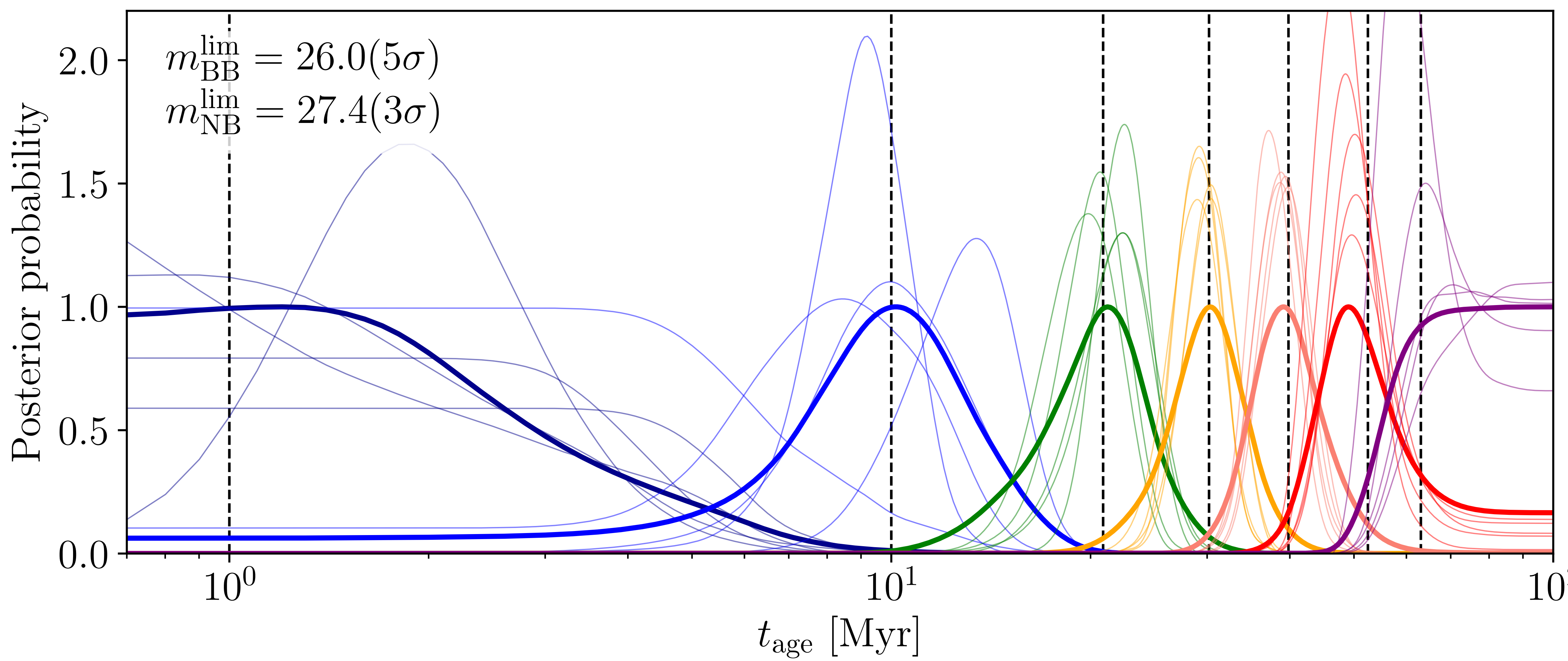
$$m_{\rm NB}^{\rm lim} = m_{\rm BB}^{\rm lim} - 2.5\log_{10} e^{-\tau_{\rm eff}(z)}$$

Forecast: constraint on the QSO lifetime t_{age}
Full Bayesian inference framework

NB flux, BB flux   Noise, continuum slope, etc

$$P(t_{\rm age}|{\rm obs.},\,{\rm systematics}) \propto P(t_{\rm age})\mathcal{L}({\rm obs.}|t_{\rm age},\,{\rm systematics})$$

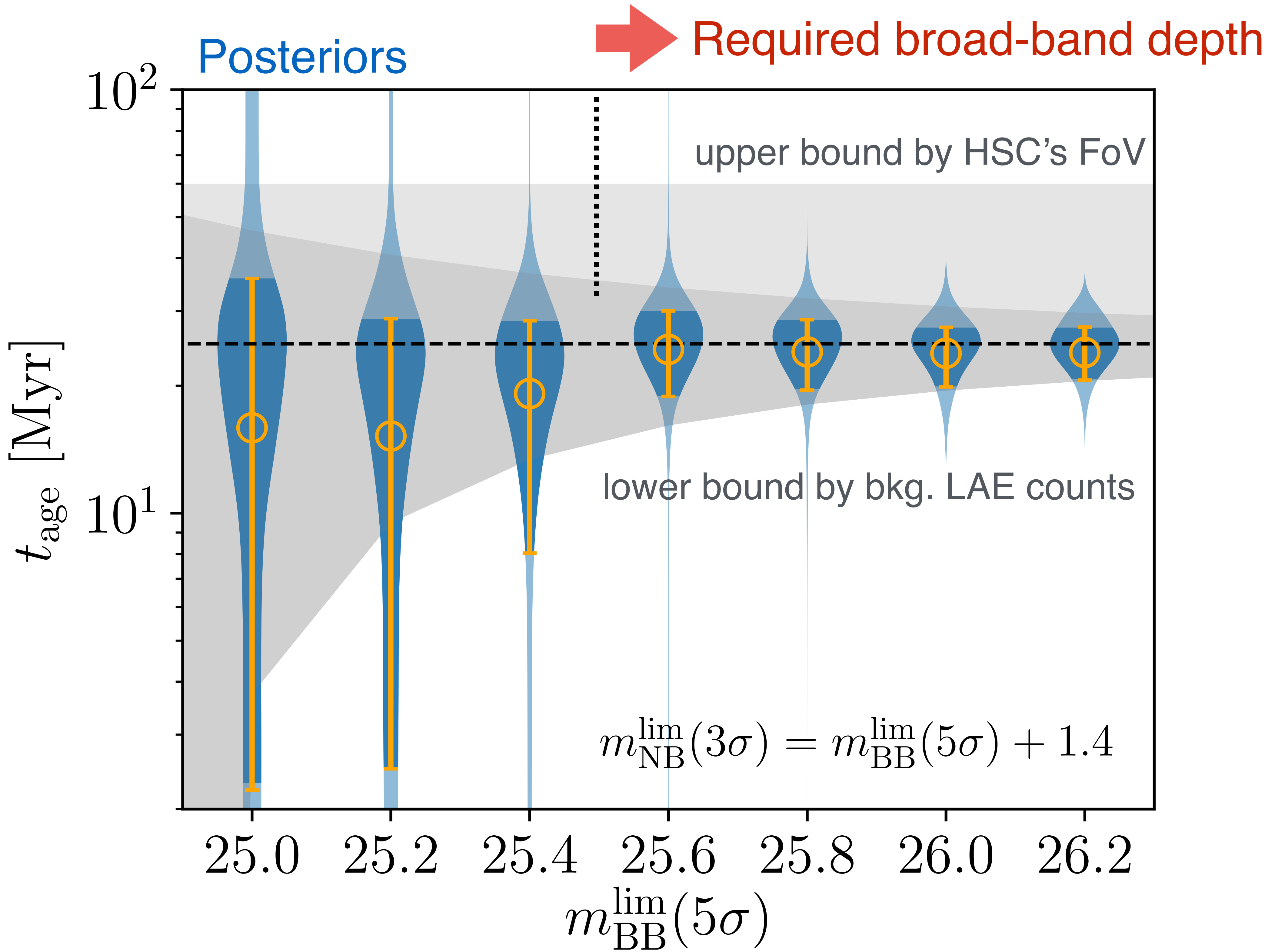
posterior   **prior**   **Likelihood** ← Forward modelled using many realisations from cosmo. simulation + RT



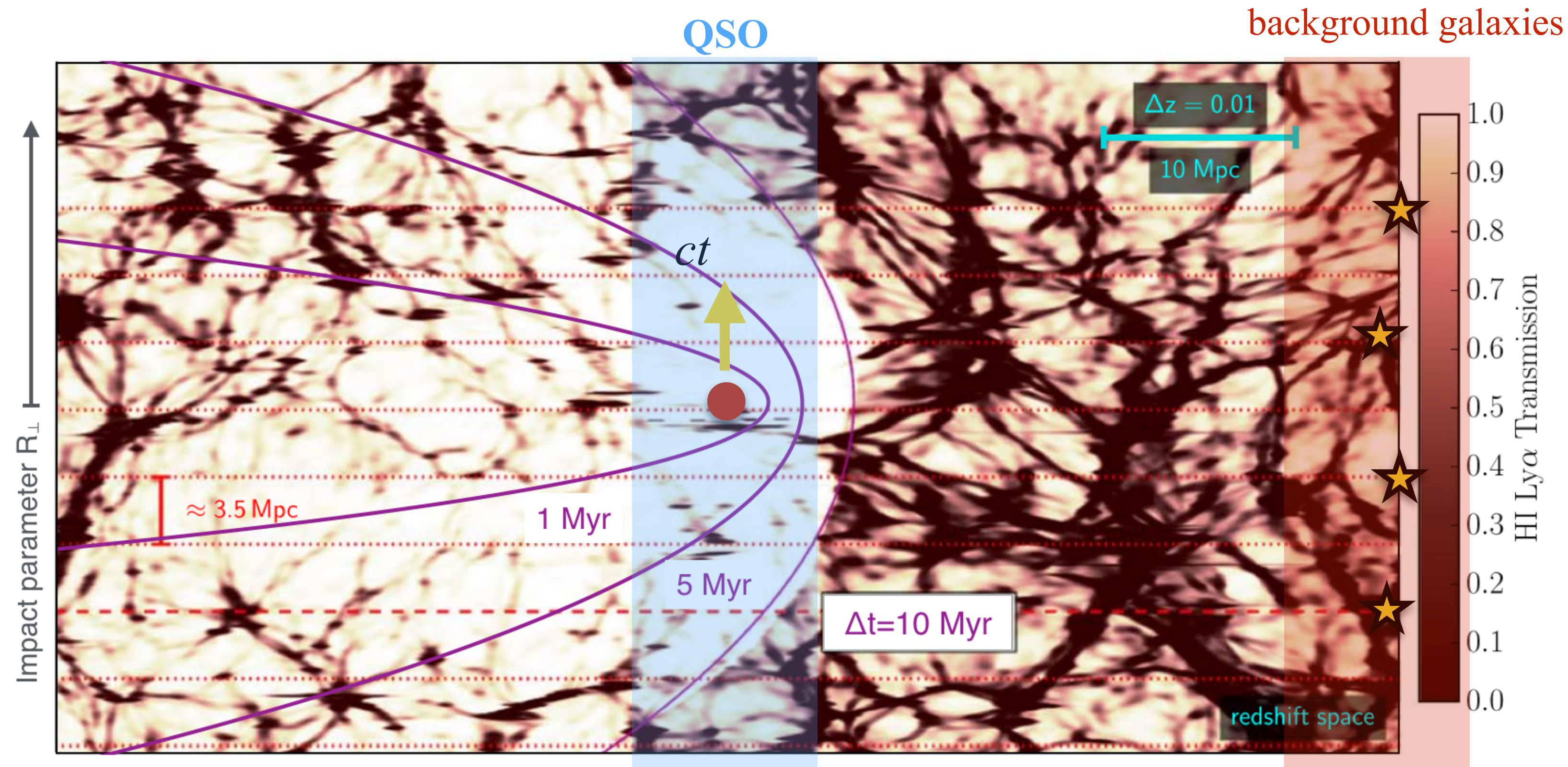
Accuracy of quasar lifetime constraint is limited by the background LAE density

$$\Delta t \sim \frac{\langle R_\perp \rangle}{c} \approx 5.81 \times 10^{[(m_{\rm uv}/26.57)^{-9.78}-1]}\ {\rm Myr}$$

Forecast: constraint on the QSO lifetime
Observational requirement



Conclusion



***Photometric IGM tomography of QSO light-echo at Mpc-scale* translates into a *Myr-scale time-domain constraint on the quasar lightcurve* of *an individual SMBH over the baseline of ~100 Myr* (≈ growth history of a SMBH)**

The photometric tomographic technique provides an economical observational strategy to search for coherent transparent IGM regions across a large area of the sky with achievable depths for Subaru/HSC

- *QSO light-echoes of massive galaxies?*
- *Ionized bubble around a protocluster?*
- *z~5.7 UV background fluctuations via ultra-deep narrow-band IGM tomography in a legacy deep field*