Probing the Duration of Quasar Accretion Episodes with He II Proximity Zones

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IPMU Postdoc Colloquium | 20.11.2020

Part 1. Introduction.

- *quasar lifetime and why should you care about it*
- *quasar proximity zones*

Part 2. Inference algorithm.

- *sample of observed quasars*
- *theory, simulations, and statistics*

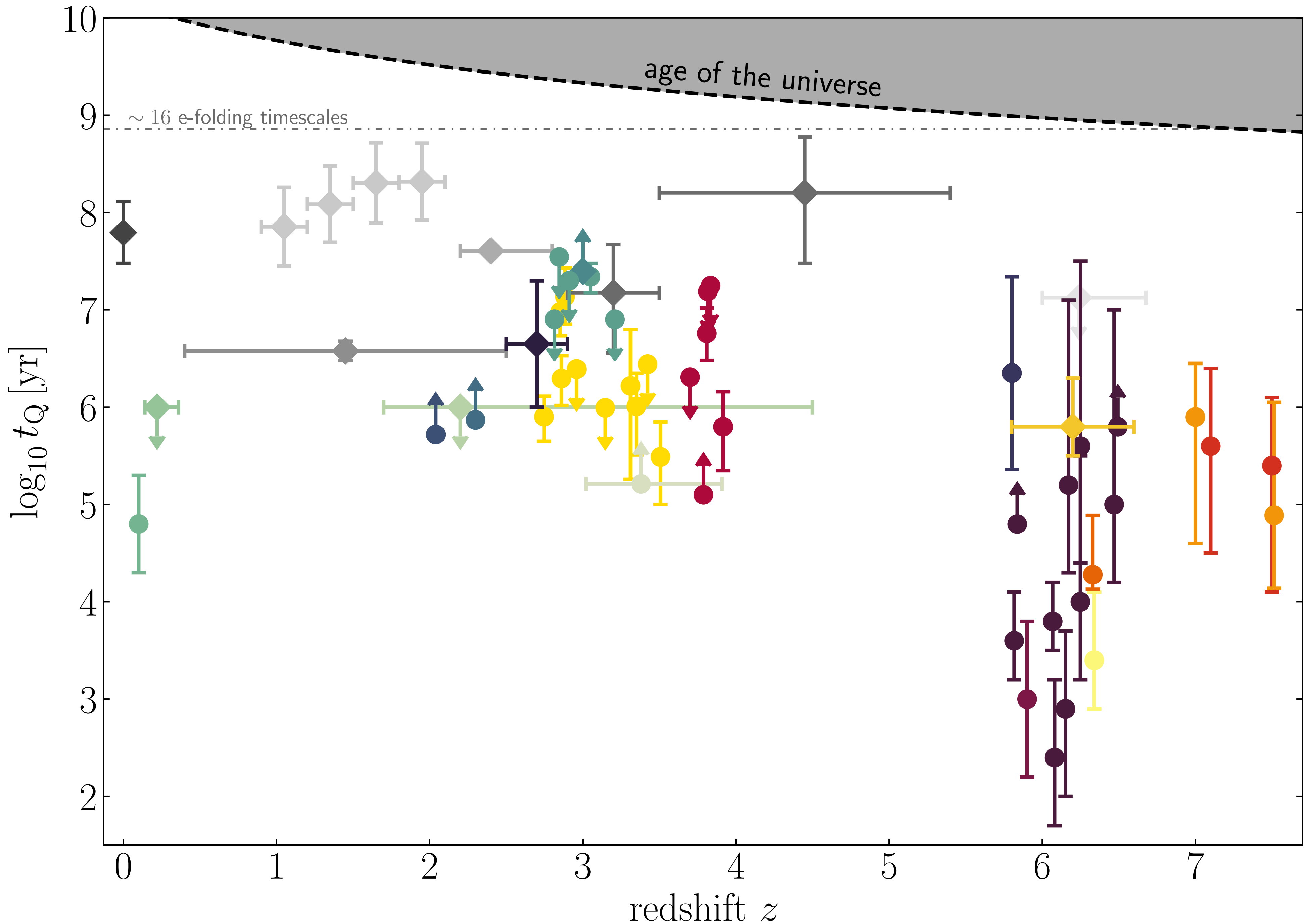
Part 3. Results.

- *individual lifetime measurements*
- *distribution of quasar lifetimes*

Part 1. Introduction.

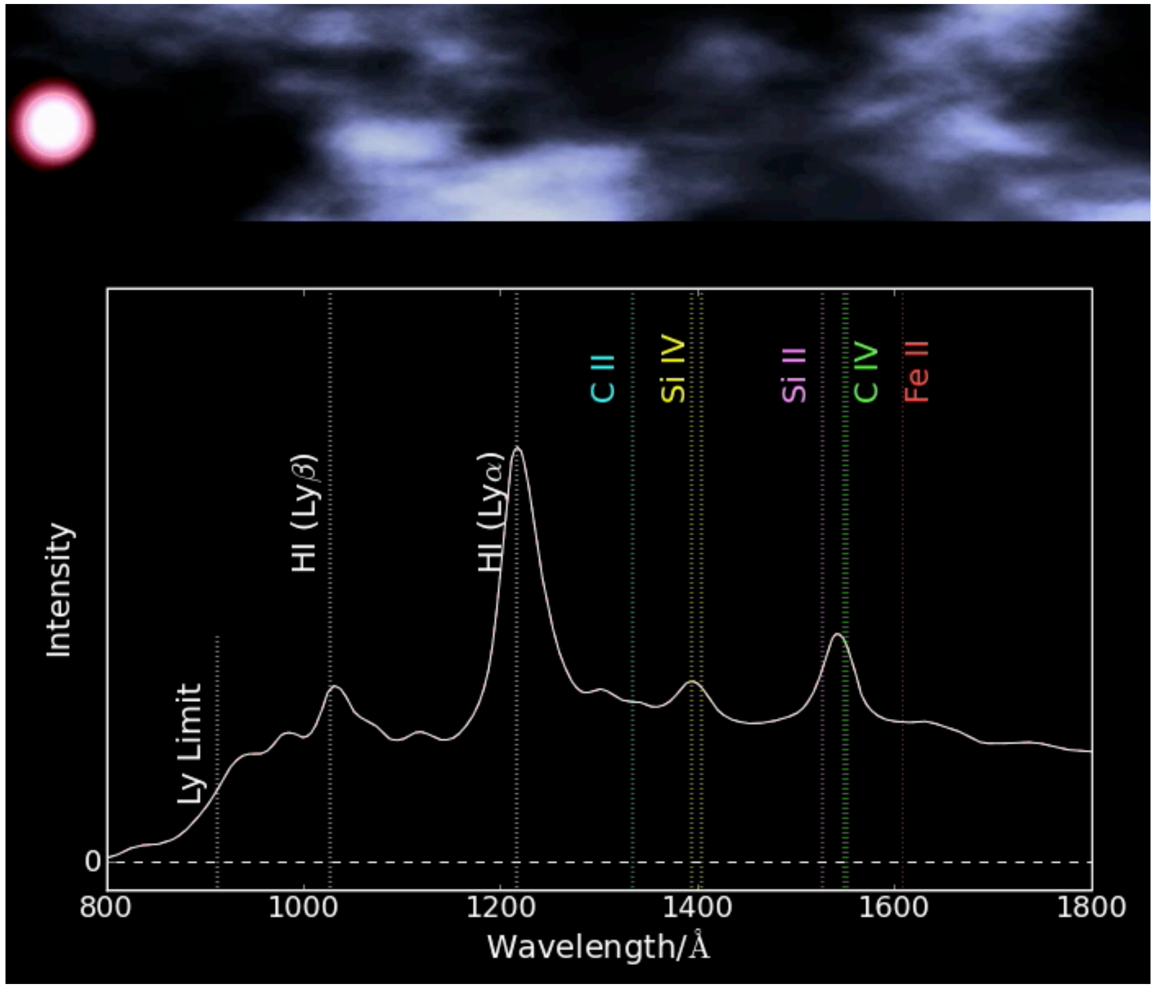
Part 1. Quest for measuring quasar lifetime

Brief (and incomplete) history of lifetime measurement quest

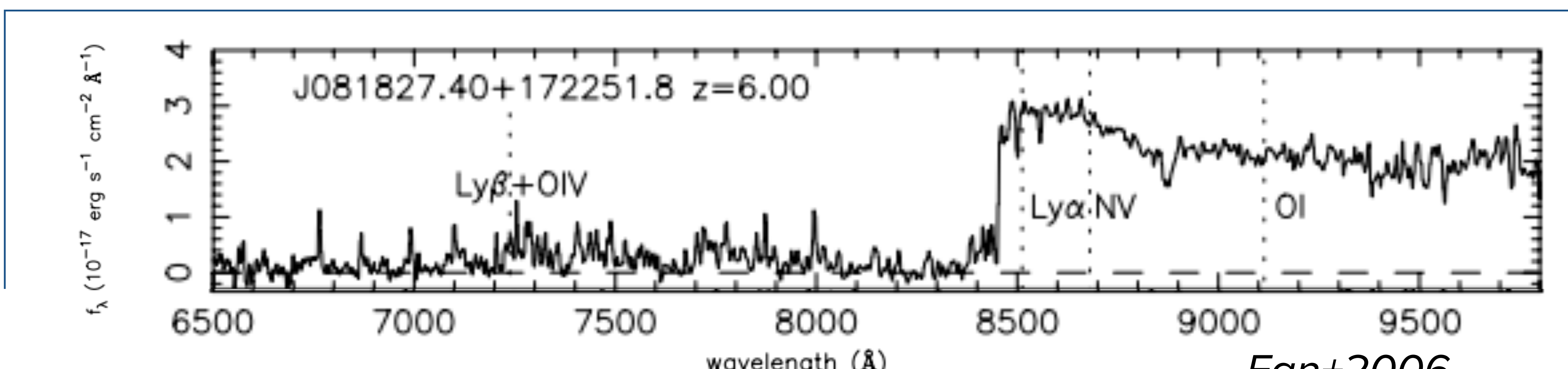


Eilers+2021 (submitted)

Part 1. Lyman-alpha forest and quasar proximity zones



Credit: Andrew Pontzen



Fan+2006

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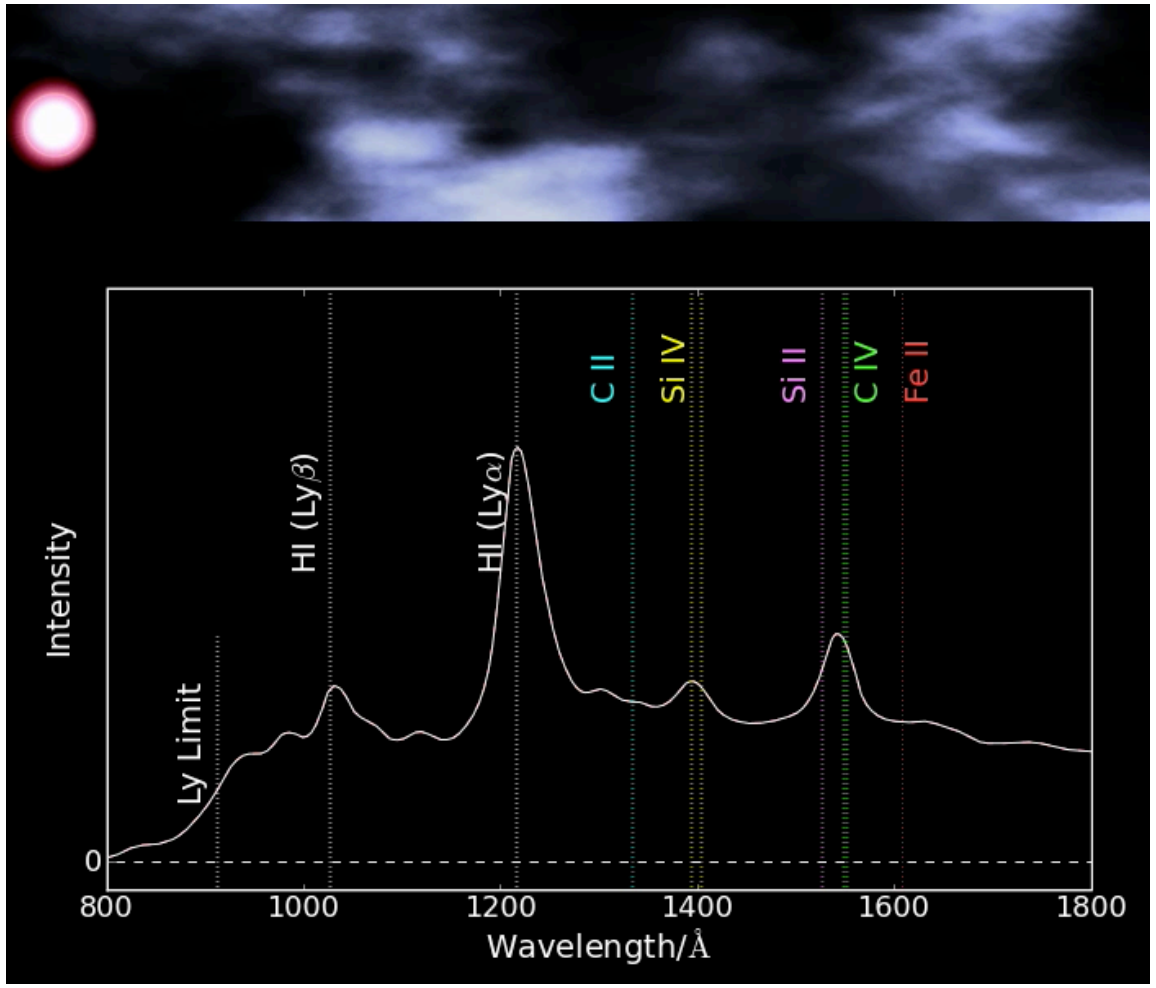

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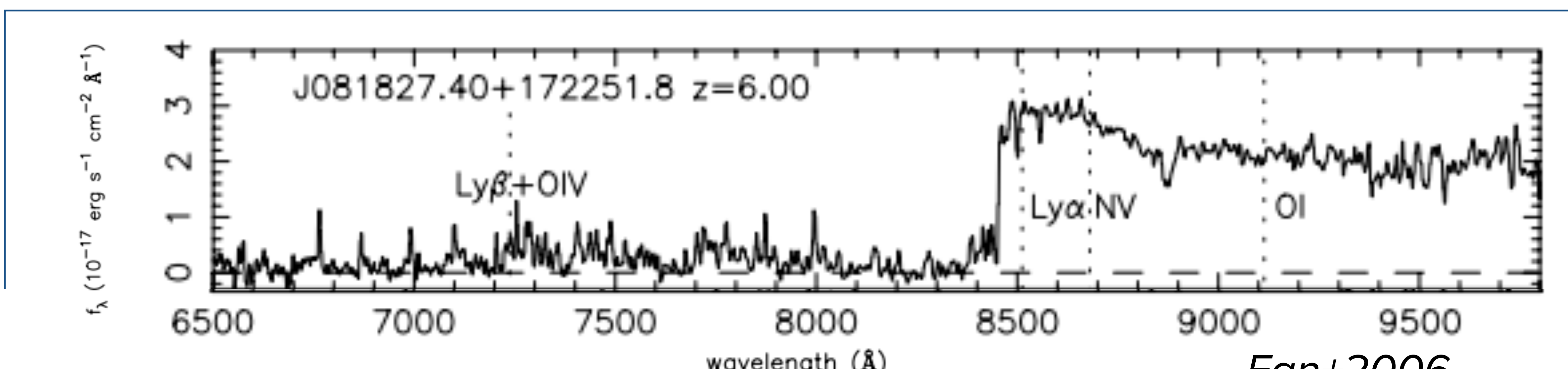

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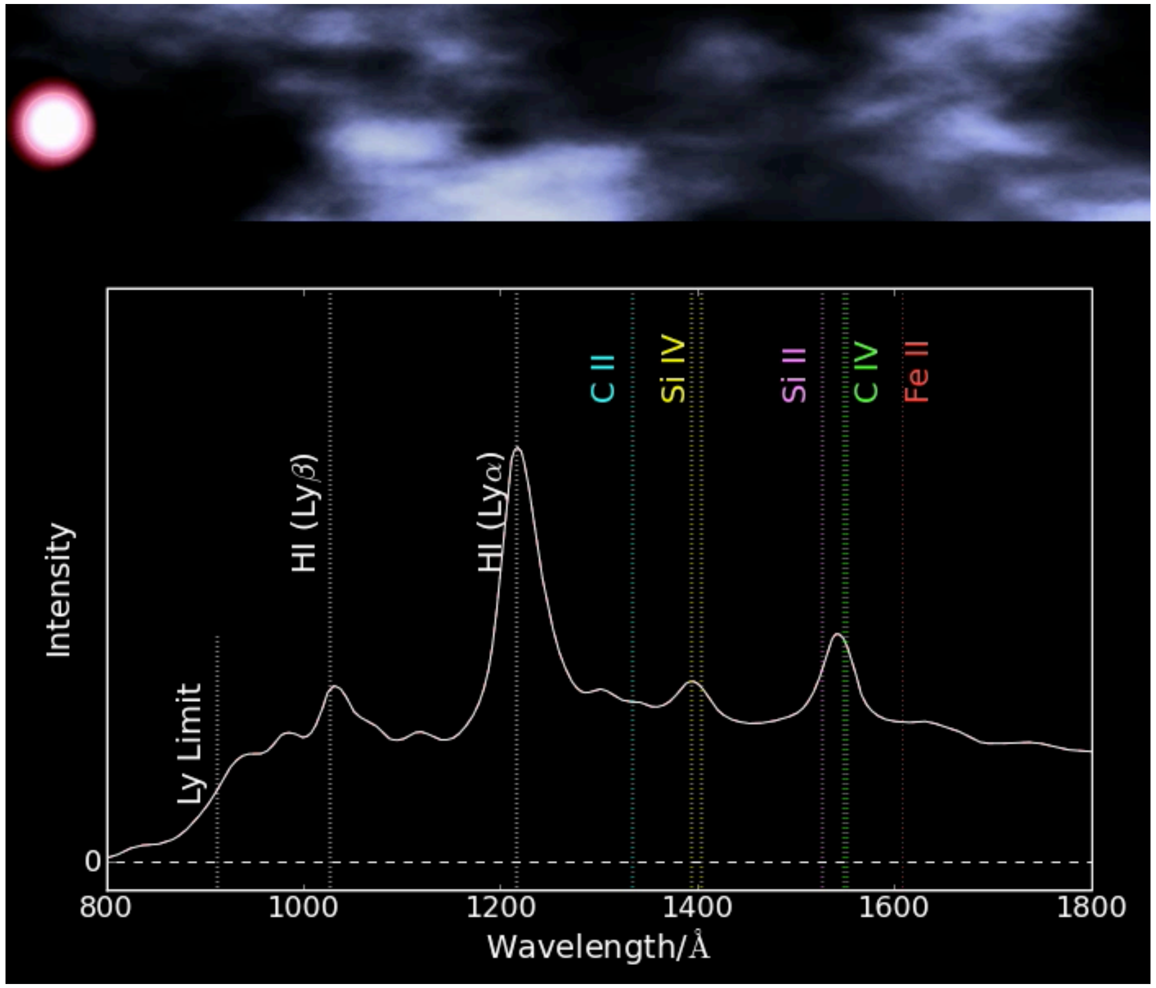

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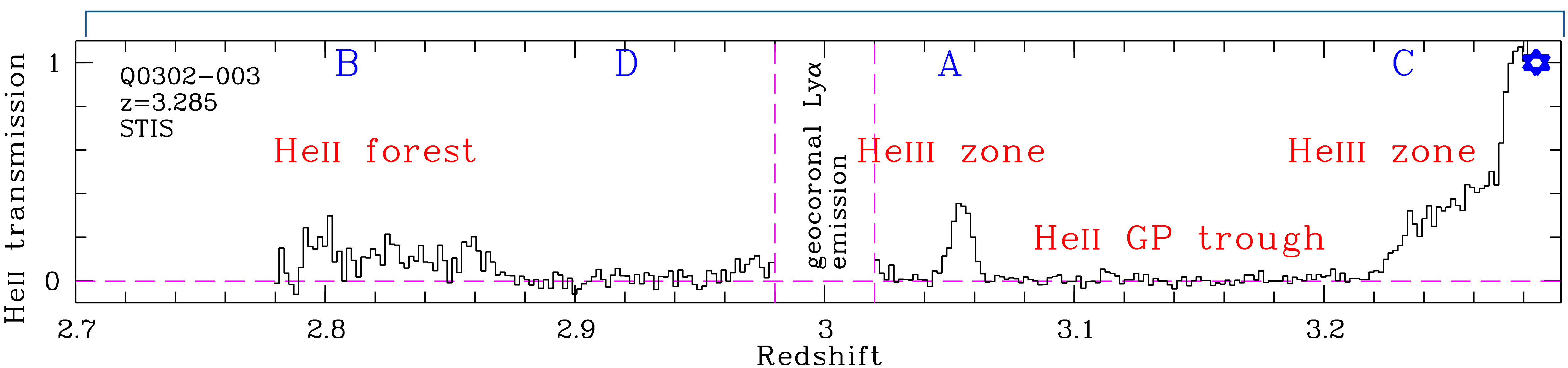
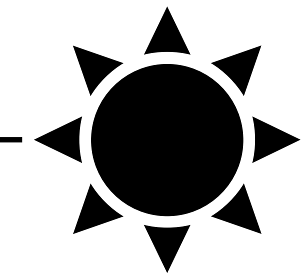


Worseck+2006

Part 1. Sensitivity of quasar proximity zones to the lifetime

$$R_{\mathrm{pz}} = f\left(t_{\mathrm{Q}}\right)$$

to Earth



$t_{\mathrm{max}} \simeq t_{\mathrm{eq}} \approx \Gamma_{\mathrm{bkg}}^{-1}$ *(Khrykin+2016)*

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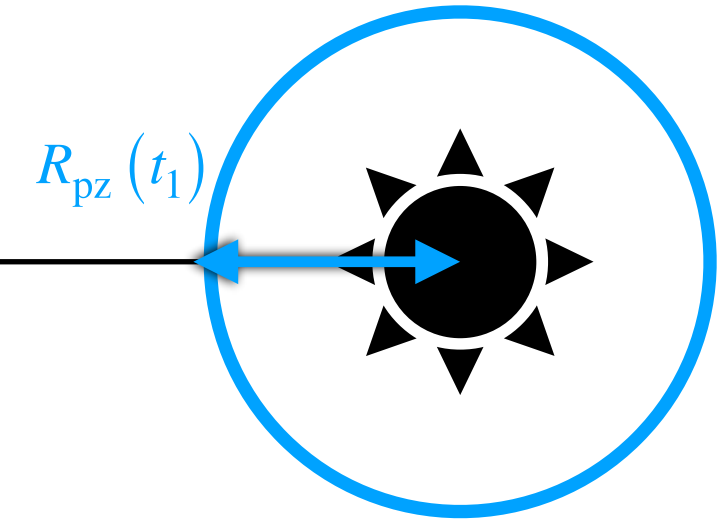

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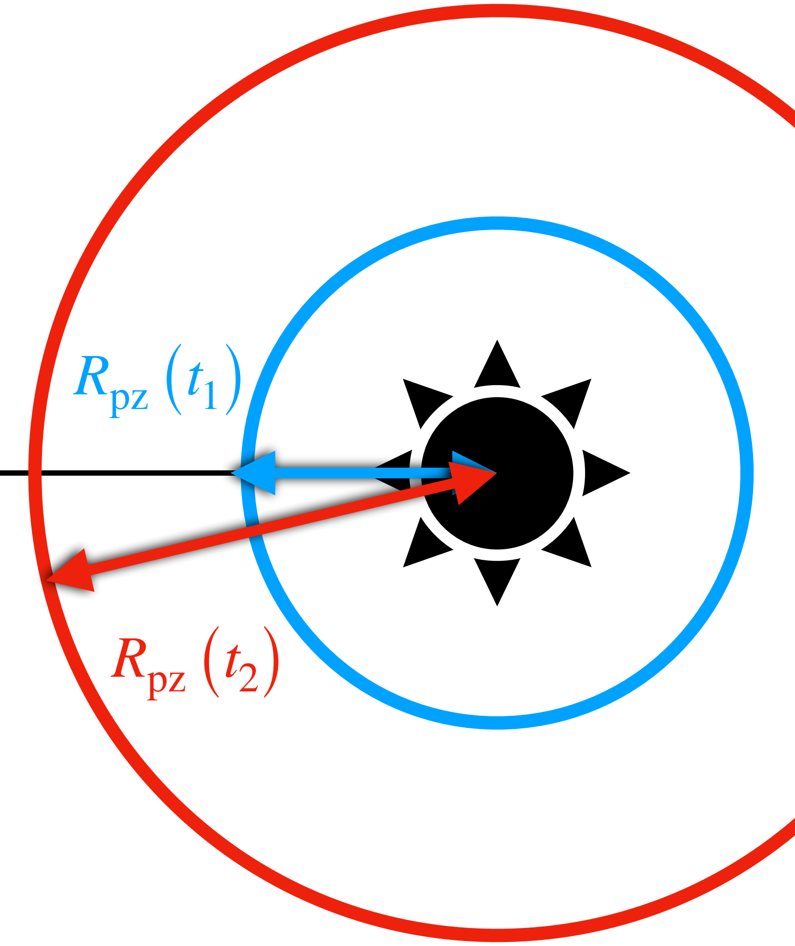

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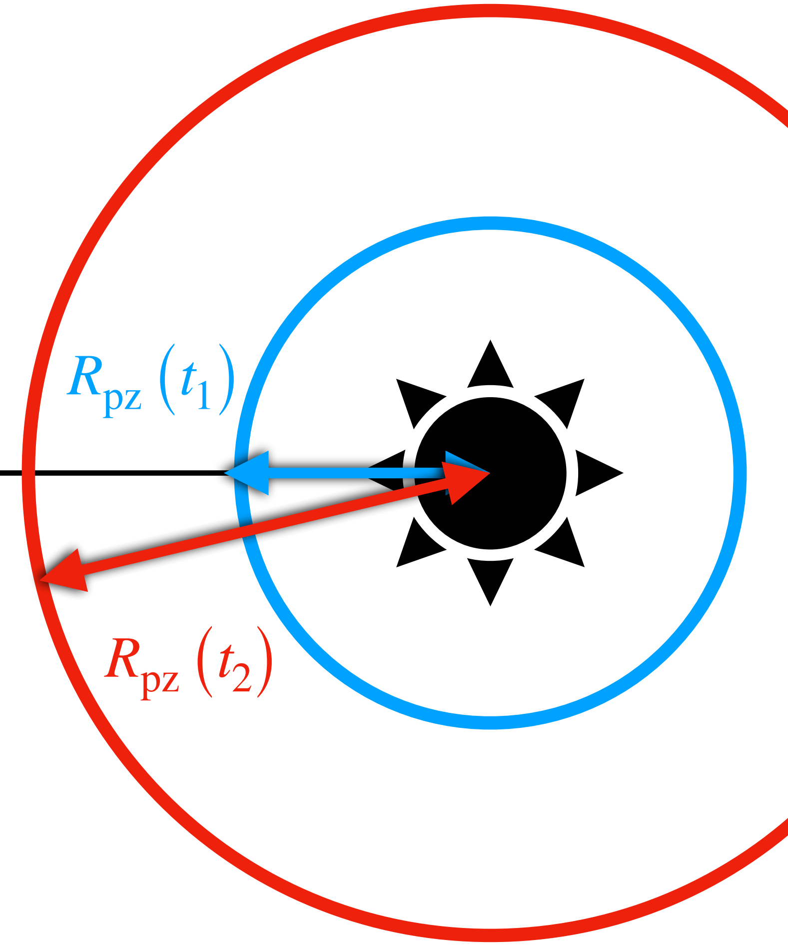
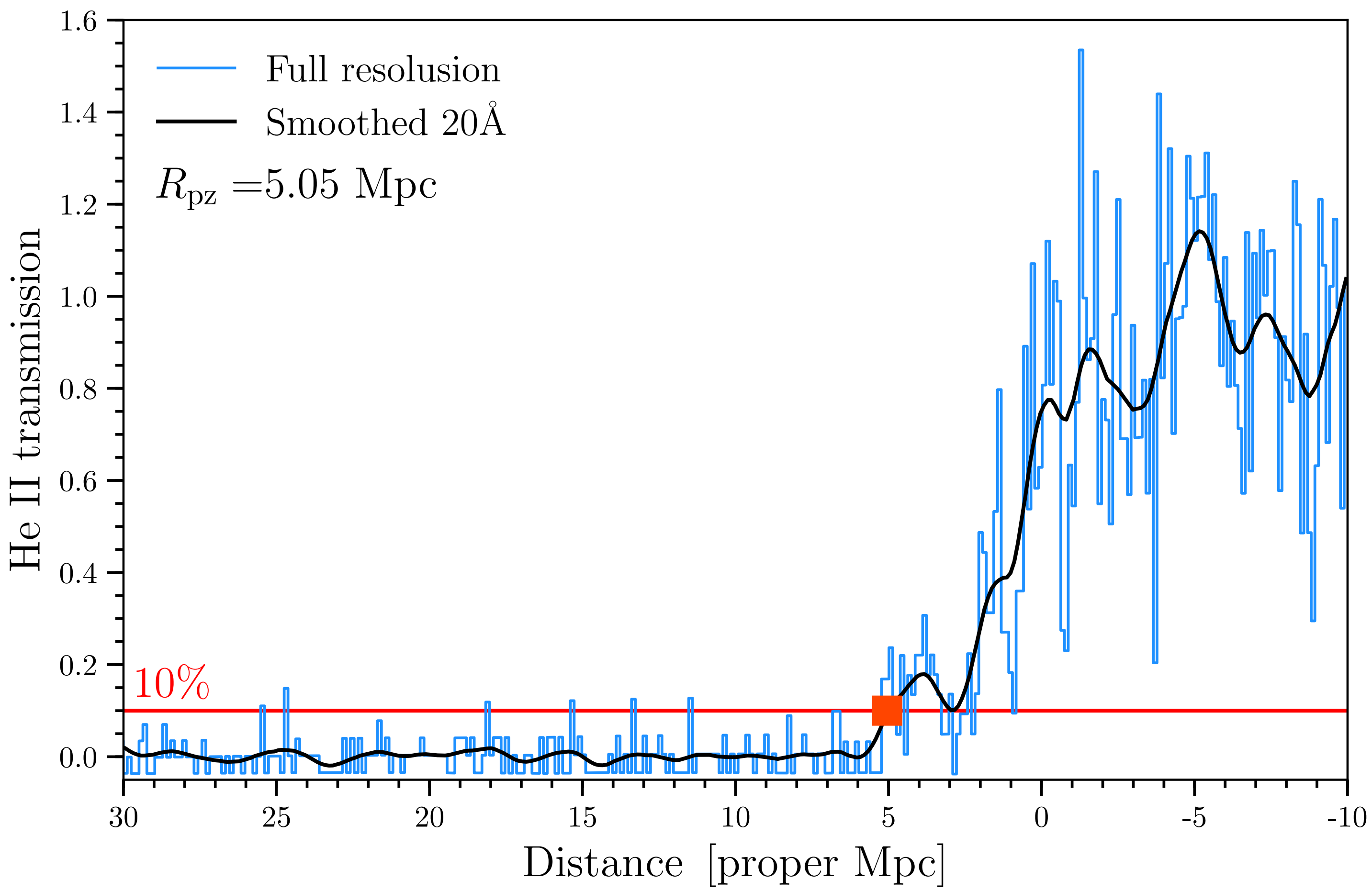
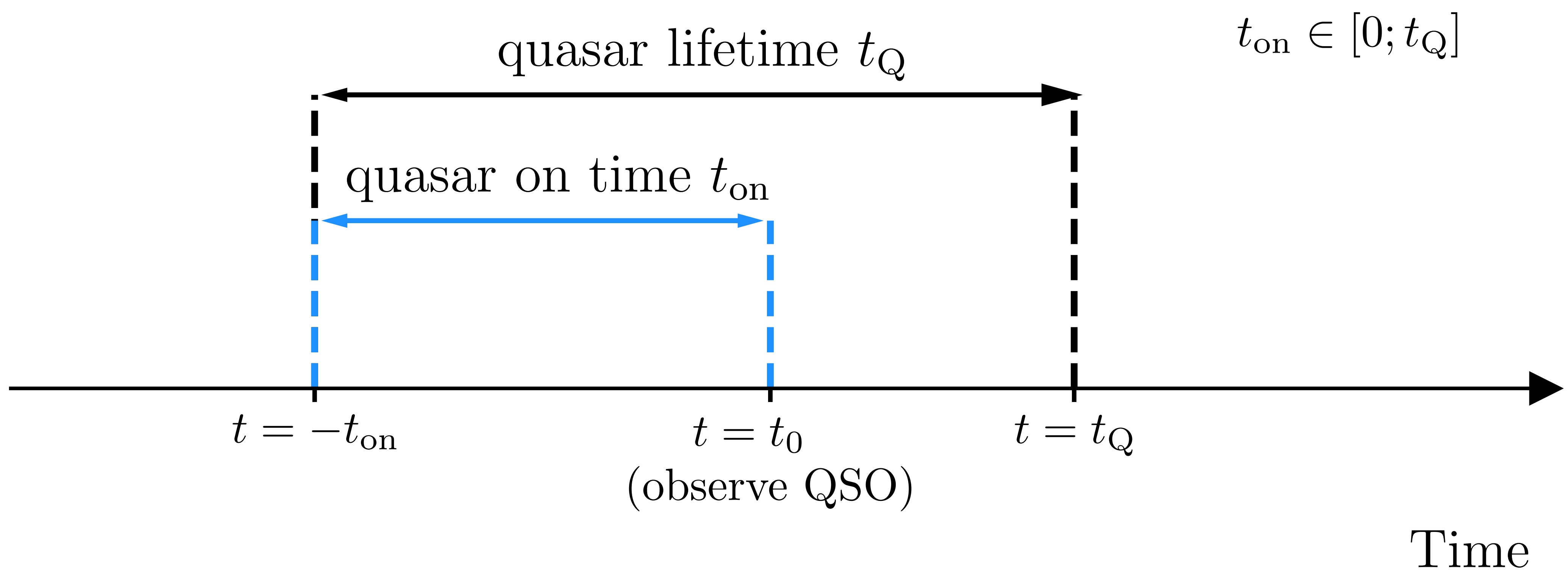




Fan et al (2006) definition of R_{pz}

$$R_{\mathrm{pz}} : \quad T < 10\,\%$$

Part 1. Let's fix the terminology, shall we? (finally…)



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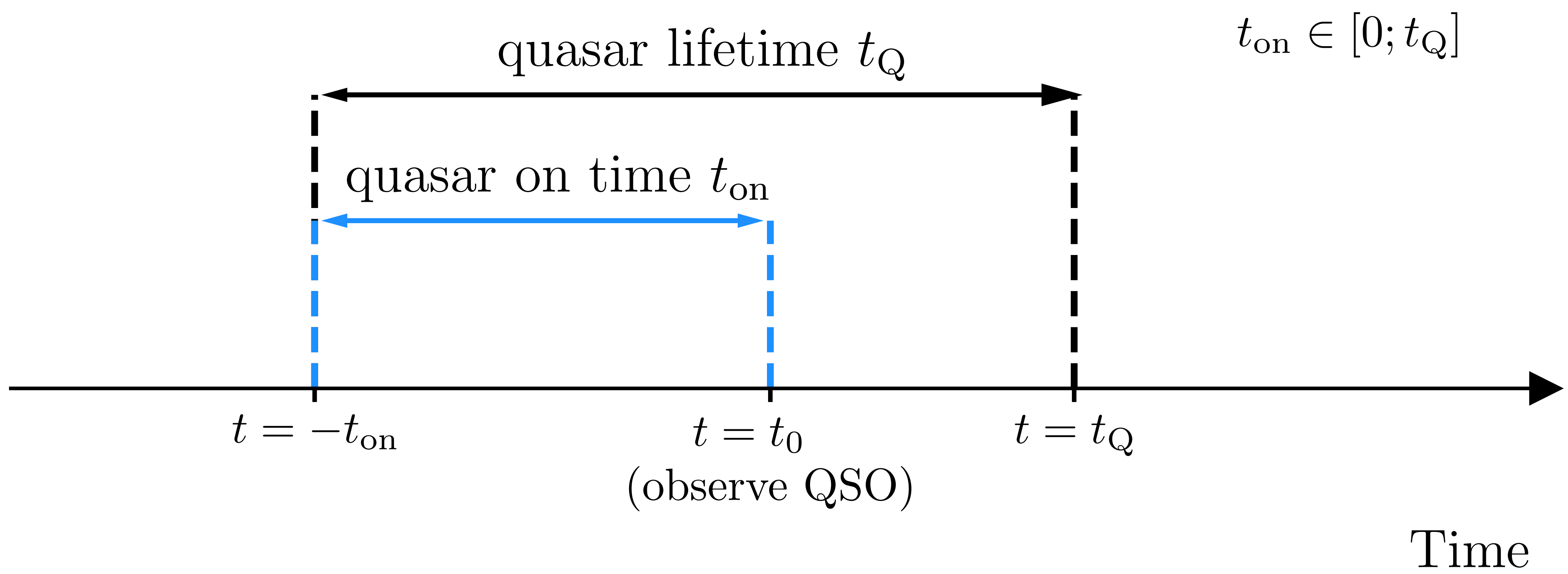

quasar lifetime *(* $t_{\rm Q}$ *)* *- duration of a single accretion episode*

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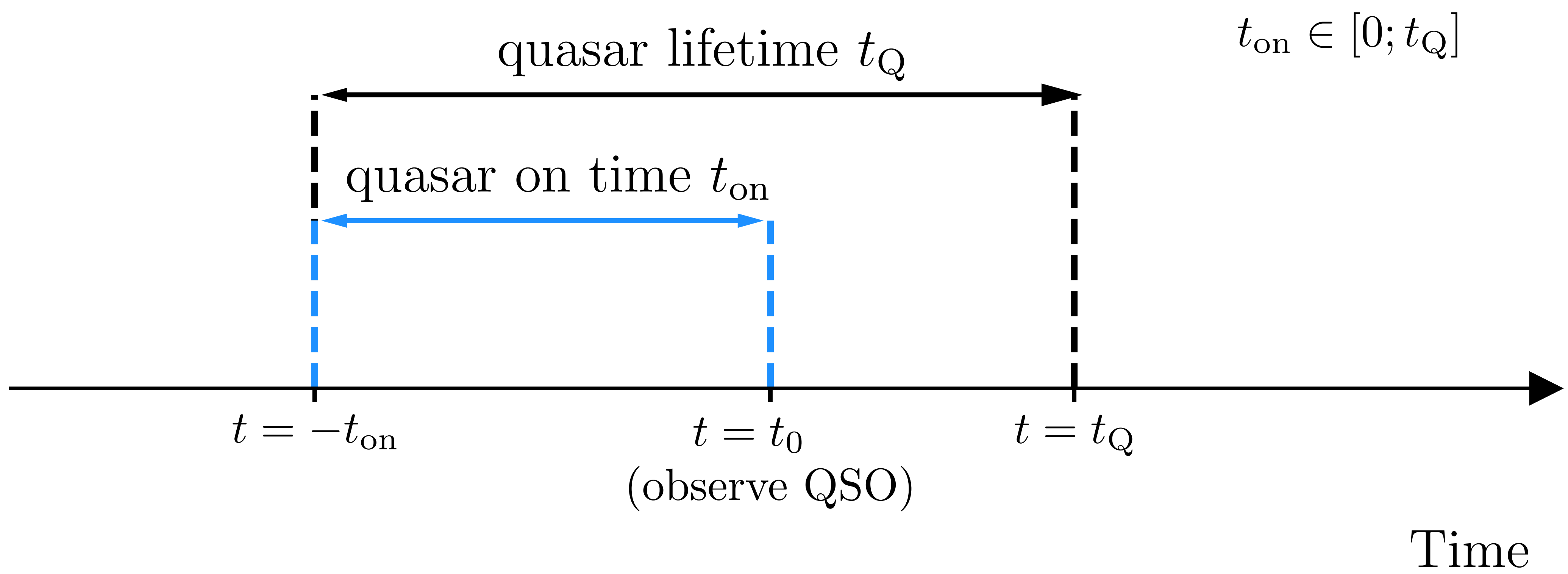


quasar lifetime *(* t_{Q} *)* — *- duration of a single accretion episode*

quasar on-time *(* t_{on} *)* — *- lower limit on* t_{Q} *from proximity zone estimates (uniformly distributed from 0 to* t_{Q} *)*

Part 2. Inference Algorithm.

HST/COS UV-spectra of 20 HeII transparent quasars at z ~ 3-4

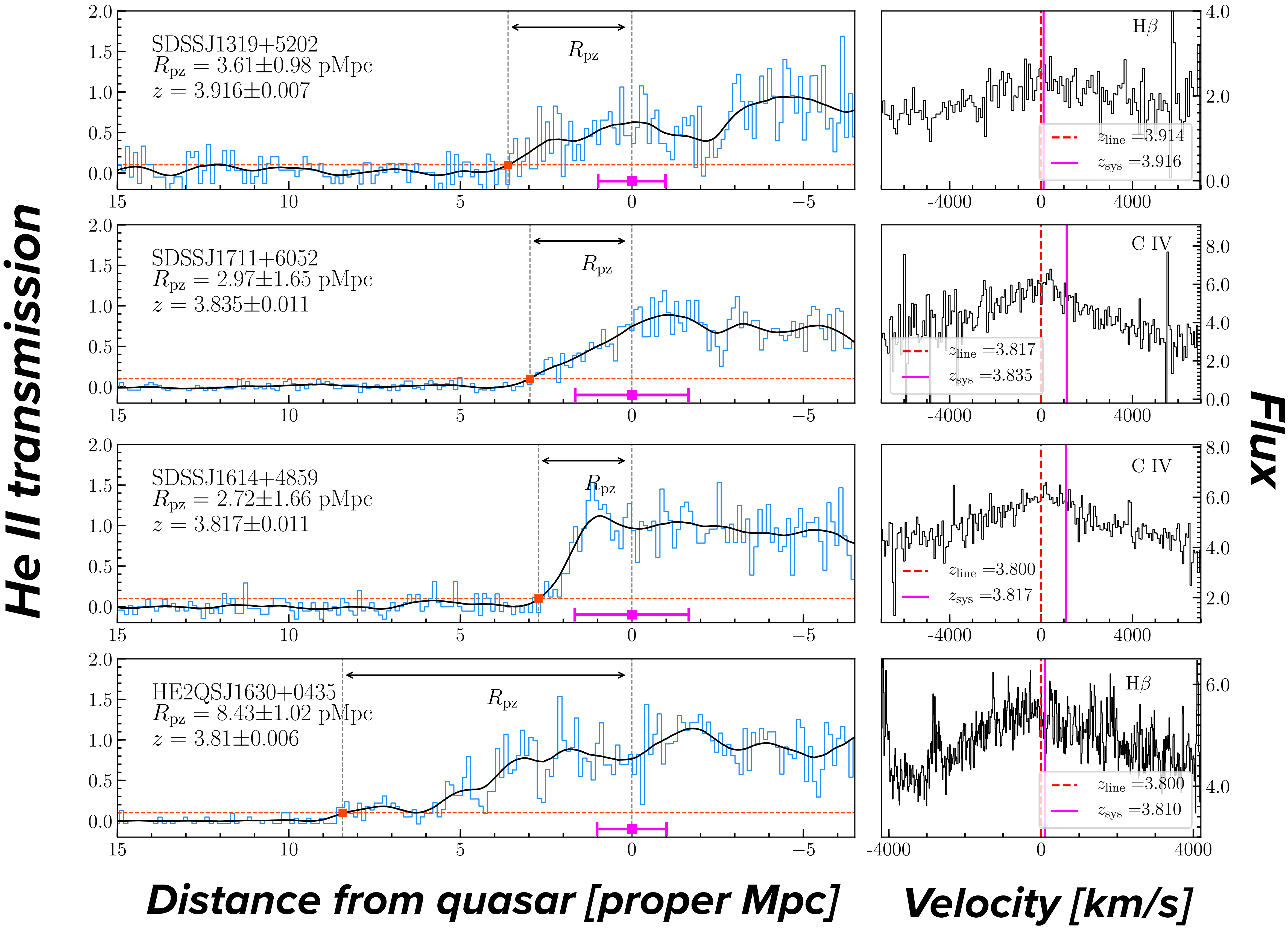
Table 1. Sample of 20 quasars with measured He II proximity zones used in this study. From left to right the columns show: quasar name, quasar position, *HST*/COS spectral resolution at 1450Å, signal-to-noise ratio near He II Ly α, quasar redshift, redshift uncertainty, spectroscopic line that was used to measure the redshift, i-band magnitude, absolute magnitude at 1450Å, He II total photon production rate and $Q_{\rm 4Ry}$, measured size of the proximity zone $R_{\rm pz}$ with corresponding 1σ redshift uncertainty, and the inferred quasar on-time $t_{\rm on}$.

Quasar	R.A. (J2000)	Decl. (J2000)	R	S/N	z	Δz km s^{-1}	z line	i-mag	M_{1450}	$\log_{10} Q_{\rm 4Ry}$ s^{-1}	$R_{\rm pz} \pm \sigma(R_{\rm pz})$ Mpc	$t_{\rm on}$ Myr
HS 1700+6416	$17^h01^m00^s.61$	$+64^\circ12'09''.1$	2100	15	2.7472	273	Mg II	15.79	-29.33	57.34	7.16 ± 1.01	
HS 1024+1849	$10^h27^m34^s.13$	$+18^\circ34'27''.5$	15000	5	2.8521	273	Mg II	17.66	-27.54	56.62	9.38 ± 0.97	
Q 1602+576	$16^h03^m55^s.92$	$+57^\circ30'54''.4$	15000	7	2.8608	273	Mg II	17.22	-27.99	56.80	6.10 ± 0.97	
PC 0058+0215	$01^h00^m58^s.39$	$+02^\circ31'31''.4$	2200	4	2.8842	273	Mg II	18.77	-26.46	56.19	7.10 ± 0.97	
SDSS J0936+2927	$09^h36^m43^s.50$	$+29^\circ27'13''.6$	2200	4	2.9248	44.4	[O III]	18.06	-27.20	56.49	8.59 ± 0.15	
SDSS J0818+4908	$08^h18^m50^s.01$	$+49^\circ08'17''.0$	2200	4	2.9598	656	C IV	18.36	-26.93	56.38	2.92 ± 2.25	
HE2QS J2157+2330	$21^h57^m43^s.63$	$+23^\circ30'37''.3$	1600	4	3.1465	44.4	[O III]	17.67	-27.77	56.72	17.40 ± 0.14	
SDSS J1237+0126	$12^h37^m48^s.99$	$+01^\circ26'07''.0$	2400	4	3.1467	273	Mg II	18.78	-26.66	56.27	1.77 ± 0.87	
Q 0302−003	$03^h04^m49^s.85$	$-00^\circ08'13''.5$	19000	3	3.2850	44.4	[O III]	17.34	-28.21	56.89	13.20 ± 0.13	
HE2QS J0233−0149	$02^h33^m06^s.01$	$-01^\circ49'50''.5$	1700	4	3.3115	656	C IV	18.41	-27.17	56.47	4.71 ± 1.98	
HS 0911+4809	$09^h15^m10^s.01$	$+47^\circ56'58''.8$	10000	6	3.3500	400	Hβ	17.77	-27.84	56.74	4.21 ± 1.19	
HE2QS J0916+2408	$09^h16^m20^s.85$	$+24^\circ08'04''.6$	1800	4	3.4231	656	C IV	18.52	-27.12	56.45	3.14 ± 1.91	
SDSS J1253+6817	$12^h53^m53^s.71$	$+68^\circ17'14''.2$	2600	7	3.4753	44.4	[O III]	18.45	-27.19	56.48	11.40 ± 0.12	
SDSS J2346−0016	$23^h46^m25^s.66$	$-00^\circ16'00''.4$	2600	8	3.5076	273	Mg II	17.68	-27.97	56.79	2.66 ± 0.77	
HE2QS J2311−1417	$23^h11^m45^s.46$	$-14^\circ17'52''.1$	2300	4	3.7003	656	C IV	18.11	−27.64	56.66	1.94 ± 1.72	
SDSS J1137+6237	$11^h37^m21^s.72$	$+62^\circ37'07''.2$	2300	4	3.7886	656	C IV	19.31	−26.46	56.19	4.92 ± 1.68	
HE2QS J1630+0435	$16^h30^m56^s.34$	$+04^\circ35'59''.4$	2000	4	3.8101	400	Hβ	17.51	−28.37	56.92	8.43 ± 1.02	
SDSS J1614+4859	$16^h14^m26^s.81$	$+48^\circ59'58''.8$	2300	3	3.8175	656	C IV	19.45	−26.34	56.14	2.72 ± 1.66	
SDSS J1711+6052	$17^h11^m34^s.41$	$+60^\circ52'40''.3$	2700	4	3.8358	656	C IV	19.34	−26.49	56.19	2.97 ± 1.65	
SDSS J1319+5202	$13^h19^m14^s.20$	$+52^\circ02'00''.1$	2700	2	3.9166	400	Hβ	17.81	−28.02	56.82	3.62 ± 0.98	

Spoiler Block

Worseck+2019, Khrykin+2019,
Worseck+ (in prep), Khrykin+ (tbs)

Part 2. Observational Sample



Part 2. Modelling the He II proximity zones

hydrodynamical simulations

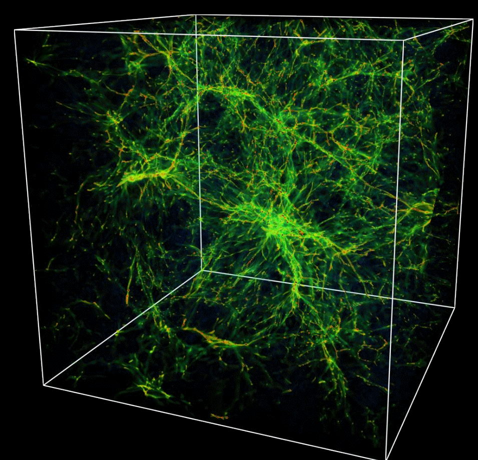


Image credit: Cen & Ostriker

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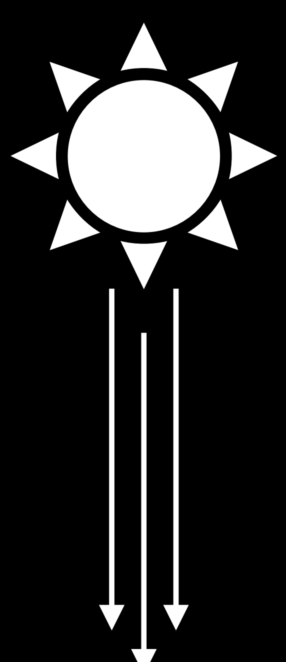
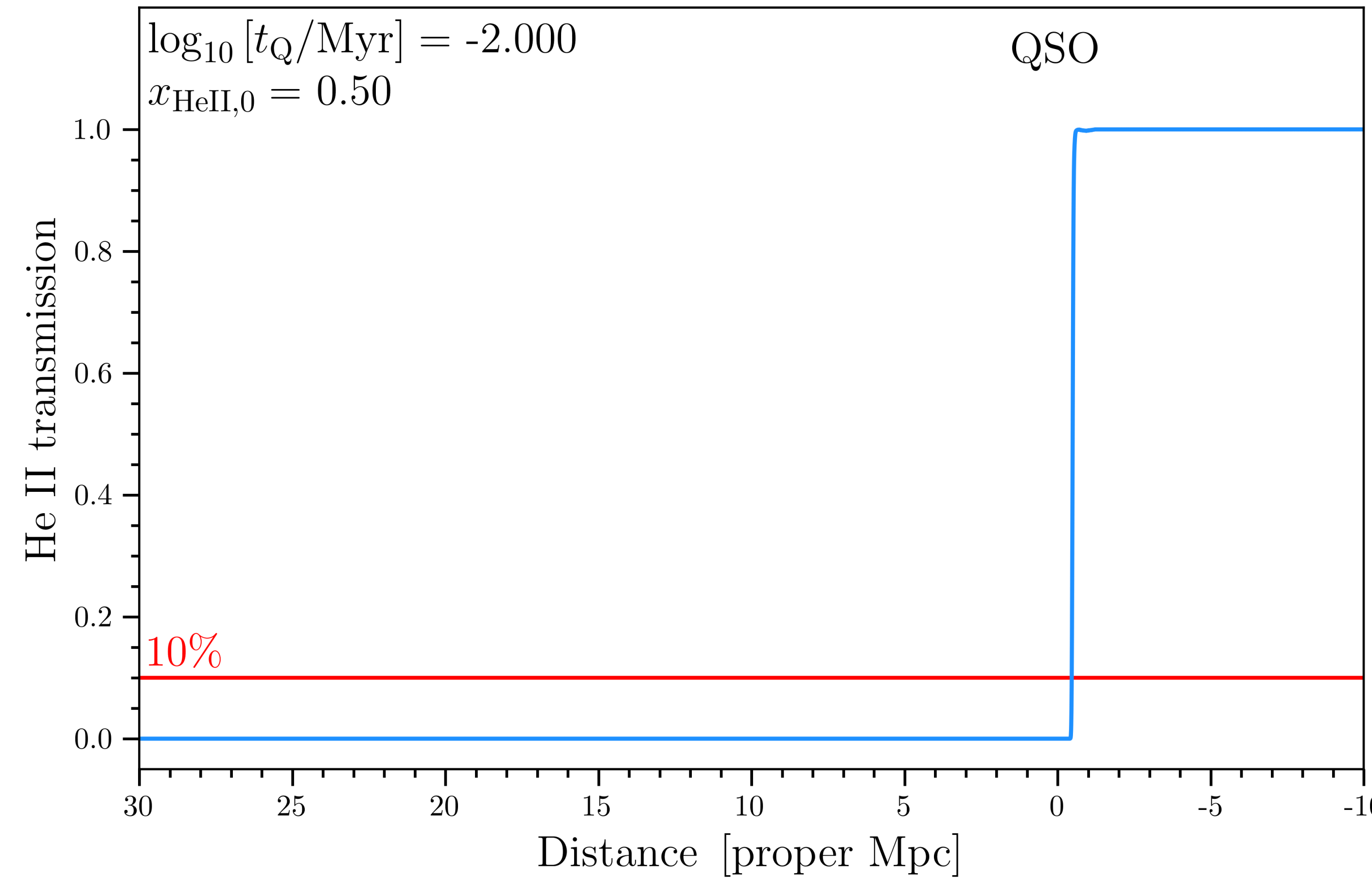
radiative transfer





Proximity zone size depends on:

1. *Quasar on-time (lifetime)*
2. *HeII ionizing background (initial He II fraction)*
3. *Quasar luminosity (fixed by observations)*

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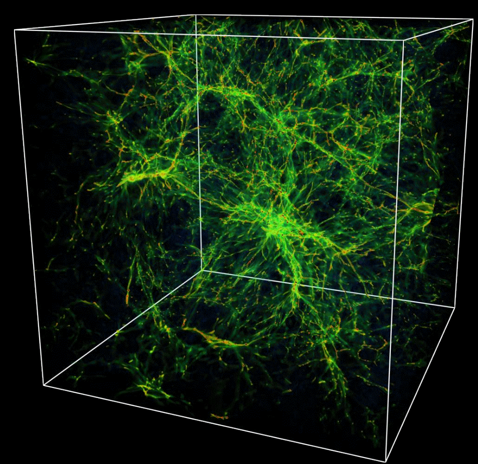

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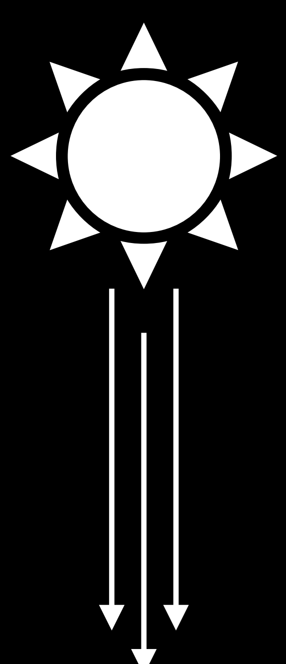

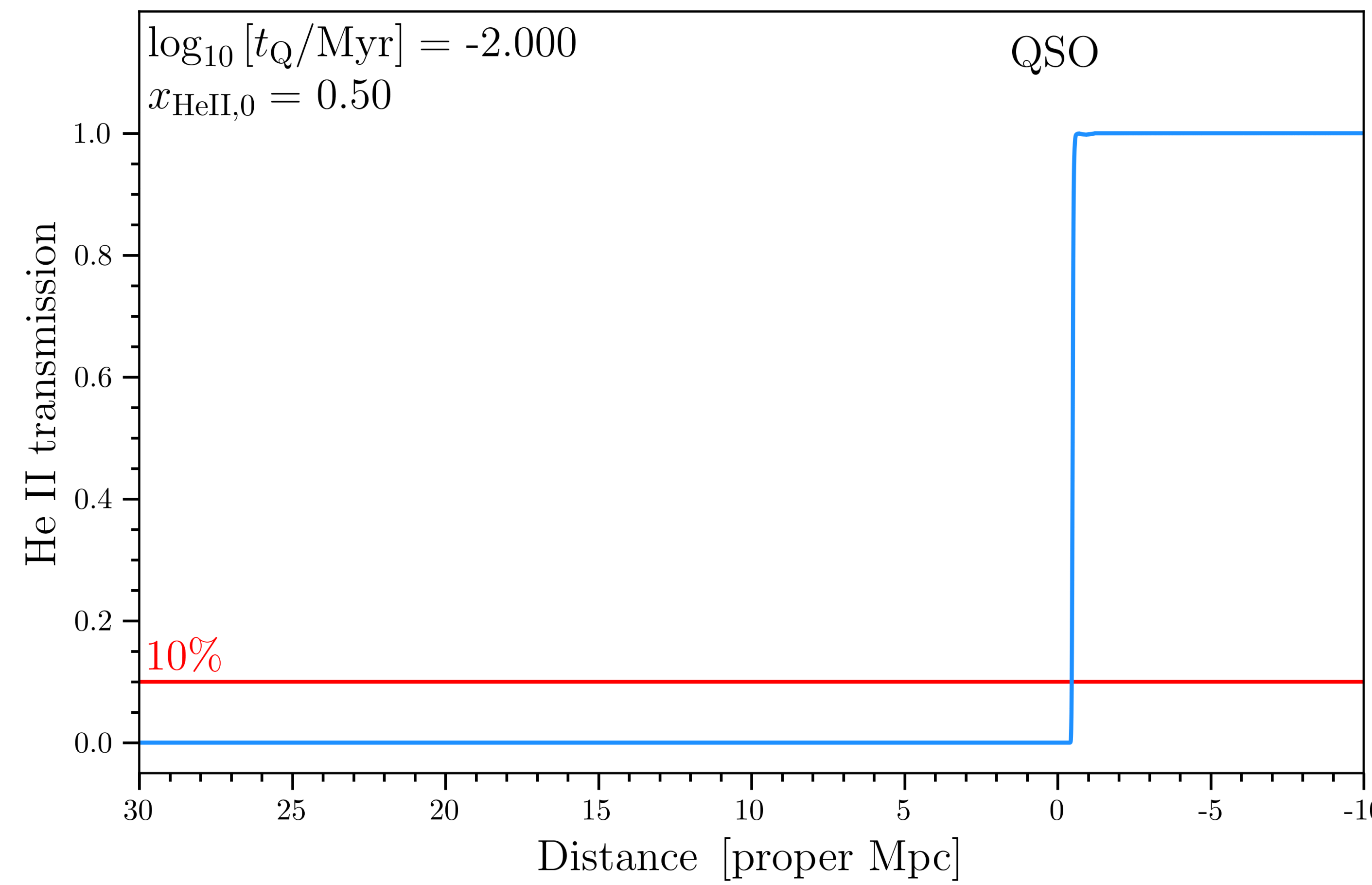

Proximity zone size depends on:

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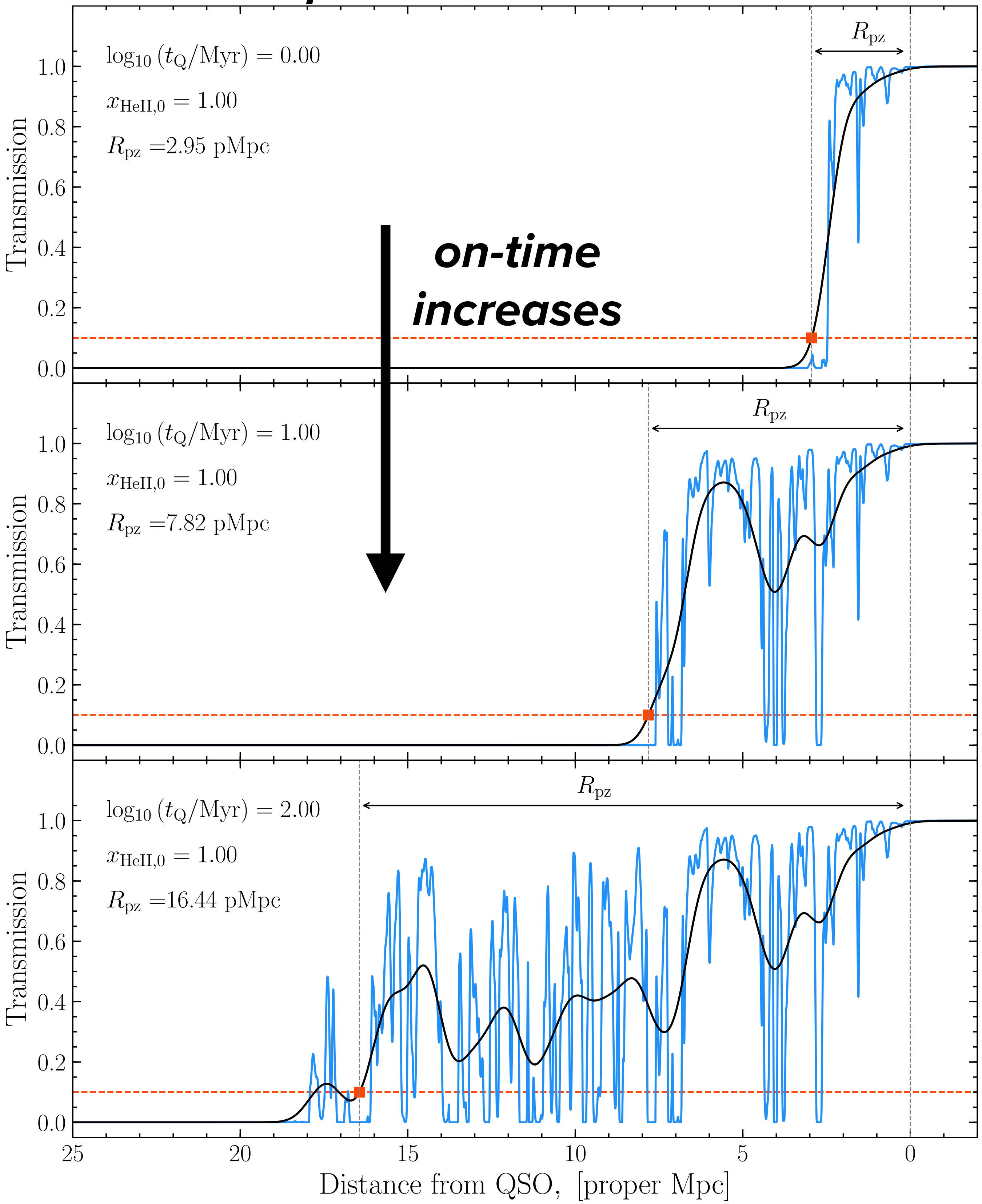
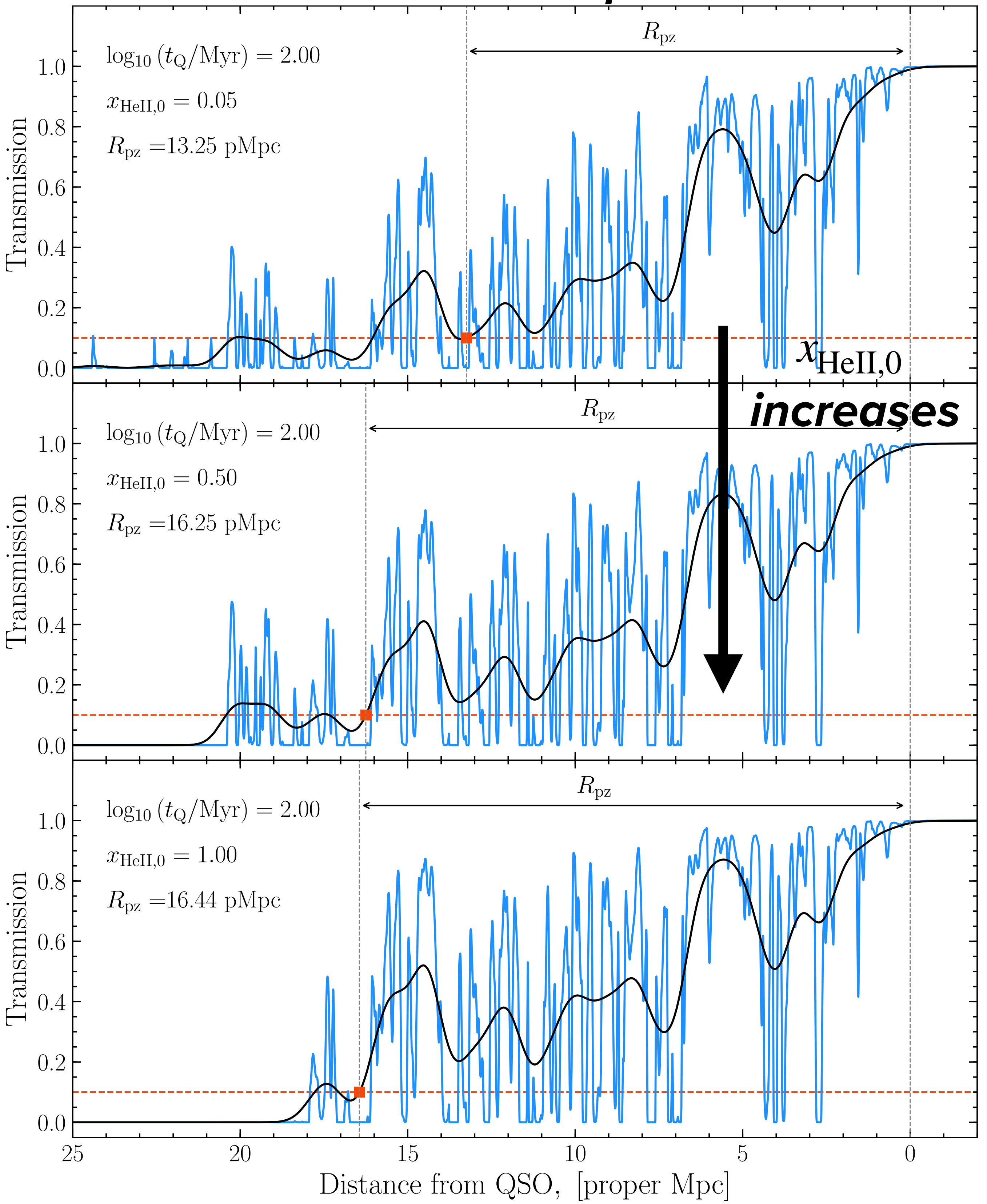
Part 2. RT simulations

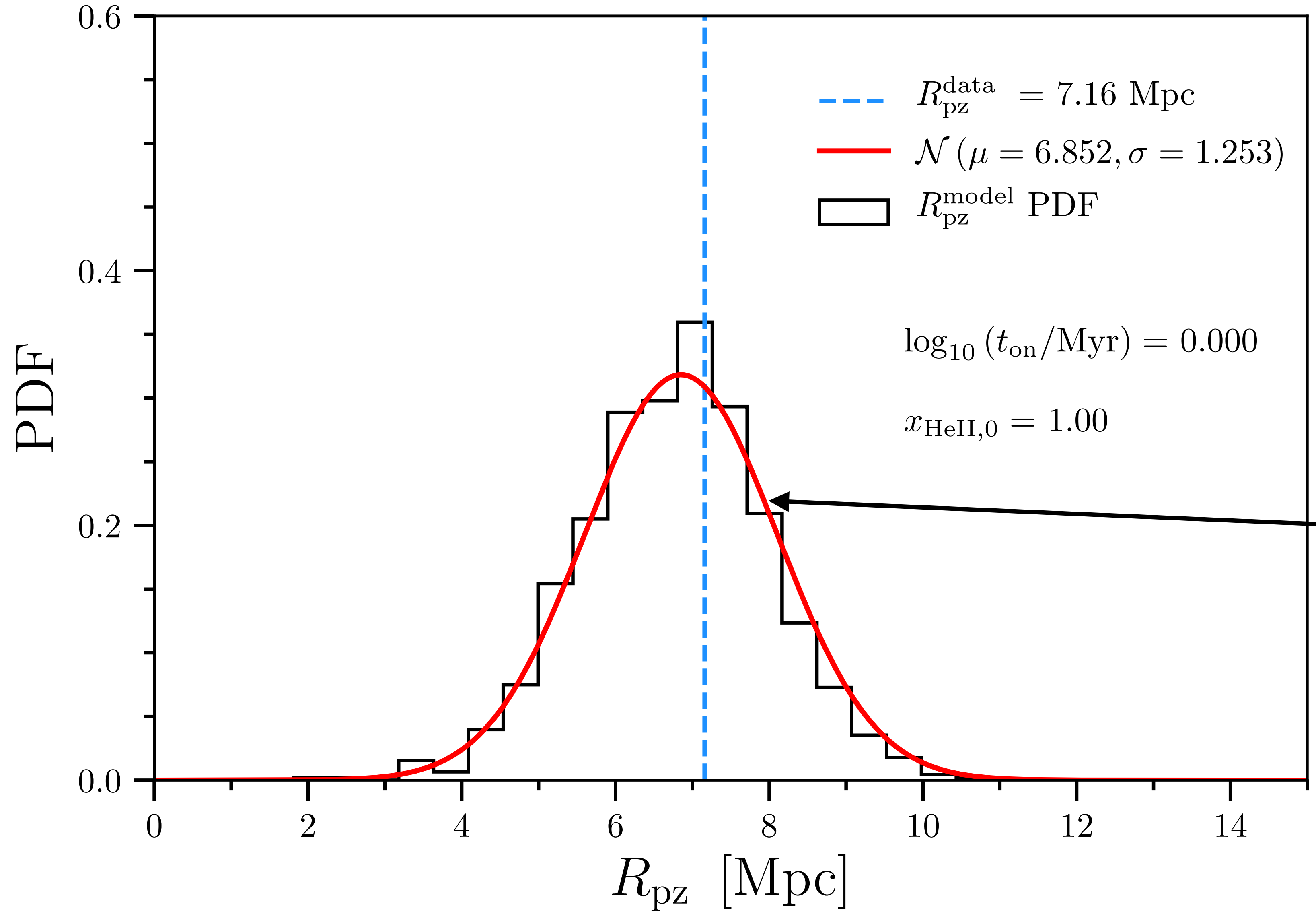
Dependence on on-time



He II Fraction Dependence



Part 2. RT simulations - distribution of proximity zone sizes



includes redshift error

Grid of 410 models (41 on-times | 10 $x_{\mathrm{HeII,0}}$ | 1000 spectra)
= 410 R_{pz} distributions per quasar

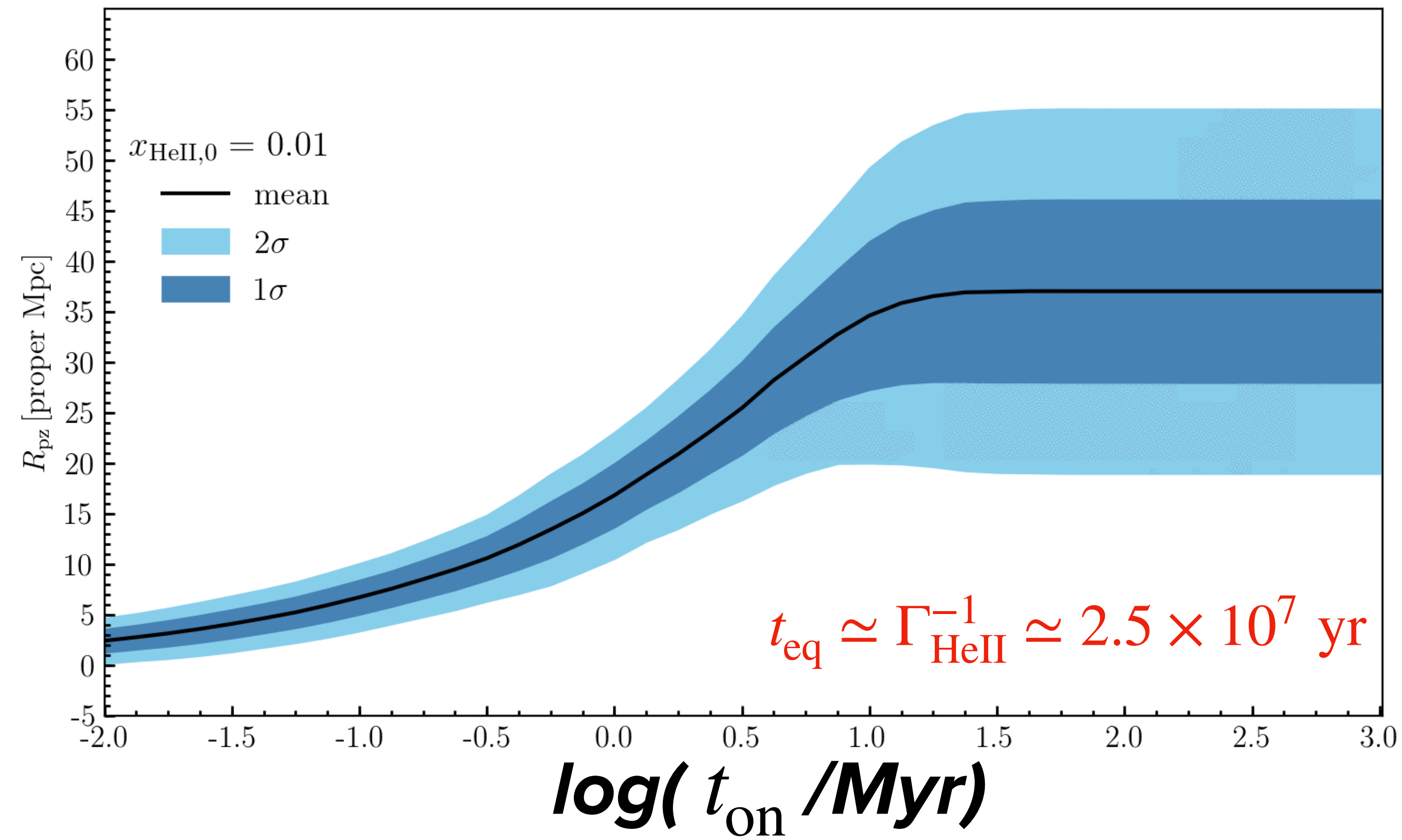
Part 2. RT simulations - distribution of proximity zone sizes

Grid of 410 models

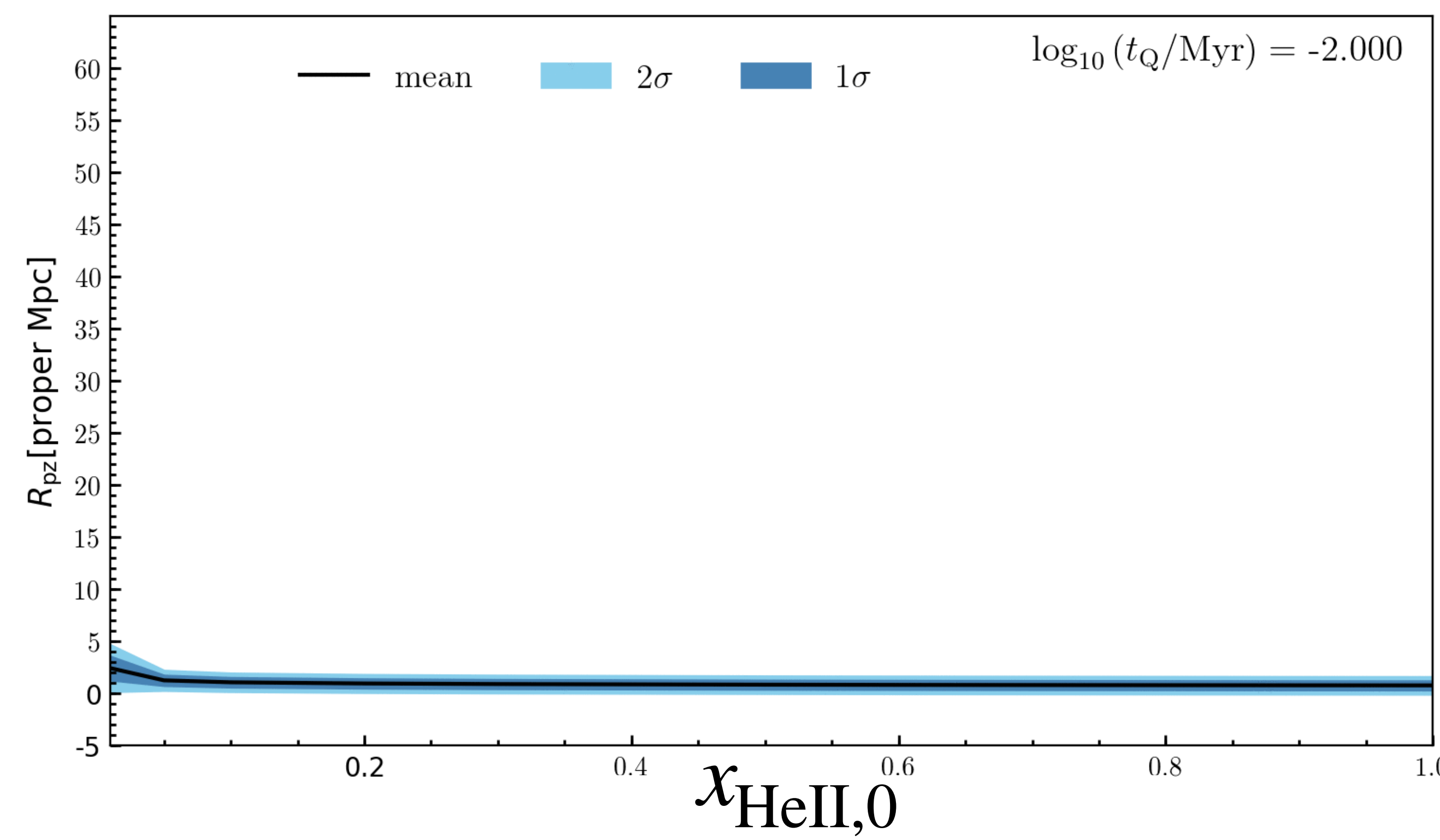
(41 on-times | 10 $x_{\mathrm{HeII,0}}$)

= 410 R_{pz} distributions

Sensitivity to quasar on-time



very little sensitivity to He II fraction under current definition of PZ



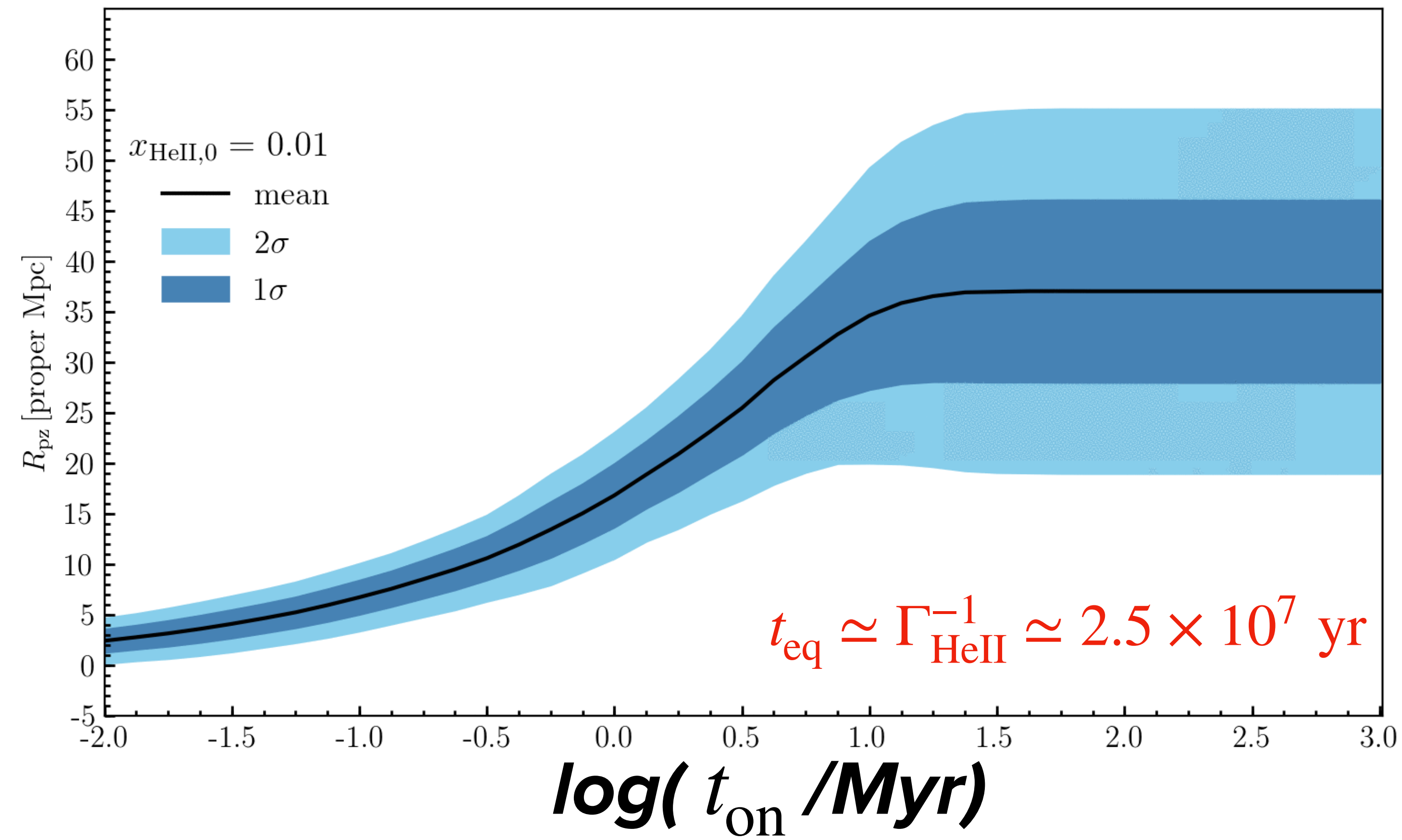
Part 2. RT simulations - distribution of proximity zone sizes

Grid of 410 models

(41 on-times | 10 $x_{\mathrm{HeII,0}}$)

= 410 R_{pz} distributions

Sensitivity to quasar on-time



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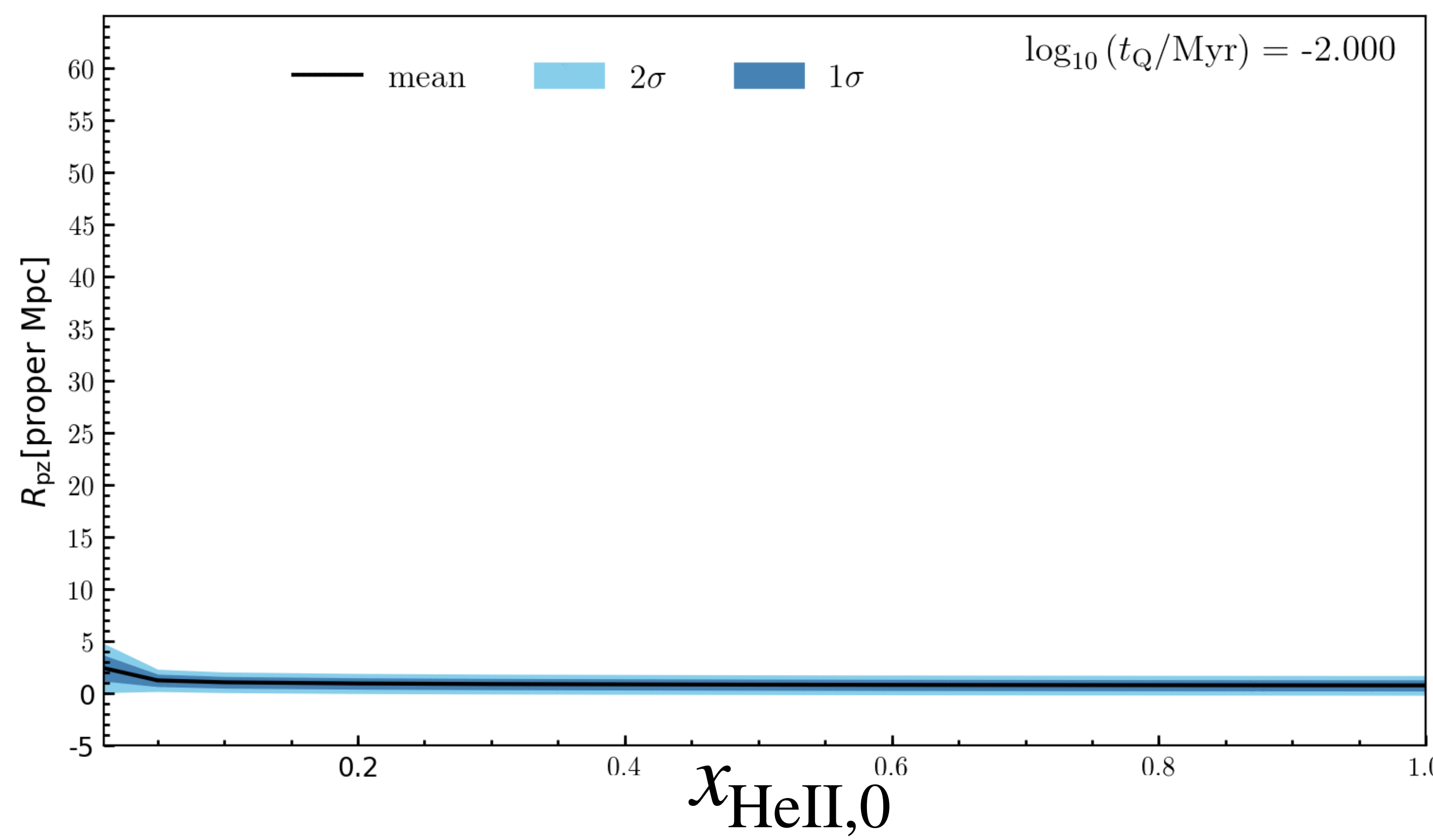

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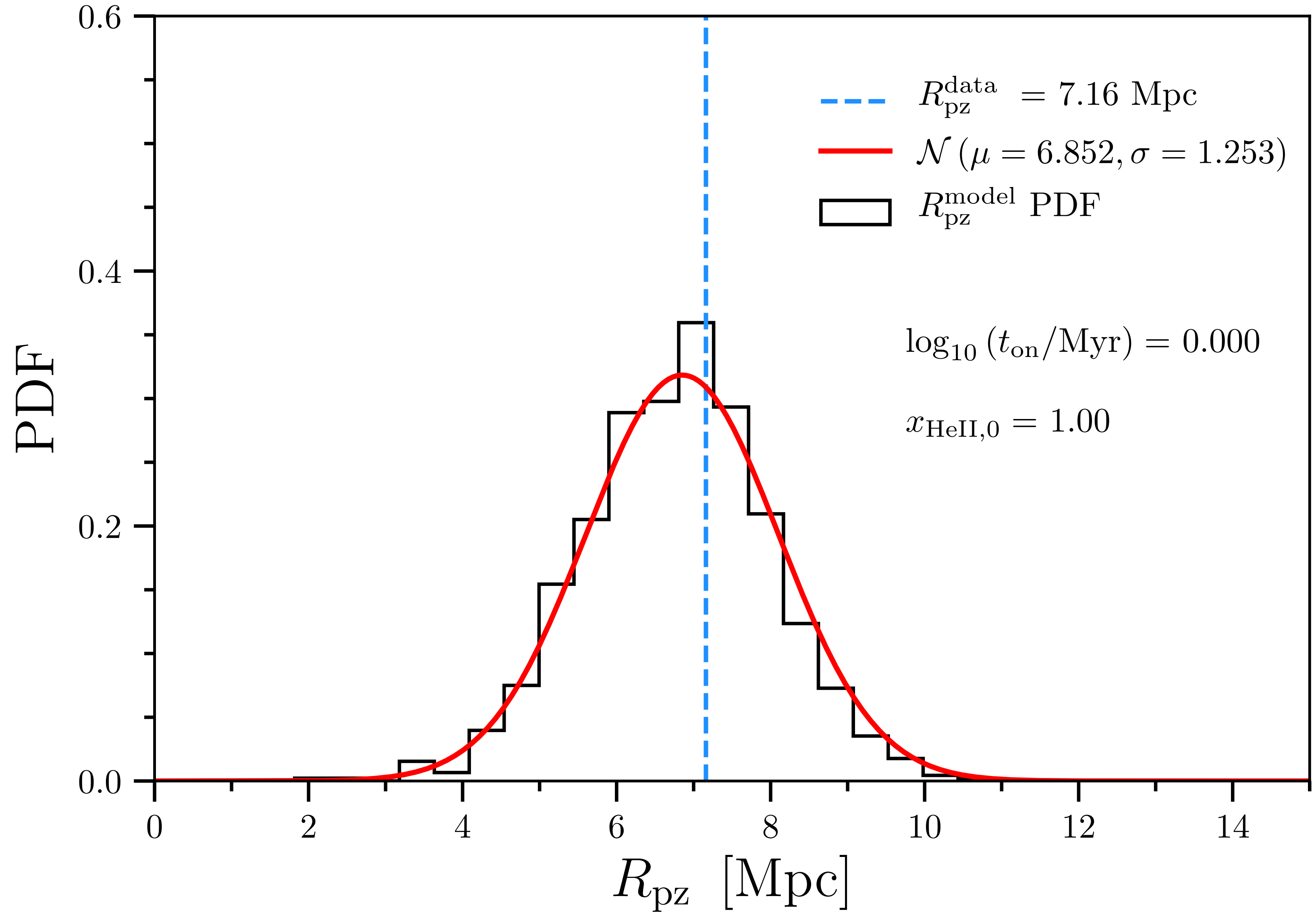

Grid of 410 models (41 on-times | 10 $x_{\rm HeII,0}$) = 410 $R_{\rm pz}$ distributions =

= 410 $\mathscr{L}\left(R_{\rm pz}^{\rm data} \,|\, \log_{10} t_{\rm on}, x_{\rm HeII,0}\right)$ per quasar

Part 3. Results.

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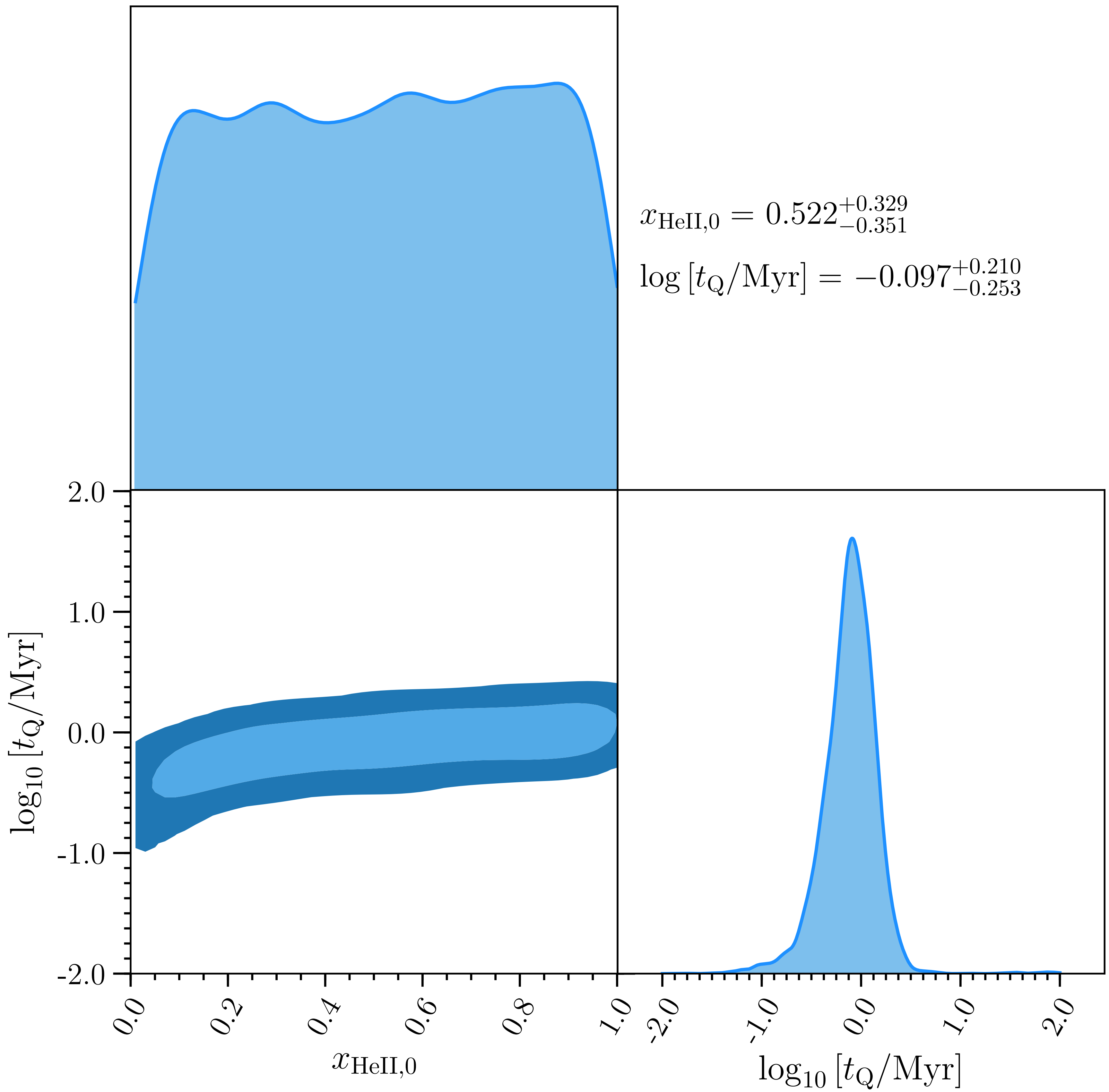
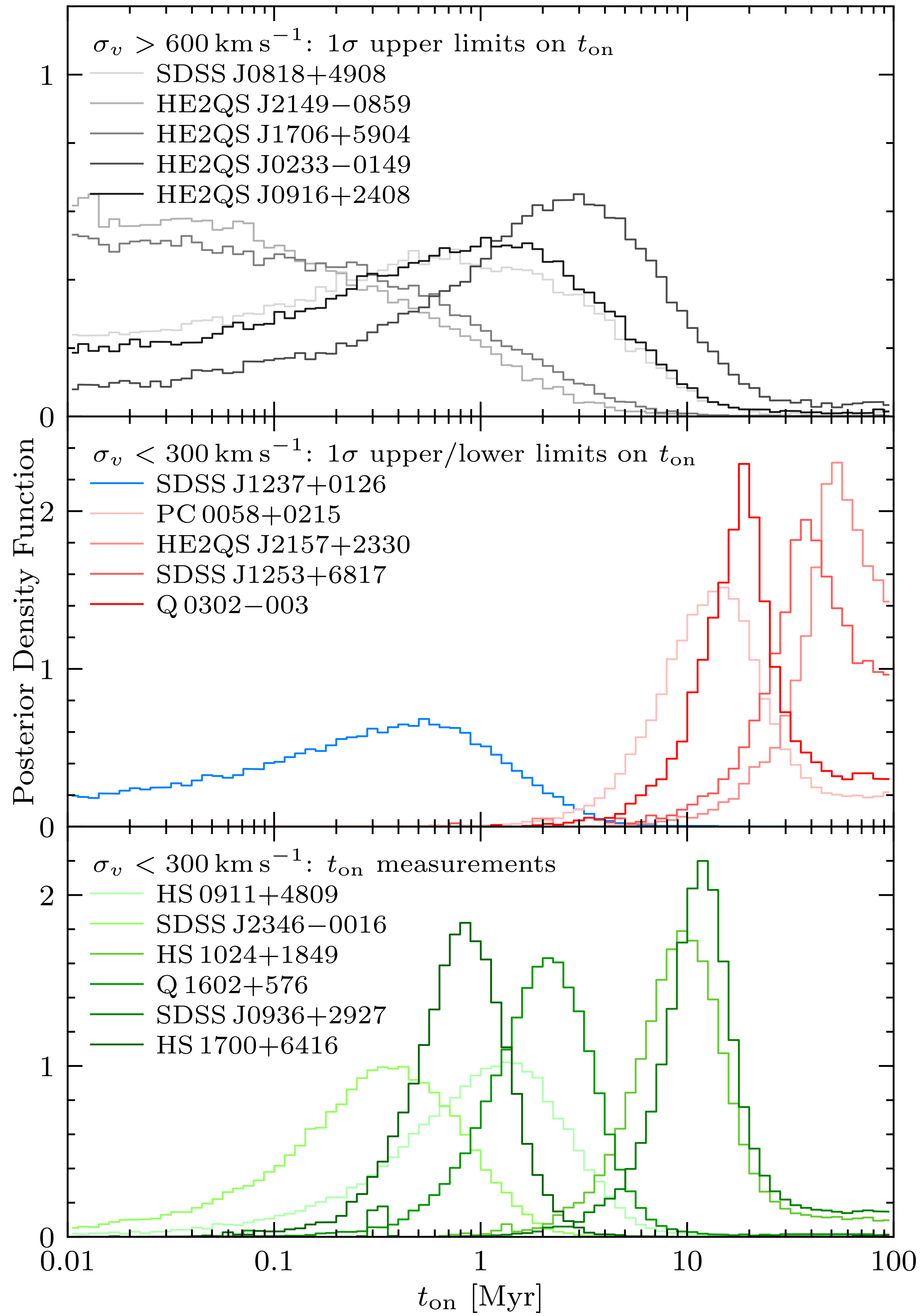
3.1 Individual measurements

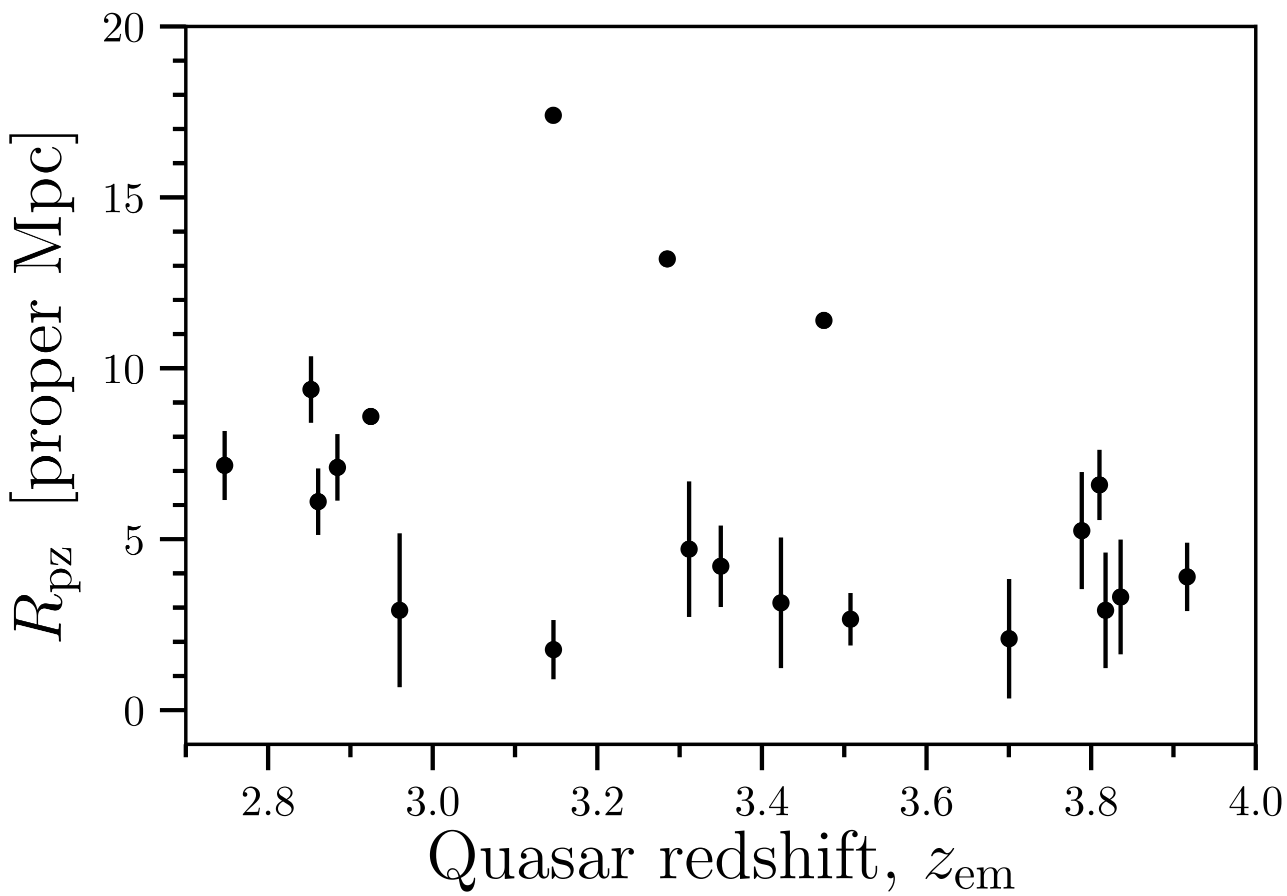
Part 3.1 Individual Measurements - MCMC Inference

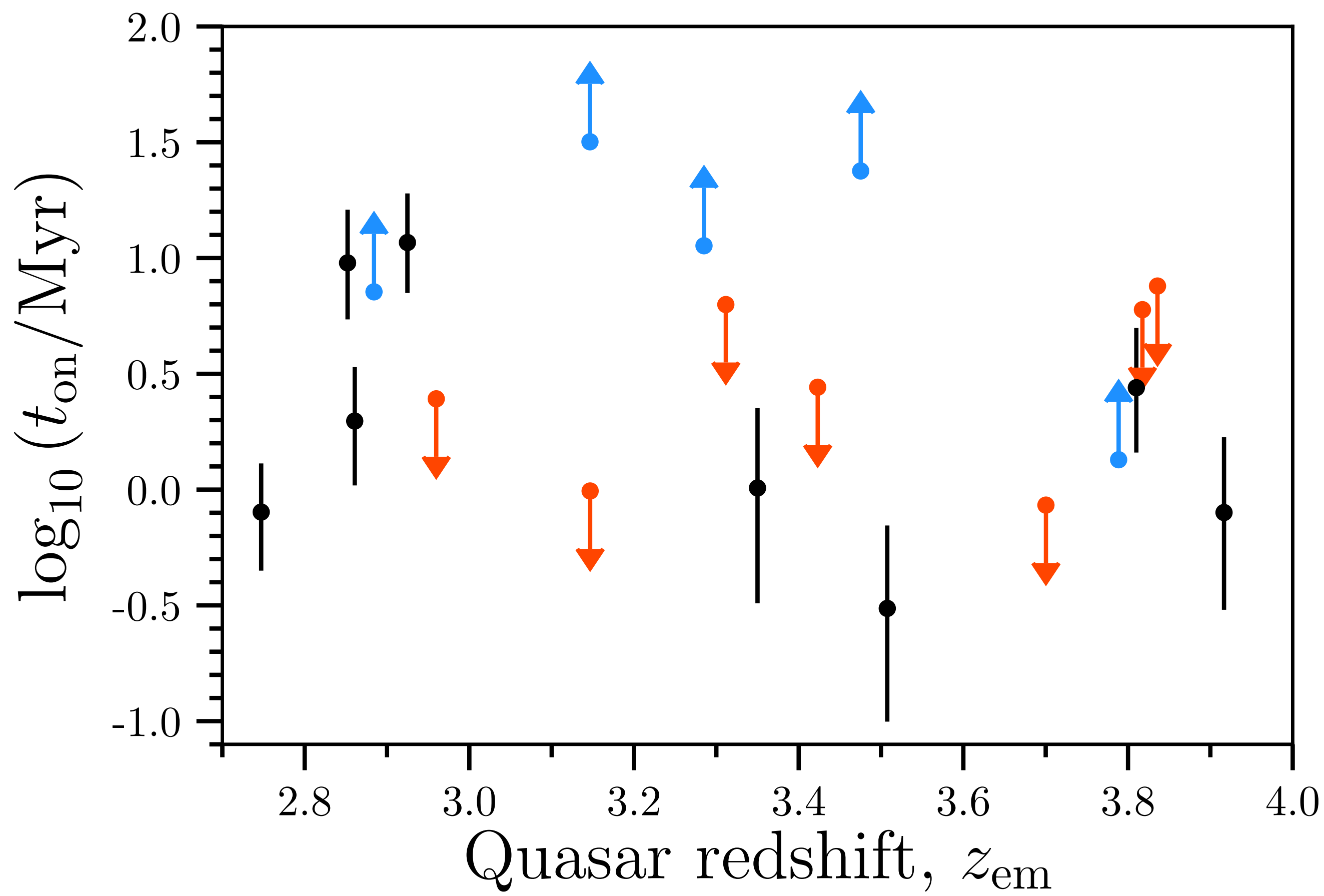


Part 3.1 Individual Measurements - MCMC Inference



Part 3.1 Individual on-times constrains



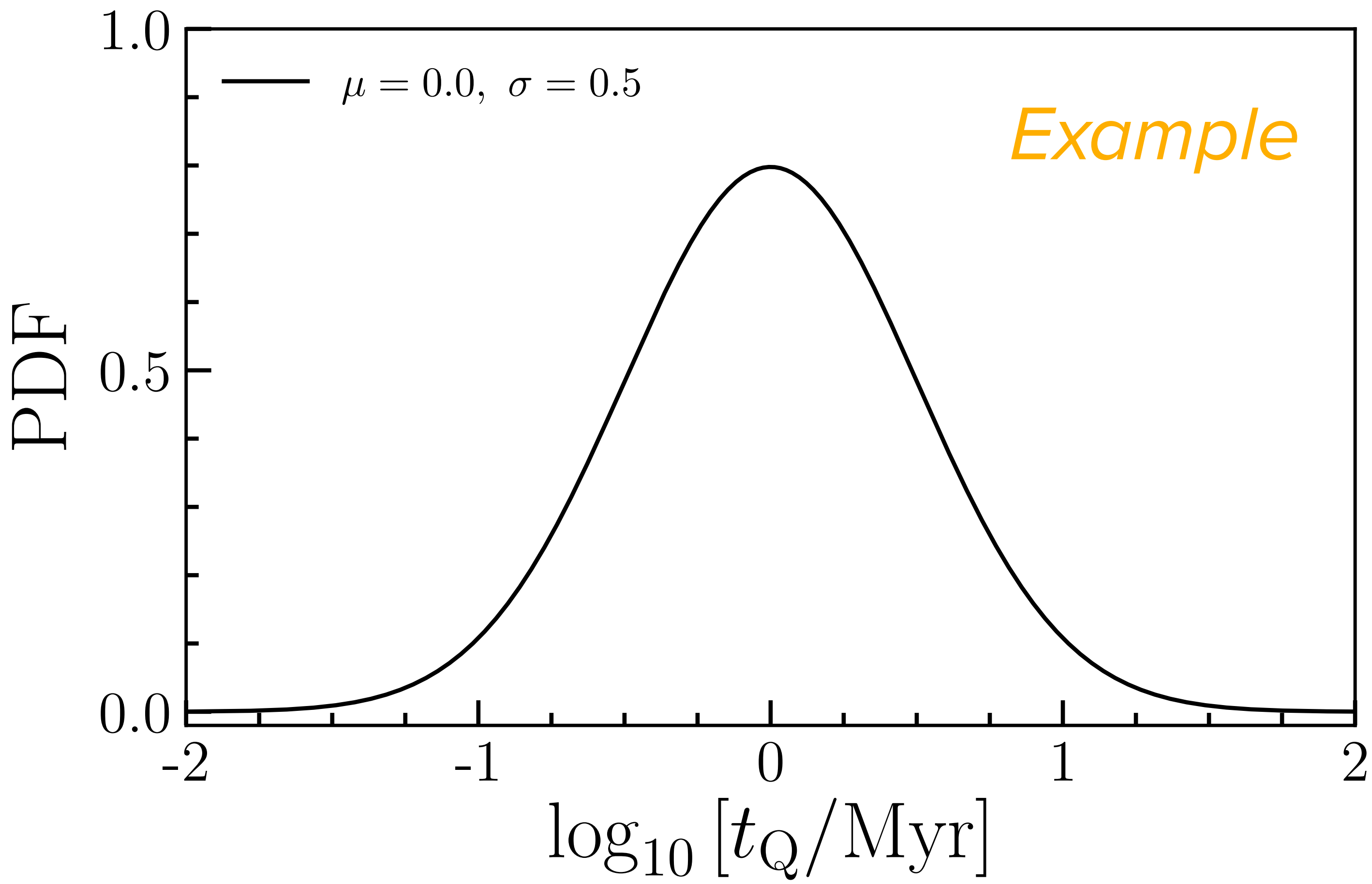


Khrykin+2019,
Worseck+ (in prep), Khrykin+ (tbs)

Part 3. Results.

3.2 Quasar Lifetimes Distribution

Part 3.2 Distribution of Lifetimes



Log-normal distribution of quasar lifetimes:

$$\mathcal{N}\left(\mu, \sigma\right)$$

$$\mu = \langle \log_{10} t_{\rm Q} \rangle$$

$$\sigma = \sigma_{\log_{10} t_{\rm Q}}$$

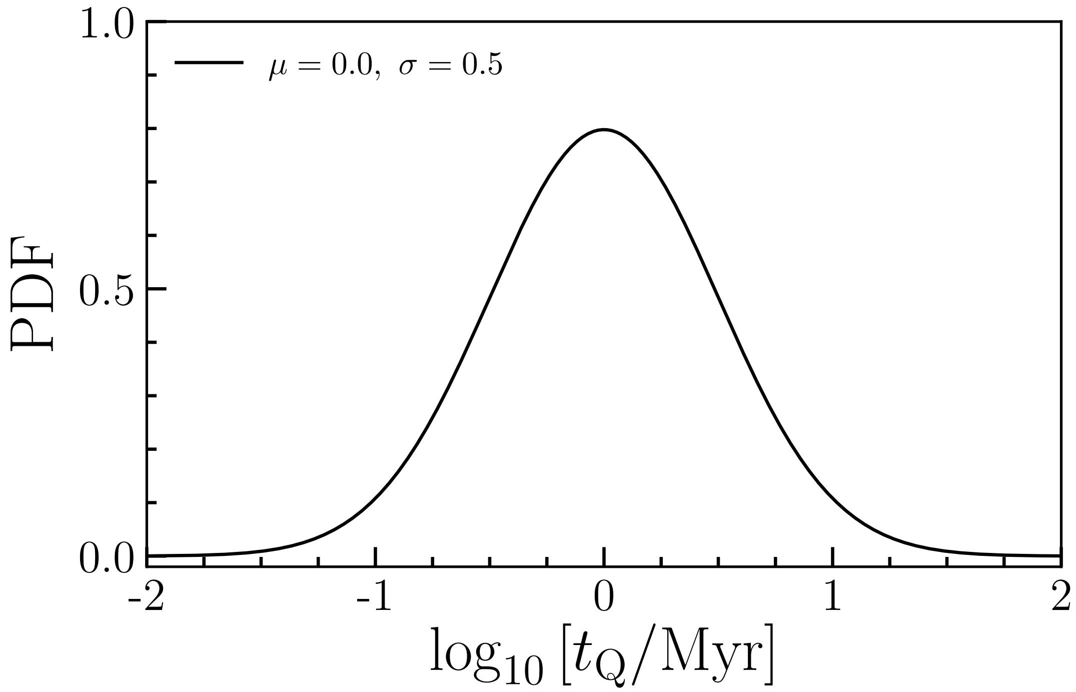
Parameter grid

$$\mu = \langle \log_{10} t_{\rm Q} \rangle \in \left[-2.000, 2.000\right],\ \Delta = 0.125$$

$$\sigma = \sigma_{\log_{10} t_{\rm Q}} \in \left[0.01, 3.0\right], \Delta = 0.1$$

Part 3.2 Distribution of Lifetimes - likelihood calculations

QLD



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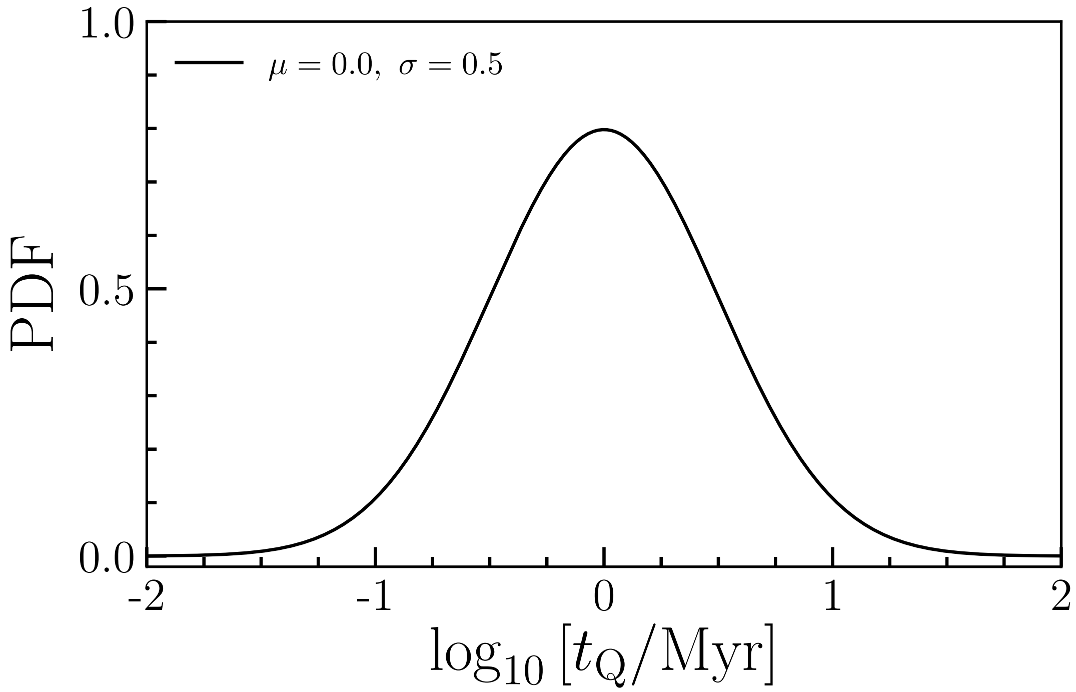

0. Choose $\{\langle \log_{10} t_{\mathrm{Q}} \rangle; \sigma_{\log_{10} t_{\mathrm{Q}}}\}$

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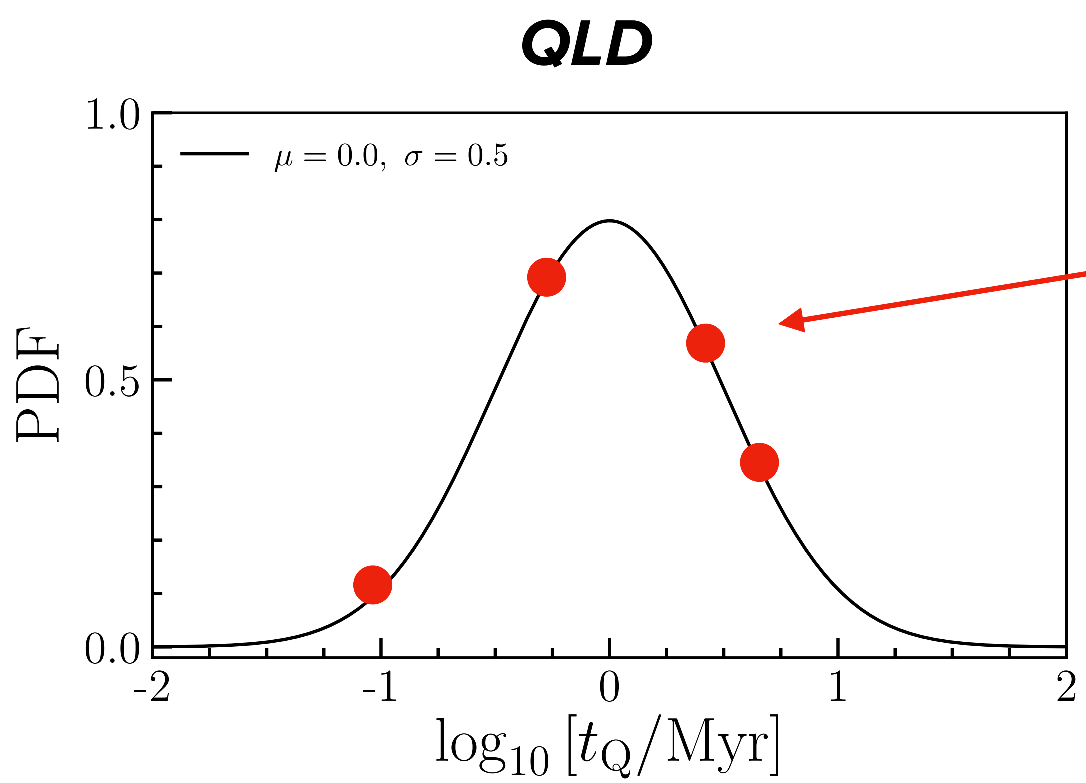
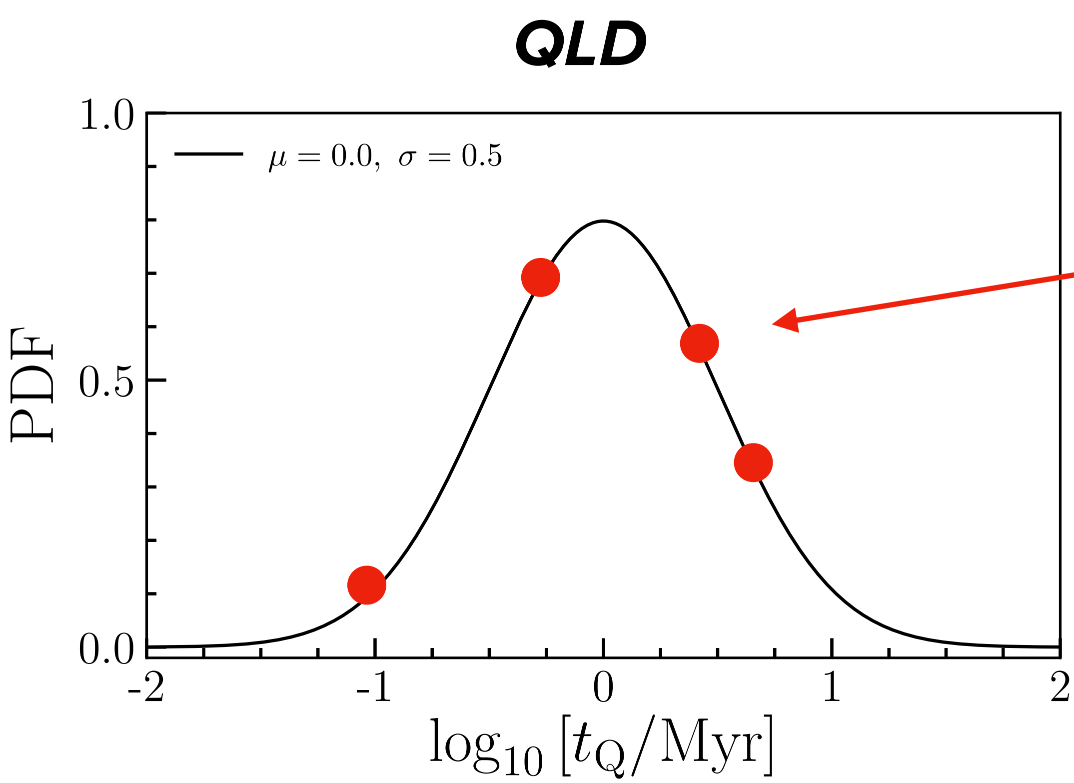


0. Choose $\{\langle \log_{10} t_{\rm Q} \rangle; \sigma_{\log_{10} t_{\rm Q}}\}$

1. Sample QLD: draw N=1000 $\log_{10} t_{\rm Q}$ *values*

Part 3.2 Distribution of Lifetimes - likelihood calculations



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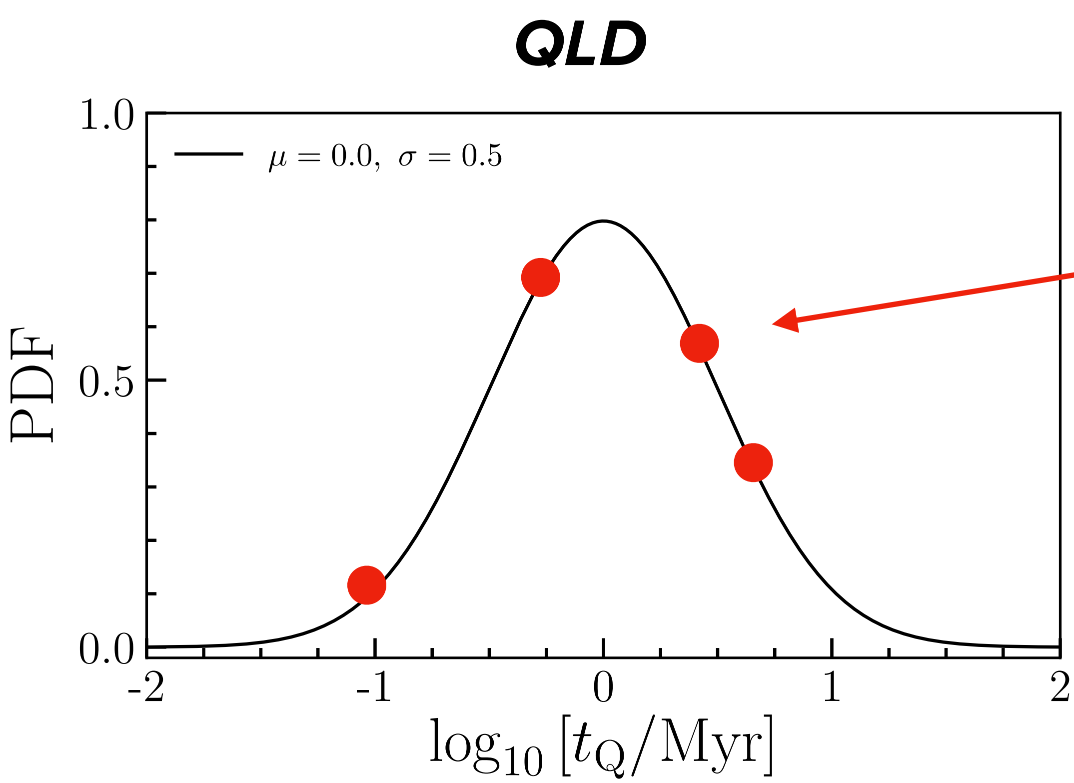

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3. Get 10000 $x_{\rm HeII,0}$ by Monte-Carlo sampling of Davies+2017 model at z in question.

Part 3.2 Distribution of Lifetimes - likelihood calculations

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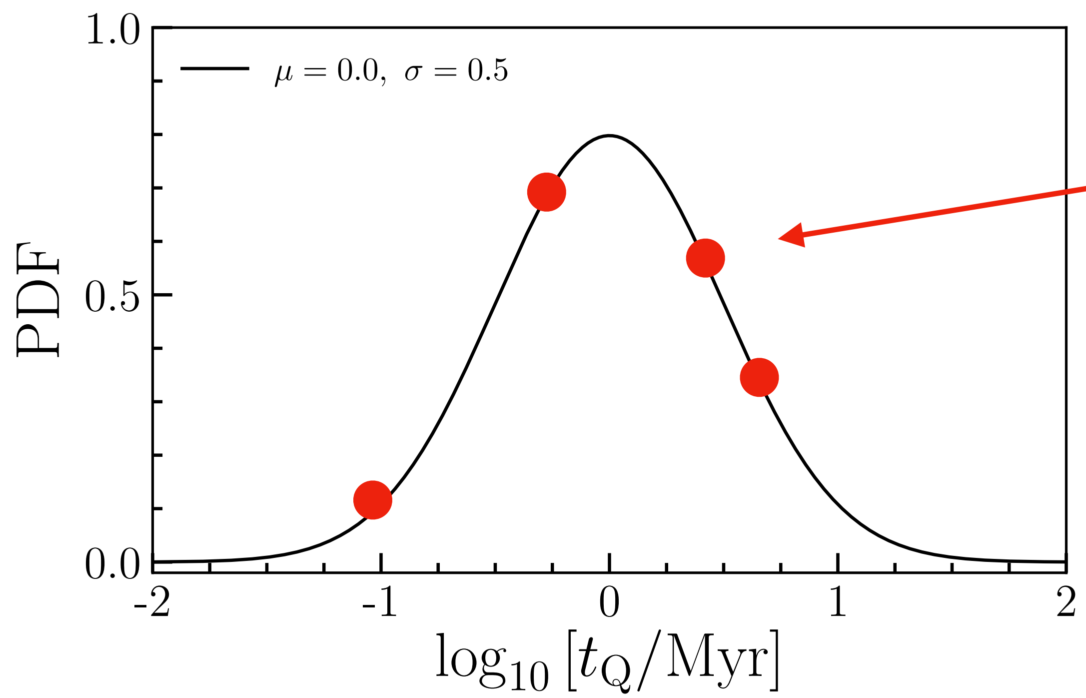


0. Choose $\{\langle \log_{10} t_Q \rangle ; \sigma_{\log_{10} t_Q}\}$

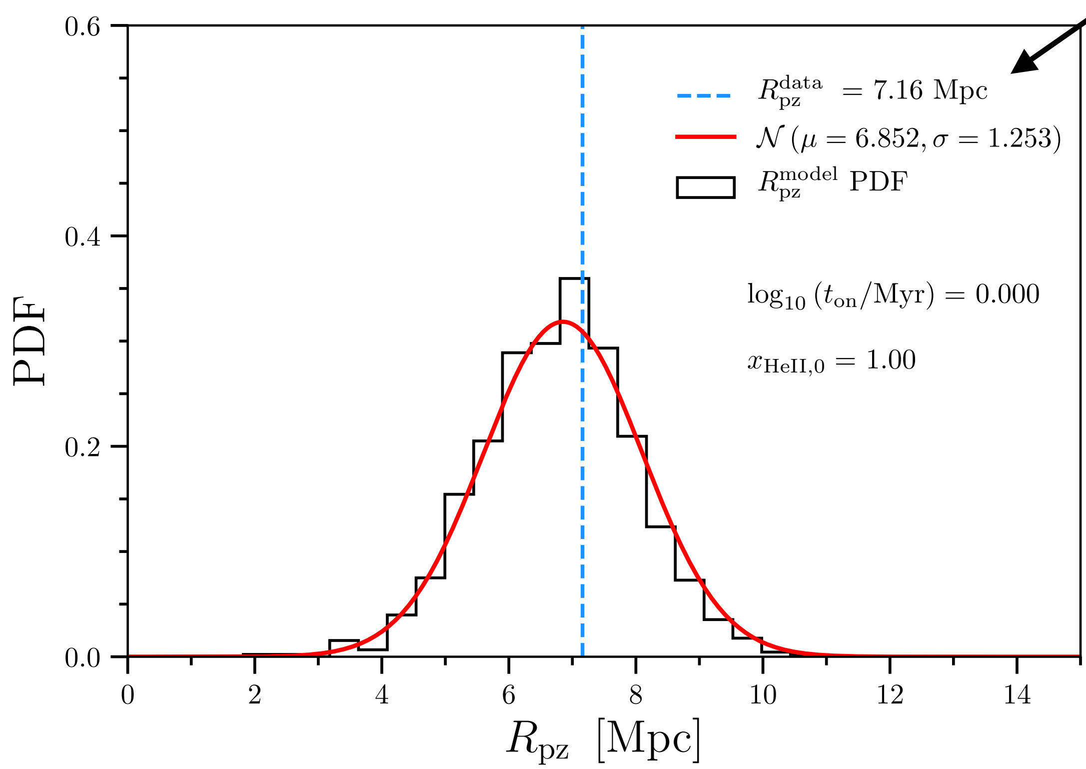
1. Sample QLD: draw N=1000 $\log_{10} t_Q$ *values*

2. Get on-times by sampling each $\log_{10} t_Q$ *value:* $t_{\mathrm{on}} = \mathscr{U}\left[0, t_Q\right]$

3. Get 10000 $x_{\mathrm{HeII,0}}$ *by Monte-Carlo sampling of Davies+2017 model at z in question.*

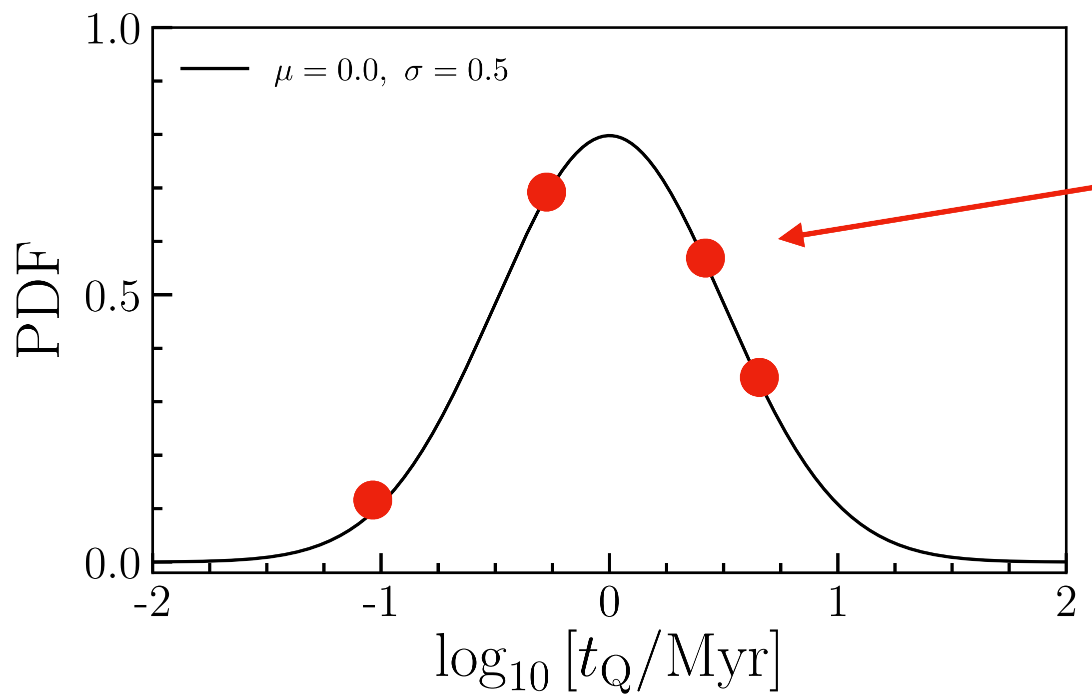
4. For each t_{on} *and* $x_{\mathrm{HeII,0}}$ *find corresponding distribution of the PZ sizes*

PZ size distribution

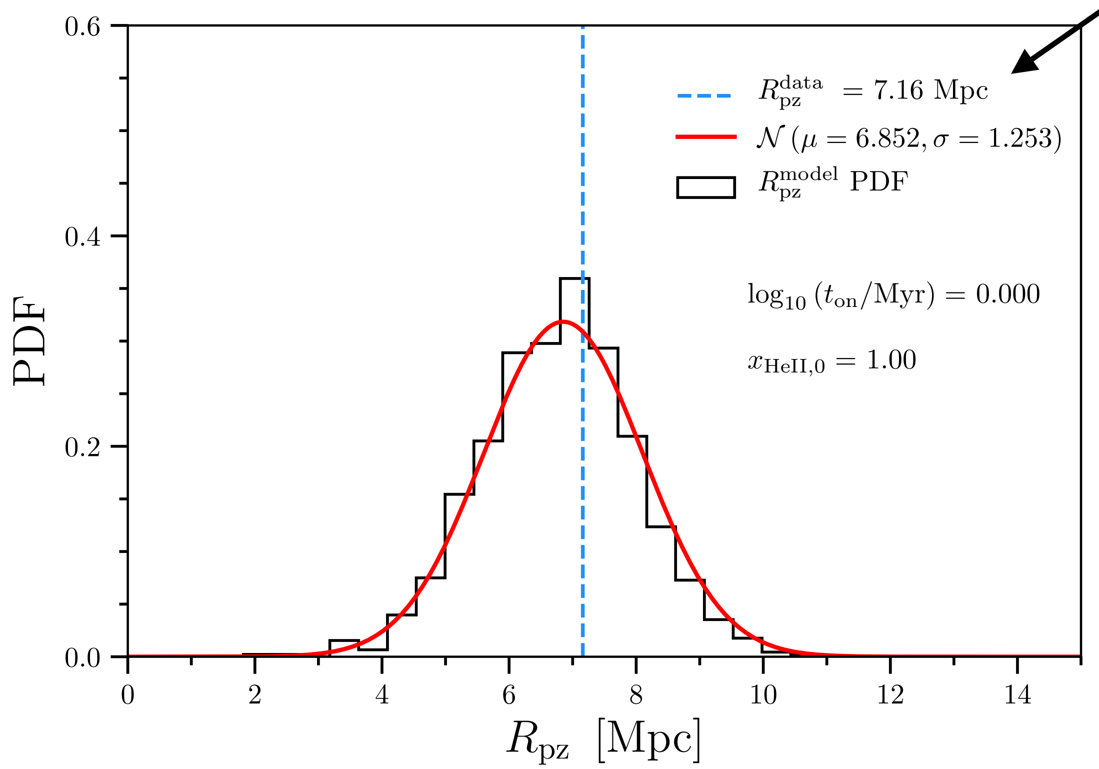


Part 3.2 Distribution of Lifetimes - likelihood calculations

QLD



PZ size distribution



0. Choose $\{\langle \log_{10} t_Q \rangle ; \sigma_{\log_{10} t_Q}\}$

1. Sample QLD: draw N=1000 $\log_{10} t_Q$ *values*

2. Get on-times by sampling each $\log_{10} t_Q$ *value:* $t_{\mathrm{on}} = \mathcal{U}\left[0, t_Q\right]$

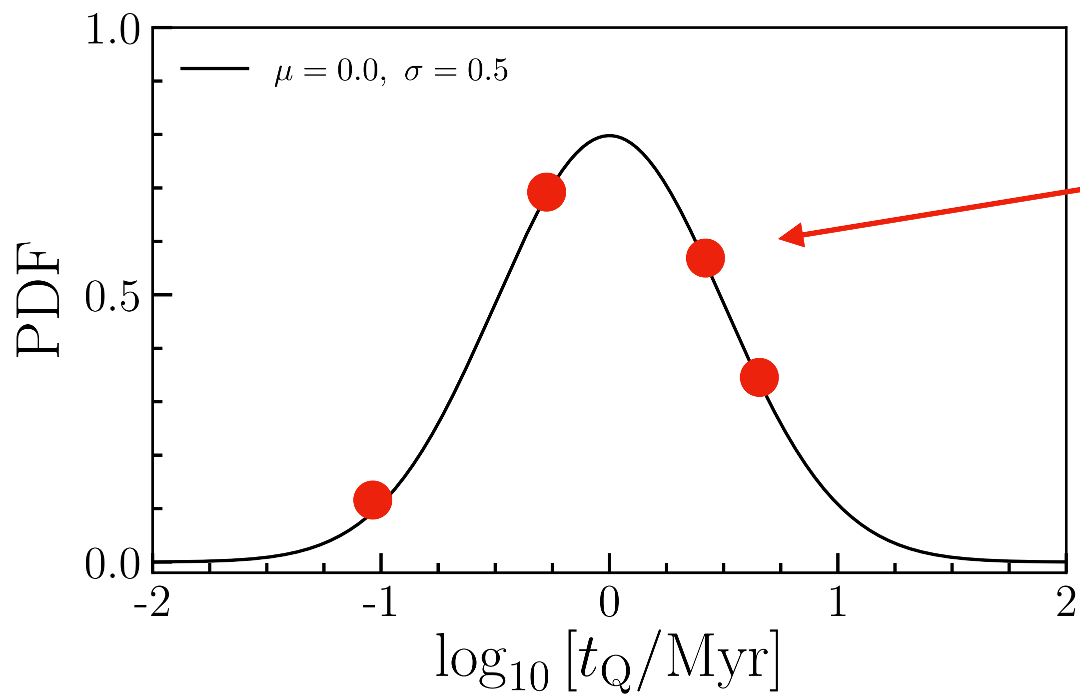
3. Get 10000 $x_{\mathrm{HeII,0}}$ *by Monte-Carlo sampling of Davies+2017 model at z in question.*

4. For each t_{on} *and* $x_{\mathrm{HeII,0}}$ *find corresponding distribution of the PZ sizes*

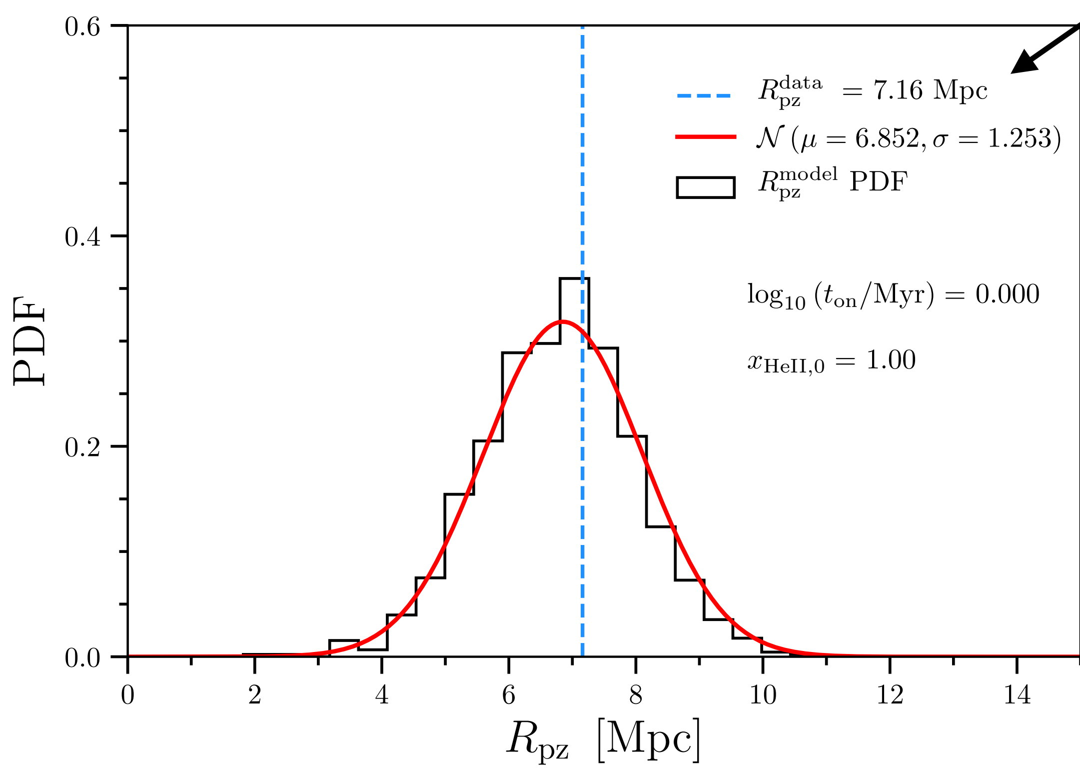
5. Draw 500 R_{pz} *values, combine them in a joint distribution. Fit joint distribution with KDE and evaluate at the* $R_{\mathrm{pz}}^{\mathrm{data}}$ *of quasar in question.*

Part 3.2 Distribution of Lifetimes - likelihood calculations

QLD



PZ size distribution



0. Choose $\{\langle \log_{10} t_{\rm Q}\rangle; \sigma_{\log_{10} t_{\rm Q}}\}$

1. Sample QLD: draw N=1000 $\log_{10} t_{\rm Q}$ values

2. Get on-times by sampling each $\log_{10} t_{\rm Q}$ value: $t_{\rm on} = \mathcal{U}\left[0, t_{\rm Q}\right]$

3. Get 10000 $x_{\rm HeII,0}$ by Monte-Carlo sampling of Davies+2017 model at z in question.

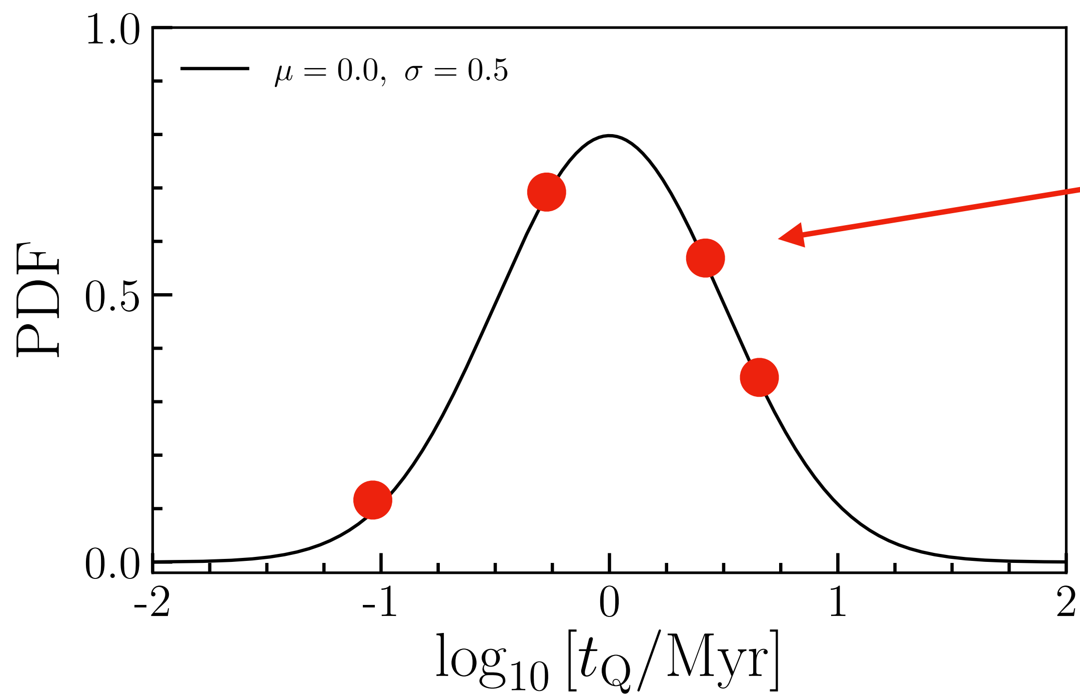
4. For each $t_{\rm on}$ and $x_{\rm HeII,0}$ find corresponding distribution of the PZ sizes

5. Draw 500 $R_{\rm pz}$ values, combine them in a joint distribution. Fit joint distribution with KDE and evaluate at the $R_{\rm pz}^{\rm data}$ of quasar in question.

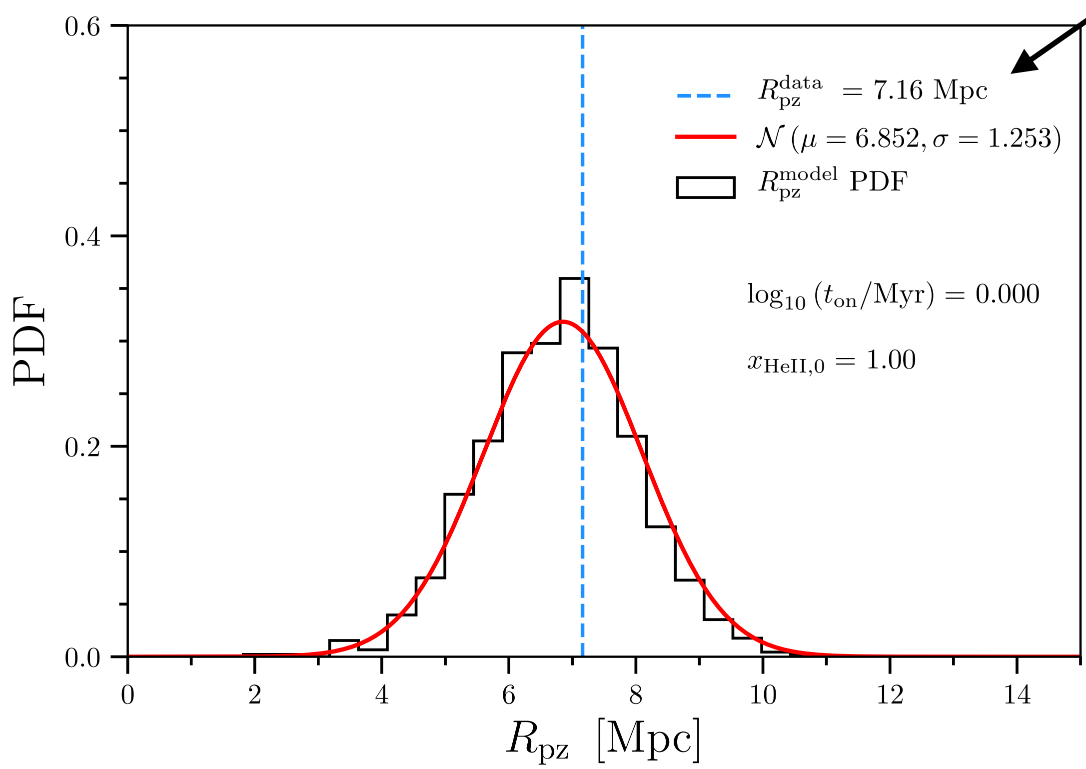
6. Repeat for each combination of $\{\langle \log_{10} t_{\rm Q}\rangle; \sigma_{\log_{10} t_{\rm Q}}\}$

Part 3.2 Distribution of Lifetimes - likelihood calculations

QLD



PZ size distribution



0. Choose $\{\langle\log_{10}t_Q\rangle; \sigma_{\log_{10}t_Q}\}$

1. Sample QLD: draw N=1000 $\log_{10}t_Q$ *values*

2. Get on-times by sampling each $\log_{10}t_Q$ *value:* $t_{on} = \mathcal{U}\left[0, t_Q\right]$

3. Get 10000 $x_{HeII,0}$ *by Monte-Carlo sampling of Davies+2017 model at z in question.*

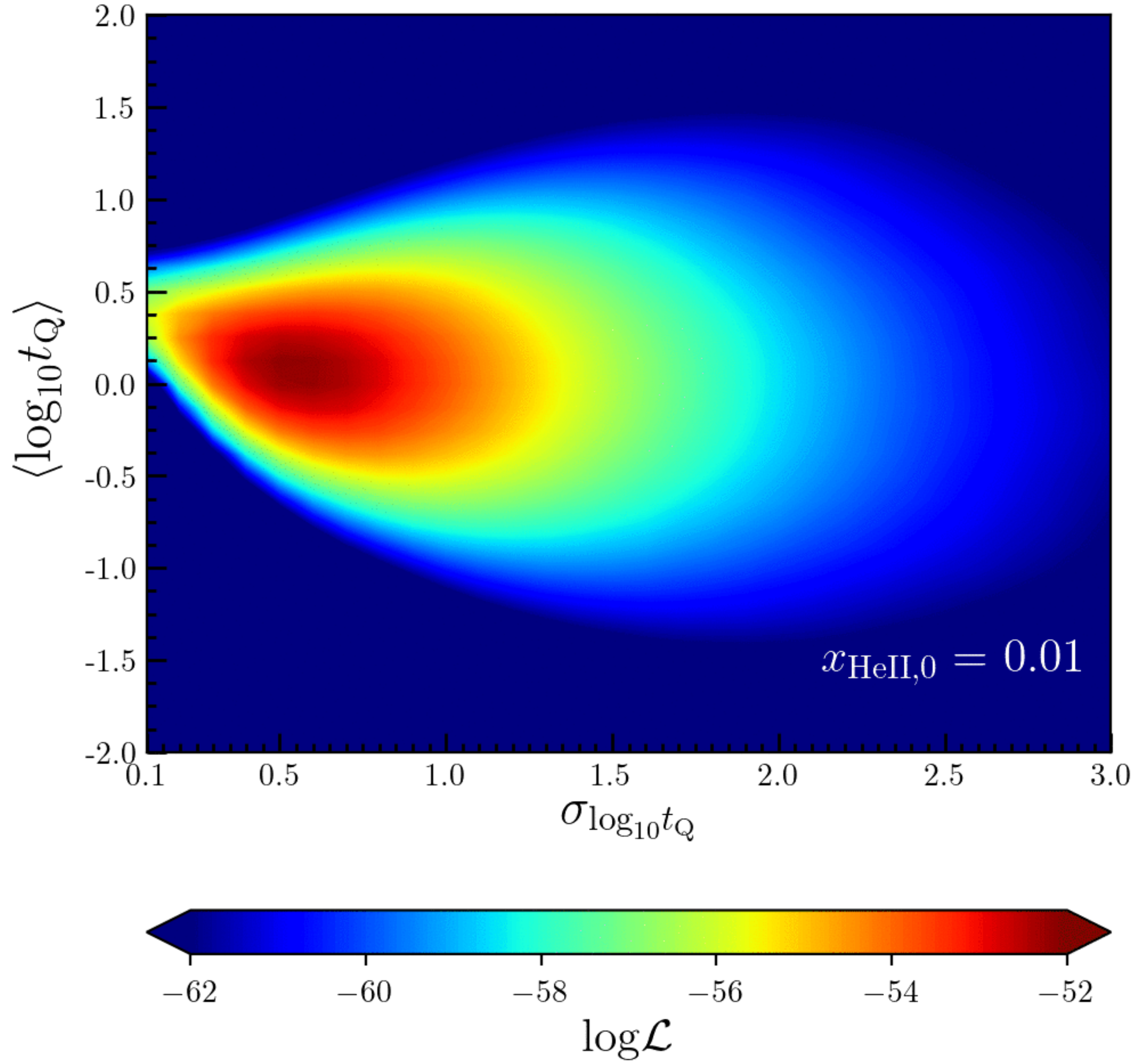
4. For each t_{on} *and* $x_{HeII,0}$ *find corresponding distribution of the PZ sizes*

5. Draw 500 R_{pz} *values, combine them in a joint distribution. Fit joint distribution with KDE and evaluate at the* R_{pz}^{data} *of quasar in question.*

6. Repeat for each combination of $\{\langle\log_{10}t_Q\rangle; \sigma_{\log_{10}t_Q}\}$

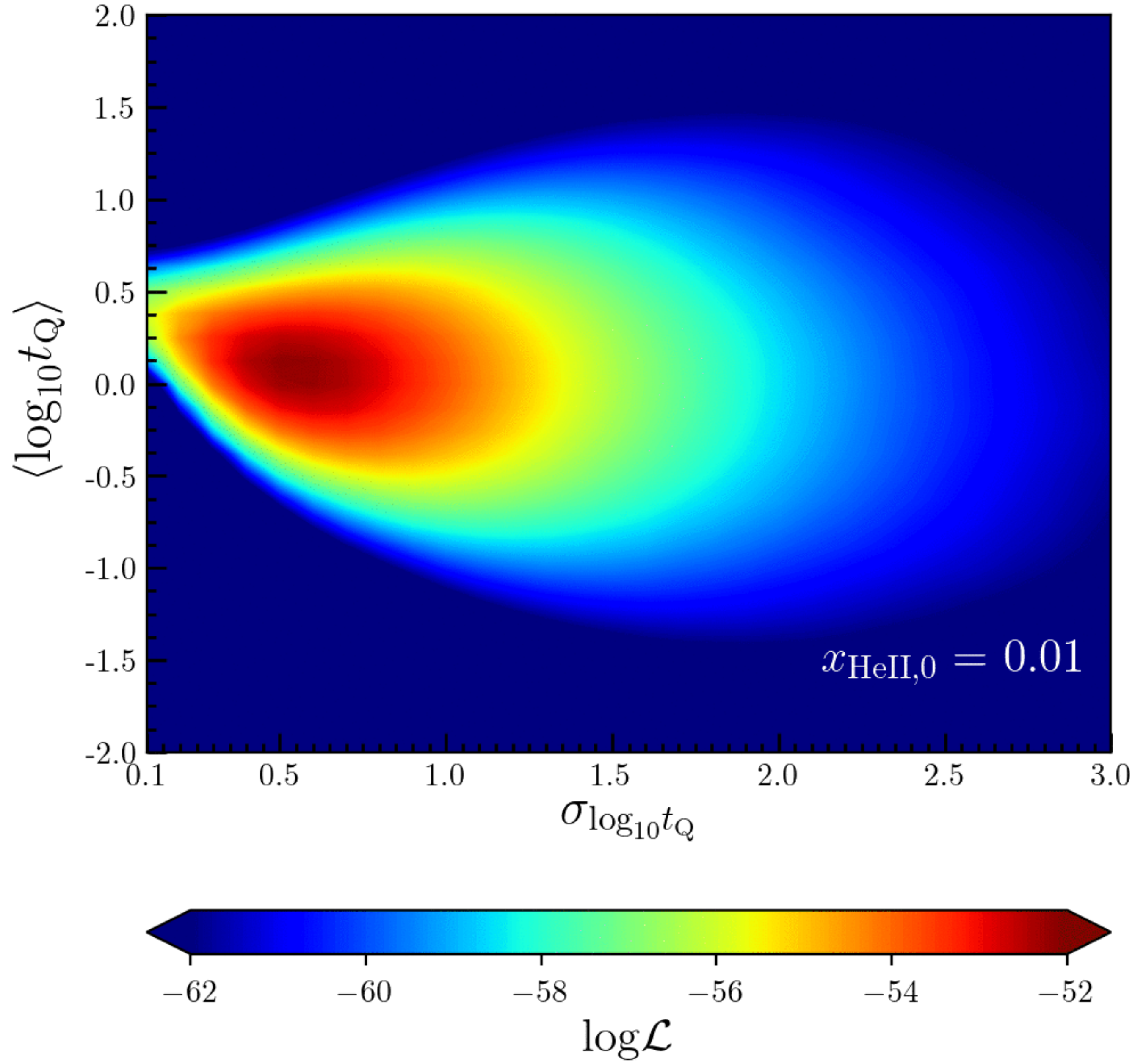
Result: 990 likelihood values per quasar

Part 3.2 Distribution of Lifetimes - joint likelihood



$$\mathcal{L}_{\rm joint} = f\left(R_{\rm pz}^{\rm data}\right) = \prod_{i=0}^{N_{\rm qso}} \mathcal{L}_{\rm qso}\left(R_{{\rm pz},i}^{\rm data} | \langle \log_{10} t_{\rm Q} \rangle, \sigma_{\log_{10} t_{\rm Q}}\right)$$

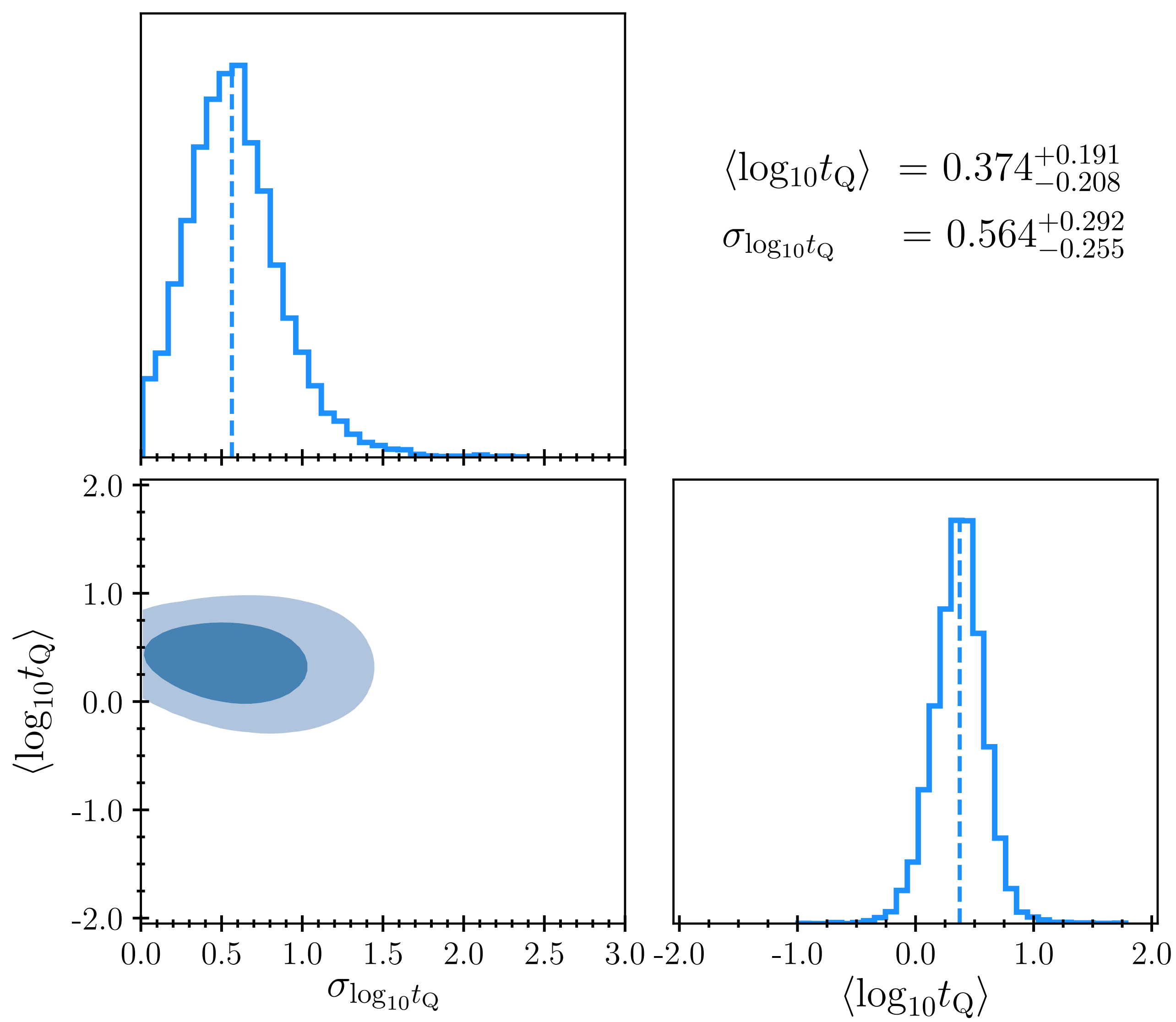
Part 3.2 Distribution of Lifetimes - joint likelihood



$$\mathcal{L}_{\mathrm{joint}} = f\left(R_{\mathrm{pz}}^{\mathrm{data}}\right) = \prod_{i=0}^{N_{\mathrm{qso}}} \mathcal{L}_{\mathrm{qso}}\left(R_{\mathrm{pz},i}^{\mathrm{data}} | \langle \log_{10} t_{\mathrm{Q}} \rangle, \sigma_{\log_{10} t_{\mathrm{Q}}}\right)$$

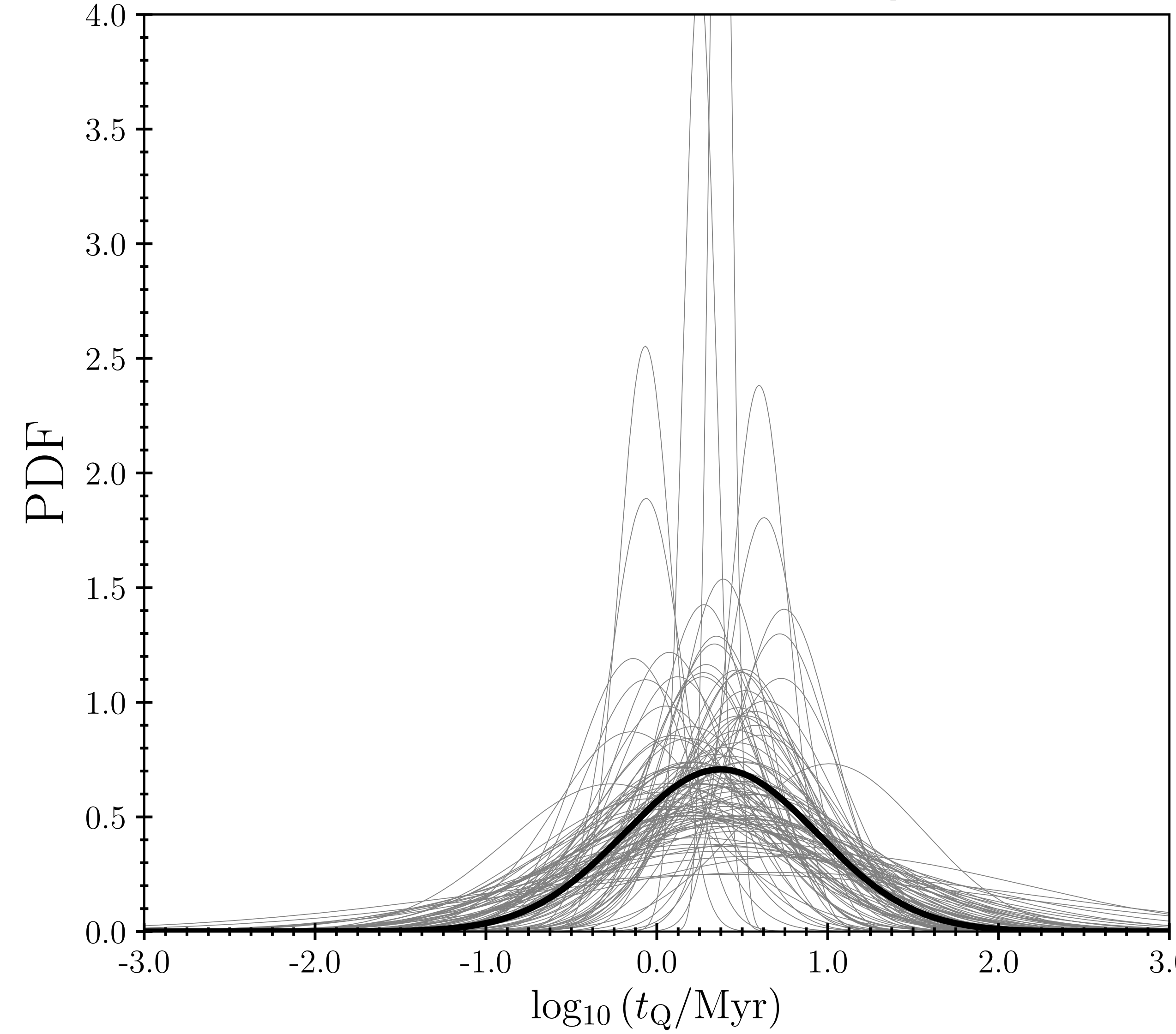
Part 3.2 Distribution of Lifetimes - MCMC Inference

standard deviation of the QLD



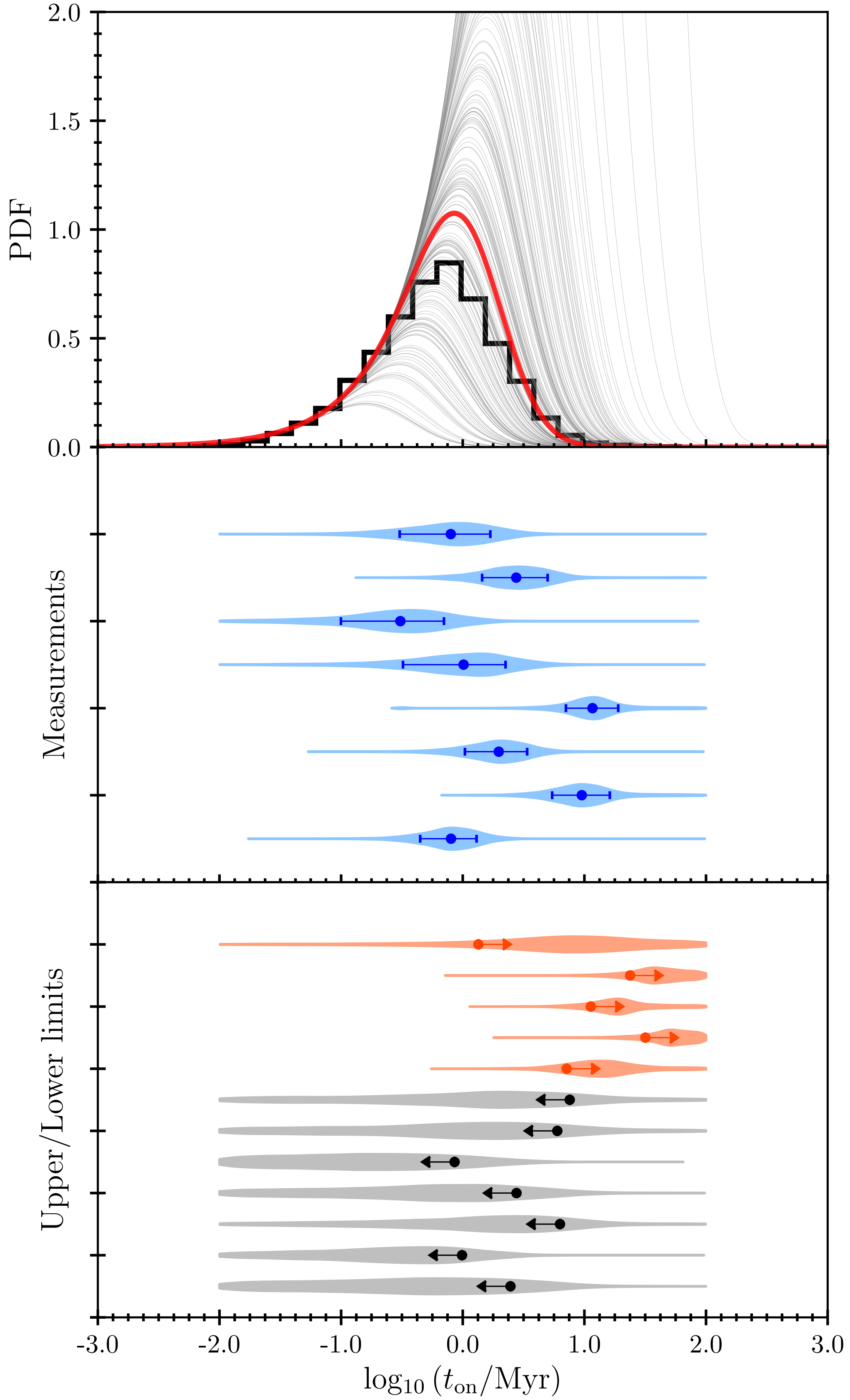
mean of the QLD

100 QLD realizations from MCMC samples



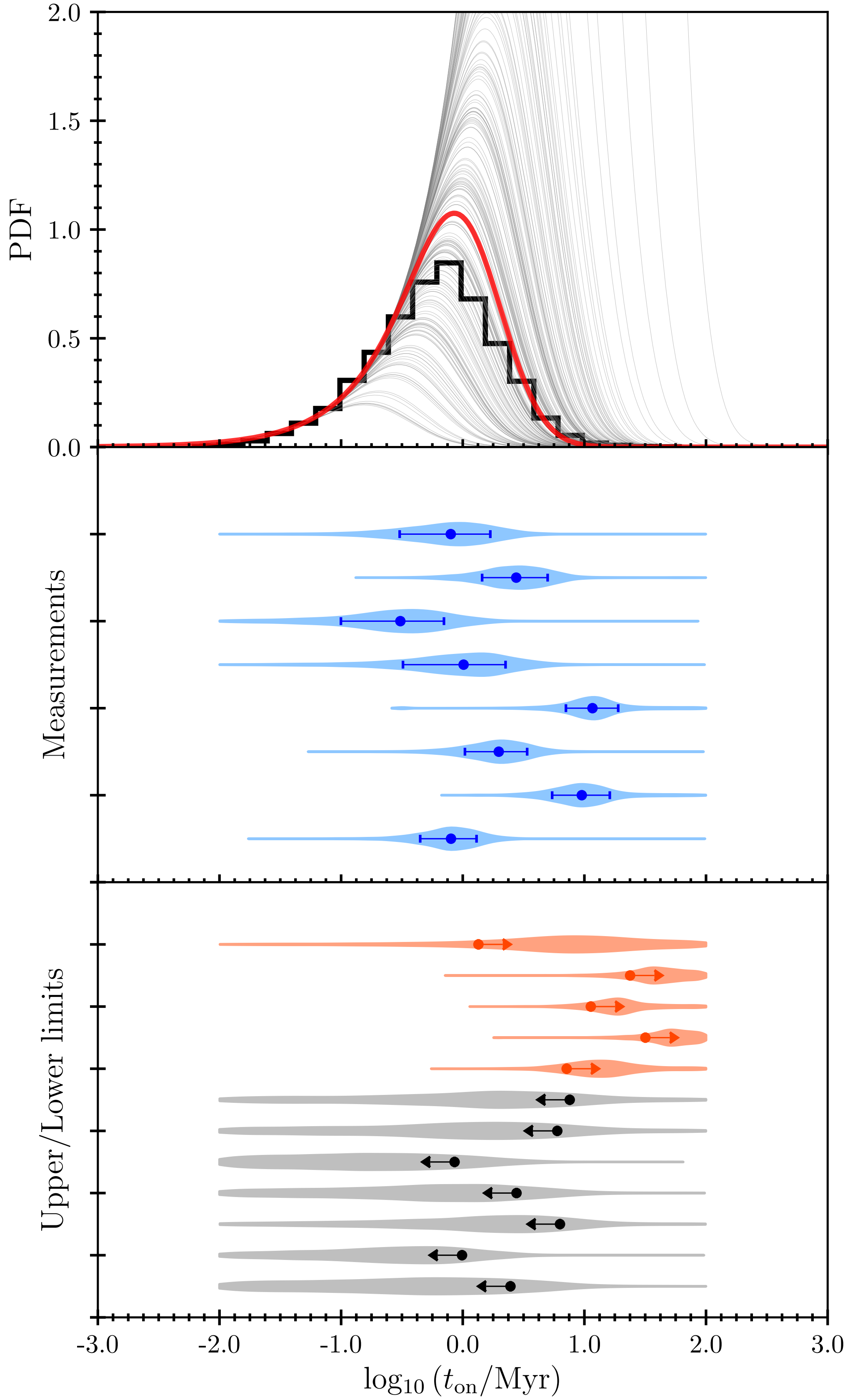
Khrykin+ (tbs)

Part 3.2 Distribution of on-times



Khrykin+ (tbs)

Part 3.2 Distribution of on-times

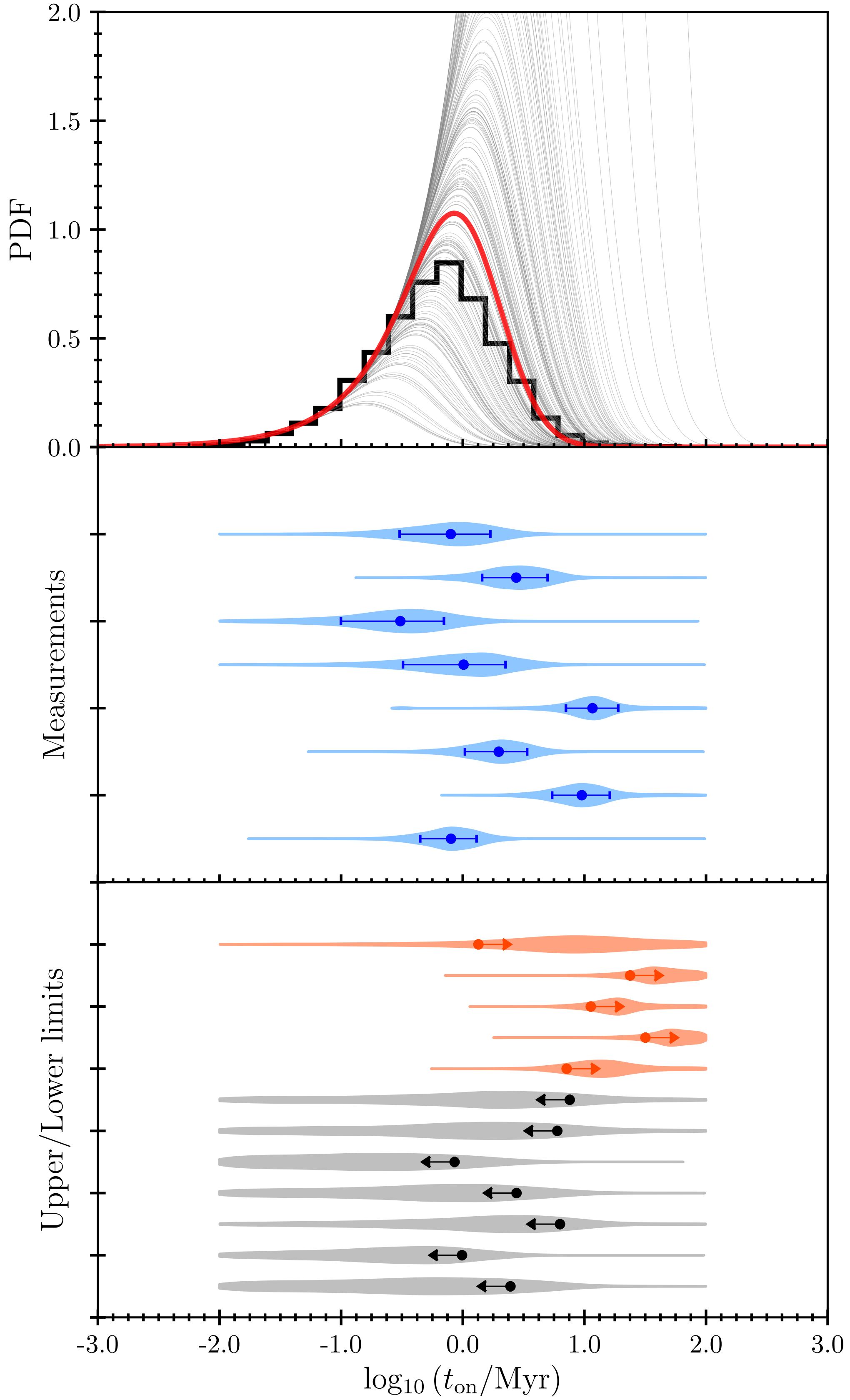


Probability of finding a quasar younger than 1000,000 yrs

Eilers+2020: $P\left(\leq 10^5 \text{ yrs}\right) \simeq 0.05 - 0.10$

Khrykin+ (tbs)

Part 3.2 Distribution of on-times



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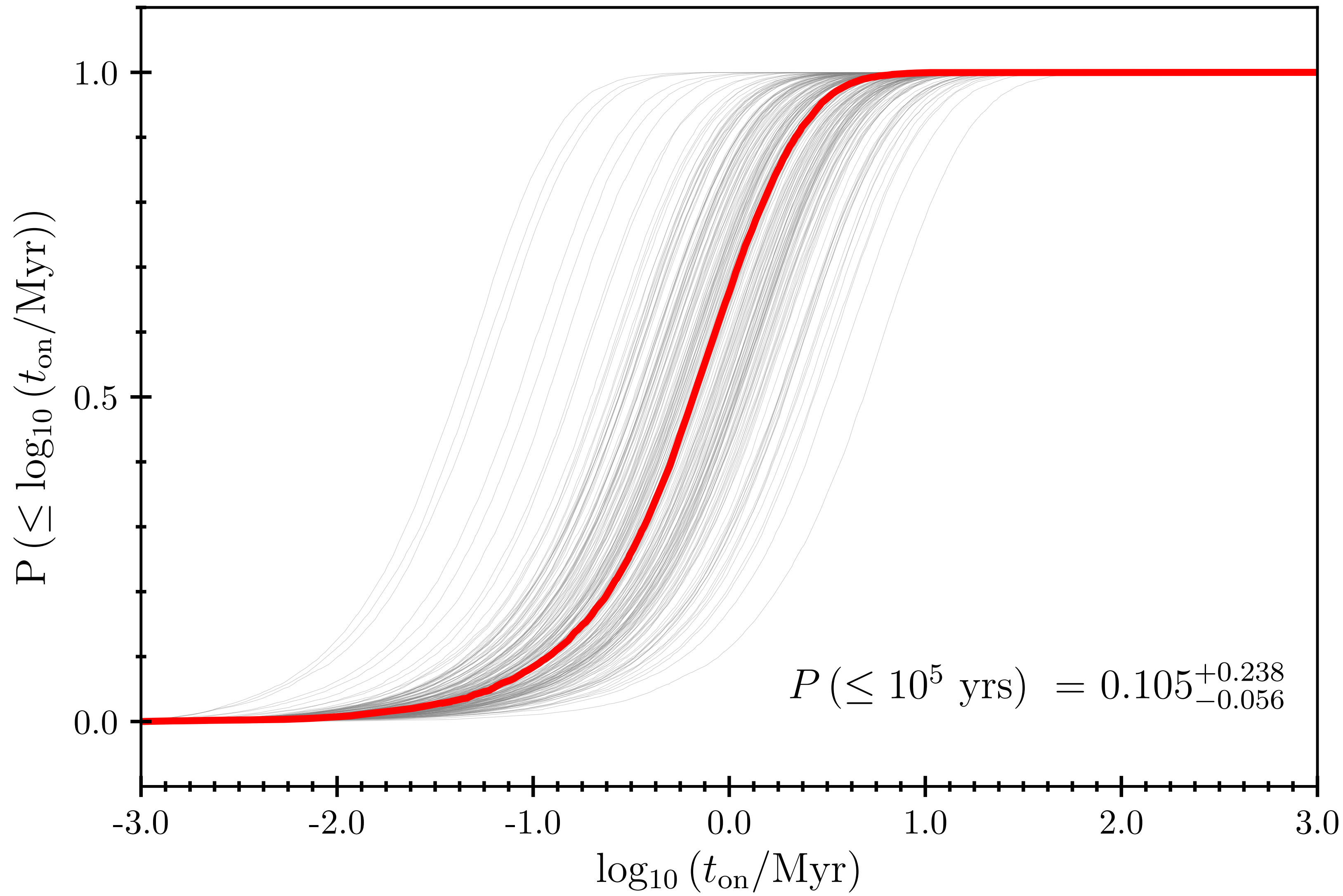

Khrykin+ (tbs)

Conclusions

We created fully Bayesian statistical algorithm to study the LoS He II Proximity Effect in spectra of individual quasars and infer the timescales of accretion on the SMBH fully marginalised over unknown IGM ionization state.

We found a broad distribution of the on-times from the analysis of 20 quasars at z = 3 - 4

For the first time we estimated the shape of the underlying quasar lifetimes distribution. Assuming the log-normal distribution, we inferred:

$$\langle \log_{10} t_{\mathrm{Q}} \rangle = 0.374^{+0.191}_{-0.208} \quad \sigma_{\log_{10} t_{\mathrm{Q}}} = 0.564^{+0.292}_{-0.255}$$

We derived a simple analytical suppression for the distribution of quasar on-times and predict that the probability of finding quasars with t_on < 10^5 yrs from the analysis of their proximity zones is $P\left(< 10^5 \text{ yrs}\right) = 0.105^{+0.238}_{-0.056}$***, comparable to the values found in observations (5-10%)***