# Prospects for constraining the age and radiation geometry of quasars with imaging and spectroscopic observations

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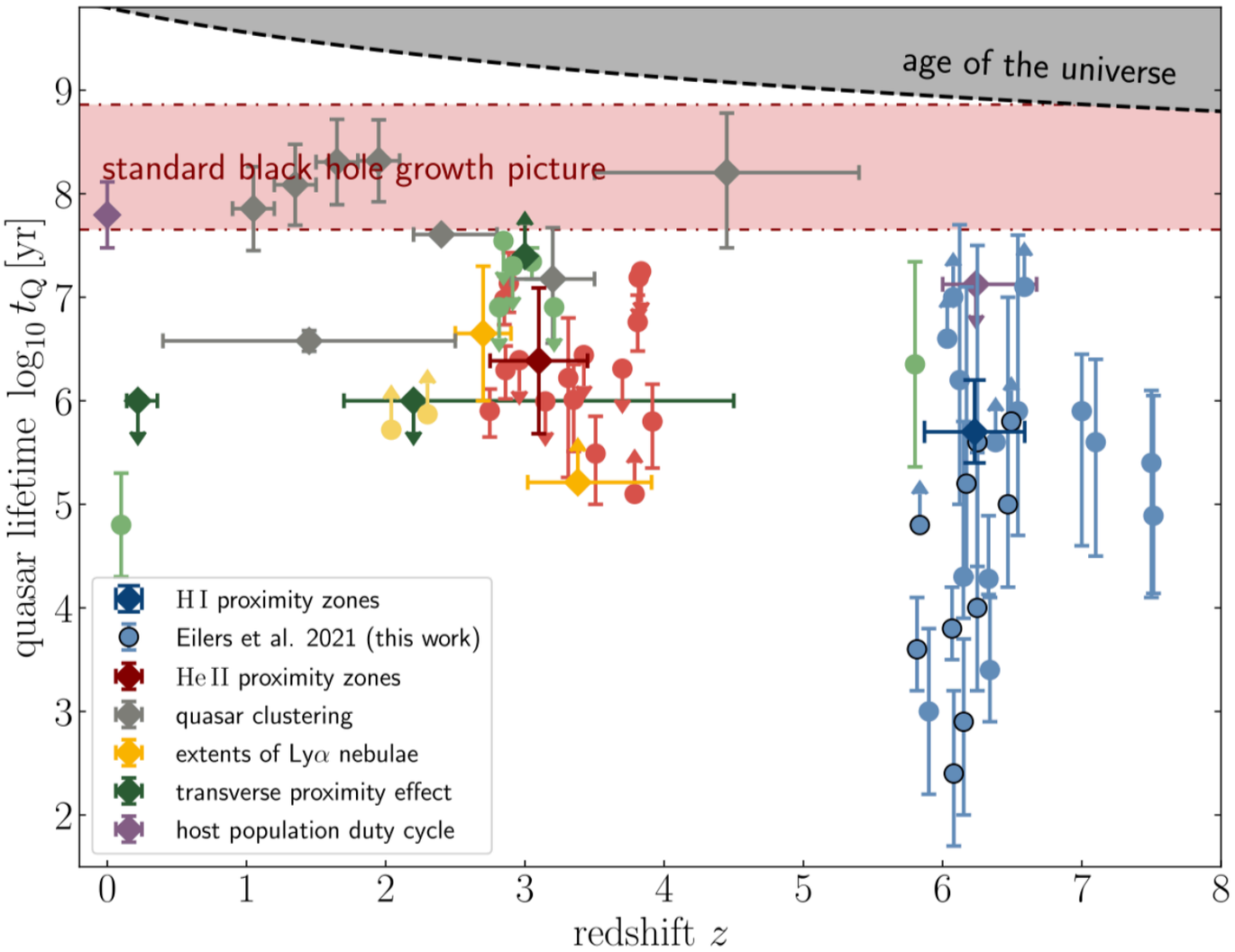
# Quasar and Light Echoes

- Quasars are the most luminous objects
- But the physical process is still unknown

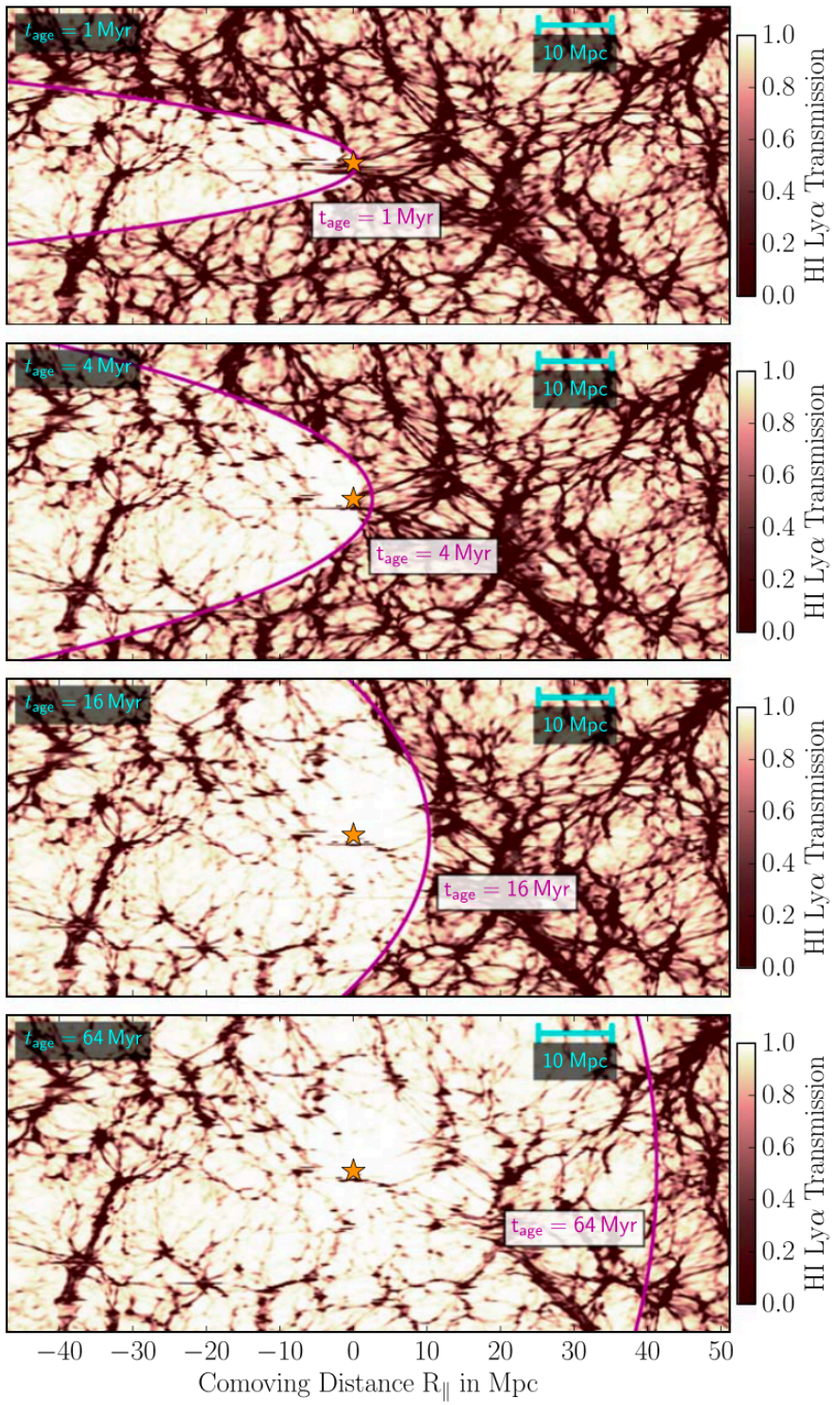
→ the lifetime is uncertain: $10^5 - 10^8 \mathrm{yr}$

(e.g., Martini+ 2003)




(Eilers+ 2021)

# Quasar and Light Echoes




(Schmidt+ 2019)

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(e.g., Martini+ 2003)

- Quasars create regions of enhanced photoionization: **proximity zone or light echo**
- The regions are characterized by the quasar lifetime or radiation cone

→ mapping quasar light echoes allows us to understand the quasar property

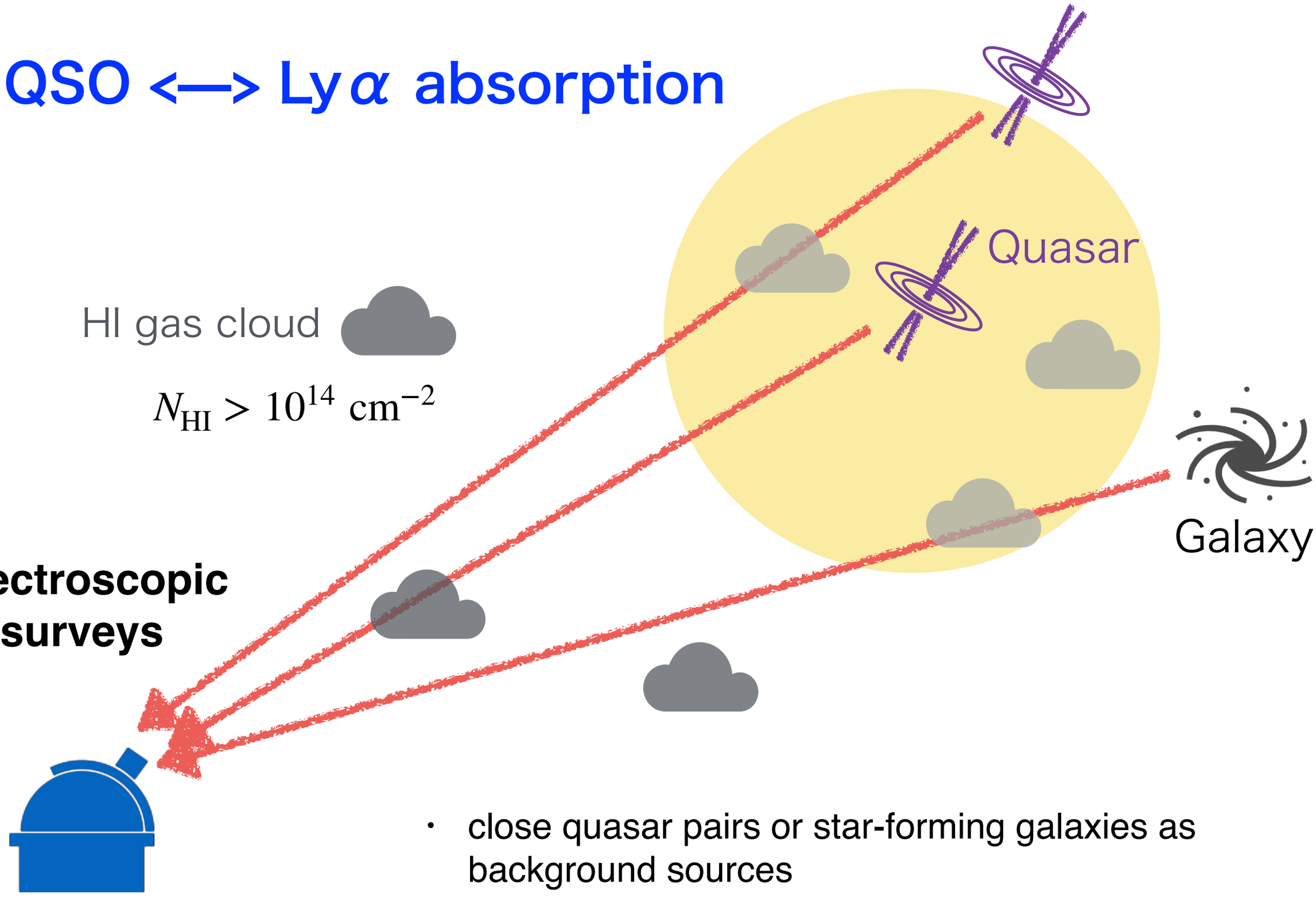
(Crotts 1989, Dobrzycki & Bechtold 1991, Adelberger 2004, Visbal & Croft 2008)

# QSO <—> Lyα absorption

HI gas cloud

$N_{\rm HI} > 10^{14}\ {\rm cm}^{-2}$

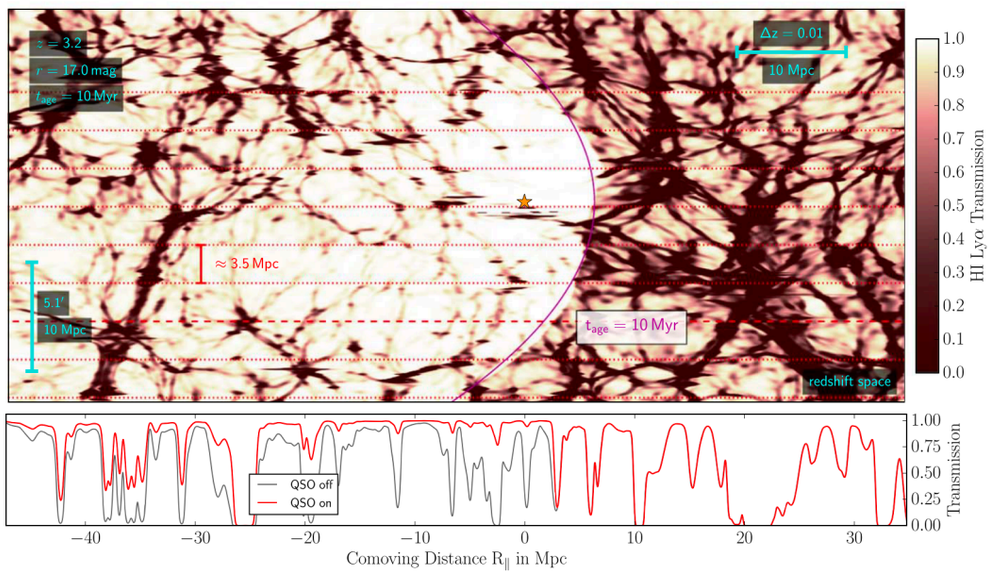
**spectroscopic surveys**



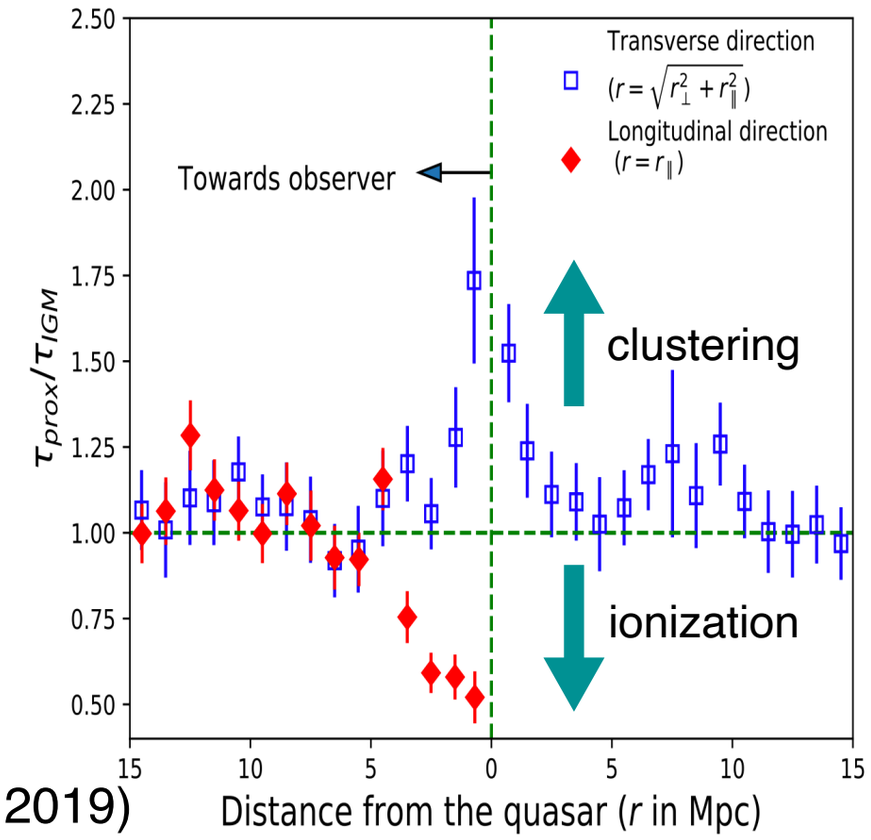

- close quasar pairs or star-forming galaxies as background sources
- Lyα absorption is reduced around foreground quasars

(Croft 2004, Jalan+ 2019)

# Variations in transmission




(Schmidt+ 2019)




(Jalan+ 2019)

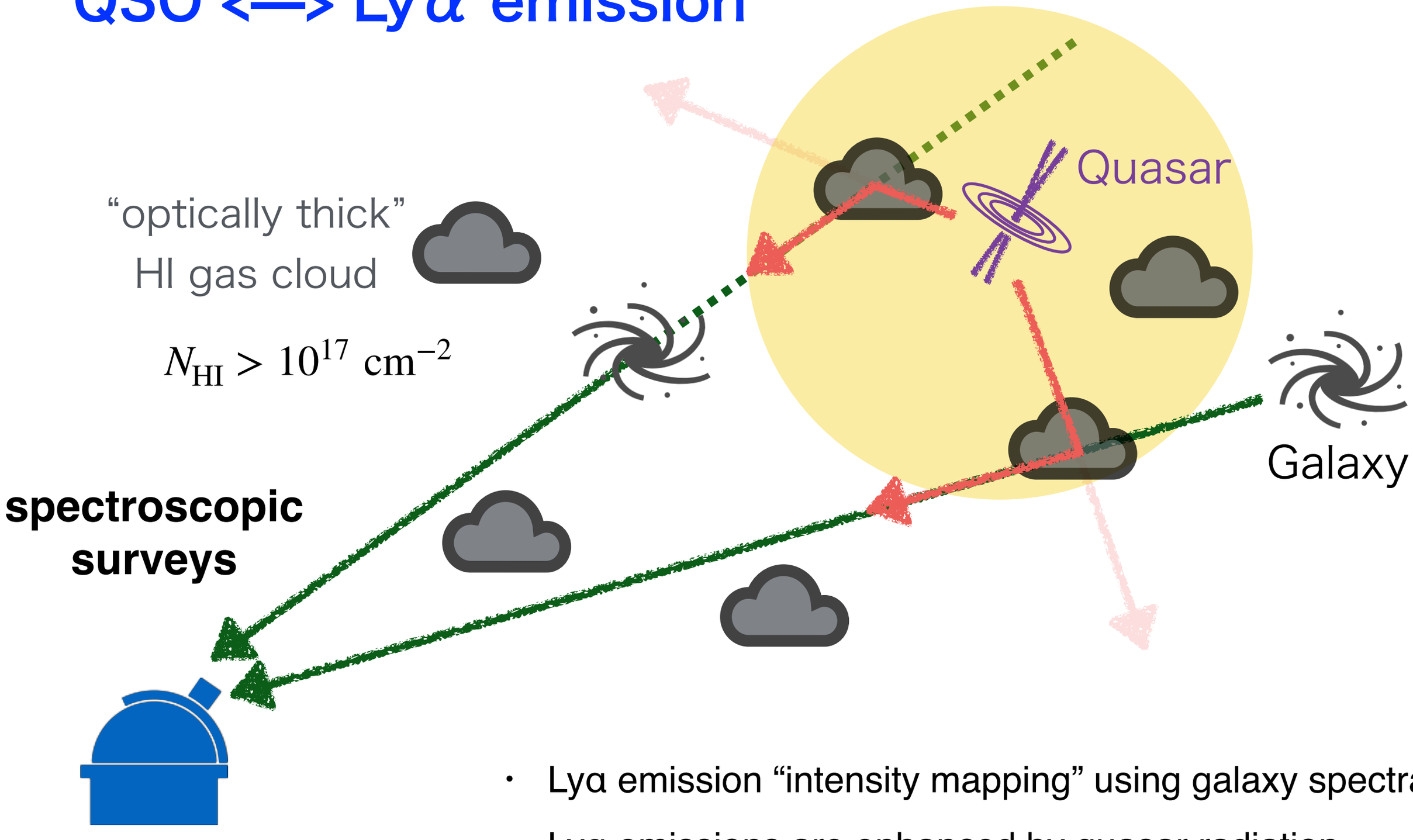
- stacking 181 projected quasar pairs at separations <1.5′ from SDSS DR12 in $2.5 < z < 3.5$

- also affected by the clustering of HI gas clouds
  >> Lyα forest-quasar cross-correlation on small scales

- comparison between both line-of-sight and transverse directions
  >> the average quasar's illumination along the transverse direction is < 27% (3σ)

→ need to consider anisotropic radiation

# QSO <—> Lyα emission

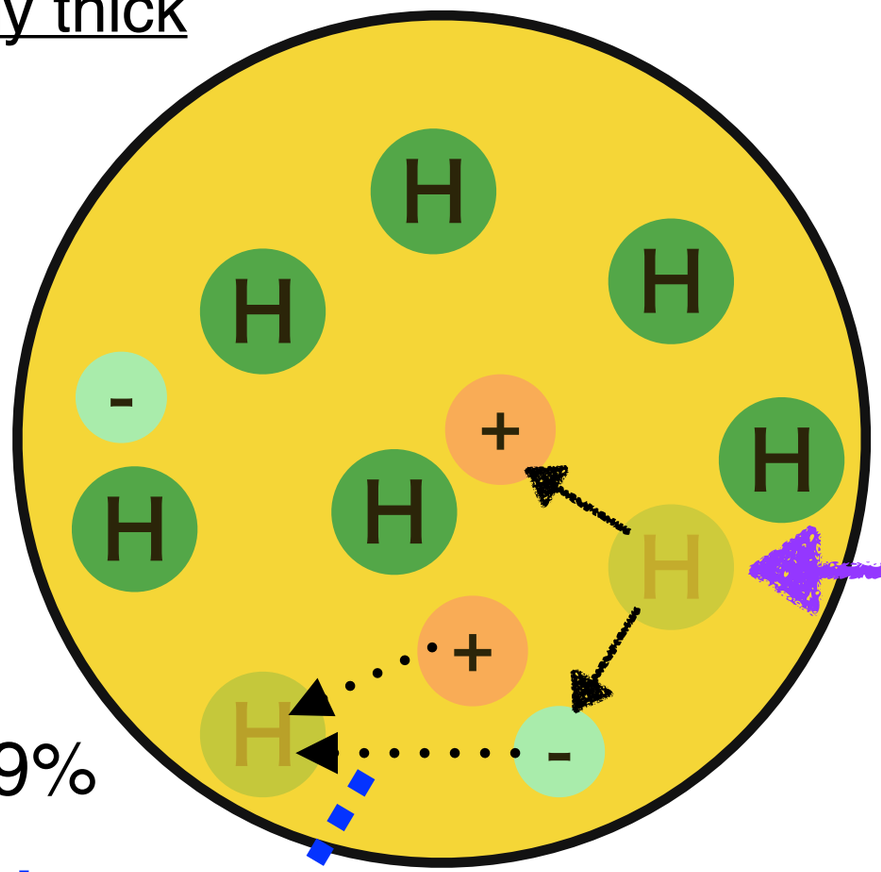



- Lyα emission “intensity mapping” using galaxy spectra
- Lyα emissions are enhanced by quasar radiation

(Croft+ 2016, 2018, Lin+ 2022)

# Fluorescence

optically thick region

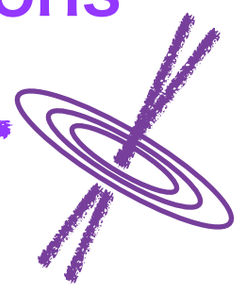



~ 69%

Ly$\alpha$ photons

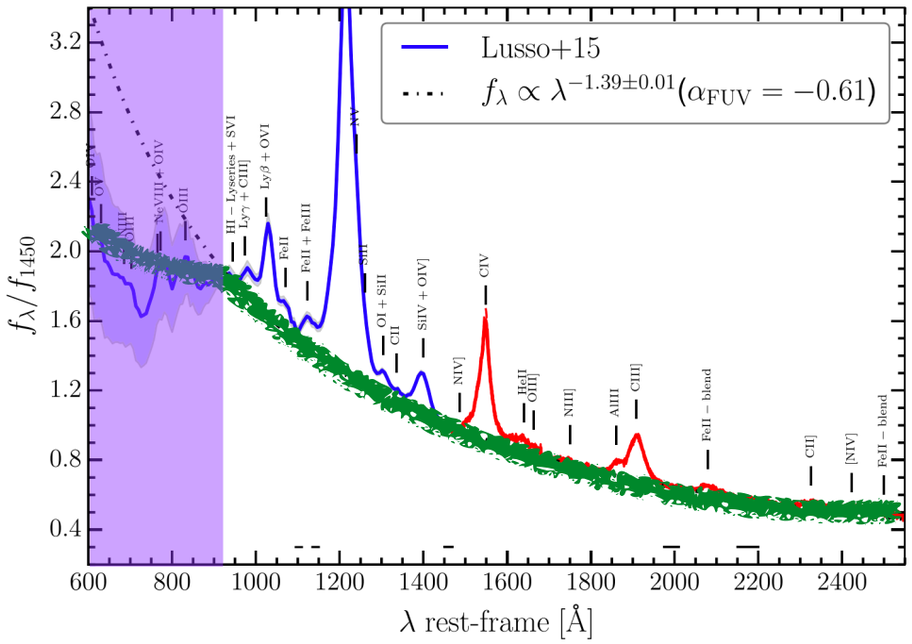
Fluorescence "mirror"

Ionizing photons



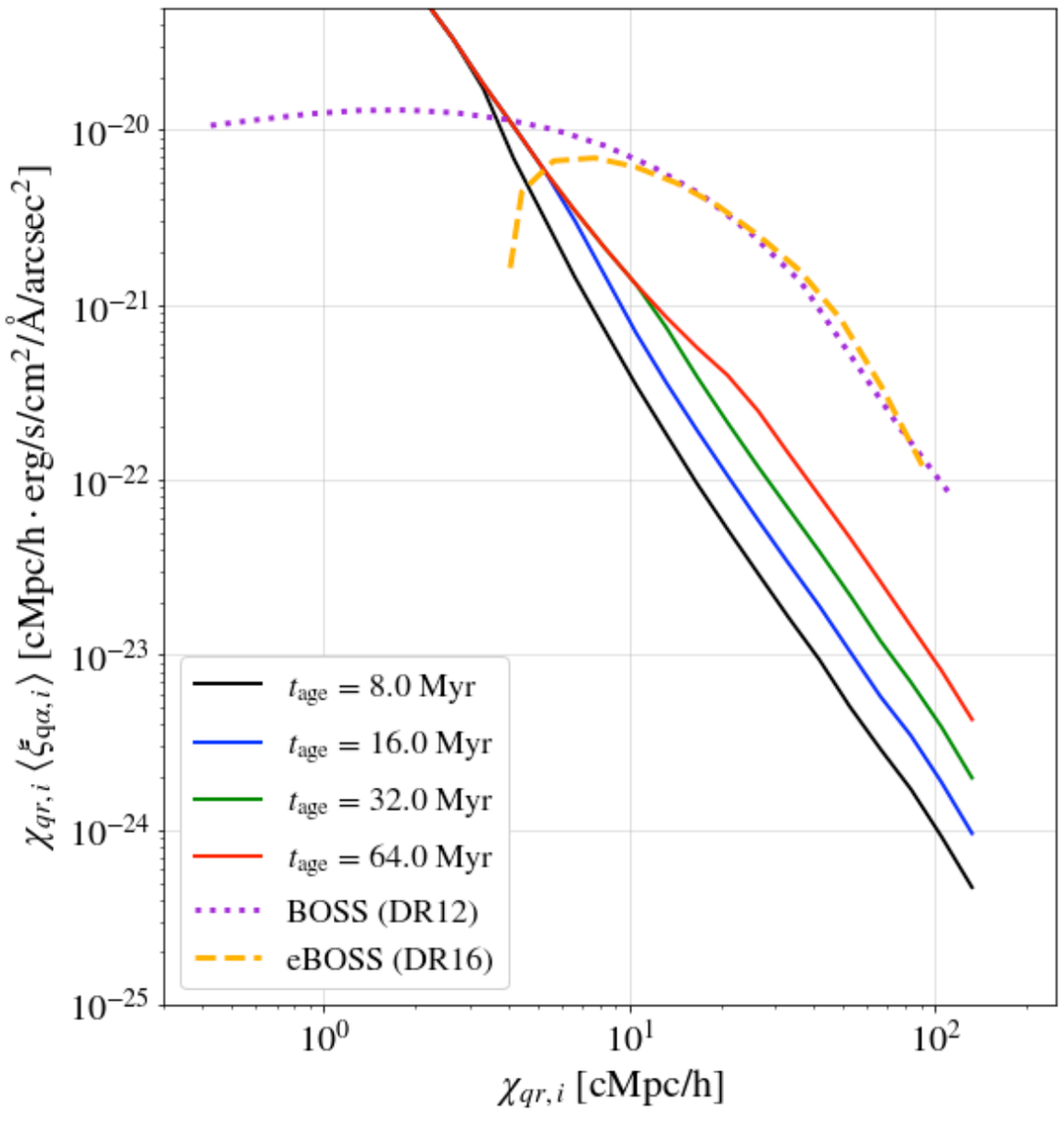
Quasar

(Lusso+ 2015)




$$L_q(\nu_q) = L_{q,\nu_L}\left(\frac{\nu_q}{\nu_L}\right)^{\alpha} \quad \alpha = \begin{cases} -0.61 & (\nu < \nu_L : \text{FUV}) \\ -1.70 & (\nu > \nu_L : \text{EUV}) \end{cases}$$

# Modeling the Ly$\alpha$ emission excess




(**RH**, Takada, and Inoue, submitted)

- assumed typical column density distribution and clustering around quasars

$$\xi_{\rm QA}(r) = \left(\frac{r}{12.5h^{-1}{\rm Mpc}}\right)^{-1.68}$$

(Prochaska+ 2013)

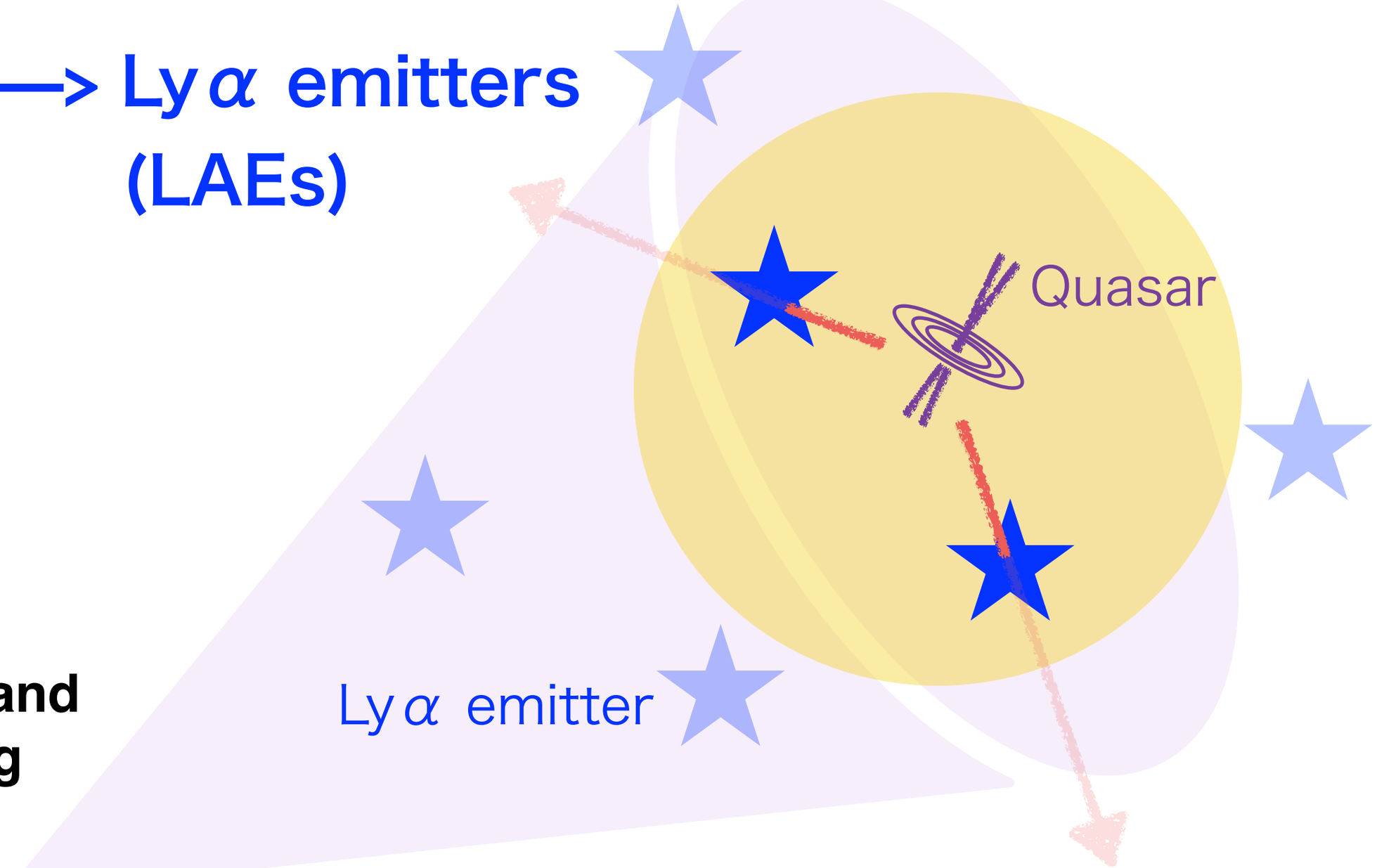
- different ages correspond to different sizes of the proximity zone

- found that the fluorescence is much larger than the resonant scattering of quasar Lyα photons

- on large scales, the contribution from star-forming galaxies is dominant…

→ can we still put an upper limit on quasar ages?

# QSO <—> Lyα emitters (LAEs)

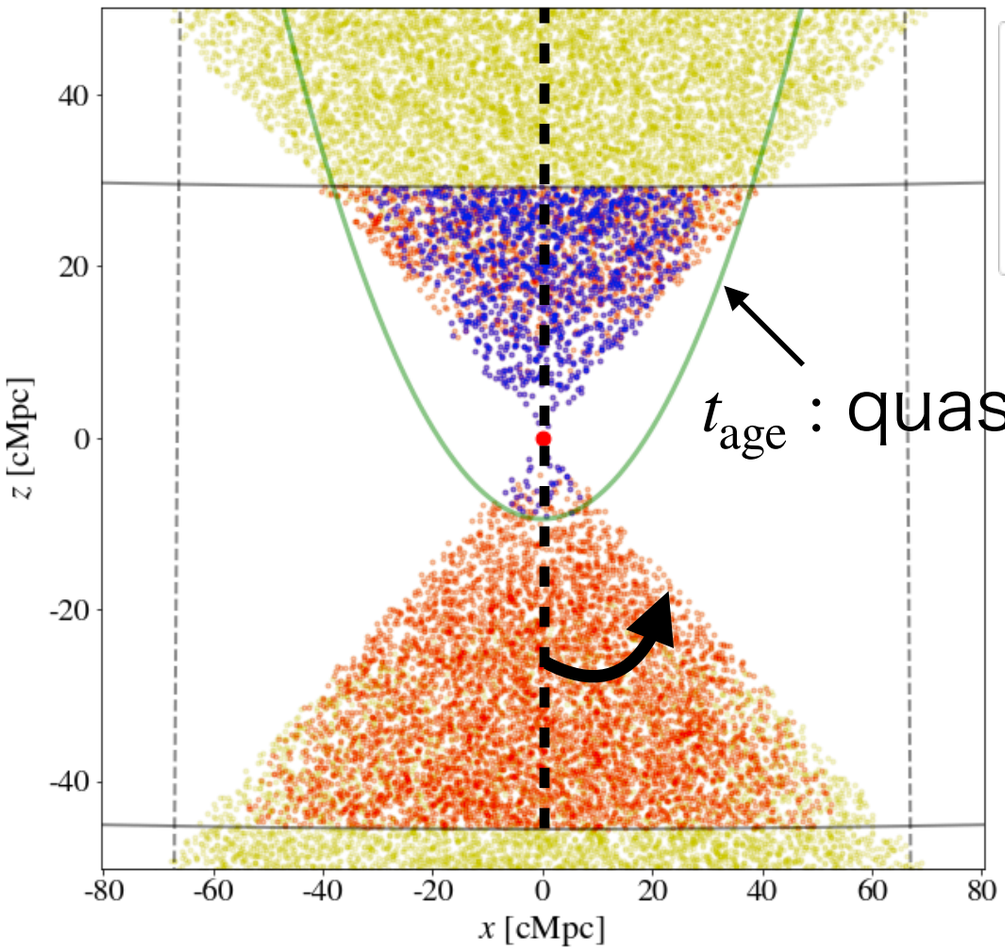


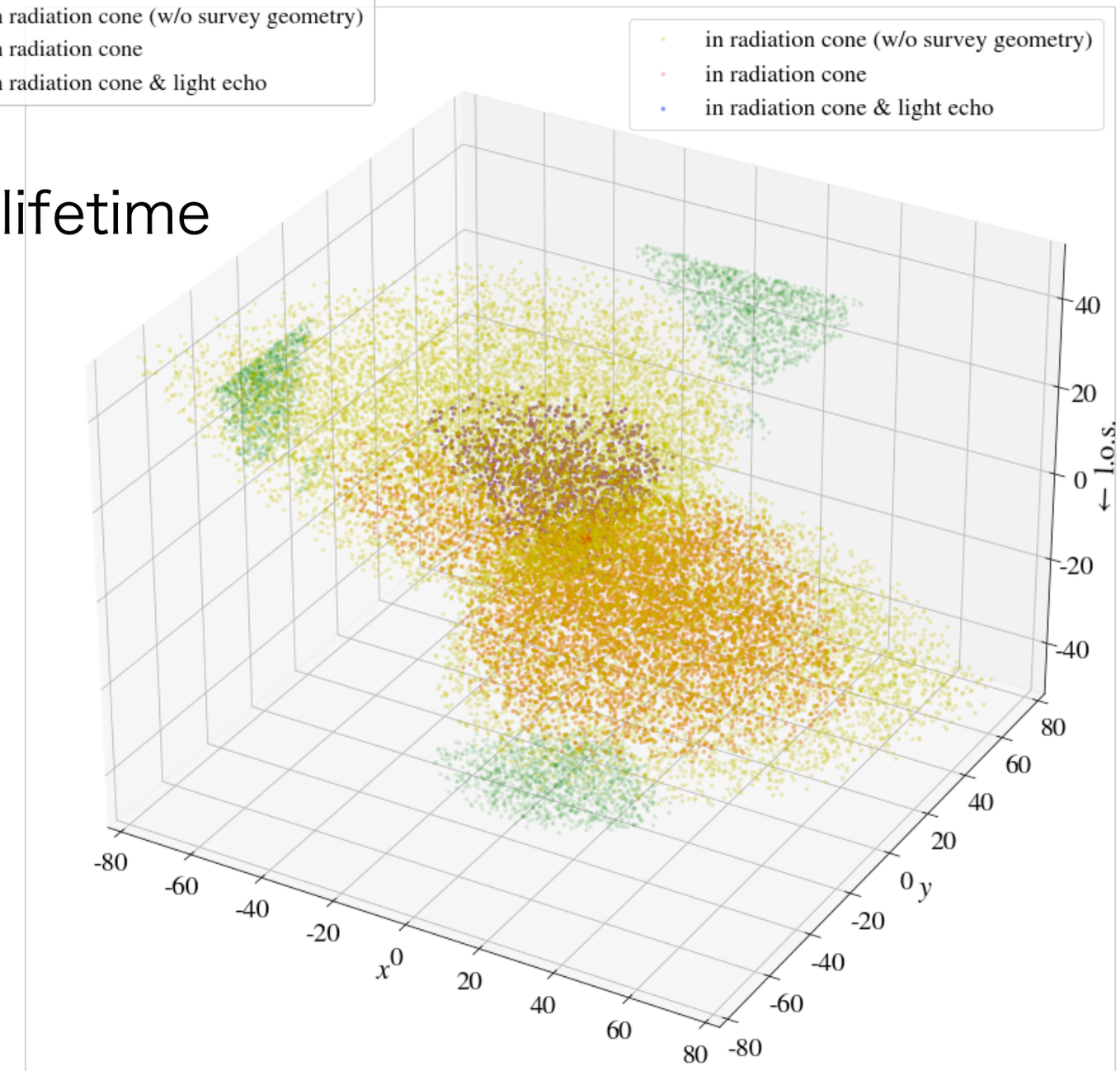

**narrow band imaging**

- narrow-band imaging of LAEs around a quasar
- LAEs are “fluorescently” illuminated by the quasar
- unusually bright LAEs should be in the proximity zone

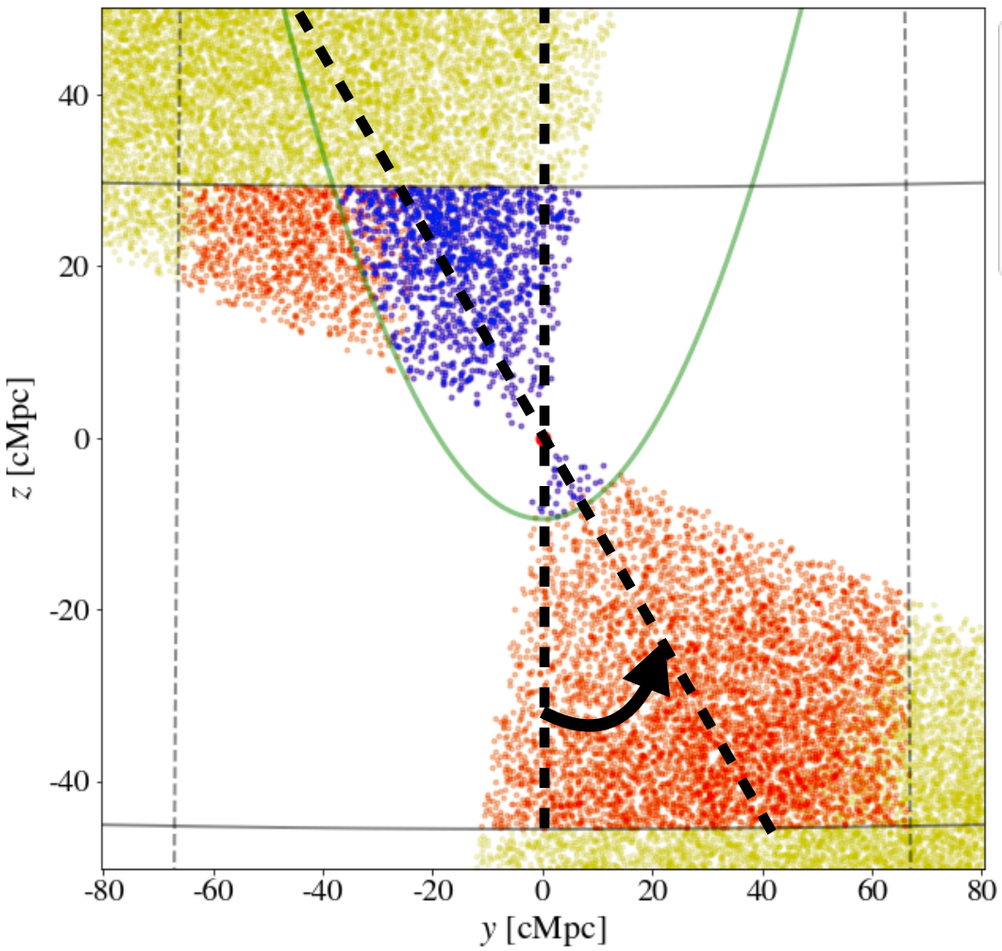
(Trainor+ 2013, Borisova+ 2016)

# Radiation geometry

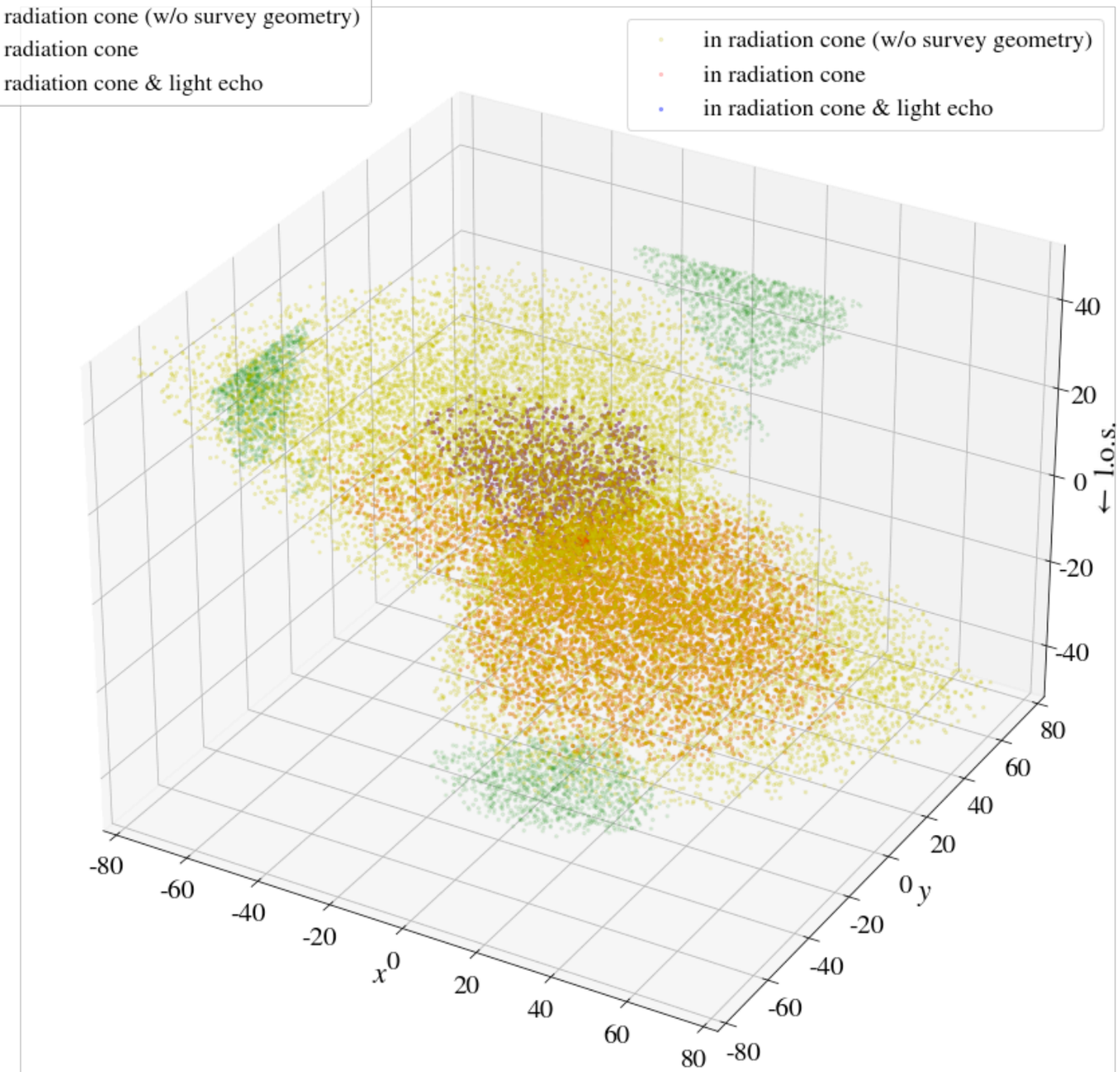


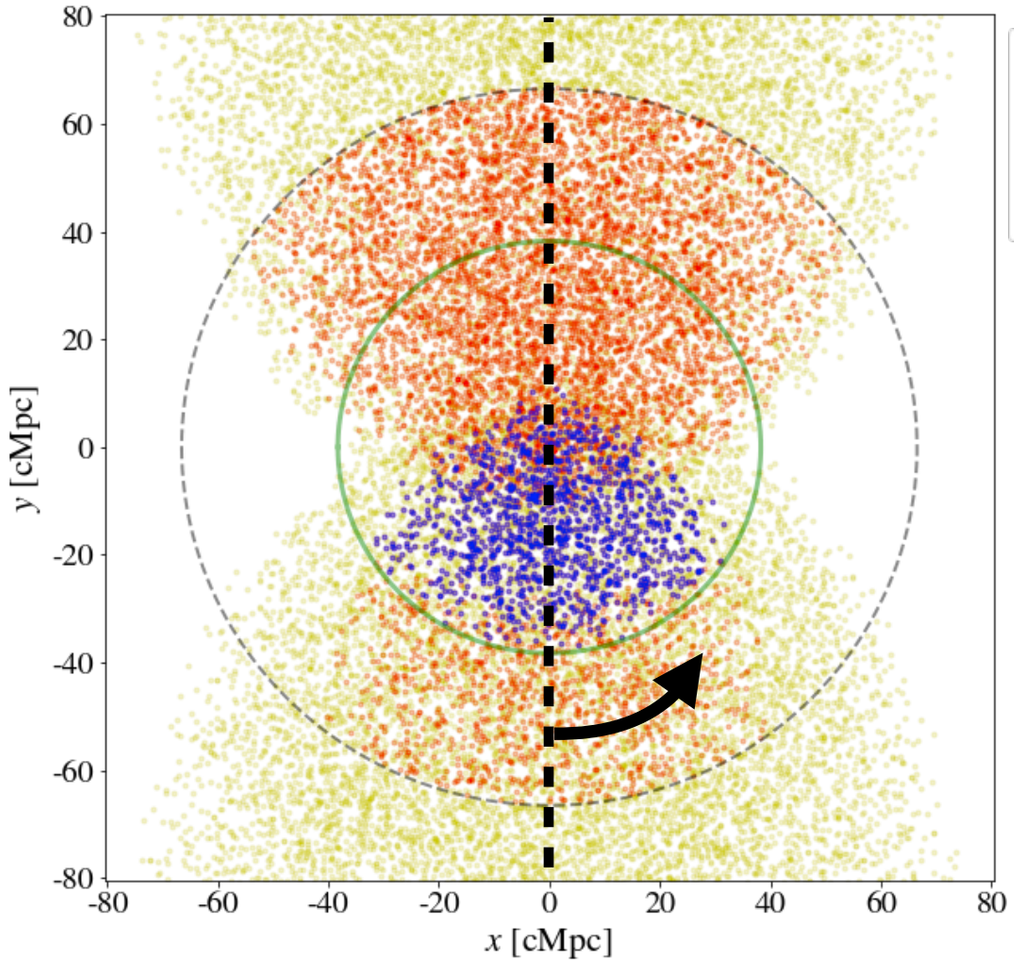
# Radiation geometry



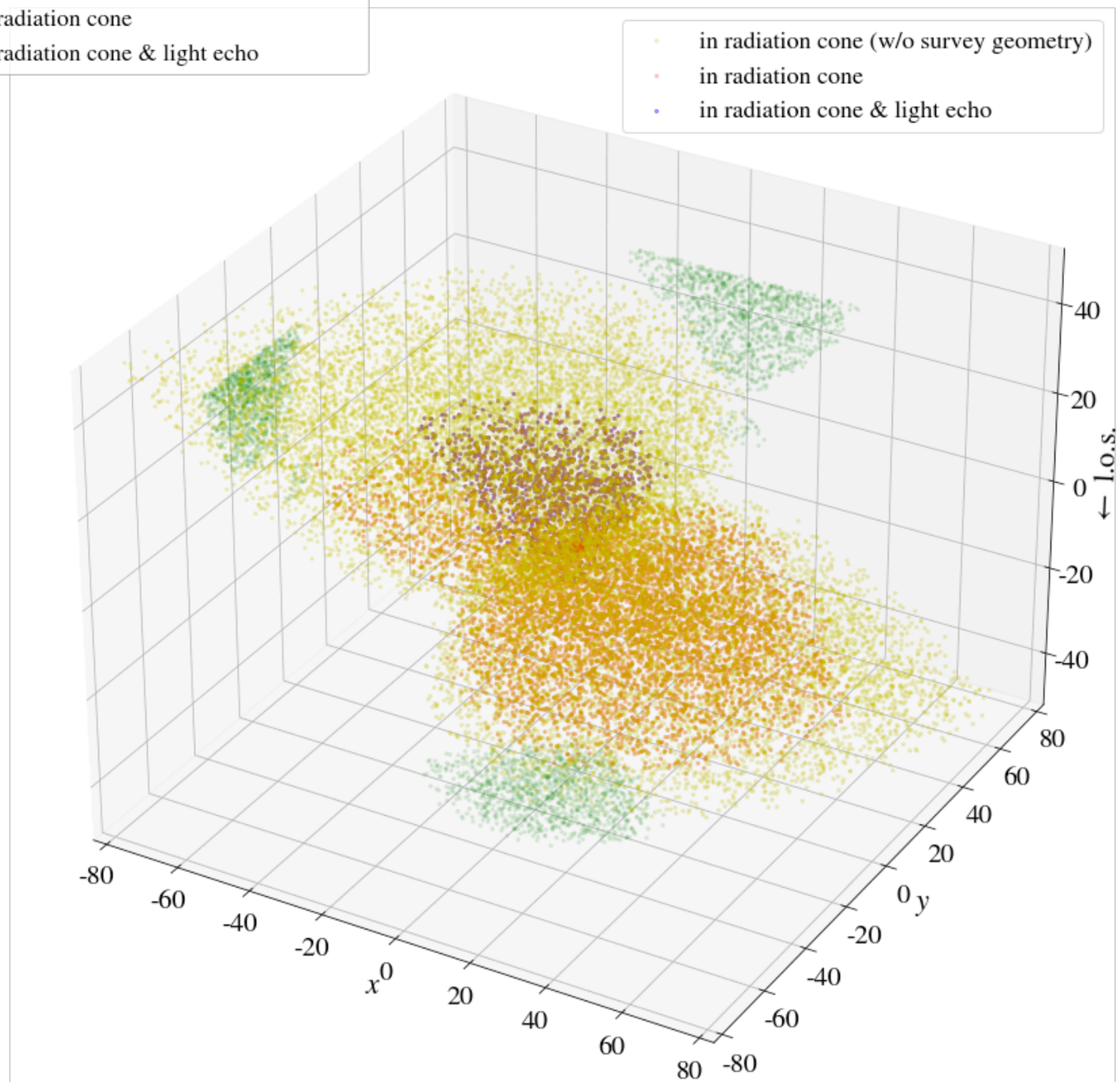

$\Psi$ : inclination angle



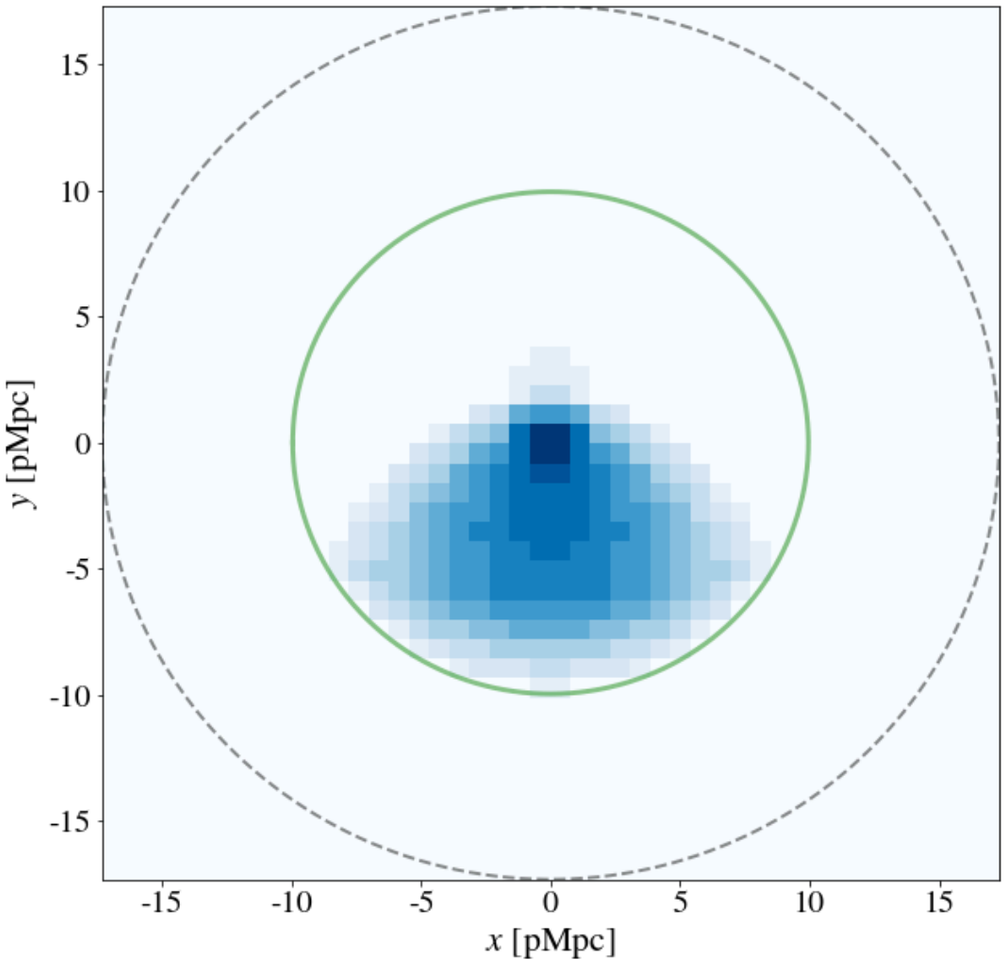
# Radiation geometry

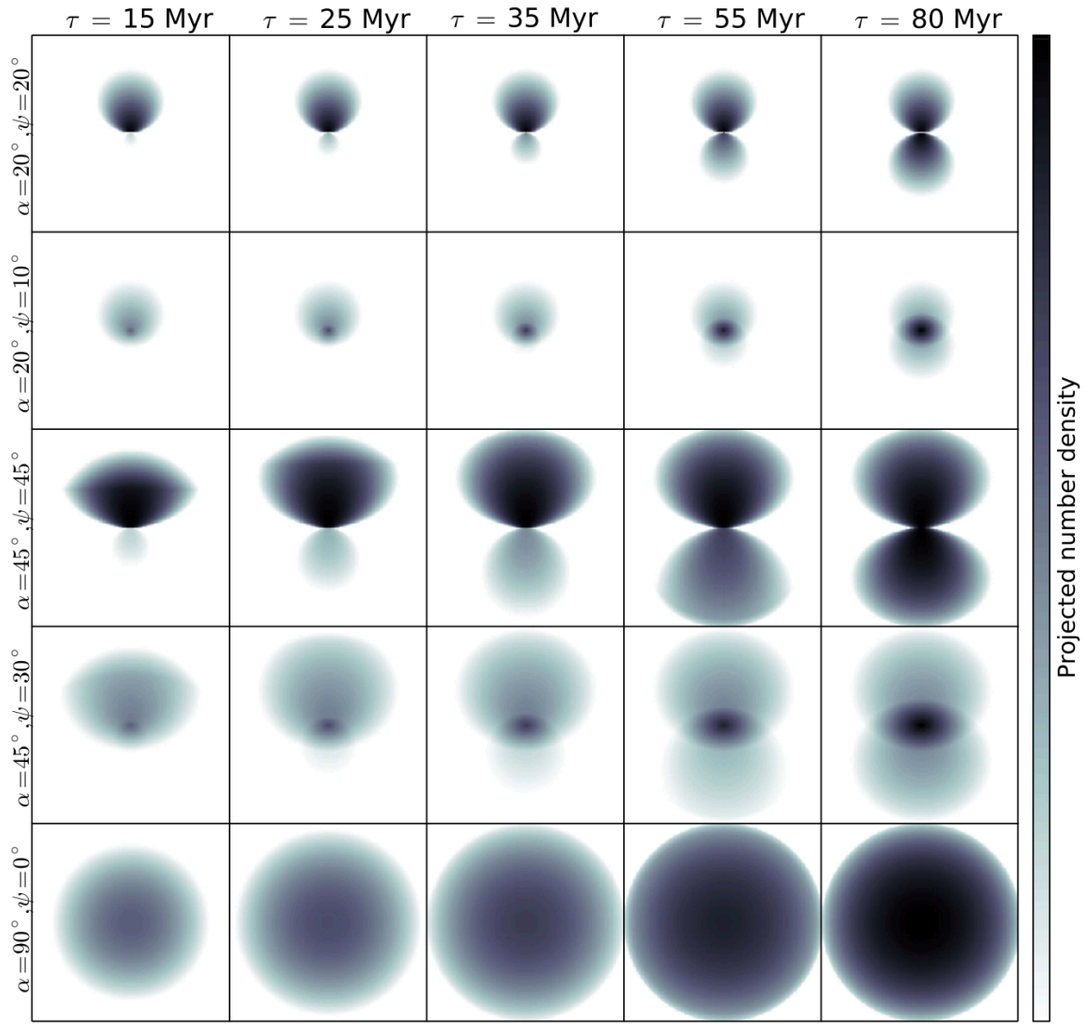



$\phi$ : azimuth angle



# Projected number density

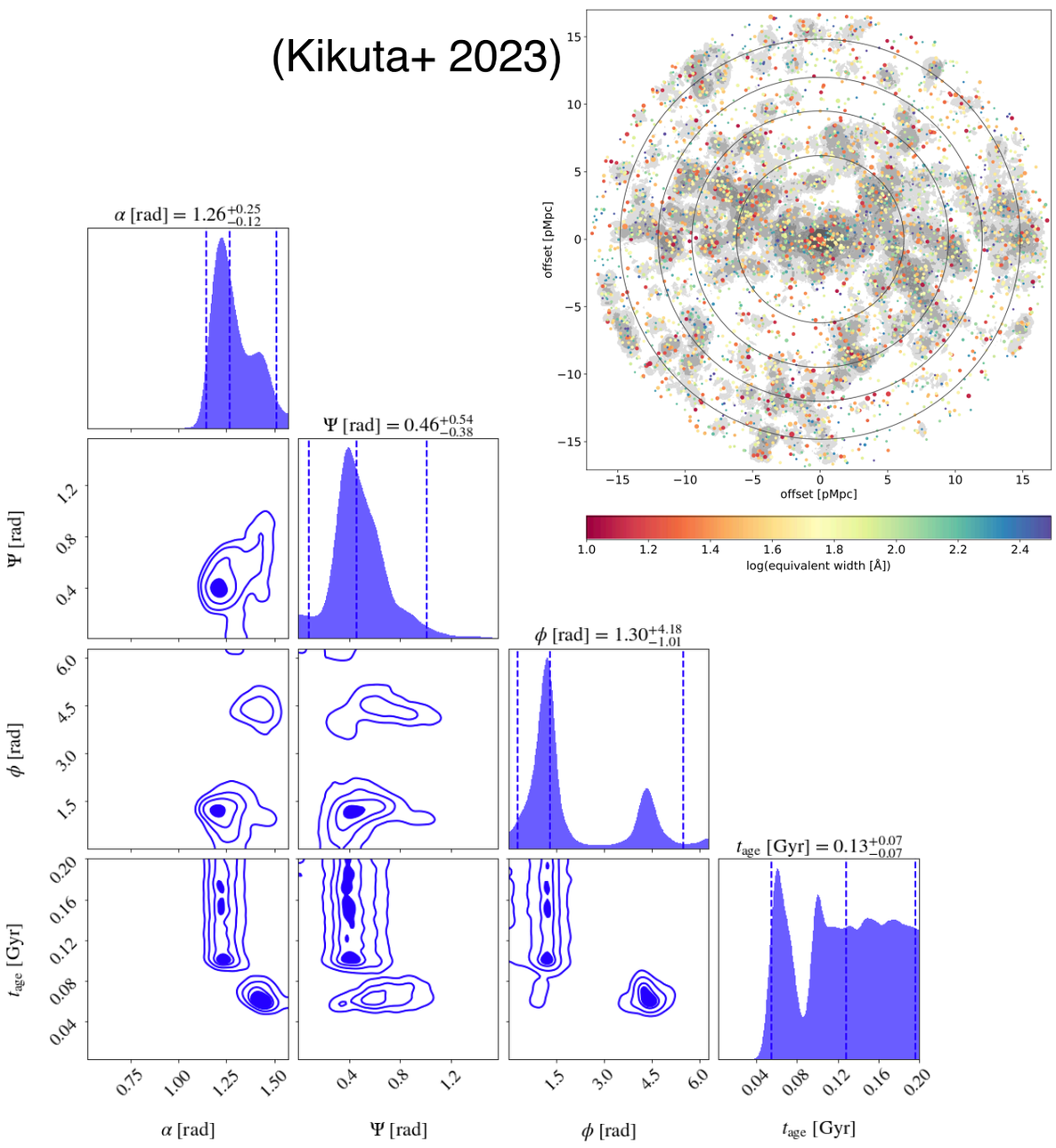



(Borisova+ 2016)

# Constraints on the age and angles

(Kikuta+ 2023)







$\alpha$ : opening angle $\phi$ : azimuth angle

$\Psi$ : inclination angle $t_{age}$ : quasar lifetime

(**RH**, Zheng, Kikuta, and Matsuda, in prep.)

- deep wide field narrow-band image (Subaru/HSC) of the bright quasar HS 1549+1919 at z~2.8
- selected 251 samples with **EW > 240 Å** from 3490 LAEs *"unusually bright"*
- improvement from Borisova+ *(*2016):
  >> # of LAEs is ~10x higher
  >> azimuth angle marginalized
- no distance dependence…
  >> not illuminated by the quasar?
  >> then, why are EWs that high?
  >> samples might include AGNs

→ What if we could get their redshifts?

# Dark Energy Spectroscopic Instrument (DESI)

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

## DESI in a nutshell: how?

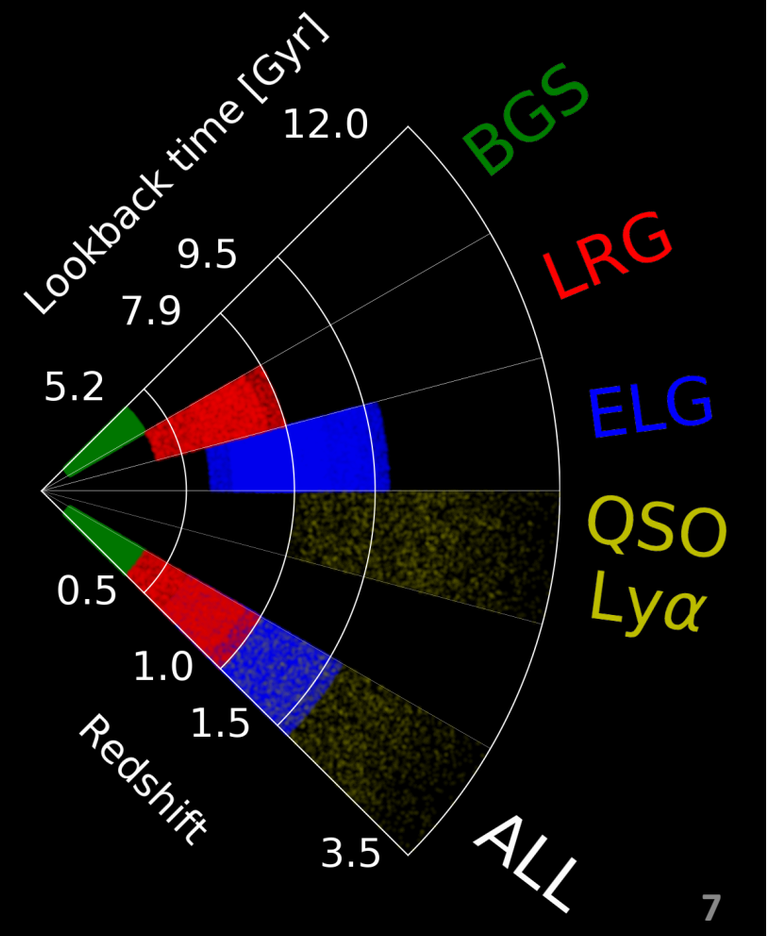
**Instrument: redshift factory**

- Mayall telescope (4m) at Kitt Peak (AZ, USA) with 8 deg$^2$ field-of-view
- 5000 fiber positioner robots in the focal plane
- high throughput (optics, spectrographs, fibers, CCDs)

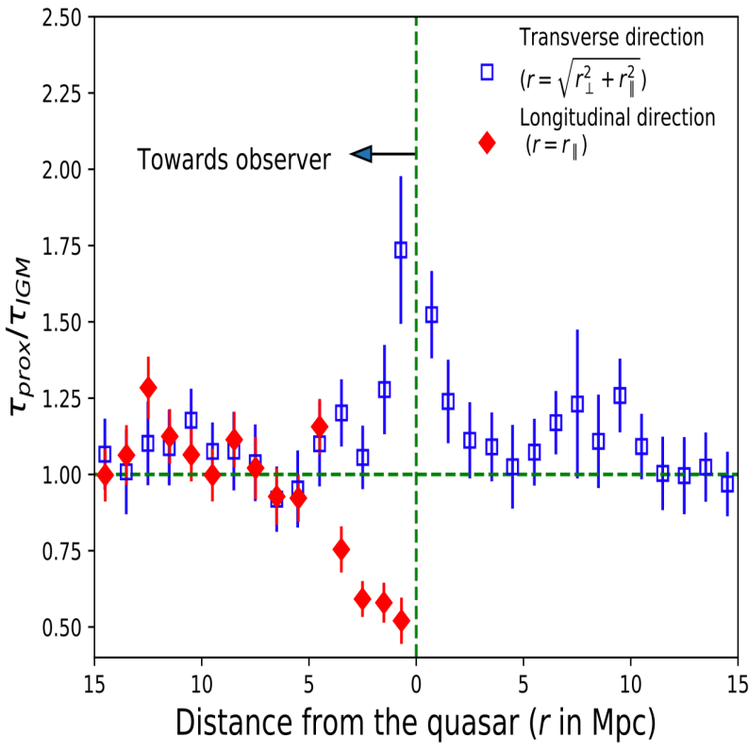
**Main Survey**

- Five years over 14,000 deg2 (1/3 of the sky) up to z < 3.5
- 40M redshifts (~10x the whole SDSS over 20 years)
- One tracer optimal for each redshift range

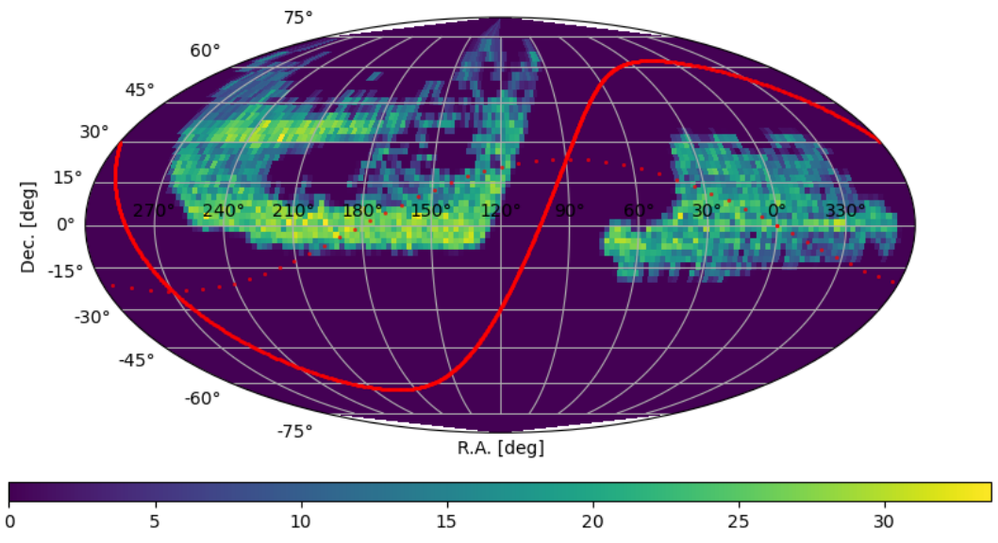
| | N | Redshift | Comments | |
|---|---|---|---|---|
| **MWS** | 6M | - | stars | bright time |
| **BGS** | 13.5M | 0.05 < z < 0.4 | bright galaxies | bright time |
| **LRG** | 8M | 0.4 < z < 1.0 | luminous red galaxies | dark time |
| **ELG** | 16M | 0.6 < z < 1.6 | emission line galaxies | dark time |
| **QSO + Lyα** | 3M | 0.9 < z < 3.5 | quasars | dark time |



# Forecast for DESI: QSO-Ly$\alpha$ absorption




(SDSS DR12, Jalan+ 2019)



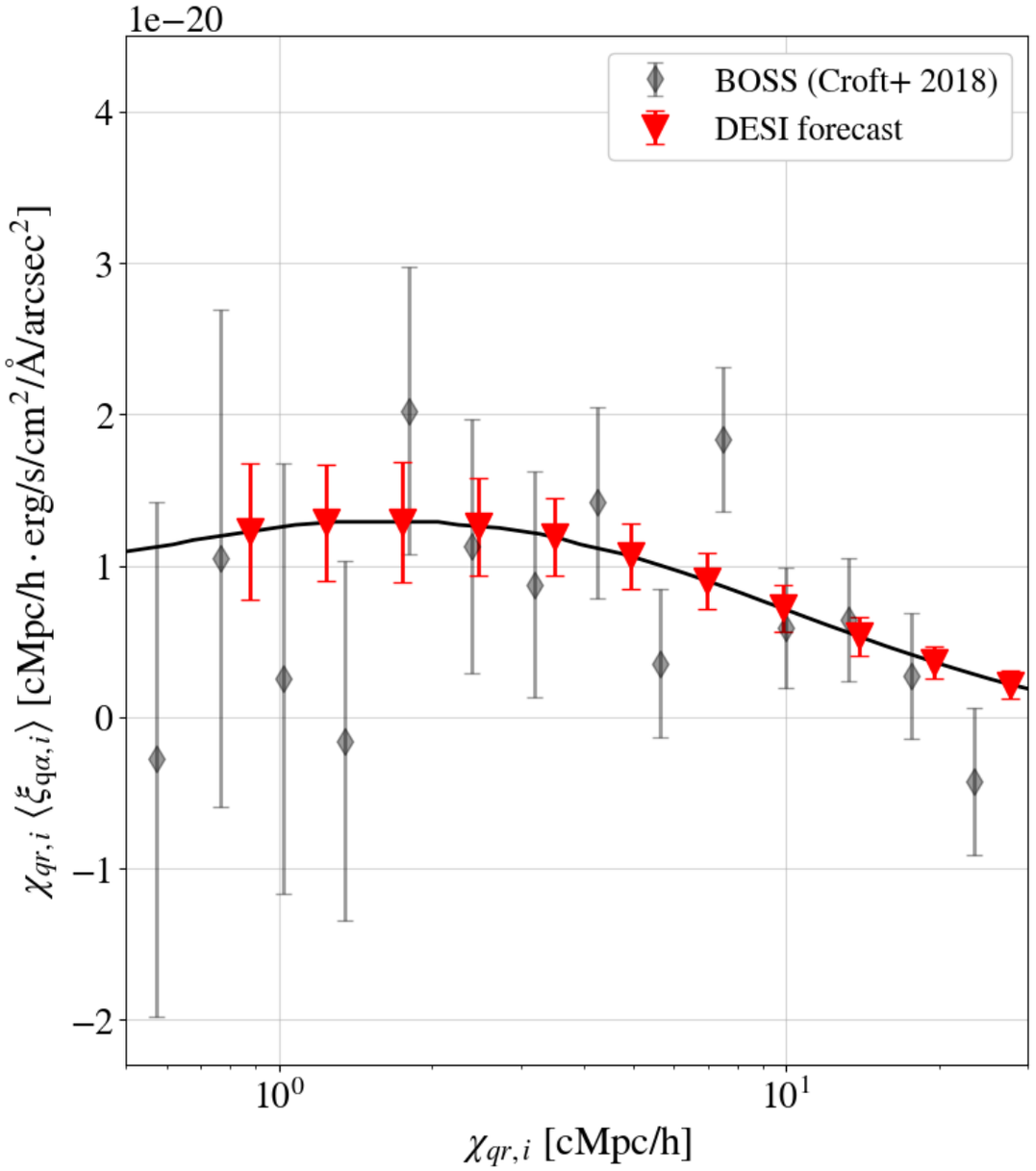

# of QSOs in DESI Y1: 1.56 M

quasar pairs at separations <1.5′ in z > 2.5

| | # of quasar pairs | Improvement of S/N |
|---|---|---|
| SDSS DR12 | 1344 | 1x |
| DESI Y1 | 3612 | 1.6x |
| DESI Y5 | > 6.7k | 2.2x |

- a control sample of Lyα absorption from the blank field that matches the redshift and the continuum S/N with those of the paired sample
- enable us to study the dependence of the proximity zone on various quasar properties

# Forecast for DESI: QSO-Ly$\alpha$ emission




**BOSS**

$$N_q = 2.2 \times 10^5$$
$$n_{\mathrm{LRG}} = 152\ \mathrm{deg}^{-2}$$

**DESI Y5**

$$N_q = 8.3 \times 10^5$$
$$n_{\mathrm{LRG}} = 605\ \mathrm{deg}^{-2}$$
$$n_{\mathrm{ELG}} = 1530\ \mathrm{deg}^{-2}$$

$$\mathrm{S/N} \propto \left(\frac{\sigma_n(\lambda_q)}{9.2\times10^{-18}\mathrm{erg\ cm^{-2}\ s^{-1}\ \AA^{-1}\ arcsec^{-2}}}\right)^{-1} \times\left[\left(\frac{t_{\mathrm{exp(tot)}}}{900\ \mathrm{s}}\right)\left(\frac{\lambda/\Delta\lambda}{1900}\right)\left(\frac{N_q}{3.3\times10^4}\right)\left(\frac{n_{\mathrm{fiber}}}{4.4\times10^3\ \mathrm{deg}^{-2}}\right)\right]^{1/2},$$

- used pixel noise of typical sky spectra
- **3x higher S/N** than BOSS

# Forecast for DESI: QSO-Ly$\alpha$ emitters

**DESI Publications Board**

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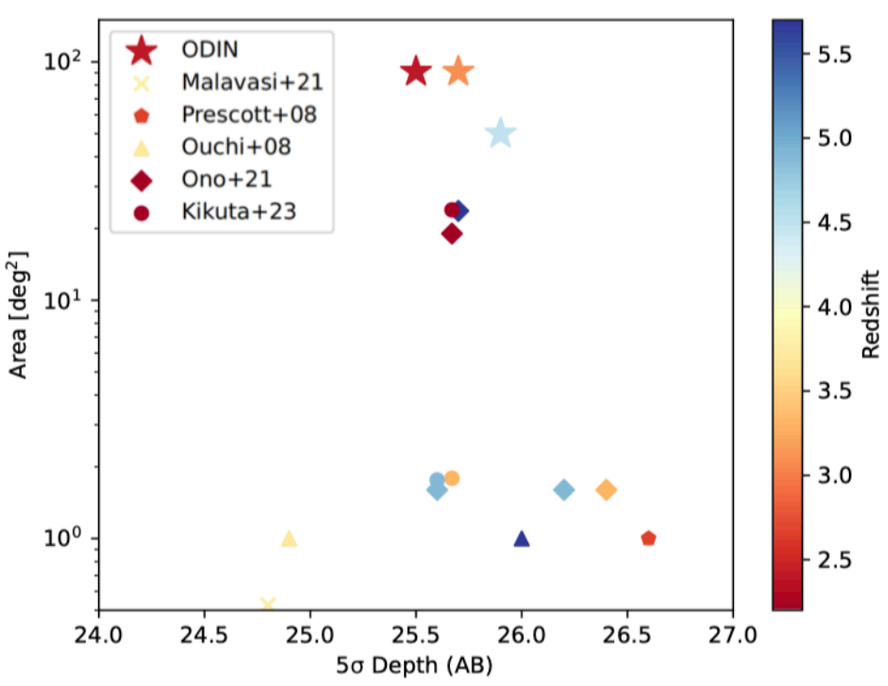
**Project: [223] ODIN+DESI: Lyman Alpha Emitters as Cosmological Tracers at z > 2**

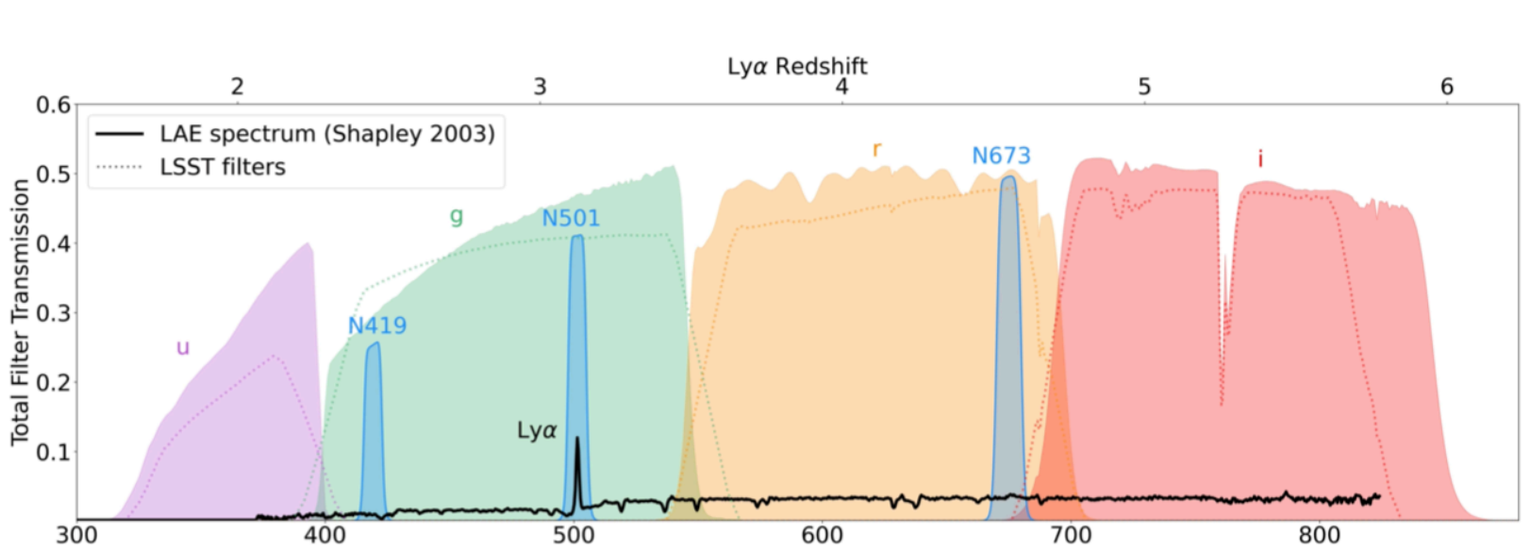
Join the Project | Send email to Project Members

**Project SWGs**

- DESI-II
- Galaxy & Quasar Physics

*ODIN (One-hundred-deg^2 DECam Imaging in Narrowbands)*




- LAEs around **a number of** quasars
- DESI (II) will provide their redshifts!

# Summary

- Mapping the quasar light echoes (proximity zones) allows us to understand the quasar emission history

- Variations in Lyα absorption with close quasar pairs
  >> need to consider anisotropic radiation
  >> DESI: **2.2x higher S/N** than SDSS DR12

- Lyα emission intensity mapping using galaxy spectra
  >> star-forming galaxies (90%) + fluorescence (10%)
  >> DESI: **3x higher S/N** than BOSS

- Narrow-band imaging of LAEs around a quasar
  >> radiation parameters constrained, but no distance dependence
  >> ODIN(+DESI): (3D distribution of) LAEs around multiple quasars