Cosmology at WST

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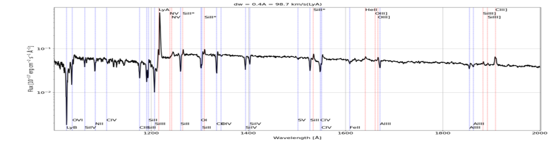
The Wide-field Spectroscopic Telescope (WST) Science White Paper,

Vincenzo Mainieri et al., arXiv:2403.05398

Action Dark Energy, IHP, October 28-30, 2024

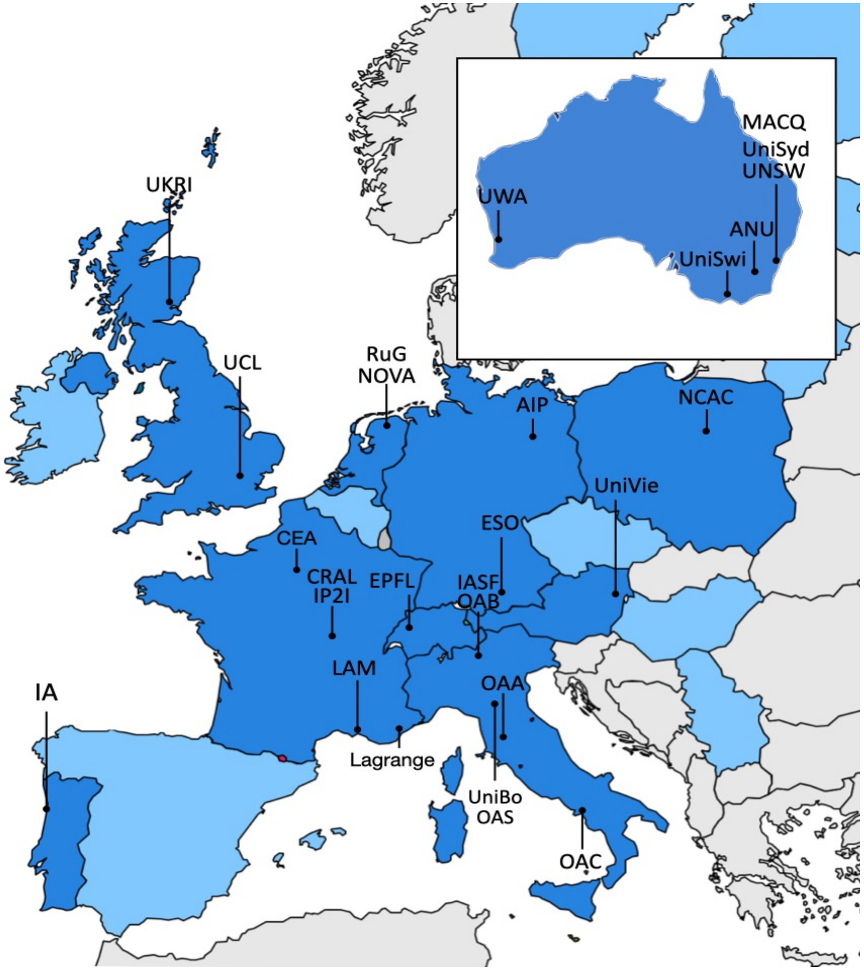


Wide-field Spectroscopic Telescope (WST)

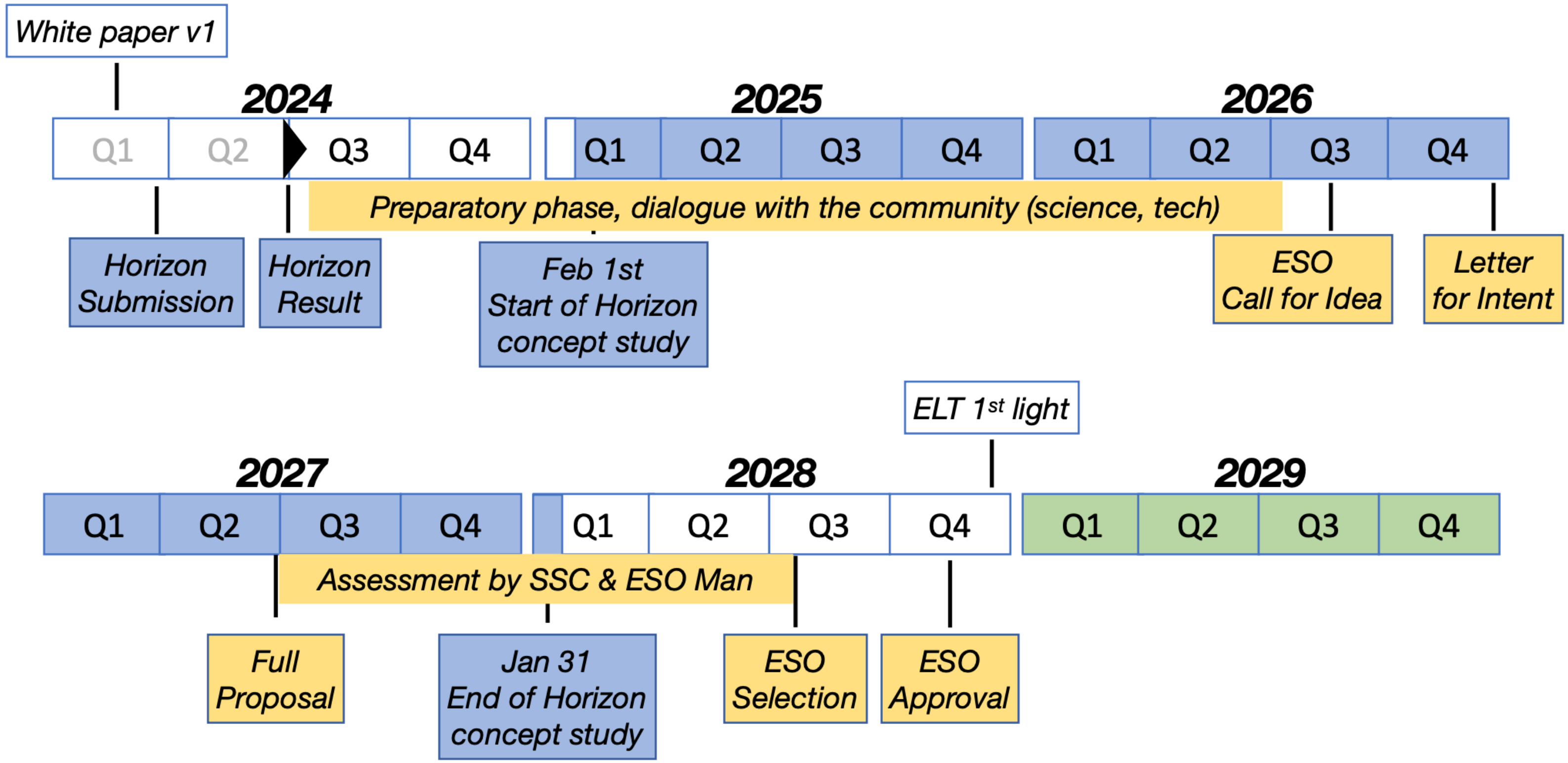
Wide-field Spectroscopic Telescope (WST)

History and current status

- Consortium created in 2021 in the context of the EU Horizon infrastructure concept call
- Resubmission of a proposal to Horizon 2024 with success
- Preparation of preliminary design (2025-2028)
- Not an ESO project yet
- But fully supported by ESO community
- First light: ~2040



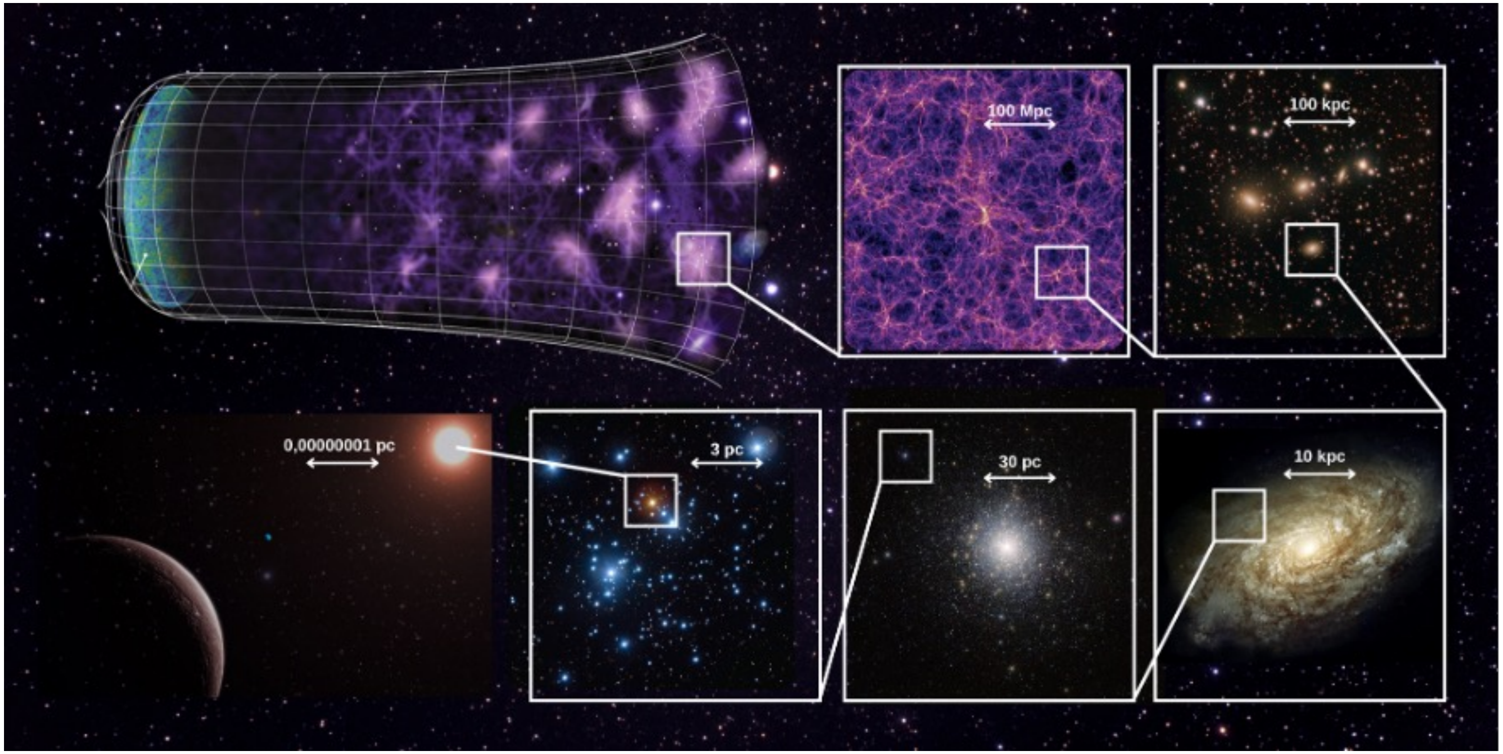
Timeline for the EU Horizon Grant



Preparing the ESO call for project after ELT

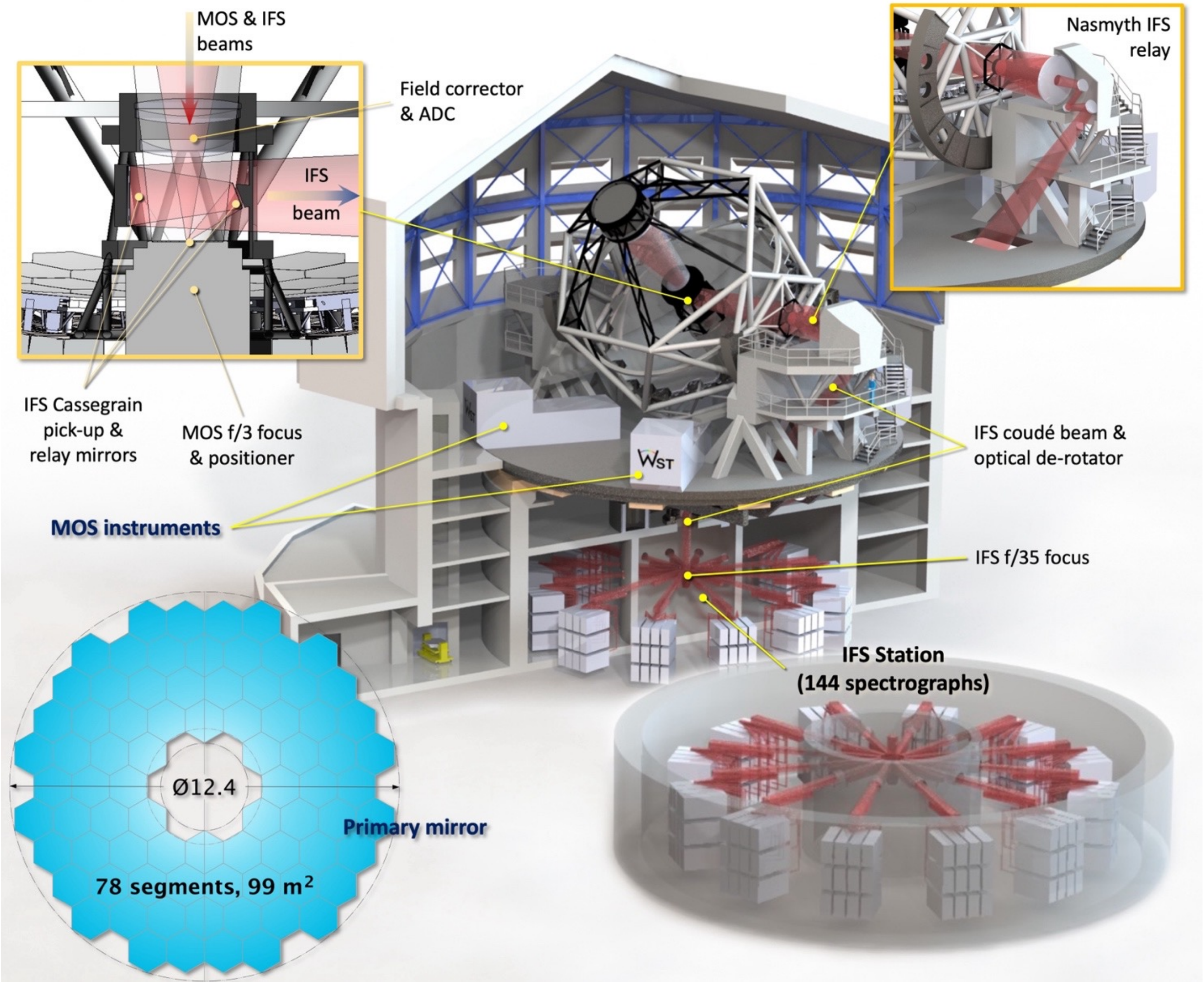
- Three year project ⇒ Full design of WST (telescope and instruments)
- Perfectly in line with ESO call

Science with WST – Four main topics



- **Cosmology:** mainly LSS for z>2
- **Extragalactic:** Cosmic web and its time evolution
- **Galactic:** Origin of elements
- **Time domain:** Gravitational waves with EM counterpart

Key numbers for a cosmological program

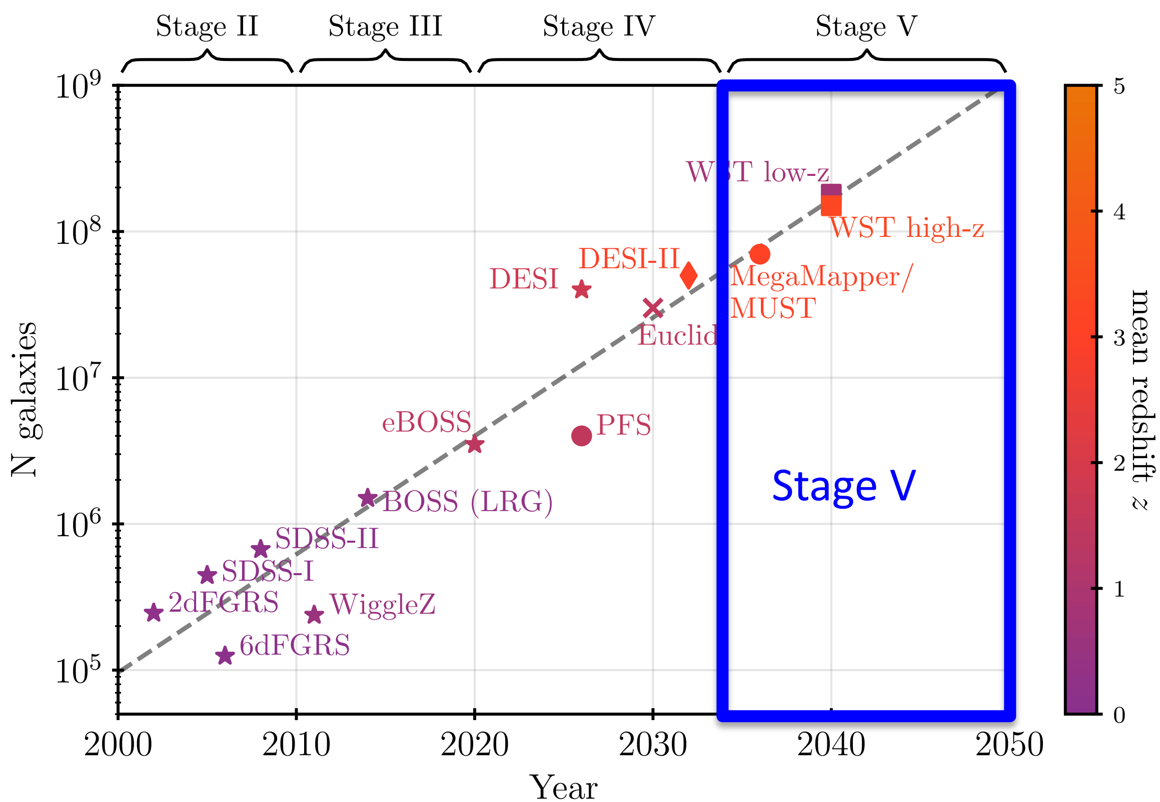


Telescope:
- 12m
- Cassegrain focus
- Segmented mirror

MOS:
- ~20000 positioners
- LR spectrograph
  - R ~3000-4000
  - $\Delta\lambda$: 370-970 nm

IFS:
- Integral field spectrograph
- 3x3 arcmin^2

Progress in Spectroscopic Surveys

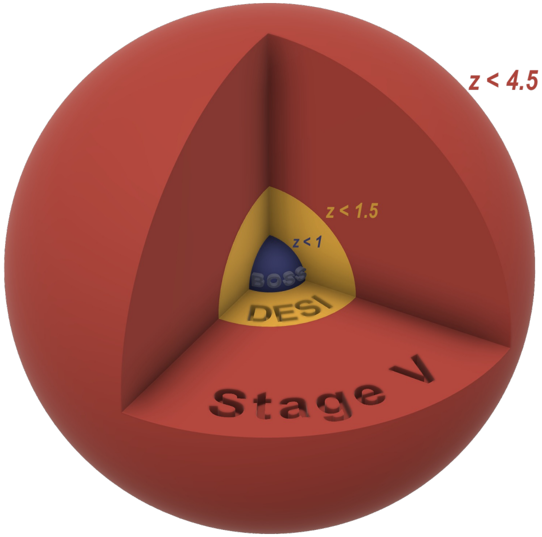


- Exponential increase in the number of redshifts
- 50,000 LRGs in SDSS-I (2005) , 40M redshifts in DESI (2025)
- Mean slope: a factor ~8 in the number of redshifts every 10 years
- Increase in redshift range: SDSS-I (z<0.5) Stage V (z>2)

Motivations for Stage V projects

Science case in LSS for stage V

- H_0 tension: Early Dark Energy
- Dynamical EoS of Dark Energy
- S8 tension: Growth of the structures
- Inflation: Scale dependence of bias, bi-spectrum
- Neutrino masses



Future spectroscopic surveys require mapping 2<z<4.5 (even 2<z<5.5) Universe

- Larger redshift range and therefore volume
- Several projects
  - **Spec-S5:** twin 6m telescopes with 13,000 robotic positioners
  - **MUST:** 6.5 telescope with ~20,000 robotic positioners
  - **WST**: ~12m telescope with ~20,000 robotic positioners
- New-developed technologies ⟶ **x10 modes** compared to DESI and Euclid

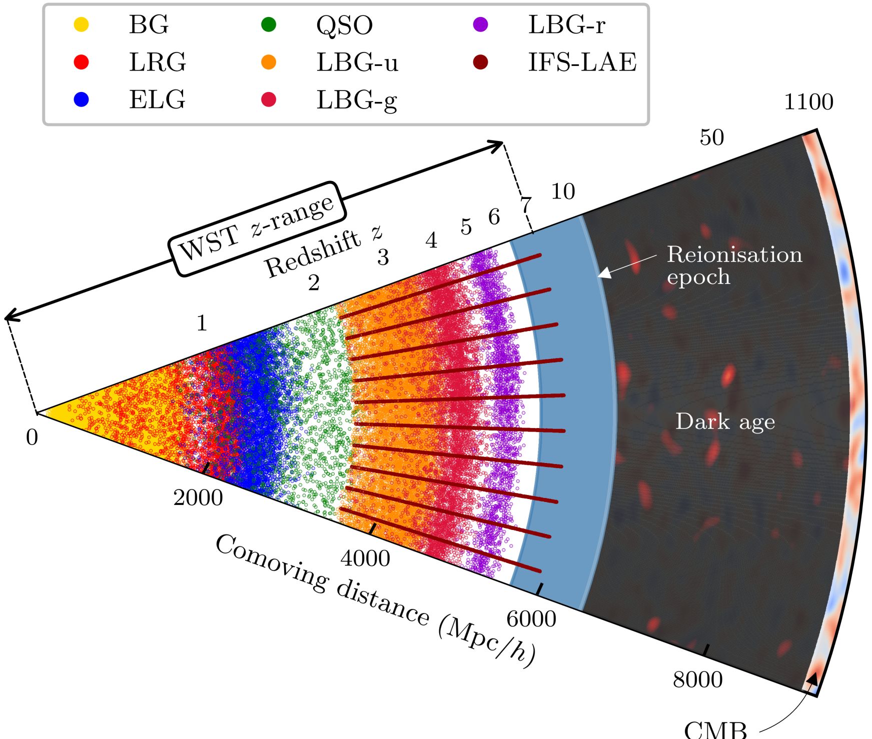
Telescopes for cosmology by 2035

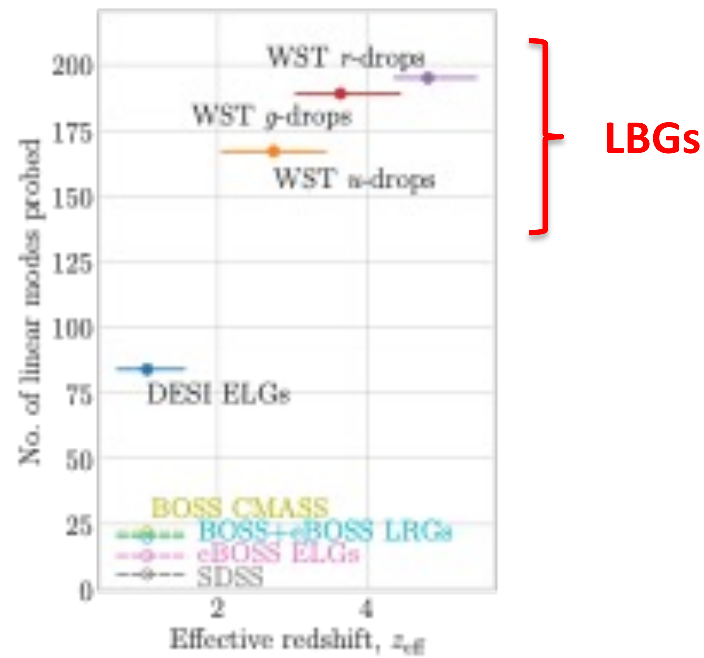
Instrument (year)	Primary/m^2	Nfiber	Reflections	Product	Speed vs SDSS
SDSS (1999)	3.68	640	0.9^2	1908	1.00
BOSS (2009)	3.68	1000	0.9^2	2980	1.56
DESI (2020)	9.5	5000	0.9^1	42,750	22.4
PFS (2024)	50	2400	0.9^1	108,000	56.6
4MOST (2024)	12	1624	0.9^2	15,800	8.3
MUST (2030)	28	20,000	0.9^2	454,000	238
Spec-S5 (Twin DESI) (2035)	30×2	13,000	0.9^1	702000	368
MSE (2040)	78	3249	0.9^1	228,000	119
WST (2040)	105	20,000	0.9^2	1,701,000	891

How to read the table? FoM?

- Speed = Surface x Number of positioners
- WST is ~2.5 times faster than Spec-S5
- Timescale: Spec-S5~ 2035 / WST ~2040

Volume to explore with WST





- **A legacy low-z (z<1.6) redshift survey** (cluster of galaxies, extragalactic transients, cross-correlation with other surveys (HI and CMB maps, Weak lensing), science of cosmic voids…)
- **A z>2 galaxy and quasar survey** (Lyman-Break galaxies, **LBG** and Ly-α Emitter Galaxies, **LAE)**

Selection of z>2 galaxies

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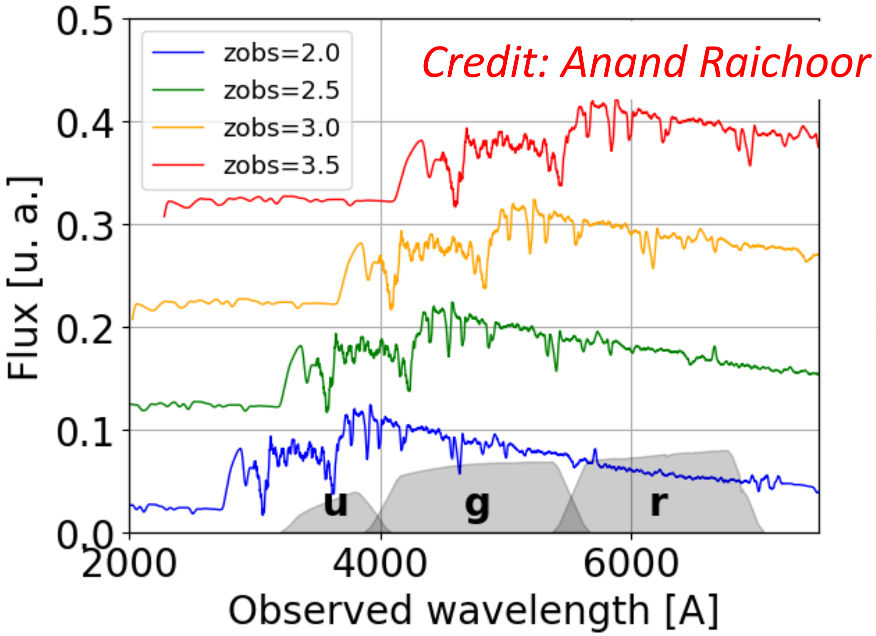
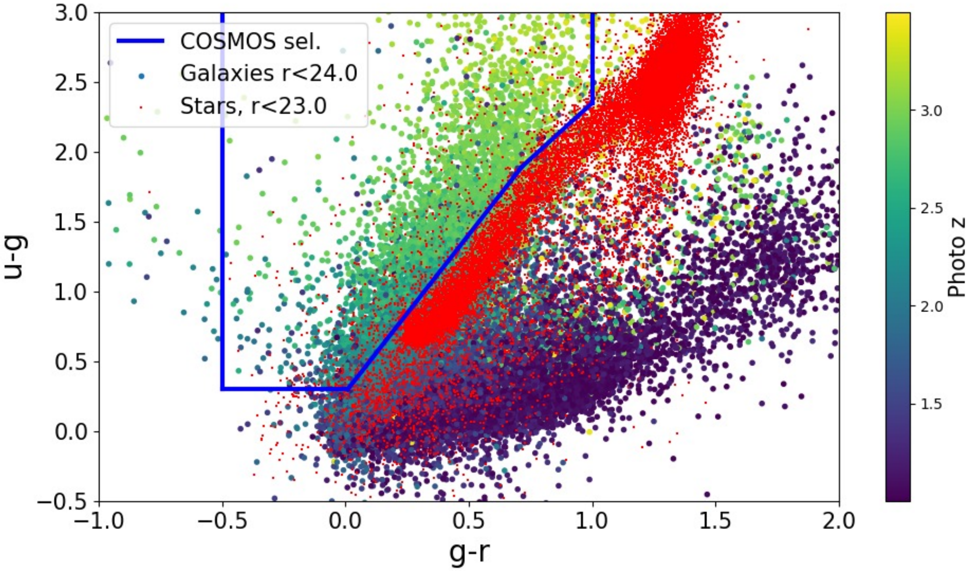
Validation with Pilot Surveys

LBG selection with u-dropouts

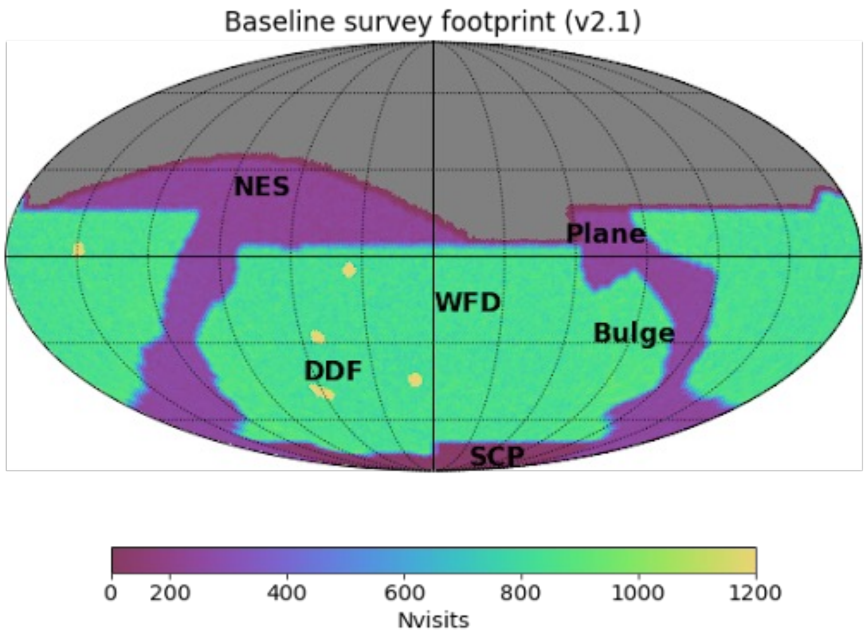


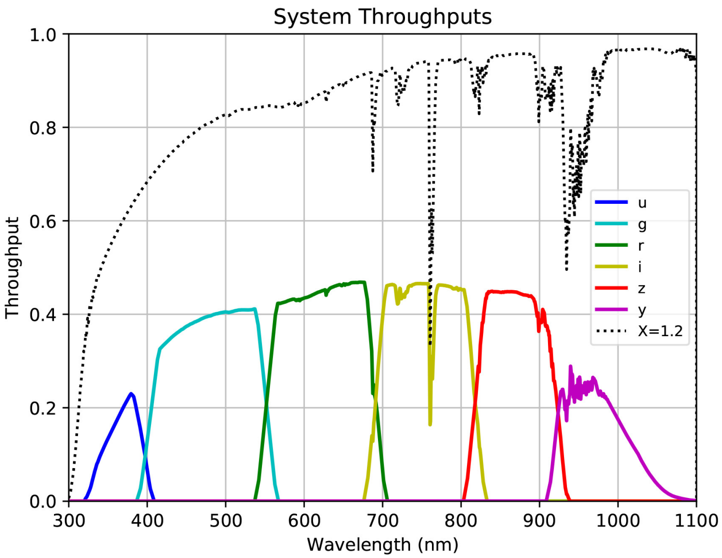


Principles

- Redshift range: 2<z<3.5
- Use the flux decrement bluewards of the Lyman limit due to HI absorption
- Need a deep u-band: LSST/Rubin In South

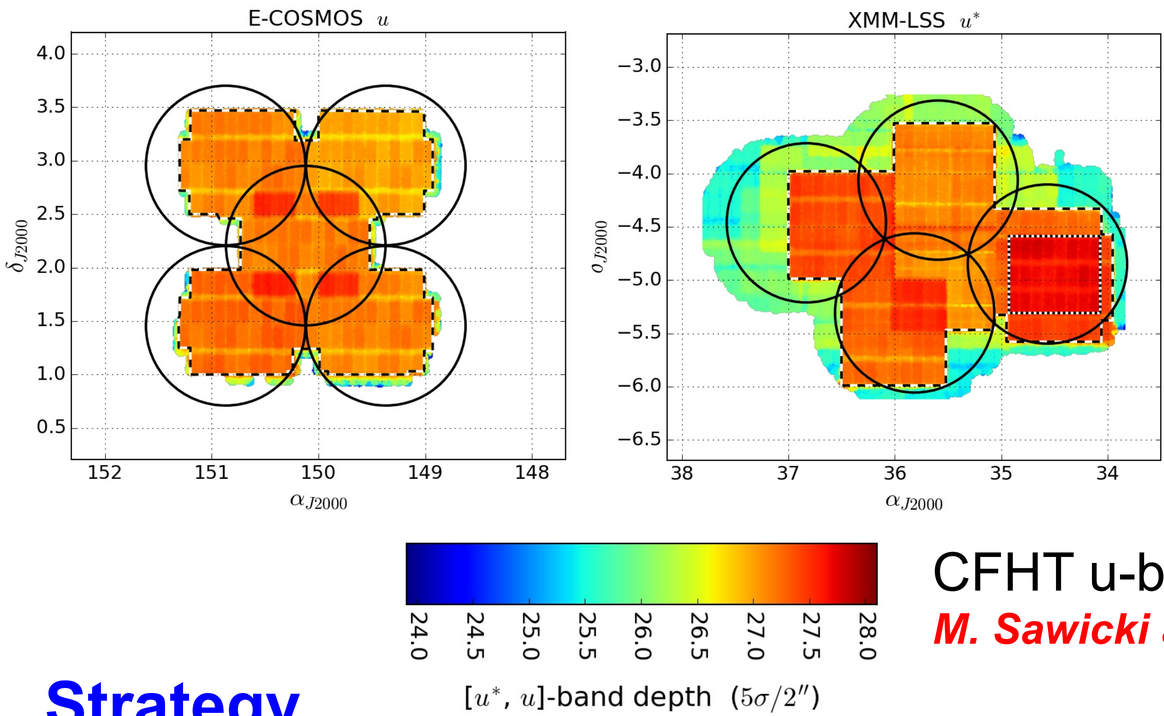
Future Imaging in South

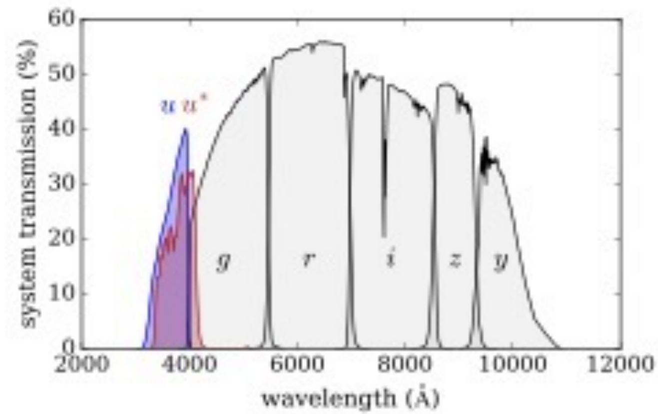




- LSST-Rubin will be available at the time of WST
- Footprint ~15,000 deg^2
- **Depth (10 years), u: 26.1**, g: 27.4, r: 27.5, i: 26.8, z:26.1, y:24.1
- Proof of principle with DESI and with CLAUDS imaging

Deep u-band imaging with CLAUDS for pilot survey





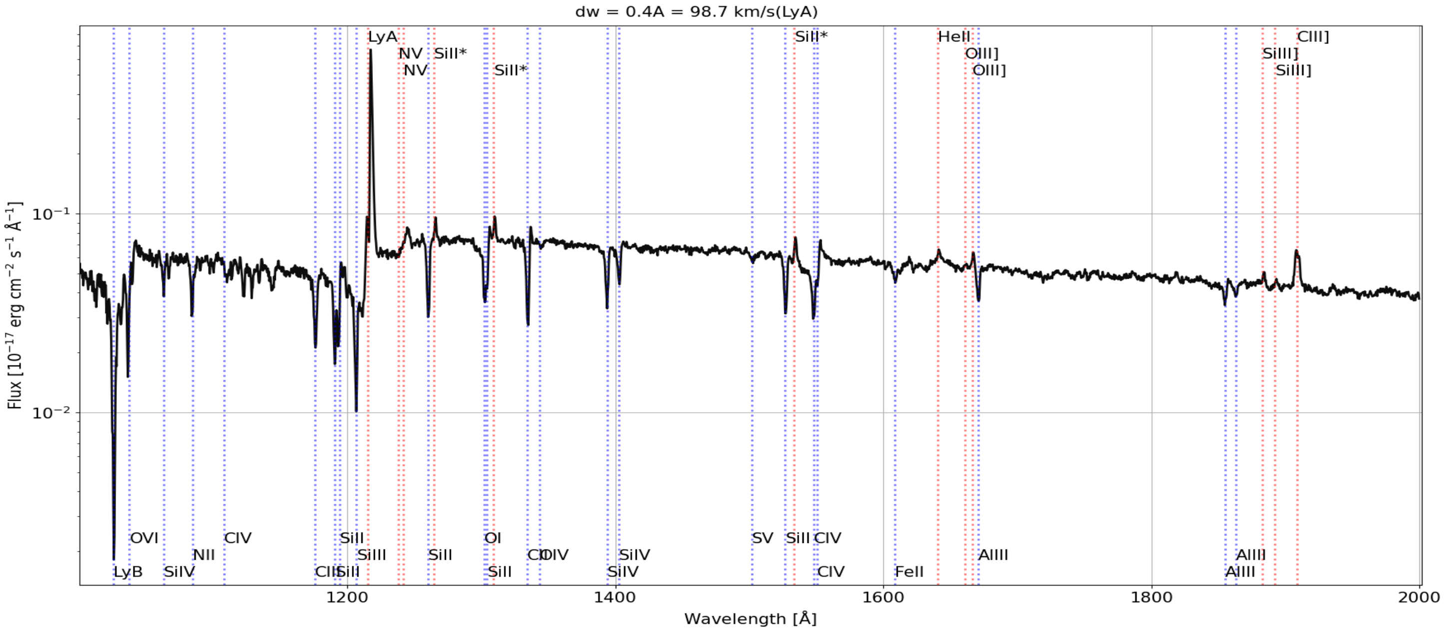
CFHT u-band + HSC grizy-bands

M. Sawicki and S. Arnouts, arXiv:1909.0589

Strategy

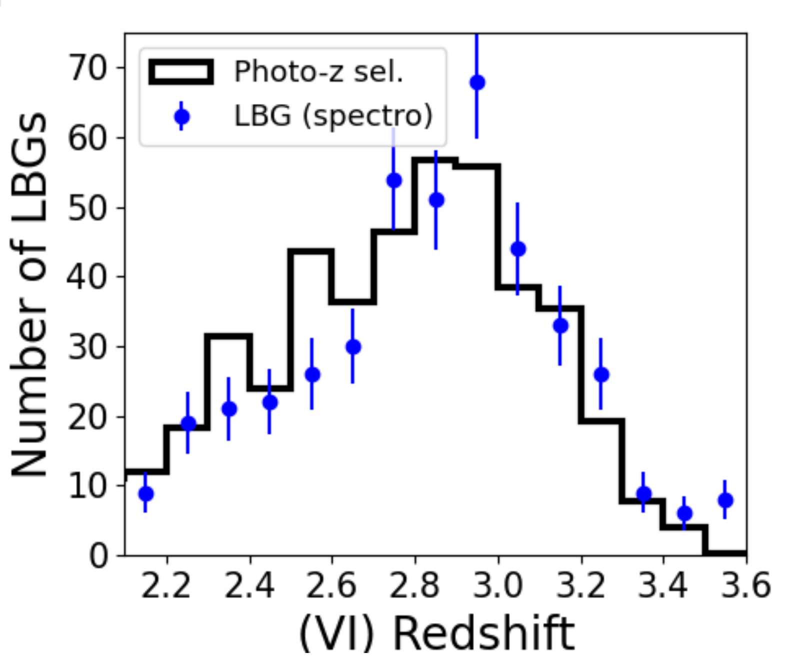
- u-dropout with CLAUDS in COSMOS and XMM fields
- Ultra-deep u-bands: u-depth better than ~27-27.5
- The depth is sufficient to validate the imaging that will be available for future spectroscopic surveys (Spec-S5, WST,….)

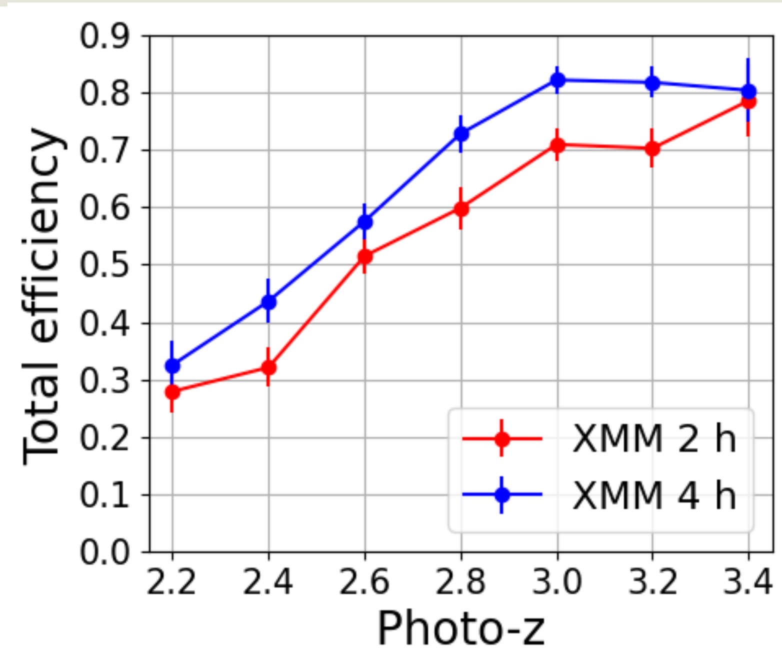
Pilot survey with DESI



– 15000 LBG Targets observed with DESI
– Two observed fields (COSMOS and XMM)
– Exposure time: from 2 hours to 5 hours
– Results in two papers:
  - *Ruhlmann-Kleider V. et al., arXiv:2404.03569 (validation of u/g dropout)*
  - *Payerne C. et al., arXiv:2410.08062 (u dropout with CFIS)*

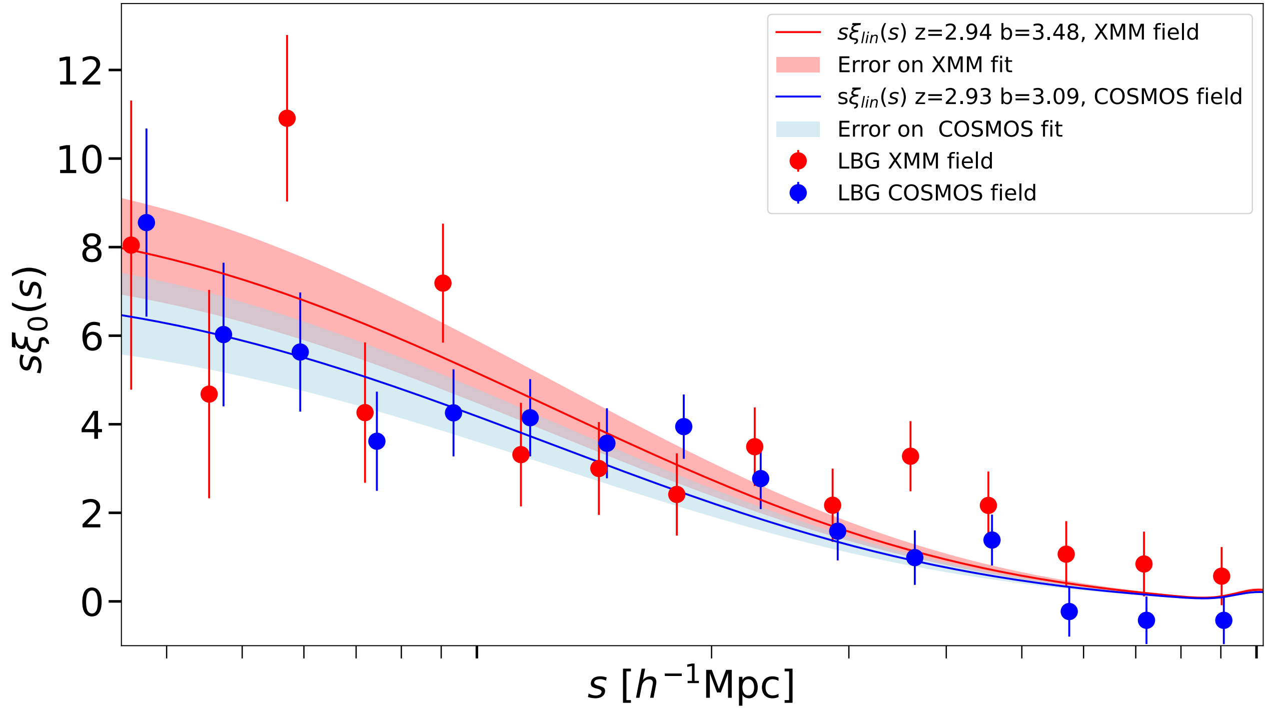
Redshift and Efficiencies





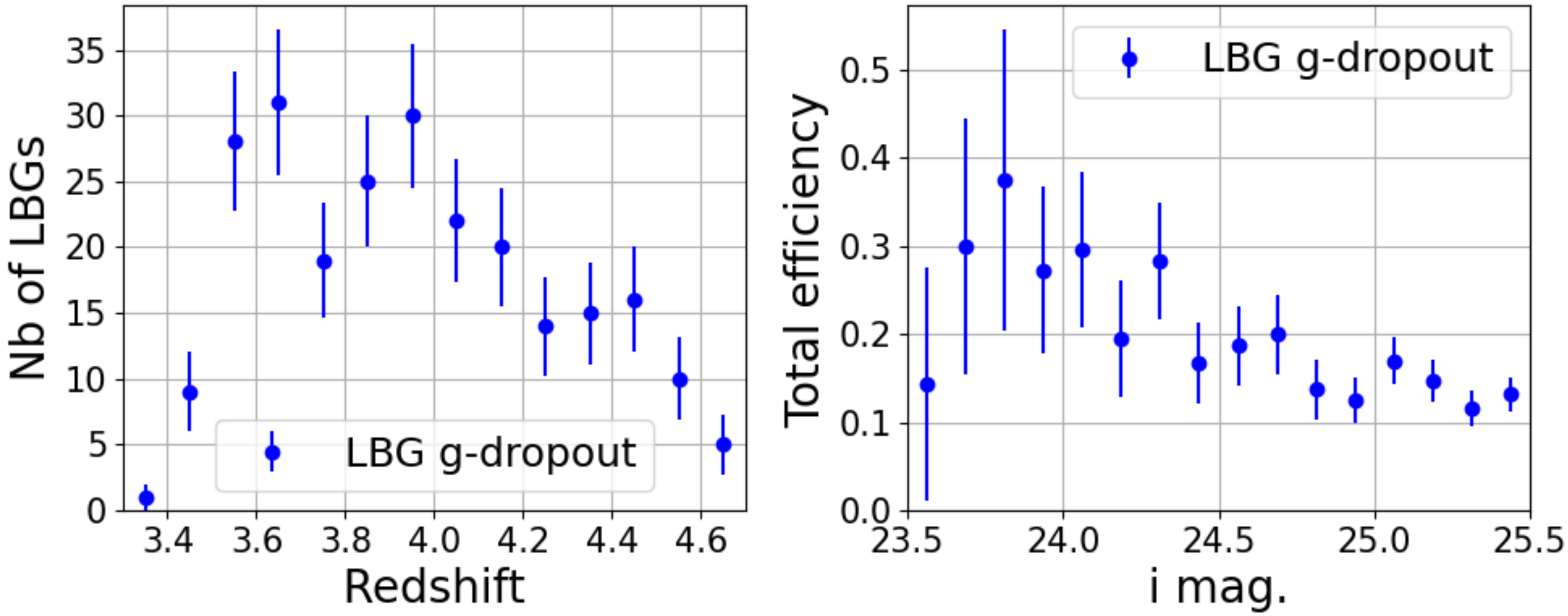
- Excellent agreement between photo-z and spectro redshifts
- Total efficiency >70% for 2 hours and z>2.8 (<0.5h with 12m Tel.)
- Low efficiency for z<2.5, two possible origins:
  - Lower SNR due to degraded throughput of the instrument in blue
  - Lower fraction of Ly-α emission (galaxy evolution)

Clustering with LBGs



- With a refined LBG sample (purity~95%)
- Enough LBGs to get an estimate of LBG bias
- At z=3, b ~3.3 $\pm$ 0.3 $\Rightarrow$ **Used in the forecasts**

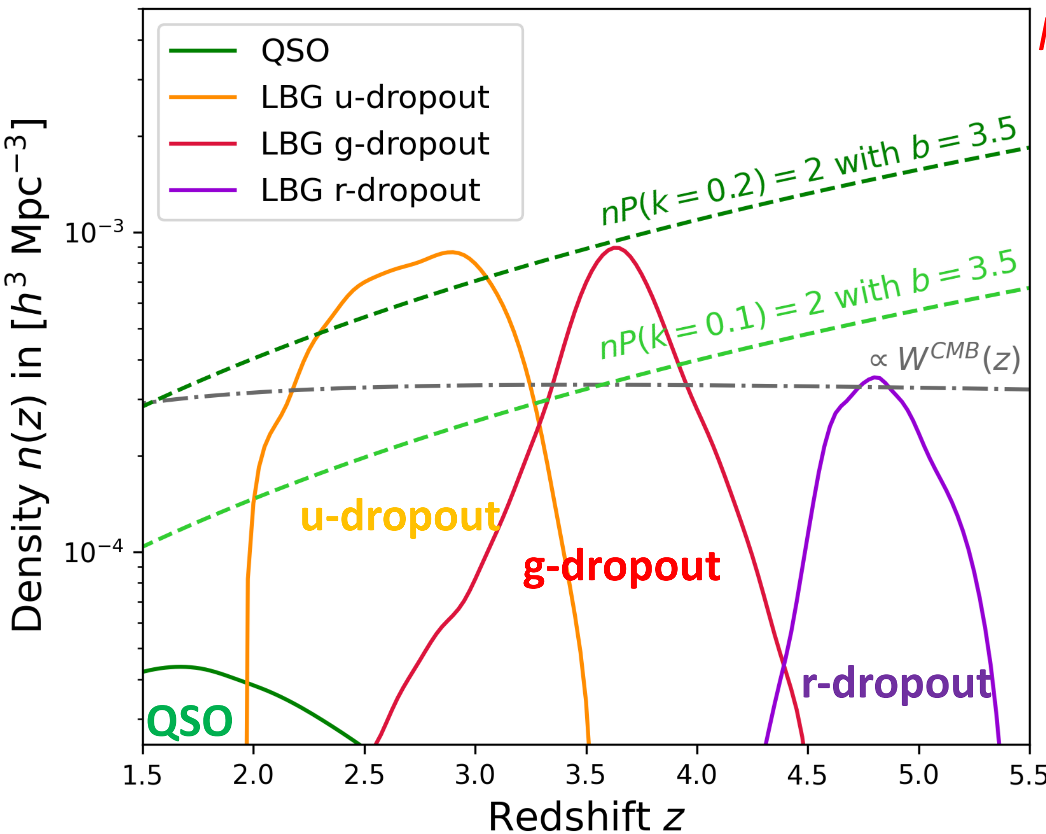
g-dropout with HSC and DESI



- Same principle: ugr bands ⟶ gri bands
- Spectro-redshift distribution (3.5<z<4.5)
- Efficiency: ~20% with 2 hours and ~35% with 5.5 hours
- For 12m telescope, it will require ~1 hour to get a efficiency at ~50%

Forecast for WST

LBG surveys – n(z)



Mainieri et al., 2024, arXiv:2403.05398

u-dropout

- r<25.0
- Exposure time < 0.5h
- Efficiency vs z: up to 70%

g-dropout

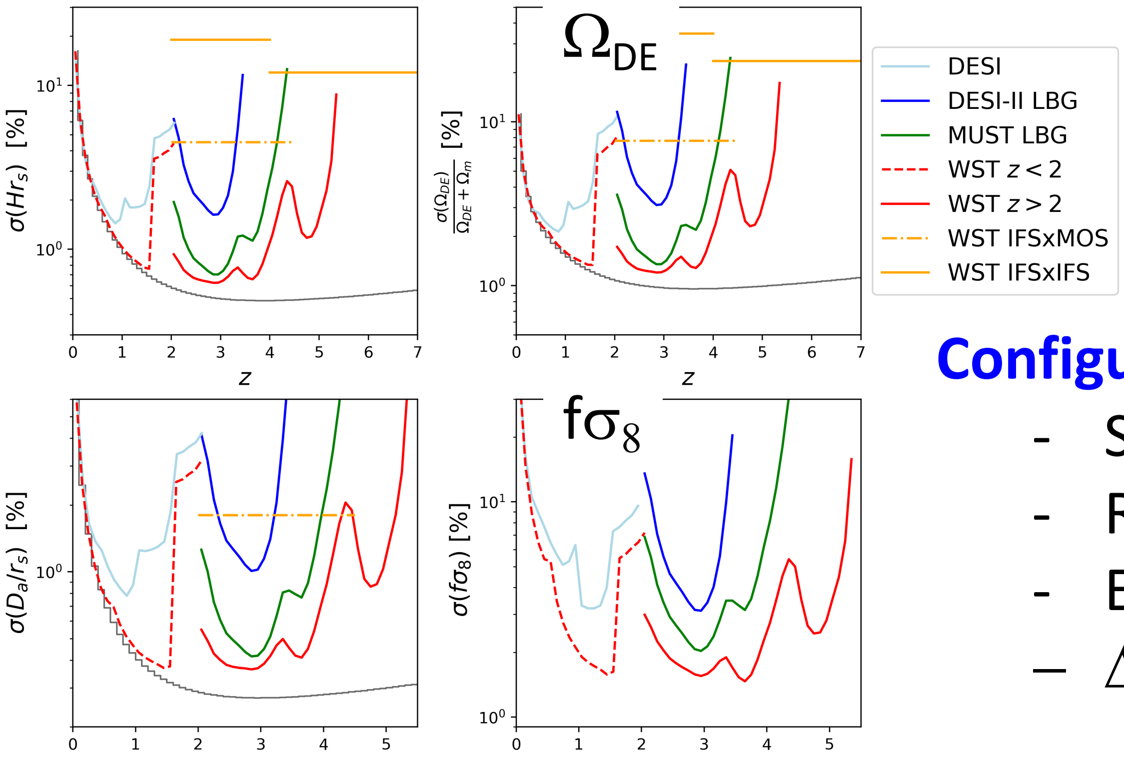
- i<25.0
- Exposure time ~ 1h
- Efficiency: 50%

r-dropout

- z<25.5
- Exposure time ~ 2h
- Efficiency: 50%

- u/g/r dropouts to select LBGs ⇒ redshift 2.0<z<5.5
- r-dropout possible with 12m telescope ⇒ Eff=50% for 2 hours
- Overlap with QSOs distribution and CMB lensing kernel

Dark Energy and structure growth

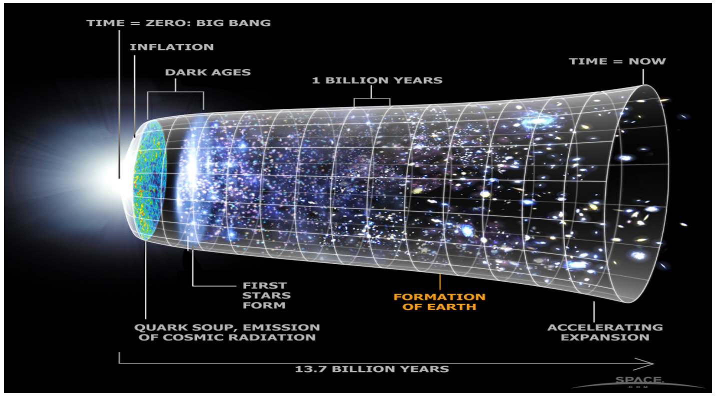


Configuration for WST

- Surface: 15,000 deg^2
- Redshift range: 2.0<z<5.5
- Exposure time: 0.5h, 1h, 2h
- Δz binning: 0.1

- DE content: for 2<z<4, almost at cosmic variance limitation
- Measurements up to z=5.5 (matter-dominated era)
- Indirect constraints on EDE models and exotic models

Testing Inflation with Non-Gaussianity



Description of the primordial potential Φ

$$\Phi = \varphi + f_{NL}.(\varphi^2 - <\varphi^2>)$$

φ : a gaussian random field
f_{NL} : amplitude of the non-Gaussianity

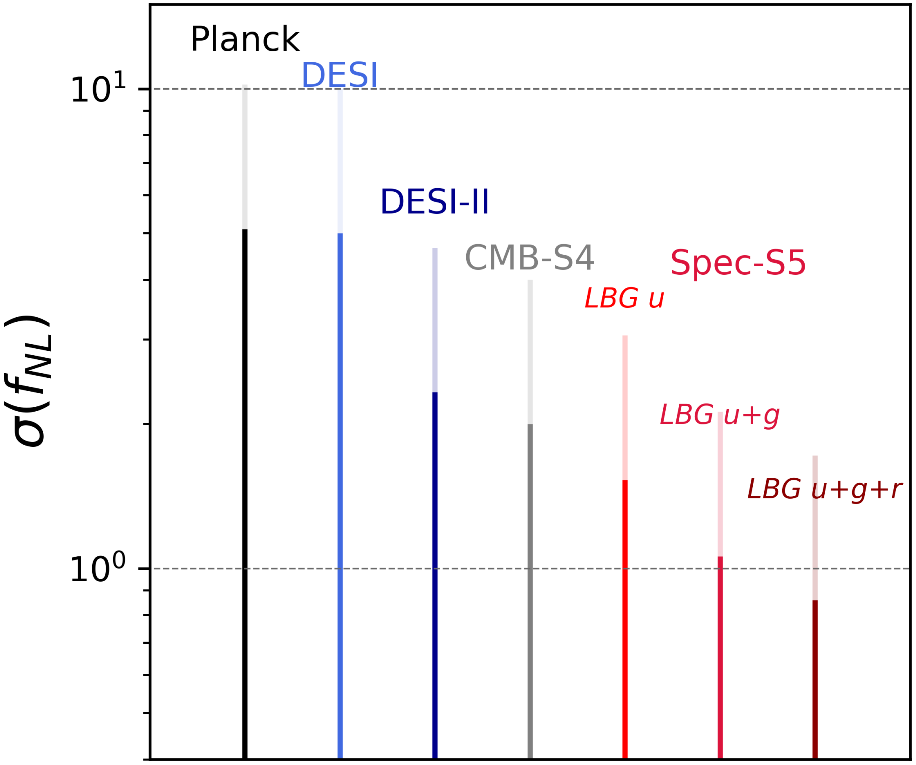
Primordial Non-Gaussianity, a test of inflation

- Primordial fluctuations distributed almost Gaussian with the simplest slow-roll models $f_{NL} \sim O(10^{-3})$
- But many alternative inflation models predict $f_{NL} > 1$
- CMB is cosmic variance limited : $\sigma(f_{NL})\sim5$

3D survey of galaxies

- Scale dependence of the bias at large scales in power spectrum
- Large volume (optimal for high-z), $\sigma(f_{NL})\sim1$ (better with bi-spectrum)

Primordial Non-Gaussianities

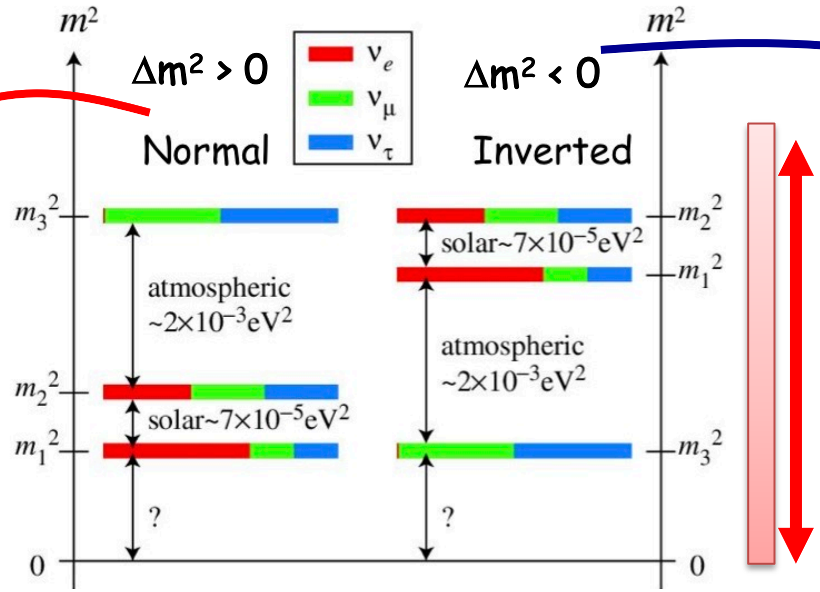


- With u/g/r dropouts we can break $\sigma(f_{NL})$ ~1 barrier
- Sensitive to inflation models with multi-fields
- Gain by adding r-dropouts: $\sigma(f_{NL})=1.06 \longrightarrow \sigma(f_{NL})=0.86$
- Possible with 12m telescope

Credit: William d'Assignies D.

Neutrino masses with cosmology

Σm > 60 meV



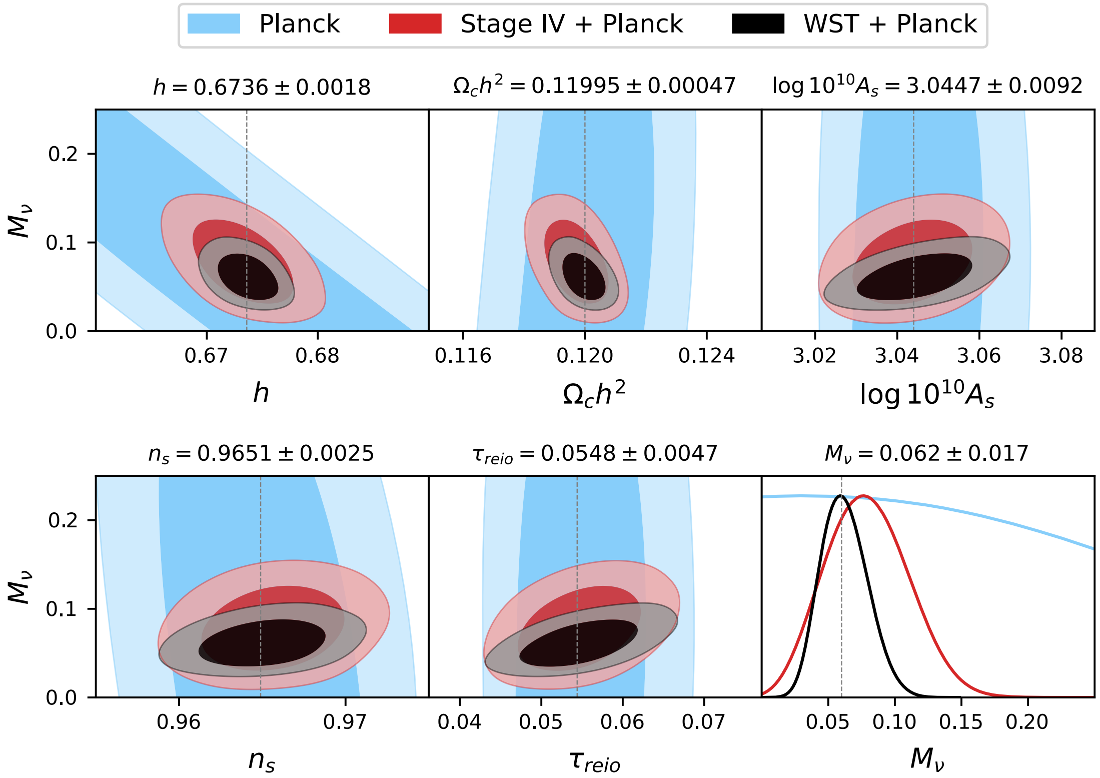
Σm > 100 meV

Cosmological neutrinos current limit <80meV at 95%

Measurement of neutrinos masses with cosmological neutrinos

- Particles Physics: atmospheric and solar oscillations
- No constraint on absolute masses
- Current constraint by cosmology **(<~80meV at 95%)**
- Normal hierarchy favored by cosmology: minimal mass~60 meV
- With **$\sigma(\Sigma m_\nu)$~20/15 meV** → Precision better than 3σ/4σ

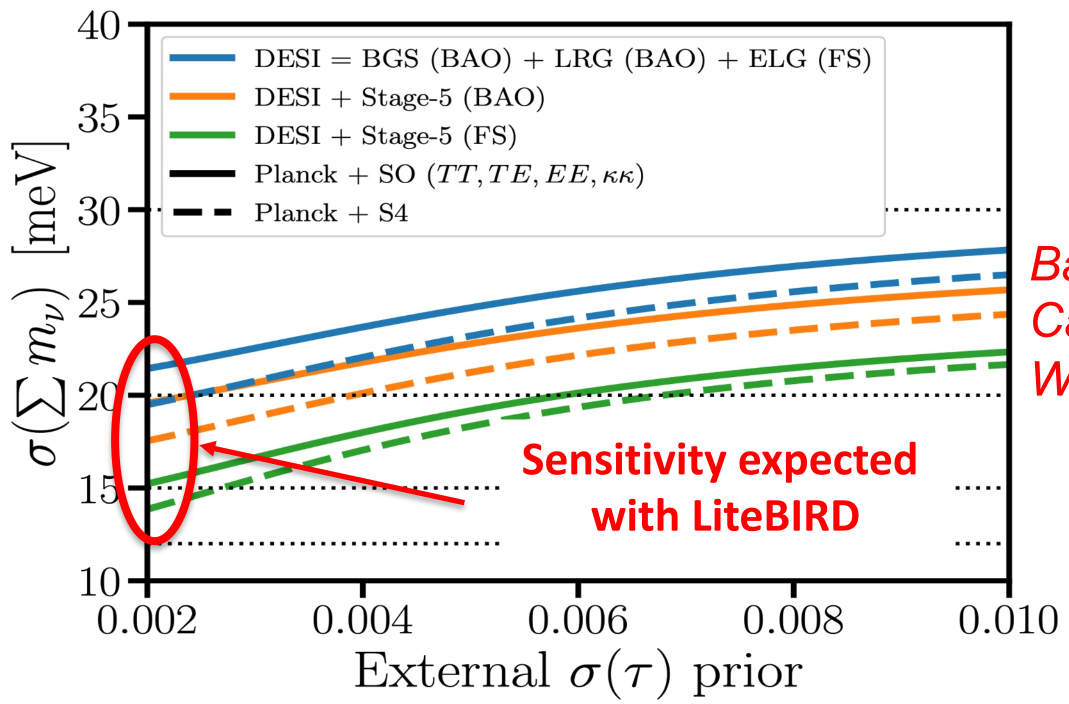
Neutrino mass



- CMB is sensitive to $\sum m_\mu$
- Degeneracy with Ω_m/H_0
- BAO measures Ω_m and breaks the degeneracies
- Full Shape analyses are directly sensitive to $\sum m_\mu$
- With WST+Planck:

$\sigma(\Sigma m_\nu)$ ~17 meV

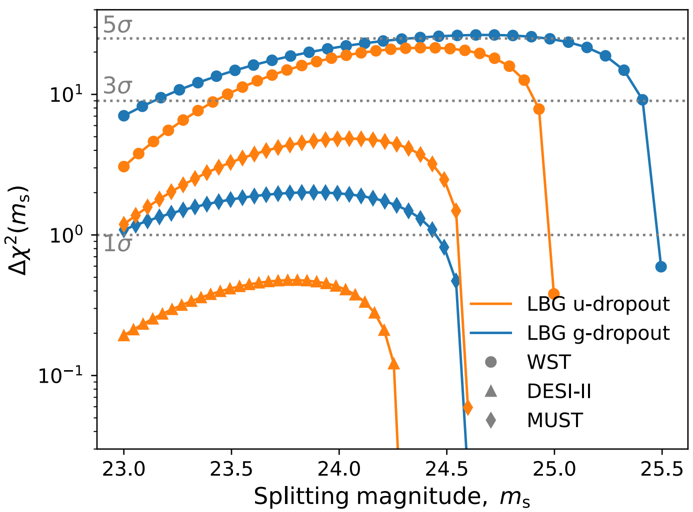
Neutrino mass with future CMB projects

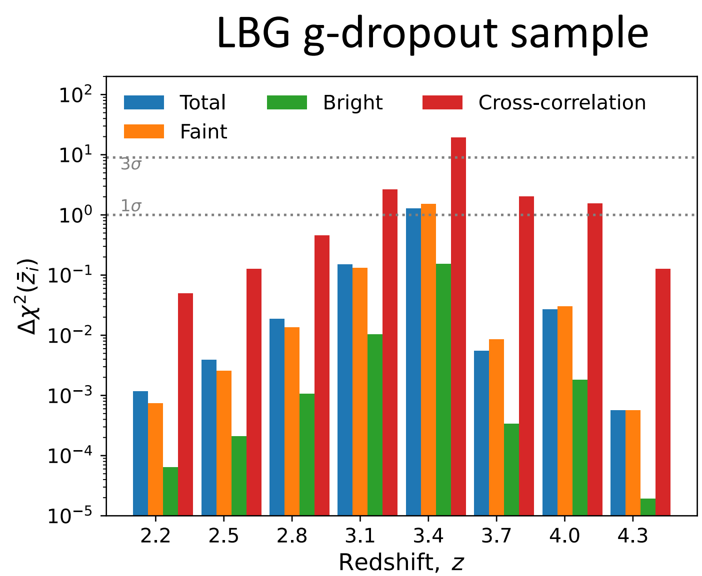


Based on Sailer, Castorina, Ferraro & White, arXiv: 2106.09713

- With LiteBIRD, expected error on $\sigma(\tau)$: ~0.02
- Sensitivity on Σm_ν < 15 meV
- Measurement of Σm_ν better than 4σ

Relativistic Doppler





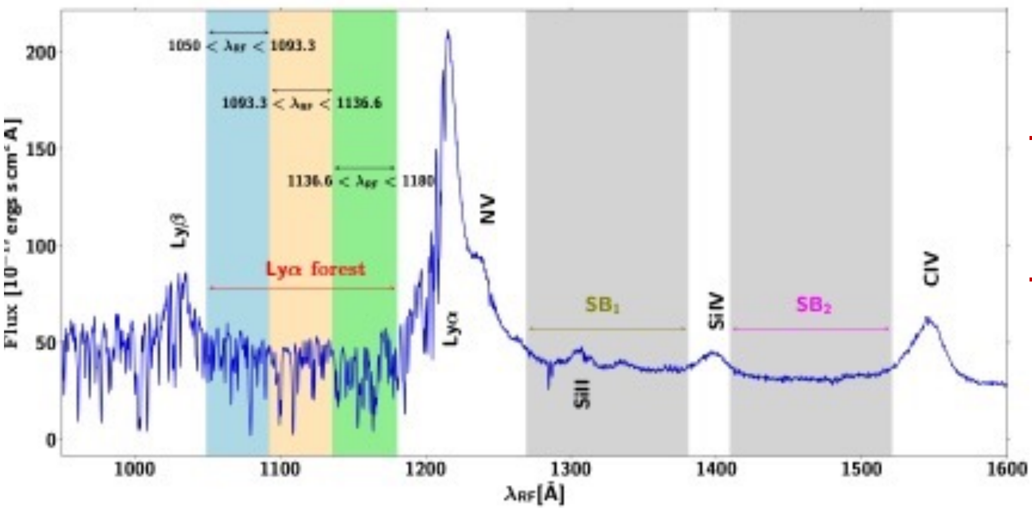
– With large amount of galaxies at high-z, galaxy clustering is sensitive to relativistic Doppler effect predicted by GR

– Split in two sub-samples (bright/faint) based on m_s

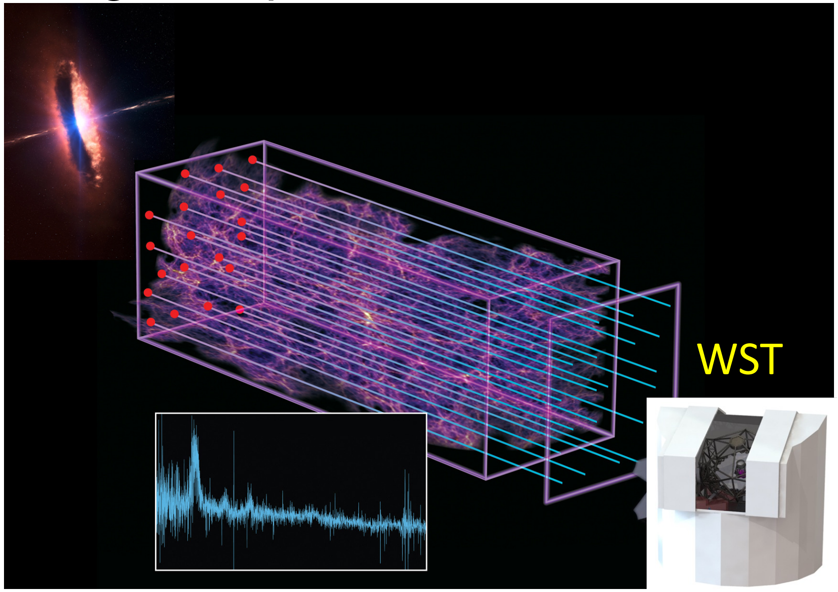
→ Cross-correlation between the two subsamples

– 4σ/5σ detection of relativistic Doppler with u/g dropouts

Another Tracer of Matter: Ly-α forest

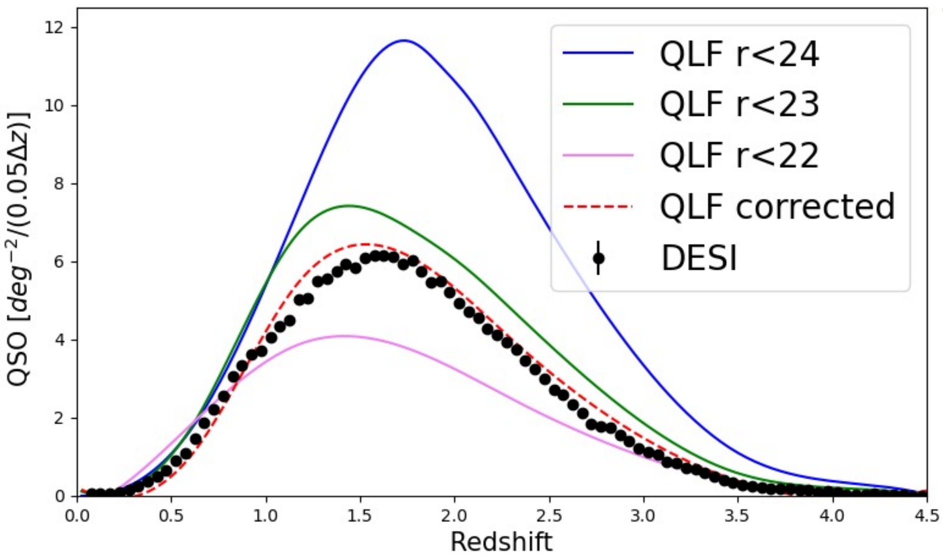


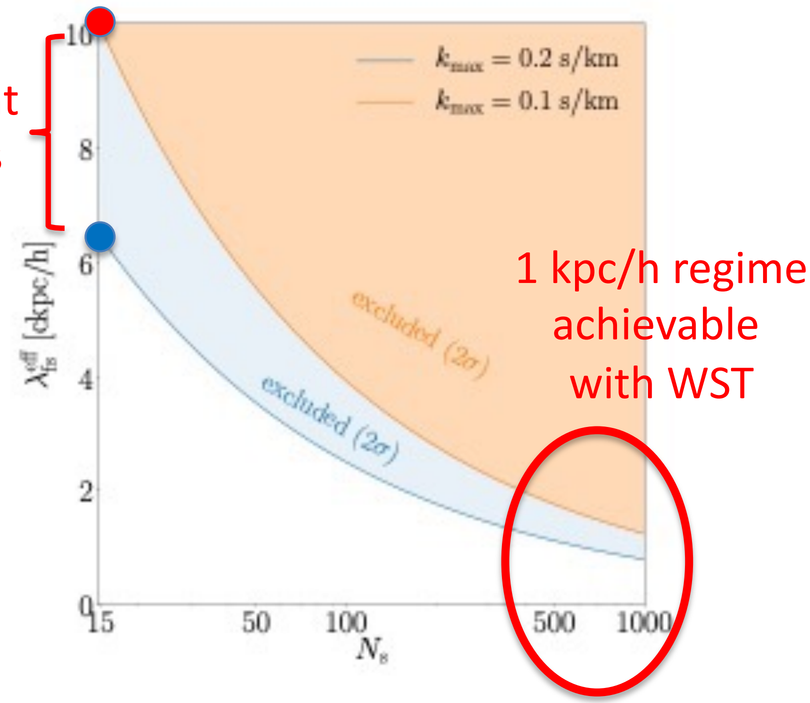
- For z>2, cross-correlation with LAE and LBG tracers
- Use Ly-α forests of quasars (2.0<z<4.5)
- HI absorption in intergalactic medium (IGM) along the line of sight of quasars



- We expect low density gas (IGM) to follow the dark matter density
- Compute correlation function between HI 'clouds'
- Measure the location of BAO
- An option: use Ly-α forest of LBGs?

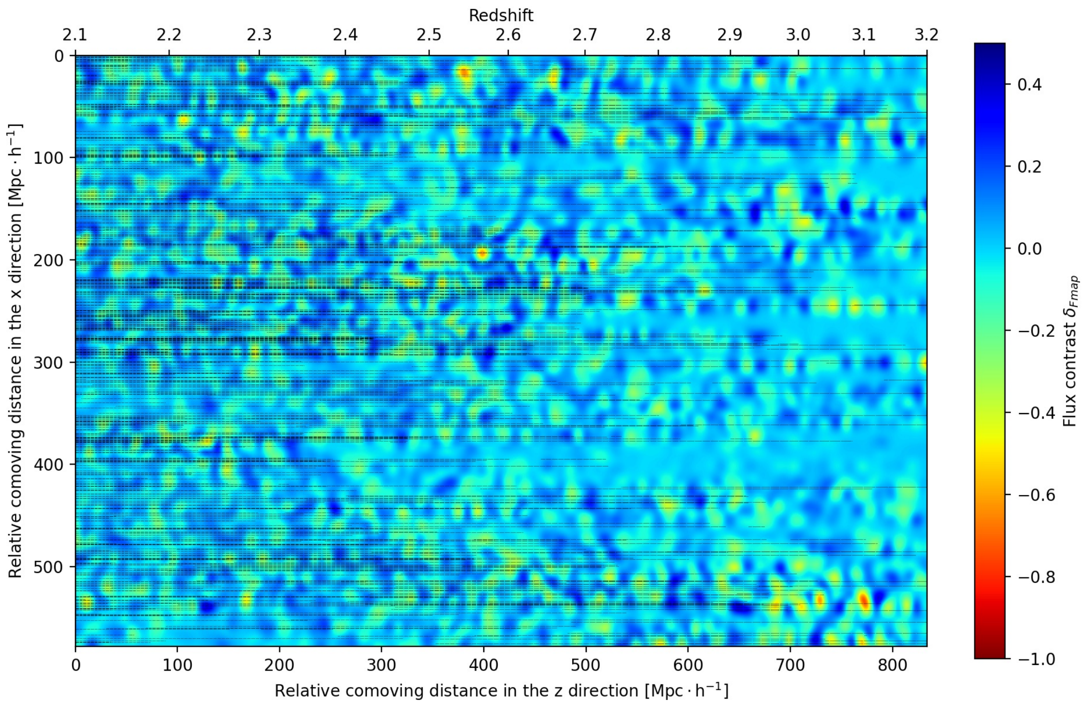
Ly-α Forest of QSOs (and LBGs?)





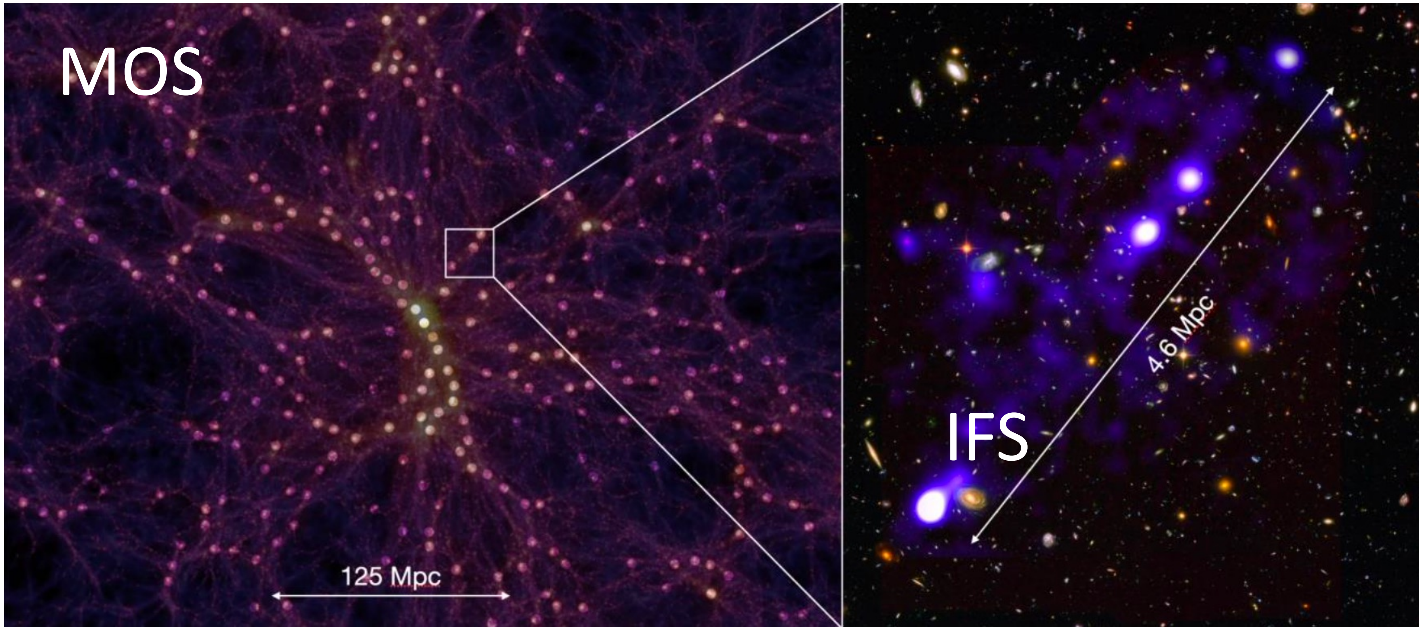
- Compared to DESI with r>24: 60 deg^{-2} → 150 deg^{-2}
- With exposure time ~0.5h: SNR~2-3 per pixel
- Gain in BAO compared to DESI: factor ~2.5
- Warm Dark Matter: 15 QSOs (z>4.0) → >1000 QSOs (z>4.0)

Ly-α Tomography



- 3D map: use Ly-a forest as tracer of IGM for 2.0<z<3.5
- u-dropouts: 500 to 1000 LoS per deg^2 with LBGs
- 150 LoS per deg^2 with QSOs
- Proto-clusters Science and Voids Science

Synergy with the IFU of WST



Integral Field Spectrograph

- IFS: 3x3 arcmin^2
- Synergy
  - MOS: Ly-α tomography with LBGs
  - IFS: resolved Ly-α emission

Conclusions

Feasibility of a high-z survey with WST

- Validation of both the u-dropout and g-dropout selections for LBGs with DESI
- Provide a realistic scenario in terms of exposure time, target density, redshift success rate and galaxy bias.

Forecasts for WST

- ~8000-10000 targets per sq. deg. with LSST 10 years
- Redshift range with LBGs: $2.0<z<5.5$
- With u/g/r dropouts **we can break $\sigma(f_{NL})$ ~1 barrier**
- Measurement of **Σm_ν better than 4σ**

Many other topics: Legacy low-z survey, WDM, Ly-α tomography with Ly-α forest of QSOs and LBGs….