Billion Object Apparatus (BOA)

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Outline

- Cosmological Motivation
- Spectroscopic Sample
- Instrumentation
- Survey Design
- Programmatics and Challenges

Cosmological Motivation

US Planning for Future Surveys

- Cosmic Visions: First step toward recognizing post-DESI, post-LSST cosmology opportunities
  - In parallel with efforts by National Academy and NOAO
- ~2-3years from now: Generate content for NSF Decadal Survey
- ~5-6years from now: SnowMASS and HEP prioritization process

Cosmic Visions Dark Energy: Science

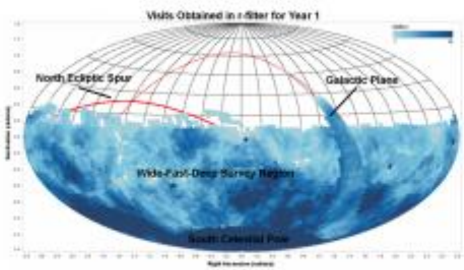
Scott Dodelson, Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uroš Seljak, Anže Slosar, Mark Trodden

Executive Summary

Cosmic surveys provide crucial information about high energy physics including strong evidence for dark energy, dark matter, and inflation. Ongoing and upcoming surveys will start to identify the underlying physics of these new phenomena, including tight constraints on the equation of state of dark energy, the viability of modified gravity, the existence of extra light species, the masses of the neutrinos, and the potential of the field that drove inflation. Even after the Stage IV experiments, DESI and LSST, complete their surveys, there will still be much information left in the sky. This additional information will enable us to understand the physics underlying the dark universe at an even deeper level and, in case Stage IV surveys find hints for physics beyond the current Standard Model of Cosmology, to revolutionize our current view of the universe. There are many ideas for how best to supplement and aid DESI and LSST in order to access some of this remaining information and how surveys beyond Stage IV can fully exploit this regime. These ideas flow to potential projects that could start construction in the 2020's.

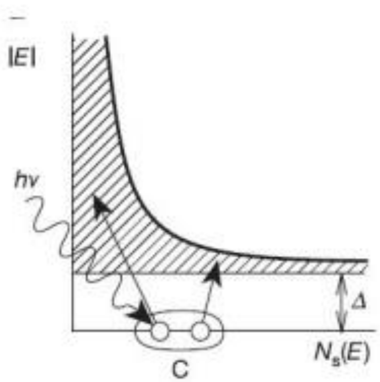
Cosmic Visions in DOE

- Several opportunities identified
  - Enhanced optical spectroscopy
  - Enhanced optical imaging
  - 21cm science



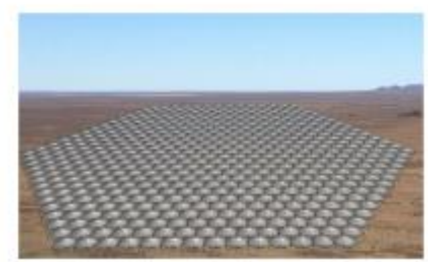
Southern Spectroscopic Survey Initiative (SSSI)

DESI-2



Low Resolution Spectroscopy
aka Hi-Res Photometry

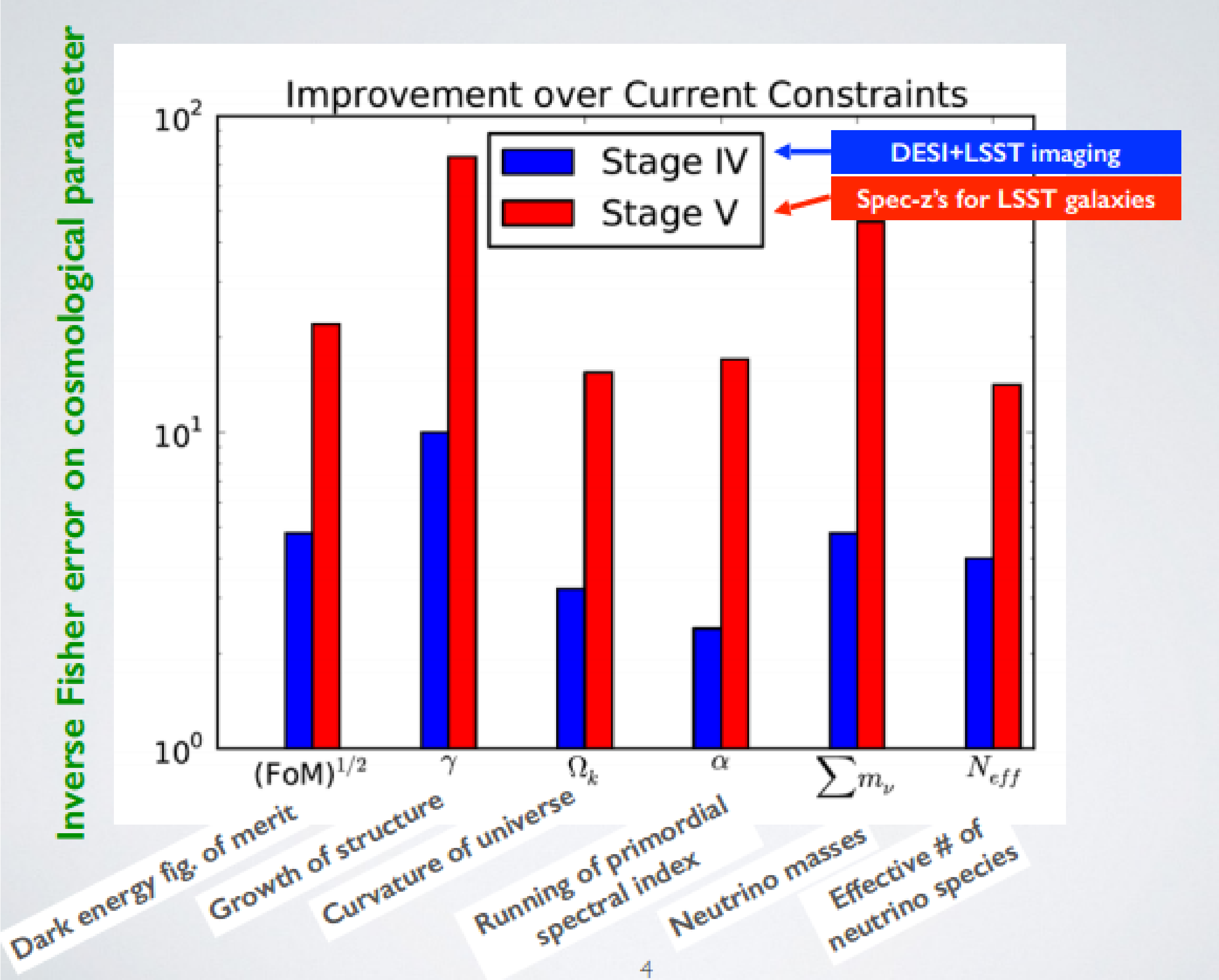
Billion Object Apparatus



21 cm

Information in the Cosmos

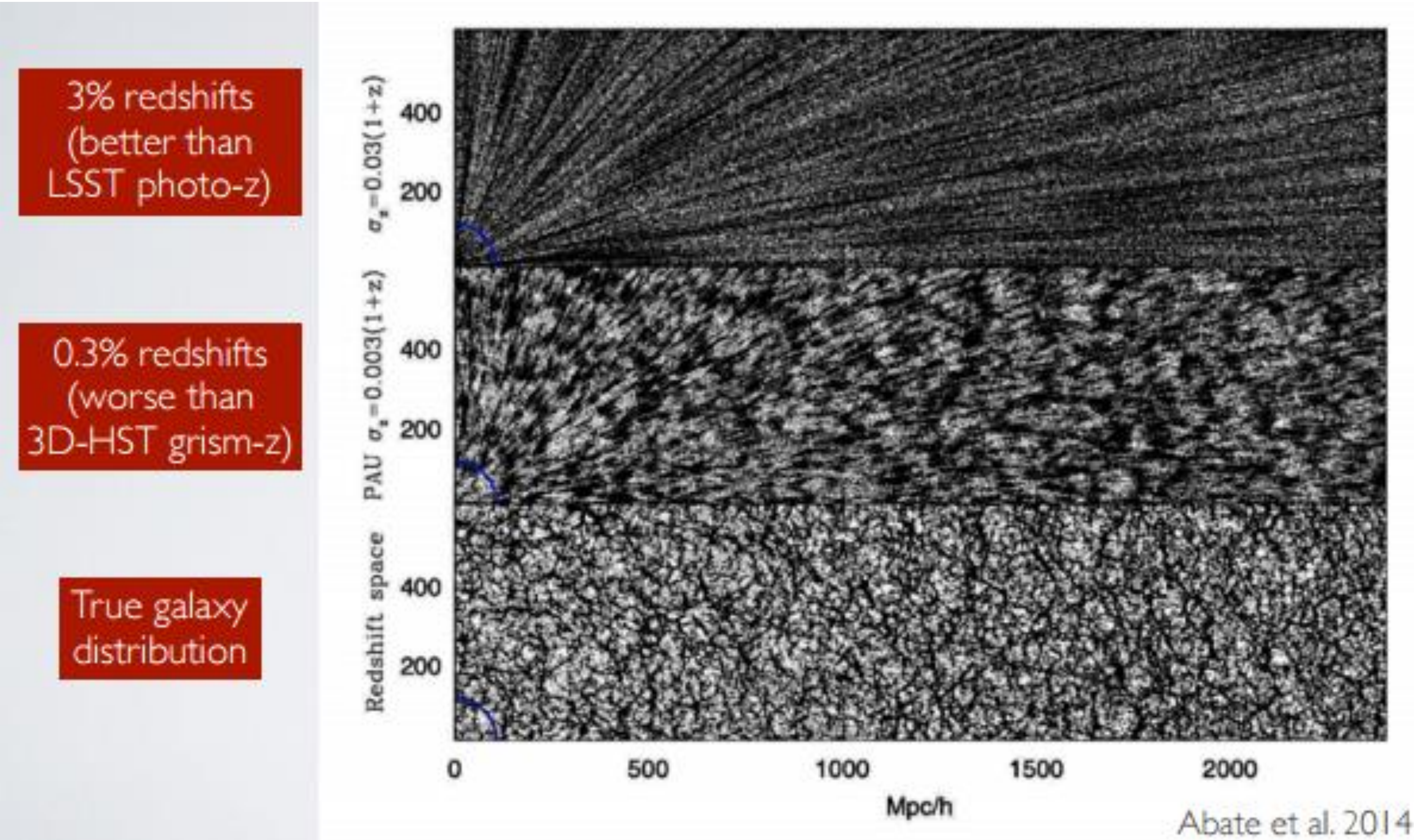
- Following DESI and LSST: Possible for major advances in standard cosmological model covering kmax<0.5 h Mpc^{-1} to z<3.5
- Not shown here: follow-up surprises from Stage-IV



Demand for Multiplexed Spectroscopy

- Three-dimensional large-scale structure measurements provide cosmological constraints through correlation statistics, void counting, cluster counts, and other means
- Mapping scales down to (quasi)-linear scales: number of 'linear modes' translates to quanta of cosmological information
- At $z<2$ →galaxy redshifts provide direct tracers
  - need high number densities: $n>1\times10^{-3}$ Mpc^{-3} at $z\sim0.5$, increasing with redshift
- Lyman-alpha forest using Lyman Break Galaxies (LBG) can now achieve this at $2<z<3.5$!
- In addition, Galaxy evolution, Milky Way, and transient science drivers
  - e.g. ESO Future of Multi-Object Spectroscopy Working Group Report
  - https://arxiv.org/ftp/arxiv/papers/1701/1701.01976.pdf

Spectroscopic versus Photometric Redshifts



Abate et al. 2014

BOSS/eBOSS/DESI

- Excellent programs
  - Measure BAO near cosmic variance limit to z<1.5
  - Percent level BAO at z>1.5
  - RSD measurements possible to kmax=0.2
  - Nearly 40M spectra
- Limited fiber budget → dependence on efficient target selections
  - Convolves complicated selection function across multiple imaging surveys
  - Sensitive to zeropoint calibration and artificial fluctuations in density from variations in imaging conditions
- Galaxies at higher redshifts are faint and hard to classify
  - LRG ID-ed by absorption, need high S/N
  - ELG ID-ed by narrow emission, separate from sky residuals
  - Wavelength coverage to lambda<1000 nm, limiting access to [OII] at z>1.6
- Systematic limitations of targeting/redshift completeness not yet clear

Statistical Limitations of BOSS/eBOSS/DESI

- BOSS/eBOSS >3 orders magnitude smaller sample than LSST
  - Galaxy population demographics not well-sampled
- DESI - science reach still not statistically limited
  - Lack mixed bias tracers and high density sampling of small-scale modes
  - Room to improve RSD at small scales ($k>0.2$)
- Statistics for future optical spectroscopic survey
  - More modes to explore
  - Can increase mix of tracer bias
  - Measure clustering to non-linear scales at $z<1.5$
  - Measure clustering to linear scales at $1.5<z<3.5$

- Potential for improved cosmology at small scales
- Potential to explore large scales to cosmic variance limit at high redshifts

- **Consider comprehensive science case for spectroscopic clustering program dedicated to saturating information content to z=3.5**

Modes Available After DESI

- Assume in the linear regime: kmax evolves as 1/g (0.15 at z=0)
- Potential to explore the nonlinear regime
  - increase kmax by factor of 2 → 8X increase in N modes
- Assume bias evolves as 0.84/g and sample modes to nP=1
- Compare to DESI: 10-15M modes

Modes available over 14,000 sqdeg in linear regime and the surface density of targets required to sample those modes

Redshift	Kmax (linear)	Modes (Millions)	N (per sqdeg)	N (nonlinear)
0.25<z<0.75	0.19	1.75	500	2000
0.75<z<1.25	0.25	7.37	1500	6000
1.25<z<1.75	0.30	17.47	3000	12000
1.75<z<2.25	0.36	31.97	4000	
2.25<z<2.75	0.41	50.67	6000	
2.75<z<3.25	0.47	73.33	7000	
3.25<z<3.75	0.53	99.75	9000	

Mode Counting

- 20k/sqdeg galaxies to z<1.75
  - 200M modes with new sample
  - Access non-linear regime
  - kmax=0.38 (z=0.5); kmax=0.6 (z=1.5)
- 20k/sqdeg galaxies at 1.75<z<3.25
  - 150M modes with new sample
  - New BAO, kmax=0.36 (z=2), kmax=0.47 a(z=3)
- 40k galaxies/sqdeg → full power spectrum to kmax=0.35 and z<3.25

Redshift	kmax	Modes (Millions)	N (per sqdeg)	N (nonlinear)
0.25<z<0.75	0.19	1.75	500	2000
0.75<z<1.25	0.25	7.37	1500	6000
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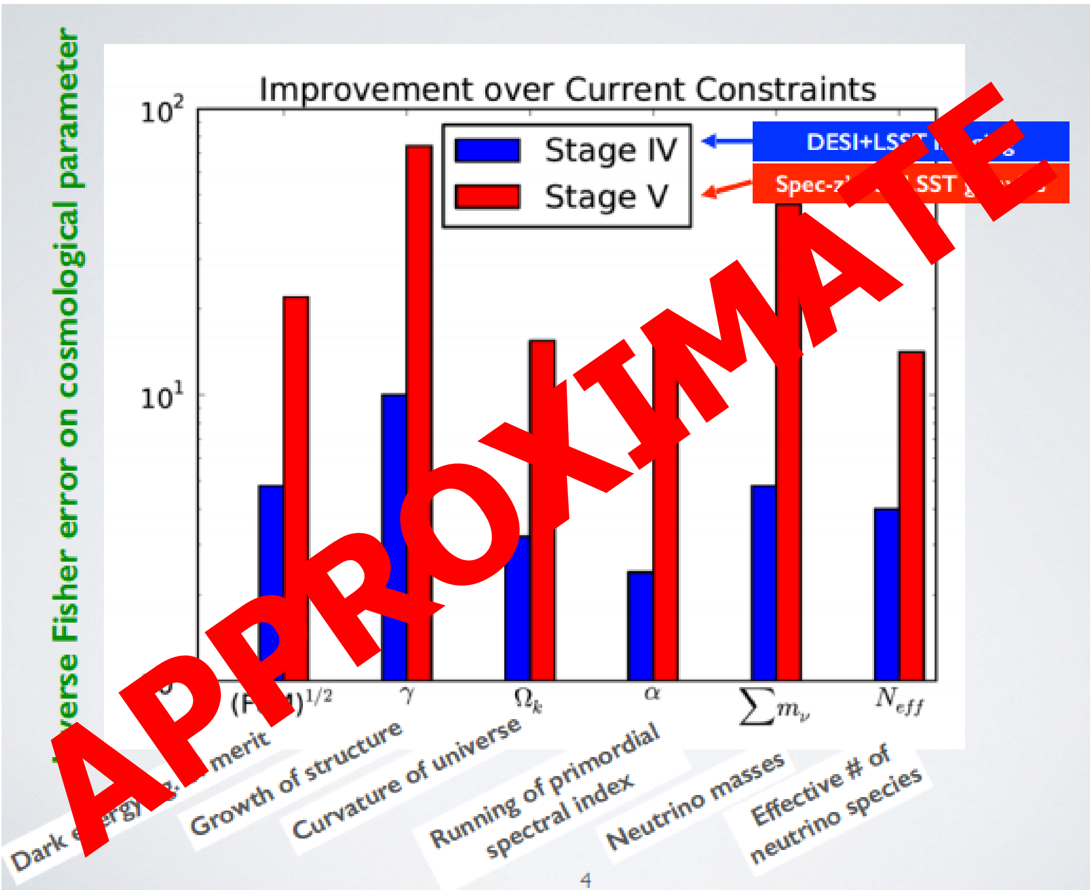
1.75<z<2.25	0.36	31.97	4000	
2.25<z<2.75	0.41	50.67	6000	
2.75<z<3.25	0.47	73.33	7000	
3.25<z<3.75	0.53	99.75	9000	

Cosmological Constraining Power

- 40k galaxies/sqdeg → full power spectrum at average kmax~0.45 to z<3.25
- 560M spectra possible with current telescope and spectrograph designs
- Significant improvement possible in constraining cosmological model
  - Close to optimal goal – need to run proper forecasts

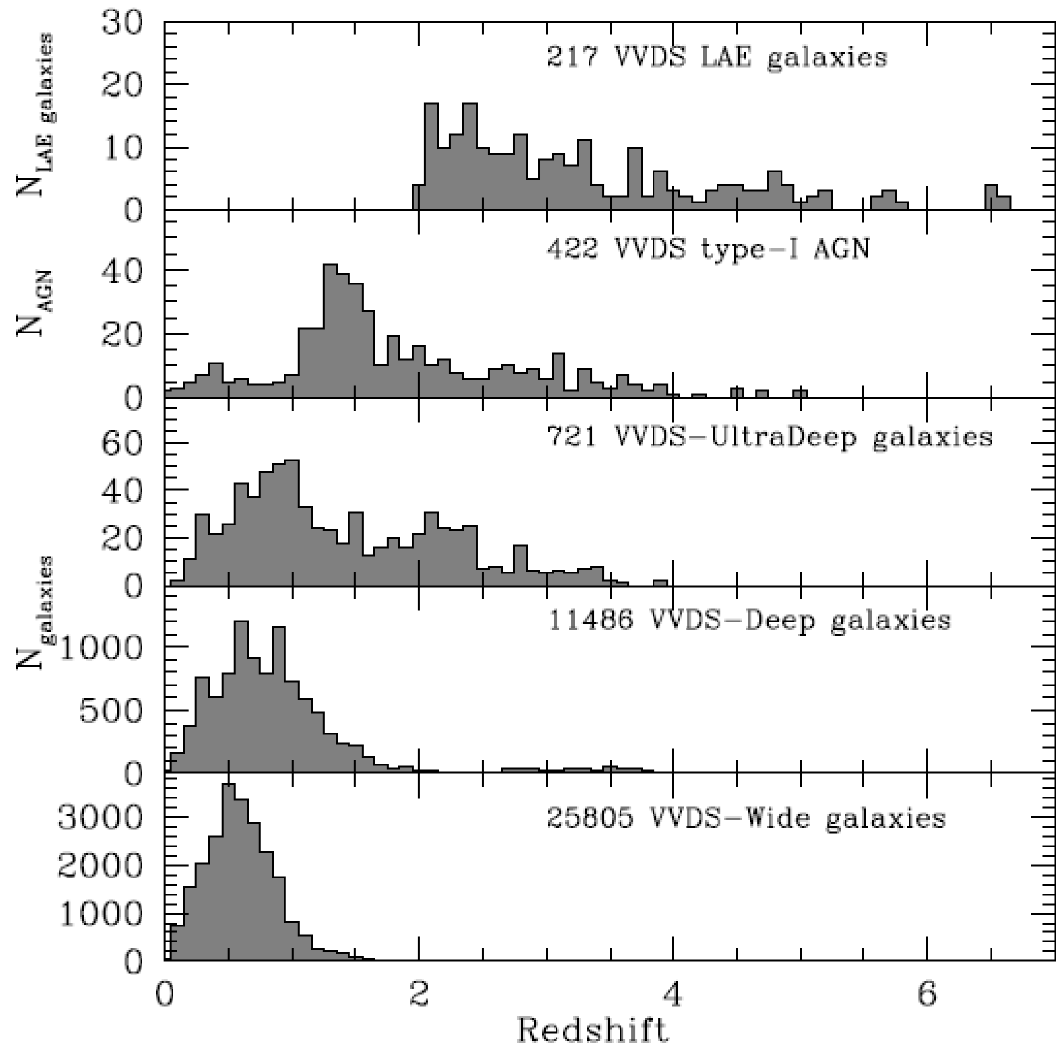


Spectroscopic Sample

Sample Selection – Goal: 20k/sqdeg at z<1.5)

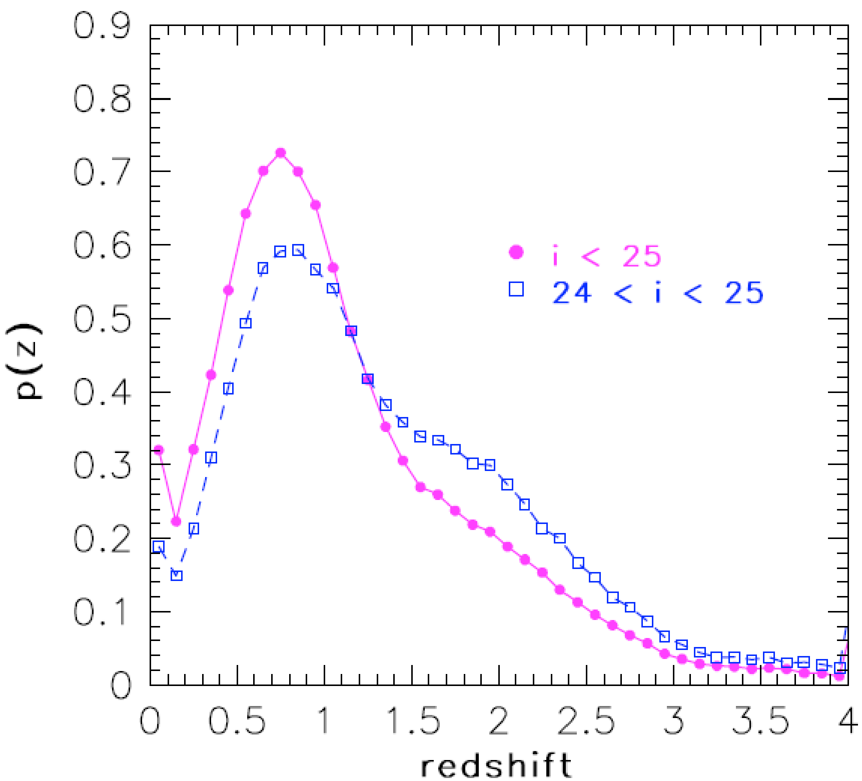
- Prior galaxy science programs → mass limited samples with 8-m telescopes
- e.g. VIMOS VLT Deep Survey (VVDS)
  - 20k per sqdeg at i<22.5
  - R=230
  - 5500<lambda<9350 \AA
- Results
  - Median(z)=0.55
  - 94% success rate (4.5hr exp)
  - 75% success rate (45min exp)
  - ~5% catastrophic failure rate
- i-band limited sample
  - Reduces imaging selection effects with simple selection
  - Saturates z<1 non-linear modes

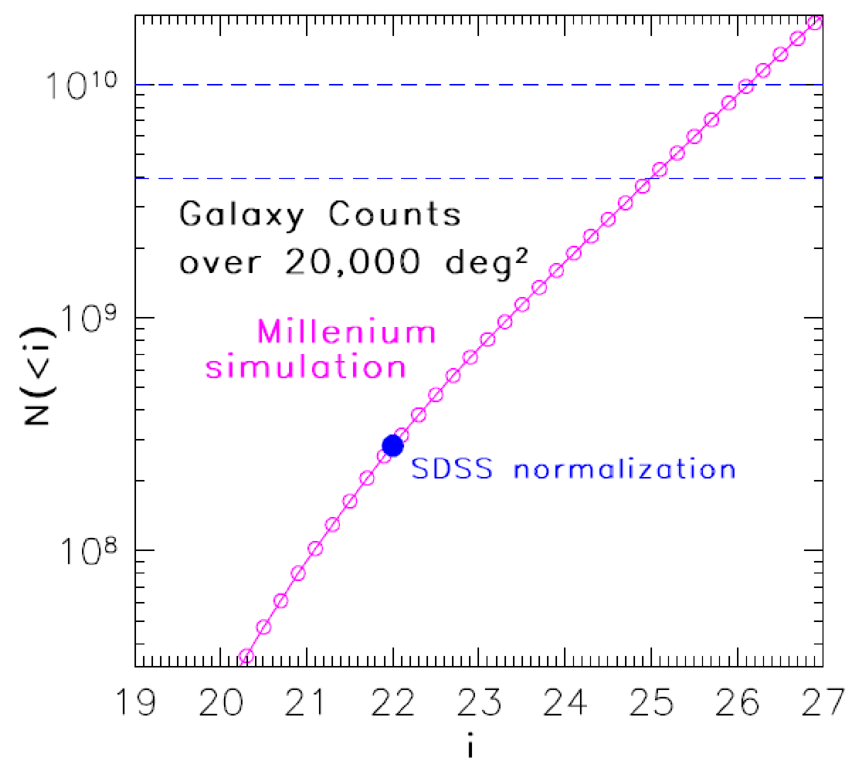
Le Fèvre, O. et al.: VVDS final data release: 35016 galaxies and AGN out to $z \sim 6.7$



Magnitude Limited Sample

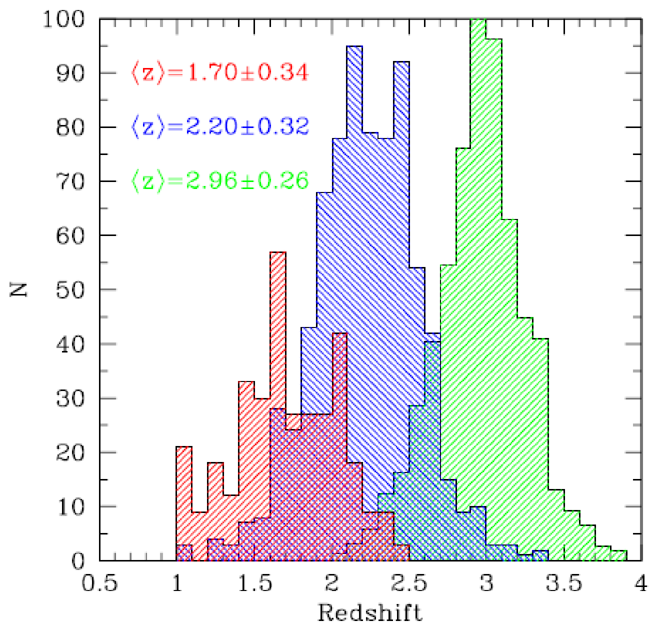
- VVDS results consistent with LSST science book assumptions
- Magnitude-limited sample favors z<1.0
- Tune magnitude limit to desired number density
  - 15k/sqdeg at i<22.0
  - 20k/sqdeg at i<22.5
- Need fainter targets and color selection to sample z>1

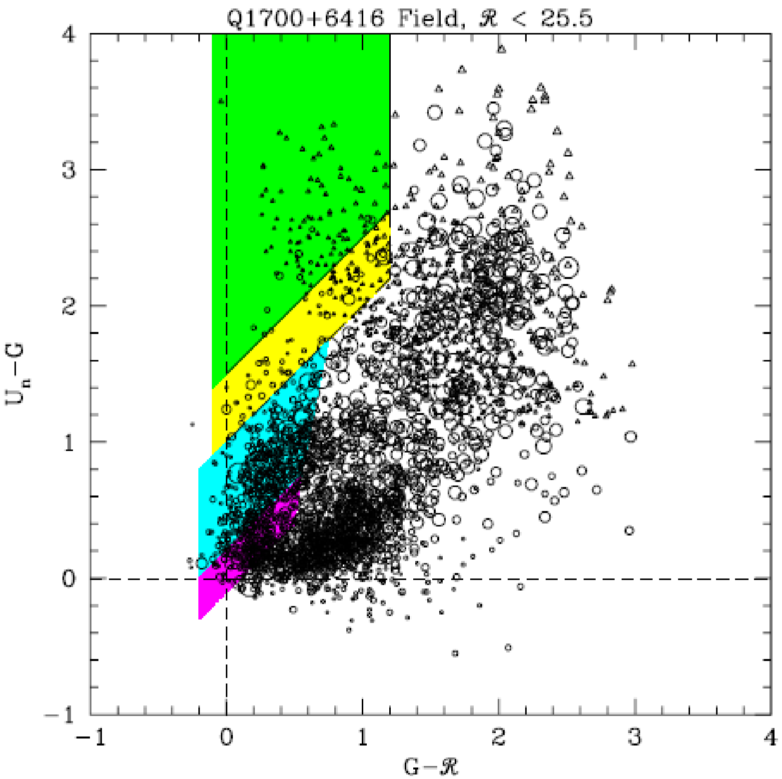




Sample selection (1.0<z<3.25)

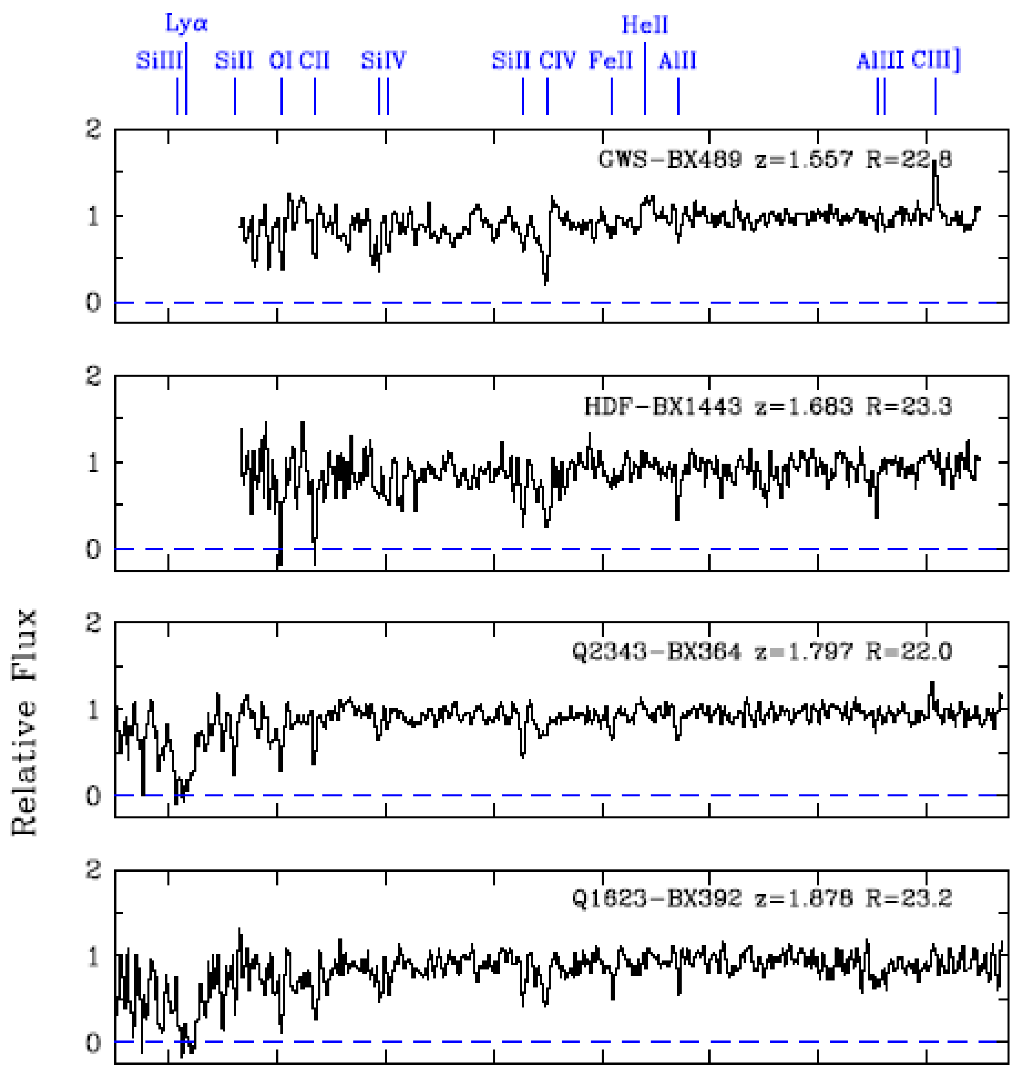
- Prior galaxy science programs → star forming samples with 10-m telescope
- e.g. Steidel et al, LRIS on Keck I
  - 30k targets per sqdeg at r<25.5 selected on (U-G) versus (G-R)
  - R=1000
  - Redshifts from UV interstellar lines
  - 1.5 hour exposures
- Results
  - 90% success rate (good conditions, r<24.5)
  - 65-70% success rate (average)





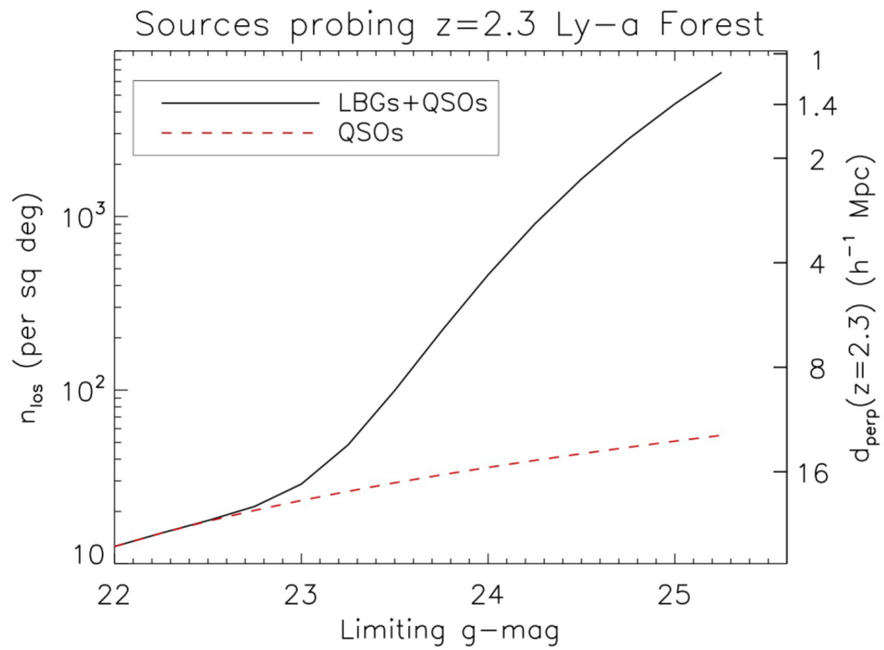
Sample selection (1.5<z<3.25)

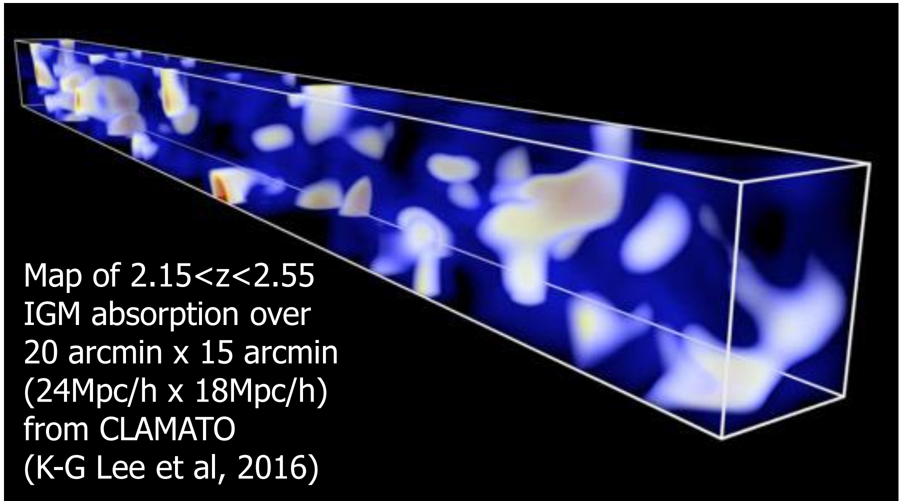
- UGR selection to r<25.5
  - Sensitive to u-band calibration
  - May have large fluctuations
  - 25% of all r<25.5 objects
- Observations at r<23.5
  - Very high success rates
  - Well-defined O, Si, C lines
- Reduce to r<24.5?
  - S/N increases by 2.5
  - Better for UV absorption
  - Ntargets~15k/sqdeg
- Redshift distributions uncertain
  - COSMOS photoz indicates 2500/sqdeg at z>2
  - Insufficient sample for z>2



Lyman-alpha Absorption Tomography at z>2

- Not enough direct tracers at z>2 to reach kmax goal
- 2500 sightlines per sq deg at r < 24.5
- Sightline separations of 2-3 Mpc/h → full 3D mapping down to non-linear scales through IGM absorption
- K-G Lee et al 2014 showed that S/N = 2-3 per angstrom sufficient for tomographic reconstruction
- Ongoing CLAMATO survey over 1 sq deg on Keck-I/LRIS
  - (http://clamato.lbl.gov)
  - 2hr exposure for r<24 → S/N~2 per angstrom in 0.7" seeing





Map of 2.15<z<2.55 IGM absorption over 20 arcmin x 15 arcmin (24Mpc/h x 18Mpc/h) from CLAMATO (K-G Lee et al, 2016)

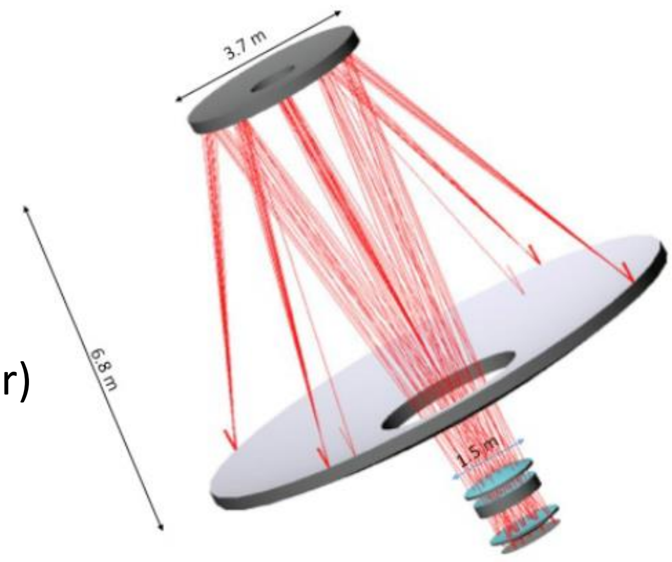
Instrumentation

Achieving the Multiplex Limit

- Traditionally, ‘survey etendue’ $A\Omega$ is defined as the product of telescope collecting area and FOV
- At high density surveys, more appropriate metric is related to multiplex factor
  - As long as the surface density of fibers is less than the surface density of targets, optimize the product of telescope area and number of fibers: A*N
  - True for fixed exposure time: hybrid exposure times discussed later
- Target density to achieve Stage V is ~40k/sqdeg
- DESI fiber density is ~700/sqdeg with 6 micron patrol radius
- Scaling to 40k/sqdeg targets requires a new regime of hyper-multiplexed spectroscopic surveys, beyond “massively-multiplexed”
- Possible to increase number of fibers by >order of magnitude with proposed telescope designs or with modifications to DESI fiber positioner design
- Goal is to maximize the size of the focal plane and number of fibers

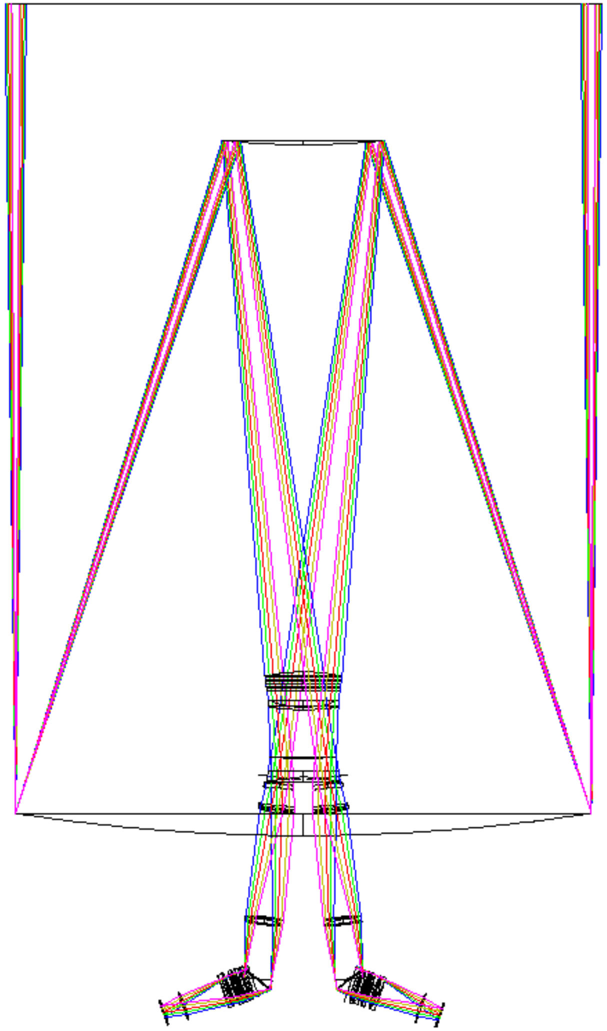
Possible Telescope Design (A)

- Design for Cass focus on 10-m class telescope
  - "Fiber Design" Pasquini et al., 2016
- 2.5 degree diameter FOV (4.9 sqdeg)
- F/3 beam
  - 145 micron/arcsec platescale
  - Well matched to SDSS fibers (180 micron diameter)
- 1.3 meter focal plane diameter
  - 2.6X DESI focal plane area
  - Hosts 13,000 fibers using DESI positioners
  - Increase to 50,000 fibers if decrease patrol radius from 6→3 micron
- 50,000 fibers over 4.9 sqdeg
  - Require average 4 visits per coordinate
  - ~12,000 observations for 14,000 sqdeg



Possible Telescope Design (B)

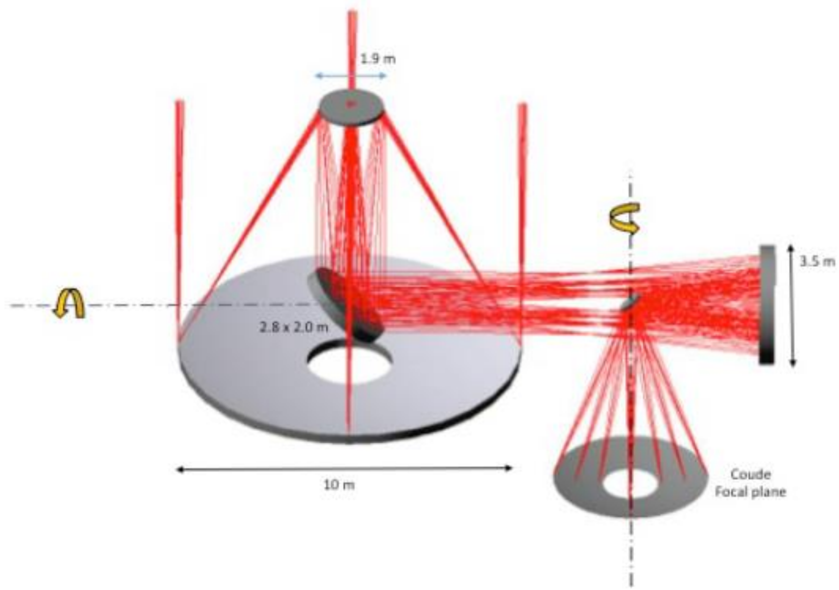
- Spectroscopic Wide Field Telescope (SWIFT)
  - NOAO 1999 proposal for 8.4-meter telescope
  - https://www.noao.edu/swift/proposal/swift.html
- 1.5 degree diameter FOV (1.75 sqdeg)
- F/4.3 beam
  - 188 micron/arcsec platescale
  - Well matched to SDSS fibers (180 micron diameter)
- 1.7 meter focal plane diameter
  - 3.5X DESI focal plane area
  - Hosts 17,500 fibers using DESI positioners
  - Increase to 70,000 fibers if decrease patrol radius from 6→3 micron
- 70,000 fibers over 1.75 sqdeg
  - Require average 1 visit per coordinate
  - ~8,000 observations for 14,000 sqdeg



Possible Telescope Design (C)

- Design for Coude focus on 10-m class telescope
  - “Ring Design” Pasquini et al., 2016
- Ring design
  - 1.5 degree diameter (1.0 sqdeg)
  - 4.6 meter focal plane diameter (Coude focus)
  - Three extra mirrors → reduced effective area due to <100% reflectivity
- 1.5 degree diameter FOV (1.0 sqdeg)
- F/17.7 beam
  - 857 micron/arcsec platescale
  - Poor match to any fiber system
- Microlenses for f-ratio conversion to F/4
  - DESI fibers → 0.6” on sky
  - e.g. Gemini: http://adsabs.harvard.edu/abs/2002PASP..114..892A
- 4.6 meter focal plane diameter
  - 30X DESI focal plane area
  - Hosts up to 150,000 fibers using DESI positioners
- Assume 50,000 fibers over 1.0 sqdeg
  - Require average 1 visit per coordinate
  - 14,000 observations for 14,000 sqdeg

  (incomplete coverage due to central obscuration)

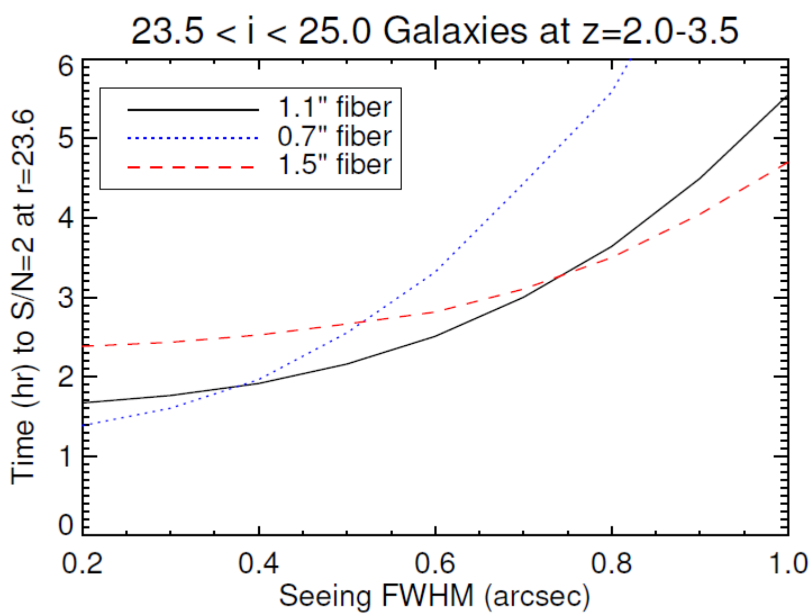


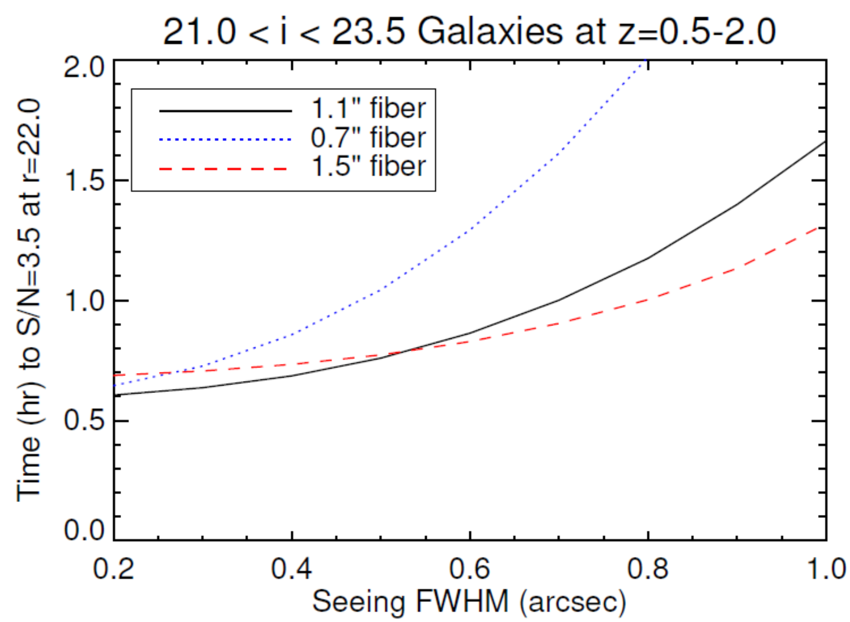
Ground Layer Adaptive Optics

- Microlens → ~0.6 arcsecond diameter fibers
  - Ground layer adaptive optics possible to match fiber diameter for point sources
- Designs tested now to cover wide field of view
  - e.g. imaka at UH 88-inch
  - 20 arcminute FOW
  - Goal to achieve FWHM~0.33” in visible and NIR
  - https://arxiv.org/ftp/arxiv/papers/1608/1608.01804.pdf

Ground Layer Adaptive Optics

- Explore sensitivity to extended sources using COSMOS Hubble ACS imaging
- AO with small fibers competitive for typical, compact high-z sources
  - Scaled to 3hr integrations (g=24.0) achieve S/N~2 per ang (CLAMATO)
  - 0.5” seeing (AO) → 20% longer exposure relative to optimal 1.1” fiber
  - AO vs non-AO → (0.5” seeing + small fibers) 2.25X faster than (1” seeing + 1.5” fiber)
- AO with small fibers less competitive for typical, extended low-z sources
  - Scaled to 1hr integrations (r=22.0) achieve S/N~3.5 per ang (DEEP2, Newman+2012)
  - 0.5” seeing (AO) → 40% longer exposure relative to optimal ~1arcsecond fiber
  - AO vs non-AO → (0.5” seeing + small fibers) 20% faster than (1” seeing + 1.5” fiber)

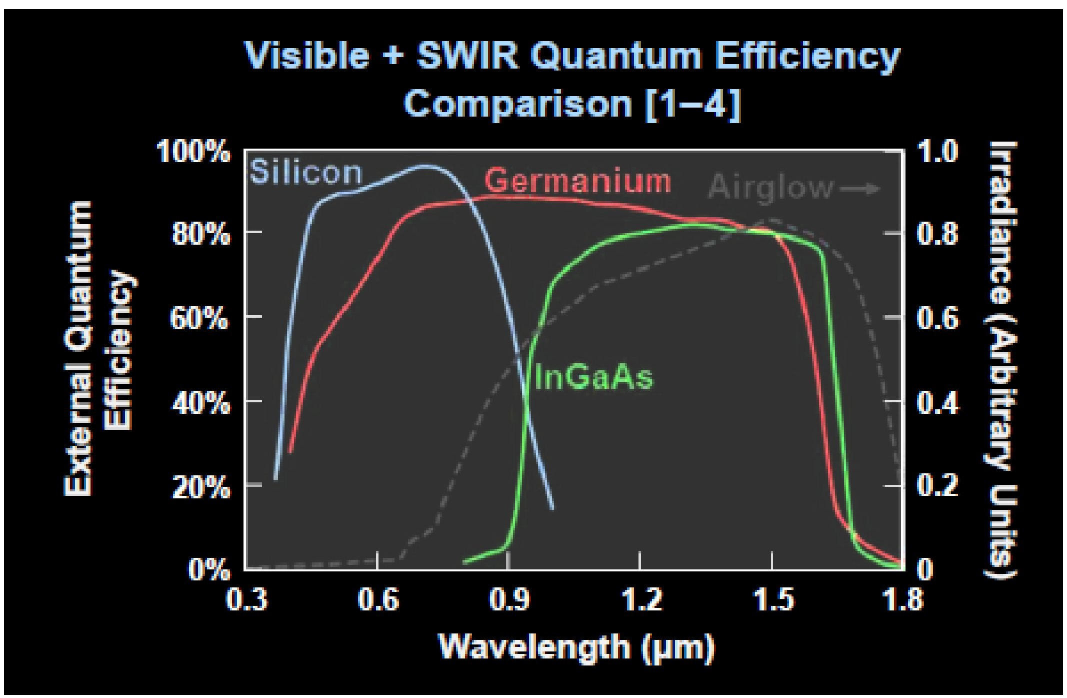


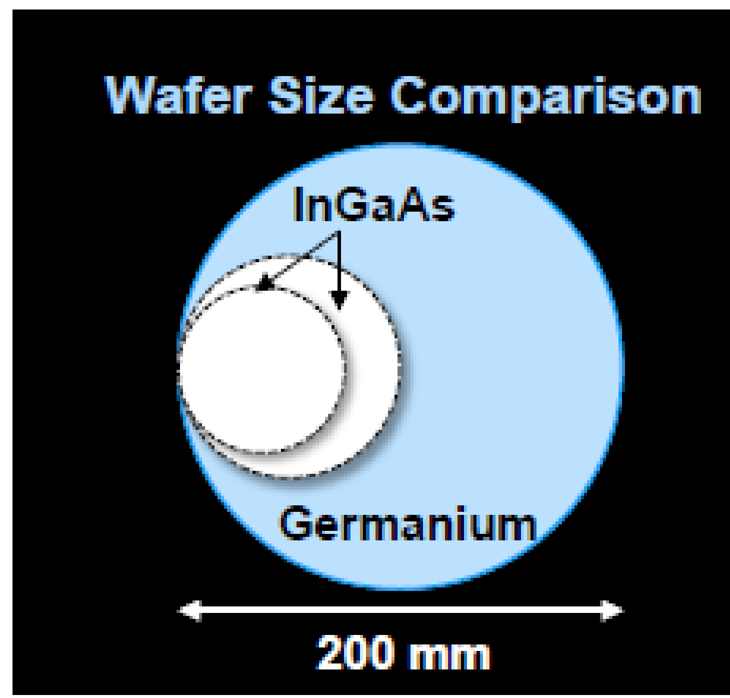


Spectrographs

- DESI design with 4th channel (r~4000 to resolve [OII])
- Silicon + Germanium CCDs
- Si for two channels, 3500<lambda<8000 \AA
  - Well-known technology
- Ge for two channels, 8000<lambda<13,000 \AA
  - New CCD's being developed at Lincoln Labs/LBNL

From Christopher Leitz (MIT LL)





Survey Design

Cosmological Survey Parameters

- 40k targets per sqdeg, 14k sqdeg
  - Magnitude limited sample to z<1.0
  - UGR selection for 1.0<z<3.25
  - 560M spectra
  - ~20X DESI
- 350M Fourier modes
  - 30X DESI
- 10m telescope
  - 6X DESI collecting area
- 1 hr exposures for ?90%? redshift success
  - 2.4X DESI exposure times
- Overall ~4X better [OII] sensitivity than DESI for low z sample
- 3600-13,000 \AA
  - Includes IR channel for [OII] detection to z=2.5
  - R~4000 for sky subtraction and [OII] identification

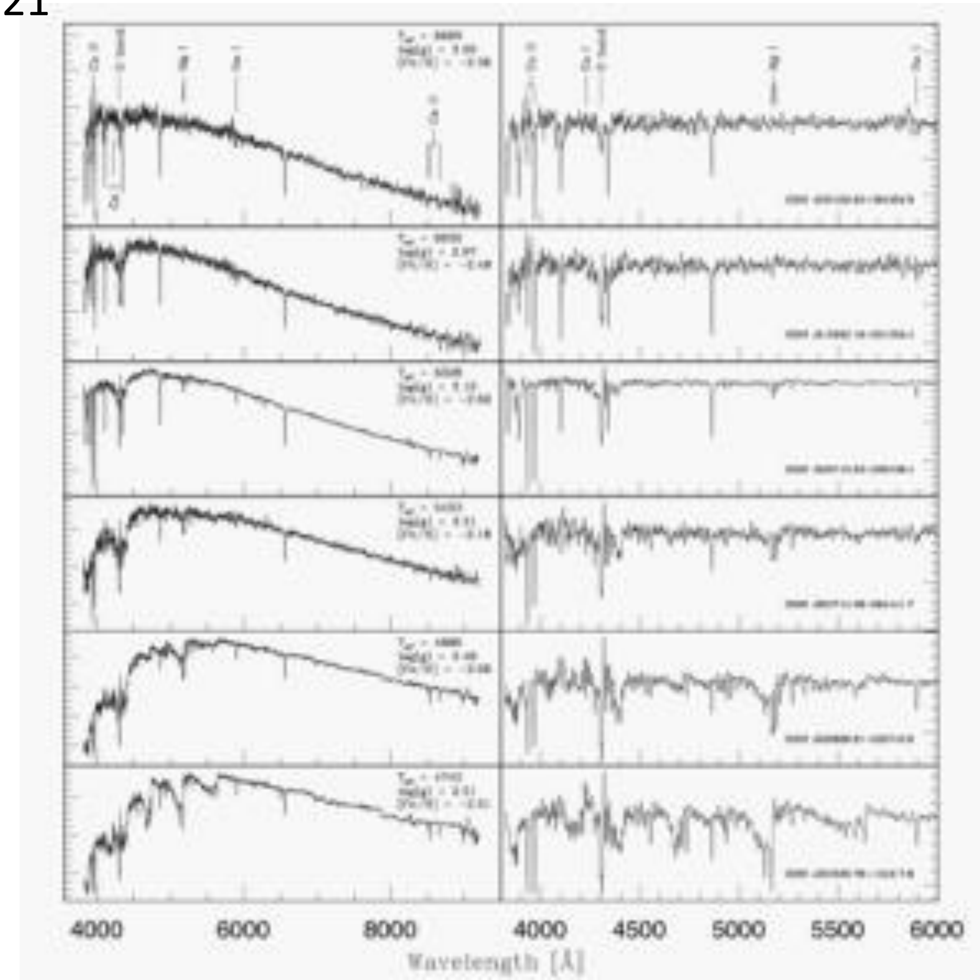
Survey Characteristics

- Conservative Assumptions
  - 1000 hours open shutter per year
  - 1 hr/exposure
  - 10 yr program
- 10,000 unique pointings
  - Telescope option (A) 85% complete
  - Telescope option (B) 125% complete
  - Telescope option (C) 70% complete
  - At >1 pass per coordinate, only option (A) has clear program to obtain sufficient integration on lyman-alpha forest tomography targets
- Assume 80% fiber efficiency
  - Trade target density vs survey area vs exposure depth
  - Only option (C) flexibility to increase Nfibers beyond requirements
  - Consider northern and southern platforms to mitigate fiber crunch
- Increase fiber density 2X for 1B spectra with bright time Milky Way program

Milky Way Science Program

- Cosmology survey on dark nights
- Observe Milky Way targets during bright time!
- Scaling from SDSS-SEGUE survey:
  - 15min exposures to get S/N>10 at g<21
- ~700M stellar spectra over 10yrs

- http://classic.sdss.org/segue/



Programmatics and Challenges

Technical Challenges

- Details of target selection and exposure depth
  - What is optimal number density for $z<1.5$ and $z>1.5$?
  - What is the expected redshift success rate versus exposure time?
  - What are requirements for spectroscopic completeness?
  - What are maximal allowable uncertainties in the selection function?
- Telescope Design and Optics
  - Consider trade of FOV against focal plane area
  - Focal plane geometry allowing complete coverage of sky
  - Ground layer AO: e.g. Imaka at UH 88-inch http://www.cfht.hawaii.edu/en/projects/IMAKA/index.php
- Fiber placement and focal plane
  - How to fill focal plane with ~100,000 fibers?
  - Reduce patrol radius by 2X relative to DESI → 4X fiber density
  - Weight of focal plane argues against prime focus
- Spectrographs
  - DESI design with 4^{th} channel possible
  - How to scale production to accommodate ~100,000 fibers?

Programmatics

- Complementarity to Stage-IV, radio, IR, and CMB surveys
  - How do we weight independent clustering science versus programs to enhance LSST/cross-correlation science?
  - How to define cosmological drivers before Stage IV begins?
- Timescale: commissioning during final years of LSST (early 2030's)
- Staged experiment
  - Generalize design for upcoming 10m-class telescopes for massive multiplexing
  - Share instrument design with DESI-II
  - Share 10m-class telescopes with Southern Spectroscopic Survey Instrument, Mauna Kea Spectroscopic Explorer, etc.
  - Instrument 10-meter telescope with ~5000-fiber spectrograph as proposed
  - Upgrade to ~100,000 fiber spectrograph after N years
- US Partners
  - Being discussed in DOE Cosmic Visions
  - Science beyond cosmology → NSF
- Global partners essential

Summary

- 350M modes to explore after DESI
  - Nonlinear scales for z<1.5
  - Linear scales for 1.5<z<3.25
- Target selections tested
  - Low z: magnitude-limited to appropriate density
  - High z: UGR selection at r<24.5 but sensitive to U-band
- Instrument
  - Requires 50,000-100,000 targets simultaneously,
  - Dedicated 10m telescope(s)
  - Examine balance of telescope size, fiber number, etc.
  - Optical to IR coverage
- Scientific argument
  - Data argument is clear: fully sample density field to z<3.25
  - Map improved sampling onto which cosmological parameters?
  - What are acceptable levels of completeness, catastrophic failures?