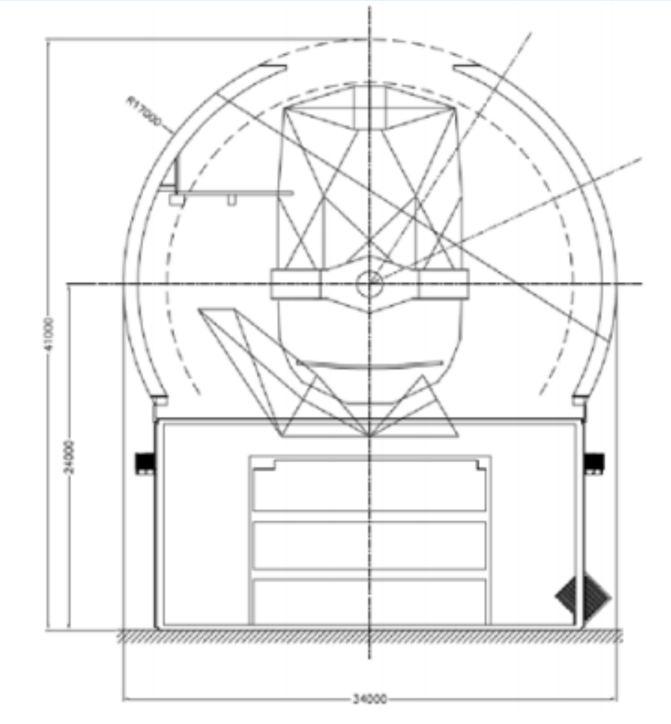
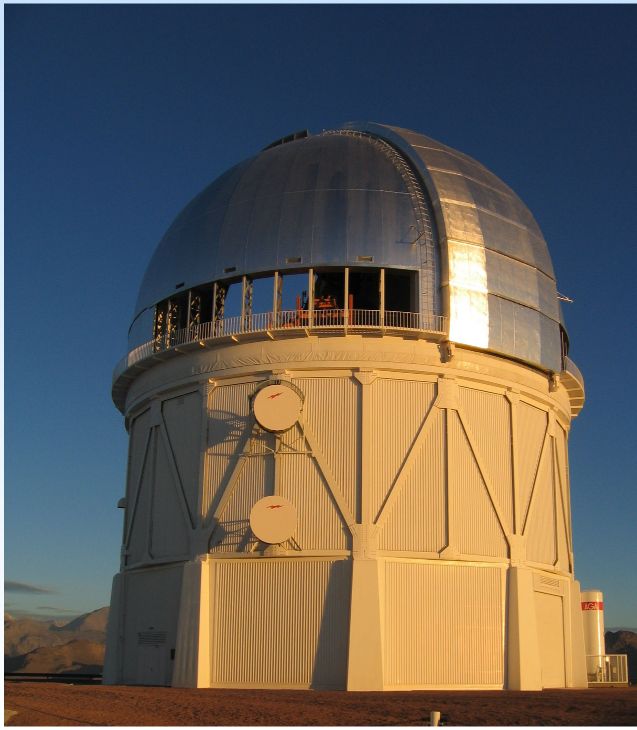
SSSI Science: Overview

Jeffrey Newman, U. Pittsburgh/PITT PACC





Outline of SSSI Science Talks

- Jeff Newman:
  - What might SSSI be?
    - Relation to Cosmic Visions and Kavli recommendations
    - Why not do this at low resolution?
  - Photometric redshift training and calibration with SSSI
  - Improving Dark Matter searches and gravitational wave cosmology with SSSI
  - Other SSSI science
  - Example SSSI surveys
- Elisabeth Krause and Amol Upadhye:
  - Constraints on cosmological parameters from SSSI
- Lindsey Bleem:
  - Cross-correlation science with SSSI

Instrument requirements to address both Cosmic Visions and Kavli MOS recommendations

- **High multiplexing**
  - **Required to get large numbers of spectra; >2500x required**
- **Coverage of full ground-based spectral window**
  - **Minimum: 0.37-1 micron, 0.35-1.3 microns preferred**
- **Significant resolution ($R=\lambda/\Delta\lambda>\sim5000$) at red end, R>2500 in blue**
  - **Allows secure redshifts from [OII] 3727 Å line at z>1**
- **Field diameters > ~20 arcmin**
  - **>1 degree preferred**
- **Large telescope aperture**
  - **Required to go faint in reasonable time**
  - **4-6m (Cosmic Visions/SSSI) vs. ~8m (Kavli)**

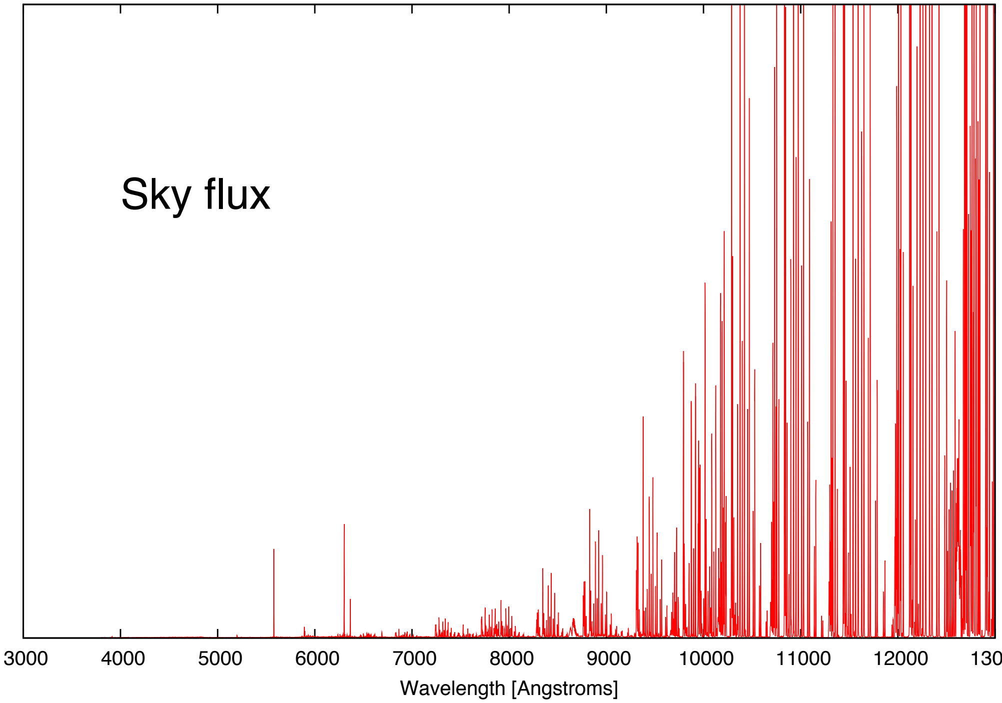
Proposed possible implementation paths for multi-object spectrograph from Kavli report

- Proposed possible implementation paths:
  1. Implement a wide-field MOS on an existing or new Southern-hemisphere telescope
  2. Obtain large amounts of community access to Subaru/PFS + DESI
  3. Buy into a proposed new project in the South (ESO wide-field MOS telescope study) or North (Maunakea Spectroscopic Explorer, Telescopio San Pedro Martir)

Why not do this at low resolution?

- **Many applications need highly secure redshifts: [OII] is only feature available past *z*=1, but requires R>4000 to split doublet and get secure *z***

- **At high resolutions, can work in dark wavelength ranges between skylines (~90% of spectrum at R=6000); at low resolution, whole red spectrum is contaminated**



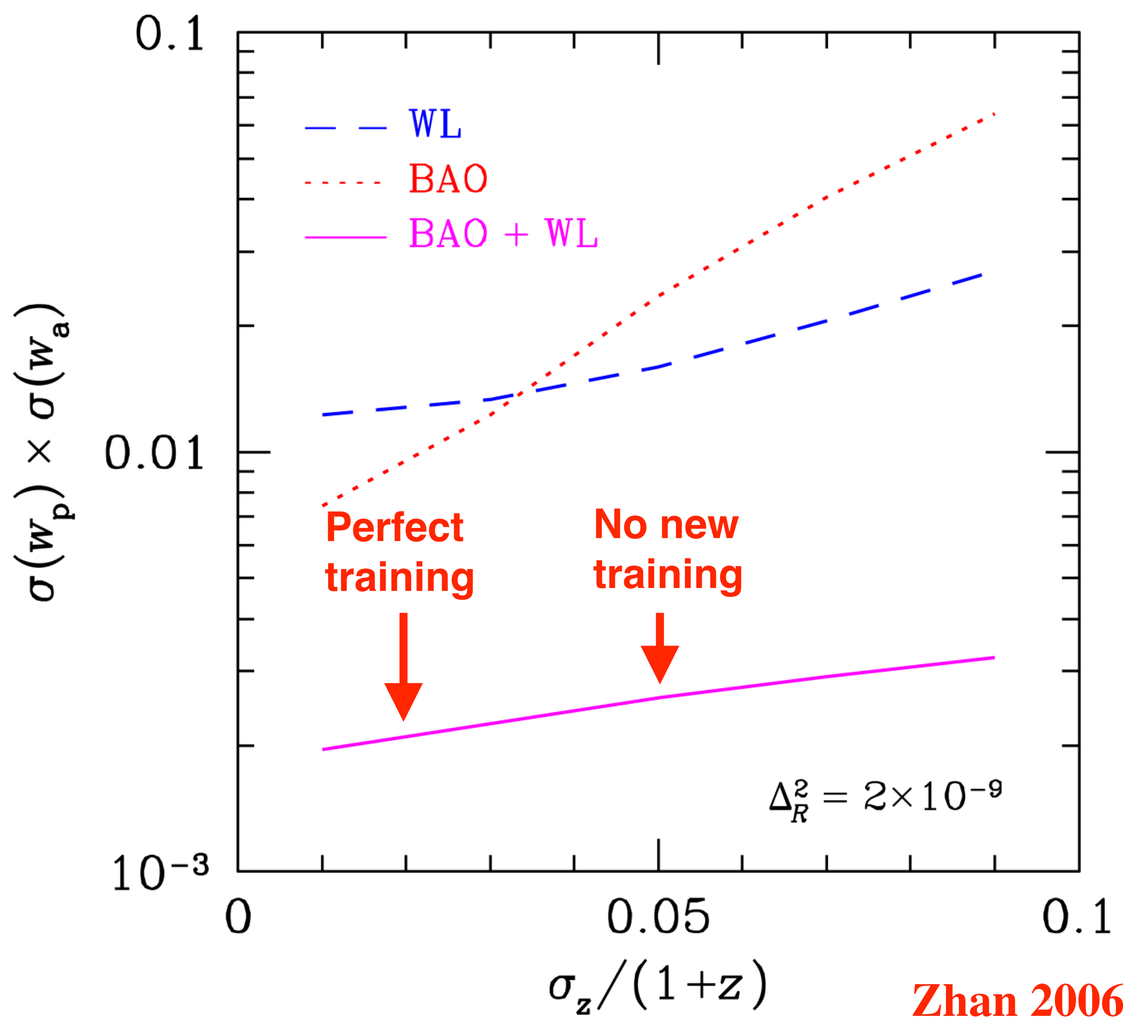
Why not do this at low resolution?

SSSI

- **The biggest challenge: it is very difficult to do much better than LSST photo-z's over wide areas at low resolution.**
- **Redshift errors for LSST-sky-area surveys will be approximately: $\sigma_z = 0.02(1+z)(A\,\Omega\,t_{survey} / A_{LSST}\,\Omega_{LSST}\,t_{survey,\,LSST})^{-1/2}\,(6/R)^{1/2}$, where A is collecting area, Ω is field of view, t_{survey} is total survey duration, and R is the spectral resolution or number of bands**
- **I.e., proportional to $(A\,\Omega\,t_{survey}\,R)^{-1/2}$**
- **E.g.: A 10-year survey on LSST would need R=24 to reduce LSST photo-z errors by a factor of 2 over the LSST footprint**
  - **A 10-year survey would need R=80 to reach that goal on Mayall/Blanco**
  - **Reducing photo-z errors to this level would improve LSST WL + BAO DETF FoM by ~10% compared to LSST photo-z's**
  - **For SSSI, we want to enable substantially larger gains**

Two spectroscopic needs for photo-z work: training and calibration

- Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves DE constraints, esp. for BAO and clusters

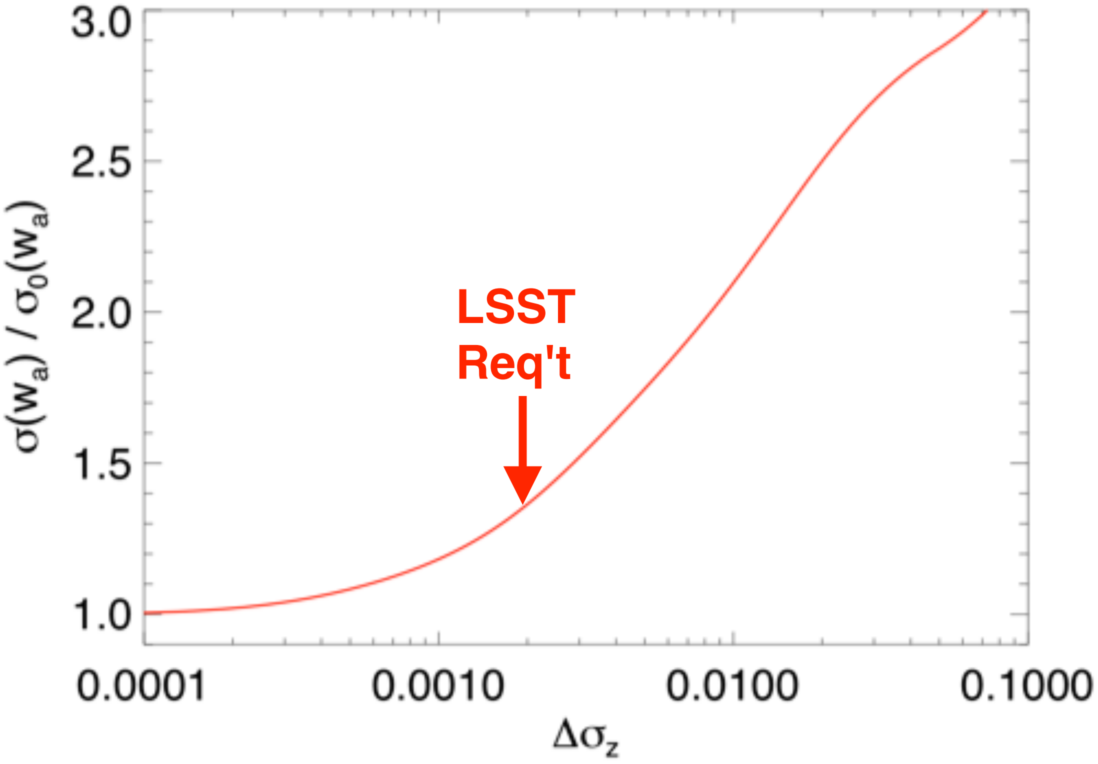


Zhan 2006

  - Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.

Two spectroscopic needs for photo-z work: training and calibration

- For weak lensing and supernovae, individual-object photo-*z*'s do not need high precision, but the calibration must be accurate - i.e., bias and errors need to be extremely well-understood



Newman et al. 2013

  - *uncertainty in* bias, $\sigma(\delta_z) = \sigma(\langle z_p - z_s \rangle)$, and in scatter, $\sigma(\sigma_z) = \sigma(\mathrm{RMS}(z_p - z_s))$, must both be <~0.002(1+*z*) for Stage IV surveys

What qualities do we desire in training spectroscopy?

- Sensitive spectroscopy of ~30,000 faint objects (to *i*=25.3 for LSST)

  - Needs a combination of large aperture and long exposure times

- High multiplexing

  - Required to get large numbers of spectra

- Coverage of full ground-based spectral window

  - Ideally, from below 4000 Å to ~1.5μm

- Significant resolution (R=λ/Δλ>~4000) at red end

  - Allows secure redshifts from [OII] 3727 Å line at z>1

- Field diameters > ~20 arcmin

  - Need to span several correlation lengths for accurate clustering

- Many fields, >~15

  - To mitigate sample/cosmic variance

Summary of (some!) potential instruments

Telescope / Instrument	Collecting Area (m^2)	Field area ($arcmin^2$)	Multiplex	Limiting factor
Keck / DEIMOS	76	54.25	150	Multiplexing
VLT / MOONS	58	500	500	Multiplexing
Subaru / PFS	53	4800	2400	# of fields
Mayall 4m / DESI	11.4	25500	5000	# of fields
WHT / WEAVE	13	11300	1000	Multiplexing
VISTA / 4MOST	10.7	14400	1400	Multiplexing
GMT/MANIFEST+GMACS	368	314	420-760	Multiplexing
TMT / WFOS	655	40	100	Multiplexing
E-ELT / MOSAIC	978	39-46	160-240	Multiplexing
Keck / FOBOS	76	314	500	Multiplexing
MSE	98	6360	3200	# of fields
Magellan / MAPS	32	6360	5000	# of fields

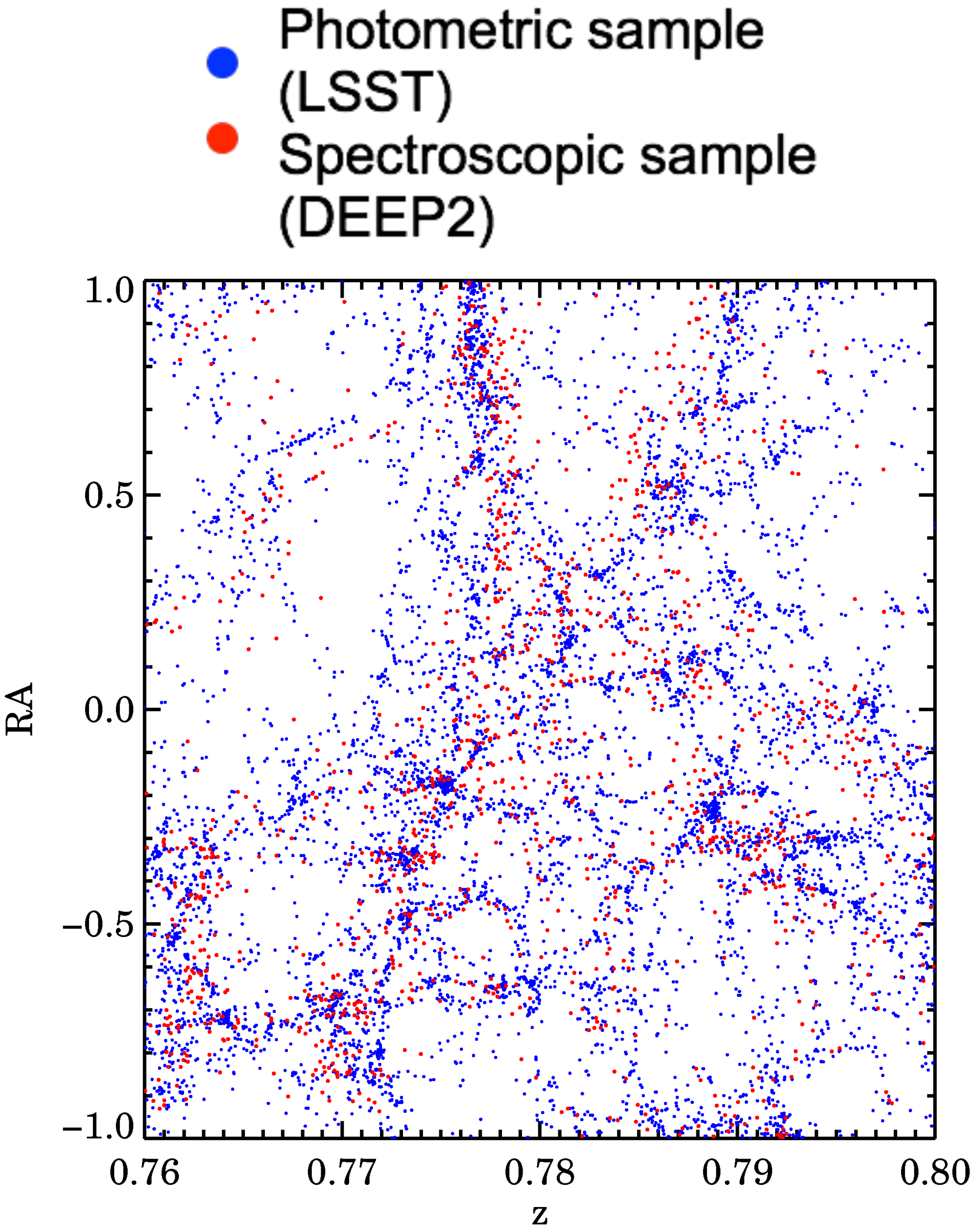
Time required for each instrument

Telescope / Instrument	Total time(y), DES / 75% complete	Total time(y), LSST / 75% complete	Total time(y), DES / 90% complete	Total time(y), LSST / 90% complete
Keck / DEIMOS	0.51	10.2	3.2	64
VLT / MOONS	0.20	4.0	1.3	25
Subaru / PFS	0.05	1.1	0.34	6.9
Mayall 4m / DESI	0.26	5.1	1.6	32
WHT / WEAVE	0.45	9.0	2.8	56
VISTA / 4MOST	0.39	7.8	2.4	48
GMT/MANIFEST+GMACS	0.02 - 0.04	0.42 - 0.75	0.13 - 0.24	2.6 - 4.7
TMT / WFOS	0.09	1.8	0.56	11
E-ELT / MOSAIC	0.02 - 0.04	0.50 - 0.74	0.16 – 0.23	3.1 - 4.7
Keck / FOBOS	0.12	2.3	0.72	14
MSE	0.03	0.60	0.19	3.7
Magellan / MAPS	0.09	1.8	0.56	11

Note: Training requirements for WFIRST are significantly more difficult to achieve than this; SSSI could be relevant for NASA as well.

Cross-correlation calibration: exploiting redshift information from galaxy clustering

- **Galaxies of all types cluster together: trace same dark matter distribution**
- **Galaxies at significantly different redshifts do not cluster together**
- **From observed clustering of objects in one sample vs. another (as well as information from autocorrelations), can determine the fraction of objects in overlapping redshift range**
- **Do this as a function of spectroscopic *z* to recover *p(z)***
- **See Newman 2008 for details.**



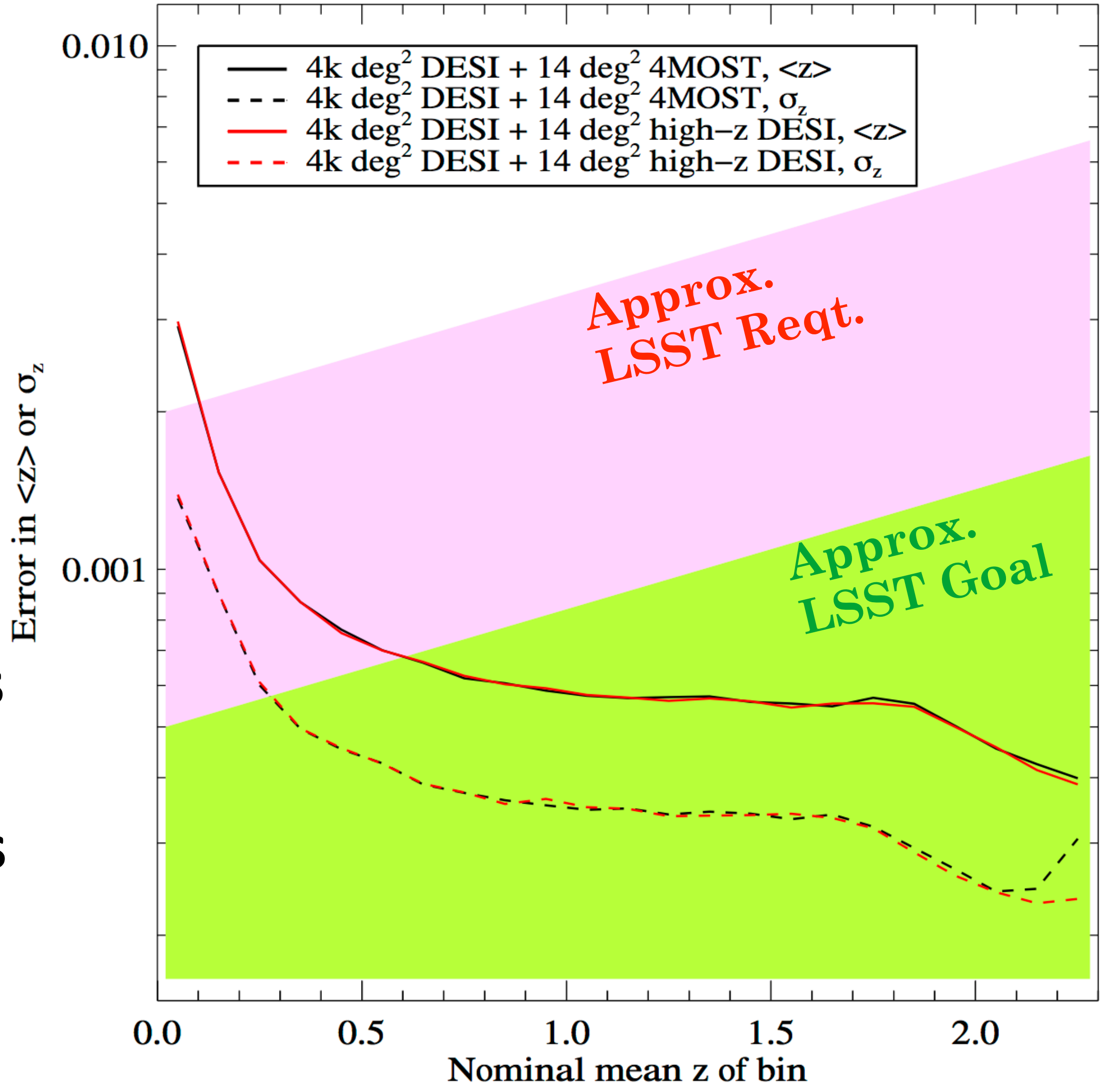
Spectroscopic requirements for cross-correlation methods

- With just 4000 sq deg. of DESI overlap, photo-z calibration would meet LSST requirements, but still be degrading Figure of Merit

- To reduce degradation to <10%, requirements are more stringent; can be met with ~18k sq. deg. of overlap with DESI + 4MOST

- If 4MOST cosmology survey goes forward, probably good enough photo-z calibration for most things we care about

- If it does not happen, we would want to do a Southern survey for cross-correlation calibration



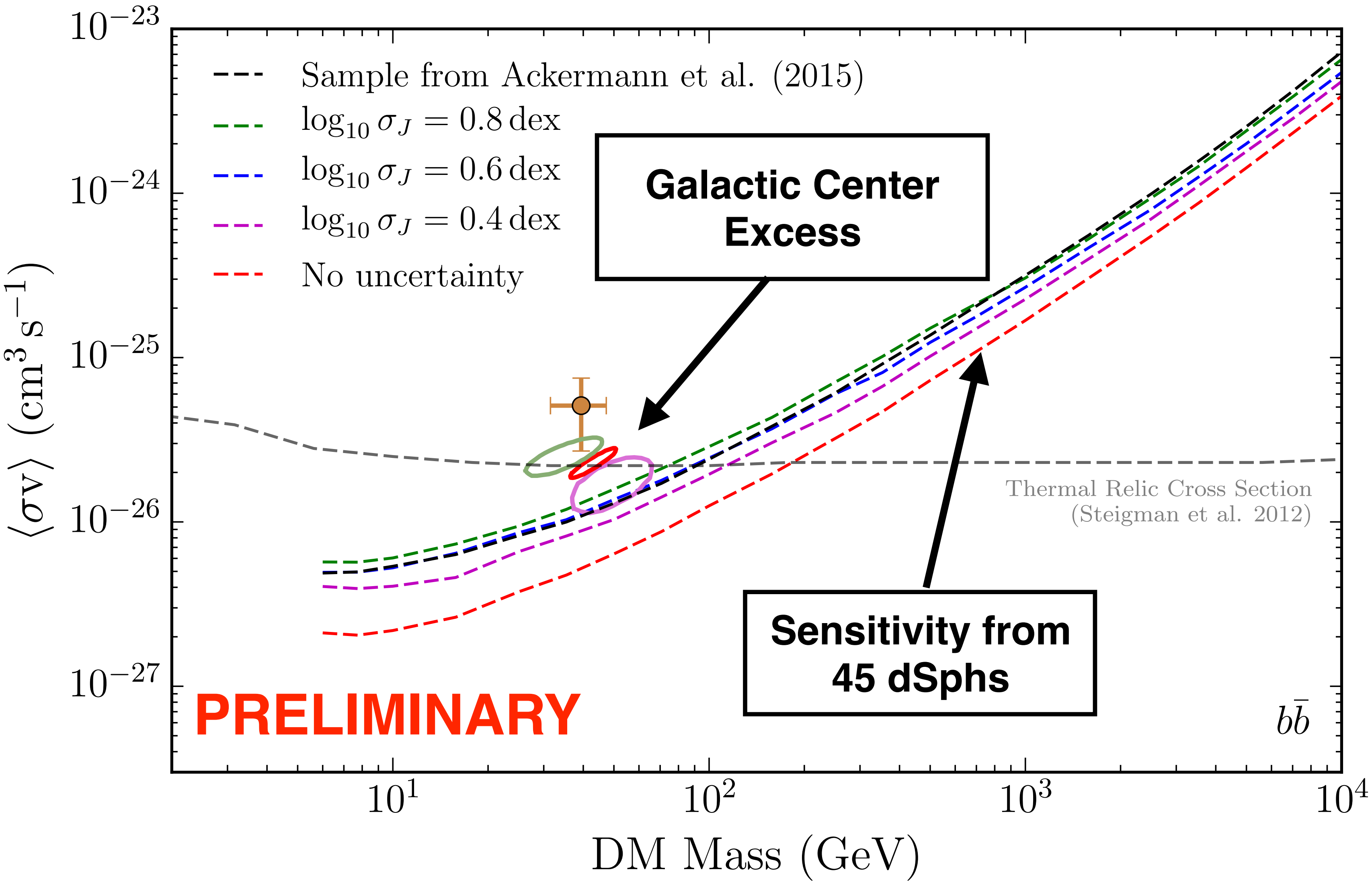
An SSSI spectrograph can enhance a variety of other cosmological studies

The same sort of spectrograph needed for photo-z training can be used to:

- Inform and test models of intrinsic alignments between galaxies that are physically near each other: a major potential weak lensing systematic
- Inform and test methods of modifying photo-z priors to account for clusters along a given line of sight
- Test modified gravity theories using cluster infall velocities
- Test dark matter theories using kinematics of galaxies in post-merger clusters (like the Bullet Cluster)
- Test models of blending effects on photometric redshifts

See upcoming Kavli/NOAO/LSST report for more details on these

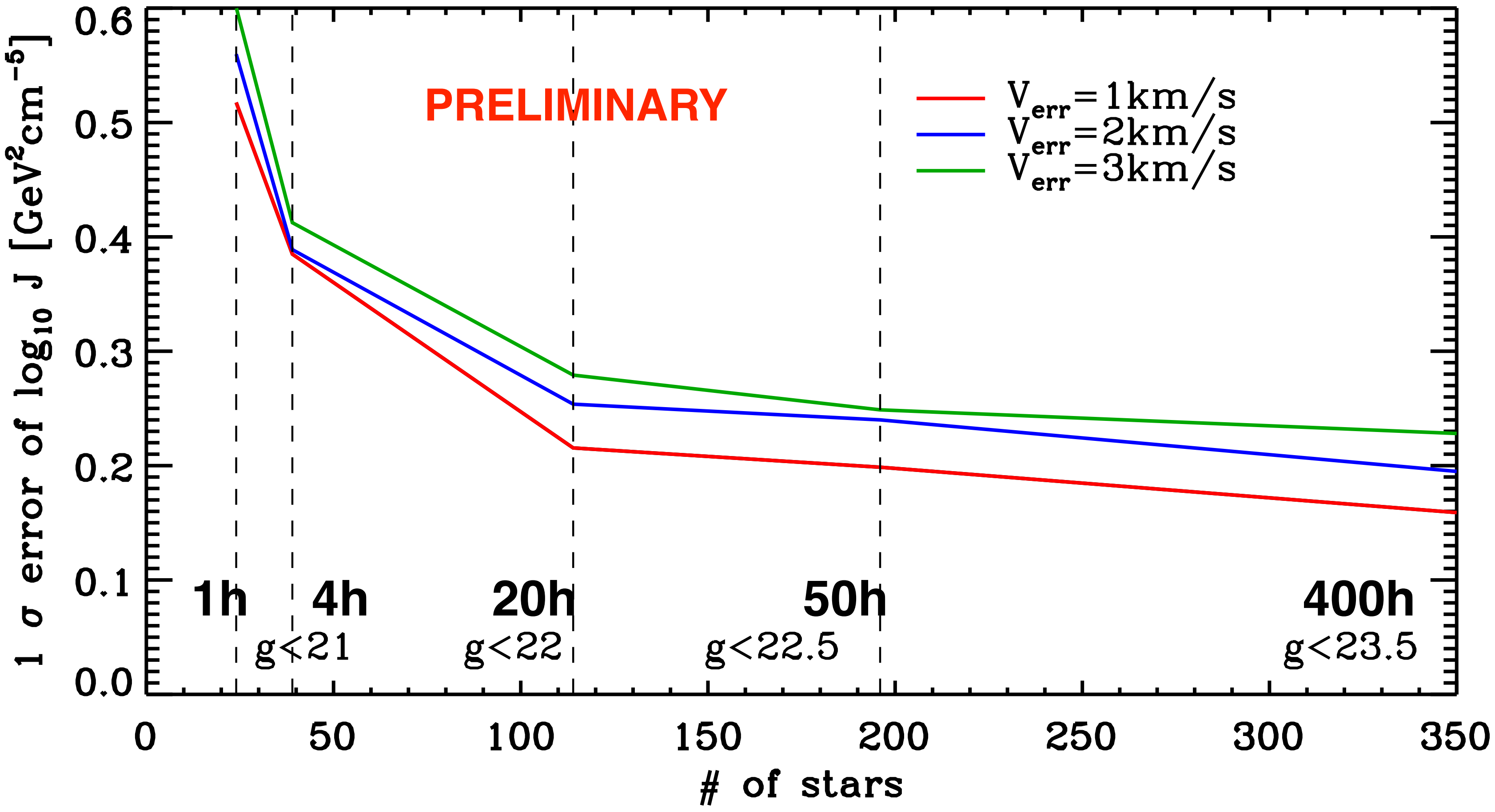
Improving indirect-detection dark matter searches with SSSI



Wang, Drlica-Wagner, Li, & Strigari, in prep.

- **Better estimates of astrophysical J factors improve sensitivity of gamma-ray DM searches**

Improving indirect-detection dark matter searches with SSSI



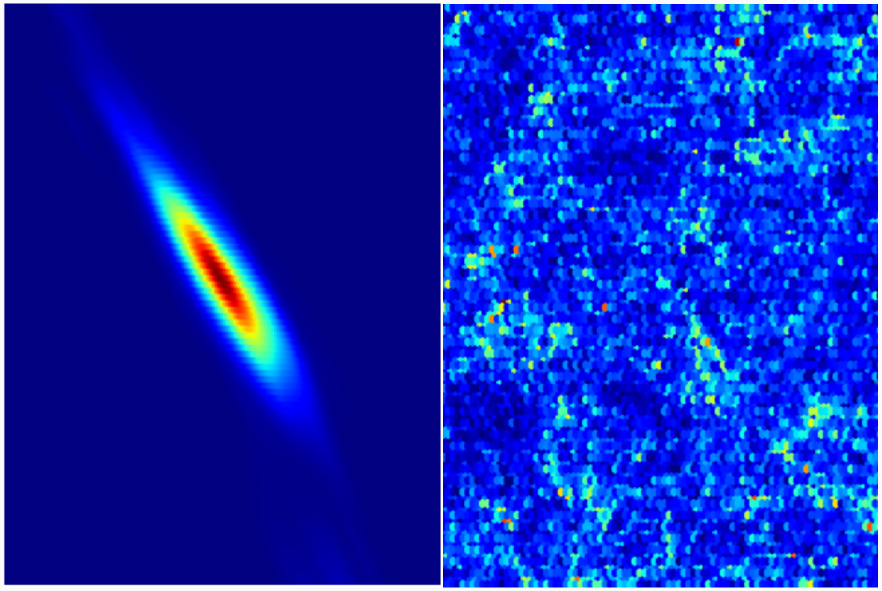
Magnitudes & exposure times are for Reticulum 2 & 6.5m telescope

- **Long exposures for many stars per dwarf are needed to reduce J-factor errors: an SSSI can help make this possible.**

Wang, Drlica-Wagner, Li, & Strigari, in prep.

Gravitational wave cosmology with SSSI

- **By mid-2020s, >2 gravitational wave sources per day will be detected, with localizations to ~90 Mpc along the line of sight and ~1 deg^2 on sky**
- **In combination with dense galaxy map, can identify over density most likely to host the GW event**
- **Enables cosmological constraints by comparing standard-siren distances to redshifts**
- **SSSI would be well-suited to producing such maps at low z**



Left: HLV spatial localization- 40° × 30°, red ×10 more likely than light blue. Right: mock galaxy catalog, $M_i < -21, z \leq 0.2$. (Buzzard v1.1)

Annis, Soares-Santos, & Brout, in prep.

SSSI-like capabilities were also identified as critical for a variety of science cases in Kavli study

SSSI

- Galaxy evolution: survey of ~100,000 galaxies to *z*=2 to study connection between galaxy properties and environment in LSST deep drilling fields
  - Requires ~1 year of time on a Subaru/PFS-like spectrograph
- Milky Way structure: spectroscopy of ~1,000,000 stars to study the build-up of the Milky Way's stellar halo
  - Requires ~1.5 years of time on a Subaru/PFS-like spectrograph
- Local dwarf galaxies: studies of stellar properties and kinematics
  - Requires >2 years of time on a Subaru/PFS-like spectrograph
- Understanding stars: studies of stellar activity and rotation
  - Requires ~0.5 years of time on a Subaru/PFS-like spectrograph
- Can also contribute to transient science by targeting LSST transients on spare fibers during other surveys, and supernova cosmology by obtaining redshifts for past photometric SN hosts

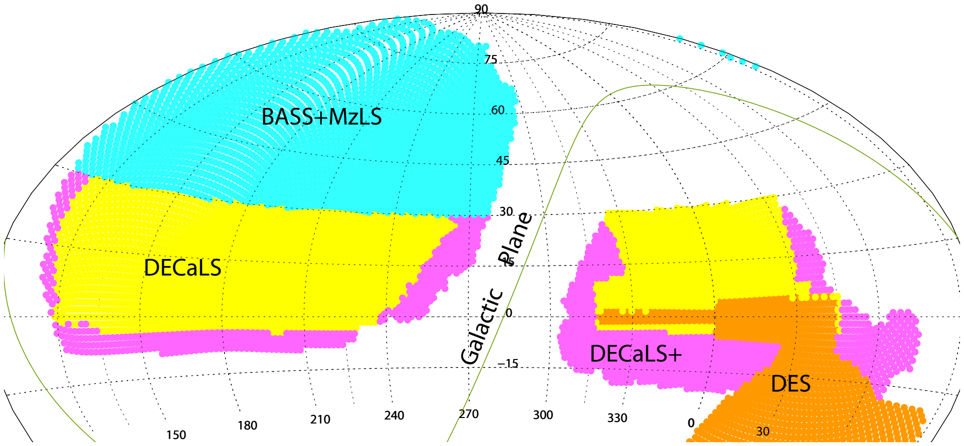
Two examples of possible SSSI surveys

- **Wide: DESI-like survey over 16,000 sq. deg. of LSST footprint not covered by DESI (also ideal for CMB-S4 cross-correlations). ~29M spectra total**

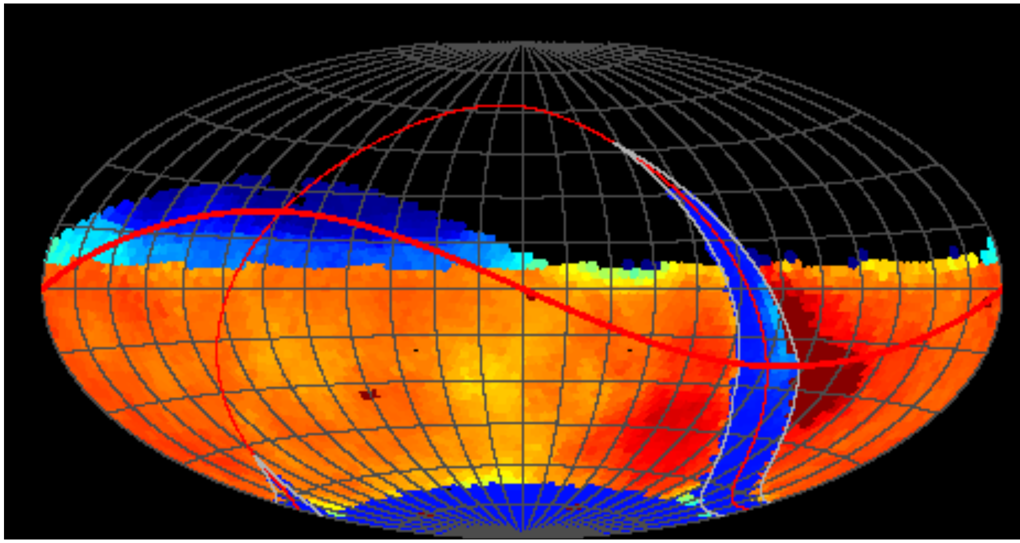
- Variants: Deep: utilize new technologies to enable capturing ELG redshifts to *z*~2.3, with high-z selection; Dense: use LSST photo-z's to enable working at lower S/N, reducing exposure times and enhancing sample size; Deep x 4: apply those techniques with Deep selection

- Note: 4MOST will be doing a ~half-DESI-density survey over this area.

DESI coverage



LSST coverage



Two examples of possible SSSI surveys

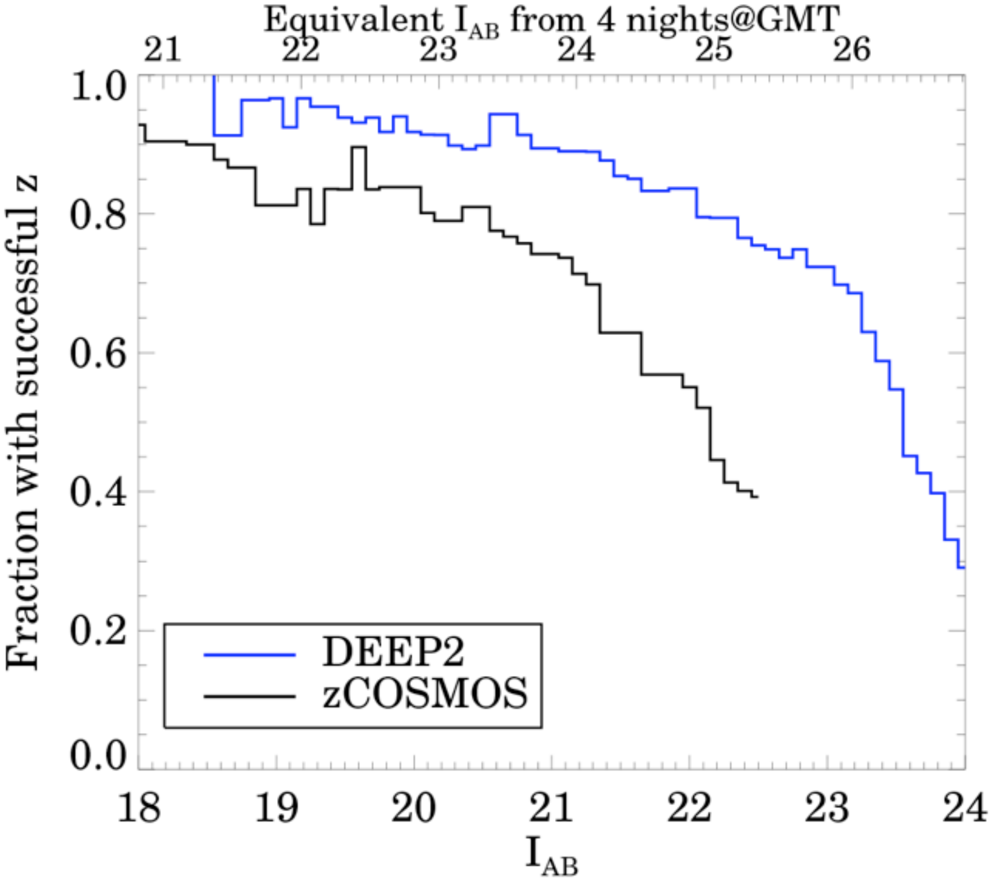
- **Ultra-deep:**

  - >30,000 galaxies over 15 fields at least 20 arcmin diameter each down to LSST weak lensing limiting magnitude (*i*~25.3)

  - Enables photo-z training for LSST

  - 15 fields to allow sample/cosmic variance to be mitigated & quantified

  - Long exposure times needed to ensure >75% redshift success rates: 100 hours at Keck to achieve DEEP2-like S/N at *i*=25.3



4 example ways of implementing SSSI: can assess survey speed for each

- **DESI-South**
  - DESI clone on Blanco 4m telescope
  - 5000x multiplexing, ~7 deg^2 FOV
- **PFS-South**
  - PFS clone on Subaru-like 8m telescope
  - 2400x multiplexing, 1.3 deg^2 FOV
- **MSE-South**
  - Spectroscopic-only 11m telescope
  - 3200x multiplexing, 1.5 deg^2 FOV
- **Magellan Apparatus for Parallelized Spectroscopy (MAPS)**
  - DESI-like instrument for 6.5m Magellan telescope (or clone)
  - 5000x multiplexing, 1.5 deg^2 FOV

Number of dark years required for each survey on various instruments/telescopes

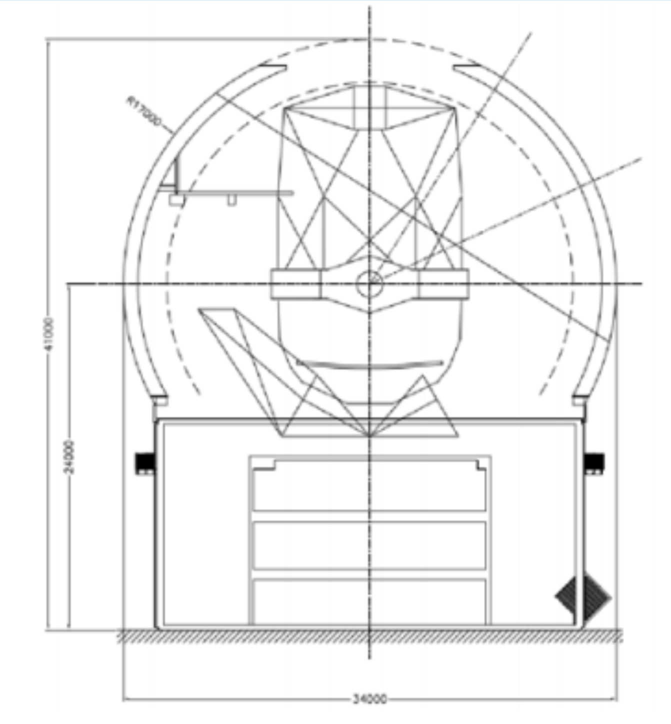
	Wide	Ultra-deep
DESI-South	1.1 years	5.1 years
PFS-South	0.7	1.1
MSE-South	0.4	0.6
Magellan/MAPS	0.7	1.8

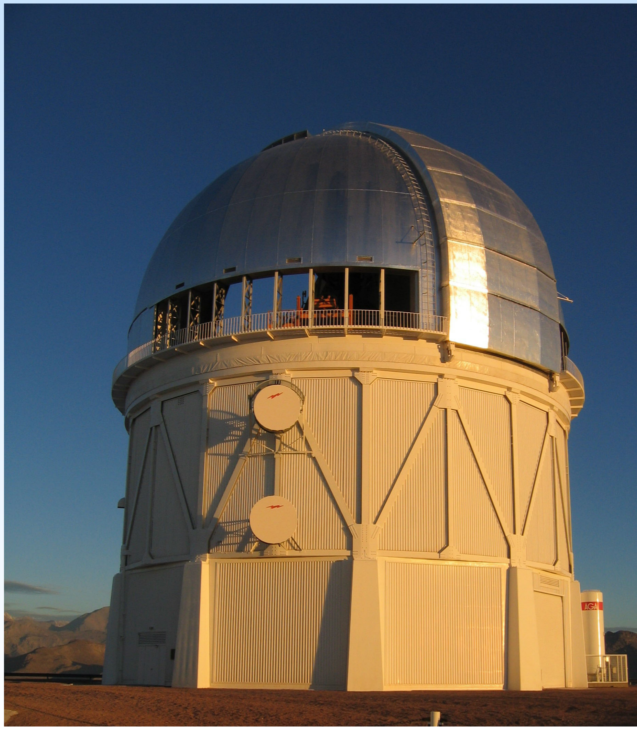
- Notes: Normalizations are optimistic, at least for Wide; the real DESI survey (which is 14k sq deg vs 16k for Wide) is more like 3 years of dark time. Relative times should be secure.
- Time estimates assume that all fibers are assigned to targets and that sky subtraction accuracy scales as photon noise.
- Minimum observation time of 5 min (including 2.5 min overheads) assumed.
- Differences in multiplexing, field sizes, and collecting area are all accounted for; instrumental efficiencies are assumed to be identical.

To be continued!

SSSI Science: Cosmological Parameters from SSSI

Elisabeth Krause, KIPAC (Stanford/SLAC)
Amol Upadhye, U. Wisconsin





Cosmological Parameters from SSSI: Prerequisites

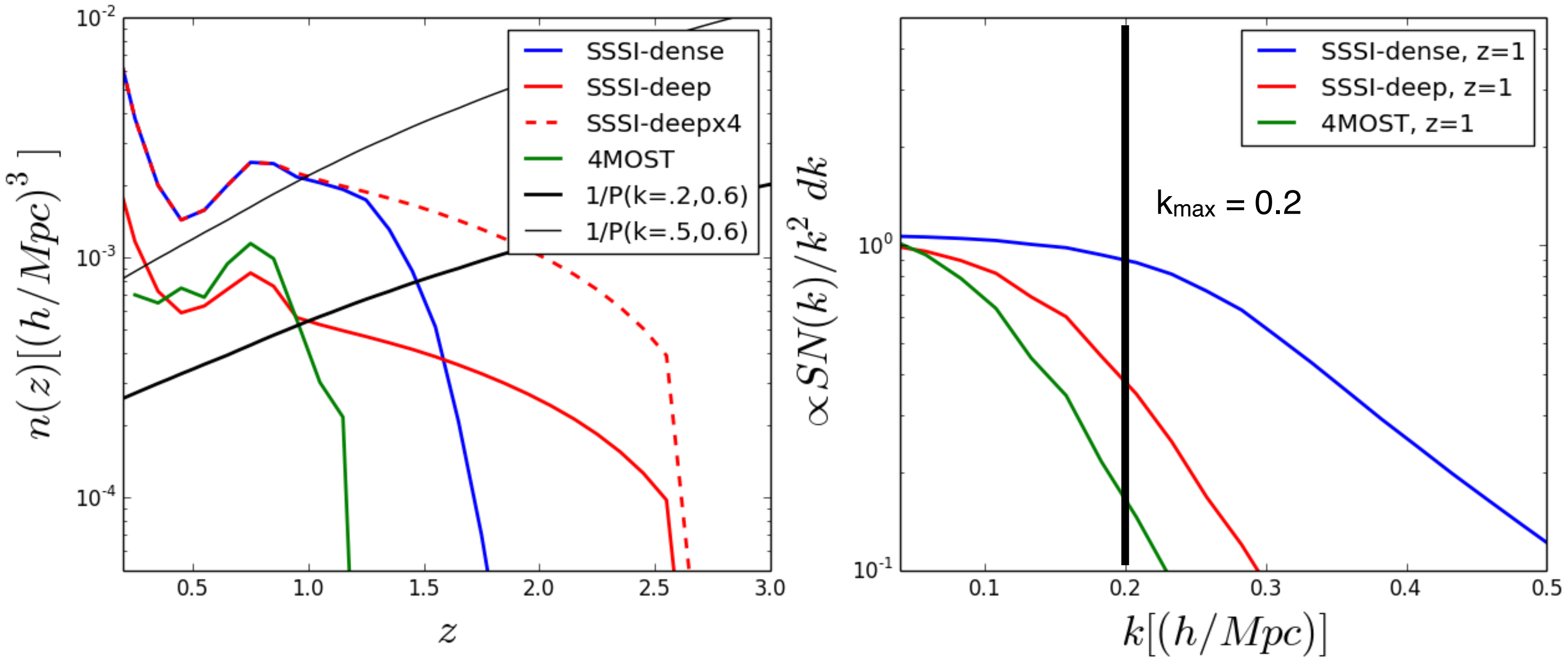
- ”Stage IV”
  - DESI + 4MOST: broadband multi-tracer RSD power spectra
  - LSST: angular clustering, galaxy clusters, WL, SN, strong lensing
- Precision Cosmology
  - Statistical power needs to be matched by systematics control
  - Overlapping surveys are not independent
- Baseline Forecasts
  - account for cross-covariance between overlapping surveys
  - ~60 nuisance parameter (LSST), ~10/(spectroscopic survey)
  - open w_aCDM cosmology
  - Linearized modified gravity effects using (μ, Σ) parameterization

(CosmoLike implementation by Miyatake & Eifler)

Cosmological Parameters from SSSI:
SSSI Modeling

- **SSSI Baseline Scenarios**

  - SSSI-dense: 4xDESI-like density -> better sampling at large k
  - SSSI-deep: DESI-like + high-z sample -> extend redshift baseline
  - multi-tracer analysis with ELG, LRG, QSO samples



- **NB: 4MOST (12K sqdeg) already included in Stage IV forecasts**

Cosmological Parameters from SSSI: Constraints

	Stage IV	+SSSI *dense*, k	+SSSI *dense*, k	+SSSI *deep*, k	+SSSI *deep*, k	+SSSI *deepx4*, k	+SSSI *deepx4*, k
FoM	1089	1486	2430	1425	1972	1697	2860
$\sigma($	0.082	0.07	0.05	0.071	0.06	0.062	0.051
$\sigma(\boldsymbol{\alpha}$	0.0028	0.0022	0.0016	0.0022	0.0019	0.002	0.0013
$\sigma(\mu)$ $\sigma(\Sigma)$	0.019, 0.033	0.014, 0.027	-	0.015, 0.028	-	0.012 0.023	-

- **NB: Lya, CMB-S4, survey cross-correlations not yet included**
- **Stage IV + SSSI includes improved photo-z calibration**

Cosmological Parameters from SSSI: Implications for Survey Design

- **Best constraints from deep + densely sampled survey (deepx4)**
- **For downscaled version, deep or dense sample yield comparable constraining power**
  - **SSSI-dense, *if theory uncertainties can be controlled***
    - SSSI-dense, *to control theory uncertainties*
  - **SSSI-deep provides more leverage on general time dependence**

Neutrino parameters from SSSI

Scenarios:

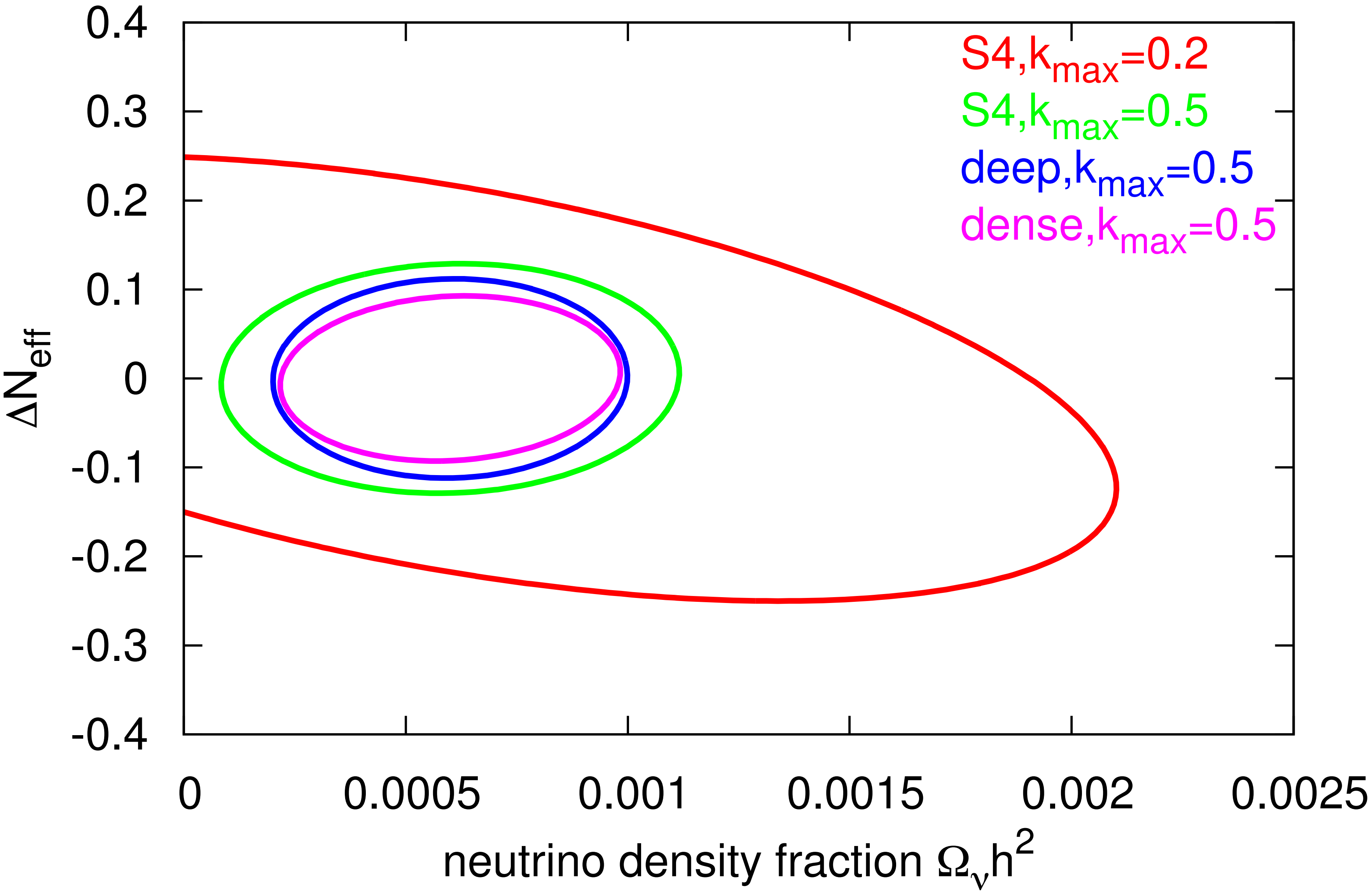
- Baseline Stage IV: LSST + DESI + 4MOST
- Deep: LSST + DESI-like + high-z
- Dense: LSST + DESI-like + 4xDESI-like density

Cosmological parameters varied: n_s, σ_8, h, $\Omega_c h^2$, $\Omega_b h^2$, $\Omega_\nu h^2$, $\Delta N_{\rm eff}$.

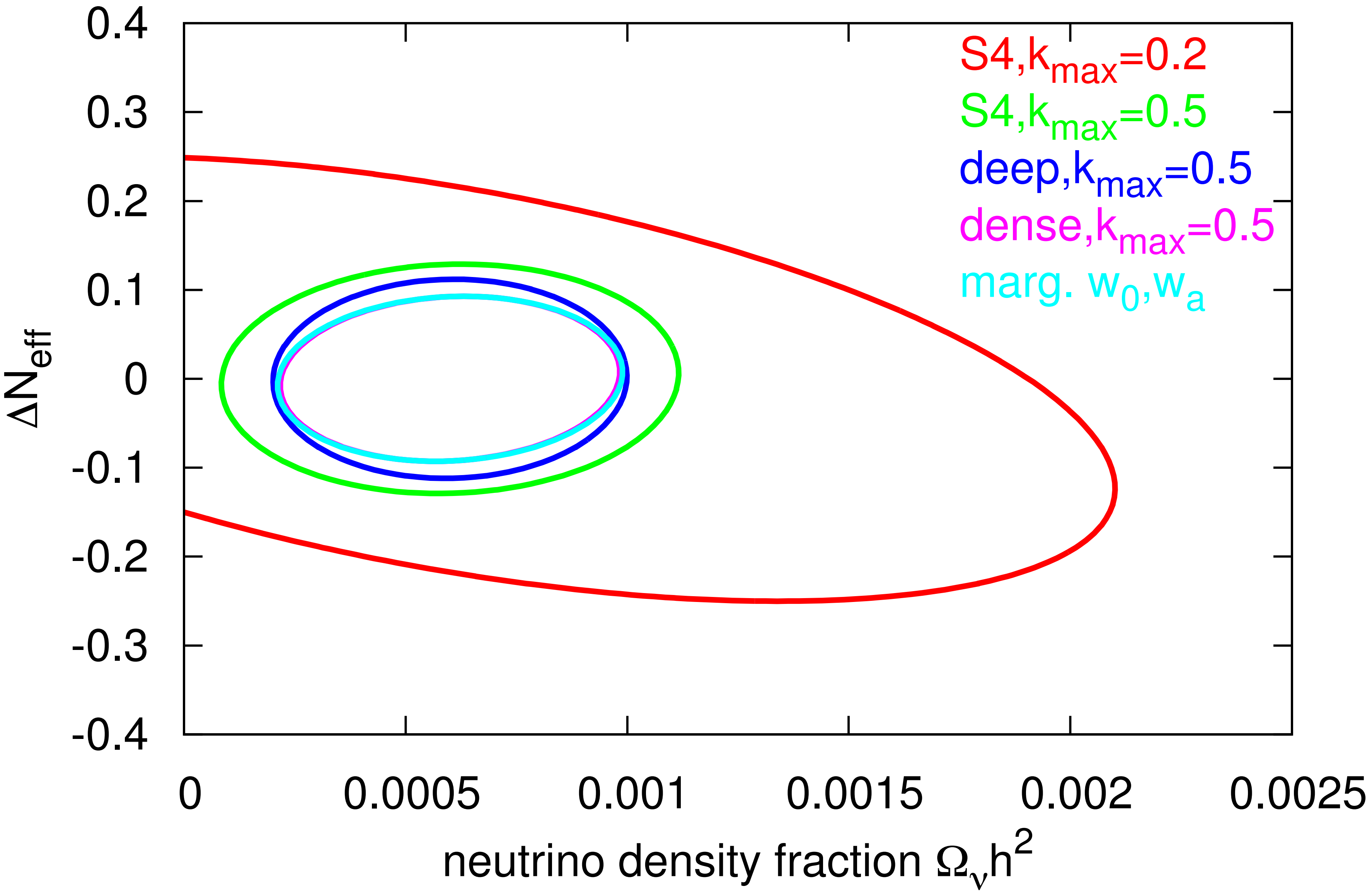
	Stage IV ($k_{\rm max} = 0.2$)	Stage IV ($k_{\rm max} = 0.5$)	+SSSI deep ($k_{\rm max} = 0.5$)	+SSSI dense ($k_{\rm max} = 0.5$)
$\sum m_\nu$	92 meV	32 meV	25 meV	24 meV
$\Delta N_{\rm eff}$	0.165	0.094	0.074	0.061

Note: Cross-correlations not included.

Neutrino parameters from SSSI

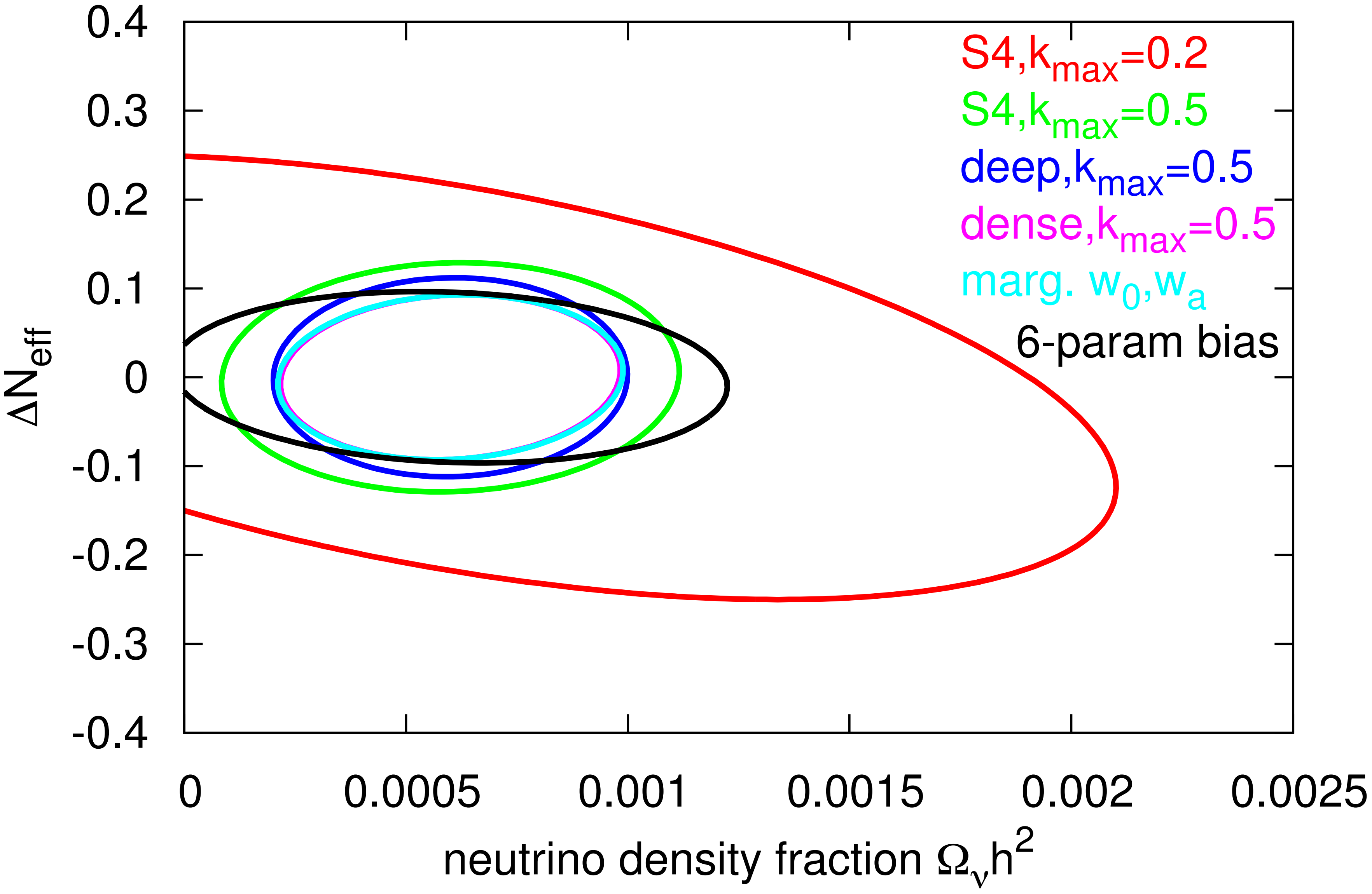


Neutrino parameters from SSSI



Marginalize over dark energy equation of state $w(a) = w_0 + (1 - a)w_a$.

Neutrino parameters from SSSI

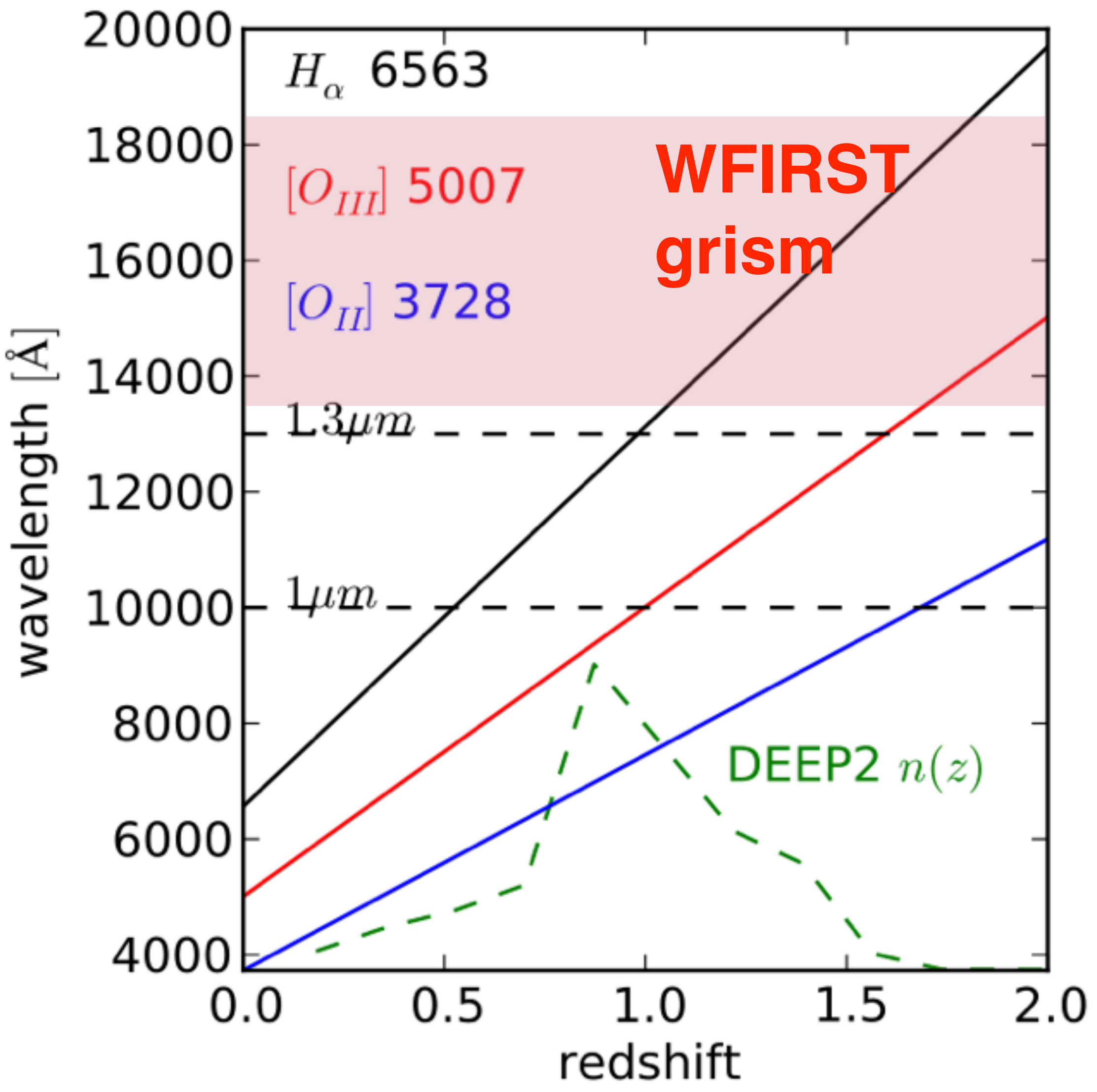


Marginalize over McDonald+Roy 2009 bias plus velocity bias.

Reference slides: more details on why low resolution is not effective for SSSI science

Need multiple features for secure redshifts; at z>1, only [OII] 3726/3729 doublet is in optical

- Major reason why VVDS and zCOSMOS have few secure redshifts past z=1
- In DESI simulations, R~4000 required to split [OII] doublet in majority of cases
- Deep WFIRST grism spectroscopy could be an interesting complement to ground-based low-R spectroscopy to z~1.7, but difficult to reach depths needed for photo-z training



Comparat et al. 2013

Scaling of redshift errors

- Centroid error for a feature is approximately:

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

- Allows simple rescaling of expected *z* errors
- FWHM $\propto$ 1/R
- S/N $\propto$ (object flux) ×(efficiency × total exposure time x collecting area)$^{1/2}$ *
- S/N $\propto$ $(1/R)^{1/2}$ for narrow-band imaging
- S/N ~independent of R for spectroscopy if features are resolved**
- S/N $\propto$ $(1/R)^{1/2}$ if features are diluted by resolution (BG $\propto$ R^{-1})**

* assuming background-limited

** assuming background-limited, pixel scale resolves FWHM, and background is not resolved into individual lines

Scaling of redshift errors

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

- Example scenarios, scaling from LSST photo-z's:
  - LSST is equivalent to R~6; if split LSST observing amongst N filters, but total time and efficiency are unchanged:
    - FWHM $\propto (6/N)$, S/N $\propto (6/N)^{1/2}$
    - Perfect template photo-z error would be $\sim(6/N)^{1/2} \times 0.02\ (1+z)$
  - Place a spectrograph with 16% efficiency (fairly typical) and resolution R on LSST and run for 10 years
    - FWHM $\propto (6/R)$, S/N $\propto (0.16*6)^{1/2}$ (as no longer divide time amongst 6 bands) $\times (6/R)^{1/2}$ (from BG)
    - Perfect template redshift error would be $\sim(6/R)^{1/2} \times 0.02\ (1+z)$
    - NB: only get this for ~5000 objects at a time...

Scaling of redshift errors

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

- Spectroscopy scaled from DEEP2 errors (R=6000, 10m, 1 hour exposures, $\sigma_z \sim 0.000033$@i=22.5, assume identical efficiency if on LSST):
    - DEEP2: R=1000 × LSST, area = 2.2 × LSST, exposure time = 0.12 × LSST, flux = 13.2 × LSST
    - Redshift error predicted for 10-year LSST survey would be $\sim(6/R)^{1/2} \times 0.015\,(1+z)$

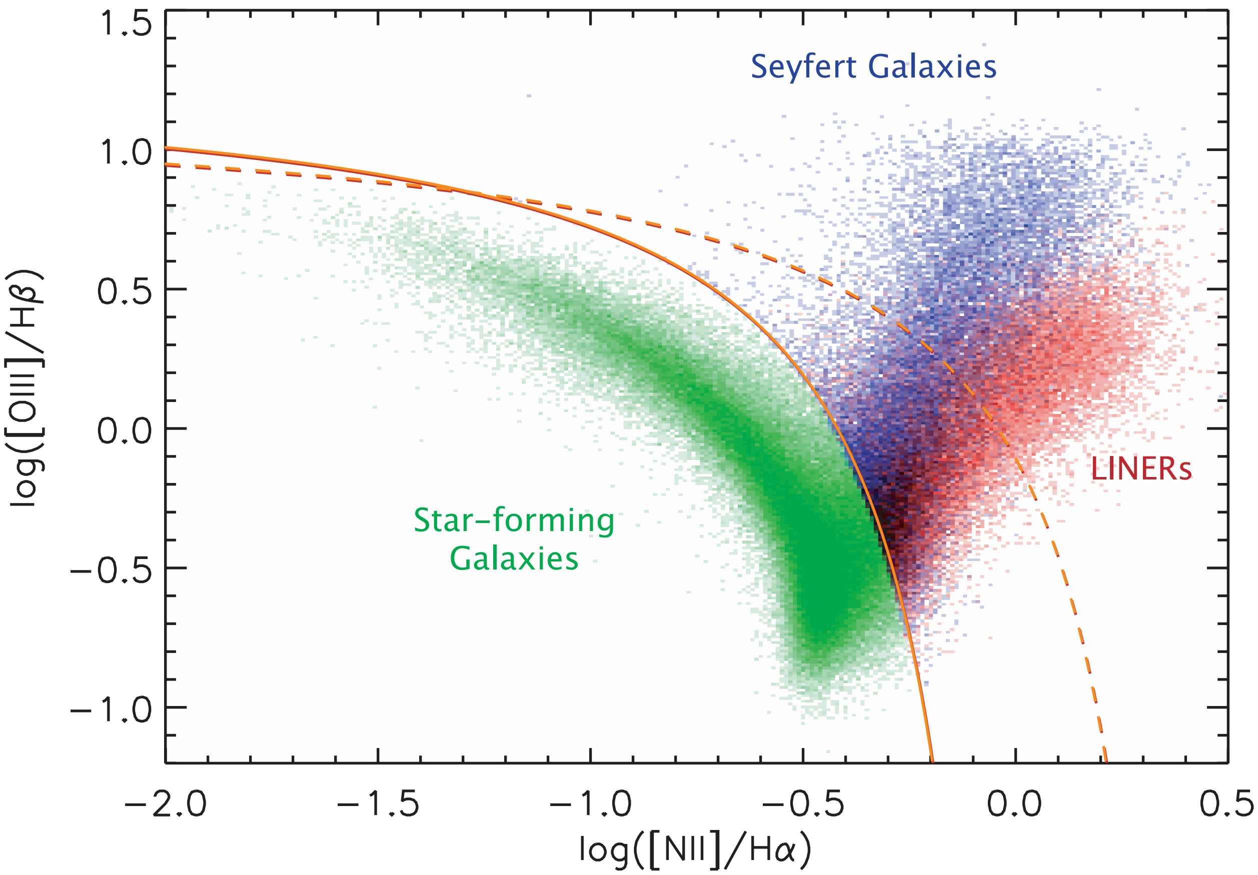
Scaling of redshift errors

$$\Delta\lambda \sim= \frac{\text{FWHM}}{\text{S/N of detection}}$$

- Spectroscopy scaled from zCOSMOS errors (R=600, 8m, 1 hour exposures, σ_z~0.00036@i=22.5, assume identical efficiency if on LSST):
  - zCOSMOS: R=100 × LSST, area = 1.4 × LSST, exposure time = 0.12 × LSST, flux = 13.2 × LSST
  - Redshift error predicted for 10-year LSST survey would be $\sim(6/R)^{1/2} \times 0.015\,(1+z)$

Beware of line misidentifications at low resolution!

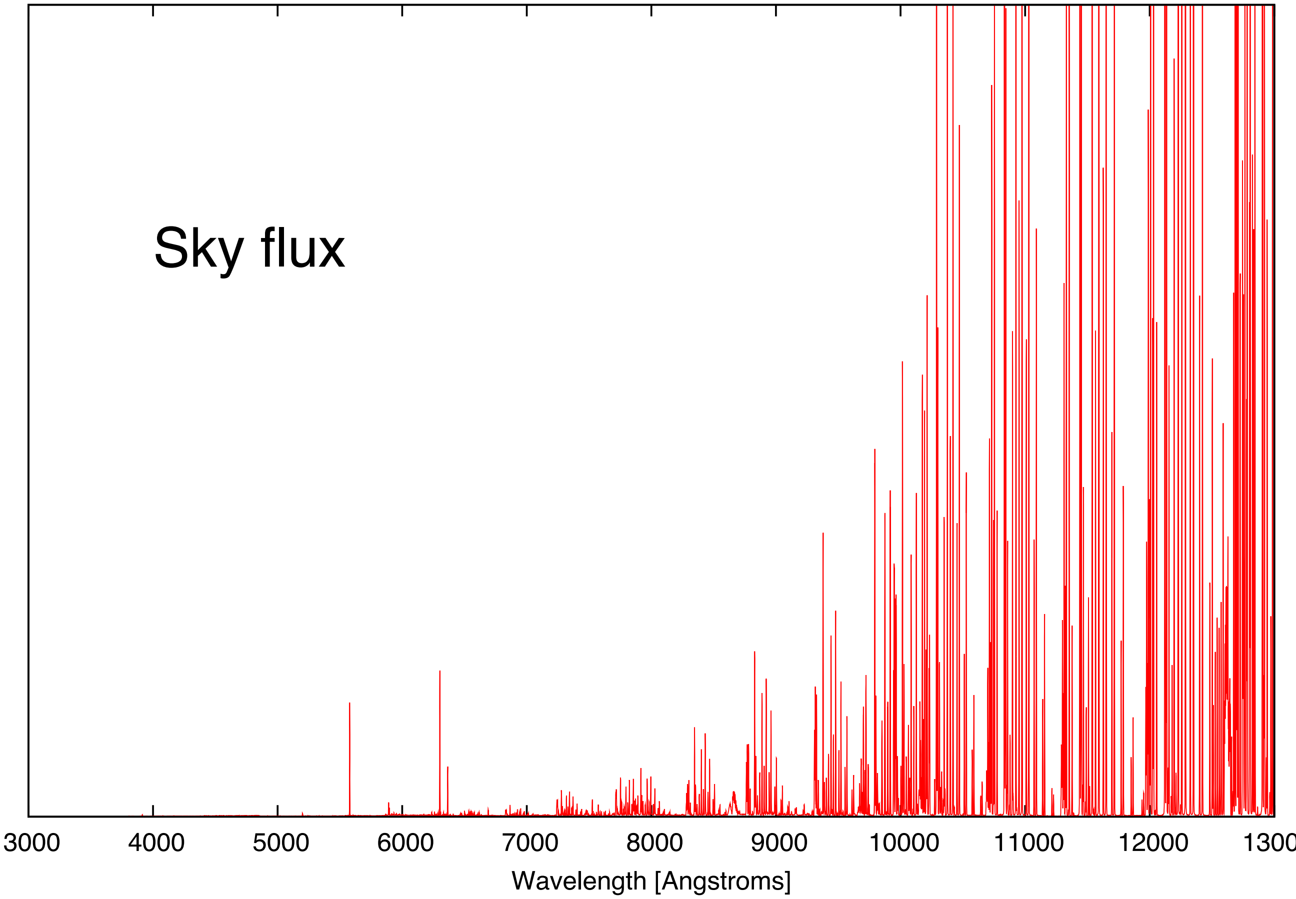
- **[NII] 6548 & 6583 are near Hα, and [OIII] 4959/5007 are near Hβ; line strengths can be >Balmer lines**
- **Important to include Seyfert-like templates in forecasts (represent ~10% of galaxies)**
- **R~1000 to clearly identify [NII]+Hα, R~100 to separate stronger [OIII] line from Hβ**



Fosbury et al. 2007

Sky backgrounds are a much worse problem at low resolution

- LSST galaxies are generally fainter than background sky
- In dark conditions, sky background is dominated by narrow OH emission lines; much darker in between
- This provides a substantial enhancement to survey speed for higher resolutions

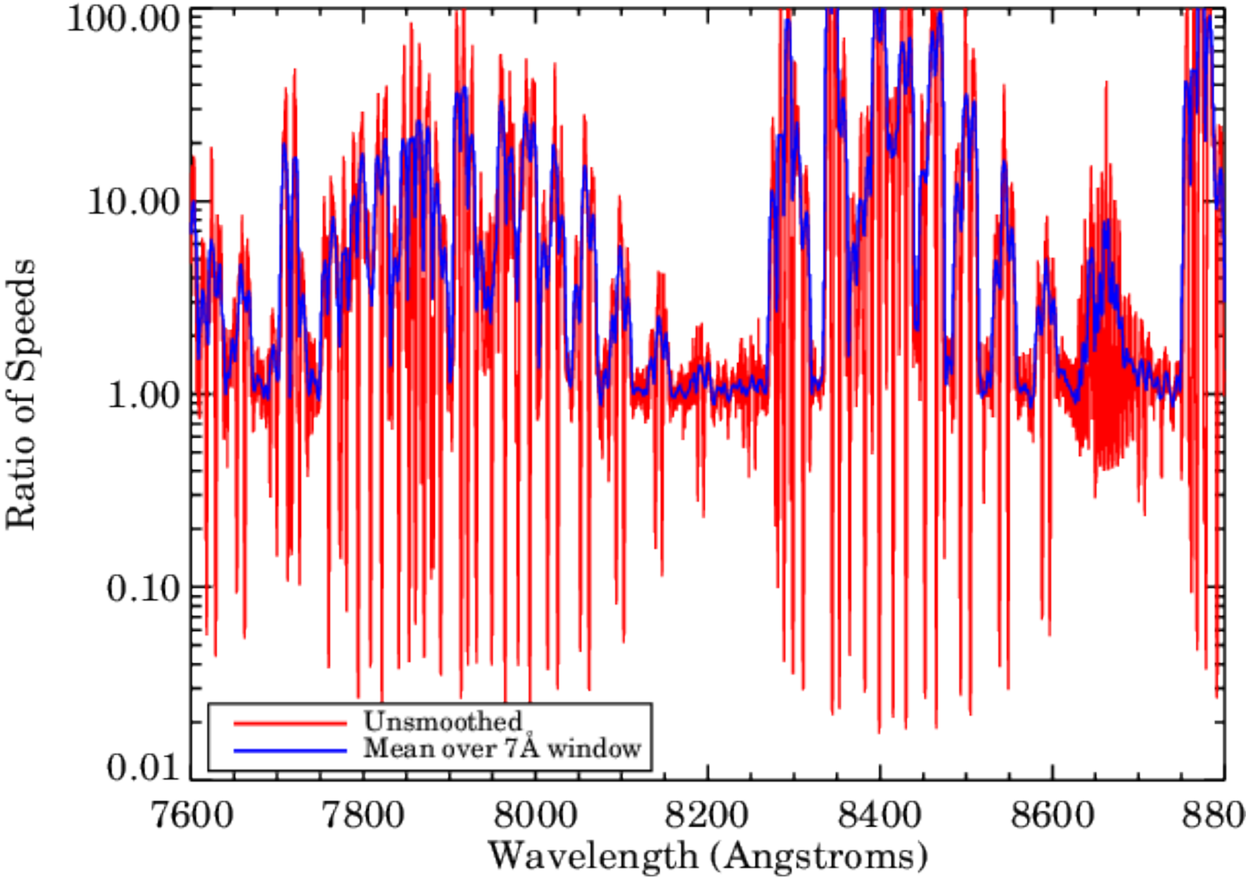


Courtesy C. Cunha

Sky backgrounds are a much worse problem at low resolution

- **LSST galaxies are generally fainter than background sky**
- **In dark conditions, sky background is dominated by narrow OH emission lines; much darker in between**
- **This provides a substantial enhancement to survey speed for higher resolutions**

R=6000 vs. R=600



Newman et al. 2012