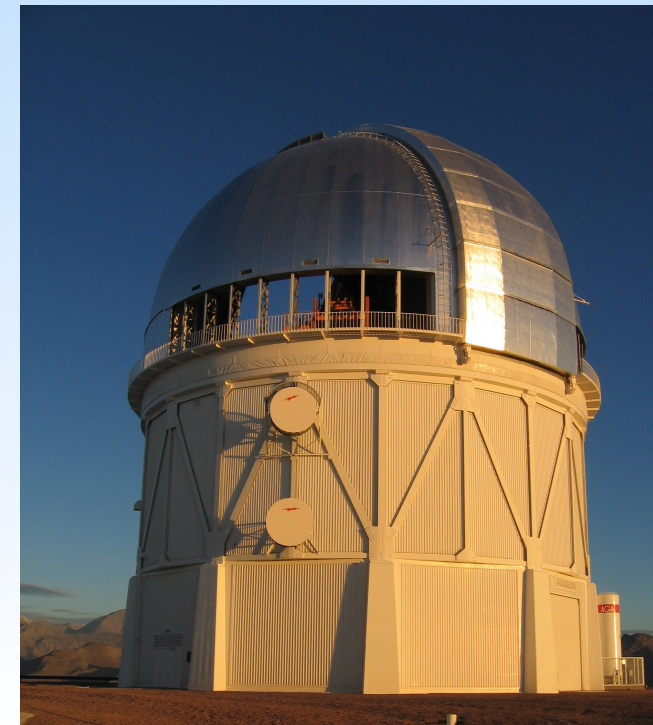
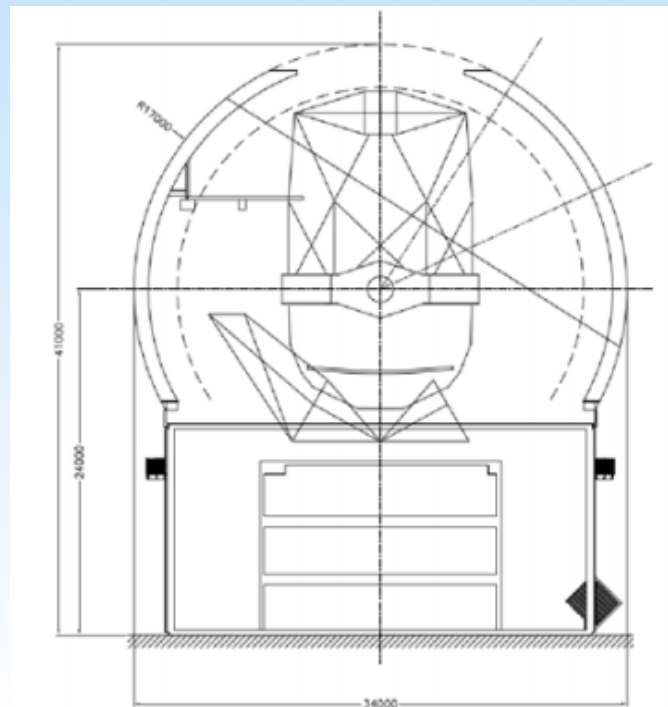


A Southern Spectroscopic Survey Instrument: Synergies with WFIRST

Jeff Newman, U. Pittsburgh/PITT PACC

with contributions from Katrin Heitmann, Josh Frieman, Lindsey Bleem and Elisabeth Krause



- **What is SSSI?**
- **What SSSI can do for WFIRST**
- **What WFIRST can do for SSSI**

- **2015: NSF-commissioned NRC report *A Strategy to Optimize the US Optical and Infrared System in the Era of LSST* (Elmegreen et al.) recommended wide-field, highly multiplexed spectroscopy on an intermediate-to-large aperture telescope in the southern hemisphere.**
- **2016: DOE-commissioned *Cosmic Visions Dark Energy* report (Dodelson et al.) identified a Southern Spectroscopic Survey facility as one way to enhance and go beyond LSST science in the next decade**
- **2016: NSF-requested NOAO-Kavli-LSST community study *Maximizing Science in the Era of LSST* (Najita, Willman et al.) recommended wide-field, highly multiplexed optical spectroscopy on an 8m+ telescope, preferably in the Southern hemisphere, to address a wide variety of science over the next decade+.**

- Close coupling of photometric and WF spectroscopic surveys pays enormous scientific dividends: SDSS, DES & OzDES, HSC & PFS, DeCALs+DES & DESI,...
- LSST+WFIRST & ???
- Grism surveys will be much shallower than imaging and will not fill this gap.
- LSST is a *deep, wide, fast* survey. Spectroscopic resources for *deep* (e.g., ELTs) and *fast* (e.g., Gemini-S Octocam) spectroscopic follow-up are being established, but not wide.
- In general, for efficient (i.e., time-limited) multi-object surveys, we need spectroscopic aperture \geq photometric aperture to have adequate numbers of photons to disperse.

Instrument requirements to address both Cosmic Visions and Kavli MOS recommendations



- **High multiplexing**
 - **Required to get large numbers of spectra**
- **Coverage of full ground-based spectral window**
 - **Minimum: 0.37-1 micron, 0.35-1.3 microns preferred**
- **Significant resolution ($R=\lambda/\Delta\lambda>\sim 5000$) at red end**
 - **Allows secure redshifts from [OII] 3727 Å line at $z>1$**
- **Field diameters $> \sim 20$ arcmin**
 - **>1 degree preferred**
- **Large telescope aperture**
 - **Needed to go faint in reasonable time**
 - **4-6m (Cosmic Visions/SSSI) vs. ~ 8 m (Kavli)**

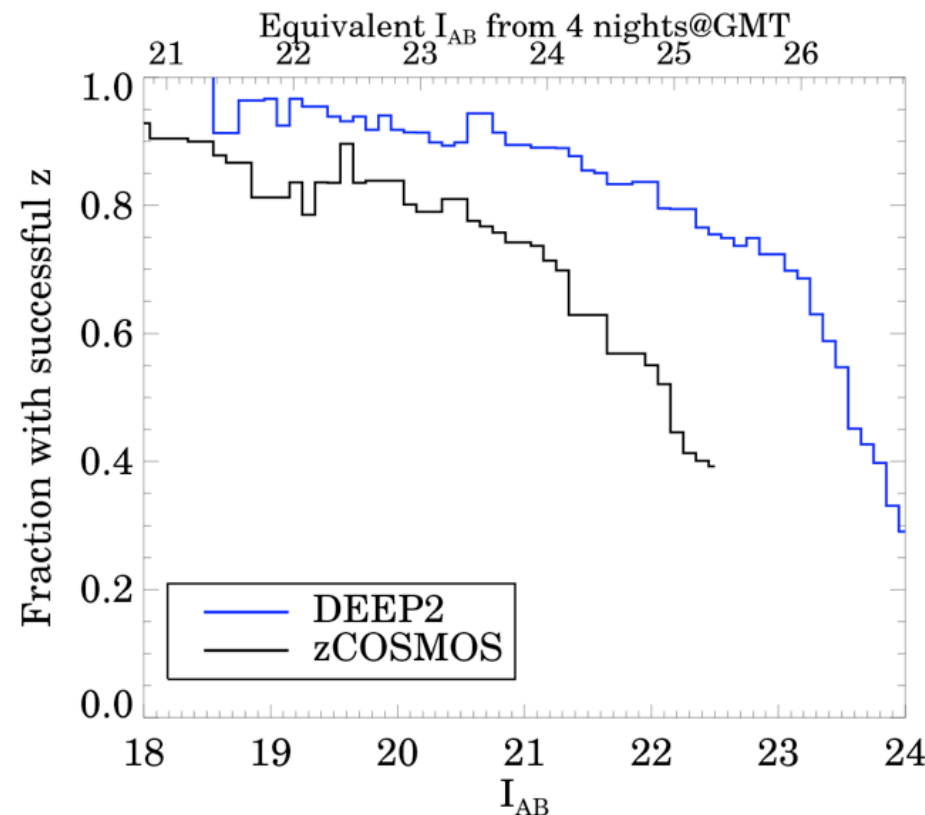
- 1. Implement a wide-field MOS on an existing or new Southern-hemisphere telescope**
 - Example: DESI fiber positioner + spectrograph design would work at a Magellan telescope with addition of an f/3 secondary, providing 1.5-2 deg diameter FoV**
 - Would provide a survey speed approaching Subaru/PFS, with potential for a much greater share of observing time**
- 2. Obtain large amounts of community access to Subaru/PFS; could access northern half of LSST footprint**
- 3. Buy into a proposed new project in the South (cf. Ellis et al. ESO wide-field MOS telescope study) or North (e.g., the proposed Maunakea Spectroscopic Explorer)**

-
- **~\$5-10M**: Upgrade DESI in North, or upgrade and move to Blanco telescope in Chile
 - **~\$40M+**: Implement DESpec on Blanco, keep DESI in North
 - **~\$75M+**: New instrument for existing or funded 6-10m telescope **OR** join existing or planned facility (PFS, MSE,...)
 - **~\$125-150M+**: New Magellan clone + instrument, or instrument on upgraded Gemini (but Gemini-S will likely be largely dedicated to LSST transient follow-up...)
 - **~\$250M-500M+**: New instrument on new 8-11m in the south. Probably would require international collaboration.
 - DES and DESI were/will be ~10 yrs from conception to survey start; LSST, ~25 yrs. More ambitious projects will be on-sky later.

WFIRST will need significantly deeper photo-z training samples than *Euclid*: an SSSI is ideal for this



- A fiducial survey for comparing MOS scenarios:
 - **>30,000 galaxies down to LSST weak lensing limiting magnitude ($i \sim 25.3$)**
 - **15 fields at least 20 arcmin diameter 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 $i=25.3$**
 - **This would be a powerful survey for studies of galaxy evolution**



Newman et al. 2015

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

Updated from Newman et al. 2015, *Spectroscopic Needs for Imaging Dark Energy Experiments*

Time required for each instrument



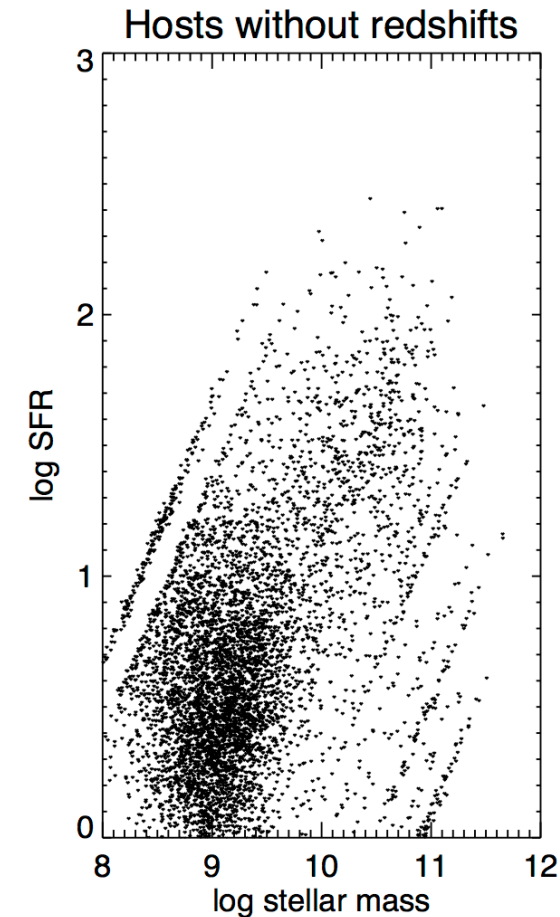
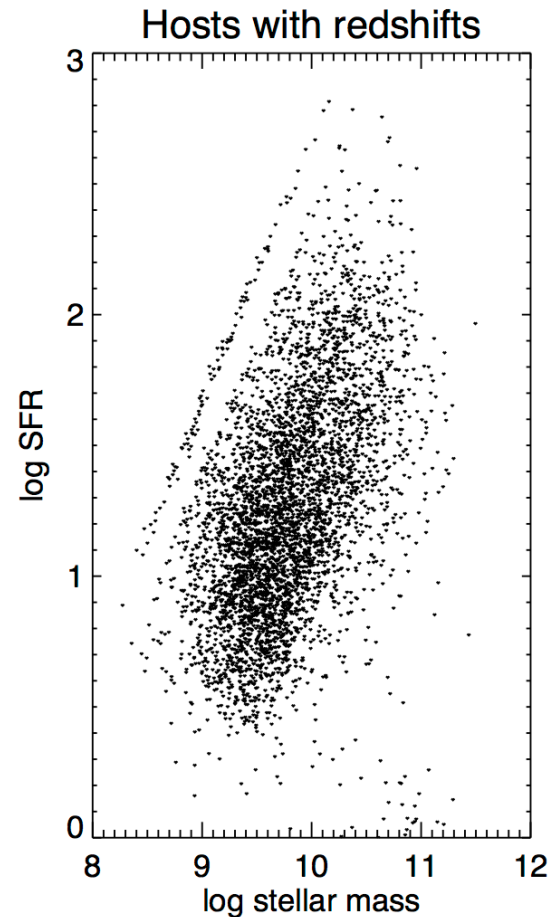
Telescope / Instrument	Total time(years), LSST / 75% complete	Total time(years), LSST / 90% complete
Keck / DEIMOS	10.2	64
VLT / MOONS	4.0	25
Subaru / PFS	1.1	6.9
Mayall 4m / DESI	5.1	32
WHT / WEAVE	9.0	56
VISTA / 4MOST	7.8	48
GMT/MANIFEST+GMACS	0.42 - 0.75	2.6 - 4.7
TMT / WFOS	1.8	11
E-ELT / MOSAIC	0.50 - 0.74	3.1 - 4.7
Keck / FOBOS	2.3	14
MSE	0.60	3.7
Magellan / MAPS	1.8	11

Updated from Newman et al. 2015

An SSSI could also be useful for providing host redshifts for WFIRST SNe Ia - with caveats...



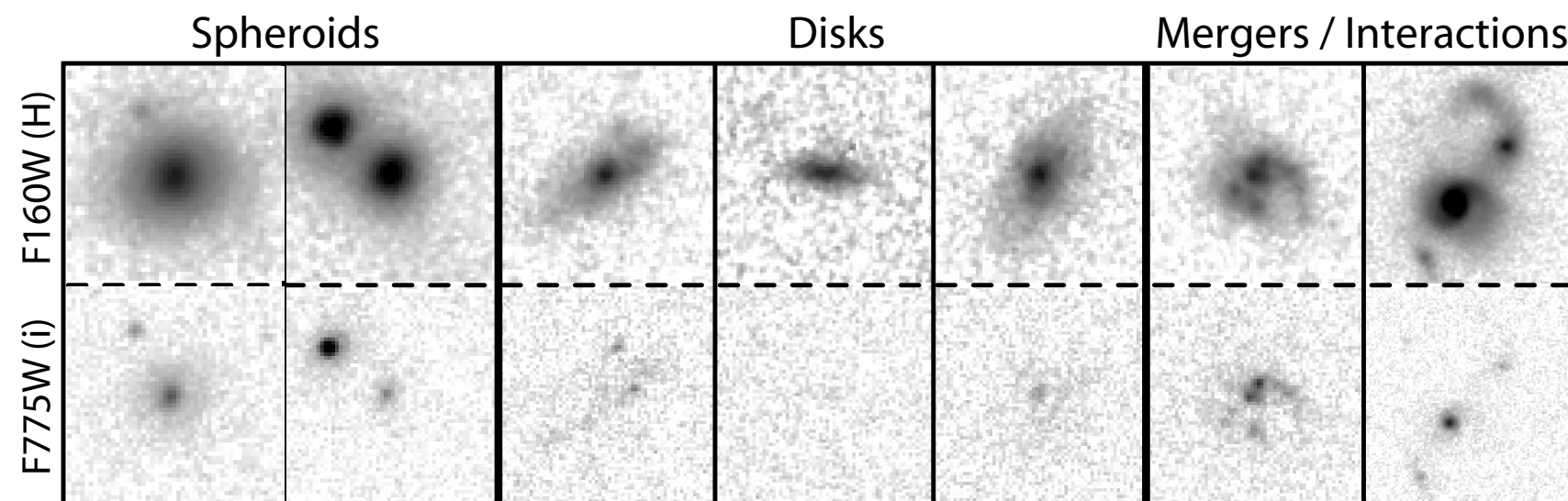
- An SSSI campaign lasting ~months could provide redshifts for a substantial fraction (~50-80%) of $z=1-2$ SN Ia hosts
- Heavily biased towards hosts with the highest star formation rates; given correlations of host properties & SN luminosity, this could be a problem for cosmological applications



WFIRST could greatly enhance the legacy value of SSSI galaxy evolution surveys



- Kavli report presents a strawman galaxy evolution survey in LSST Deep Drilling fields
 - Focused on the evolution of the connection between galaxy properties and environment
 - Mass-complete down to 10^{10} MSun at $z=2$
 - ~130,000 galaxies in total
- *WFIRST* imaging would enable a clean *J*-limited selection
- *WFIRST* would enable rest-optical morphology to be incorporated into the study



Credit:
CANDELS
team

- Kavli report identified SSSI as a critical complement to LSST for studies of stars, Milky Way structure, local dwarf galaxies, galaxy evolution, and cosmology
- These science cases will generally also apply to *WFIRST* HLS and/or GO science
 - Especially photo-z training
- For more details, see SSSI presentations at <https://kicp-workshops.uchicago.edu/FutureSurveys/presentations.php> and <https://indico.hep.anl.gov/indico/conferenceOtherViews.py?view=standard&confId=1035>
- If you are interested in helping to develop the science case for SSSI, contact me at janewman@pitt.edu: the Decadal survey will be coming soon!

An SSSI spectrograph can enhance a variety of other cosmological studies

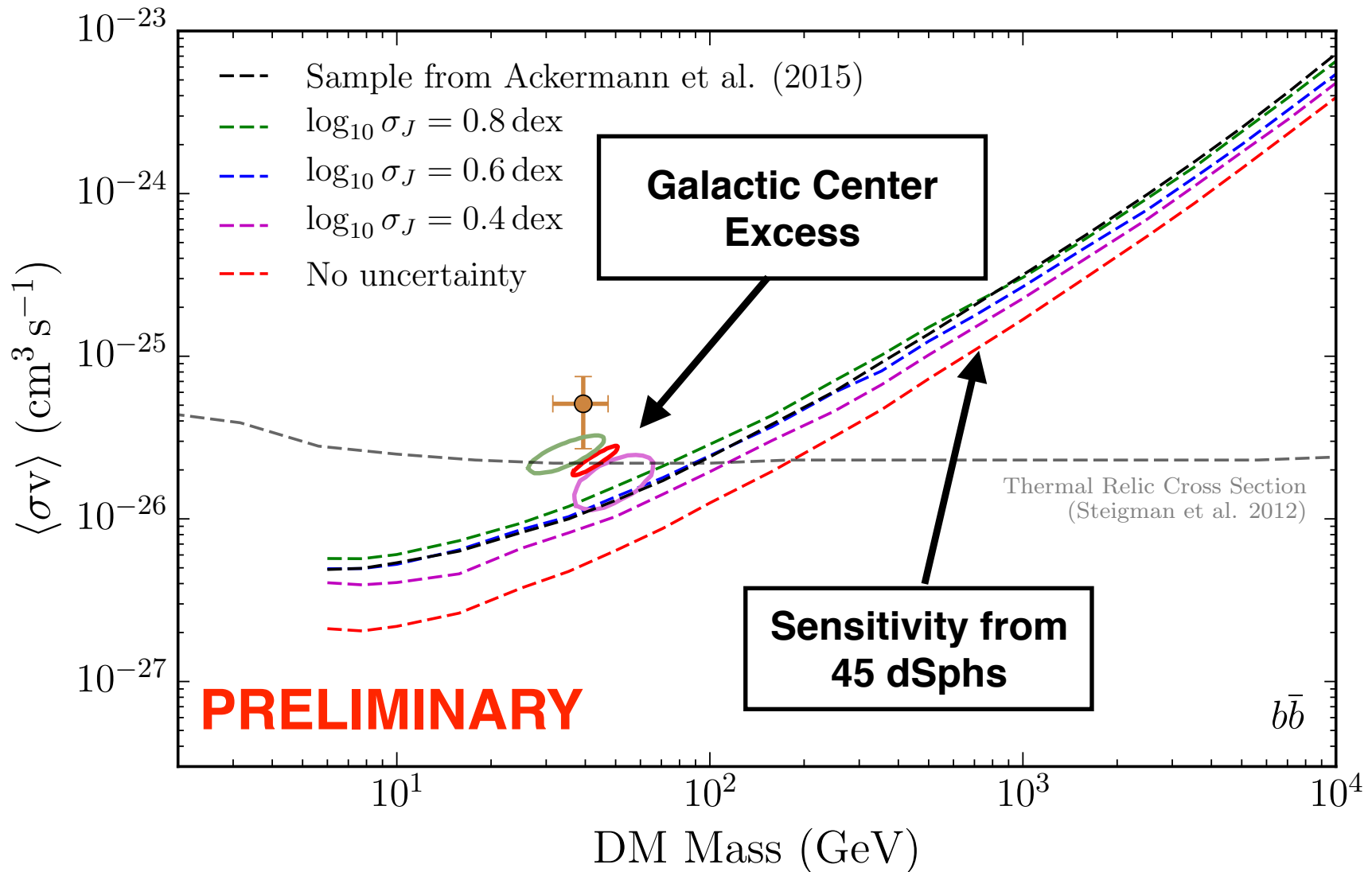


The same sort of spectrograph needed for photo-z training can be used to:

- 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

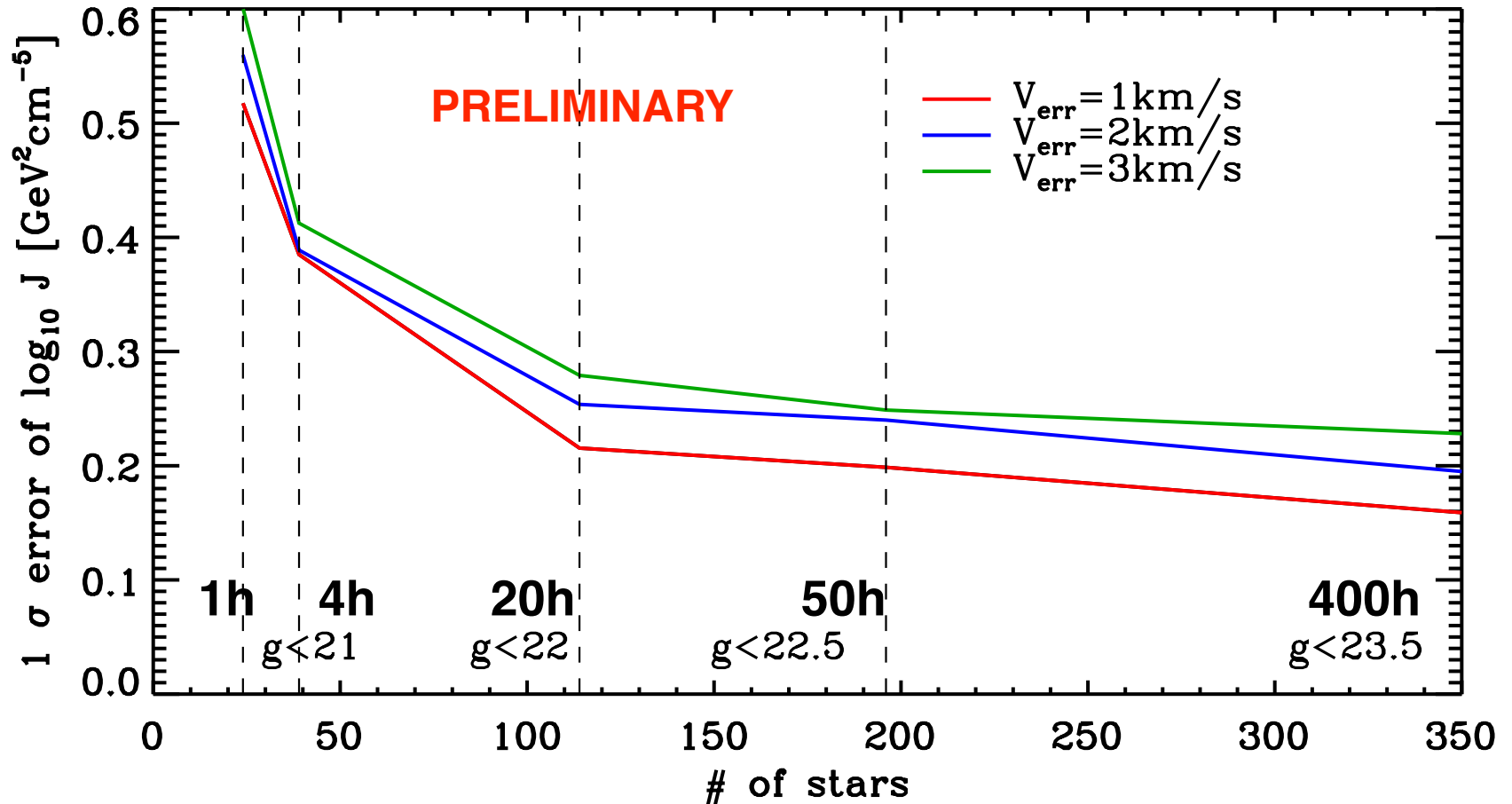
Improving indirect-detection dark matter searches with SSSI



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

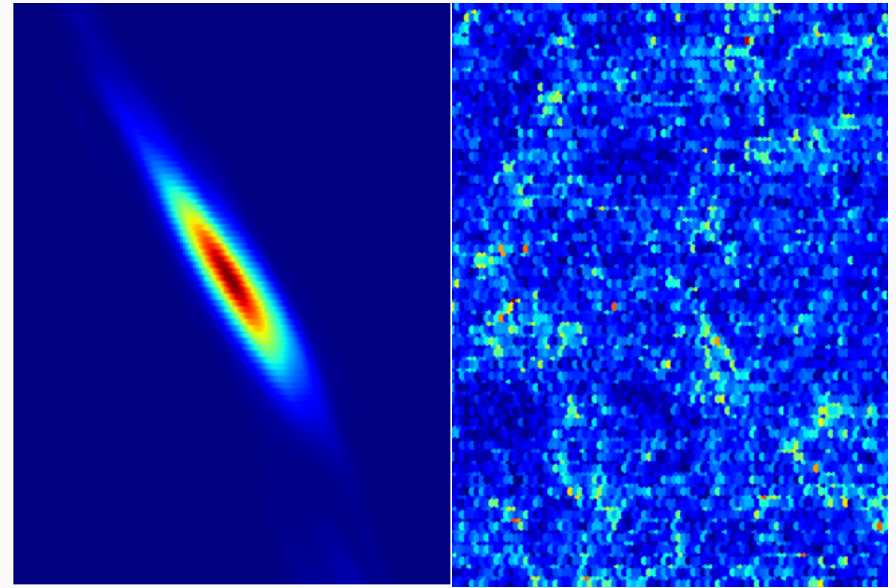


Magnitudes & exposure times are for Reticulum 2 & 6.5m telescope

- 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.

- By mid-2020s, >2 gravitational wave sources per day will be detected, with localizations to ~ 90 Mpc along the line of sight and ~ 1 deg² 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- $40^\circ \times 30^\circ$, red $\times 10$ more likely than light blue. Right: mock galaxy catalog, $M_i < -21$, $z \leq 0.2$. (Buzzard v1.1)

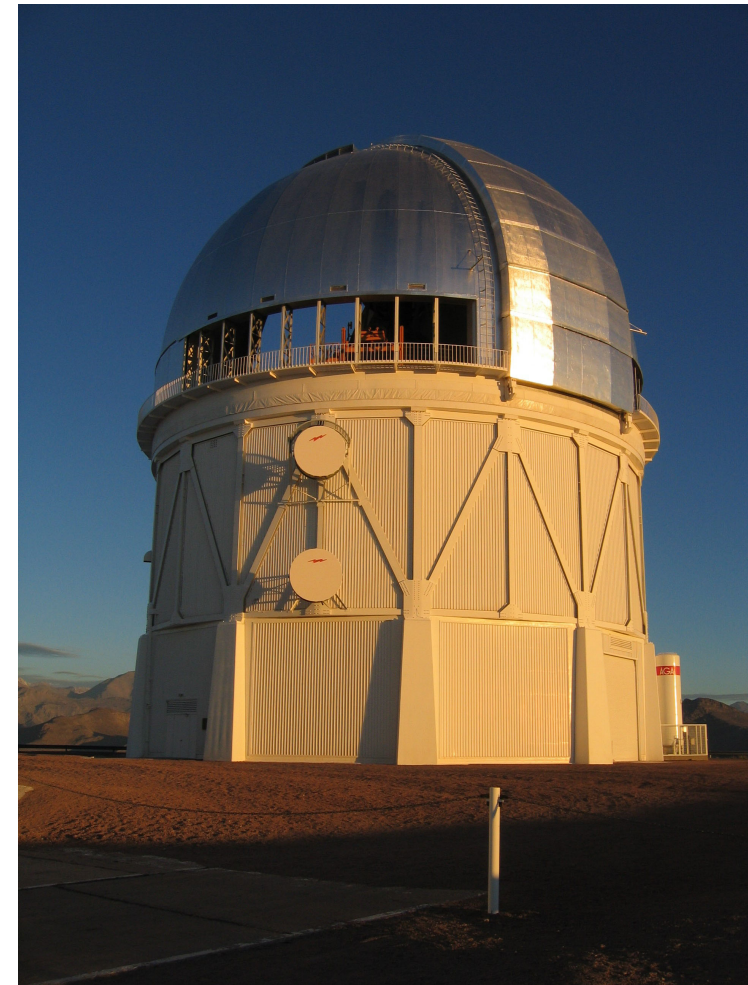
**Annis, Soares-Santos, & Brout,
in prep.**

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

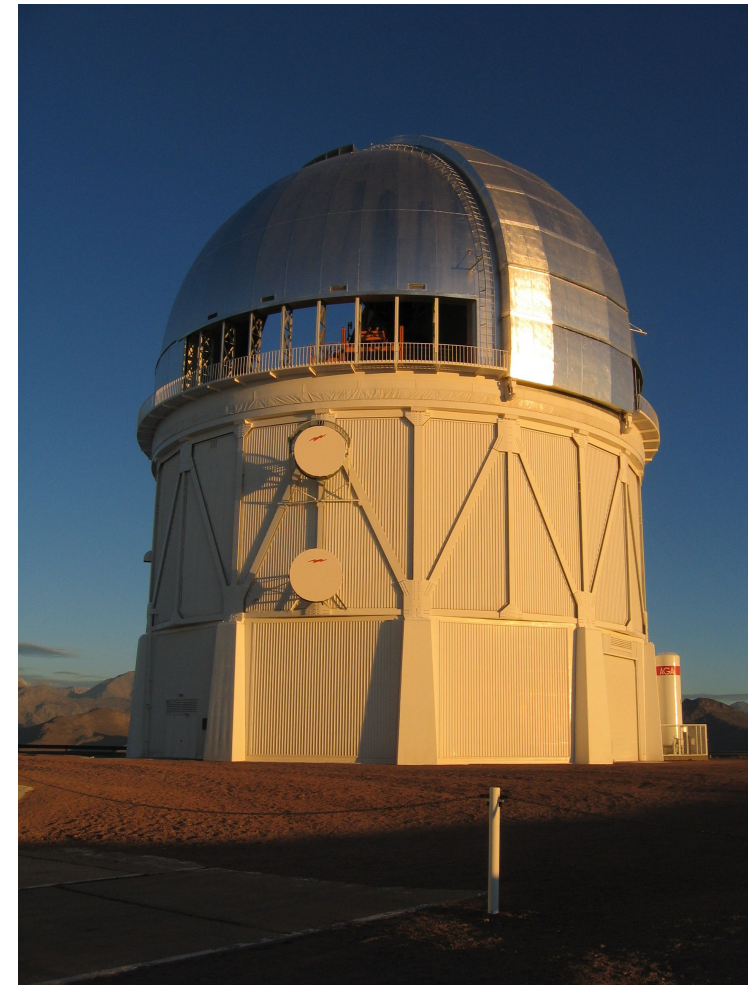


- **Galaxy evolution: survey of $\sim 100,000$ galaxies to $z=2$ to study connection between galaxy properties and environment in LSST deep drilling fields**
 - Requires ~ 1 year of time on a Subaru/PFS-like spectrograph
- **Milky Way structure: spectroscopy of $\sim 1,000,000$ stars to study the build-up 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**

- Same telescope used for DES: 4m diameter, currently w/ 3 deg² FOV
- Successful experience with DOE/NSF/NOAO partnership
- Clone or move DESI: 5000x multiplexing, ~7 deg² FOV
 - ~few M\$ for move or ~60M\$ for clone
- DESpec: 5000x multiplex, 3 deg² FOV with existing corrector, interchangeable w/ DECam:
 - ~40M\$



- **Pros:**
 - Largest field of view w/ DESI move or clone
 - Moving DESI cheapest option for an SSSI; mid-2020s possible
- **Cons:**
 - Small aperture requires long survey times
 - Earthquake safety of DESI corrector?
 - Kavli/NOAO/LSST report will recommend DECam stay on Blanco at minimum 3 years into LSST survey; would delay SSSI deployment unless DESpec option



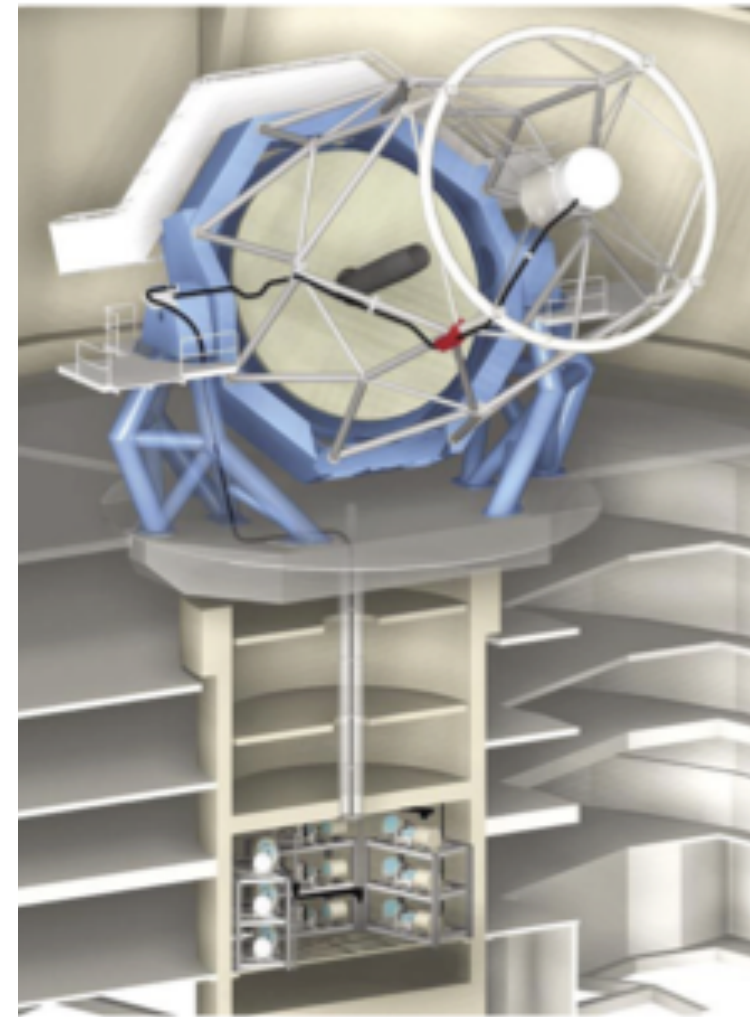
- **Two 6.5 diameter telescopes**
- **Potential f/3 secondary would match DESI input beam and enable 1.5-2 deg diameter field of view with 3000-6000 positioners**
- **New secondary would cost ~\$few M million, plus ~\$75M+(?) for instrument**
- **Magellan institutions with majority of time interested in partnership: successful model with SDSS4/APOGEE-South**
- **SSSI instrument could form the basis of a SDSS6 survey; potential public/private partnership**



- **Pros:**
 - Larger collecting area
 - Existing telescope makes earlier schedule possible: mid-2020s?
- **Cons:**
 - Would prefer even larger aperture, >8m (Kavli/NOAO/LSST)
 - If use an existing Magellan telescope, must navigate politics of Magellan institutions, time access likely limited.
- **Build a 3rd Magellan telescope for this? Add \$75M+ and additional construction time.**



- 8m telescope, US(NSF)-led international consortium
- Current FOV is small
- With ~\$50M upgrade, could get 1.5 deg FOV, plus ~\$75M instrument: WFMOS redux.
- Pros:
 - Larger collecting area; US-led
- Cons:
 - Total cost >~\$125M
 - Gemini-South planned to have lead role in LSST transient follow-up. Probably not available before late 2020s.
- Gemini-North might be more available, but in wrong hemisphere.



- 4m diameter
- Latitude 32N
- Could use (possibly upgraded) DESI instrument from mid-2020s
- Pros:
 - Enables SSSI science without new instrument
- Cons:
 - Northernmost option, can access $\ll \frac{1}{2}$ of LSST area
 - Very large amounts of time required to do SSSI program on 4m
 - Gets worse at the higher airmasses required to reach into LSST footprint from Kitt Peak



- Magellan clone, 6.5m diameter
- Latitude 30N
- \$74M projected telescope budget, plus ~\$75M+(?) for instrument
- Pros:
 - **Simpler politics than Magellan, enthusiasm of partners to host an SSSI-like instrument**
- Cons:
 - **Northern hemisphere**
 - **Smaller than some other options**
 - **Not yet certain to be built, time access likely limited.**



- 8m diameter, wide-field telescope
- PFS spectrograph, 2400 fibers over 1.3 deg, under construction, commissioning to be completed 2019
- Pros:
 - Enables SSSI without new instrument
- Cons:
 - Northern hemisphere, but can access majority of LSST footprint
 - Limited time access: must compete with other Japanese priorities and potential time allocations for WFIRST
 - Subaru relatively expensive to build + operate



- 10m diameter, narrower-field telescope
- FOBOS: proposed 500-object spectrograph
- Designed for high efficiency: could have comparable survey speeds to PFS
- Pros:
 - Large telescope aperture
 - Could enable kinematic weak lensing via mini-IFUs
- Cons:
 - Northern hemisphere, but accesses majority of LSST footprint
 - Very limited multiplexing and FOV
 - Limited time available: largest Keck programs to date have been ~100 nights



- **11m diameter telescope with 1.5 degree field of view, replacing CFHT**
- **Designed solely for spectroscopy with an SSSI-like (3200-fiber) instrument**
- **Pros:**
 - **Large aperture, wide field, very high survey speed**
 - **Enthusiastic about collaborating**
- **Cons:**
 - **Northern hemisphere, but accesses majority of LSST footprint**
 - **Not yet funded; timescale?**
 - **Cost to join: \$50 million (in-kind via instrument construction?)**
- **Note: similar telescope concepts for South under ESO discussion.**



-
- **Strawman: 8m+ telescope with >1.5 degree field of view**
 - **Designed ab initio for WF, highly multiplexed spectroscopy**
 - **Pros:**
 - **Large aperture, wide field, very high survey speed, access, LSST overlap**
 - **Cons:**
 - **Cost and timescale**

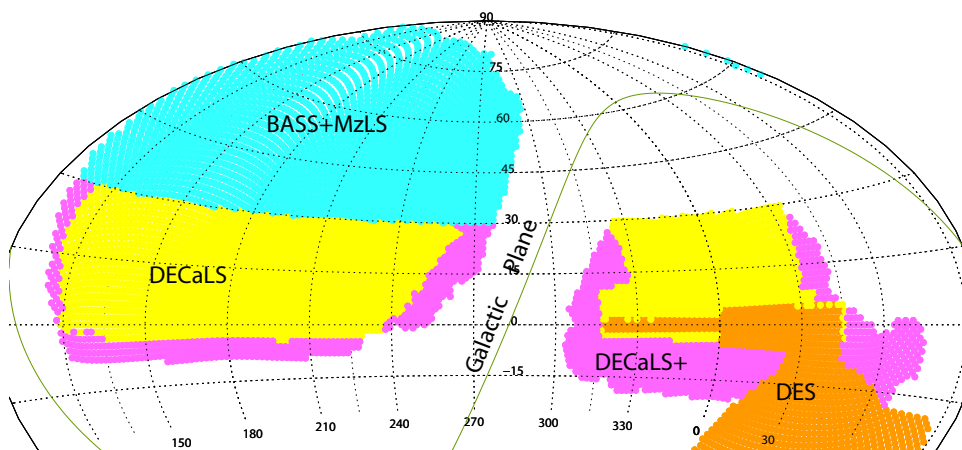
- **Astronomy community has identified SSSI-like instrument as a priority, but will want to enable non-cosmic science.**
- **DOE focus is on cosmology only**
- **SSSI would be relevant to NASA for WFIRST photo-z training**
- **Private consortia with existing or to-be-built 6-10m telescopes may be interested in partnering for cash or instrument.**
- **The international community also recognizes and is discussing the potential benefits for such a capability in the LSST era. International partnerships possible and may be necessary for larger-scale implementations of SSSI.**

Three example fiducial surveys:

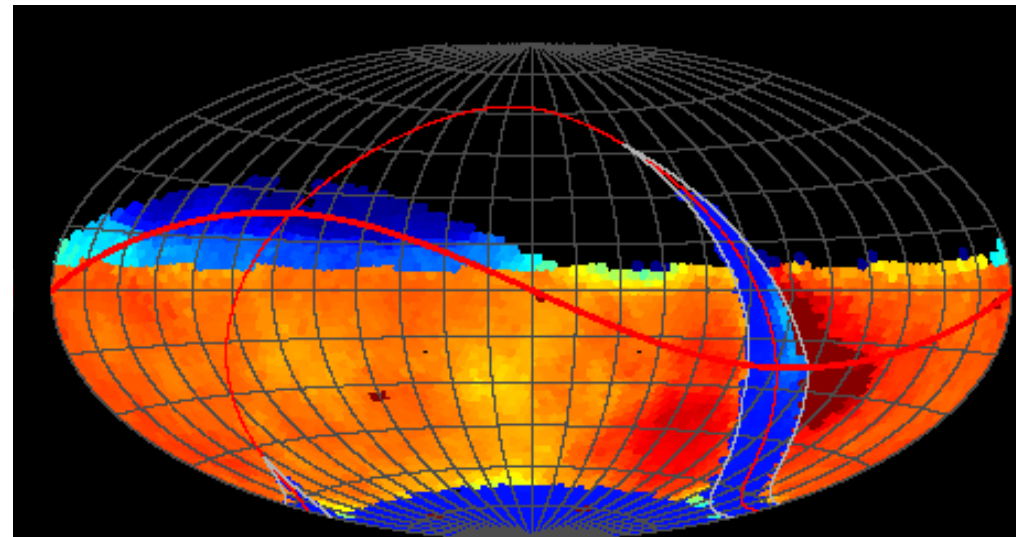
- **Wide**

- DESI-like high-z survey over 16,000 sq. deg. of LSST footprint not covered by DESI (CMB-S4 area is same size -- a cross-correlation survey would be similar)
- ~29M spectra total
- Note: 4MOST will be doing a ~half-DESI-density survey over this area (but no BGS equivalent). Is the extra density/z range worthwhile?

DESI coverage



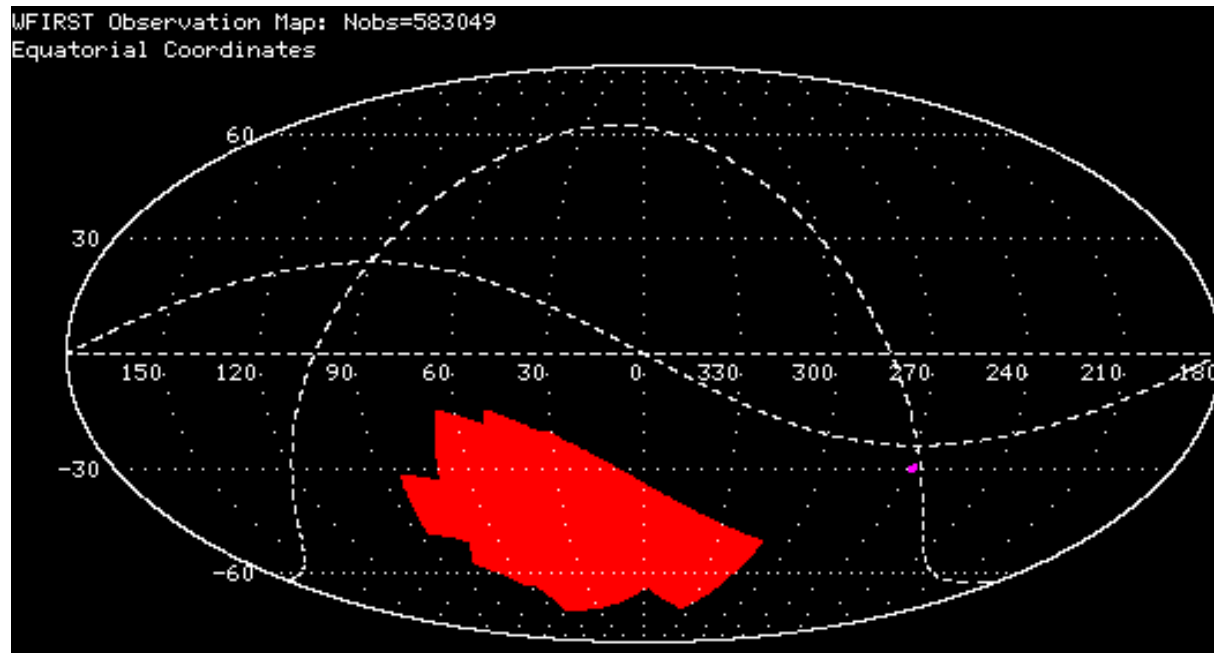
LSST coverage



Three example fiducial surveys:

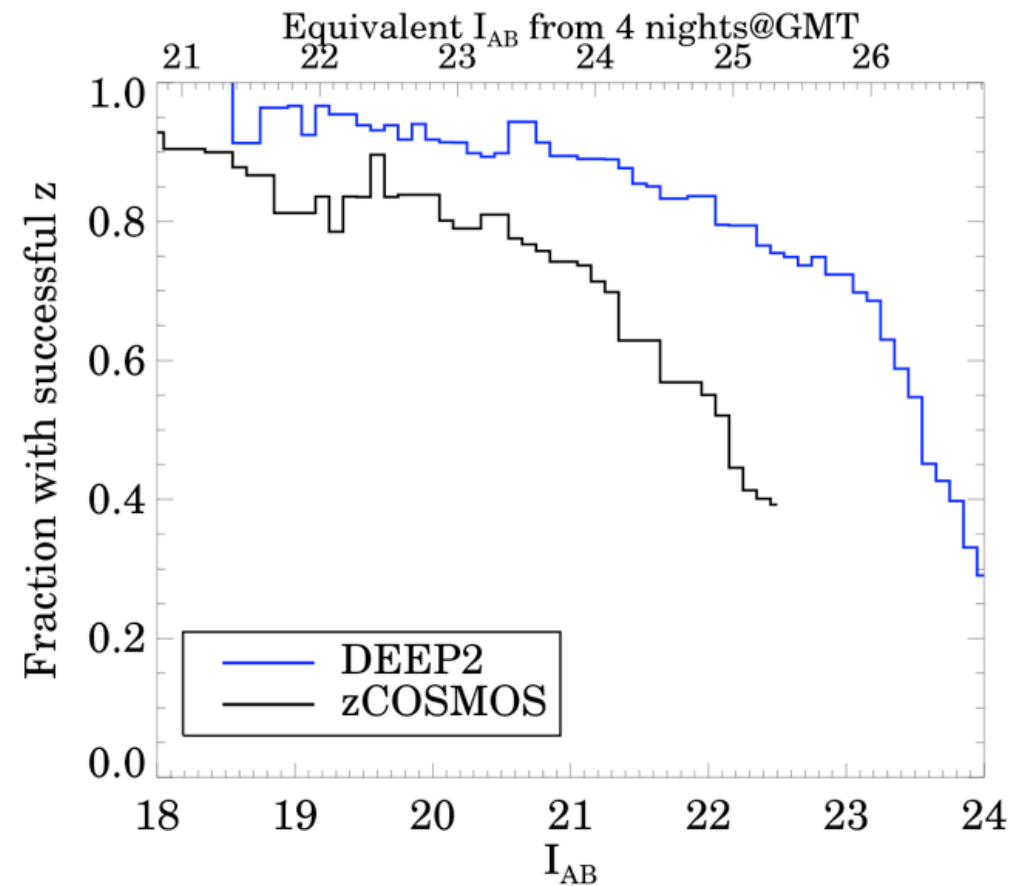
- **Intermediate**

- Survey of all galaxies to $i \sim 22.25$ over 2700 sq. deg. WFIRST area
- 42M galaxies total (4.4 per sq. arcmin)
- 2x DESI exposure time assumed (should yield $\sim 75\%$ redshift completeness, scaling from DEEP2)
- Dense map of LSS ($\sim 9x$ DESI density)
- Useful for cross-correlation studies, etc.
- Could optimize for CMB-S4 rather than WFIRST



Three example fiducial surveys:

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



Number of dark years required for each survey on each instrument/telescope



	Wide	Intermediate	Deep
DESI-South	1.1 years	3.1 years	5.1 years
PFS-South	0.7	1.7	1.1
MSE-South	0.4	0.8	0.6
Magellan/MAPS	0.7	1.2	1.8

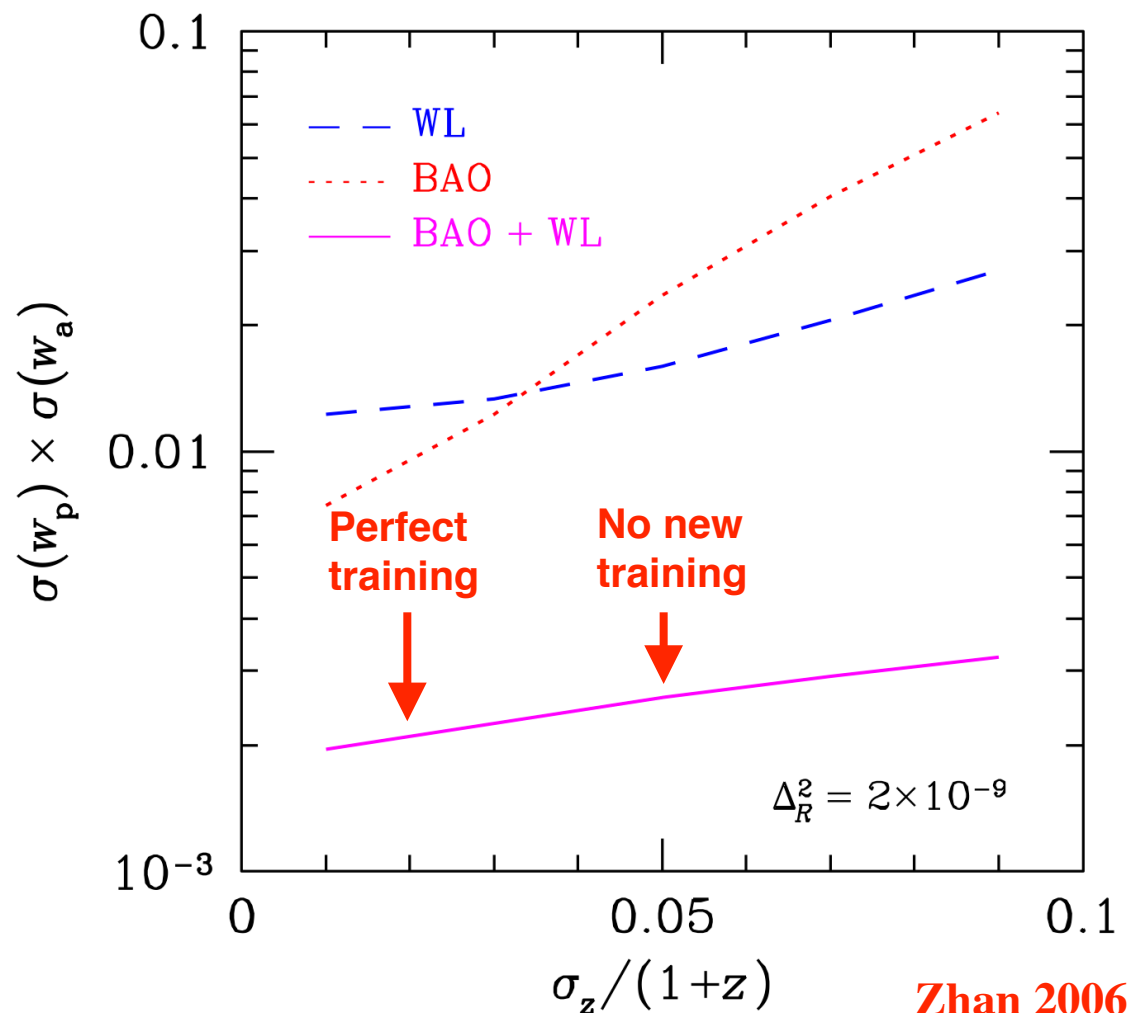
- **Notes: Normalizations are optimistic, at least for Wide; the real DESI survey (which is 14k sq deg vs 16k for Wide) is more like 3 years of dark time.**
- **Time estimates assume that all fibers are assigned to targets and that sky subtraction accuracy scales as photon noise.**
- **Minimum observation 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.**

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



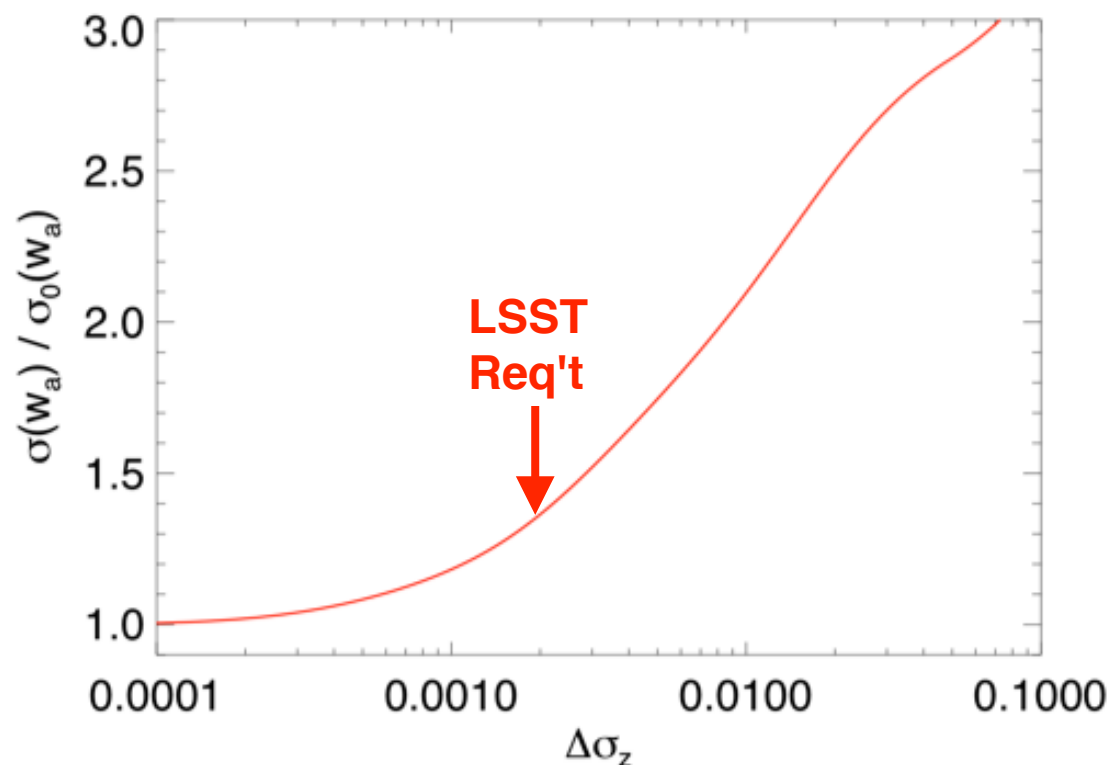
- Training datasets will contribute to calibration of photo-z's.
~Perfect training sets can solve calibration needs.

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

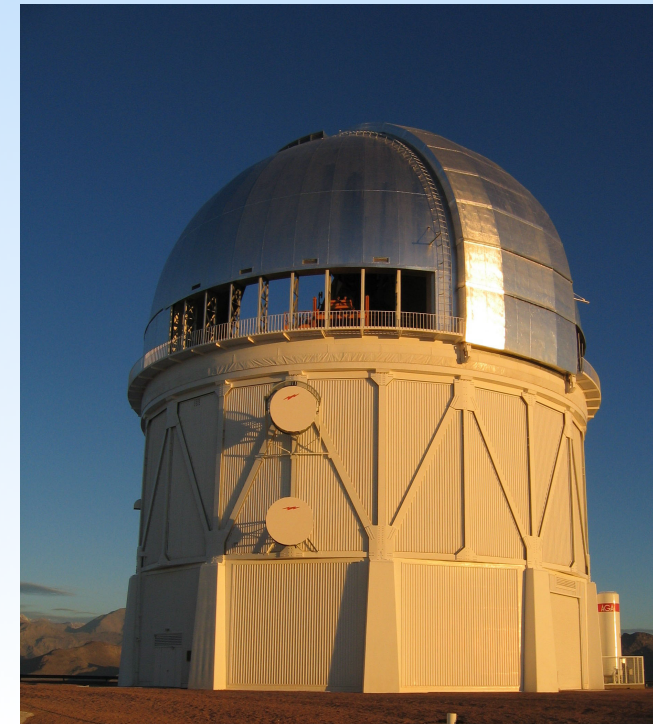
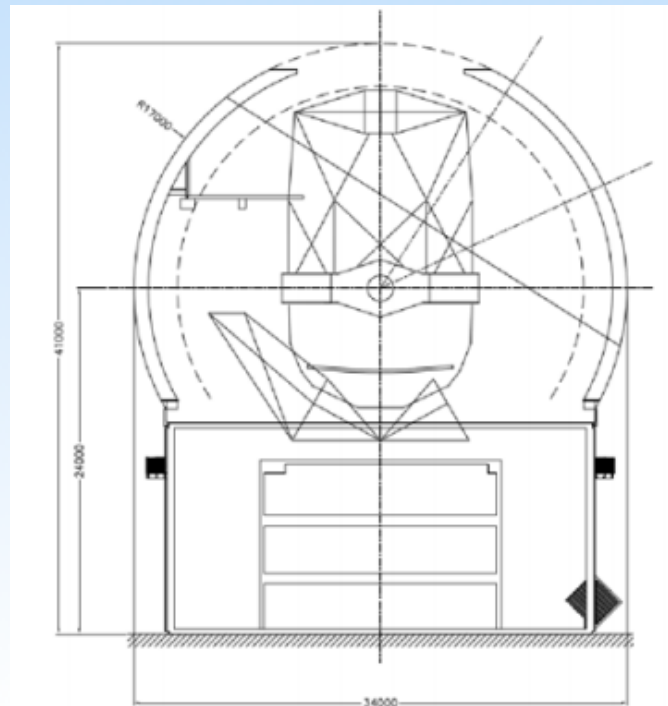


Newman et al. 2013

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

SSSI Science: Cosmological Parameters from SSSI

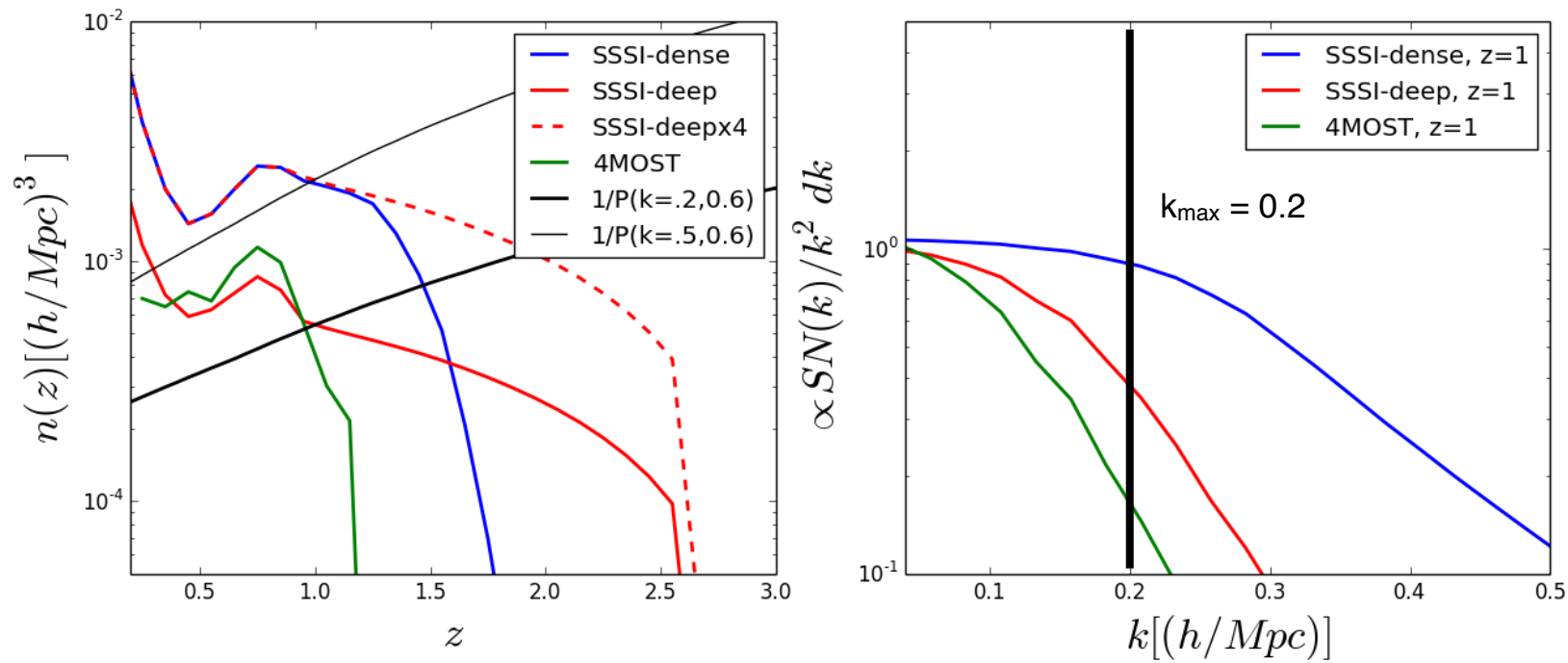
Elisabeth Krause, KIPAC (Stanford/SLAC)
Amol Upadhye, U. Wisconsin



- **”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_a CDM cosmology**
 - **Linearized modified gravity effects using (μ, Σ) parameterization (CosmoLike implementation by Miyatake & Eifler)**

- SSSI Baseline Scenarios

- SSSI-dense: 4xDES-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

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

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

- 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**

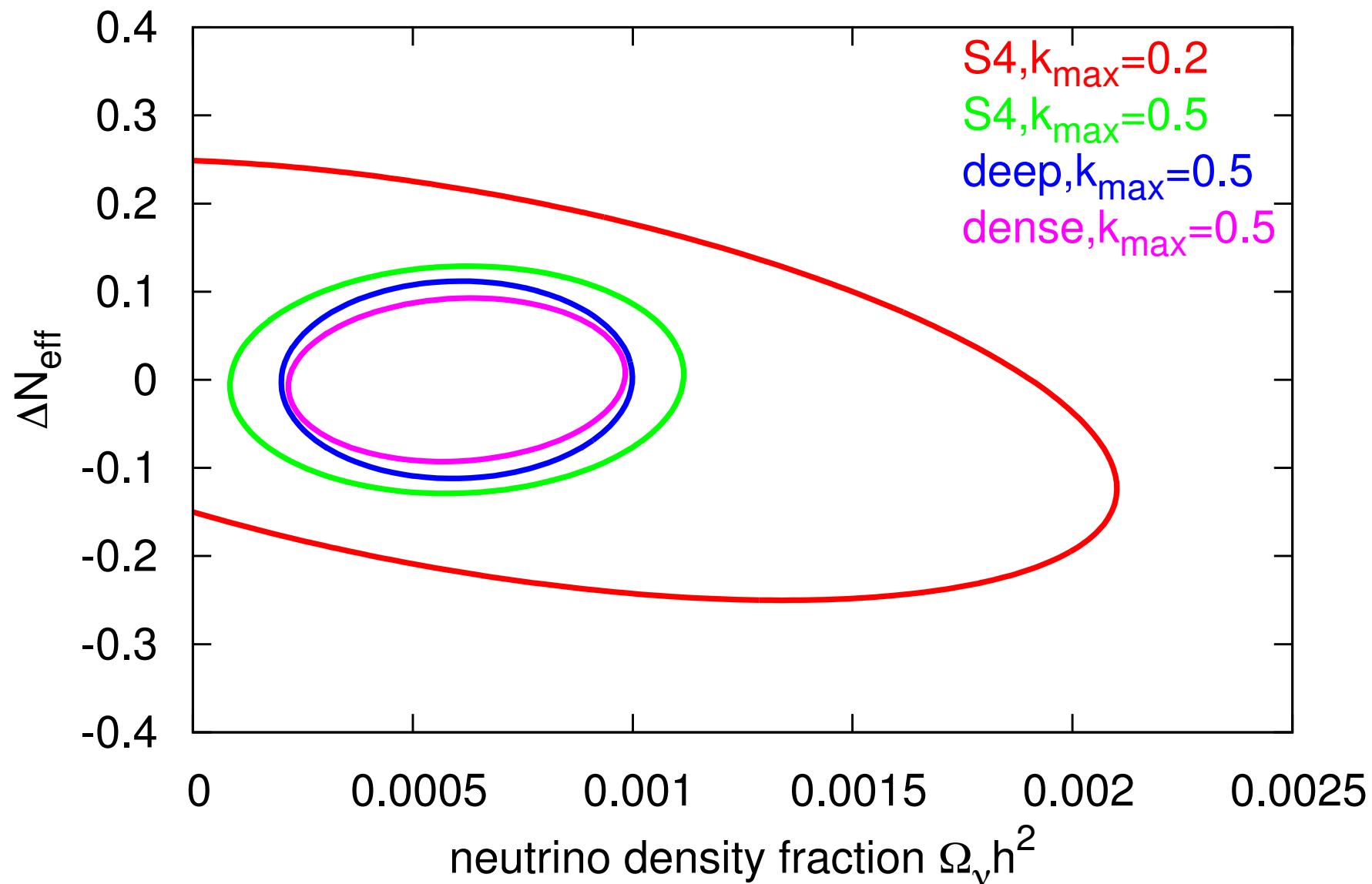
Scenarios:

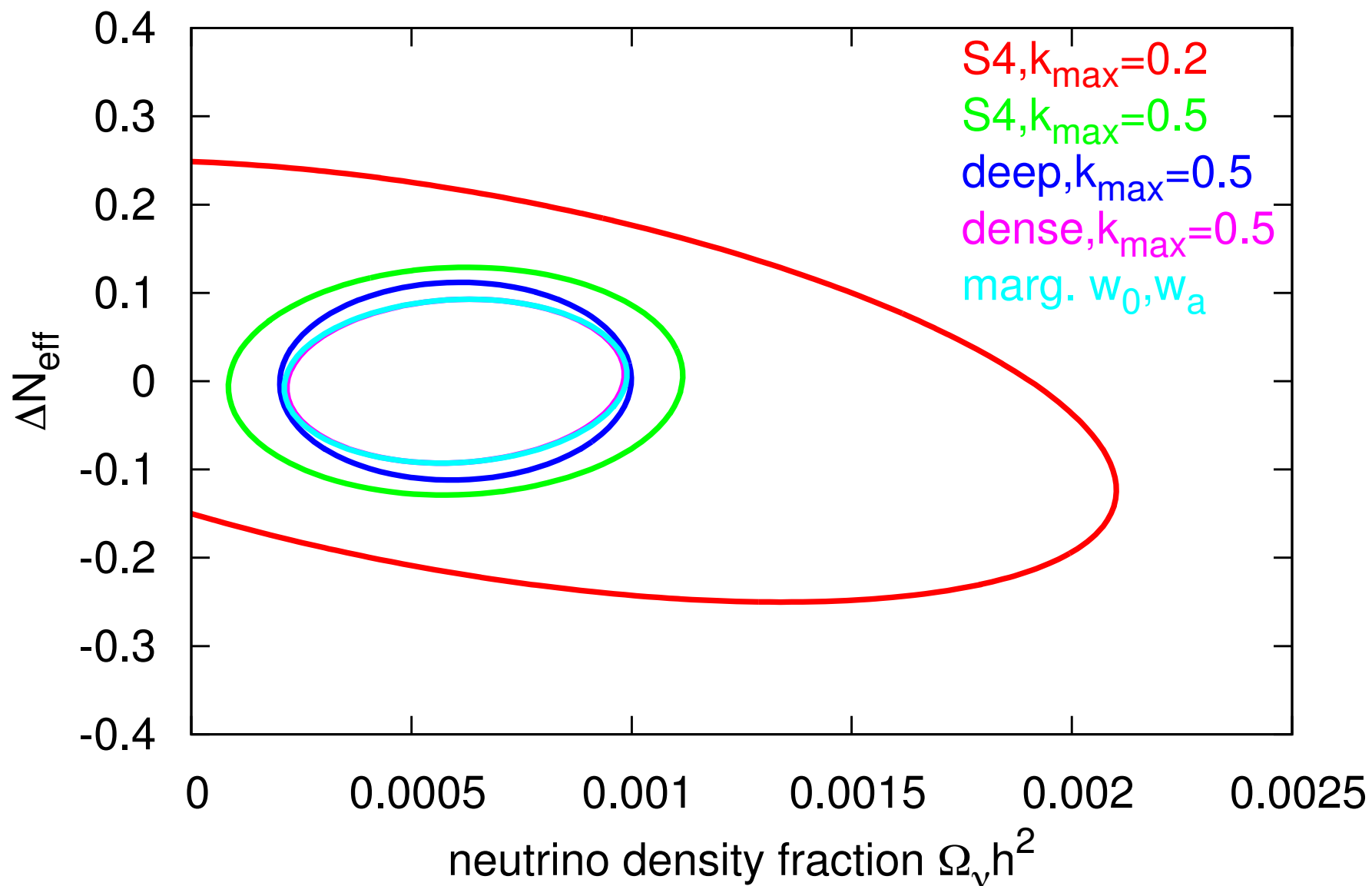
- ▶ Baseline Stage IV: LSST + DESI + 4MOST
- ▶ Deep: LSST + DESI-like + high-z
- ▶ Dense: LSST + DESI-like + 4xDESI-like density

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

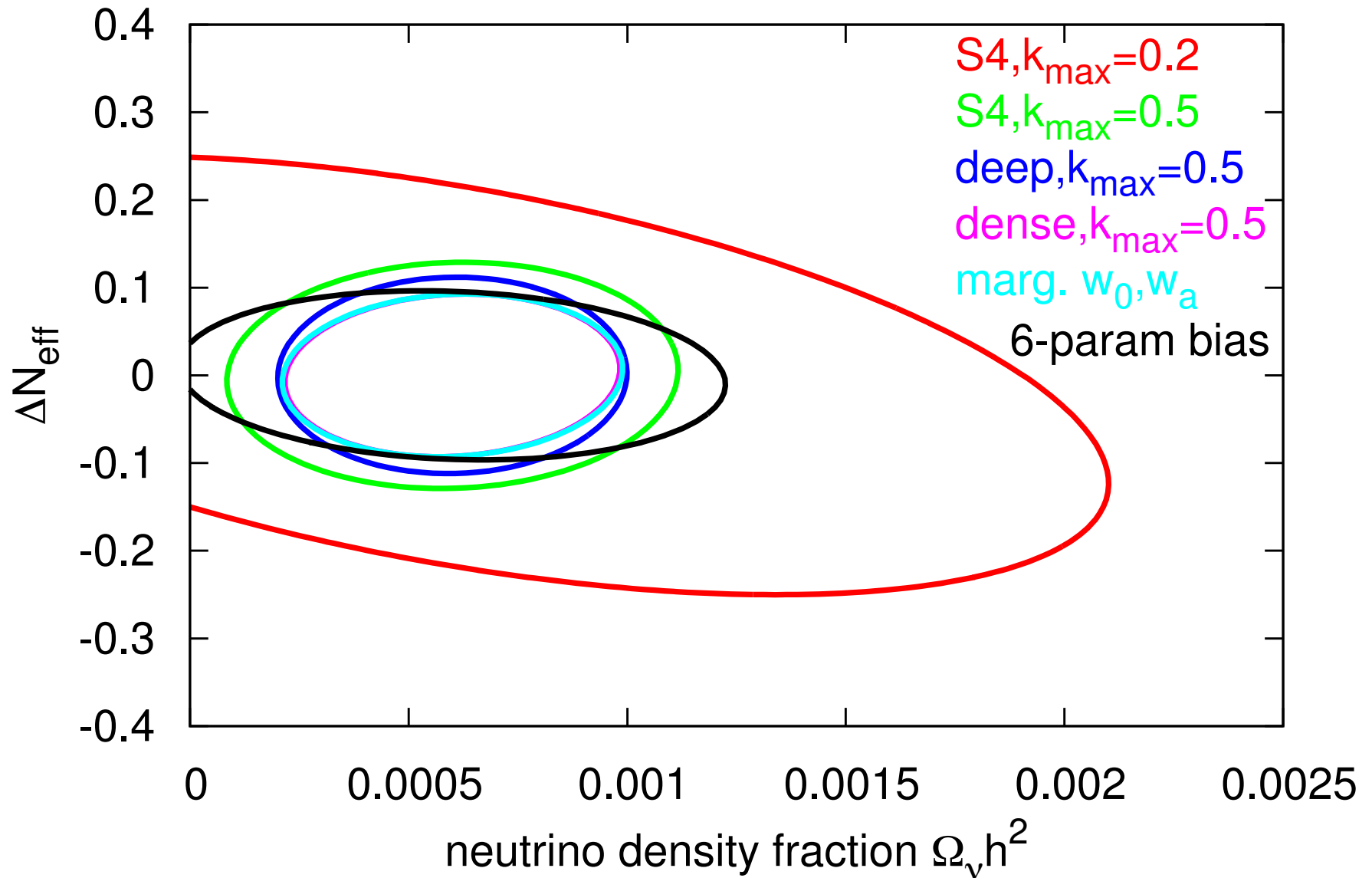
	Stage IV ($k_{\text{max}} = 0.2$)	Stage IV ($k_{\text{max}} = 0.5$)	+SSSI deep ($k_{\text{max}} = 0.5$)	+SSSI dense ($k_{\text{max}} = 0.5$)
$\sum m_\nu$	92 meV	32 meV	25 meV	24 meV
ΔN_{eff}	0.165	0.094	0.074	0.061

Note: Cross-correlations not included.





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



Marginalize over McDonald+Roy 2009 bias plus velocity bias.