Physics with Future Spectroscopic Surveys

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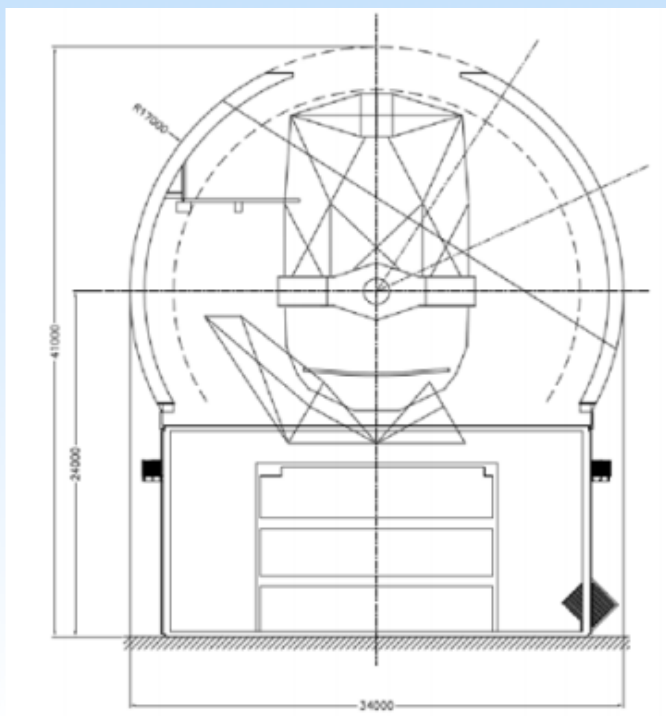
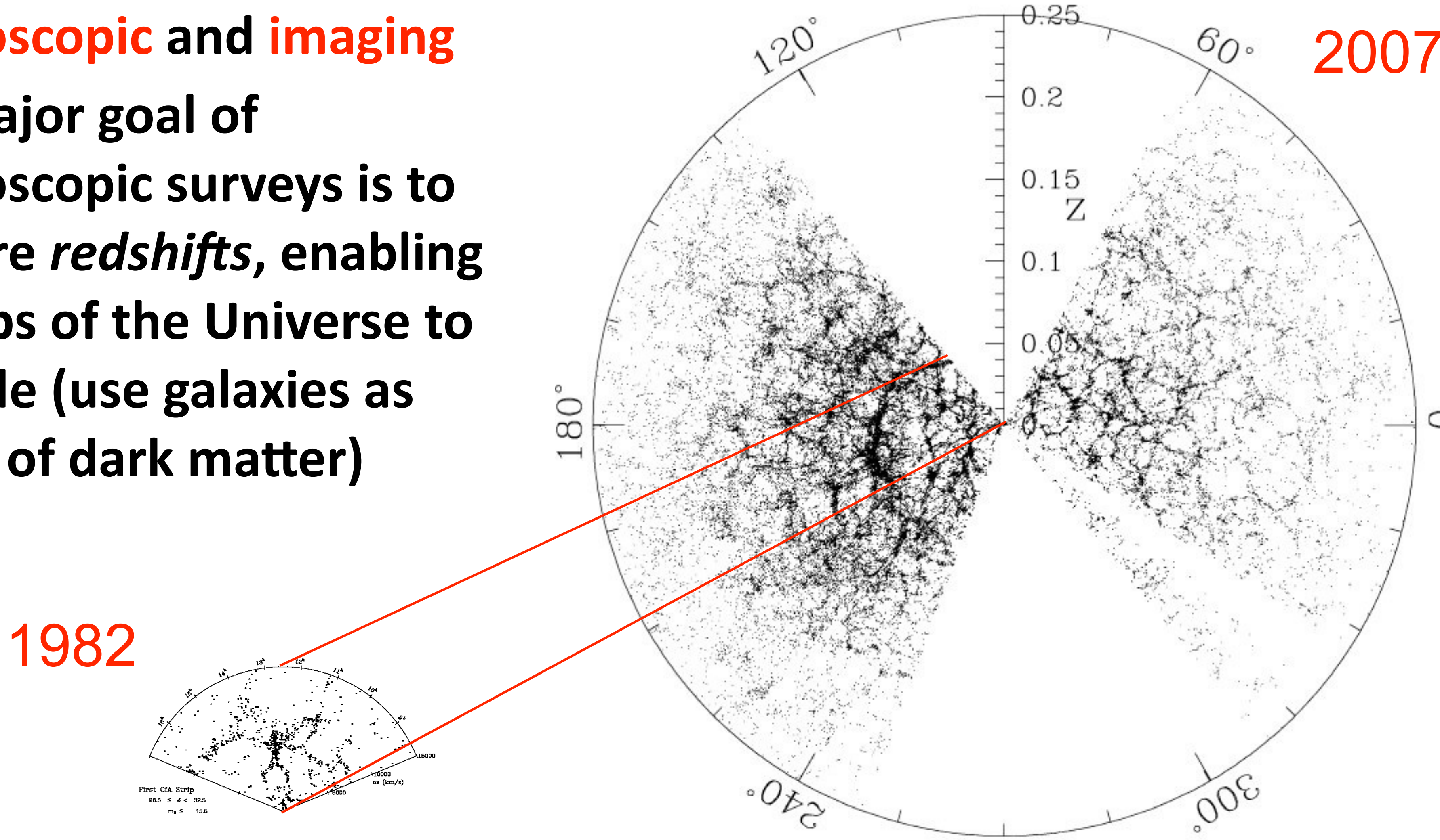


Outline

- Ways in which spectroscopic survey experiments constrain fundamental physics
  - Dark Energy
  - Modified Gravity
  - Σm_ν
  - Inflation constraints
- Current, future, and potential experiments
  - eBOSS and DESI
  - DESI upgrades
  - The Southern Spectroscopic Survey Instrument (SSSI)
  - The Billion Object Apparatus (BOA)
- What sort of detector technologies could make a difference?
  - What resolution do we need?

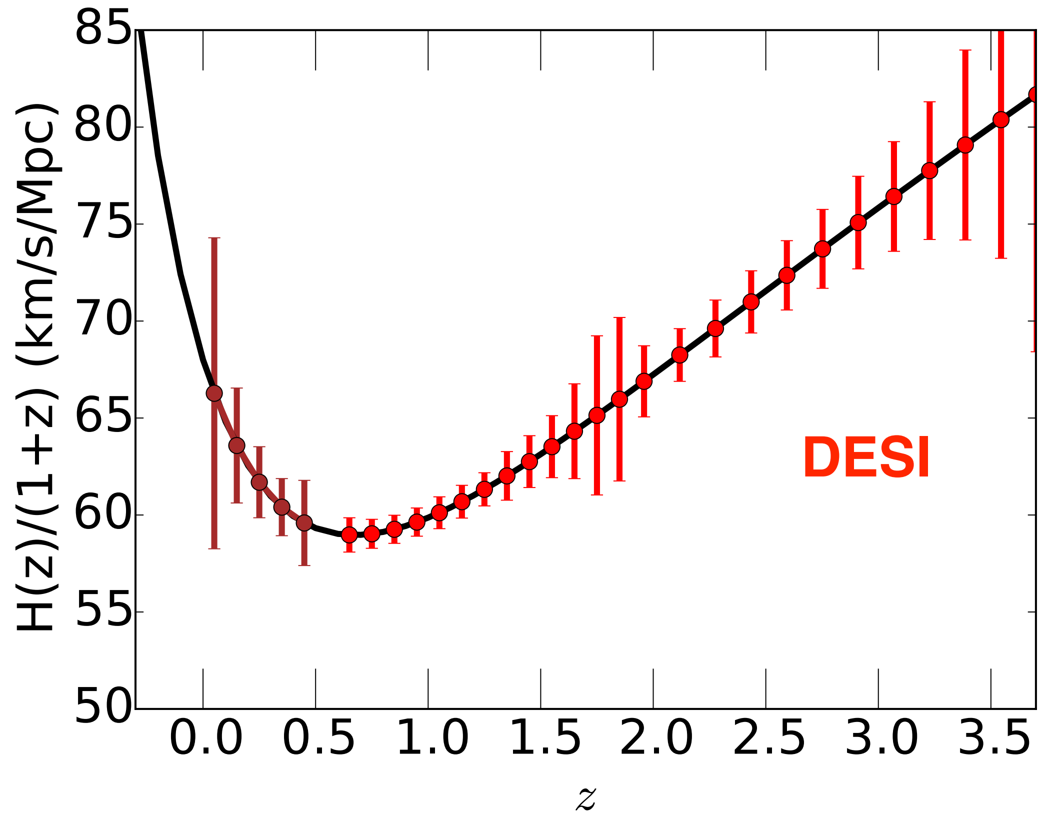
Introduction to Surveys

- Attempt to obtain uniform, statistical samples of objects, enabling a wide variety of cosmological studies
- Two basic types: spectroscopic and imaging
- The major goal of spectroscopic surveys is to measure *redshifts*, enabling 3D maps of the Universe to be made (use galaxies as tracers of dark matter)



By measuring the BAO angular and redshift scales as a function of redshift, constrain the distance-redshift relation / expansion history of the Universe

- **Classical 'standard ruler' test**
- **Measures how the Universe has grown over time**
  - **Depends on amounts & equation of state ($w = P/\rho$) of dark matter and dark energy**



- **Relies on measurements of redshifts and angles: minimal systematics**
- **cf. Yun Wang's talk**

Image: DESI FDR report

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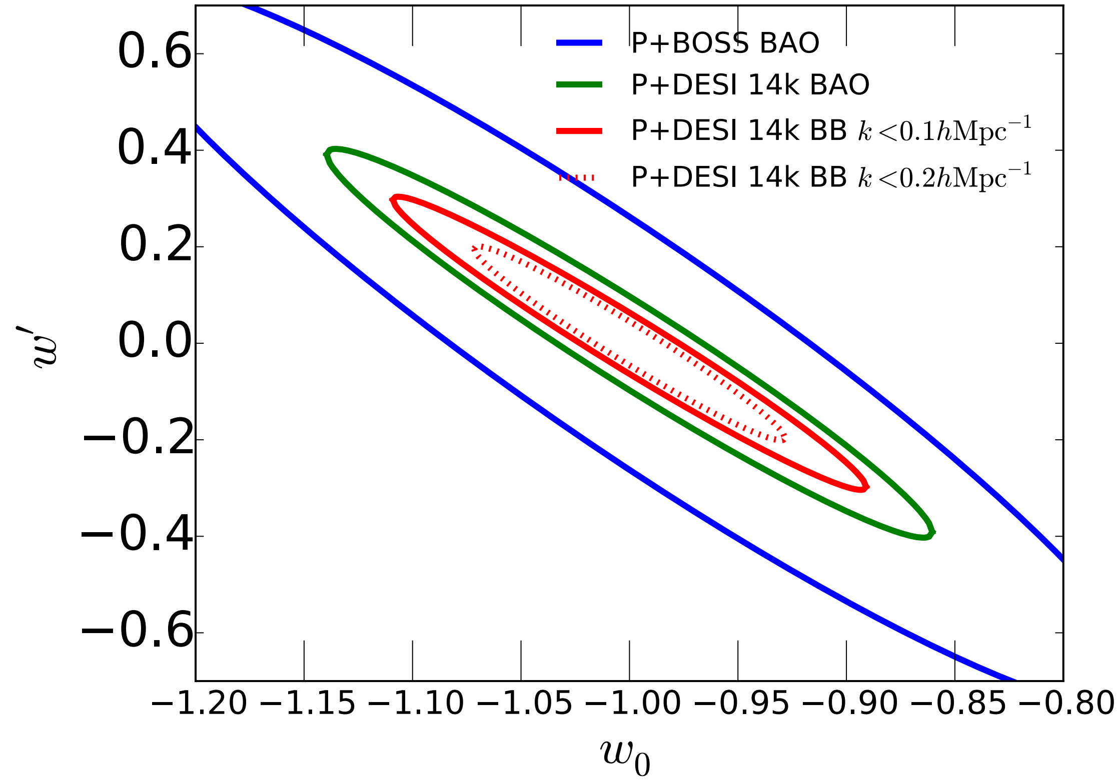

- **Relies on measurements of redshifts and angles: minimal systematics**
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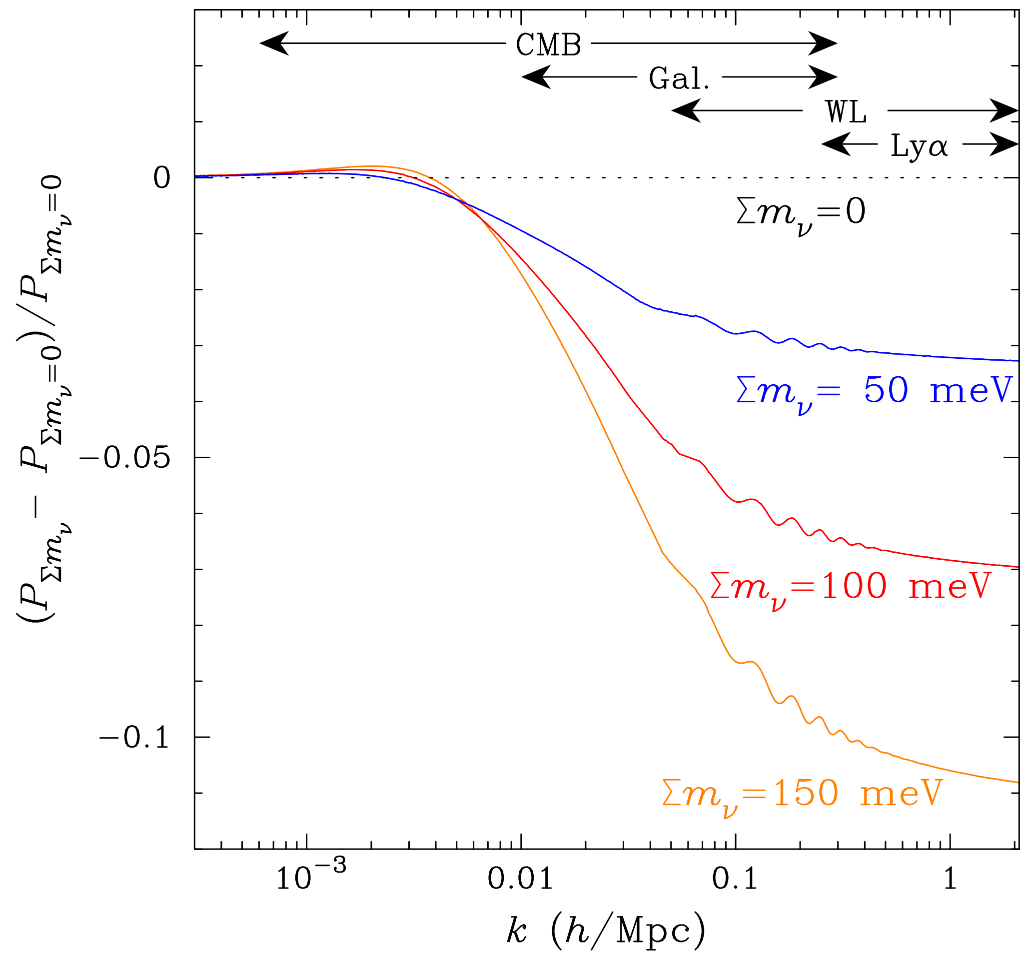
Image: DESI FDR report

Clustering measurements from spectroscopic measurements have many other uses

- **Neutrinos in the early universe were highly relativistic, stream away from matter**
- **The more massive neutrinos are, the more they suppress growth of overdensities - alters power spectrum, esp. <1 h^{-1} Mpc**
- **This can be detected using galaxies or Lyman alpha absorption of quasar light**

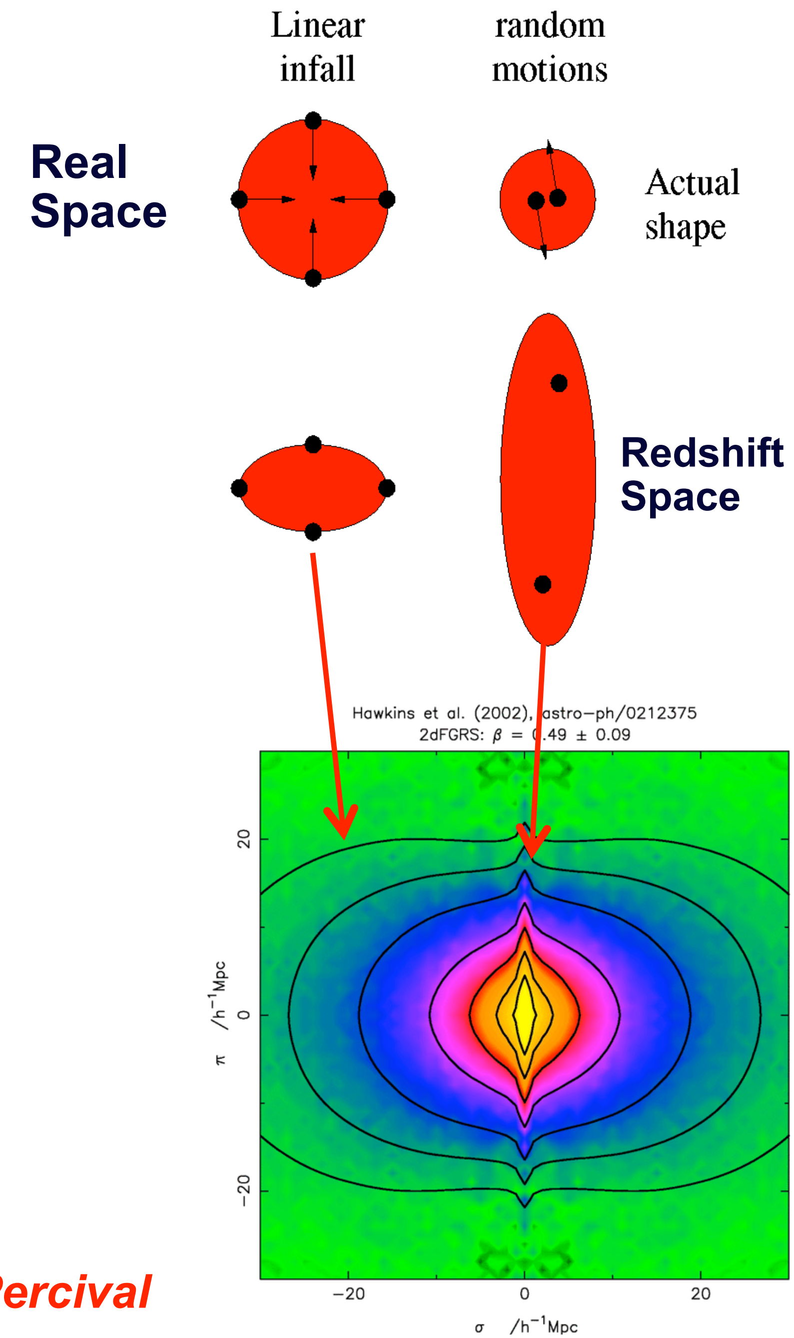


Abazajian et al. 2013

- **Planck: σ(Σm_ν)~ 0.16 eV, σ(N_ν) = 0.16**
- **Planck + DESI: σ (Σm_ν) = 0.02-0.03 eV, σ(N_ν) = 0.06 - 0.10**
- **Sufficient to distinguish normal vs. inverted hierarchy**

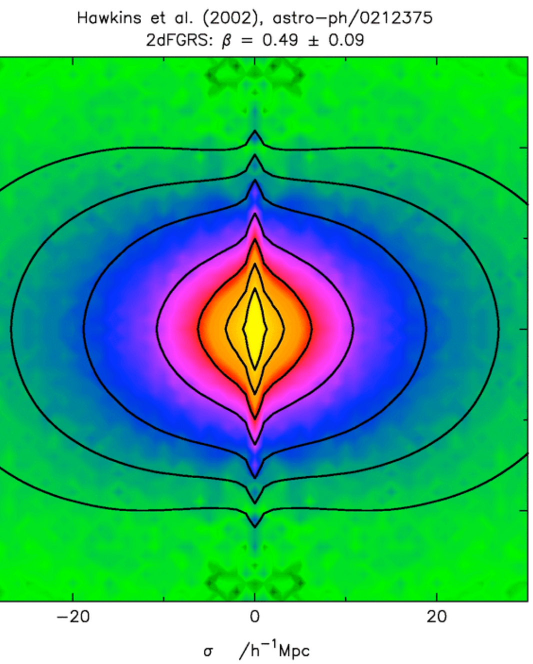
Constraining modified gravity theories with galaxy motions

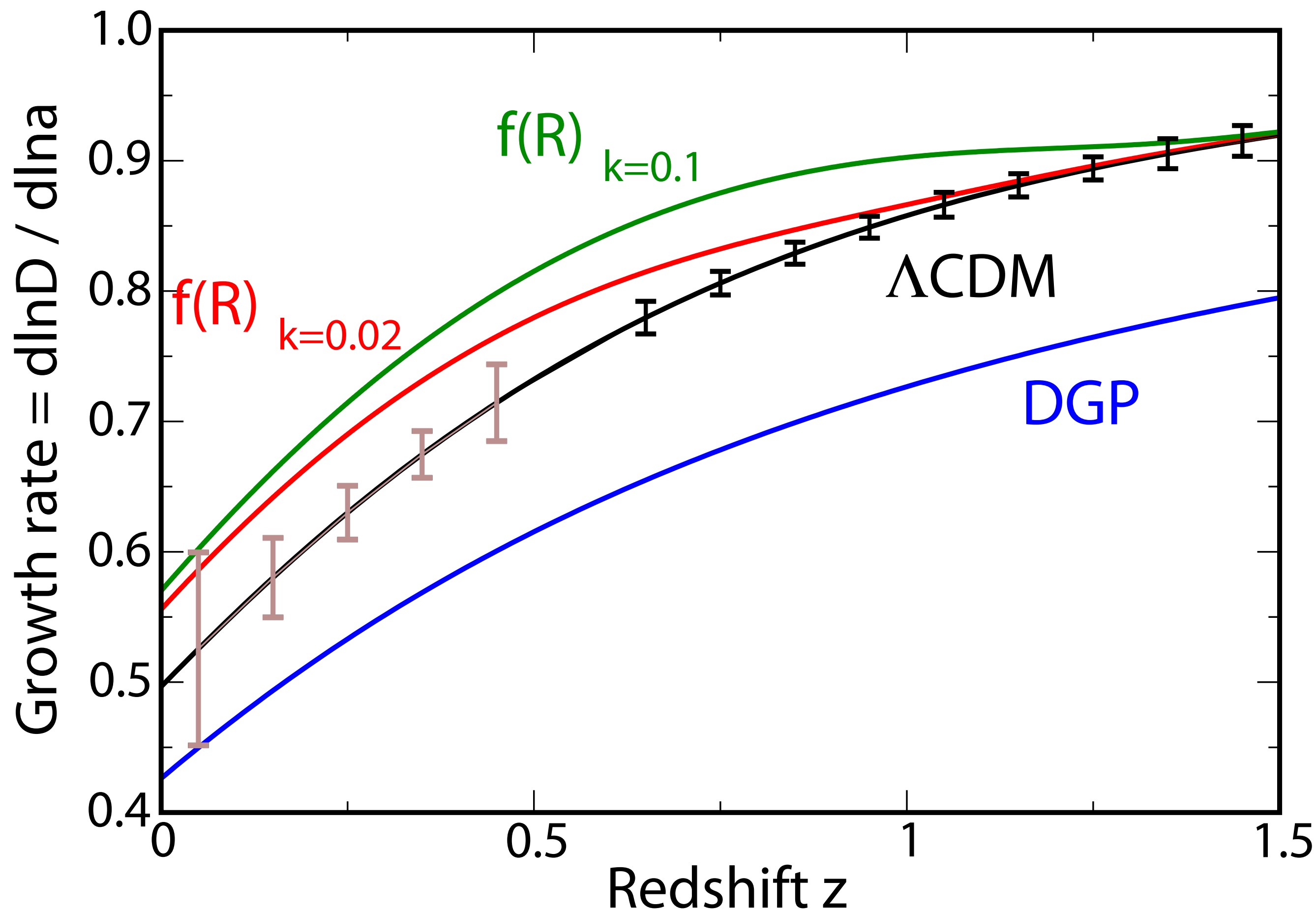
- Galaxy clustering does not intrinsically depend on direction
- However, relative velocities of galaxies do affect the redshifts we measure
- As overdensities grow over time, galaxies and dark matter flow in - contours of constant clustering are compressed in redshift direction
- Strength of infall depends on
  growth rate of structure
- If GR holds, this growth rate can be
  predicted from the expansion
  history (measured via e.g. BAO)



Courtesy: Will Percival

Constraining modified gravity theories with galaxy motions: Predicted DESI constraints





DESI FDR report

Constraining inflation: Predicted DESI constraints

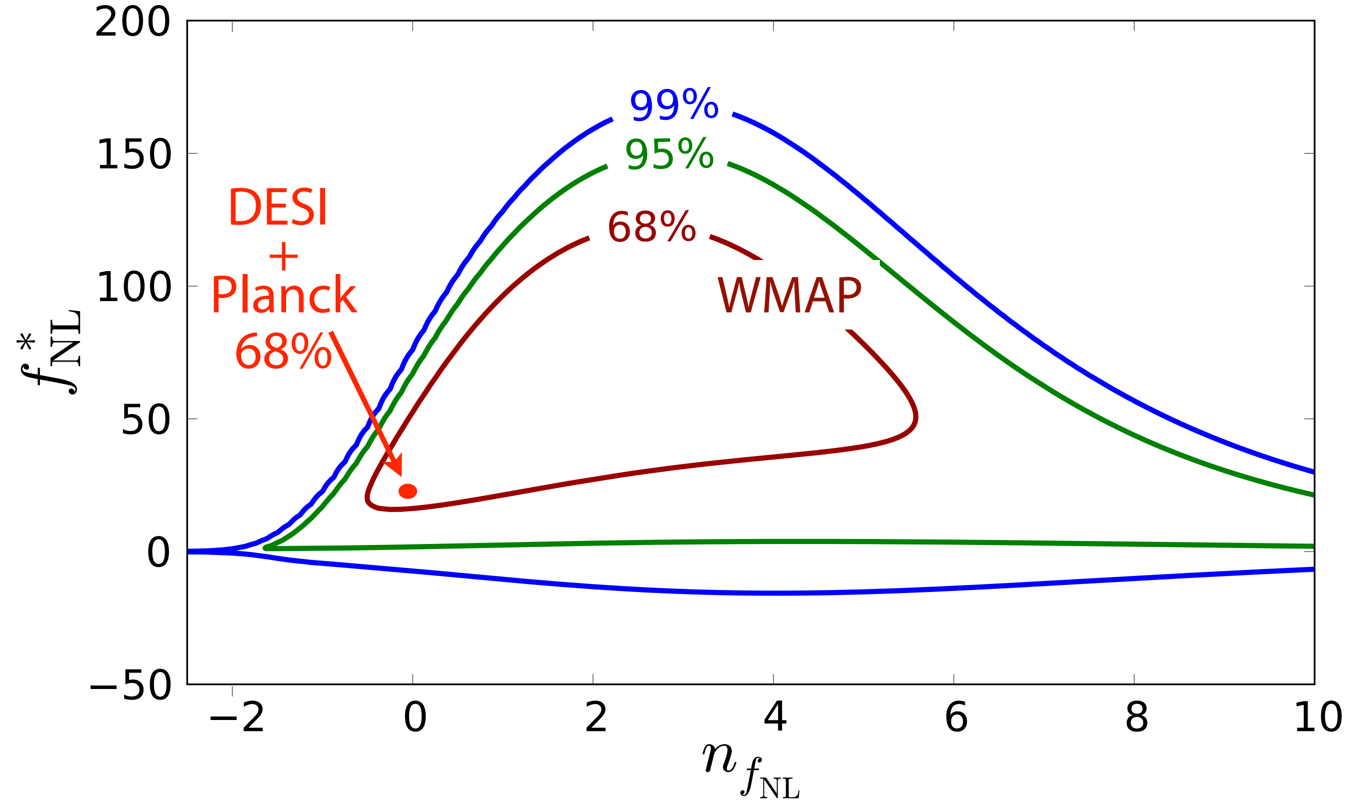


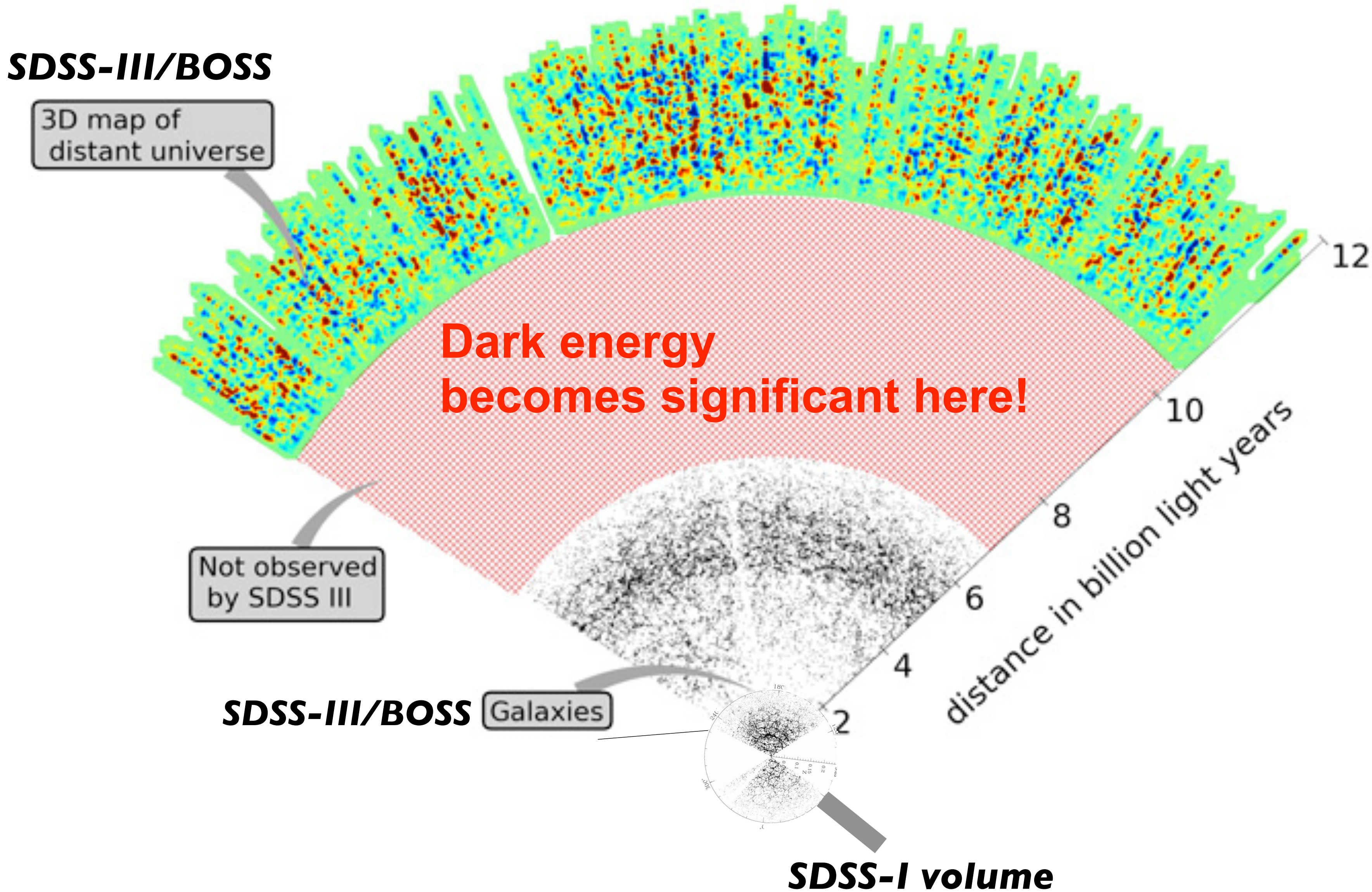
Image: DESI FDR report

- **cf. Dragan Huterer's talk**
- **Constraints for model where non-Gaussianity is scale dependent,**

$$f_{\rm NL}(k) = f^*_{\rm NL}(k/k_*)^{n_{f_{\rm NL}}}$$

- **DESI + Planck: σ(f_{NL}) ~ 2**

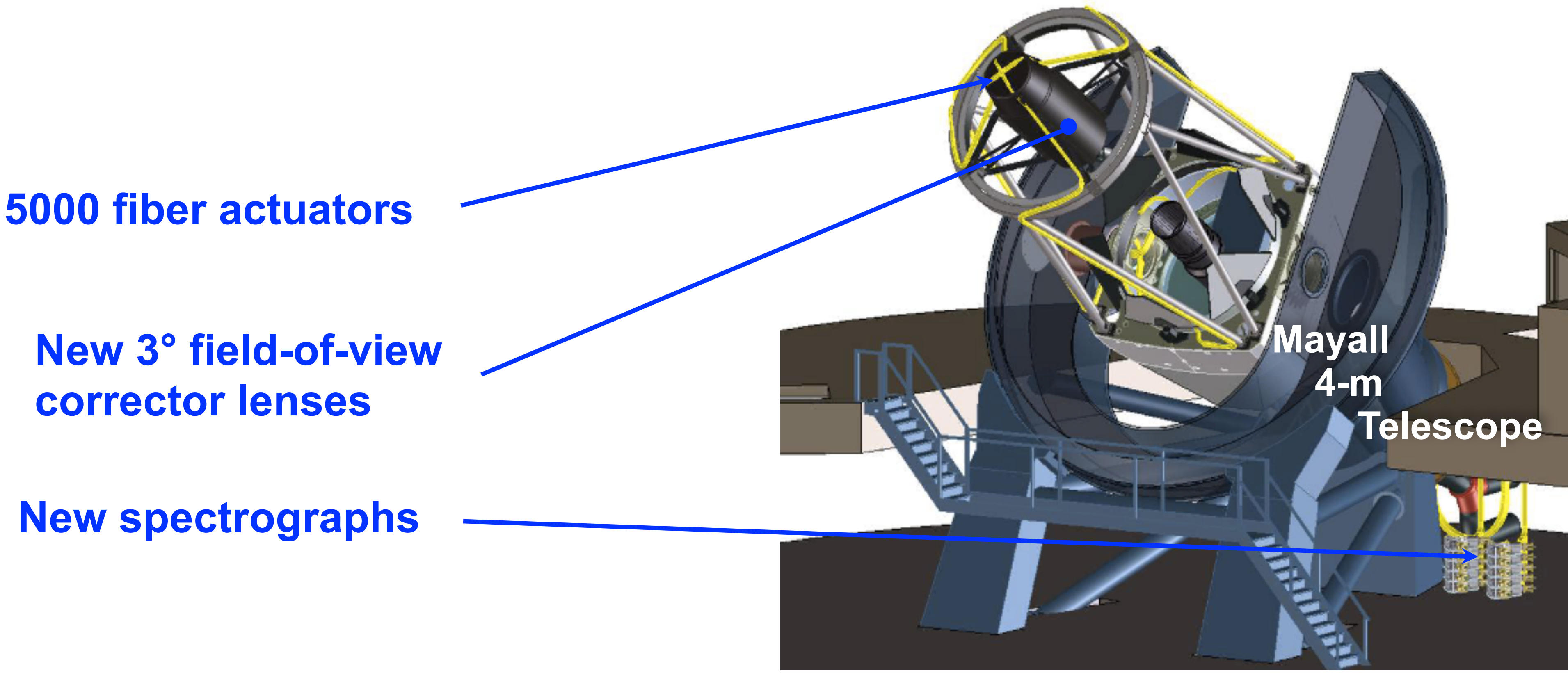
Current surveys have a major blind spot



Slide Courtesy: David Schlegel

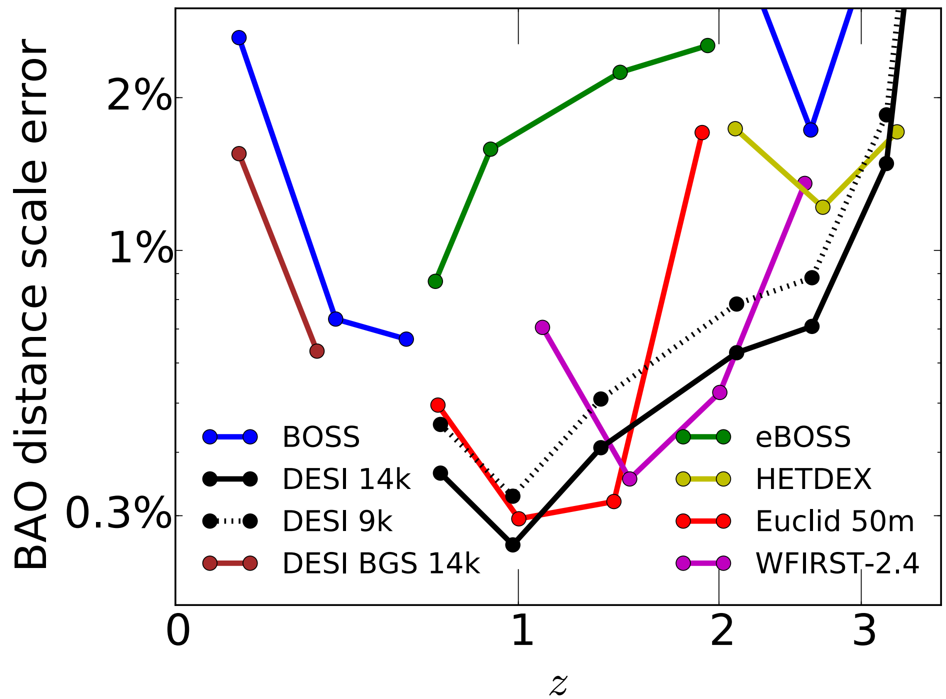
DESI will provide definitive measurements in this regime

- Adds new full-optical spectrograph to 4m Mayall telescope
- 5000 fibers with robotic positioners, 7.5 sq. deg.
- BAO survey of >30 million galaxies & QSOs, 0 < z < 3.5, over ~14k square degrees
- "Stage IV" BAO, ~10x better than state of the art, ~2019-2024
- Methods being tested in prototype SDSS-IV/eBOSS project



DESI upgrade concept

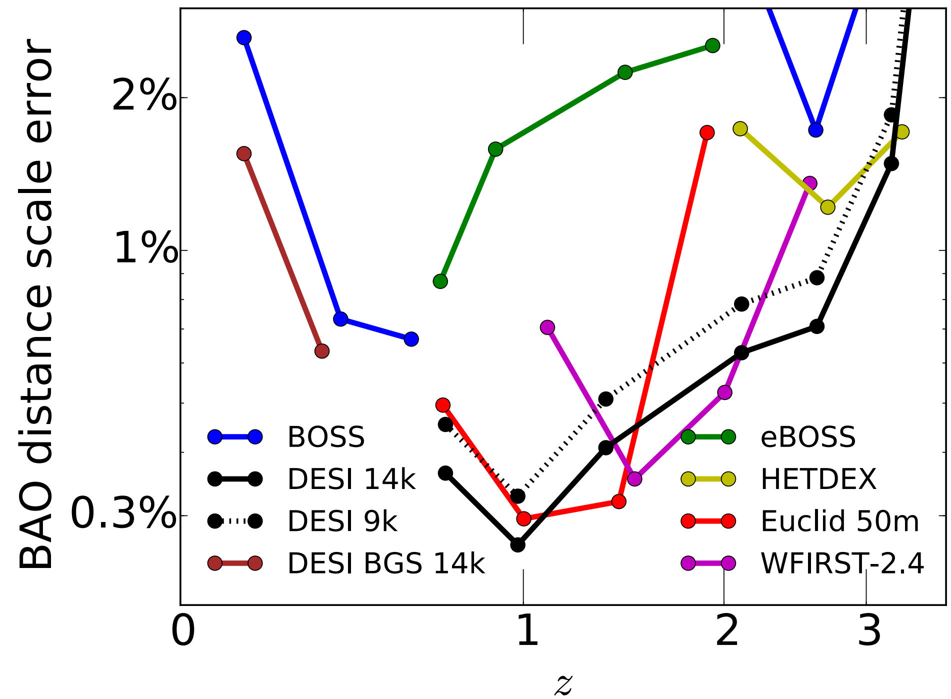
- **Greatest room for improvement over DESI at higher redshifts >1.5**
- **Enabling ground-based BAO measurements at higher *z* would require spectroscopy in near-IR: very expensive and high thermal background with existing detectors**

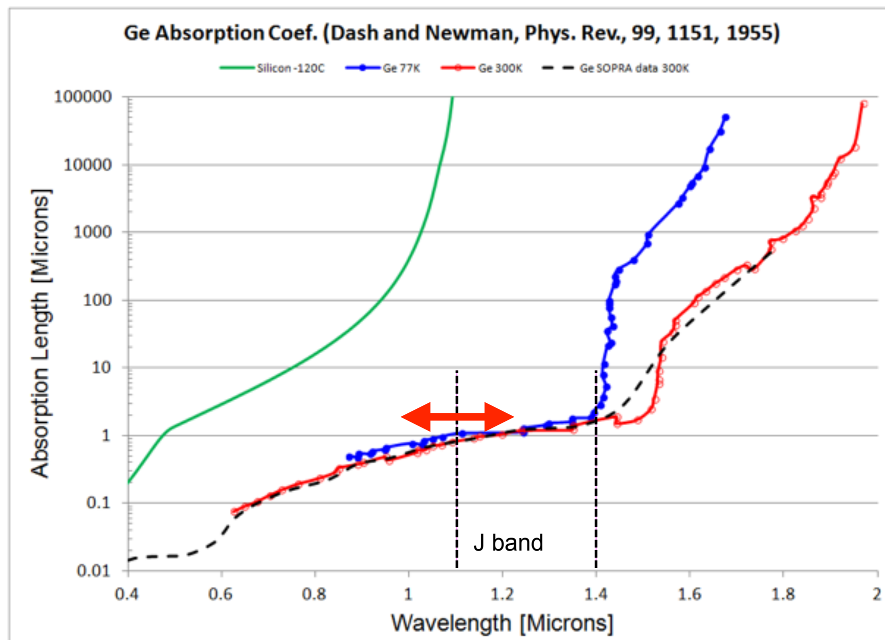


DESI FDR report

DESI upgrade concept

- Greatest room for improvement over DESI at higher redshifts >1.5
- Enabling ground-based BAO measurements at higher *z* would require spectroscopy in near-IR: very expensive and high thermal background with existing detectors
- Could address by adding fourth, near-IR arm to DESI spectrographs and conducting new survey
- Ge bandgap is ~optimal for this: hybrid Ge-Si CCDs could be a key enabling technology
- Could deploy at Mayall telescope in North or nearly-identical Blanco telescope in Southern hemisphere



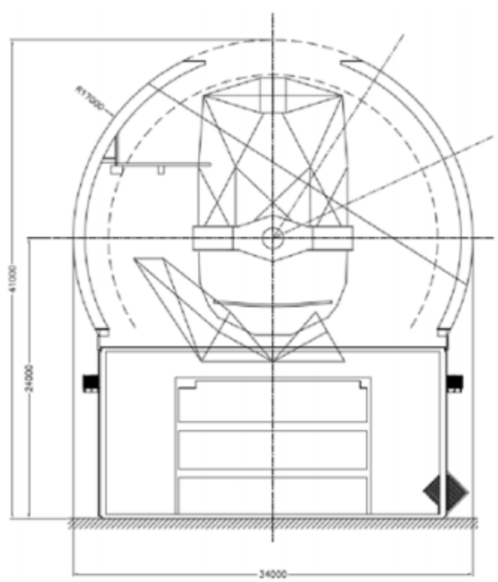


A Southern Spectroscopic Survey Instrument: SSSI

- **DOE and NSF-commissioned reports (e.g. https://arxiv.org/abs/1610.01661) have both recommended very similar wide-field multi-object spectrograph capabilities; requirements include:**
  - **>2500x multiplexing**
  - **Wavelength range 0.37-1 micron minimum(0.35-1.3 microns preferred)**
  - **Significant resolution ($R=\lambda/\Delta\lambda>\sim 5000$) at red end**
  - **Field diameter ≳20 arcmin (>1 deg preferred)**
  - **Large telescope aperture (8+m preferred)**
- **Would enable many science studies complementary to LSST (for cosmology and beyond)**
- **Wide variety of cross-correlation science with LSST & CMB-S4**

A Southern Spectroscopic Survey Instrument: SSSI

- Can be implemented with designs very similar to DESI at 6.5m Magellan telescope (1.5-2 deg FoV possible); or collaborate on proposed 11-12m telescopes from Canada or Europe
- ~6,000x multiplexing can be achieved with current technology; if shrink fiber positioners (requires smaller motors), ~15,000x doable
- Could reuse DESI/DESI upgrade spectrographs but deploy on a more capable platform
- Would enable DESI-like surveys in South AND photometric redshift training surveys, enhancing LSST performance



Cosmological Parameters from SSSI: Constraints

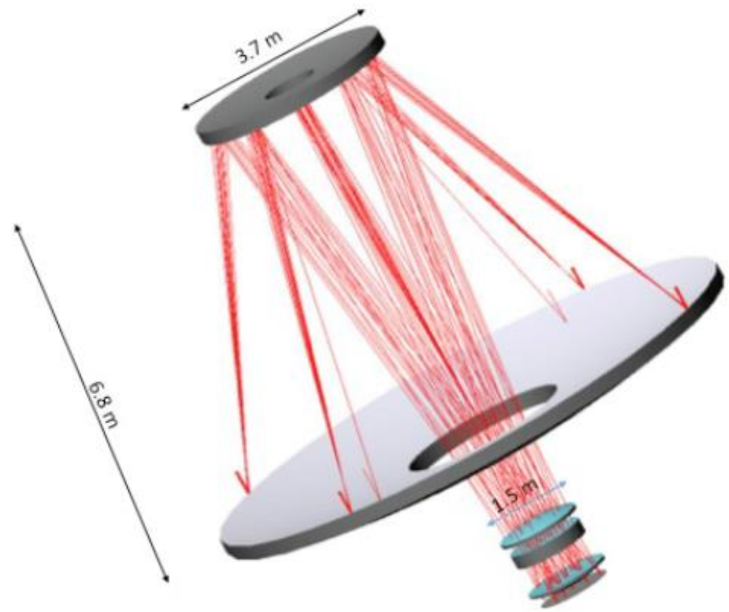
	Stage IV	+SSSI *dense*, k	+SSSI *dense*, k	+SSSI *deep*, k	+SSSI *deep*, k	+SSSI *deepx4*, k	+SSSI *deepx4*, k
FoM	1089	1486	2430	1425	1972	1697	2860
$\sigma($	0.082	0.07	0.05	0.071	0.06	0.062	0.051
$\sigma(\boldsymbol{\alpha}$	0.0028	0.0022	0.0016	0.0022	0.0019	0.002	0.0013
$\sigma(\mu)$ $\sigma(\Sigma)$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

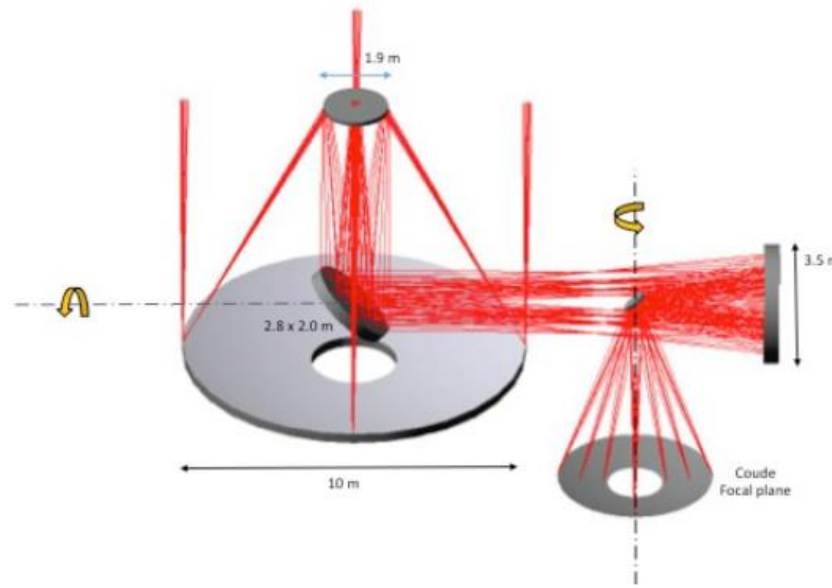
- **NB: Lya, CMB-S4, survey cross-correlations not yet included**
- **Stage IV + SSSI includes improved photo-z calibration**

Slide: Elisabeth Krause

A Billion Object Apparatus: BOA

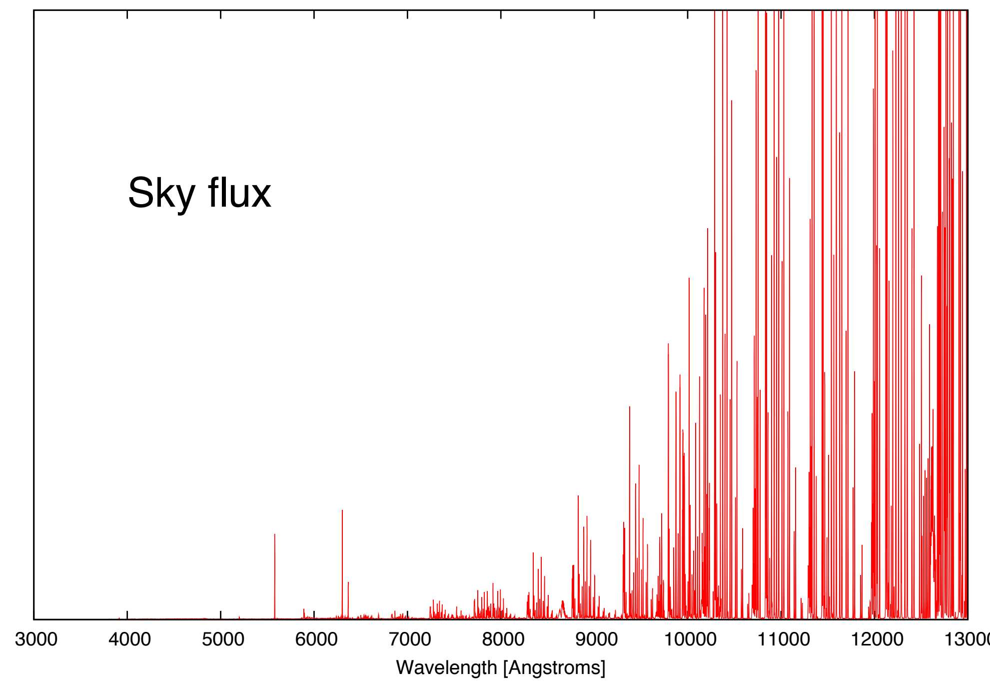
- **Concept: measure ~500 million redshifts to *z*=2.5, ~10x DESI density**
- **Would require ~10m telescope, 100,000 fibers/positioners (vs 5000 for DESI) or other method of getting light to spectrographs, 5 sq. deg FoV, and 10 years of survey time**
- **Costs scale primarily with #s of positioners/spectrographs; if utilize DESI designs, this would cost ~20x DESI = $1 billion (excluding telescope costs)**
- **If SSSI is deployed on a ~11-12m telescope, could later upgrade positioners and spectrographs to achieve BOA goals**





What sort of technologies would enable better spectroscopic surveys?

- DESI is costing ~$2/expected spectrum to construct; doing a BOA would require new, cheaper technologies
  - Need cheaper fiber positioners (or alternative method of channelling light to spectrographs -- micro mirrors, etc.)
  - Plus cheaper spectrographs
- Germanium CCDs or other IR detector improvements
- OH emission line suppression

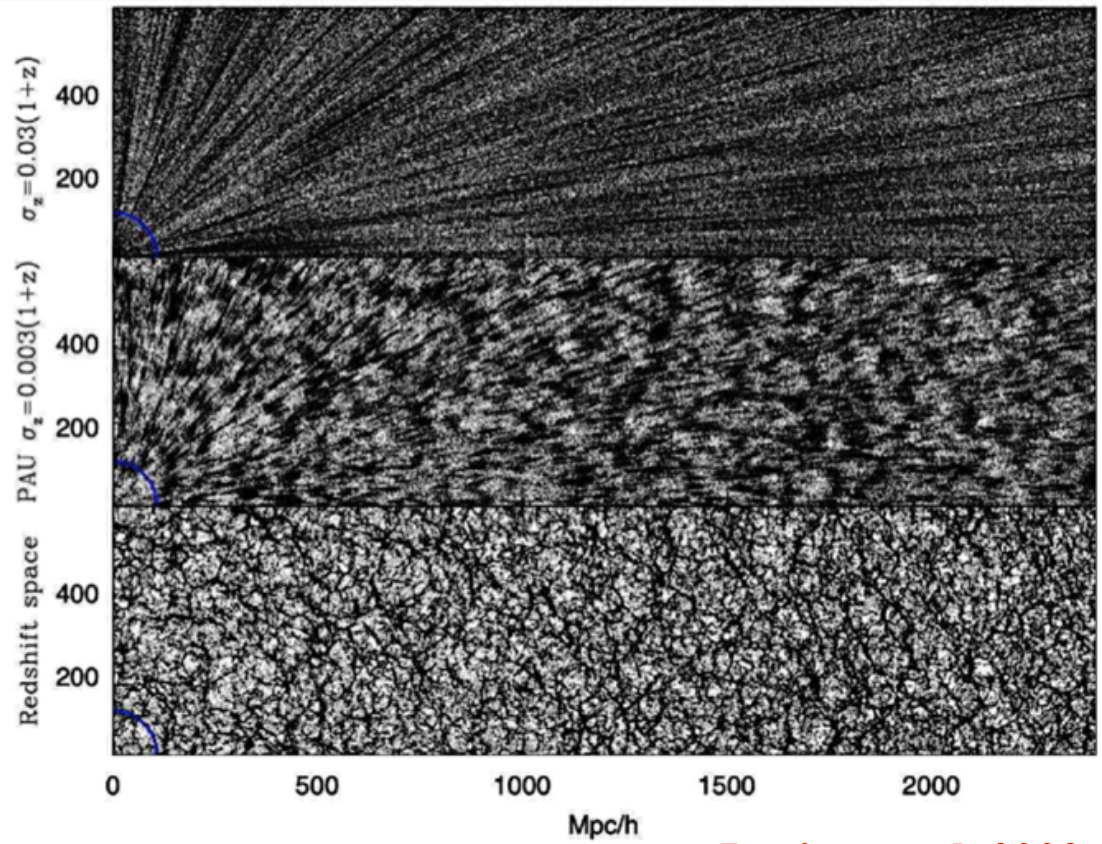


C. Cunha

Can we win with massively-multiplexed, low resolution spectroscopy?

- Scale of BAO feature is large: can resolve well with ~0.003(1+z) redshift errors, readily achievable to *z*~1 with R~100 spectroscopy

- Redshift-space distortions are more difficult at low *R*, though



Benitez et al. 2009

- Note: many applications need secure redshifts; R>4000 required to split [OII] doublet and get secure *z* at z>1

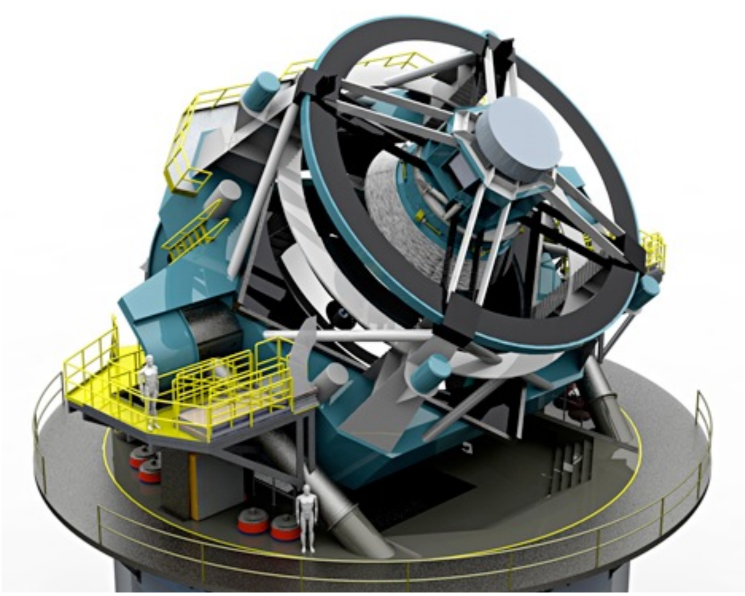
- At high resolutions, can also work in dark wavelength ranges between skylines (~90% of spectrum at R=6000); at low resolution, whole red spectrum is contaminated

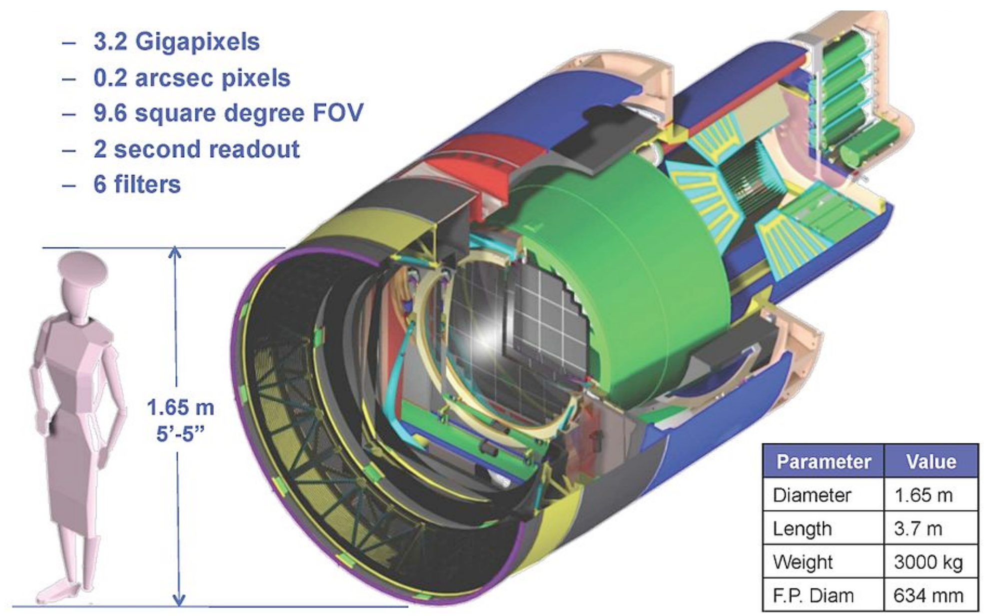
Can we win with massively-multiplexed, low resolution spectroscopy?

- **Limit to keep in mind: it is very difficult to do much better than LSST photometric redshifts over very wide areas at low resolution.**
- **Redshift errors for LSST-sky-area surveys to LSST depth will be $\sigma_z \simeq 0.02(1+z)(A\,\Omega\,t_{survey} / A_{LSST}\,\Omega_{LSST}\,t_{survey,\,LSST})^{-1/2}\,(6/R)^{1/2}$, where A is collecting area, Ω is field of view, t_{survey} is total survey duration, and R is the spectral resolution ($\lambda/\Delta\lambda$)**
- **I.e., proportional to $(A\,\Omega\,t_{survey}\,R)^{-1/2}$**
- **E.g.: A 10-year survey on LSST would need *R*=24 (600) to reduce LSST redshift errors by a factor of 2 (10) over the LSST footprint**
  - **A 10-year survey would need *R*=80 (2000) to reach those goals on Mayall/Blanco**

Ideal scenario: what sort of radically new detector technologies would we want, if we could develop them?

- Spectrum at every pixel of very large format detector array
- High energy/wavelength resolution: $R=\lambda/\Delta\lambda>5000$
- Negligible readout noise
- Continuous readout / time sensitivity: could identify gravitational wave counterparts by combining temporal and spatial coincidence
- Low cost per detector area
- Goal: turn LSST into spectroscopic telescope post-2032 (infeasible with fiber-fed spectrographs)





Conclusions

- Spectroscopic surveys can help to constrain fundamental physics in a variety of ways:
  - Dark Energy equation of state measurements
  - Tests of modified gravity
  - Constraints on neutrino properties
  - Constraints on inflation
- DESI will be the preeminent Stage IV spectroscopic survey, starting 2019
- Cosmic Visions has identified a potential roadmap for next steps after DESI: DESI upgrades, SSSI, and BOA
- Key challenges: develop new technologies to enable spectroscopy with LSST and/or make BOA feasible

Ge/Si hybrid CCDs

Ge CCD detectors are in development

- Most fabrication steps identical to silicon CCDs
- Final processing would be at labs
- Readout systems would be identical to CCDs