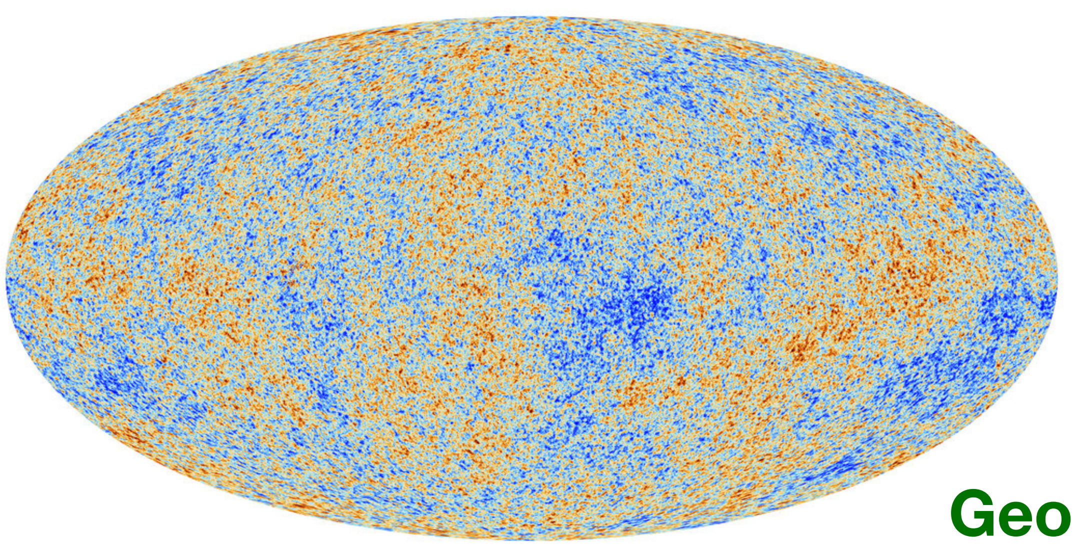
Opportunities for Type Ia Supernova Peculiar Velocity Surveys

Alex Kim
Lawrence Berkeley National Laboratory

Galaxy Positions Probe Dark Energy and Gravity

Energy density fluctuations
CMB, z~1100

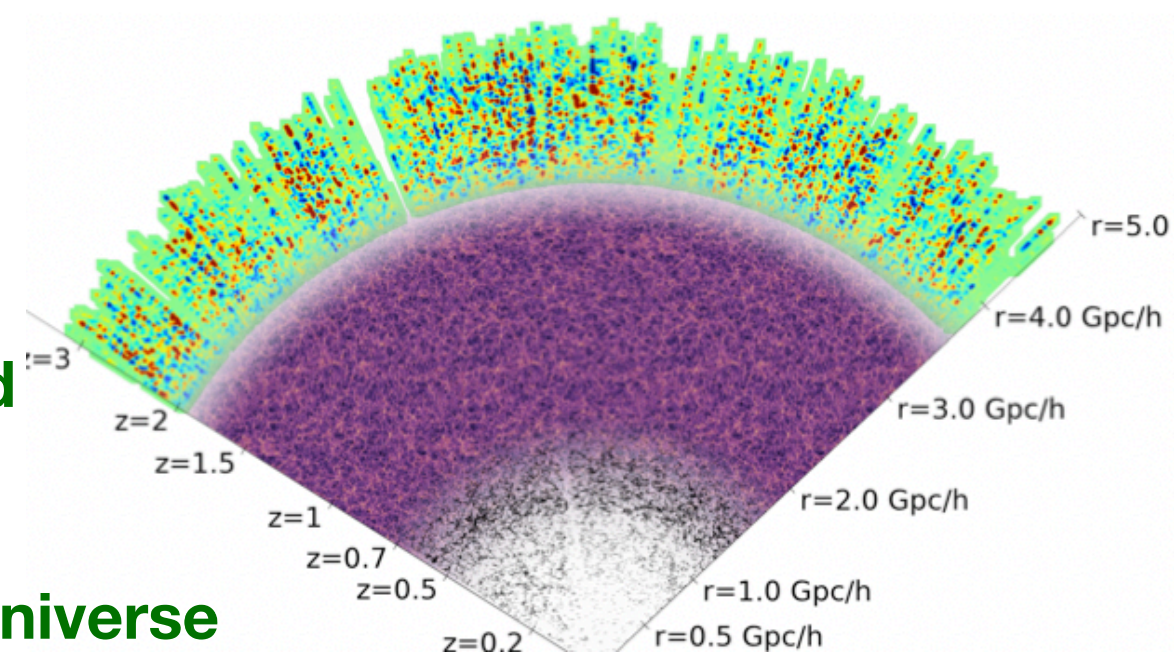


Gravity

Background Expansion

Geometry of the Universe

Galaxy positions
0<z<3



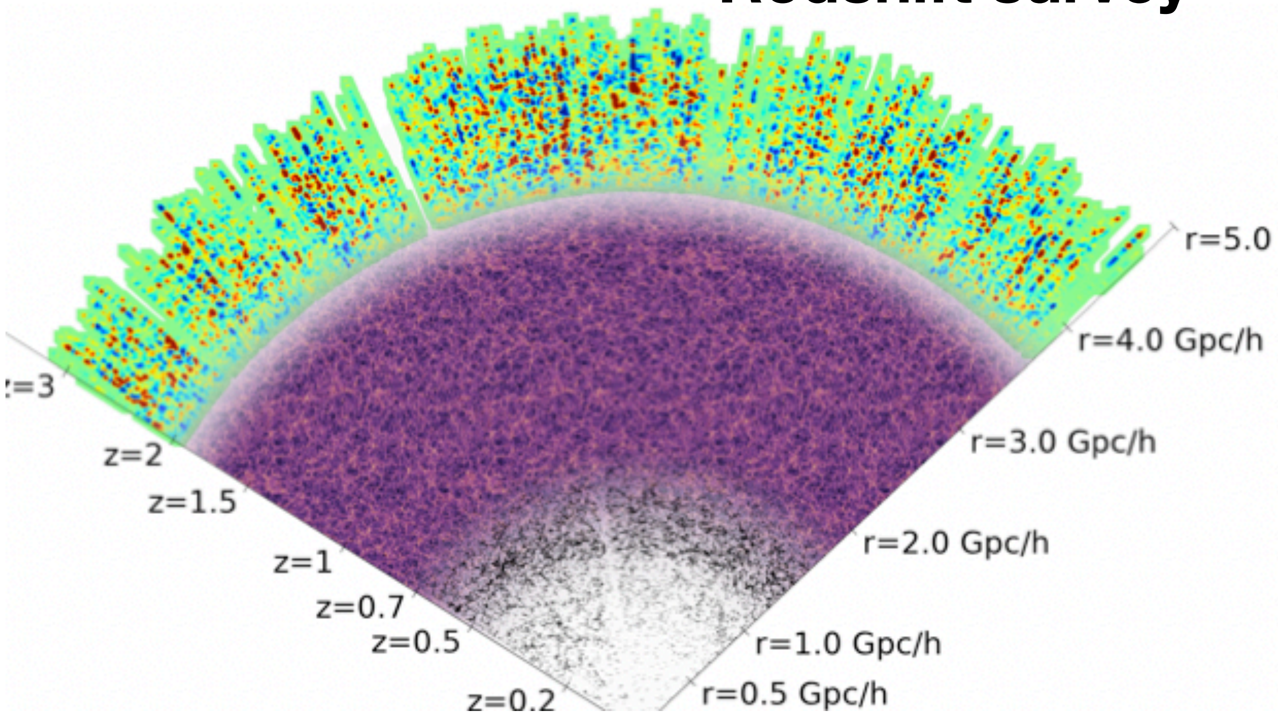
Amplitude and clumpiness of density fluctuations precisely measured by Planck

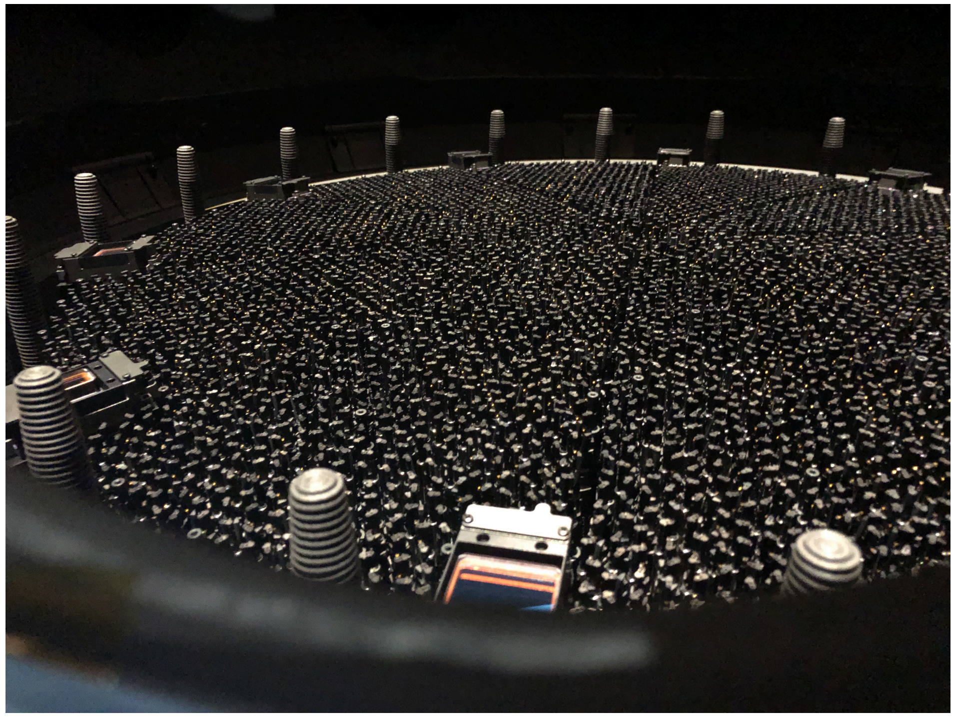
Amplitude and clumpiness of galaxy positions measured by galaxy surveys

Galaxy Positions Probe Dark Energy and Gravity — Hence DESI

KPNO 4m telescope

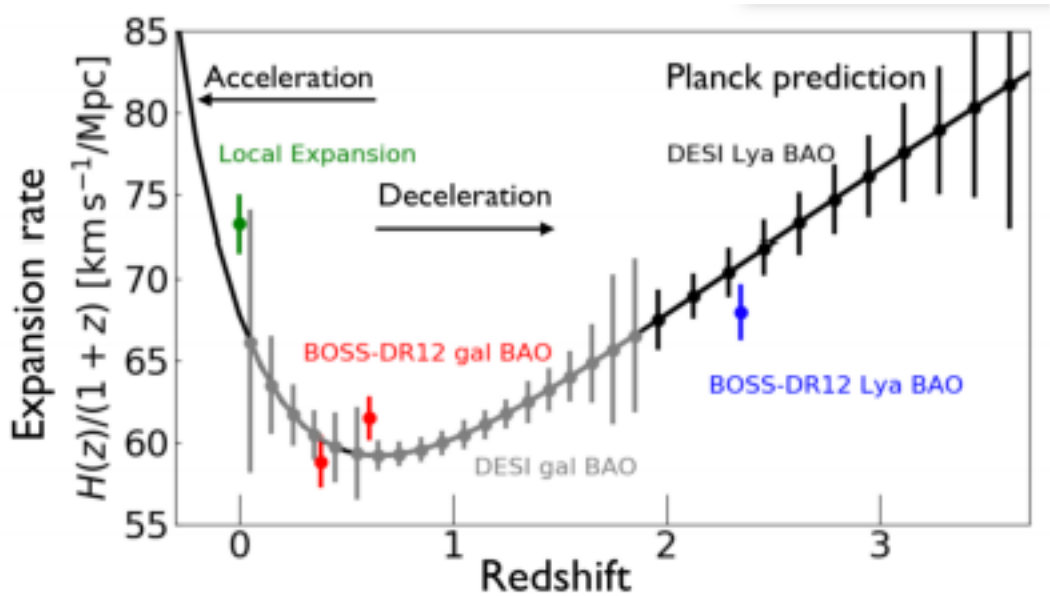
Redshift survey





DESI multiobject spectrograph

Cosmology



Snowmass2021 - Letter of Interest

Deep Multi-object Spectroscopy to Enhance Dark Energy Science from LSST

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Jeffrey A. Newman, University of Pittsburgh and PITT PACC
Collaboration: LSST Dark Energy Science Collaboration (LSST DESC)
Contact Email: janewman@pitt.edu

Abstract: Access to deep ($i \sim 25$), highly-multiplexed optical and near-infrared multi-object spectroscopy (MOS) on 8–40m telescopes would greatly improve measurements of cosmological parameters from the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST). The largest gain would come from improvements to LSST photometric redshifts, which are employed directly or indirectly for every major LSST cosmological probe. Deep spectroscopic datasets will enable reduced uncertainties in the redshifts of individual objects via optimized training. The resulting data will also constrain the impact of blending on photo-z's. Focused spectroscopic campaigns can also improve weak lensing cosmology by constraining the intrinsic alignments between the orientations of galaxies. Galaxy cluster studies can be enhanced by measuring motions of galaxies in and around clusters and by testing photo-z performance in regions of high surface density. Photometric redshift and intrinsic alignment studies are best-suited to instruments on large-aperture telescopes with wider fields of view (e.g., Subaru/PFS, MSE, Keck/FOBOS or GMT/MANIFEST), but cluster investigations can be pursued with smaller-field instruments (e.g., Gemini/GMOS, Keck/DEIMOS, or TMT/WFOS). Large numbers of telescope-nights will be needed to accomplish all of these goals.

Snowmass2021 - Letter of Interest

Wide-field Multi-object Spectroscopy to Enhance Dark Energy Science from LSST [1]

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Rachel Mandelbaum (Carnegie Mellon University)
Collaboration: LSST Dark Energy Science Collaboration (LSST DESC)
Contact Email: rmandelb@andrew.cmu.edu

Abstract: Data from wide-field (> 20 deg^2 total survey area), highly-multiplexed optical and near-infrared multi-object spectroscopy on 4–15m telescopes would help the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) its full potential. This could come in the form of new large surveys and/or adding additional targets to already-planned projects. Photometric redshifts can be calibrated with high precision using cross-correlations of LSST objects against spectroscopic samples that span thousands of square degrees. Cross-correlations of faint LSST galaxies or lensing maps with spectroscopic samples can constrain intrinsic alignment systematics and provide new tests of modified gravity theories. Large numbers of LSST strong lens systems and supernovae can be studied efficiently by piggybacking on large-area spectroscopic surveys. Finally, redshifts can be measured for a high fraction of the supernovae in the Rubin Deep Drilling Fields (DDFs) by targeting their hosts with wide-field spectrographs. For wide-area surveys, DESI or MSE in the northern portion of the LSST footprint or 4MOST in the south would be good options; DESI, 4MOST, Subaru/PFS, or MSE would be well-suited for DDF surveys. The most efficient solution would be a new wide-field, highly-multiplexed spectroscopic instrument in the southern hemisphere with > 6m aperture.

Snowmass2021 - Letter of Interest

The Maunakea Spectroscopic Explorer

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information:
Submitter Name/Institution: Jennifer Marshall (Maunakea Spectroscopic Explorer and Texas A&M University)
Contact Email: marshall@mse.cfht.hawaii.edu

Additional authors: Additional authors appear at the end of this document.

Collaboration: Maunakea Spectroscopic Explorer Collaboration

Abstract: The Maunakea Spectroscopic Explorer (MSE) is the first of the future generation of dedicated observational facilities that enable massively multiplexed spectroscopic study of faint astrophysical objects. MSE is designed to enable transformative science, being completely dedicated to large-scale multi-object spectroscopic surveys, each studying thousands to millions of objects. MSE will use an 11.25 meter aperture telescope to feed thousands of fibers over a 1.5 square degree field of view and has the capability to observe at optical and near-Infrared wavelengths at a range of spectral resolutions, with all spectral resolutions available at all times across the entire field. MSE will collect more than 10 million fiber-hours of spectroscopic observations every year and is designed to excel at precision studies of large samples of faint astrophysical targets. With these capabilities, MSE stands as a premier facility for next-generation experimental astrophysical studies of the nature of dark matter, dark energy, and the universe as a whole.

The US Extremely Large Telescope Program

Topical Group(s): (check all that apply by copying/pasting ☐/☑)

☐ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
☑ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
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☑ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information:
Mark Dickinson (NSF's NOIRLab) [med@noao.edu]
for the US Extremely Large Telescope Program

Authors: (long author lists can be placed after the text)

Abstract: (maximum 200 words)
Progress on many important astrophysical problems requires new observations with substantially higher angular resolution and greater sensitivity than today's optical-infrared telescopes can provide. A new generation of Extremely Large Telescopes (ELTs) with >20m primary mirror diameters, operating with next-generation adaptive optics systems that deliver diffraction-limited image quality, will provide transformational new research capabilities. ELTs will enable major advances in several research topics within the Cosmic Frontiers theme including the nature of dark matter; unprecedentedly precise measurement of the cosmic expansion rate; the physics of compact object mergers identified by gravitational wave events; and tests of General Relativity's description of gravity in close proximity to the supermassive black hole in the center of our Galaxy. The US ELT Program, a collaboration between NSF's NOIRLab and the Thirty Meter Telescope and Giant Magellan Telescope projects, proposes to complete construction of a bi-hemispheric system that will provide US researchers with unique ELT coverage of the whole sky and a powerful suite of instruments. The proposed federal funding would ensure 25% or greater open access to both telescopes for investigators at any US research institution.

Snowmass2021 - Letter of Interest

Next-generation Spectroscopic [1] Surveys with DESI

Thematic Areas: (check all that apply ☐/■)

☐ (CF1) Dark Matter: Particle Like
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■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information:
Kyle Dawson (University of Utah): kdawson@astro.utah.edu
Collaboration: DESI Collaboration

Authors: James Annis (Fermilab), Stephen Bailey (LBNL), Charles Baltay (Yale Univ.), Peter Behroozi (Univ. of Arizona), Segev BenZvi (Univ. of Rochester), Adam S. Bolton (NOIRLab), Elizabeth Buckley-Geer (Fermilab), Robert Cahn (LBNL), Kyle Dawson (Univ. of Utah), Arjun Dey (NOIRLab), Daniel Eisenstein (Center for Astrophysics | Harvard & Smithsonian), Xiaohui Fan (Univesity of Arizona), Simone Ferraro (LBNL), Gaston Gutierrez (Fermilab), Daniel Gruen (SLAC), Julien Guy (LBNL), Salman Habib (ANL), Katrin Heitmann (ANL), Klaus Honscheid (Ohio State Univ.), Dragan Huterer (Univ. of Michigan), Robert Kehoe (Southern Methodist Univ.), Alex G. Kim (LBNL), David Kirkby (UC Irvine), Ofer Lahav (UCL), Chien-Hsiu Lee (NOIRLab), Michael E. Levi (LBNL), Zarija Lukić (LBNL), Paul Martini (Ohio State Univ.), Patrick McDonald (LBNL), John Moustakas (Siena College), Adam D. Myers (Univ. of Wyoming), Jeffrey A. Newman (U. Pittsburgh & PITT PACC), Peter Nugent (LBNL, UC Berkeley), Nikhil Padmanabhan (Yale Univ.), Nathalie Palanque-Delabrouille (Saclay), Claire Poppet (UC Berkeley), Constance Rockosi (UC Santa Cruz), Lado Samushia (Kansas State Univ.), Edward Schlafly (LLNL), David Schlegel (LBNL), Michael Schubnell (Univ. of Michigan), Hee-Jong Seo (Ohio Univ.), Zachary Slepian (Univ. of Florida), David Sprayberry (NOIRLab), Gregory Tarlé (Univ. of Michigan), Jeremy Tinker (New York Univ.), David Weinberg (Ohio State Univ.), Risa Wechsler (Stanford Univ., SLAC)

Abstract: After its initial five-year spectroscopic survey to use the clustering of matter as a probe of dark energy, the Dark Energy Spectroscopic Instrument (DESI) will remain one of the world's best facilities for wide-field spectroscopy. In this letter of interest, we present options for the continued use of DESI for further constraining the nature of dark energy, neutrinos, inflation, and physics beyond the standard model in the second half of the decade. More about the DESI instrument and survey can be found at https://www.desi.lbl.gov

Galaxy Positions and Velocities Related

- Initial universe was homogeneous, galaxies moved to new positions to produce structure
- Motion on top of cosmological expansion called “peculiar velocity”

Millenium Simulation

Powerful Probe of the Universe Motivating Projects is the Next Decade

- Galaxy surveys are a powerful probe of the growth of structure, gravity, and the primordial universe, and so motivate projects and facilities in the next decade

- Peculiar velocities and galaxy overdensities share the same cosmological information

$$\frac{\partial \delta}{\partial \tau} + \nabla \cdot [(1+\delta)\mathbf{v}] = 0$$

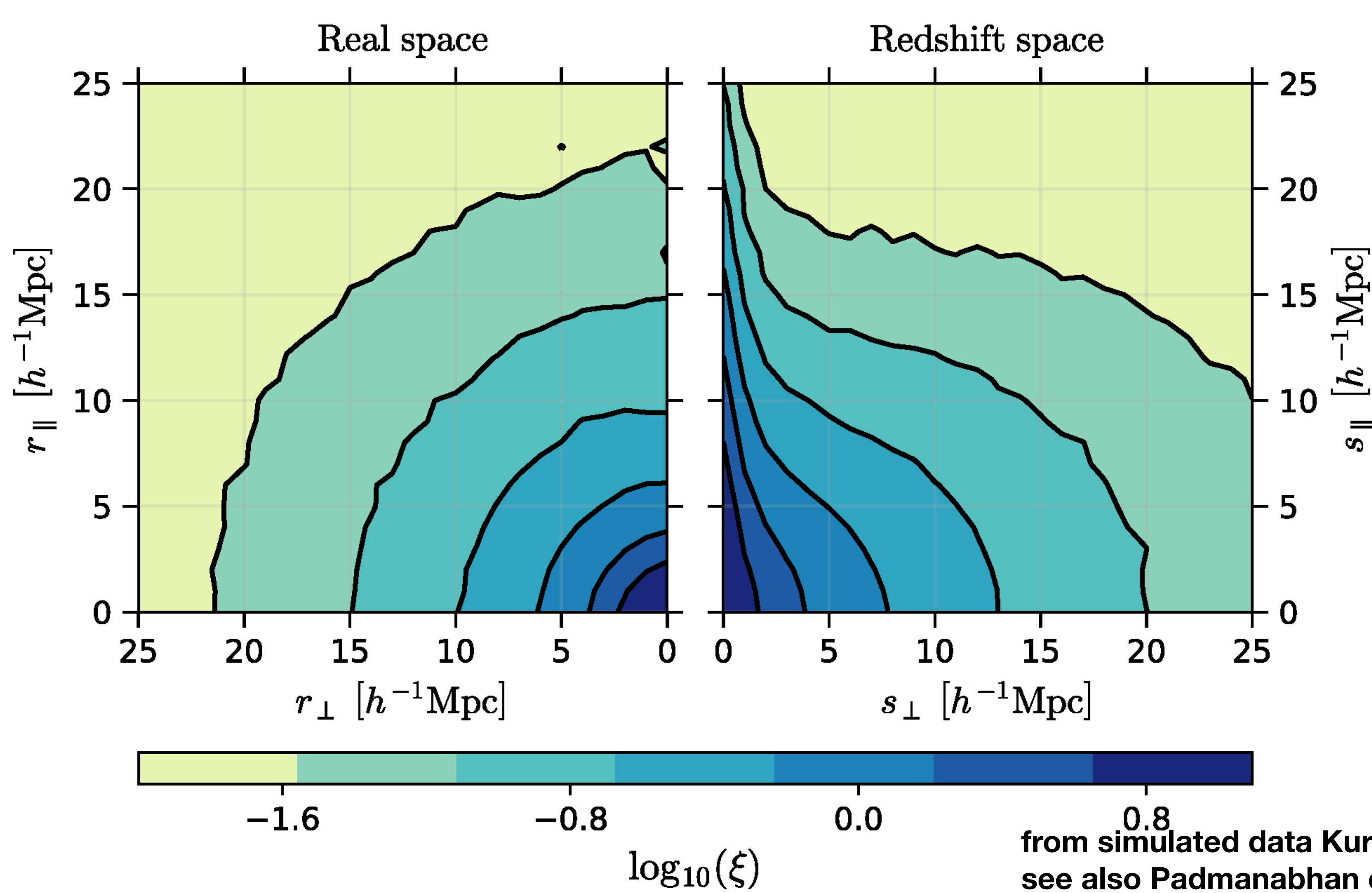
Conservation of Mass

Connection between density overdensities and peculiar velocities

… by the law of transitivity …

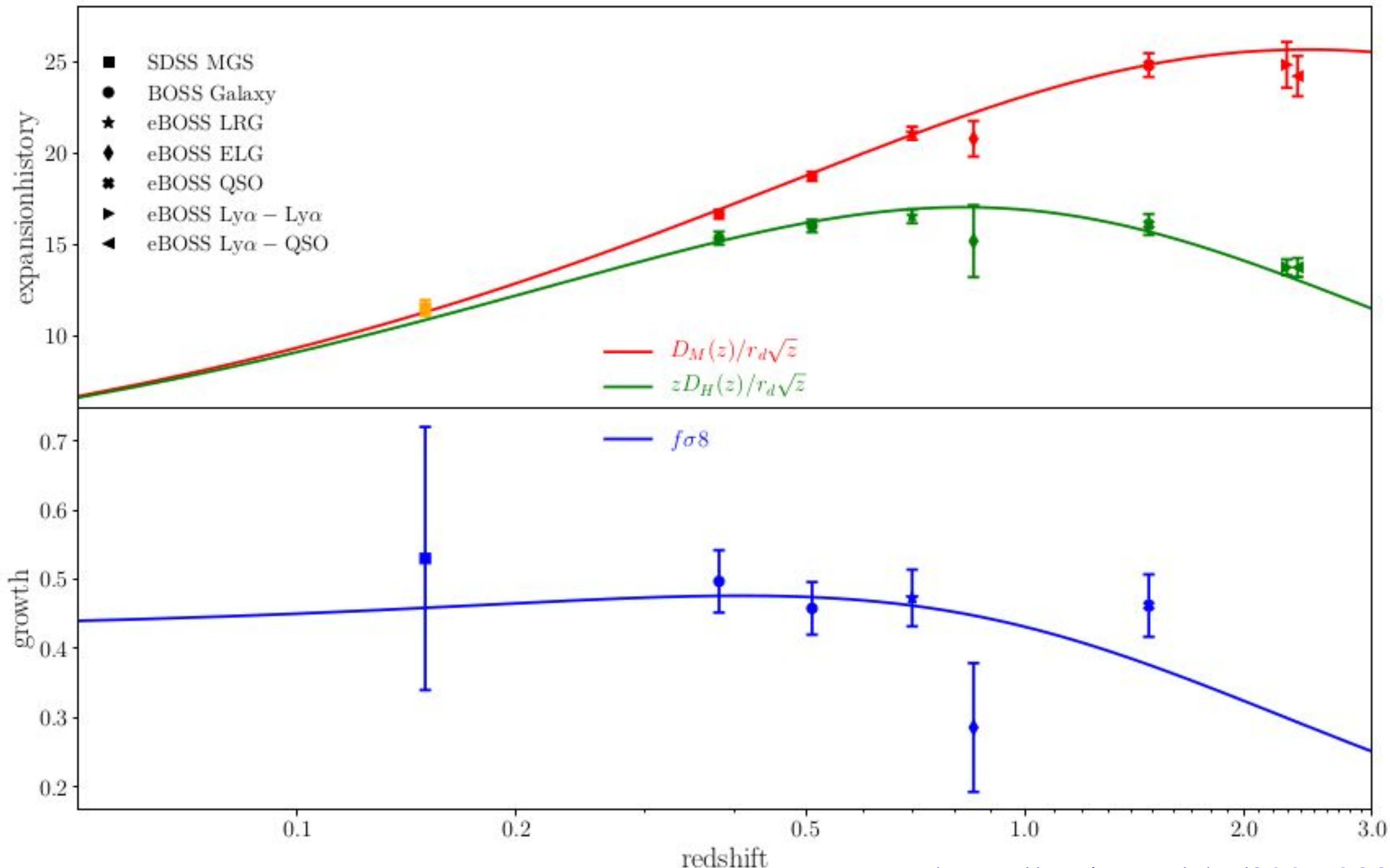
- Peculiar velocities are a powerful probe of the growth of structure, gravity, and the primordial universe, and so should motivate projects and facilities in the next decade

Peculiar Velocities ARE Motivating Projects Today: Redshift Space Distortions



from simulated data Kuruvulla and Porciani (2018)
see also Padmanabhan et al. (2012)

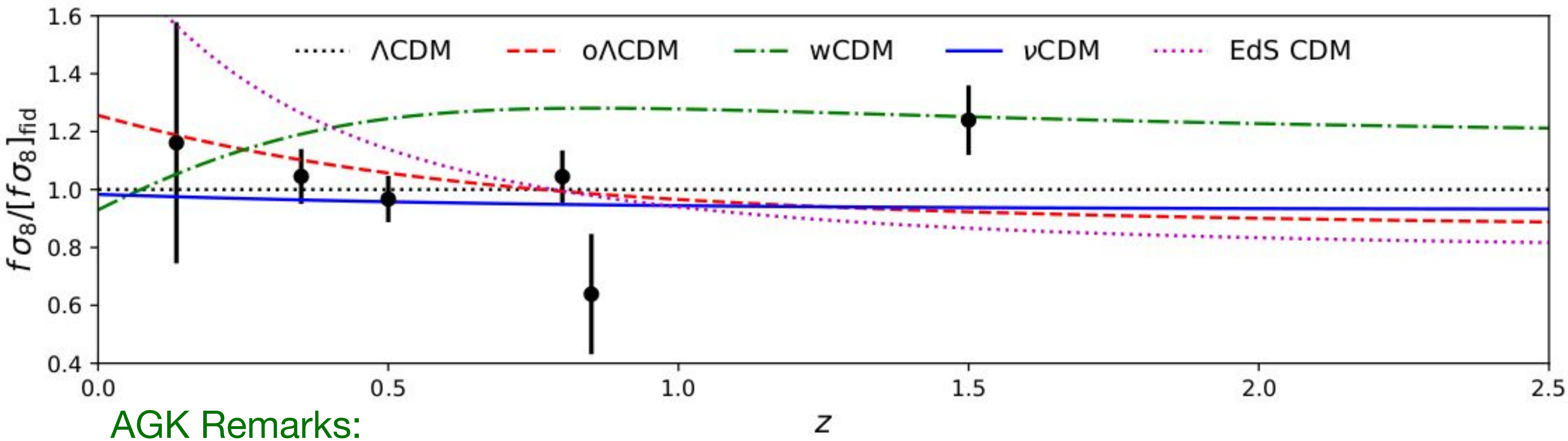
All BAO and RSD Measurements



https://arxiv.org/abs/2007.08991

RSD, Lensing, and CMB

- RSD-only from SDSS/BOSS/eBOSS
- Weak Lensing (WL) from DES (Troxel et al, 2018) and Planck
- Planck temperature and polarization (Planck Collaboration, 2018)



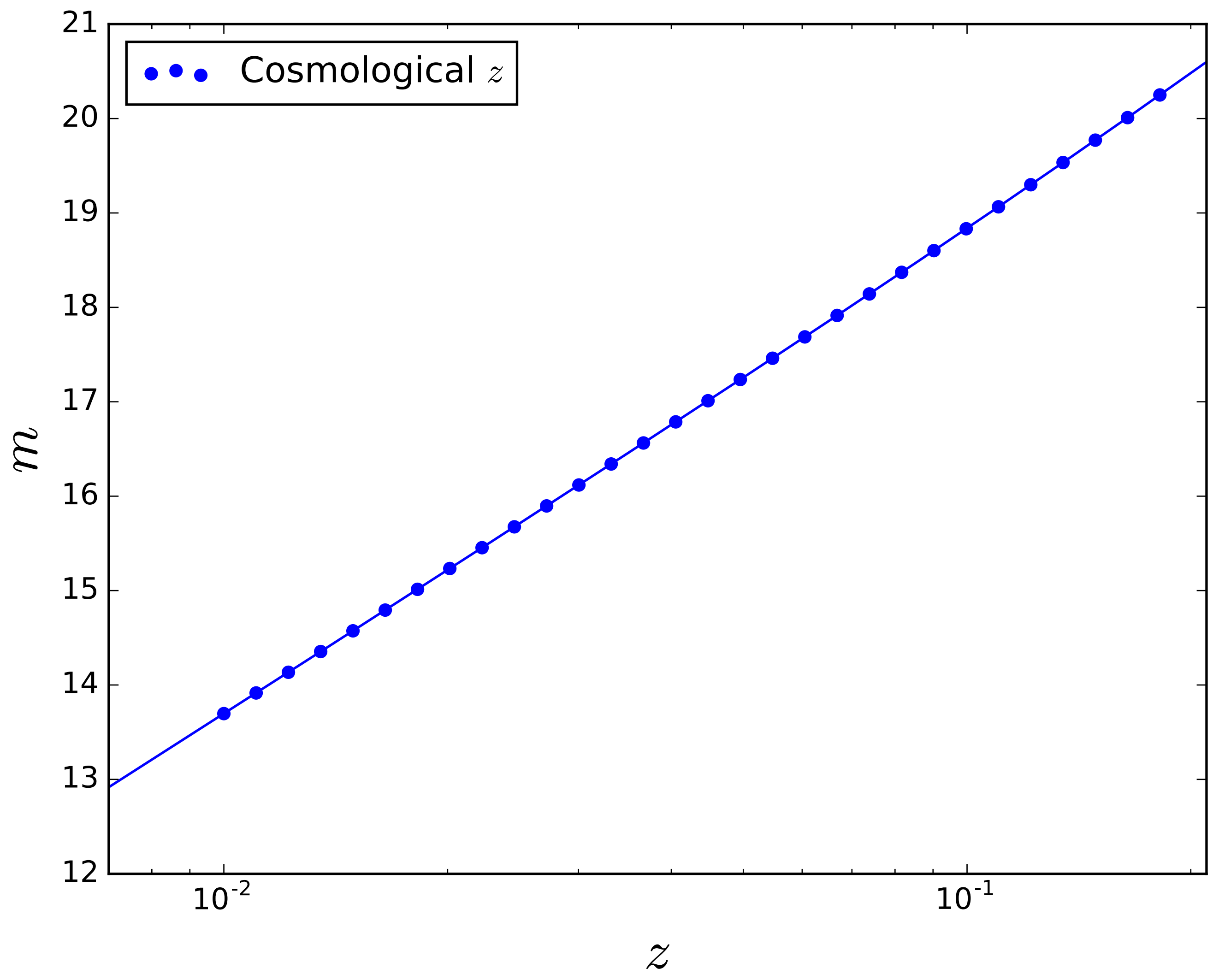
AGK Remarks:

- Models deviate at low redshift
- RSD has poor signal-to-noise at low redshift because of limited volume

https://arxiv.org/abs/2007.08991

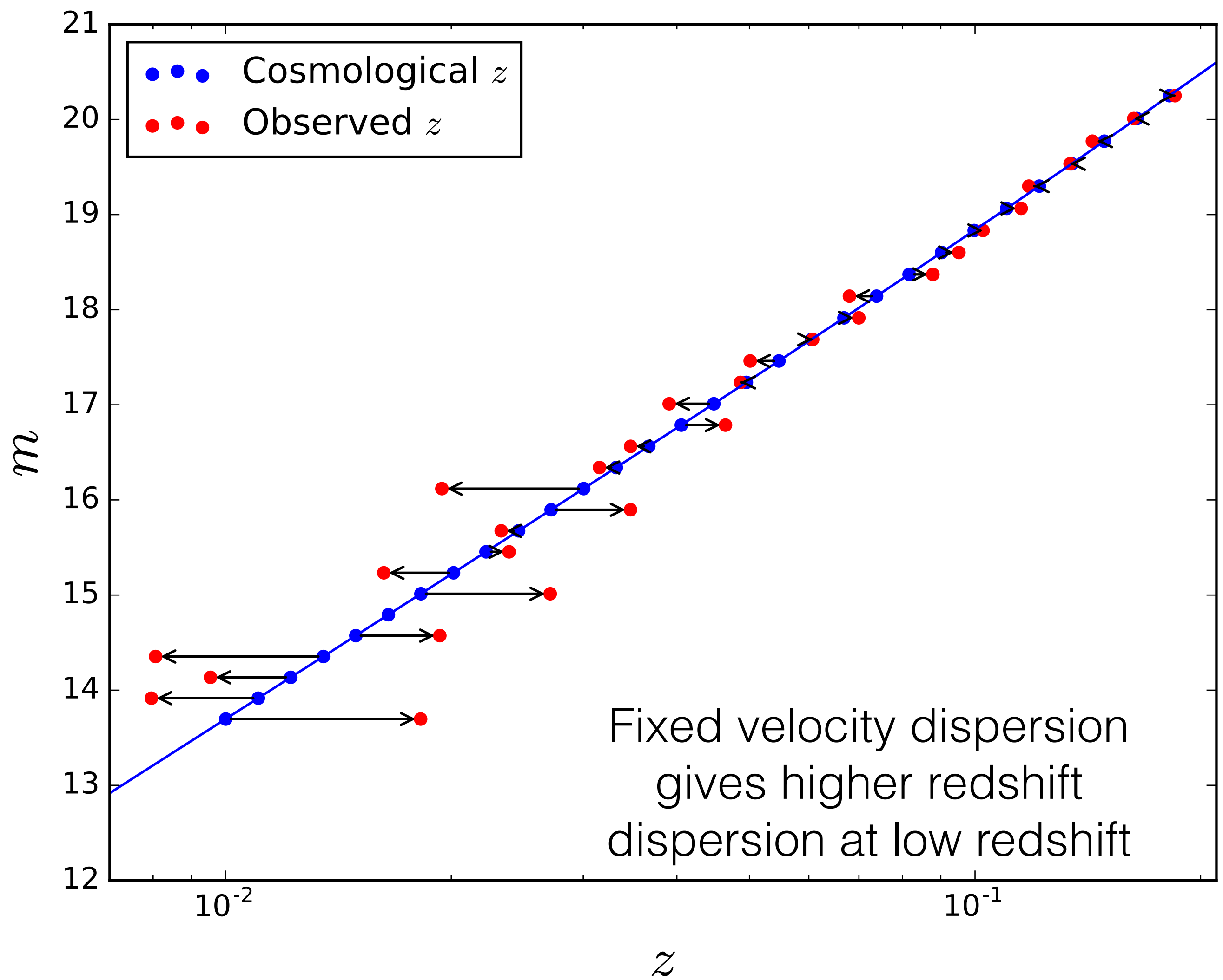
Peculiar Velocities ARE a Motivating Projects Today: Peculiar Magnitudes/Distances

Hubble Diagram: Cosmological Redshift



- Perfect distance indicators lie on nominal distance-redshift relationship (e.g. Hubble law) when using the cosmological redshift

Hubble Diagram: Observed Redshift

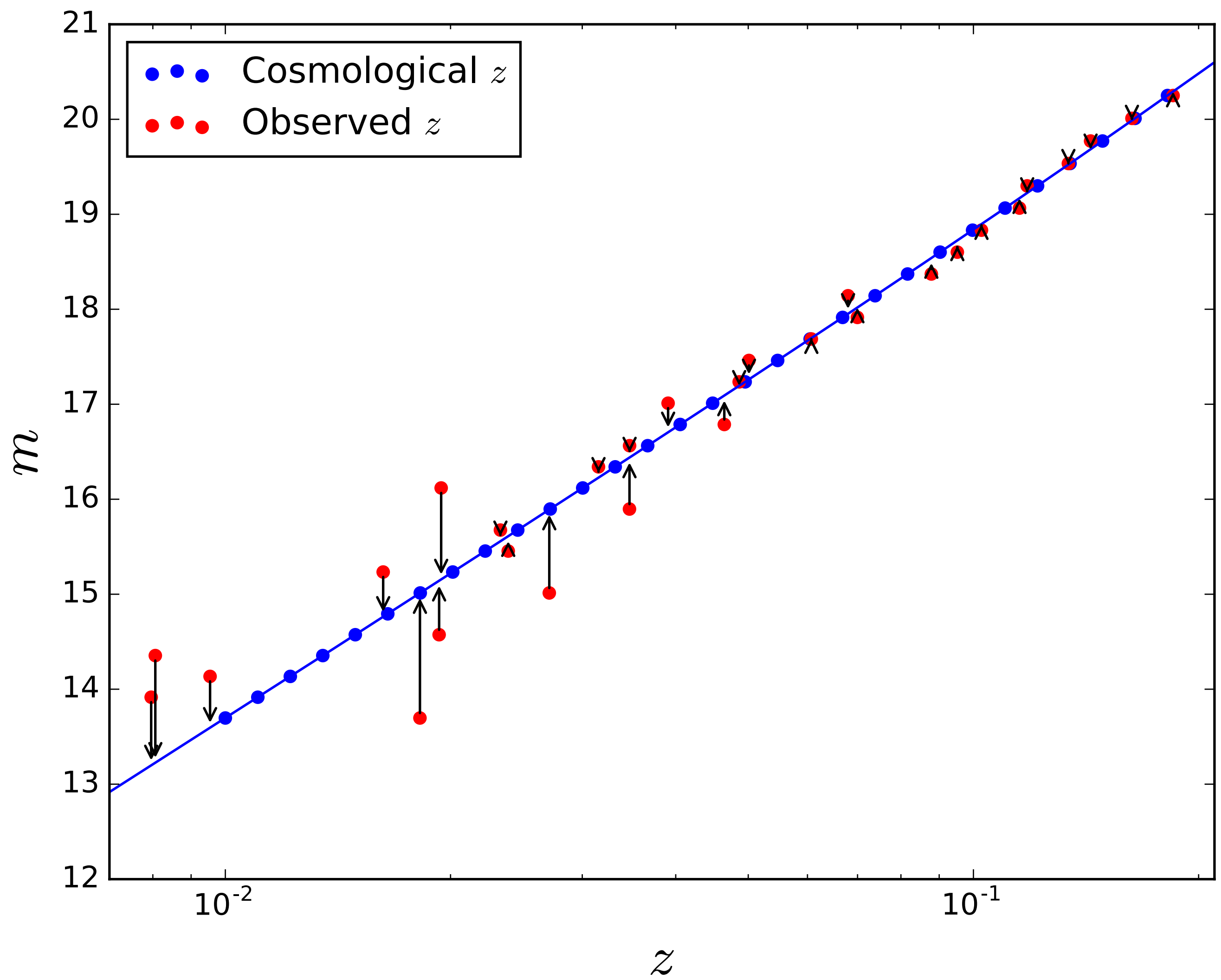


- Perfect standard candles with motion relative to the Hubble flow do not lie on nominal distance-redshift relationship when using the observed redshift

$$(1 + z_{obs}) = (1 + z_{cosmo})(1 + z_{pec})$$

$$1 + z_{pec} = \sqrt{\frac{1 + v_{pec,\parallel}}{1 - v_{pec,\parallel}}}$$

Interpreting Observed Redshift as Cosmological Redshift: Peculiar Magnitude/Distance



- Redshift offset can be equivalently described as a peculiar magnitude offset
  - Usually redshift errors are "negligible"
- m proportional to $f\sigma_8$, v proportional to $Hf\sigma_8$

Galaxy Distance Probes

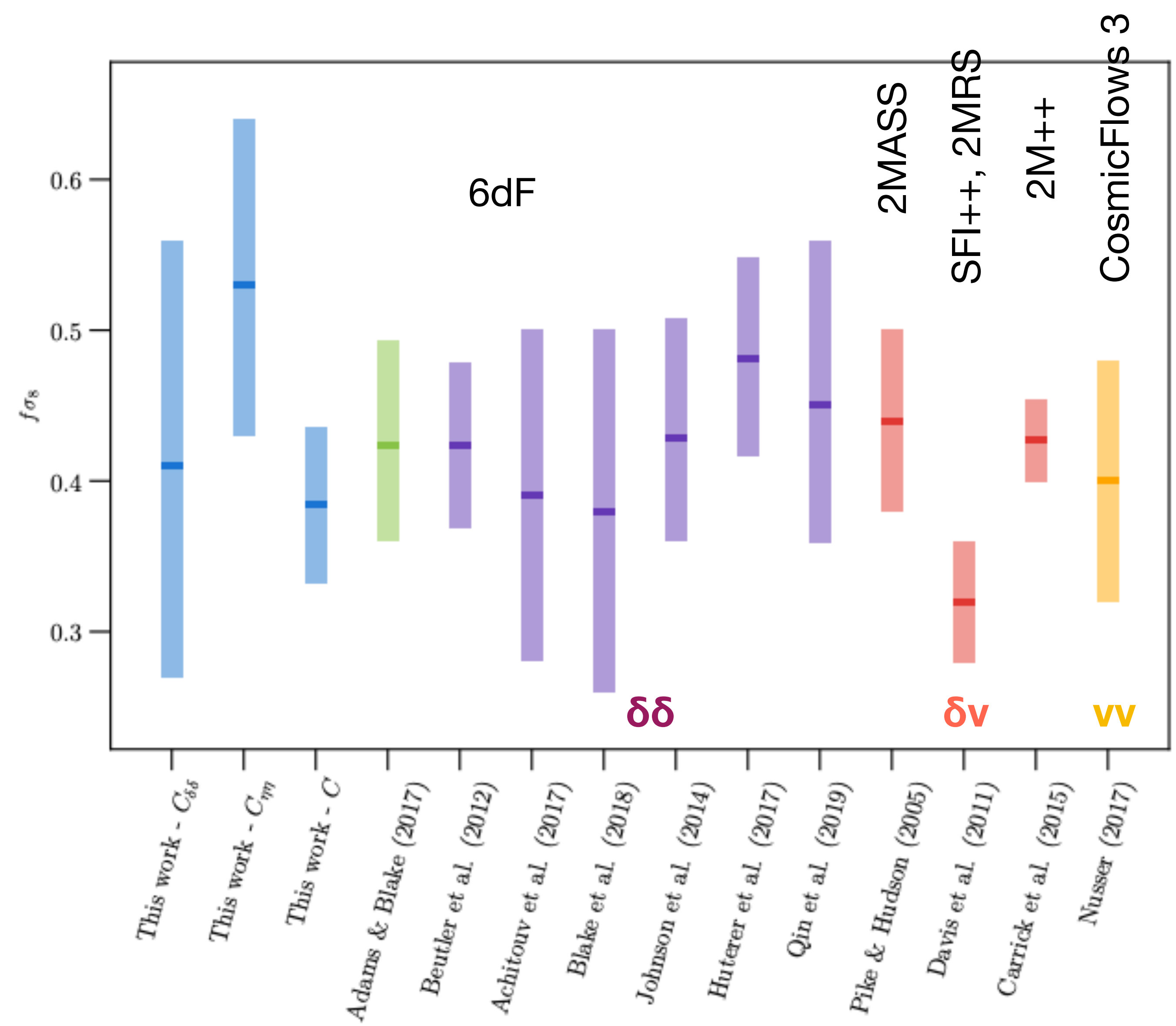
- Tully - Fisher: Correlation for spiral galaxies between luminosity and rotation speed

- Fundamental Plane: Correlation for elliptical galaxies between radius, velocity dispersion, and surface brightness

- ~20% distance uncertainties

Recent Results

- 6-degree Field Galaxy Survey (6dFGS)
    - Southern sky - galactic plane
    - 70k galaxies K<12.9, z<0.1
    - 10k Fundamental Plane galaxies
    - z< 0.057
- $f\sigma_8 = 0.384 \pm 0.052$(stat) ± 0.061(sys)
- Demonstrates benefit of cross-correlation of density and velocity fields



Adams and Blake (2020)

Type Ia Supernova Distances Can Outperform T-F, FP

The power of peculiar velocity surveys can be compared using

Ω	Solid Angle Coverage
z_{max}	Depth
$\frac{\sigma_m^2}{n}$	Distance precision and source density

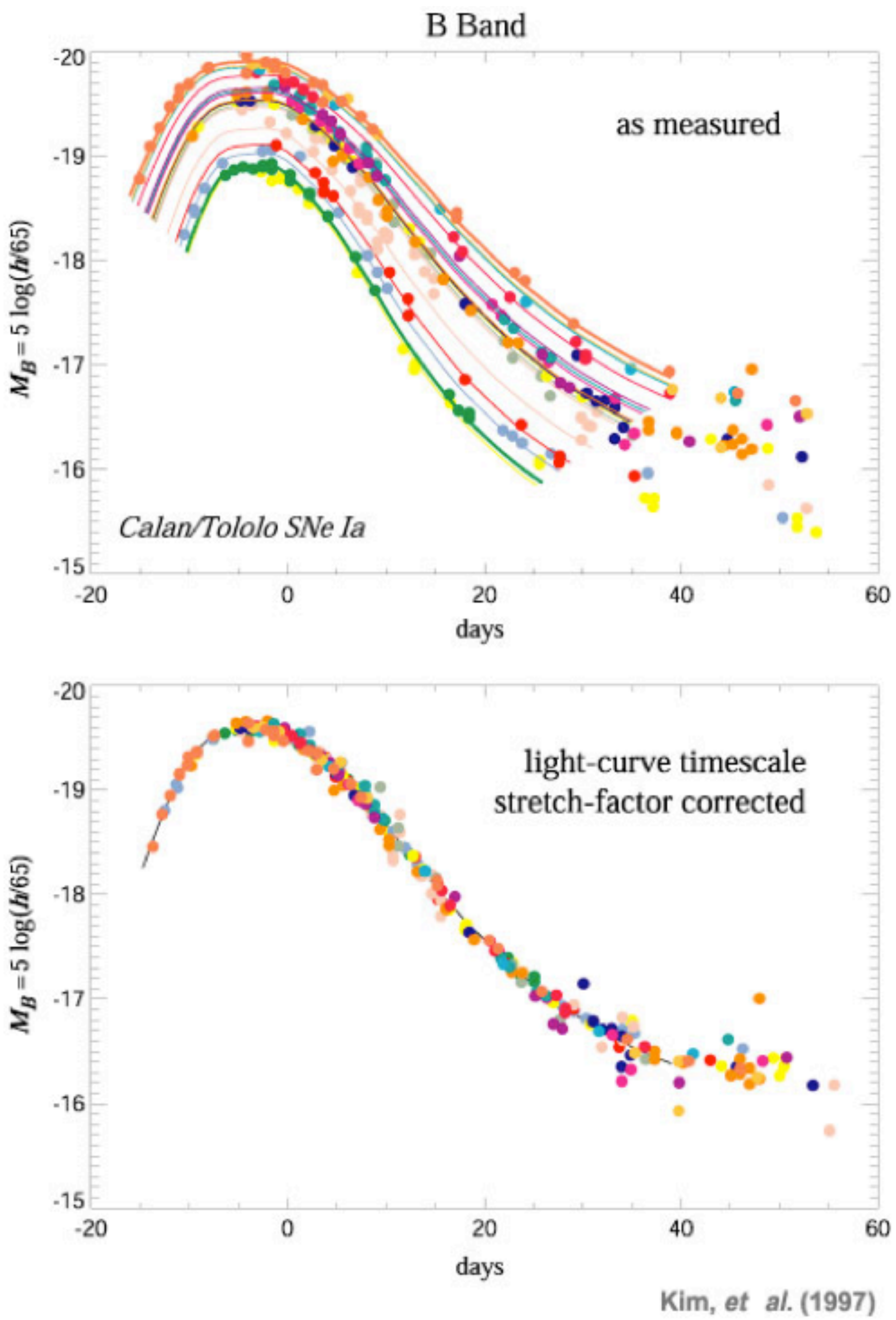
Why now?

From σ_m : 1 SN Ia = 30 Fundamental Plane galaxies

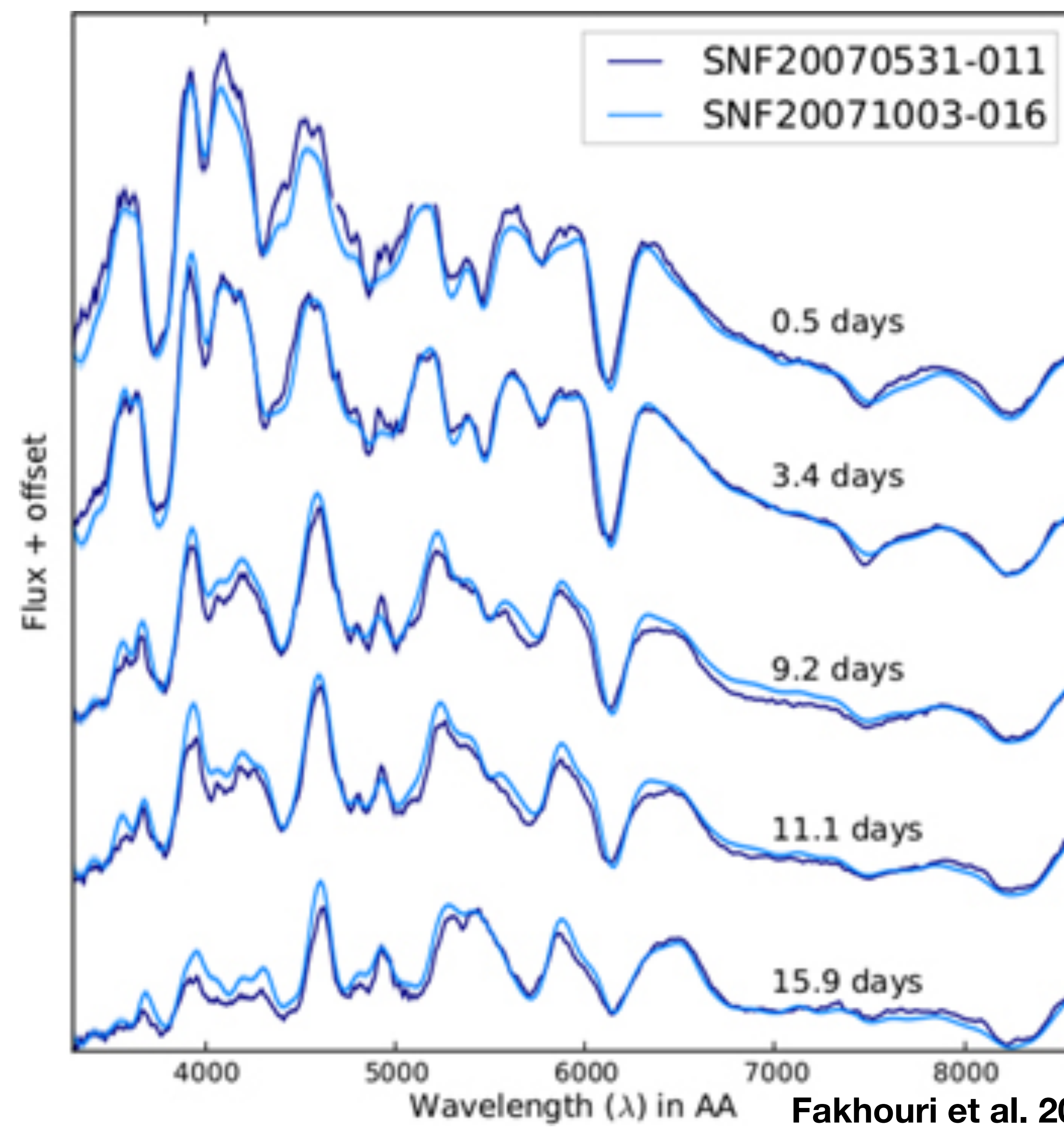
ZTF, ZTF-II, LSST discover SNe Ia with competitive Ω, z_{max} and n

Improved Precisions of Type Ia Supernova Distances (Peculiar Velocities)

Excellent multi-band light curves can give 6% distance precisions



Good spectrophotometry can give 4% distance precisions

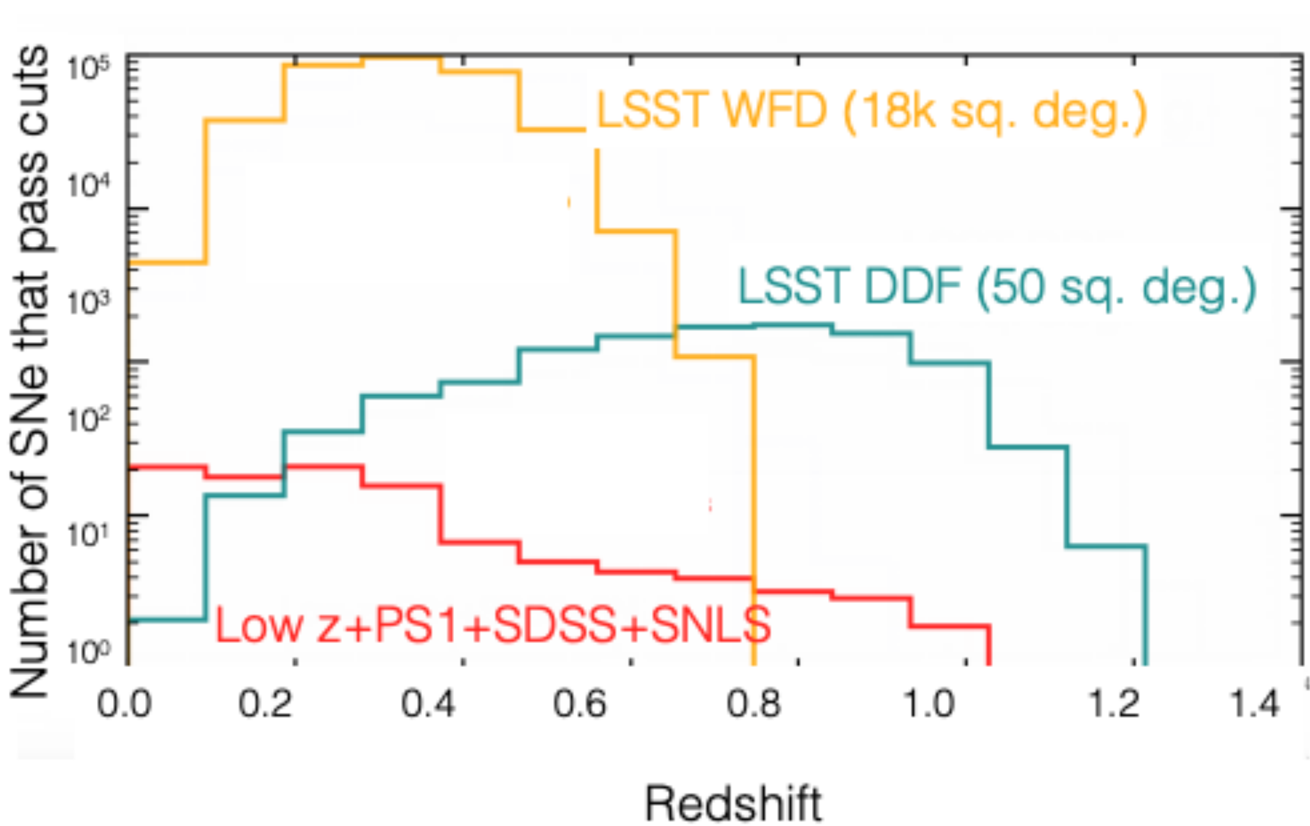


Fakhouri et al. 2005

LSST (& ZTF-II+) : Free All-Sky Sources of SNe Ia

- ZTF-II will continue to be a source of northern sky SNe for 3 years (5000 classified SNe Ia *z<0.09*); ZTF-III?

- Vera C. Rubin Observatory LSST a source of southern sky SNe for 10 years: ~ 50k (unclassified) SNe Ia at *z<0.15*



Mandelbaum et al. 2019

Type Ia Supernova Distances Can Outperform T-F, FP

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From σ_m : 1 SN Ia = 30 Fundamental Plane galaxies

Why now?

ZTF, ZTF-II, LSST discover SNe Ia with competitive Ω, z_{max} and n

n is "infinite" for the patient

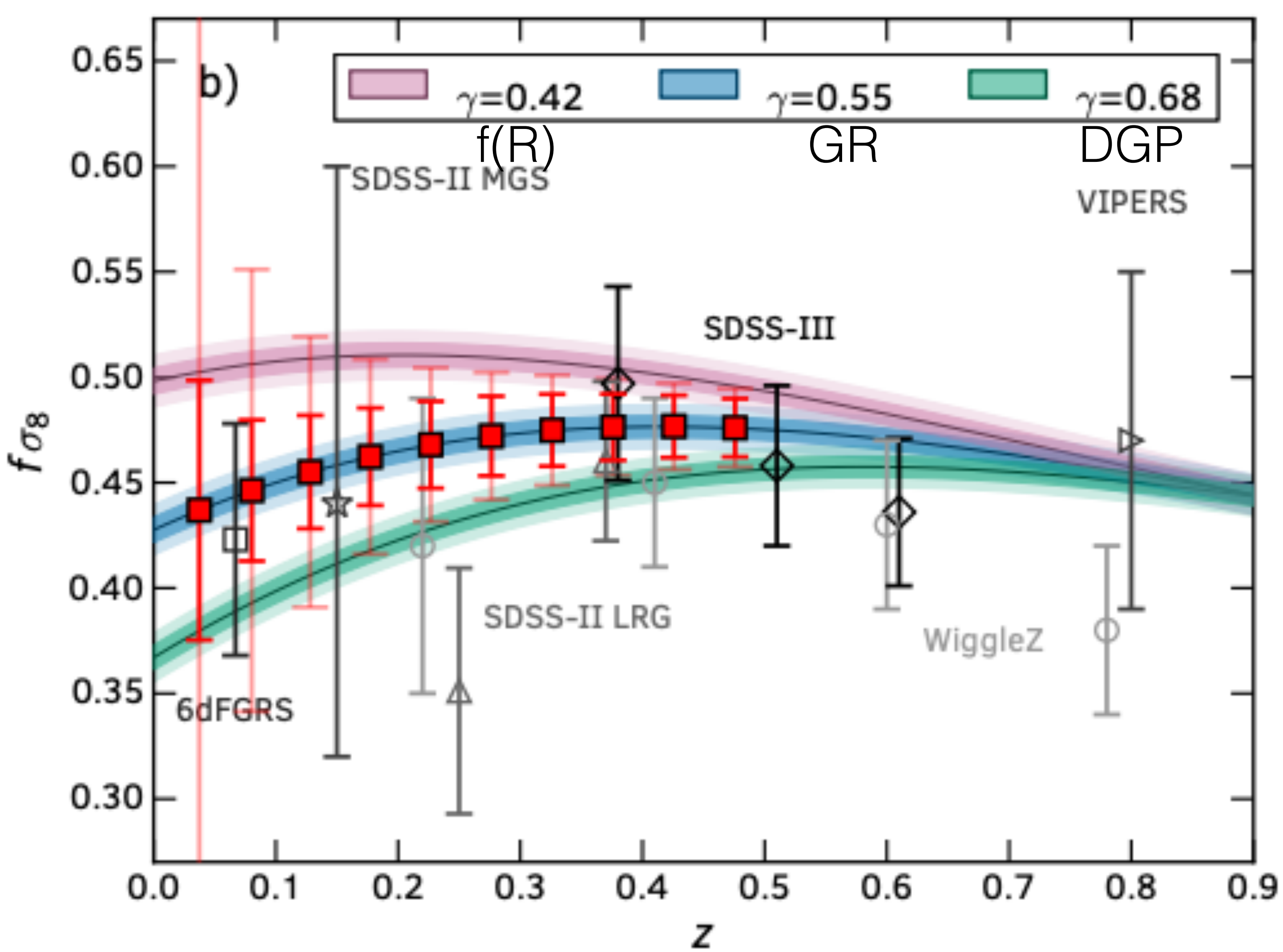
TAIPAN

$$\frac{\sigma_m^2}{n} = \frac{0.45^2}{2 \times 10^{-3} h^3}[\mathrm{mag}^2\,\mathrm{Mpc}^3]$$
$$= 90h^3[\mathrm{mag}^2\,\mathrm{Mpc}^3]$$

LSST 10-year

$$\frac{\sigma_m^2}{n} = \frac{0.08^2}{5 \times 10^{-4} h^3}[\mathrm{mag}^2\,\mathrm{Mpc}^3]$$
$$= 13h^3[\mathrm{mag}^2\,\mathrm{Mpc}^3]$$

SN Ia $f\sigma_8$ Projections for the Rubin Observatory



Howlett, Robotham, Lagos, and Kim (2017)

- Red points LSST SNe
  - Inner error bar SN RSD and PV
- Covers low z<0.2 redshifts
- <10% precision in several redshift bins

Measures of $f\sigma_8$ is a Measure of Fundamental Physics

Peculiar Velocities -> $f\sigma_8$ Related -> Gravity

Evolution of σ_8 depends on gravity

Growth rate depends on gravity. An excellent empirical parameterization is:

$$f = \Omega_M^\gamma$$

$$f\boldsymbol{\sigma_8} = \Omega_M^\gamma \exp\left(\int_a^1 \Omega_M^\gamma \, d\ln a\right)$$

γ: growth index

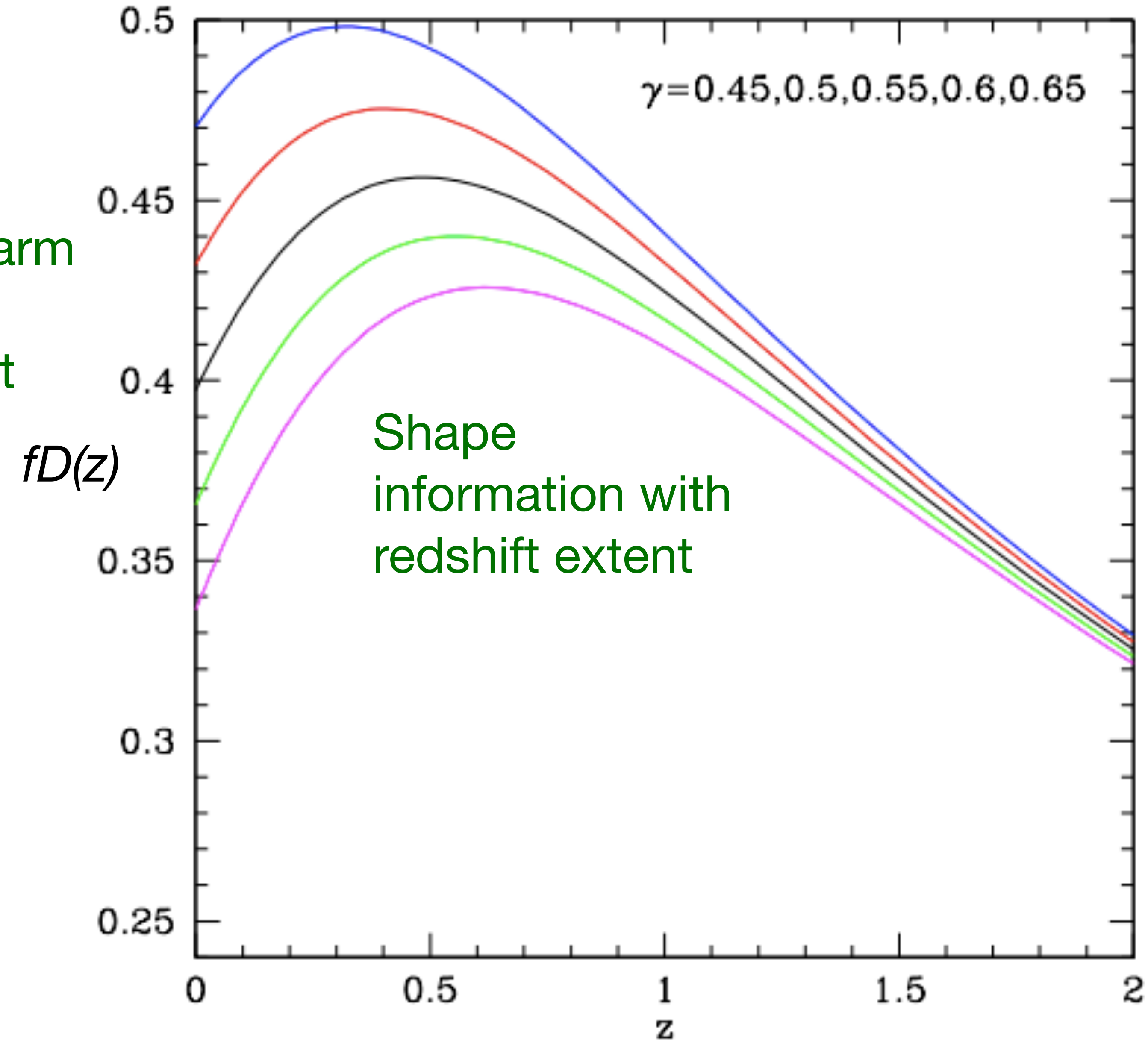
General Relativity, $f(R)$, and DGP gravity predict values of the growth index of $\gamma = 0.55, 0.42, 0.68$

Linder (2005), Linder & Cahn (2007)

target is to resolve $\Delta\gamma$=0.13

fD(z) depends on γ, i.e. the theory of gravity

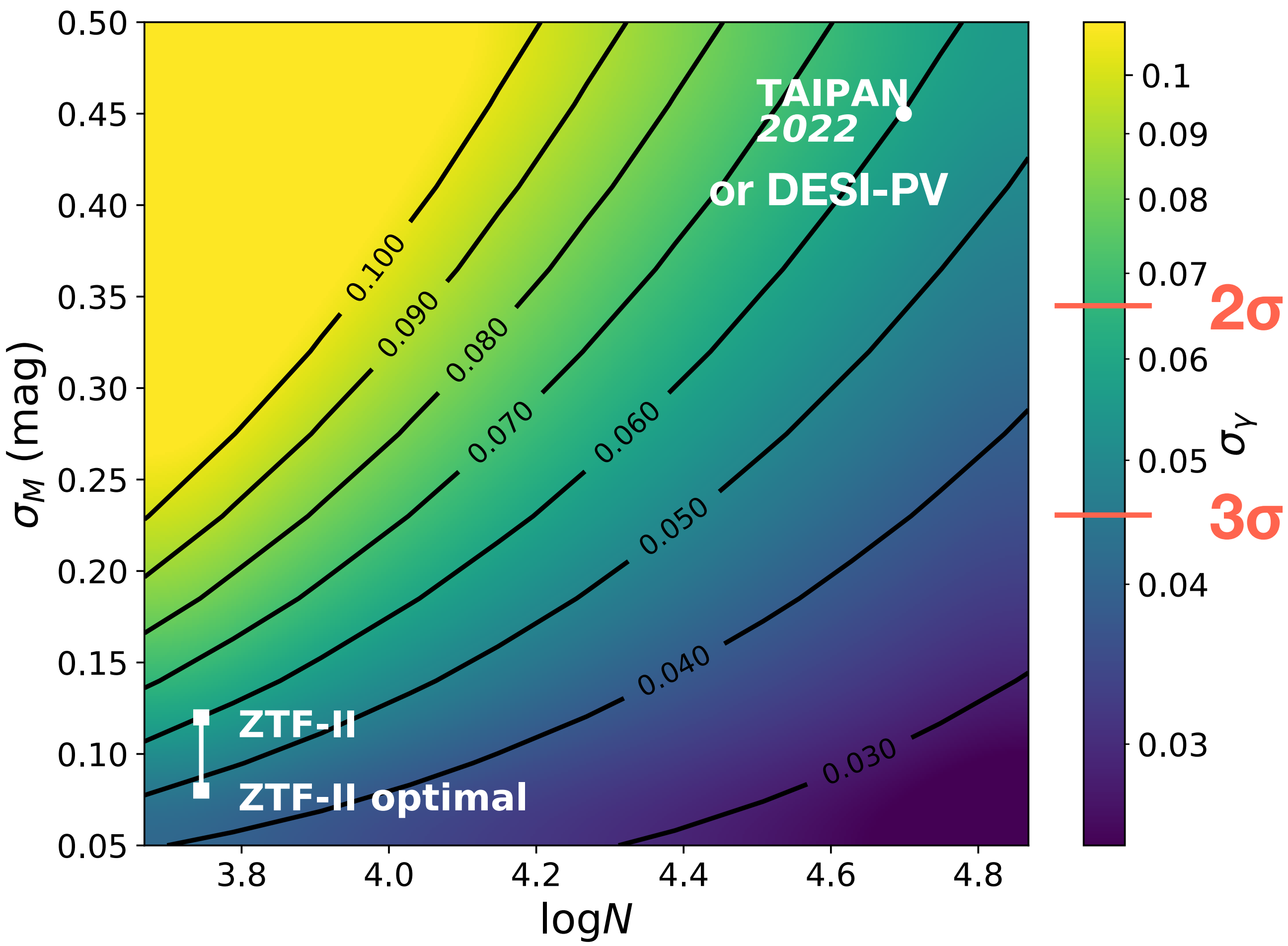
Lever-arm at low redshift



Linder (2013)

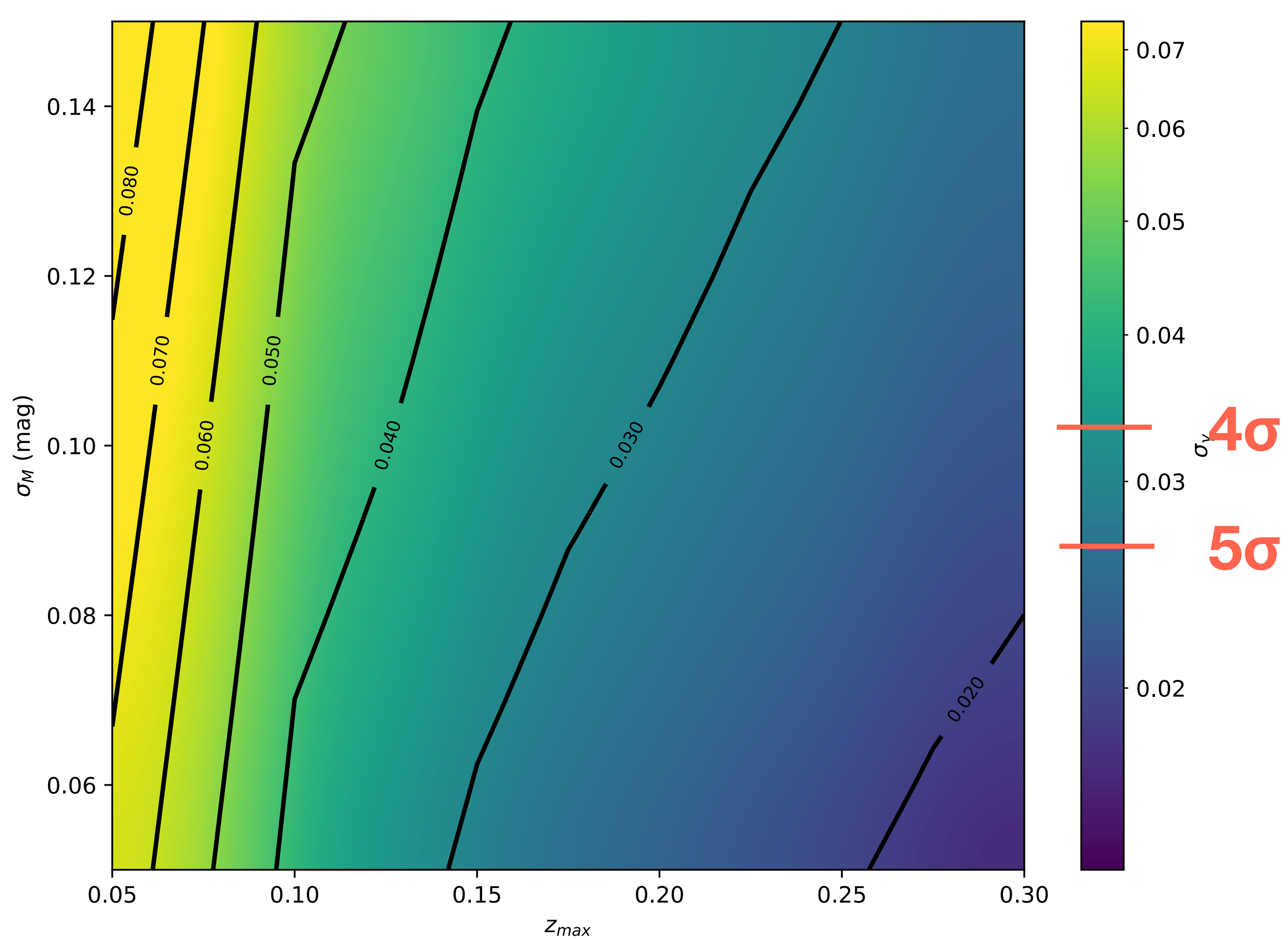
Projections for γ

ZTF2 and DESI z<0.1
~4 year



Can distinguish between the models in the previous slide at 2-3σ

10-year LSST

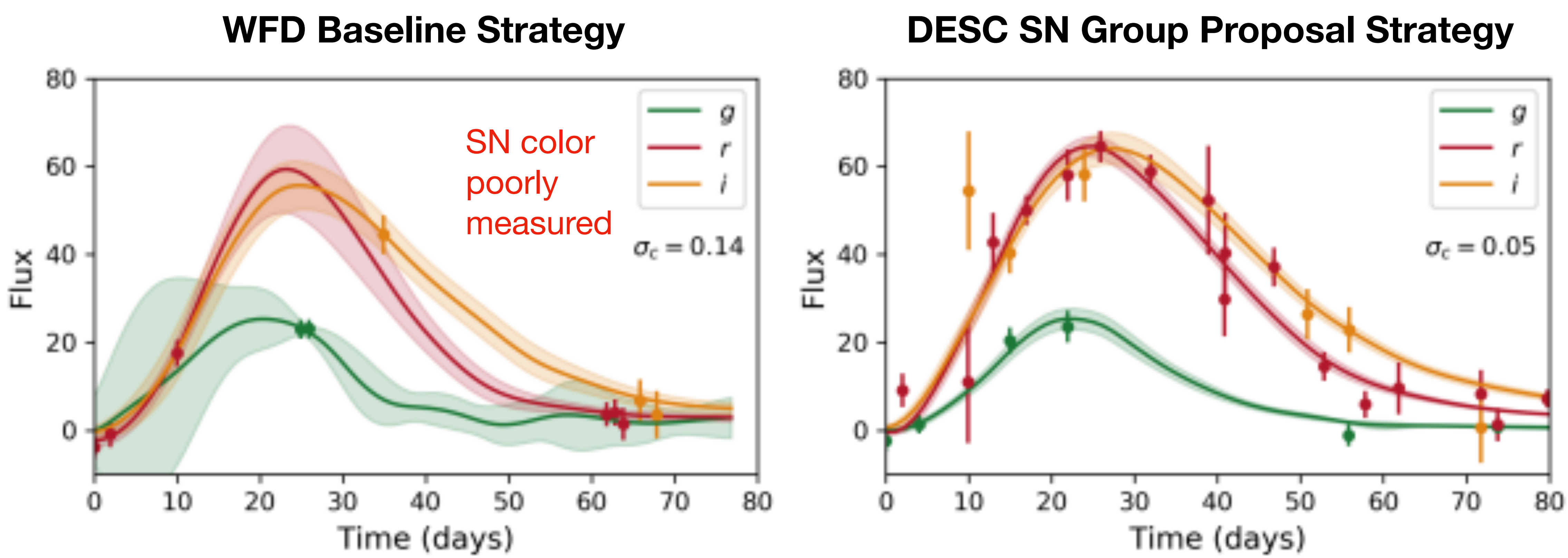


More sources and going to higher redshift can distinguish models up to 5σ depending on follow-up

Need Resources Beyond Wide-Field Imaging Surveys

LSST (and ZTF-II) are Not Enough: Photometry TBD

LSST Survey strategy may not yield precision light curves/ distances



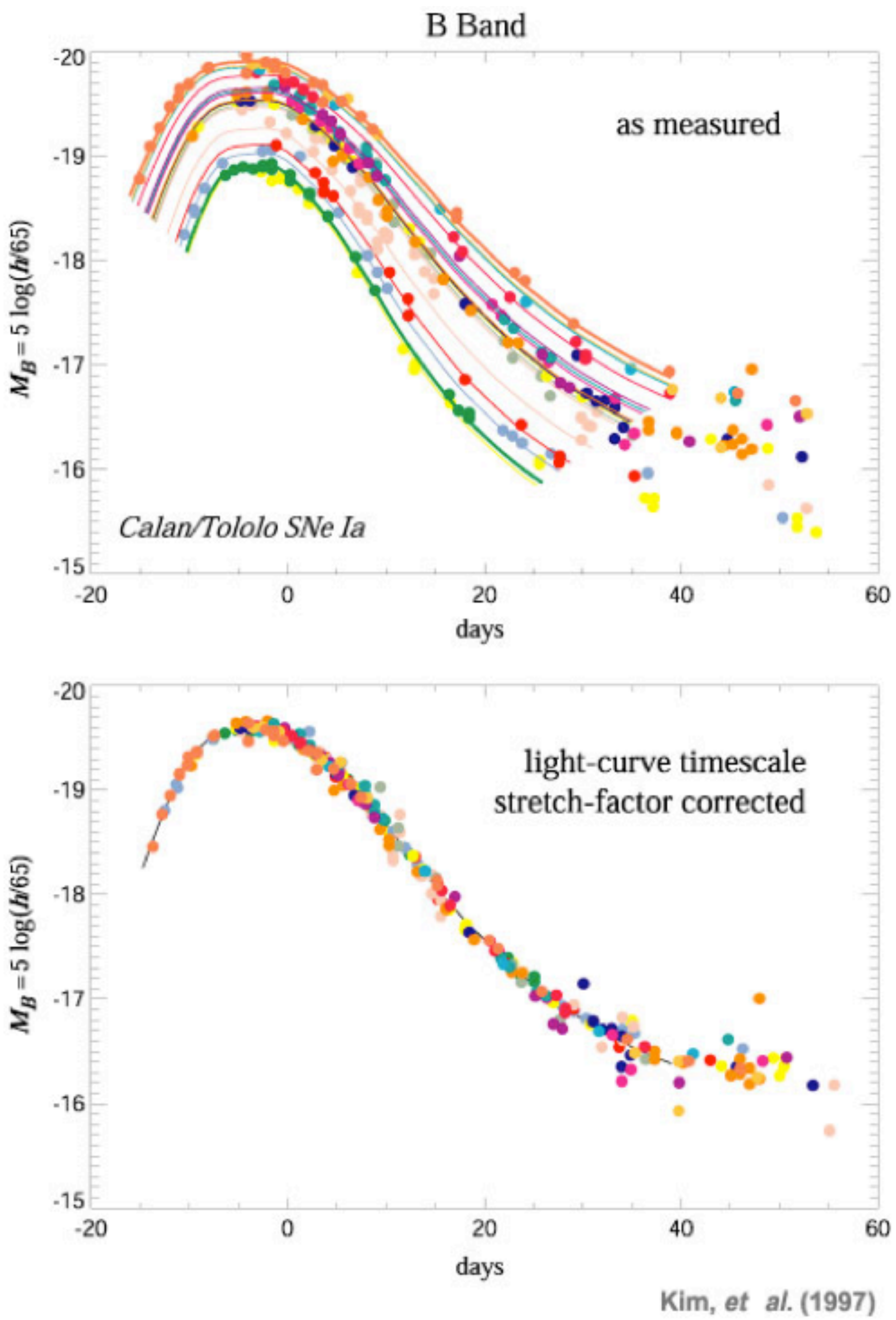
Lochner et al. (2018)

Won't know for a while, Survey Cadence Optimization Committee recommendation tentatively due Dec 31, 2021

LSST (and ZTF-II) are Not Enough: Spectroscopy

- Spectroscopy required for redshift, classification, and precision distance

Excellent multi-band light curves can give 6% distance precisions



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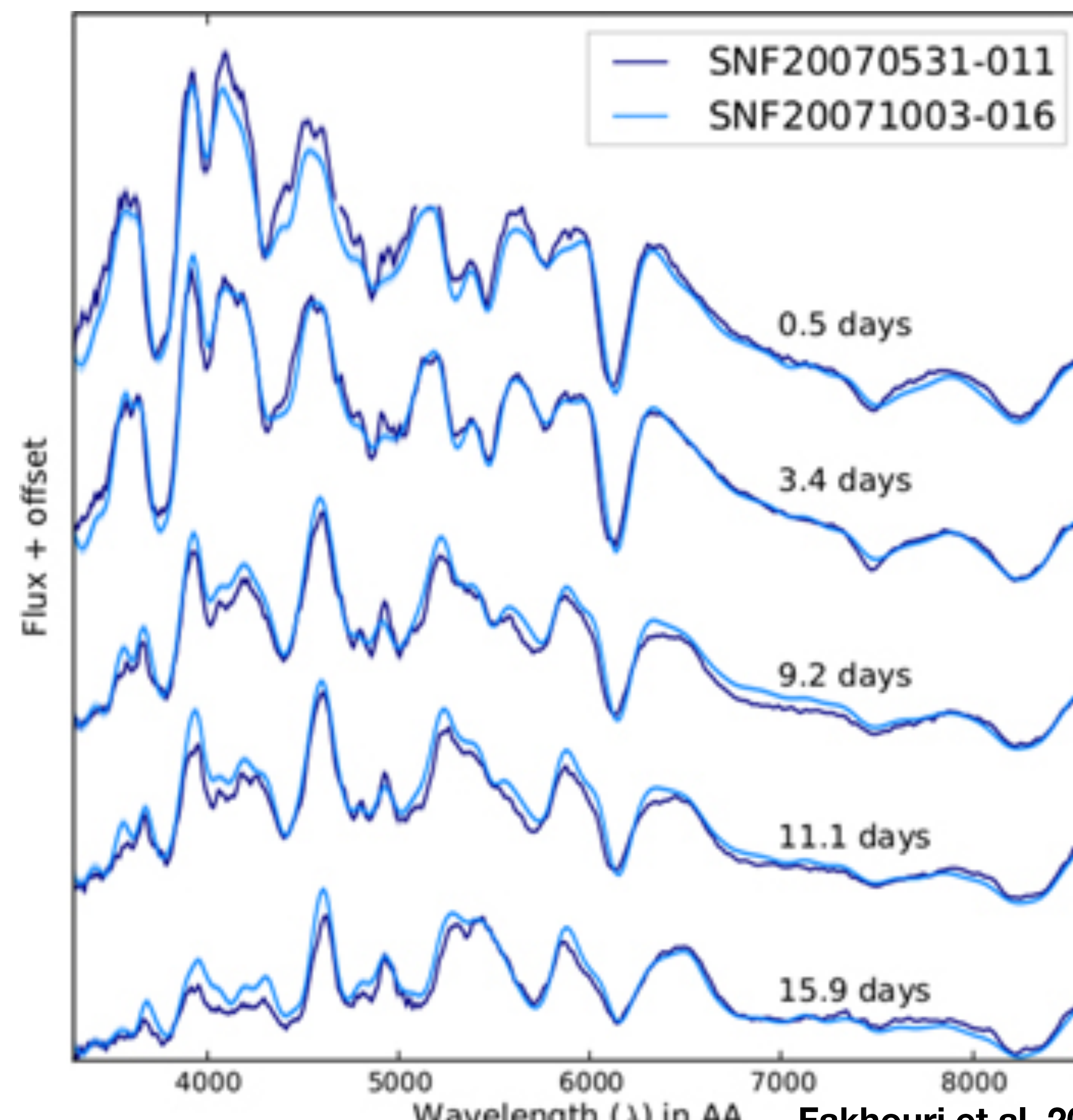
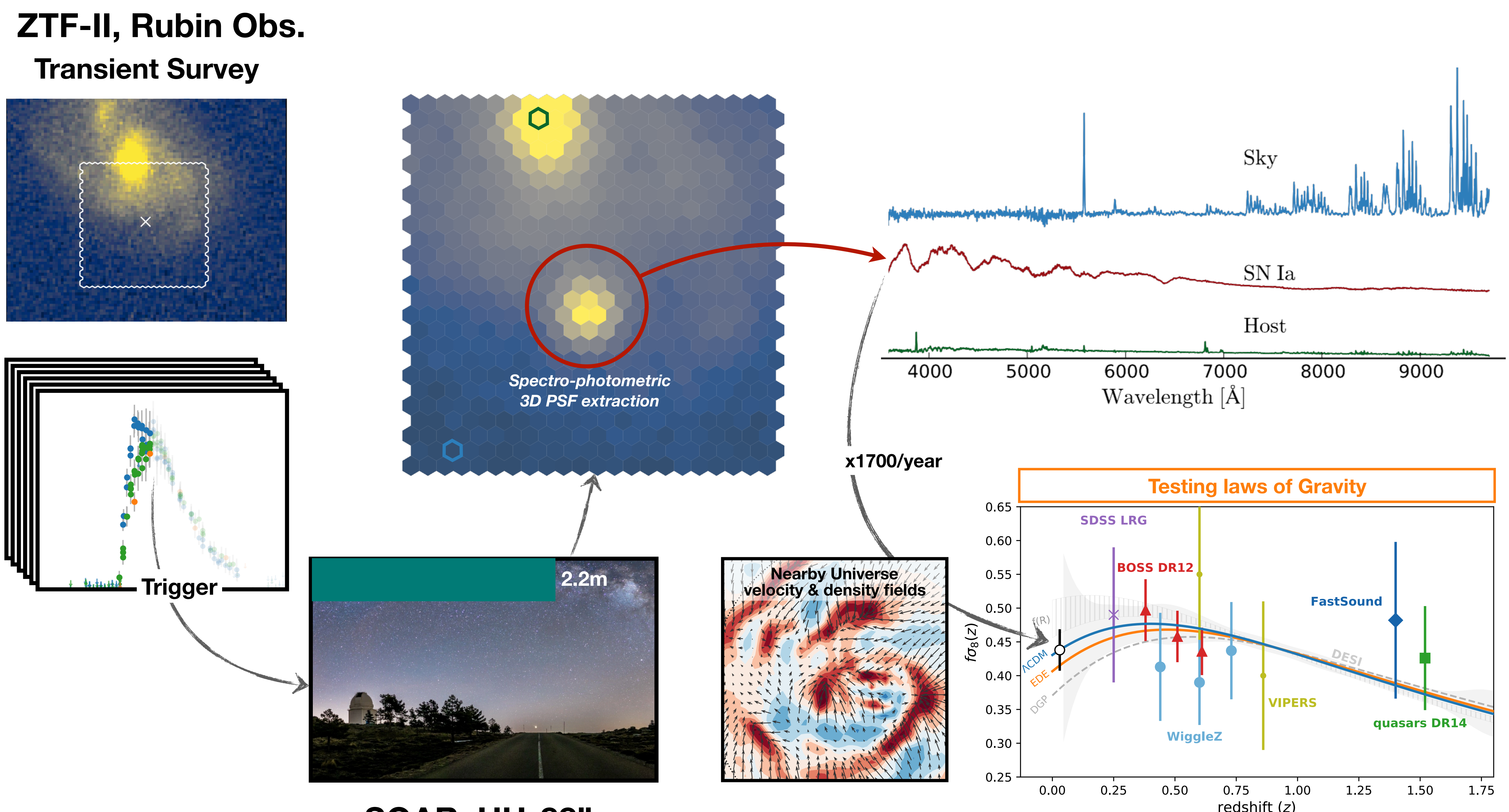


Fakhouri et al. 2005

PV SNIa Follow-up Network

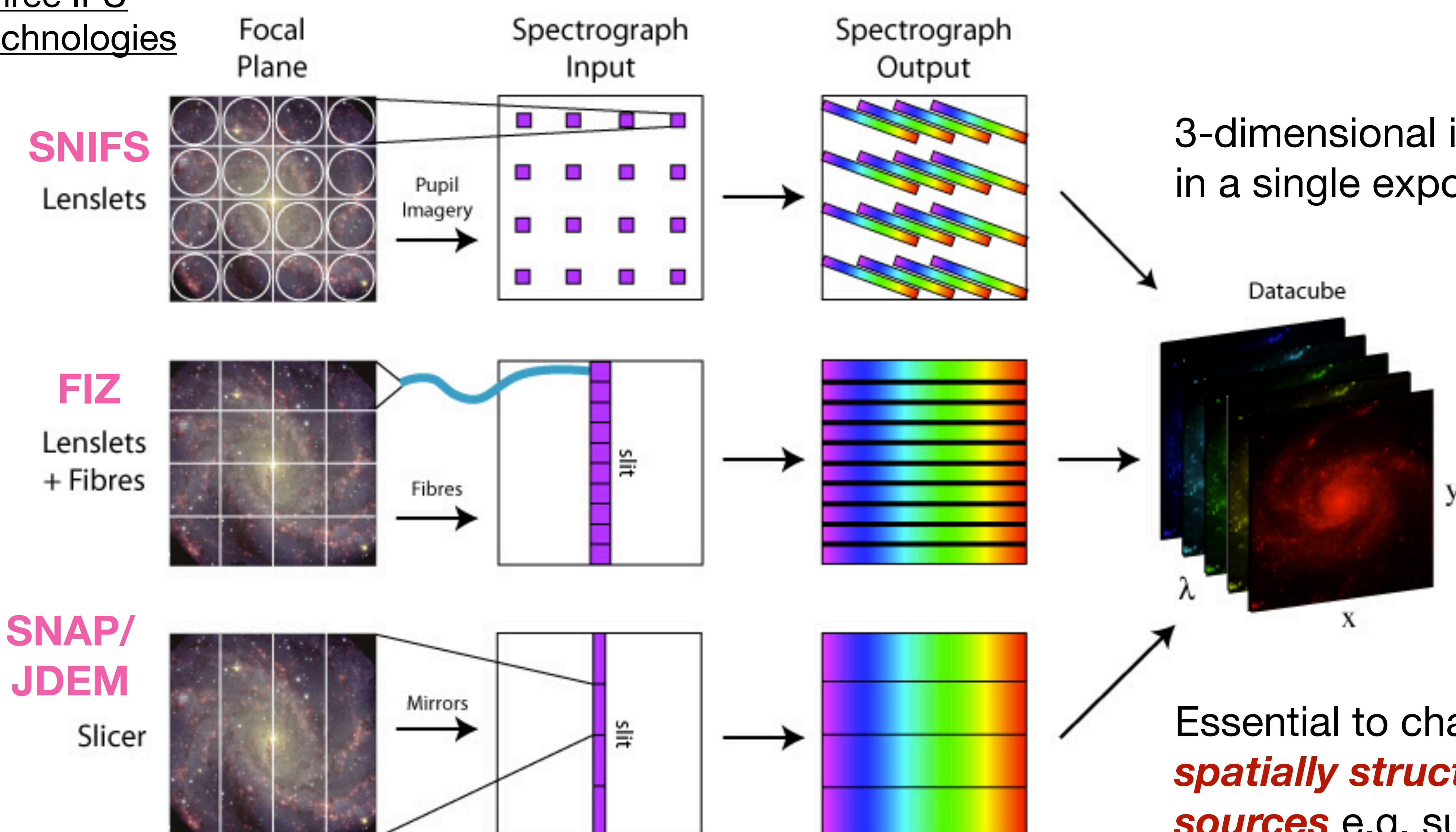


SOAR, UH-88”
ESO VLT Survey Telescope
Tokyo Atacama Observatory Telescope

adapted from Galbany, Kim, Rigault

Integral Field Unit and Integral Field Spectroscopy

<u>Three IFU technologies</u>



3-dimensional information in a single exposure

Essential to characterize ***spatially structured, sources*** e.g. supernova host galaxies

Scale of Investment

- Peculiar velocity / low redshift: one 2m —eight 4m facilities
- Refurbish older instruments, commitment of observatories, instrument R&D
- Leverage existing resources: DESI, 4MOST, SOXS, SNIFS
- *Importance of science and risk mitigation should have us move away from repeatedly applying for telescope time*

Peculiar Velocity Studies Advocated by the DOE Cosmic Frontier Community

A Project Matrix

In the following table, we provide a summary for the possible start dates and rough cost estimates for the different components of our Small Projects Portfolio.

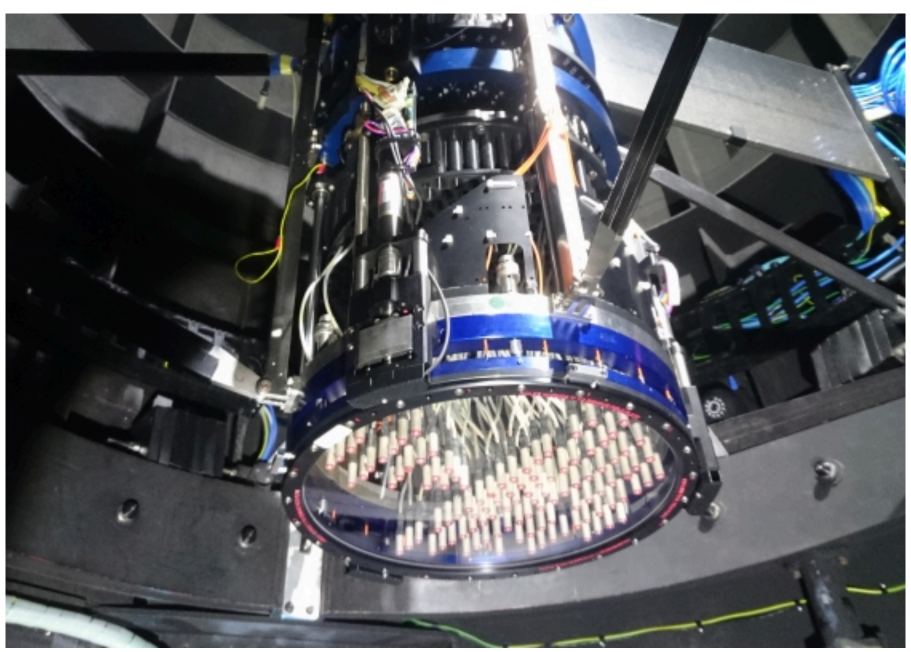
Readiness	Total Cost <$1M	 $1M - $3M
<2020	*Extending DESI/LSST**: - Photometric calibration instrumentation - Narrow-band or offset broad-band imaging - WFIRST + LSST synergies	*Theoretical and Simulation Advances*: - Modeling & simulations for small scale clustering - Modeling & simulations beyond ΛCDM - Multiwavelength Virtual Observatory - Enabling Community Science
2020-23	*Extending DESI/LSST**: - Personnel costs for ground-based spectroscopy - Peculiar velocity studies - LSST and DESI + CMB S4 synergies	*New Technology Developments*: - Ground layer adaptive optics over 10 deg^2 field of view - Germanium CCDs manufactured at scale - Fiber Positioner Systems at 5 mm pitch

from “Cosmic Visions Dark Energy Panel: Small Projects Portfolio”; Dawson et al. (2018)

Upcoming Galaxy/Peculiar Velocity Surveys: TAIPAN, Wallaby

TAIPAN (?)

- 150-fibre robot positioner and dedicated spectrograph
- 1.2m UK Schmidt Telescope
- Million z<0.3 galaxies in the South
  - ~100k good for fundamental plane distance



Starbug fiber positioner technology

WALLABY

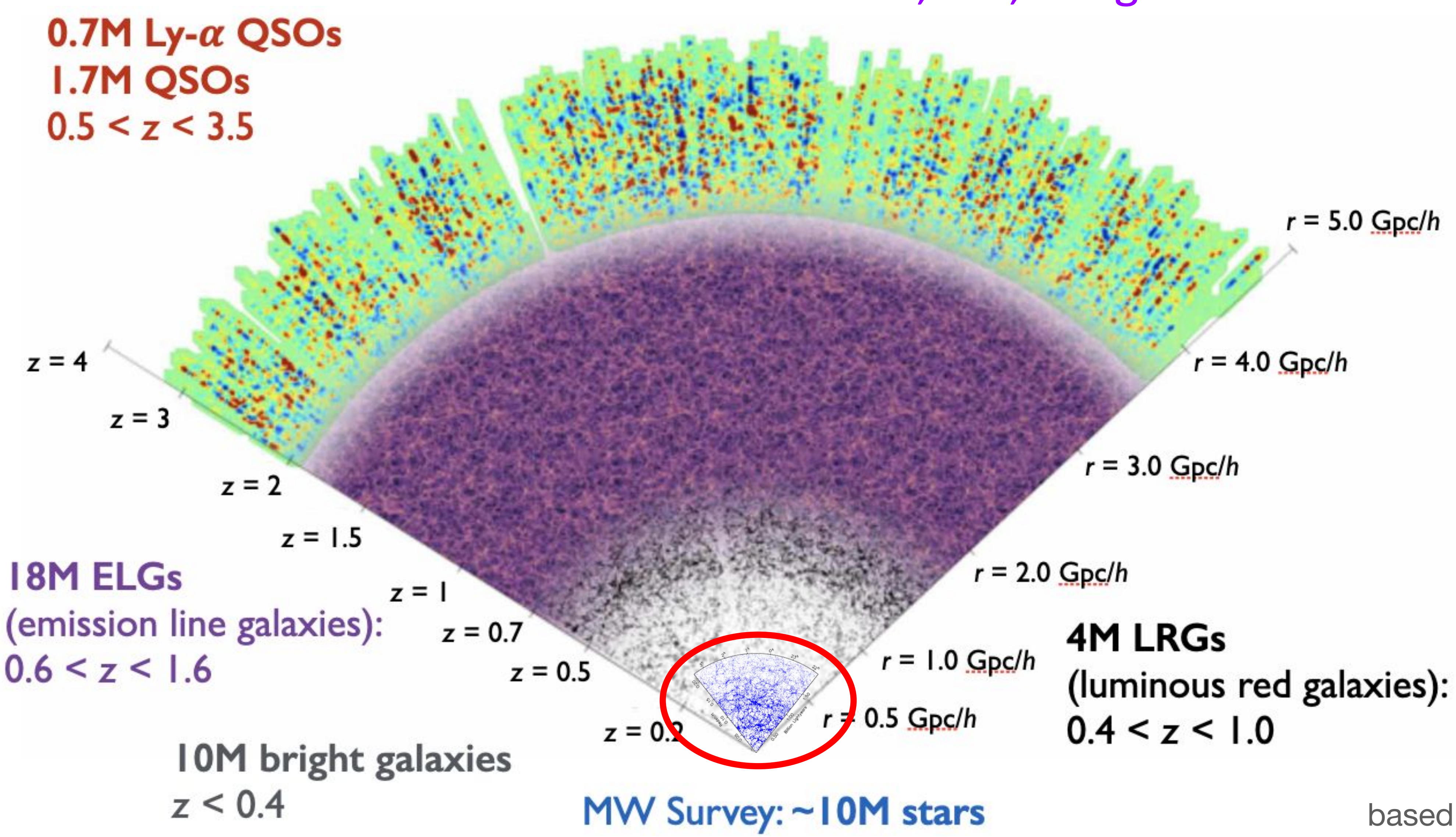
- HI survey
- Australian SKA Pathfinder
- 800k galaxies
  - ~40k Tully-Fisher distances

DESI as a Peculiar Velocity Survey

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Dark Energy Spectroscopic Instrument

DESI: ~35,000,000 galaxies: 2021-2026



based on from BenZvi

DESI Can Produce the Largest PV Catalog

- Modest (1M) spare DESI fiber allocation
- Build signal-to-noise for precision velocity dispersion measurement to enable Fundamental Plane distances of early-type galaxies
- Place fibers along spiral arms to measure rotation curves to enable Tully-Fisher distances to spiral galaxies

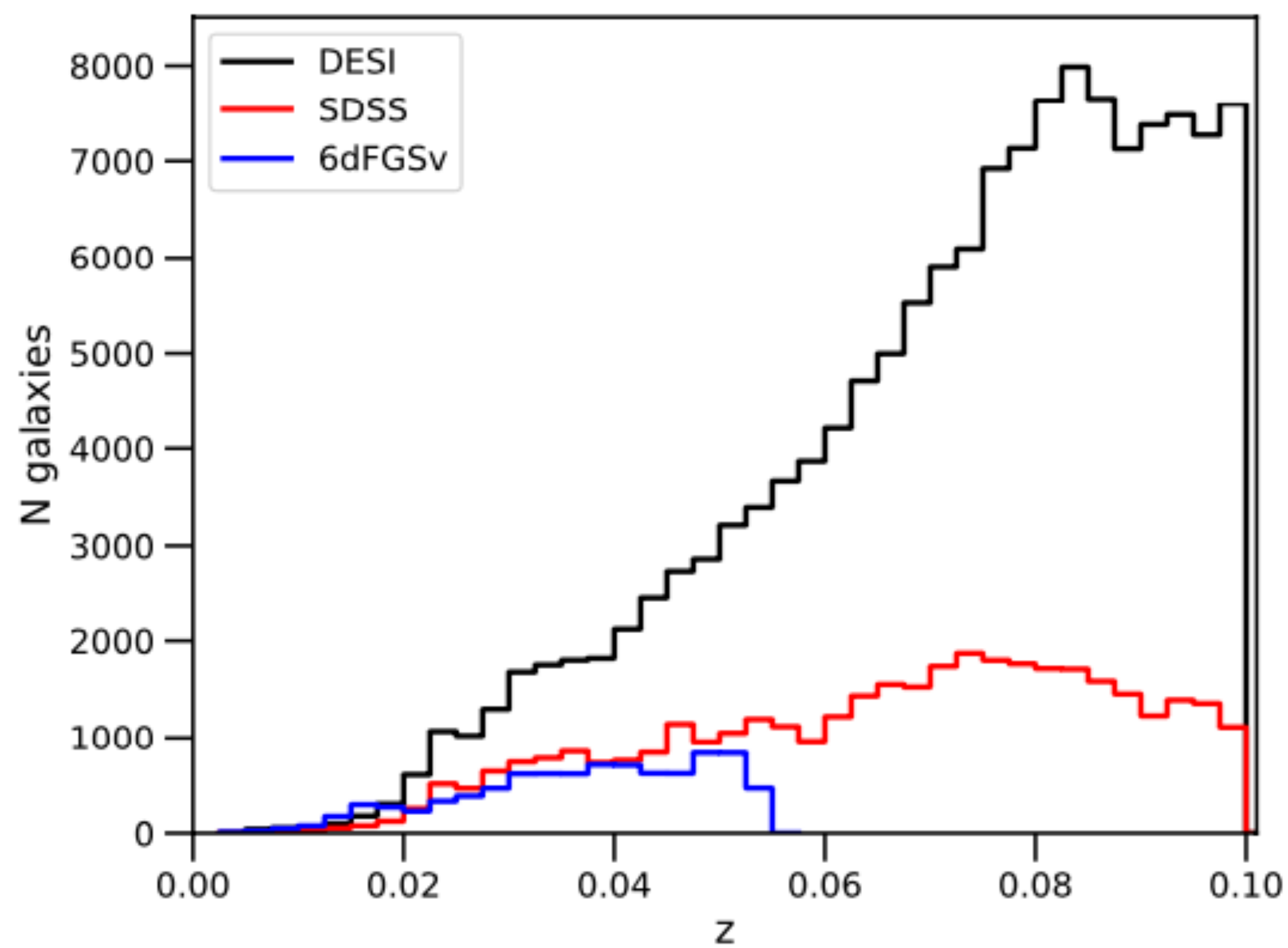
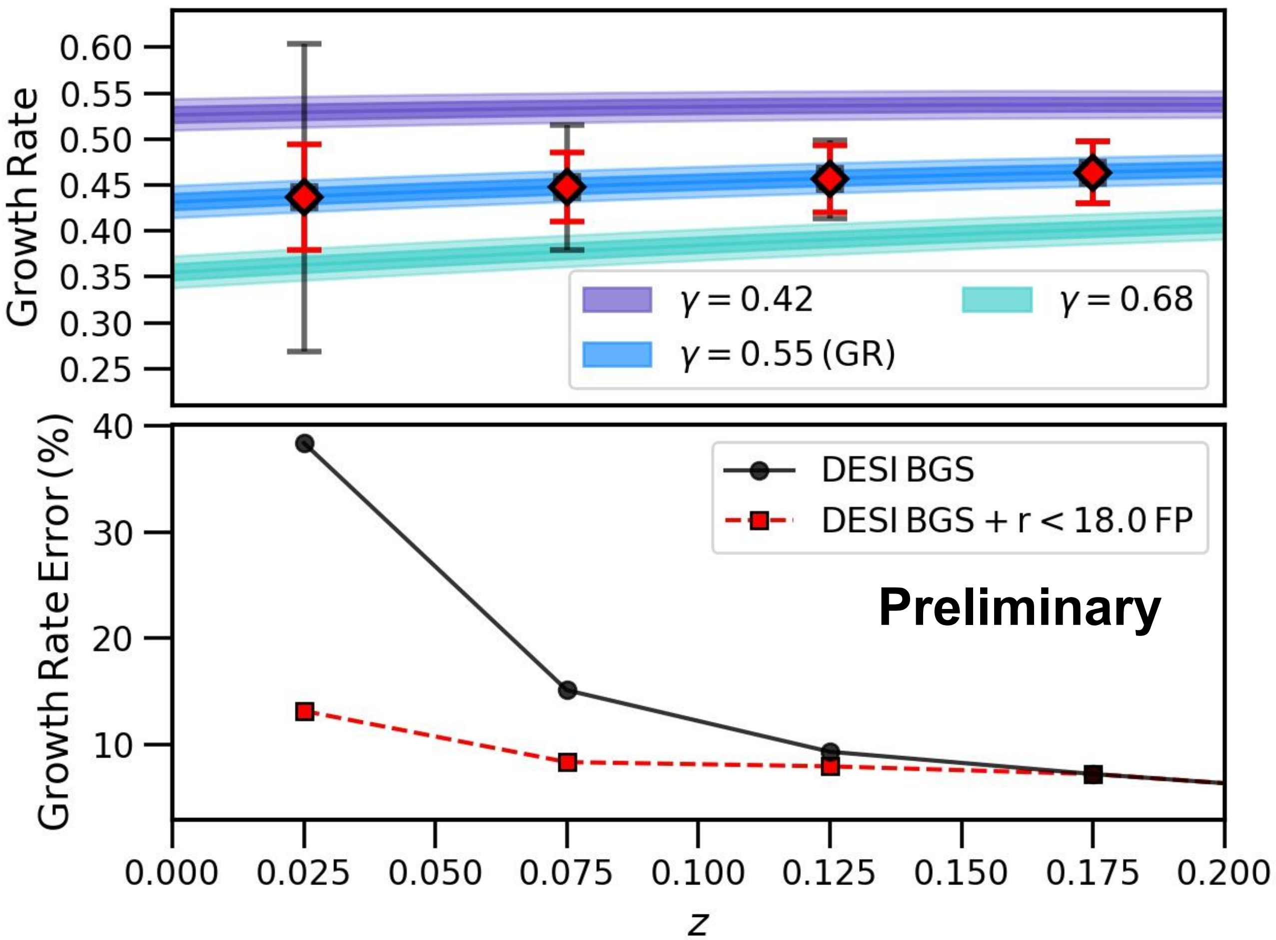
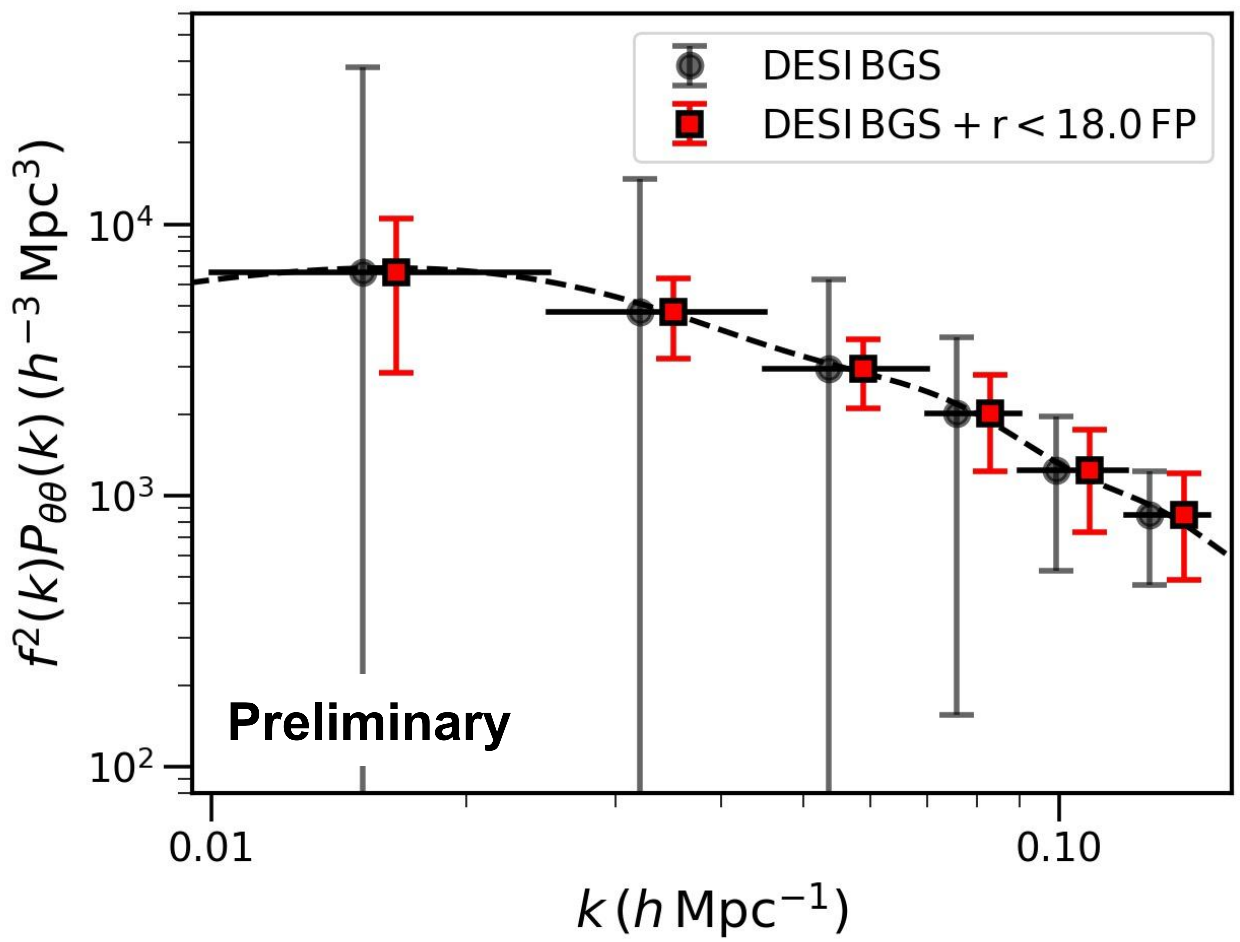


Figure 2: **Expected number of DESI peculiar velocity measurements as a function of redshift**. This is compared to peculiar velocities from 6dFGSv and SDSS which are currently the largest single catalogues available.

Primary Science:

The DESI PV survey addresses a key science goal of DESI by precisely measuring the time and scale dependence of the growth rate of structure, augmenting DESI BGS.





from a presentation by C. Howlett

Conclusions

- Peculiar velocities are a powerful probe of the growth of structure and the gravity that drives that growth
- SN Ia PV occupy the low-z niche where there is with CMB there is leverage to test theories and galaxy surveys are limited
- Enabled by planned powerful imaging surveys that produce competitive number of $z<0.2$ SN Ia discoveries
- Complete followup requires
  - ~1, 2m-class telescopes for follow-up spectroscopy for $z<0.08$
  - plus ~7, 4m-class telescopes for $z<0.2$
  - the right instruments on those telescopes
- International community can participate in the Snowmass process
  - https://snowmass21.org/