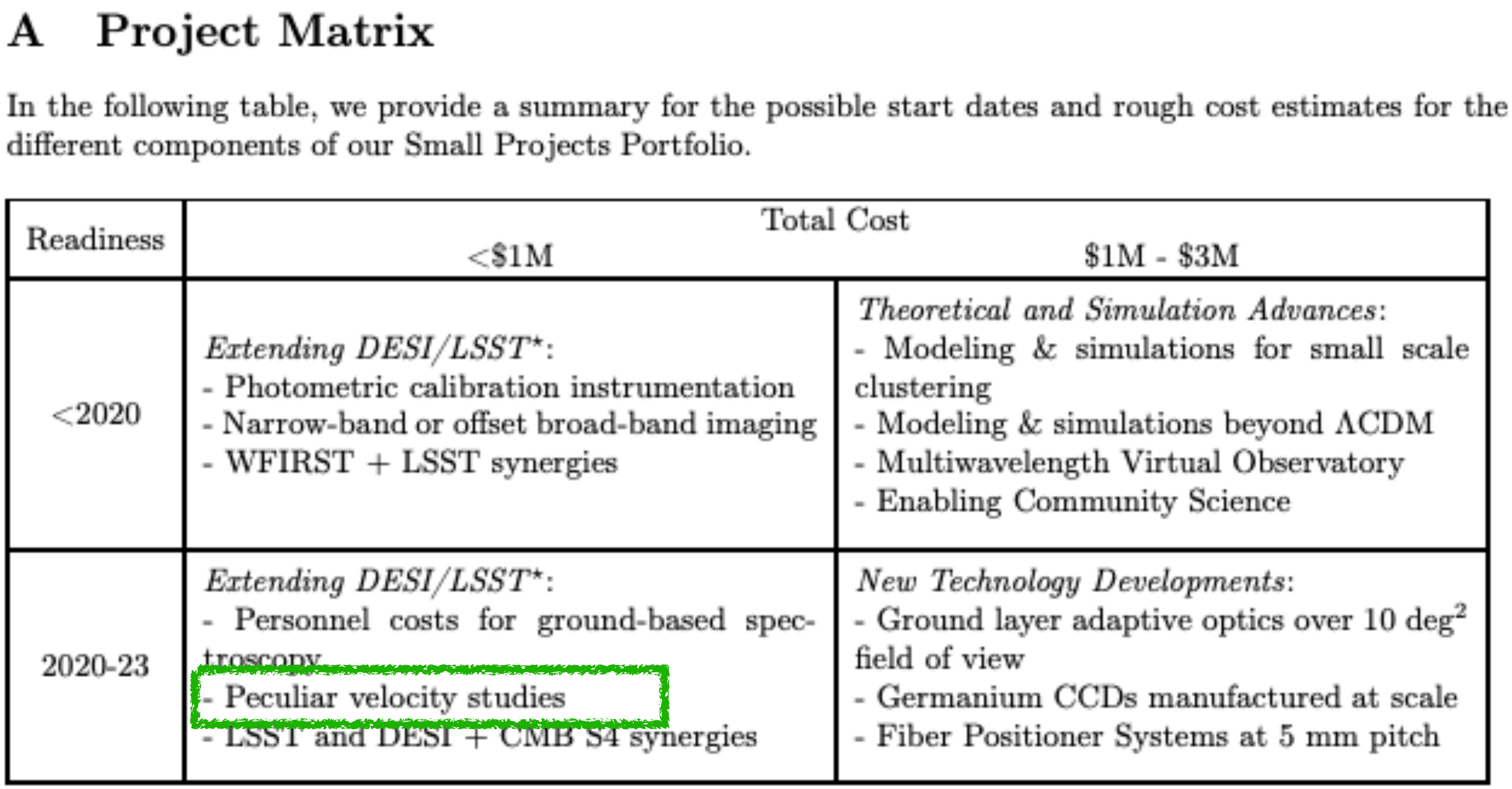
Opportunities for Peculiar Velocity Surveys Using DESI, ZTF-II, and the Vera C. Rubin Observatory

Alex Kim
LBNL

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.

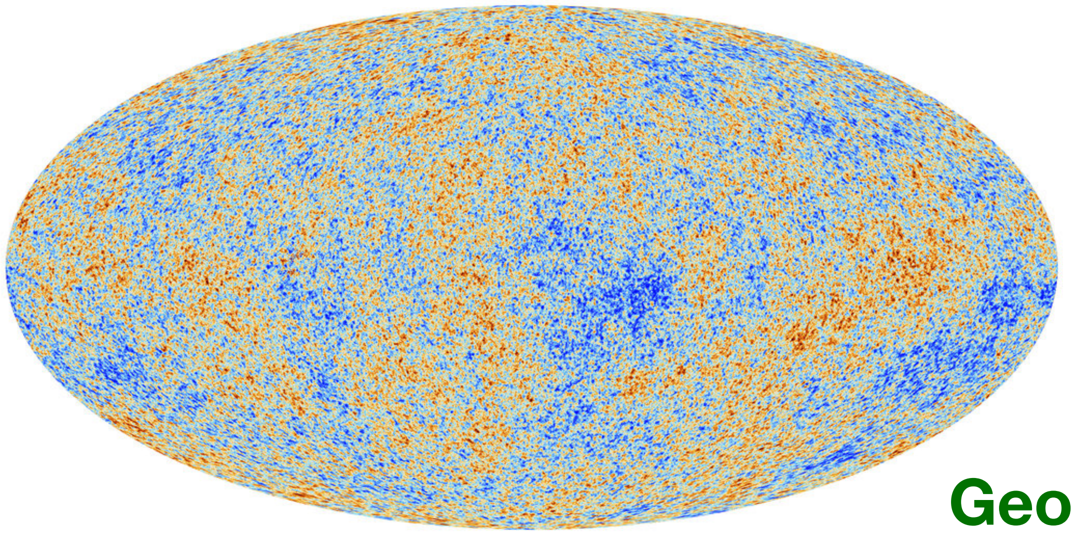
Readiness	Total Cost	
	<$1M	$1M - $3M
<2020	*Extending DESI/LSST**: - Photometric calibration instrumentation - Narrow-band or offset broad-band imaging - WFIRST + LSST synergies	*Theoretical and Simulation Advances*: - Modeling & simulations for small scale clustering - Modeling & simulations beyond 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)

Start with something familiar to LBL: galaxy redshift surveys

Galaxy Positions Probe Dark Energy and Gravity

Energy density fluctuations
CMB, z~1100



Amplitude and clumpiness of density fluctuations precisely measured by Planck

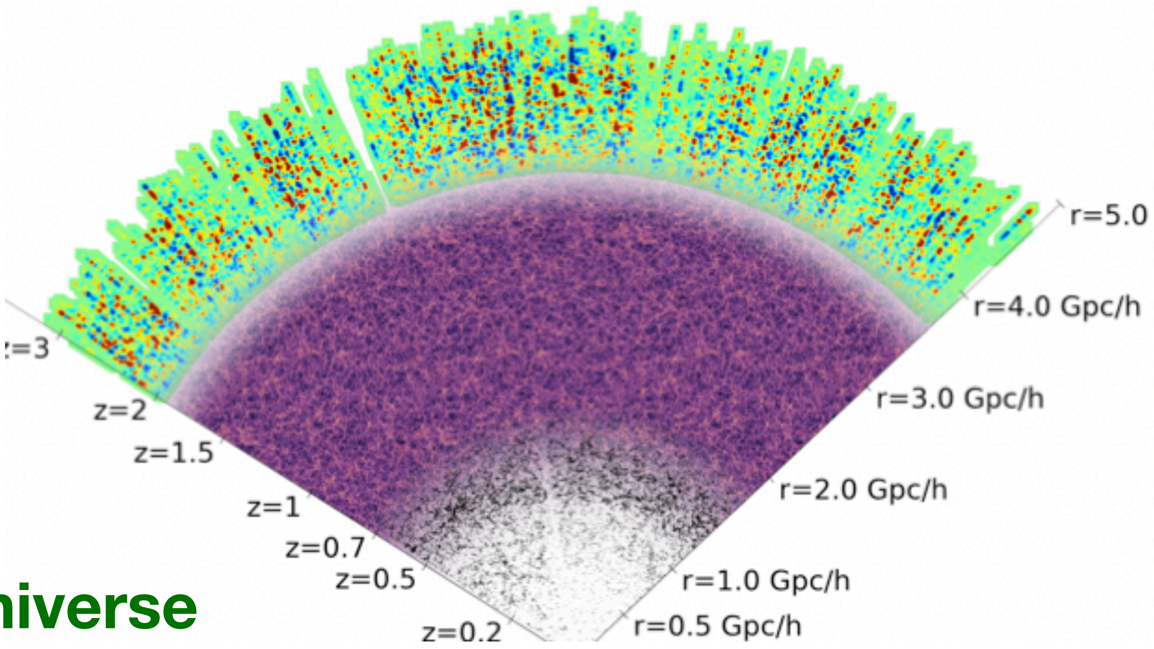
Gravity

→

Background Expansion

Geometry of the Universe

Galaxy positions
0<z<3

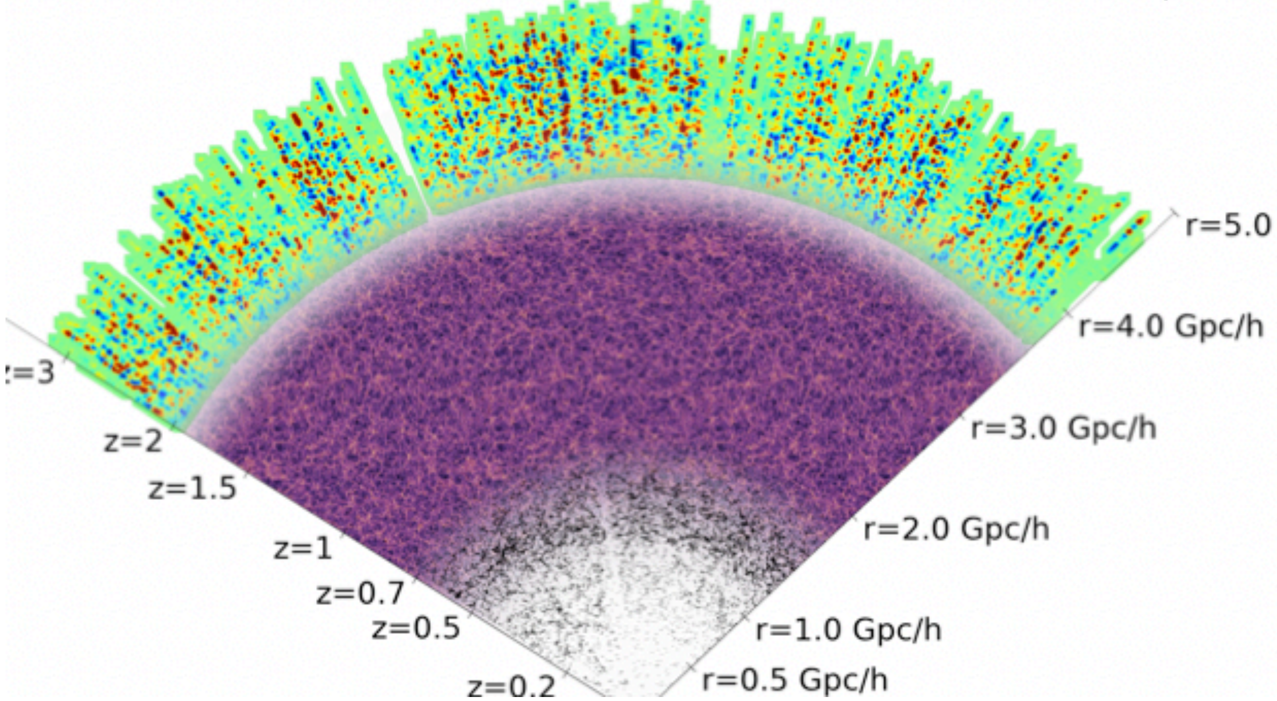


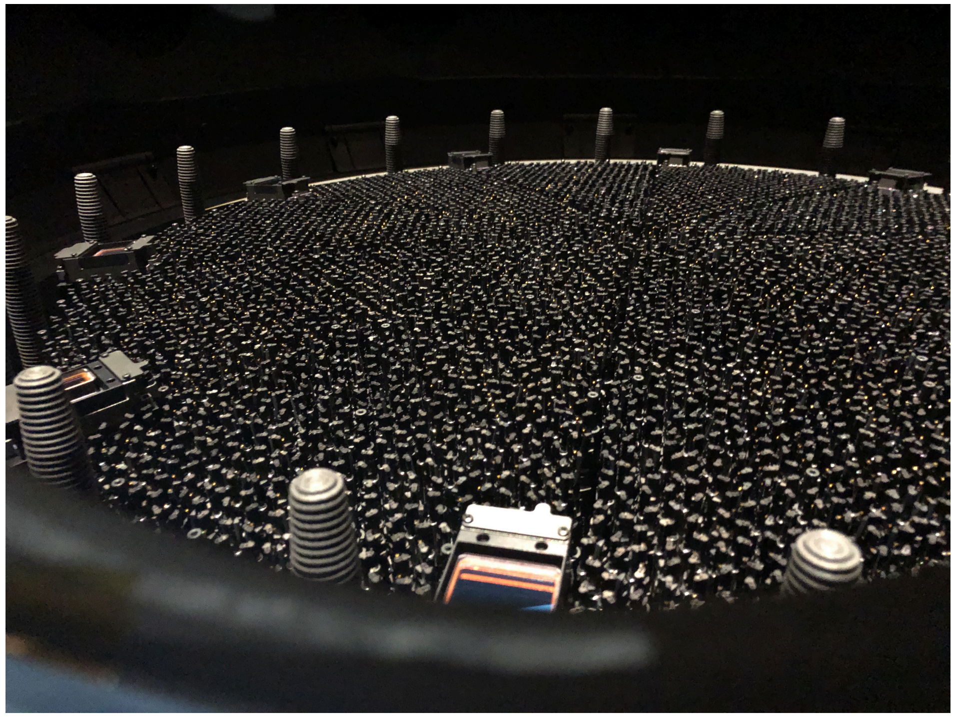
Amplitude and clumpiness of galaxy positions measured by galaxy surveys

Galaxy Positions Probe Dark Energy and Gravity — Hence DESI

KPNO 4m telescope

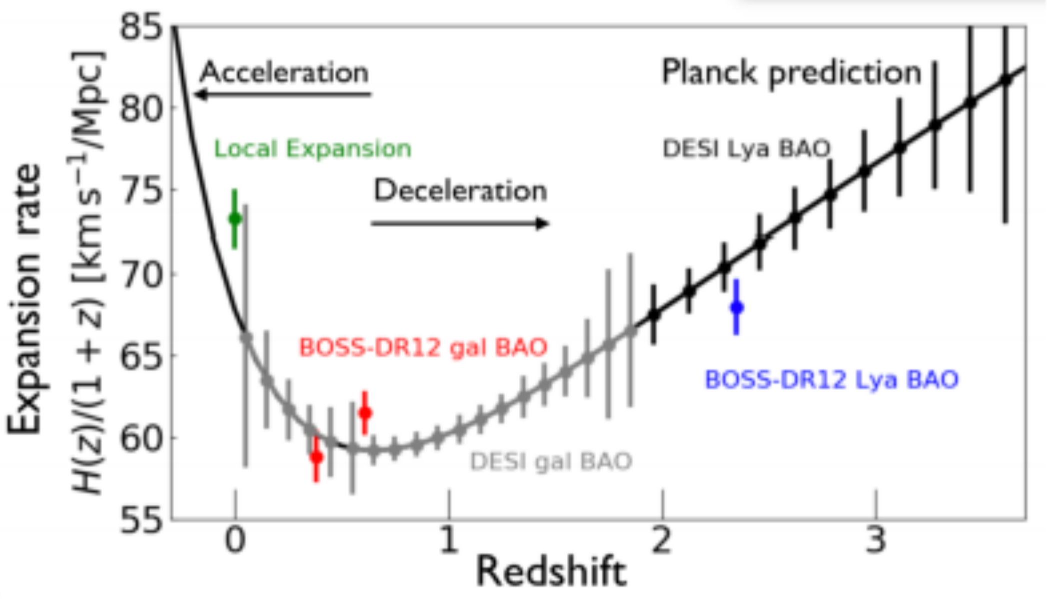
Redshift survey





DESI multiobject spectrograph

Cosmology



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

Two Ways to Observe the Effect of Peculiar Velocities

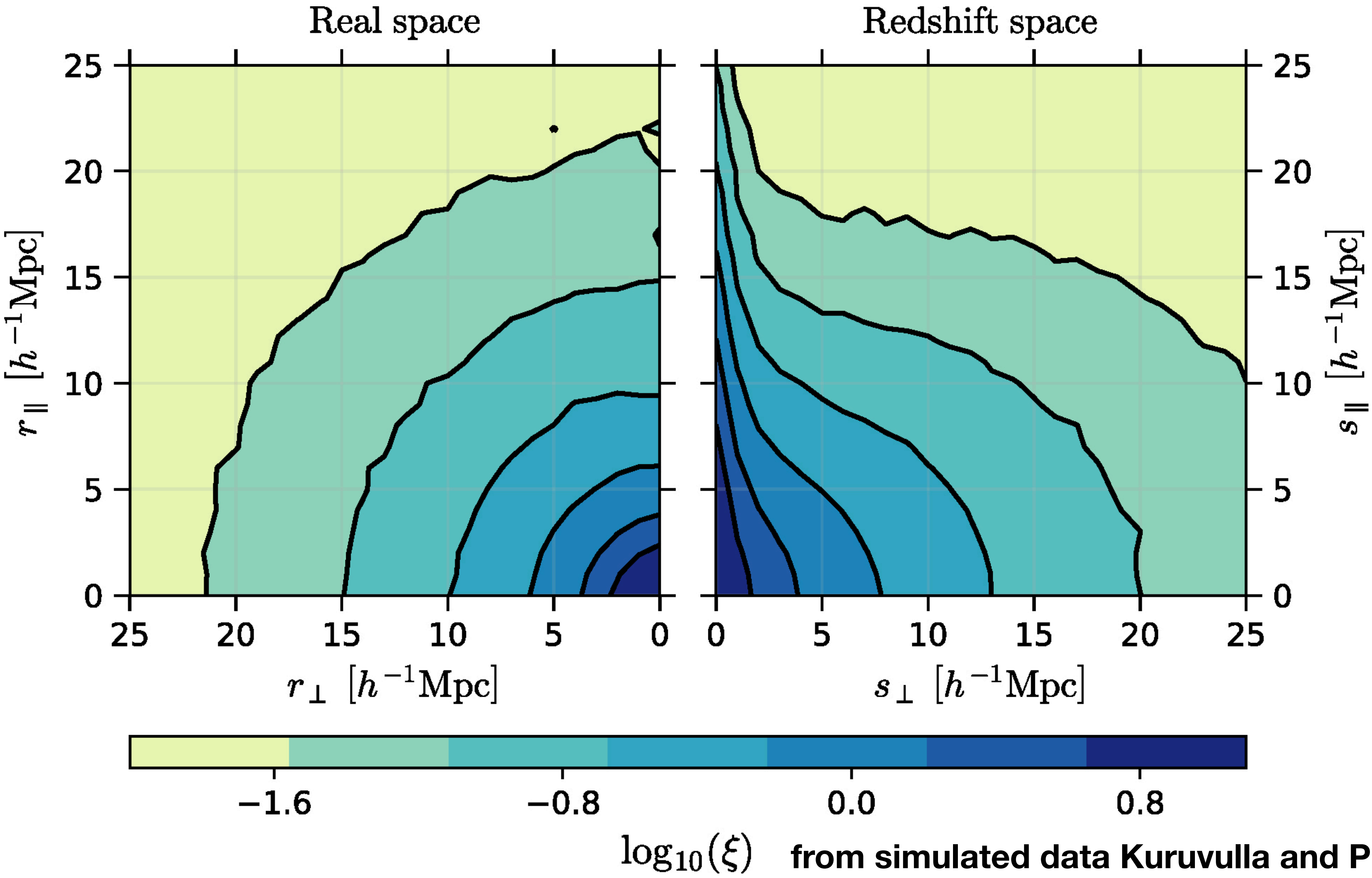
Can’t directly measure peculiar velocities since its signal is mixed in with cosmological redshift

- Redshift Space Distortions (RSD)
  - Compare contaminated radial distance (redshift) with uncontaminated perpendicular distance (angles)
- “Peculiar Distances” or “Peculiar Magnitudes”
  - Independent measure of cosmological redshift

Redshift Space Distortions

Universe is isotropic: Correlations in galaxy positions depend on separation but not direction

Velocity contamination in the radial distance but not in the transverse direction distorts the symmetry



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

Redshift Space Distortions

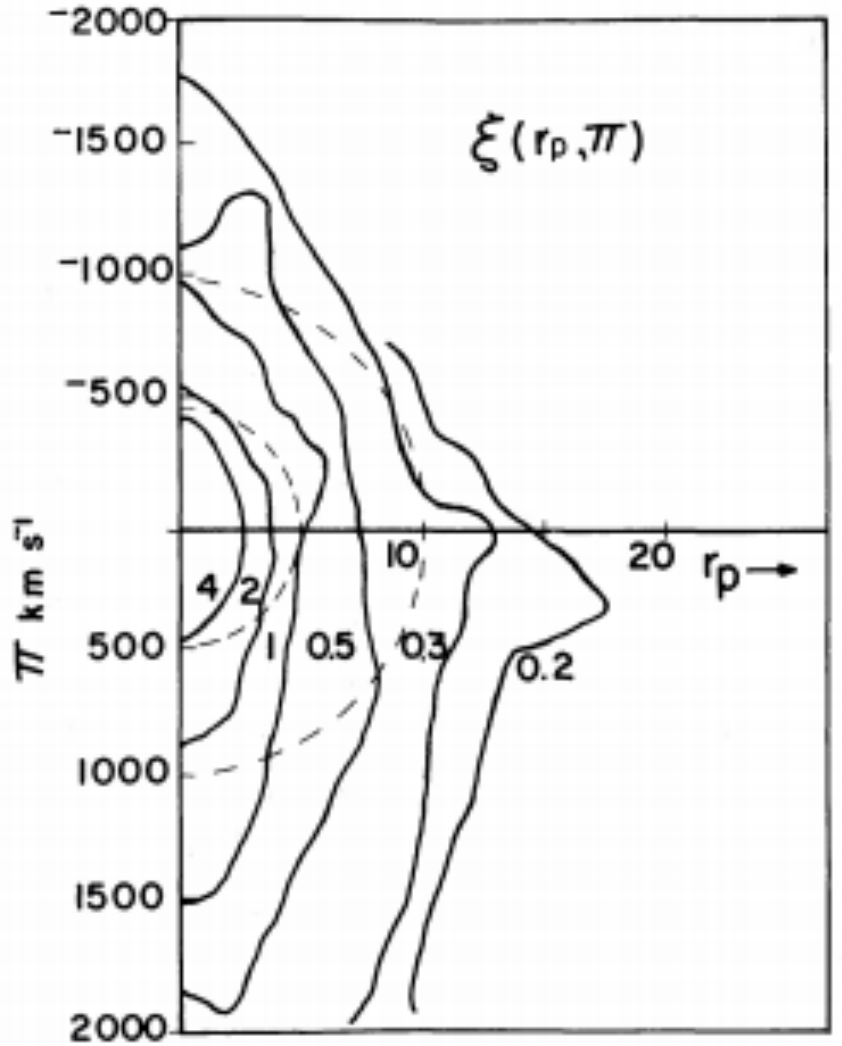
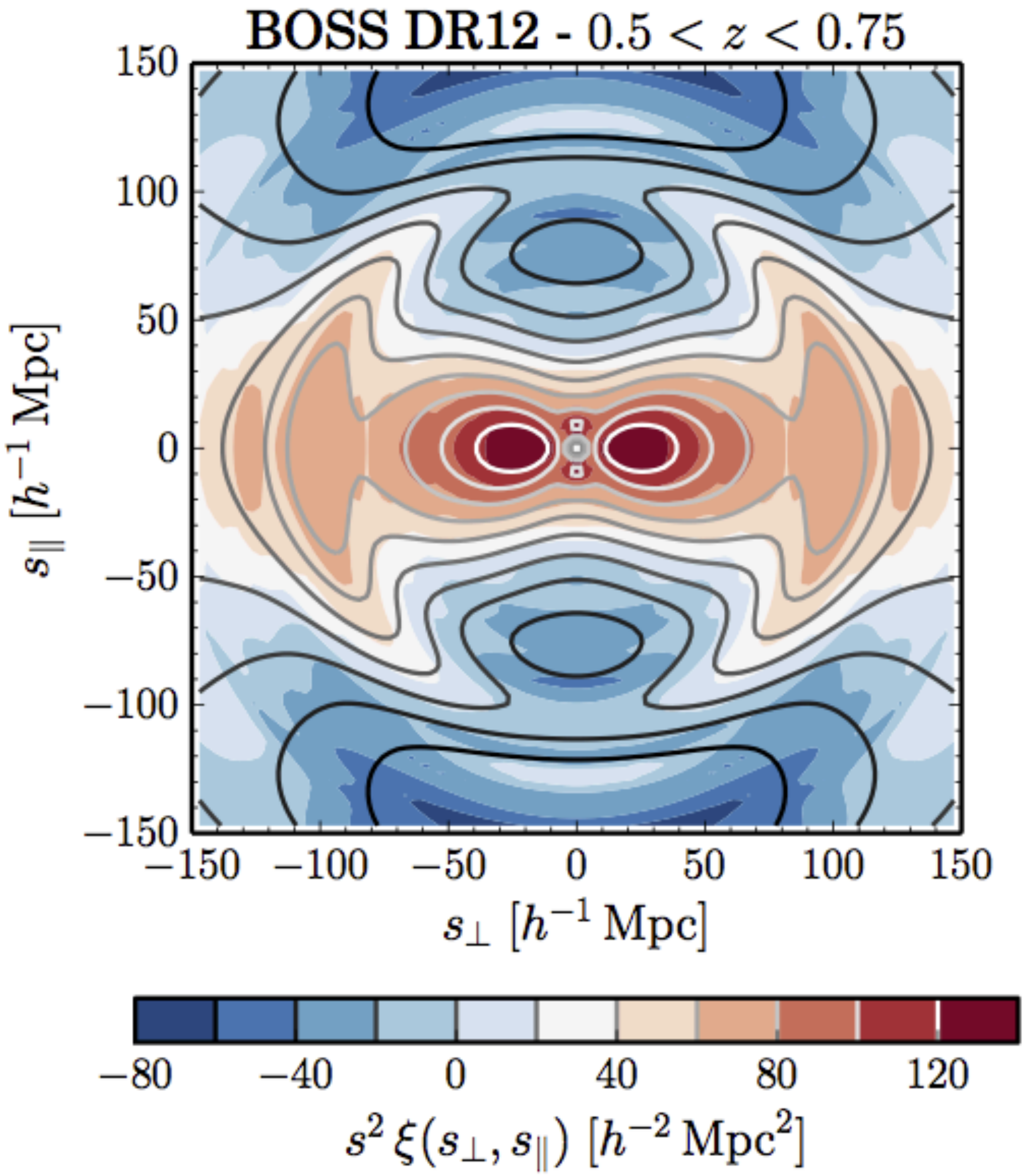


FIG. 4.—The two-point correlation as a function of separations r_p and π perpendicular and parallel to the line of sight. The lines are contours of fixed $\xi(r_p, \pi)$. The dashed semicircles show the expected shape of the contours if peculiar velocities were negligible.

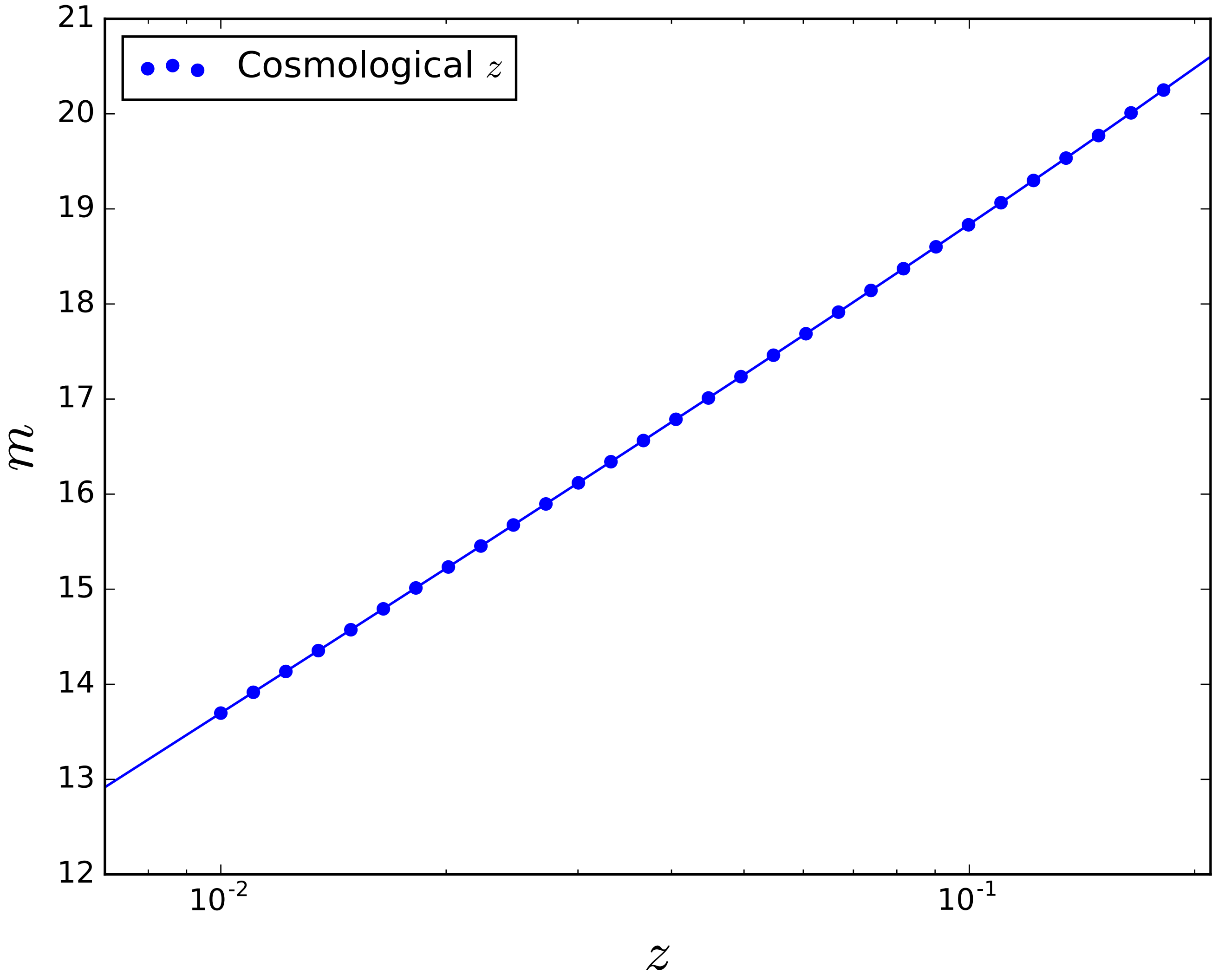
Davis & Peebles (1983)



Alam et al. (2006)

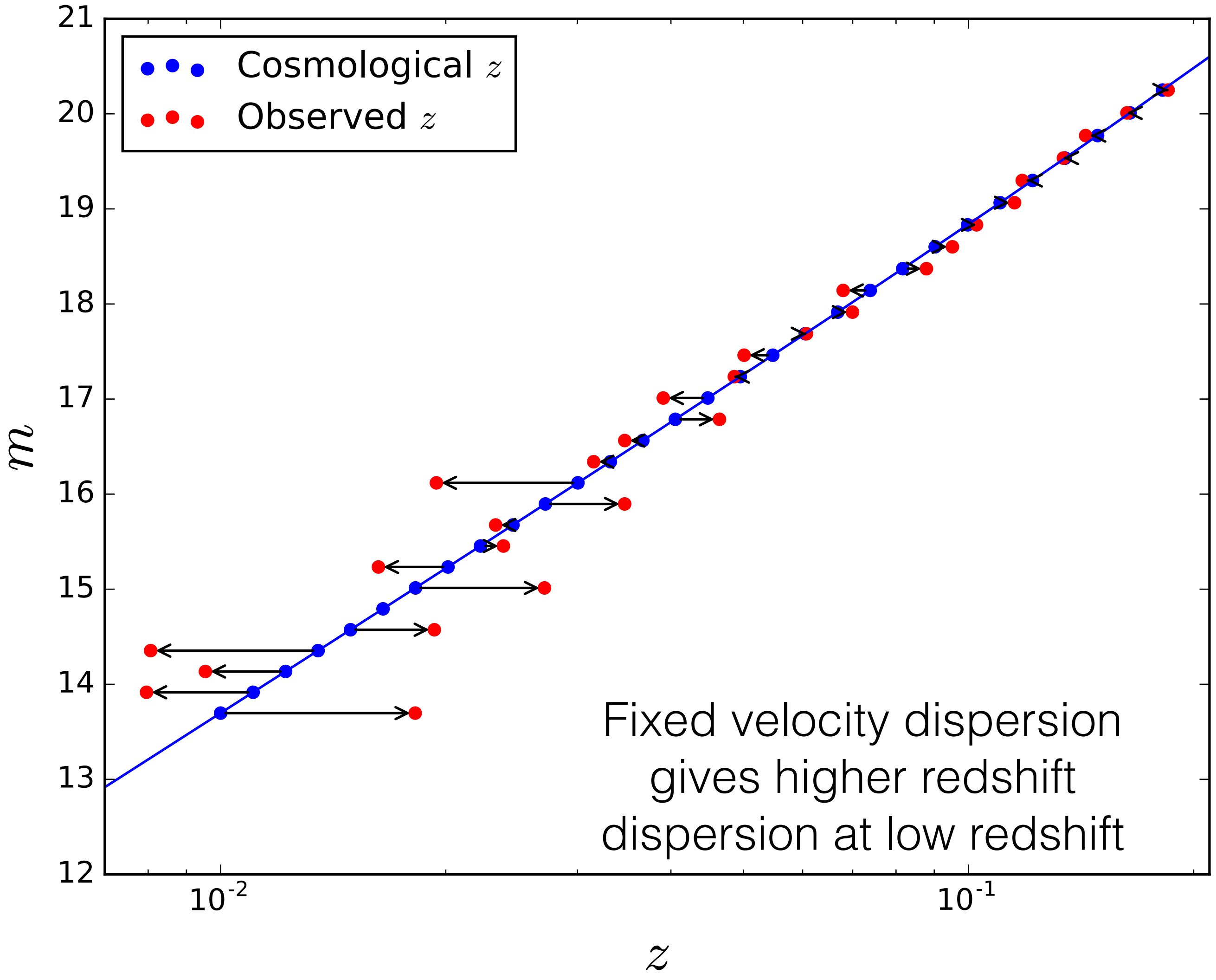
Peculiar Distances / Peculiar Magnitudes

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

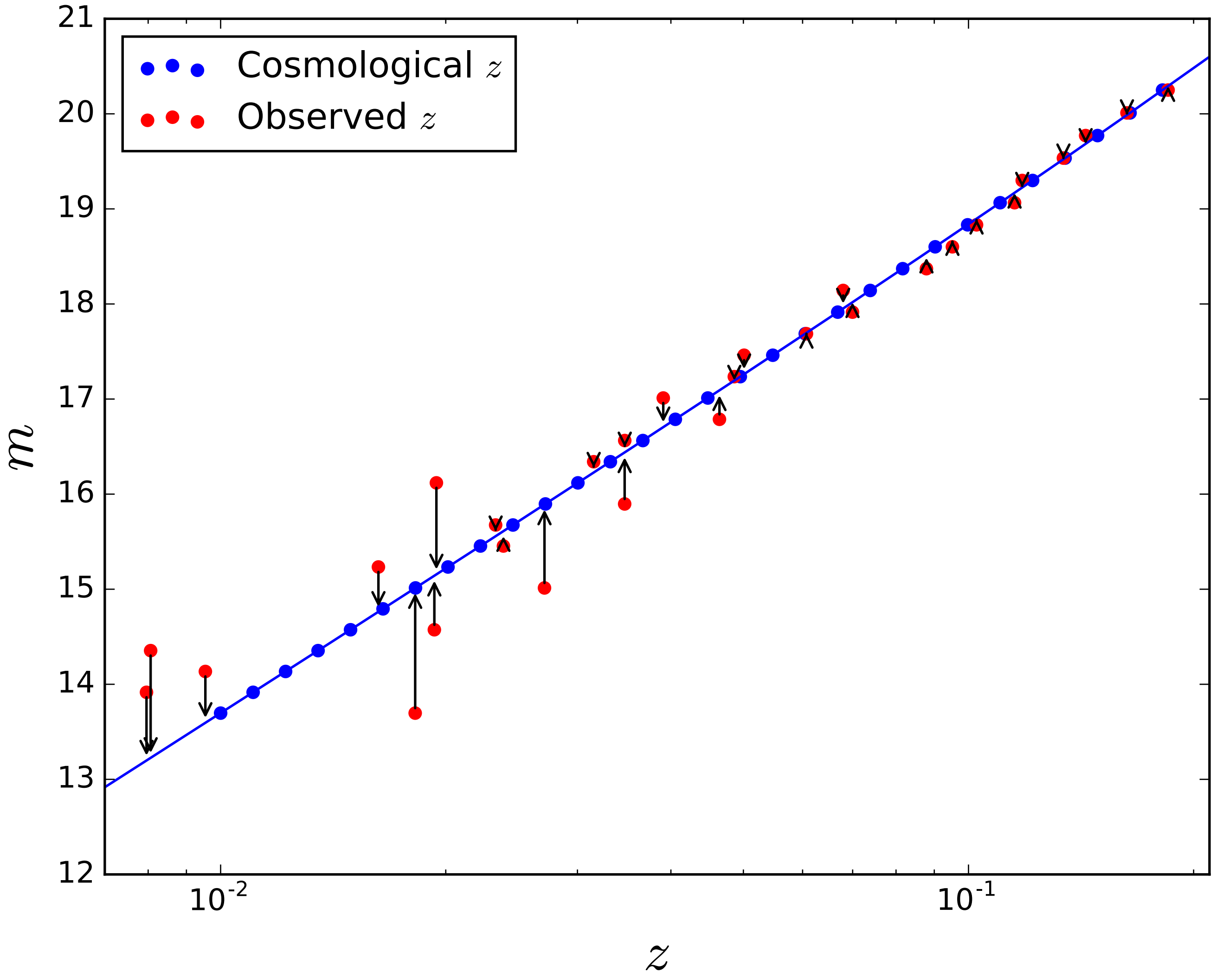


- Perfect standard candles with motion relative to the Hubble flow do not lie on nominal distance-redshift relationship when using the observed redshift

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

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

Interpreting Observed Redshift as Cosmological Redshift: Peculiar Magnitude



- Redshift offset can be equivalently described as a peculiar magnitude offset
    - Usually redshift errors are “negligible”

Connecting peculiar velocities to physics

Peculiar Velocities Related to Energy Overdensities and Gravity

- Contents of the universe described by the equations of fluid dynamics for an expanding system

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

Conservation of Mass

$$\frac{\partial a\mathbf{v}}{a\partial \tau} + \mathbf{v} \cdot \nabla \mathbf{v} = -\nabla \phi$$

Momentum-Force

$$\nabla^2 \phi = \frac{3}{2}\Omega_M H^2 a^2 \delta.$$

Gravitational Potential

Connection between density overdensities and peculiar velocities

Evolution of density overdensities and peculiar velocities depend on gravity

Peculiar Velocities Related to fD Related to Gravity

Solution is straightforward in the linear regime:

$$\frac{\partial^2\delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial\delta}{\partial t} = 4\pi G\rho_M\delta$$

$$\delta(\mathbf{x},t) = D(t)\delta(\mathbf{x})$$

$D(t)$**:** "linear growth factor"

$f(t) \equiv \frac{d\ln D}{d\ln a}$**:** "growth rate"

Evolution of D(t) depends on gravity

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

$$f = \Omega_M^\gamma$$

$$fD = \Omega_M^\gamma \exp\left(\int_a^1 \Omega_M^\gamma d\ln a\right)$$

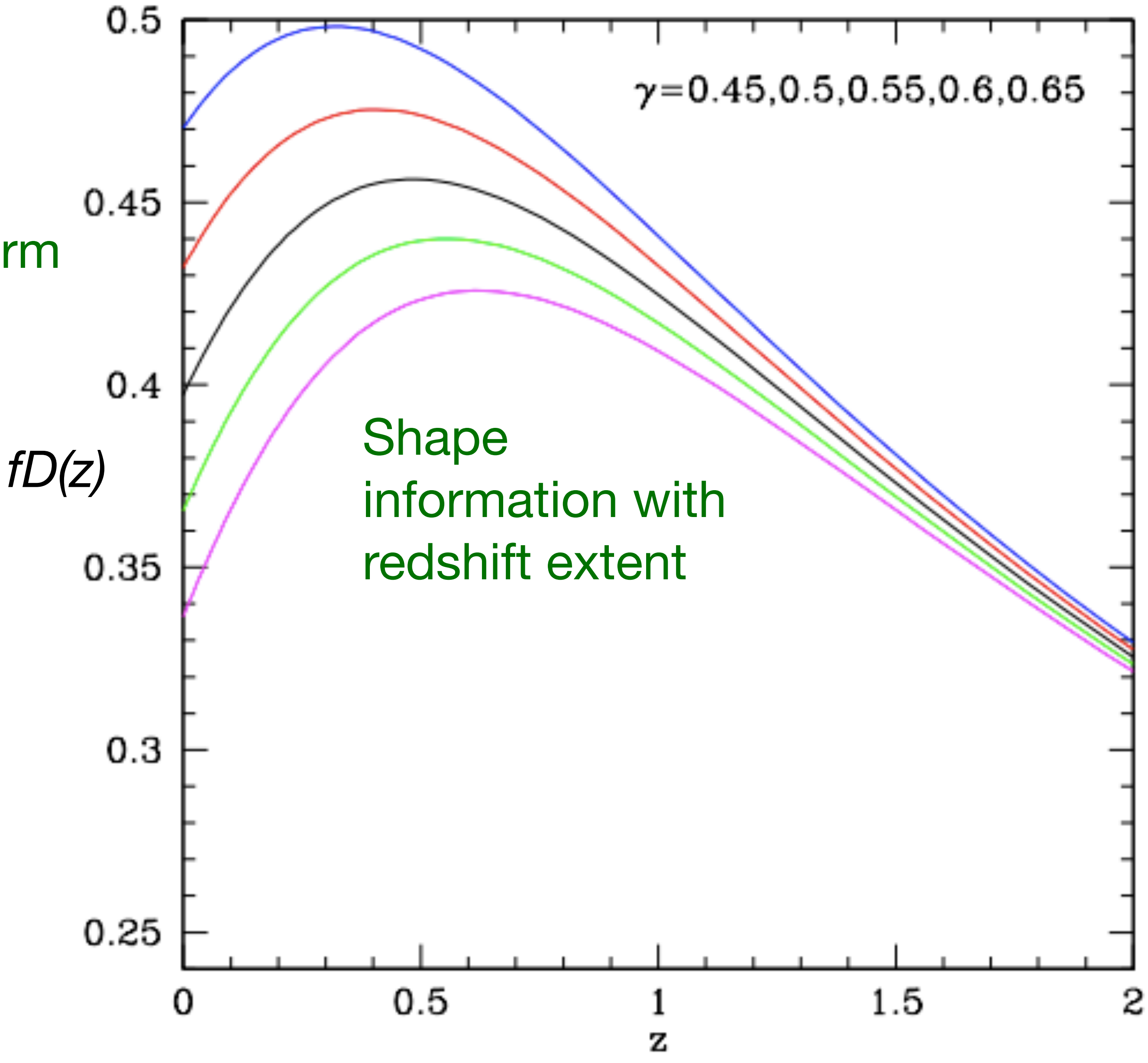
γ: growth index

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 Δγ=0.13

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



Lever-arm at low redshift

Shape information with redshift extent

Linder (2013)

Remark on D and σ_8

- In linear theory $\sigma_8(z)$ is equivalent to $D(z)$ and a normalization convention
  - D used in presenting theory, σ_8 in reporting measurements
- $f\sigma_8$ projections presented later are really fD projections and do not capture non-linear richness of σ_8

Connecting Galaxy Survey and Peculiar Velocity Fields Gives fσ_8

Conservation of mass (continuity equation)

$$Haf\delta(\mathbf{x}) + \nabla \cdot \mathbf{v}(\mathbf{x}) = 0$$

$$Ha\frac{f}{b}\delta^g(\mathbf{x}) + \nabla \cdot \mathbf{v}(\mathbf{x}) = 0$$

Direct comparison of the two fields in the same volume gives β=f/b

Measure the clustering of galaxies on 8h^{-1} Mpc scales gives $\sigma_{8,g}$

$$\beta\sigma_8^g = \frac{f}{b}(b\sigma_8) = f\sigma_8$$

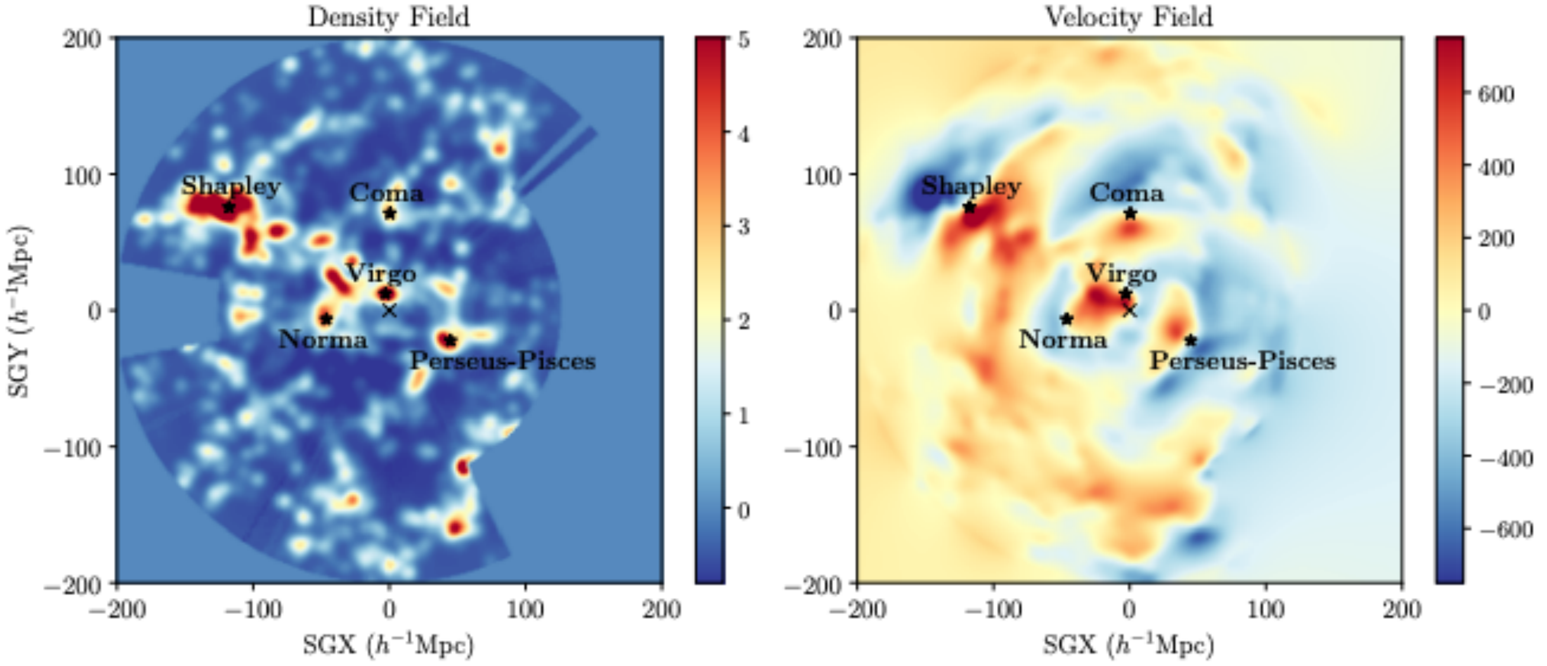
Direct Comparison Between Galaxy Density and Velocity Fields

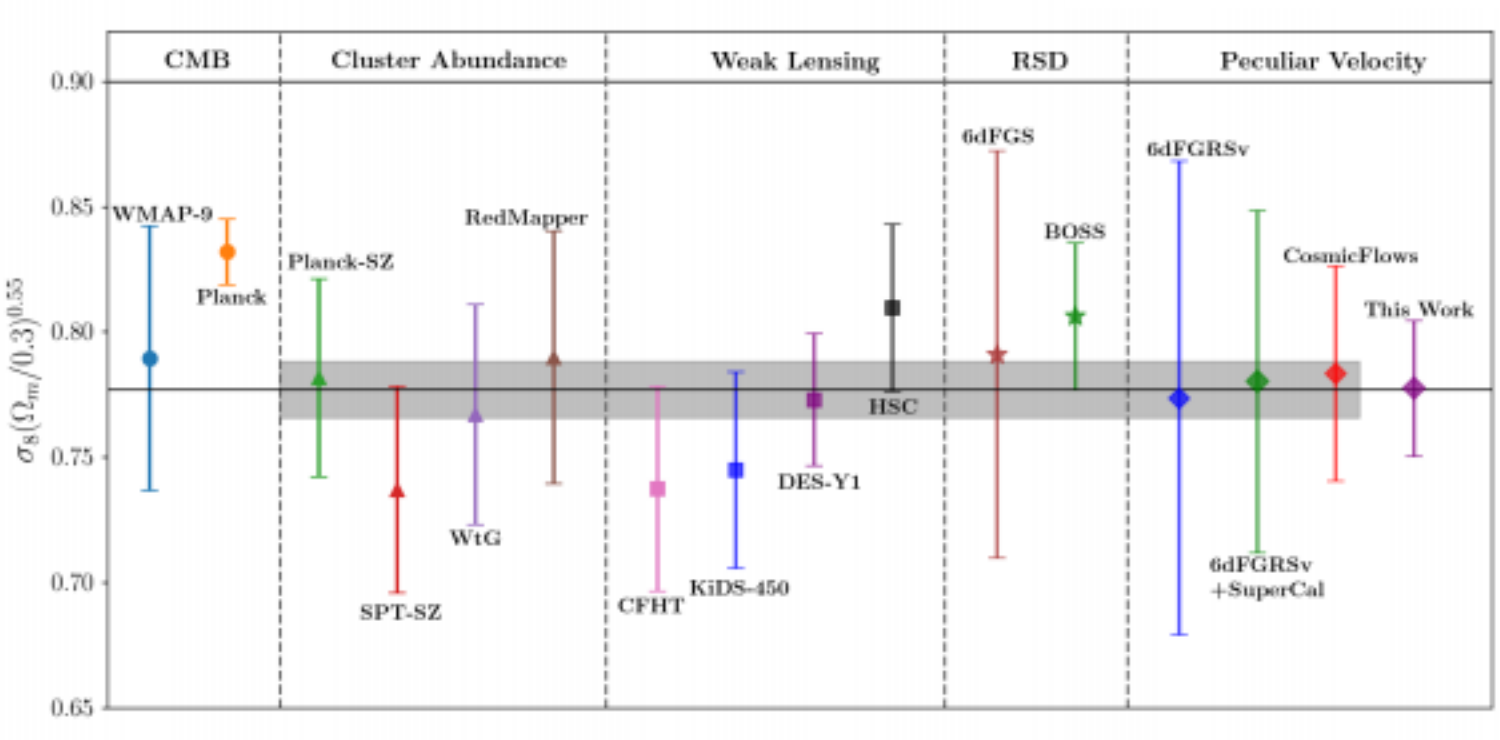
Direct comparison in Fourier space of the two fields gives …

$$\delta^g(\mathbf{k},x) \approx b\,\delta(\mathbf{k},x)$$

l.o.s. $v(\mathbf{k},x) = \dfrac{i\mu}{k} aHf\,\delta(\mathbf{k},x)$

$$\beta = \frac{f}{b}$$





… combined with galaxy clustering gives …

$$\beta\sigma_8^g = \frac{f}{b}(b\sigma_8) = f\sigma_8$$

Boruah, Hudson, and Lavaux (2019)

Connecting Galaxy Surveys, Peculiar Magnitudes With CMB Give *fD*

CMB and galaxy surveys occupy different volumes so their fields can’t be directly compared…

… but their clustering properties can be

$$\delta^s(\mathbf{k},x) \approx (b+f\mu^2)\delta(\mathbf{k},x)$$

$$v(\mathbf{k},x) = \frac{i\mu}{k} aHf\delta(\mathbf{k},x)$$

$$\longrightarrow$$

In linear theory

$$P_{\delta^g\delta^g}(a) \approx (b+f\mu^2)^2 D^2 P_{\delta\delta}(a_{\mathrm{CMB}})$$

$$P_{vv}(a) = \left(\frac{\mu}{k}\right)^2 (aHfD)^2 P_{\delta\delta}(a_{\mathrm{CMB}})$$

$$P_{\delta^g v}(a) = (b+f\mu^2)\frac{\mu}{k} aHfD^2 P_{\delta\delta}(a_{\mathrm{CMB}})$$

and for peculiar magnitudes

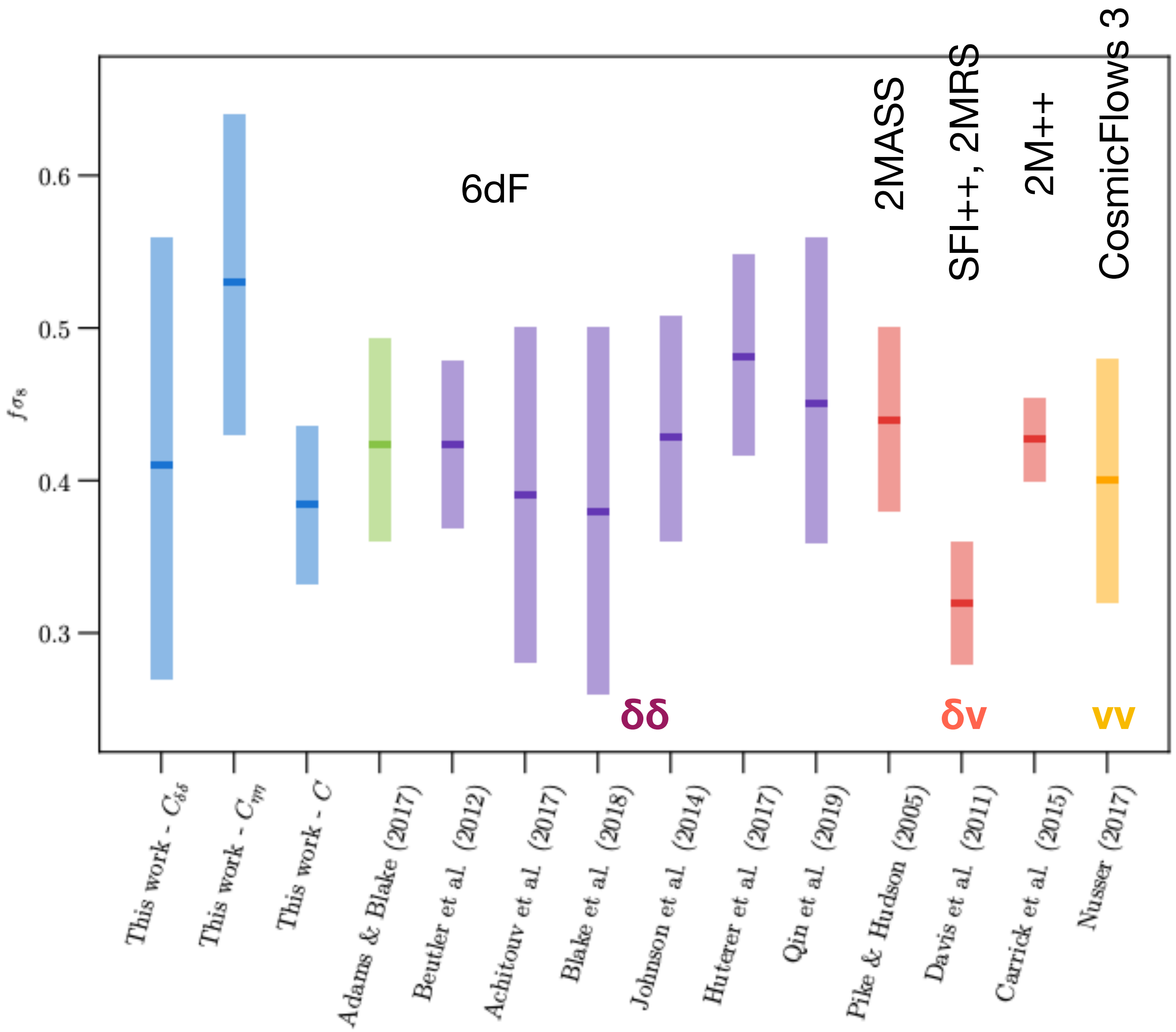
Note *H* replaced by d_L

“clean” *fD* dependence

$$P_{mm}(a) \approx \left(\frac{5}{\ln 10}\right)^2 \left(\frac{\mu}{k}\right)^2 \left(\frac{fD}{ad_L}\right)^2 P_{\delta\delta}(a_{\mathrm{CMB}})$$

Recent Results

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



Adams and Blake (2020)

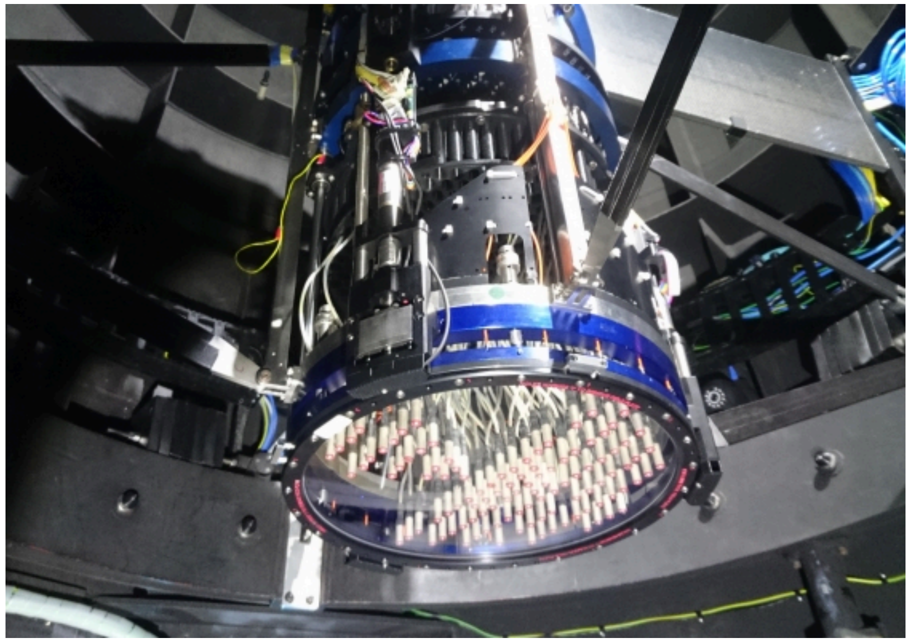
Galaxy Distance Probes

- 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

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

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

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

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

LSST 10-year

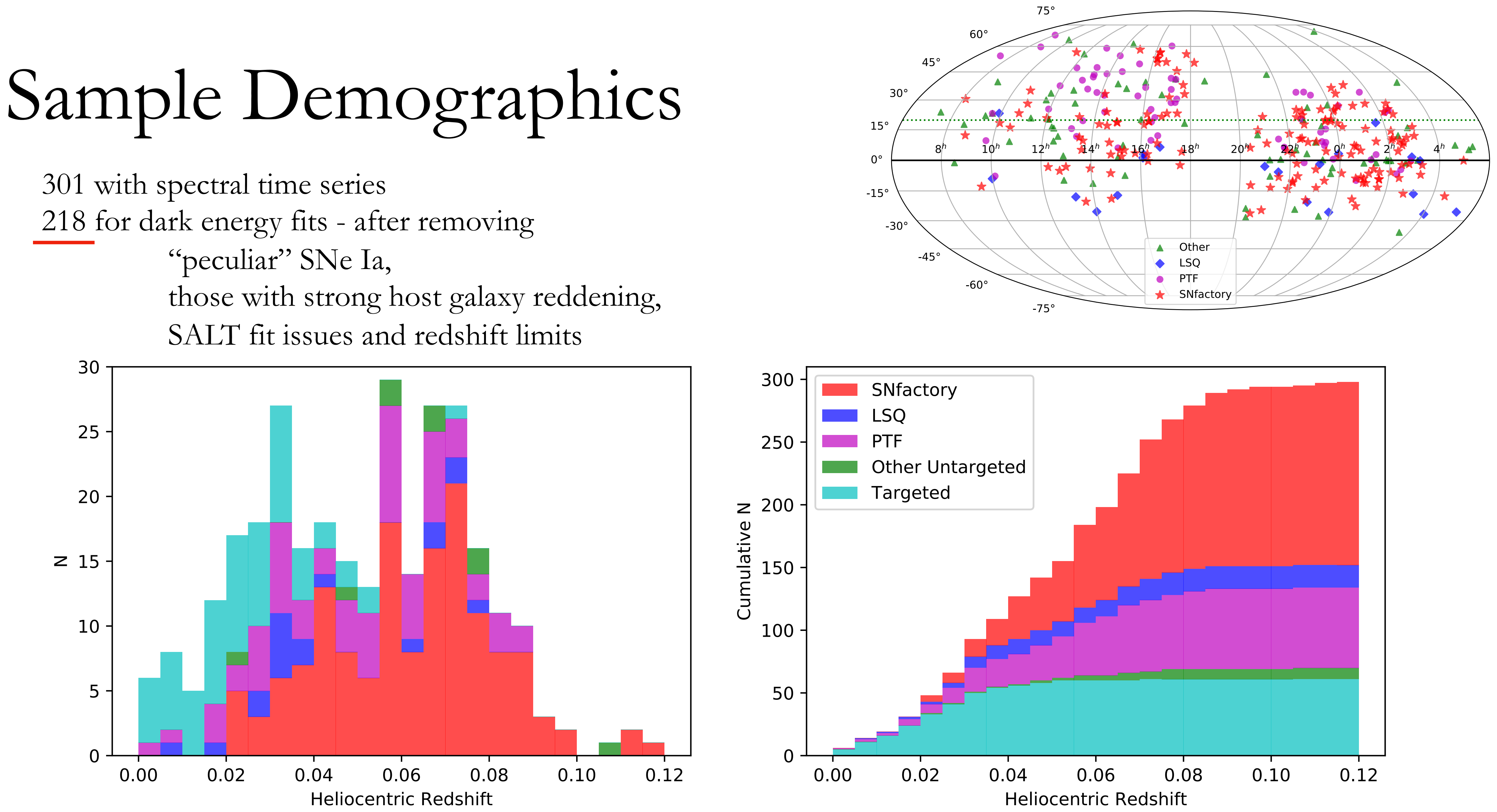
$$\frac{\sigma_m^2}{n} = \frac{0.08^2}{5 \times 10^{-4} h^3} [\mathrm{mag}^2\,\mathrm{Mpc}^3]$$
$$= 13 h^3 [\mathrm{mag}^2\,\mathrm{Mpc}^3]$$

Opportunities for LBL

Peculiar Magnitudes with SNfactory SNe

Cosmology analysis well advanced

Hubble residuals, i.e. peculiar magnitudes soon available



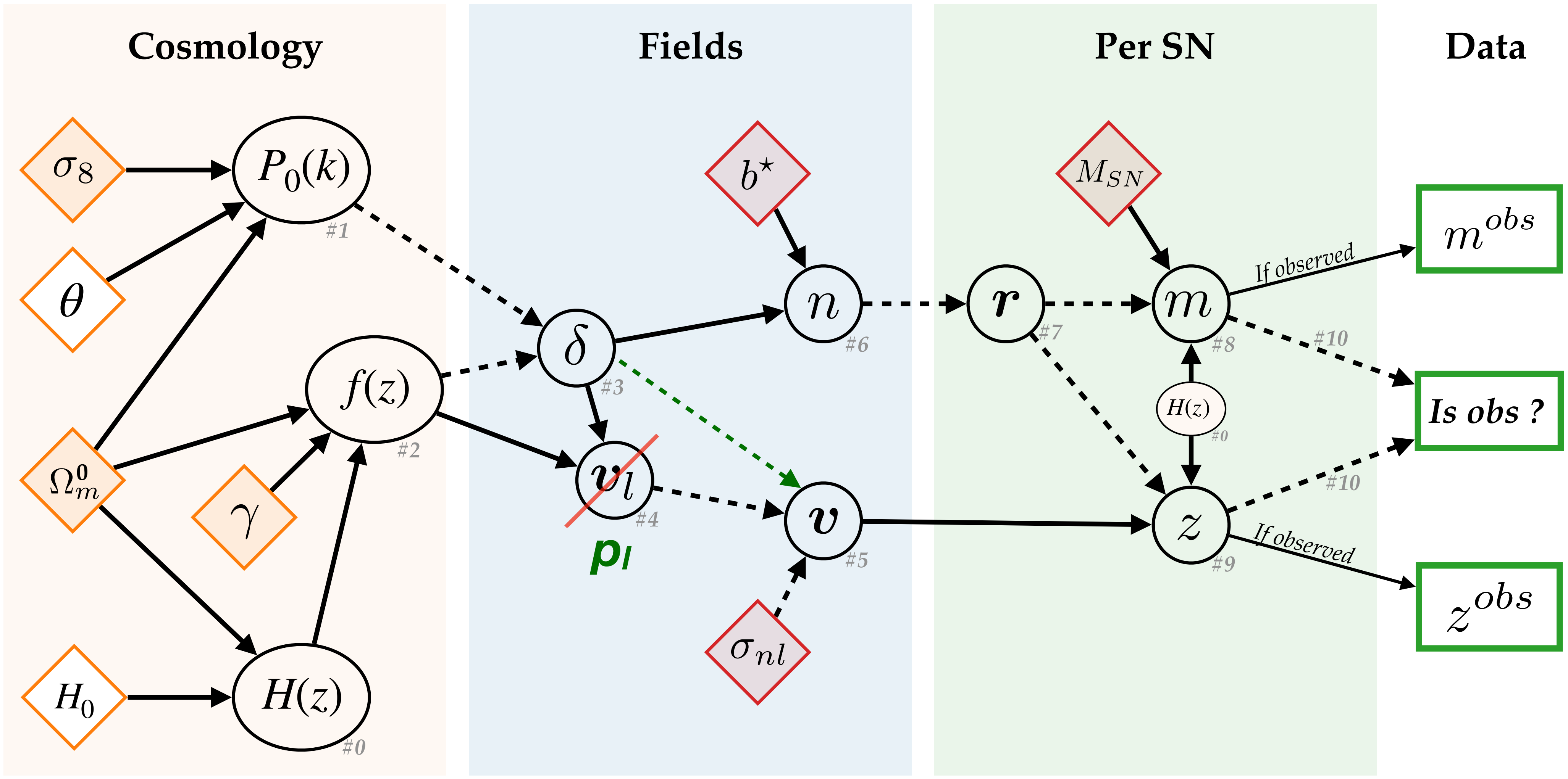
Sample Demographics

301 with spectral time series
218 for dark energy fits - after removing
“peculiar” SNe Ia,
those with strong host galaxy reddening,
SALT fit issues and redshift limits

from Aldering 2020

Hierarchical Analysis

Avoids of biases of some previous linear analyses ◀············



Parameters: ◇ Cosmo. Fitted ◇ Cosmo. Fixed ◇ Nuisance

Relations: → Predictive ⇢ Statistical

Equations: ○ #x

Observables: ▭

Graziani, Rigault, Kim, and Copin (in prep)

Hierarchical modeling with the Differentiable Universe Initiative (Lanusse, Hahn, Modi)
Beyond first order (e.g. Chen, Vlah & White 2020; Seljak & McDonald 2011)

DESI Surveys

Survey	Object Class	# of Targets	Redshift Range
Bright Galaxy Survey (BGS)	Bright Galaxies $r<19.5$	20M	$0<z<0.4$
Bright Galaxy Survey (BGS)	Milky Way Stars	10M	N/A
Main	Luminious Red Galaxies	4.2M	$0.4<z<1.0$
Main	Emission Line Galaxies	18M	$0.6<z<1.6$
Main	Quasars	2.4M	$0.5<z<3.5$

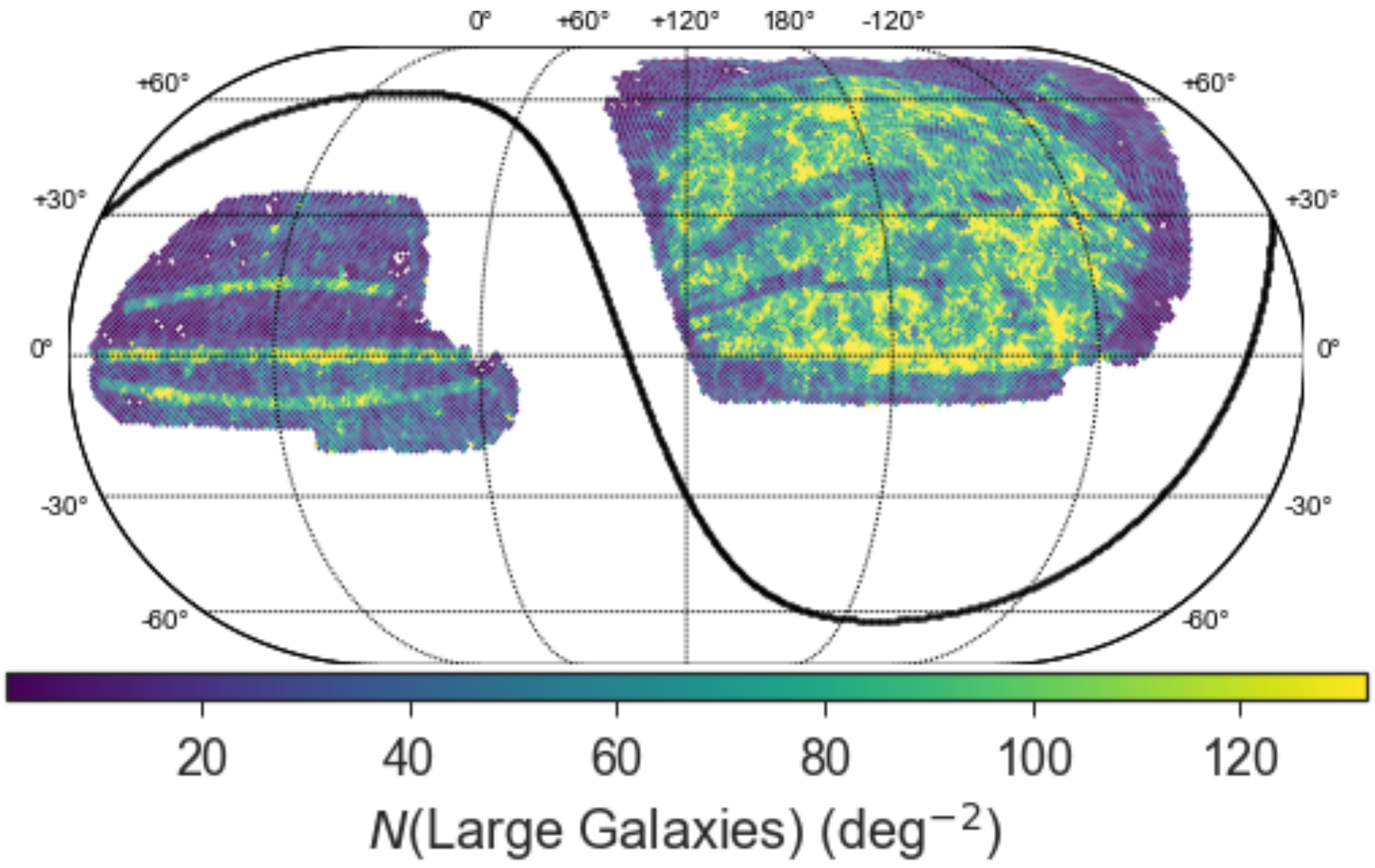
There is room for one more!

14k deg sq

Legacy Surveys Large Galaxy Atlas (LSLGA)

or the *NASA Legacy Surveys Atlas* (NLSA) if we had gotten funding!

Moustakas, Lang, Blanton et al., in prep.



Roughly 290k “known” galaxies with D(25)>20 arcsec assembled from Hyperleda.

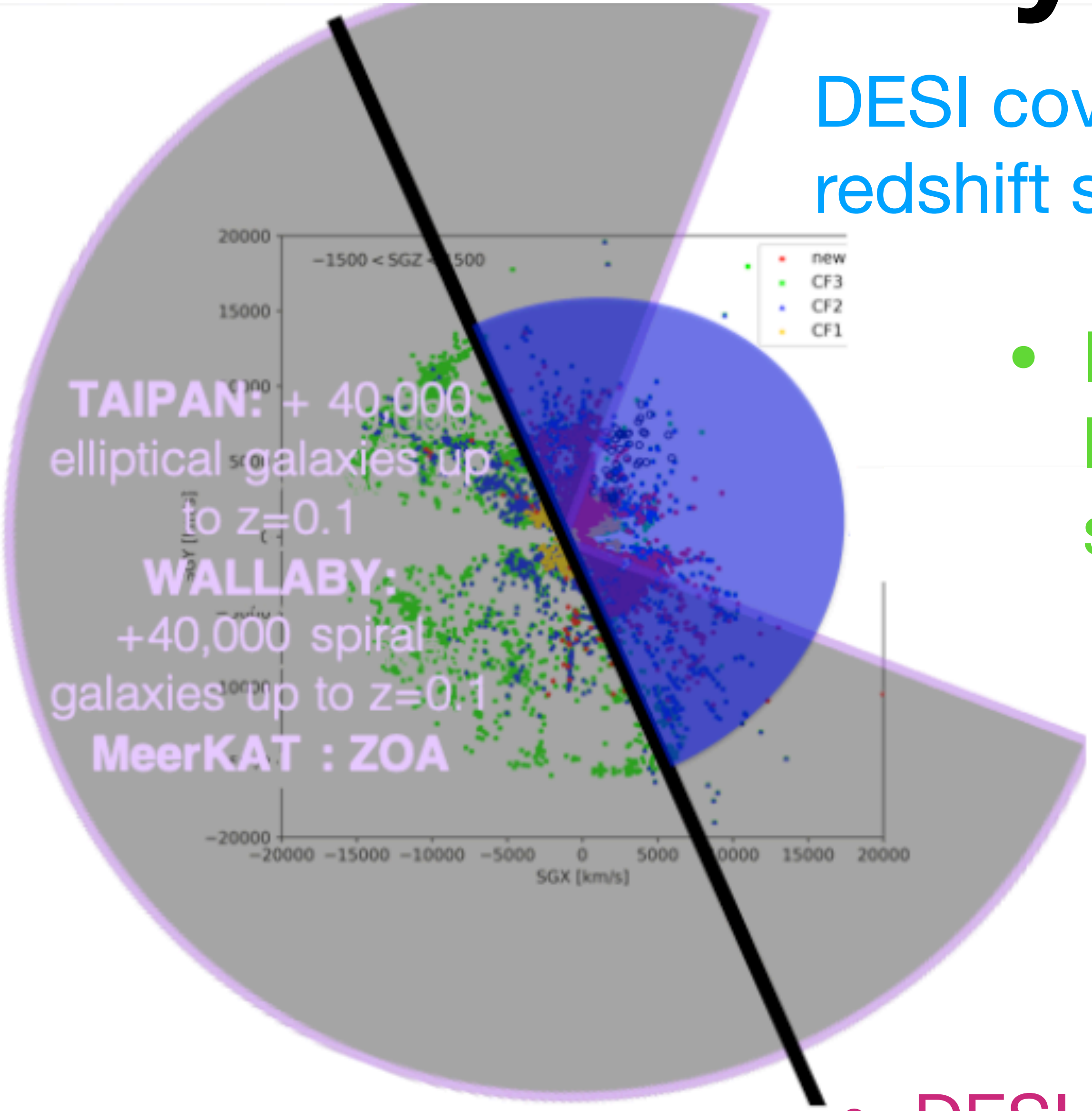
(comparable toTAIPAN and WALLABY!)

https://github.com/moustakas/LSLGA

/global/project/projectdirs/cosmo/staging/largegalaxies/v2.0

DESI as a Fundamental Plane AND Tully-Fisher Survey

DESI covers the North complement planned redshift surveys that cover the South



TAIPAN: + 40,000 elliptical galaxies up to z=0.1

WALLABY: +40,000 spiral galaxies up to z=0.1

MeerKAT : ZOA

figure from Courtois, Howlett

- DESI "Bright Galaxy Survey" magnitude r<19.5 limited survey — fainter than the TAIPAN i<17 survey
  - Photometry from DESI Legacy Imaging Surveys DR8 verified
  - BGS spectroscopy good enough? TBD
- DESI LSLGA (J. Moustakas)
  - Photometry optimized relative to Tractor DR8
  - Need to figure out where best to position fibers

DESI: SNe Ia from ZTF, ZTF-II

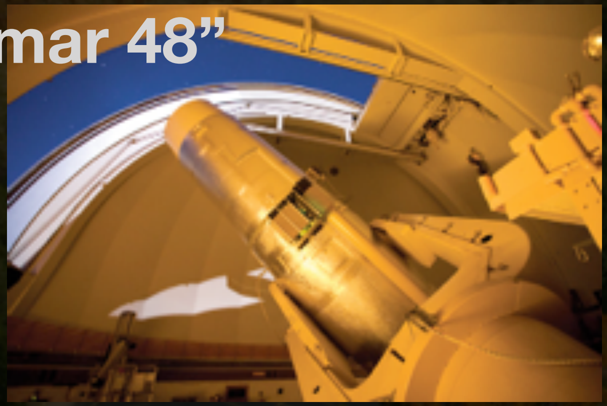
The ZTF Bright Transient Survey BTS

Magnitude limited survey, spectroscopically complete to 18.5 mag.

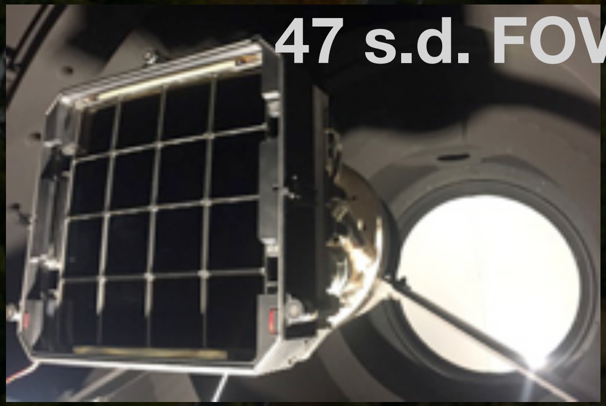
1. Catalog all SN candidates < 19 mag and send to the Transient Name Server
2. Classify all <18.5 mag SNe using mainly Palomar 60 inch with SEDM
3. Classify 19 to 18.5 mag sources selectively

Data from the public ZTF Northern Sky Survey

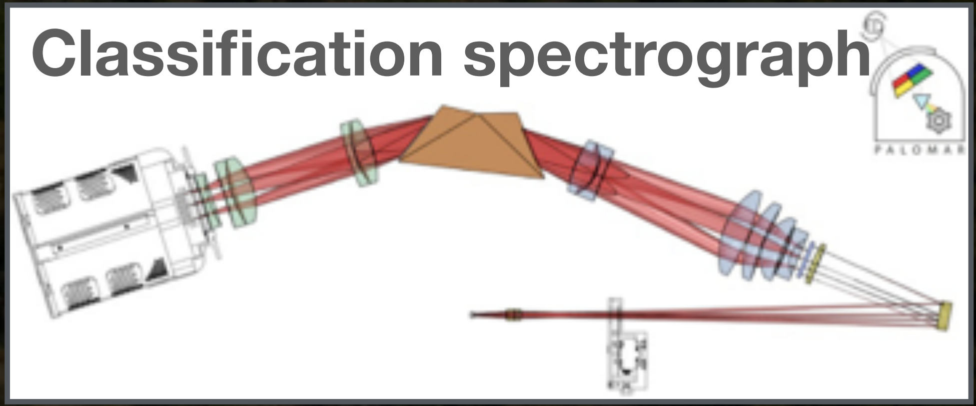
("Celestial Cinematography"; Bellm & Kulkarni, 2017, Nature Astronomy 1, 71)



Palomar 48”



47 s.d. FOV



Classification spectrograph

from Fremling

3 day cadence, Northern Sky in g & r filters

Classified SN Count (2018-2019)

m < 19 (incomplete)

2283 supernovae

- 1614 Ia
  - incl. 4 Iax
- 144 Ib/c
  - incl. 9 Ibn, 17 Ic-BL, 21 SLSN-I
- 509 II
  - incl. 44 IIb, 18 IIn, 18 SLSN-II

\+ 10 TDEs

\+ 14 "other" (ILRTs, FBOTs, LBVs)

m < 18.5 ("complete")

1557 supernovae

- 1111 Ia
  - incl. 3 Iax
- 96 Ib/c
  - incl. 9 Ibn, 15 Ic-BL, 10 SLSN-I
- 338 II
  - incl. 28 IIb, 53 IIn, 14 SLSN-II

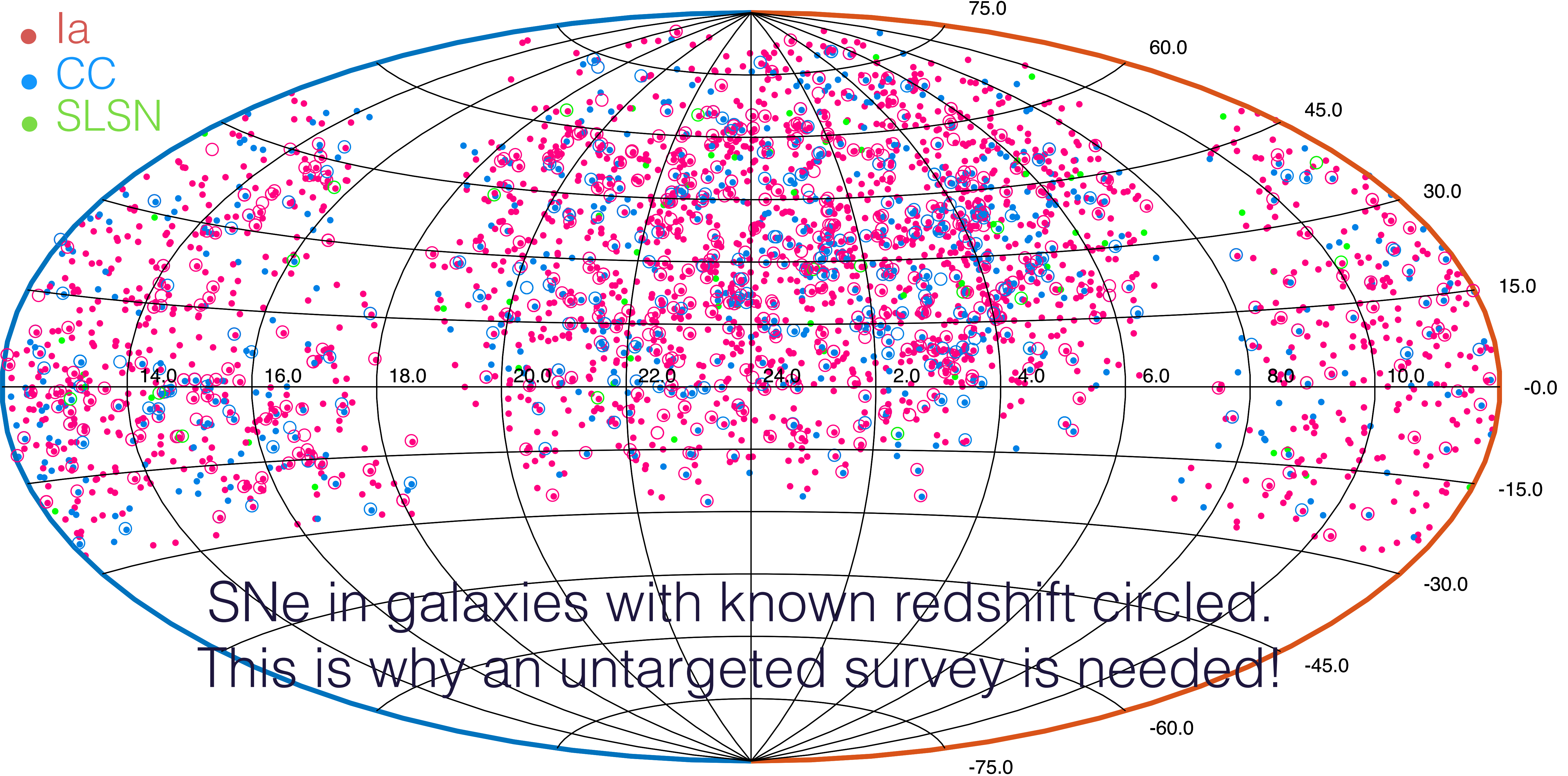
\+ 7 TDEs

\+ 10 "other"

~800/yr compared to ~200 previous

from Fremling

BTS SN sky positions

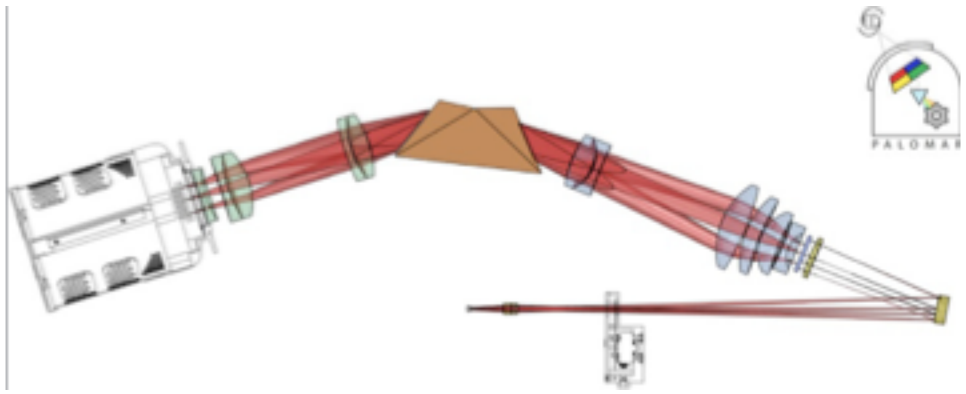


SNe in galaxies with known redshift circled.
This is why an untargeted survey is needed!

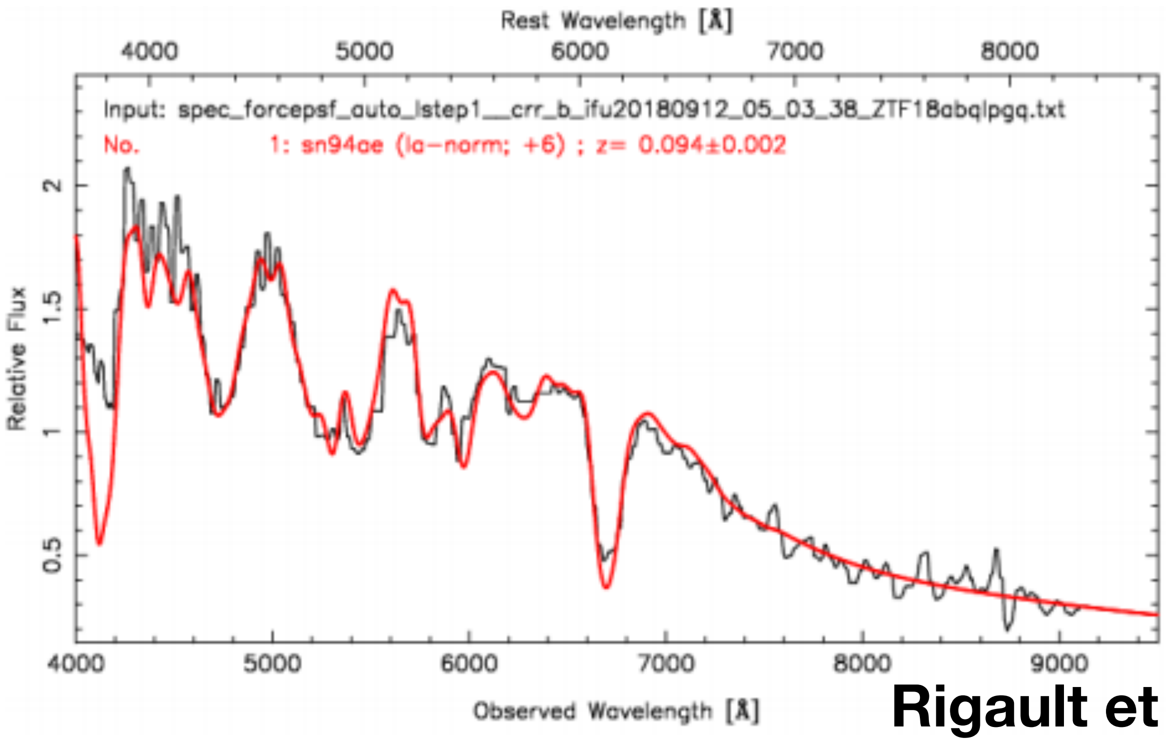
from Fremling

Where DESI Comes In

SEDMachine has R~100

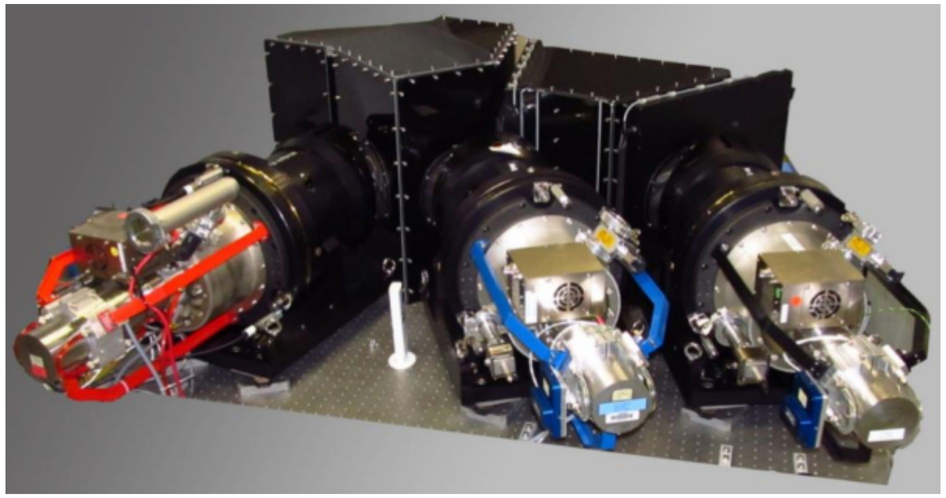


propagates into a poor peculiar velocity precision — host redshift needed from somewhere

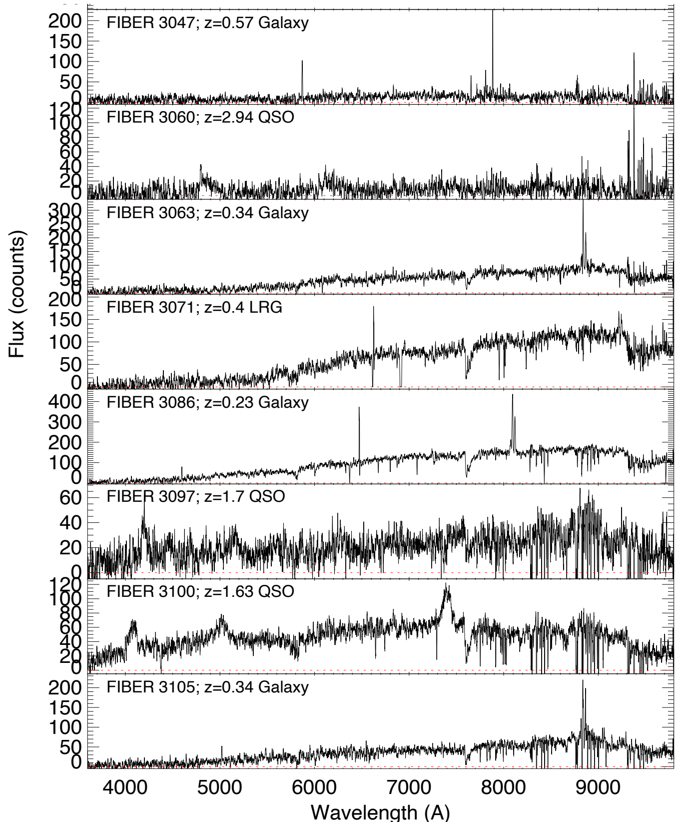


Rigault et al. 2019

DESI has R~2000-5000



negligible contribution to peculiar velocity uncertainty



SNe Ia With a DESI BGS Redshift

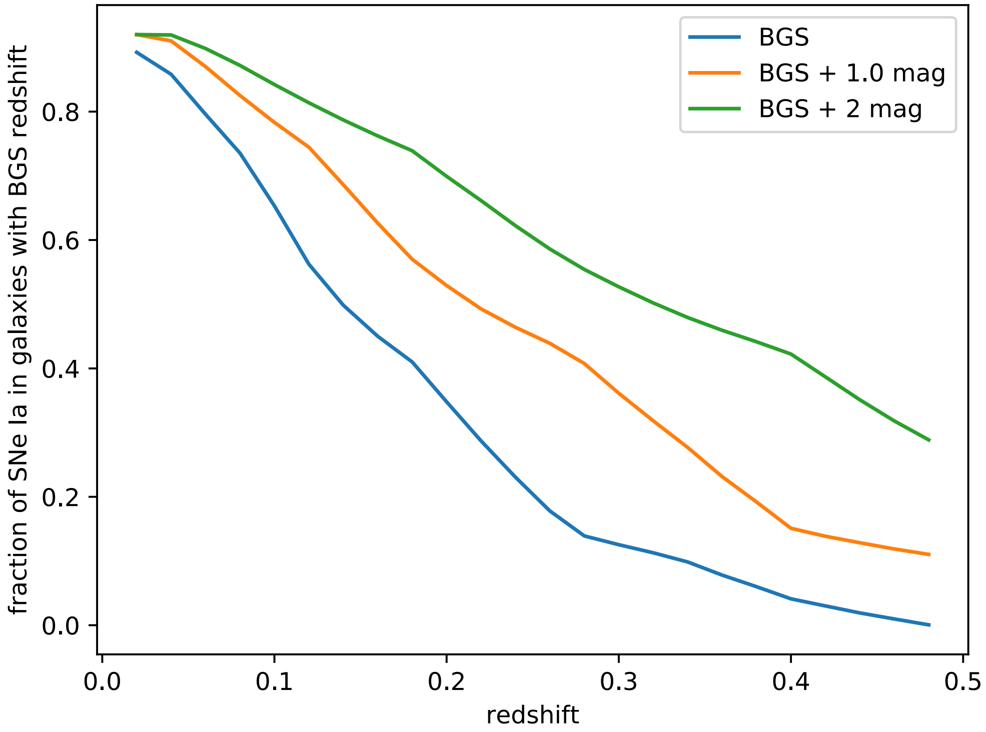


Figure 2: Fraction of supernovae in the DESI footprint that occur in a host galaxy with a successful DESI redshift from the BGS. Also shown are the fractions of supernovae that would occur in a host galaxy with a successful DESI redshift (now assuming 100% fiber-allocation efficiency) in observations 1 or 2 mag deeper than the nominal BGS exposure (Made with mock.py.)

- Vast majority of $z<0.1$ SN Ia hosts already in the BGS

Coordinated ZTF-DESI SN Ia Peculiar Velocity Program

- Necessary ingredients: SN Discovery, SN Typing (early and late), SN Distance (through multi-band light curves plus supplemental data), Host Galaxy Redshift

- ZTF+SED Machine contribute to the ingredient list
  - Transient discovery
  - Coarse host redshift
  - SN Ia typing
  - SN Ia distance

- DESI contributes to the ingredient list
  - Host-galaxy redshifts *before* discovery aid typing
  - Precise host-galaxy redshifts with <0.5% accuracy
    - BGS and mop-up
  - SN typing of a subset of targets

in discussions with J. Nordin

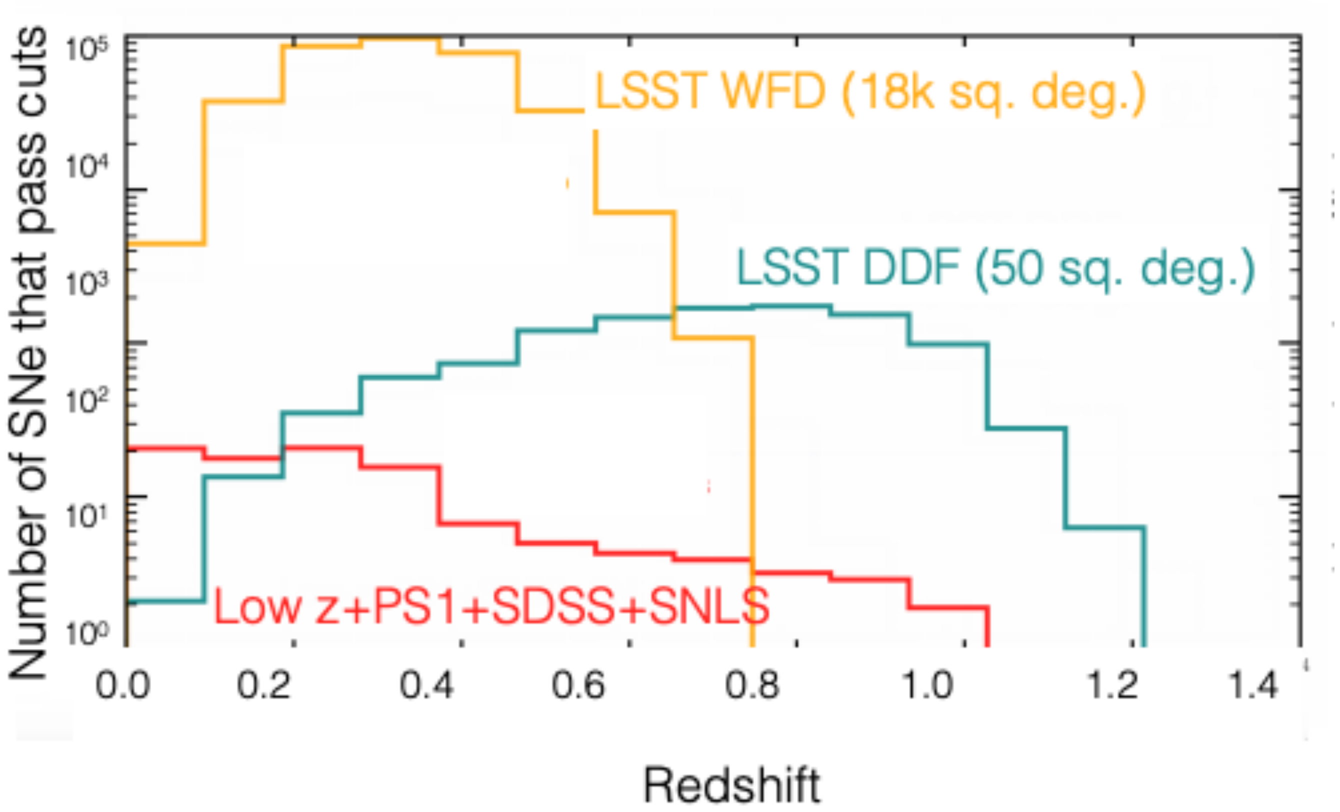
ZTF-II Partnership

- ZTF-II public survey uses 50% time for *gr* imaging survey, SEDMachine classifications
    - nb. *gr* survey great for discoveries we need, precision SN distances need additional data
- ZTF-II partnership gets 30% time to do its own surveys
    - Likely are *i* survey, increased cadence/depth, classification of more objects
    - $200k/yr for 3 years

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?

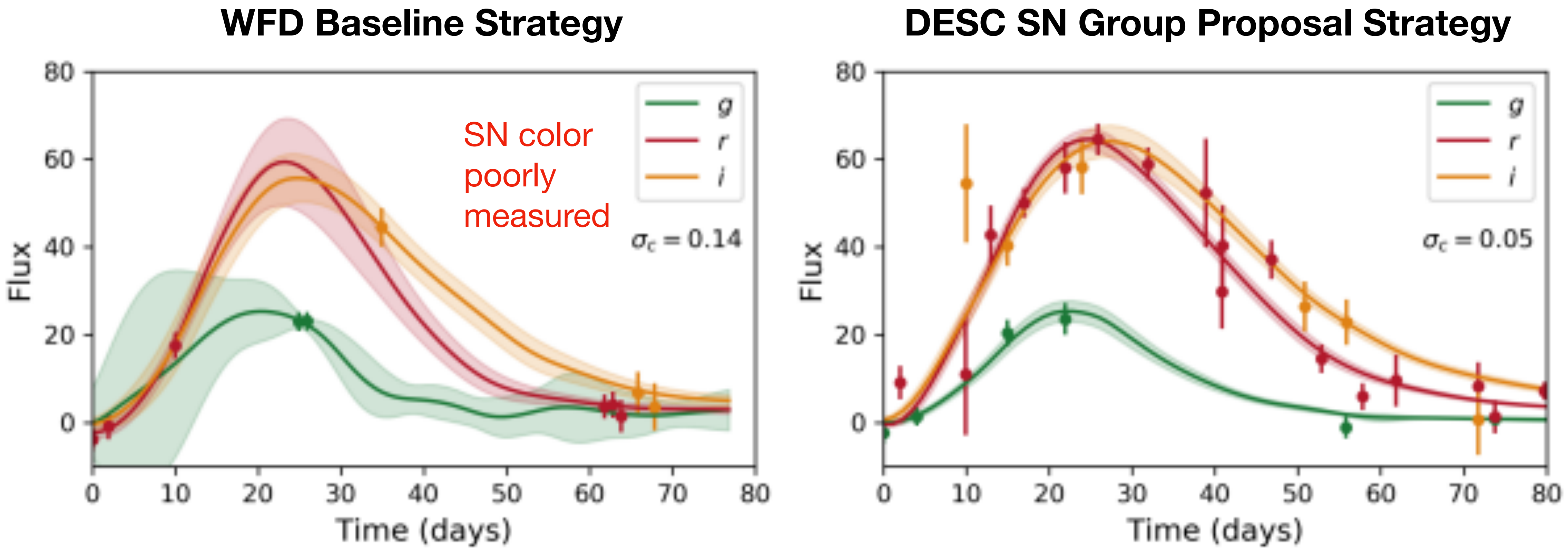
- Vera C. Rubin Observatory LSST a source of southern sky SNe for 10 years: ~ 50k (unclassified) SNe Ia at $z<0.15$



Mandelbaum et al. 2019

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

LSST Survey strategy may not yield precision light curves/ distances



Lochner et al. (2018)

Supplemental Photometry (ZTF - South)

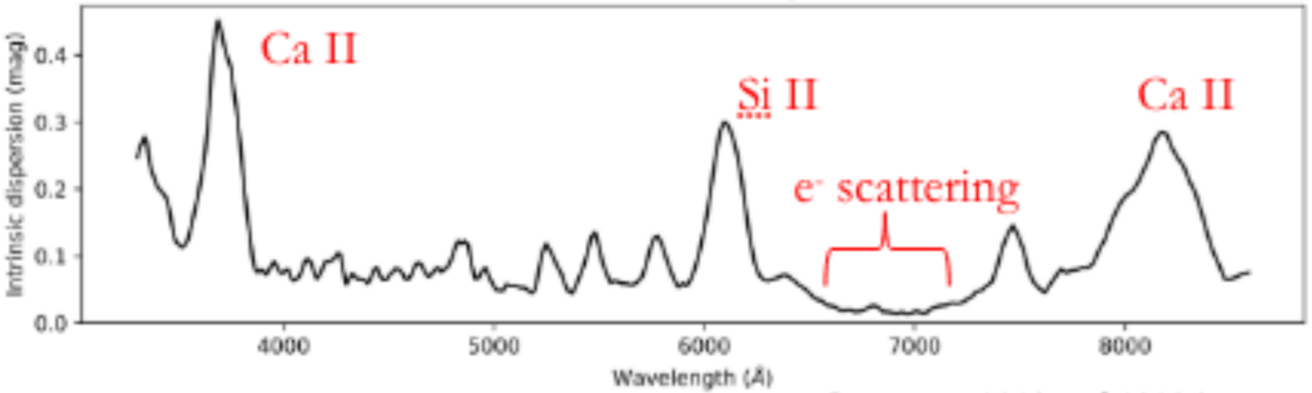
- Fill in light curves for early classification
- Photometry at peak when LSST CCDs saturate
- Complementary filter
- ESO 1-metre Schmidt telescope
  - ~ 29 sq. deg. usable focal plane
  - available? (Nugent)

ESO 1-metre Schmidt telescope

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

Lacking: Redshift, classification, and precision distance

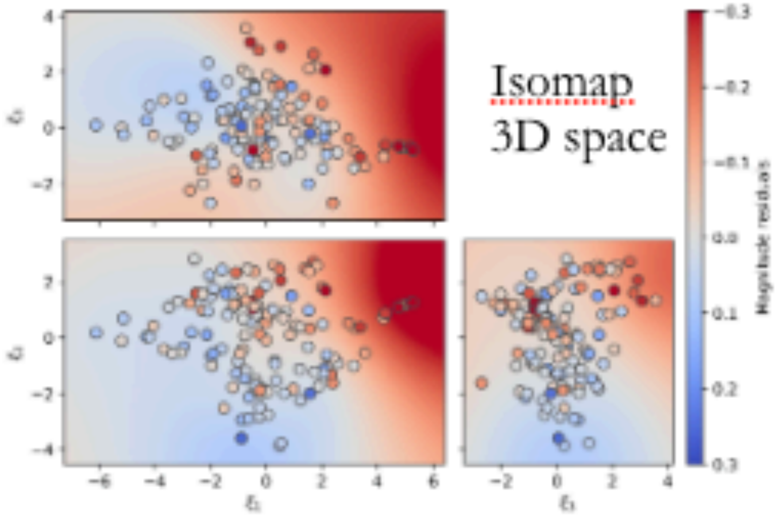
Between absorption lines SNe Ia are remarkable uniform



Boone++ 2019 and 2020 in prep

Linear standardization + spectral lines leads to SN systematic errors

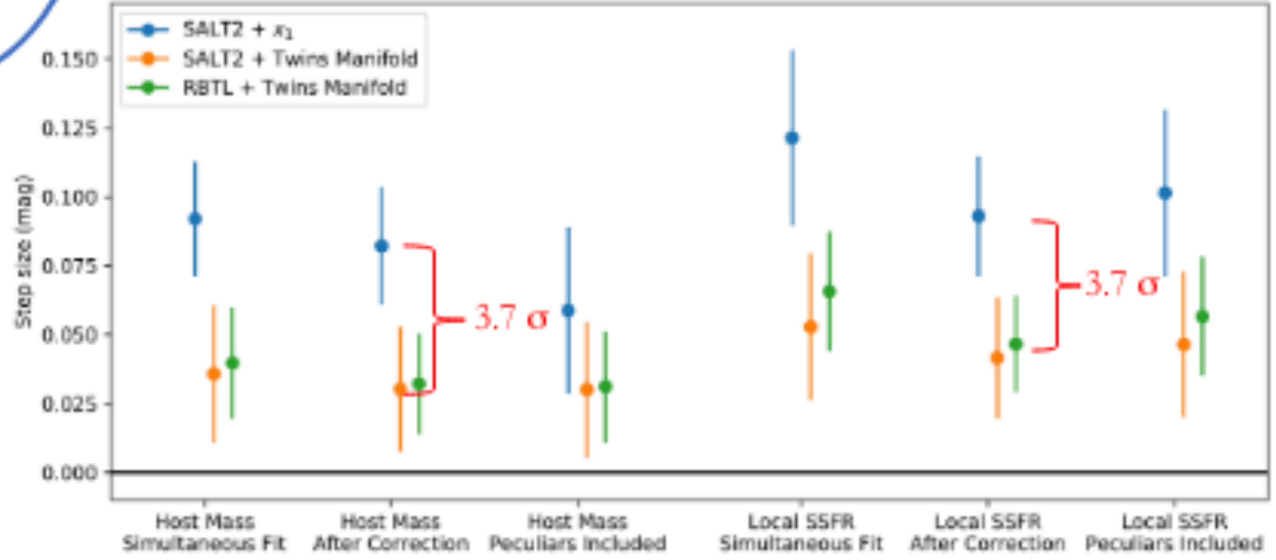
3.7+ σ reduction in host systematics
Within < 1.9 σ of being zero



Boone++ 2019 and 2020 in prep

3D non-linear space – a manifold

Cuts the standardization residuals in half!



Boone++ 2019 and 2020 in prep

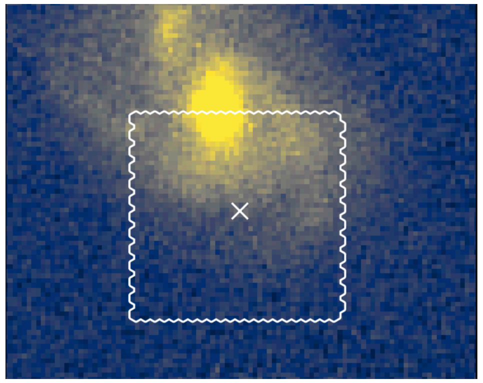
0.08 mag dispersion
Fakhouri et al. (2015)

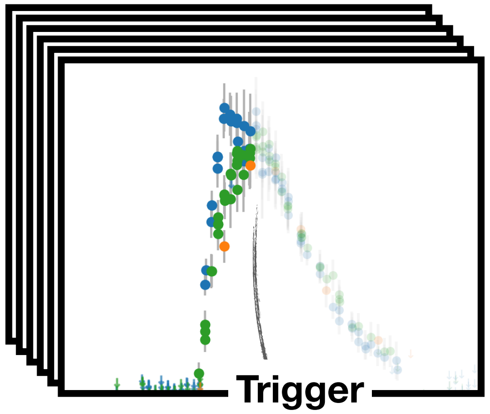
from Aldering (2020)

PV SNIa Follow-up Network

ZTF-II, Rubin Obs.

Transient Survey

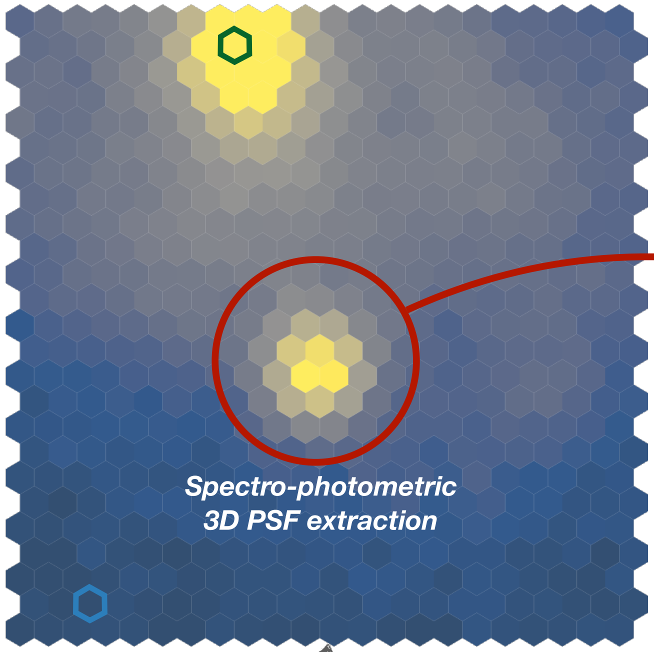


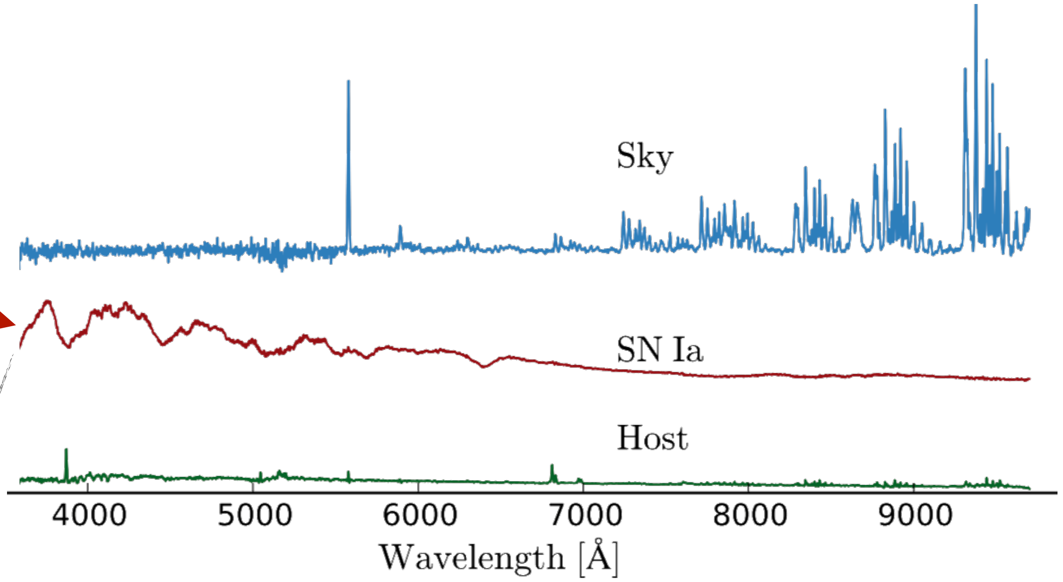


SNIFS

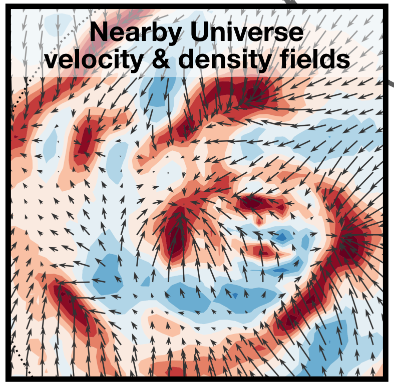
LBL-built IFU Spectrograph?

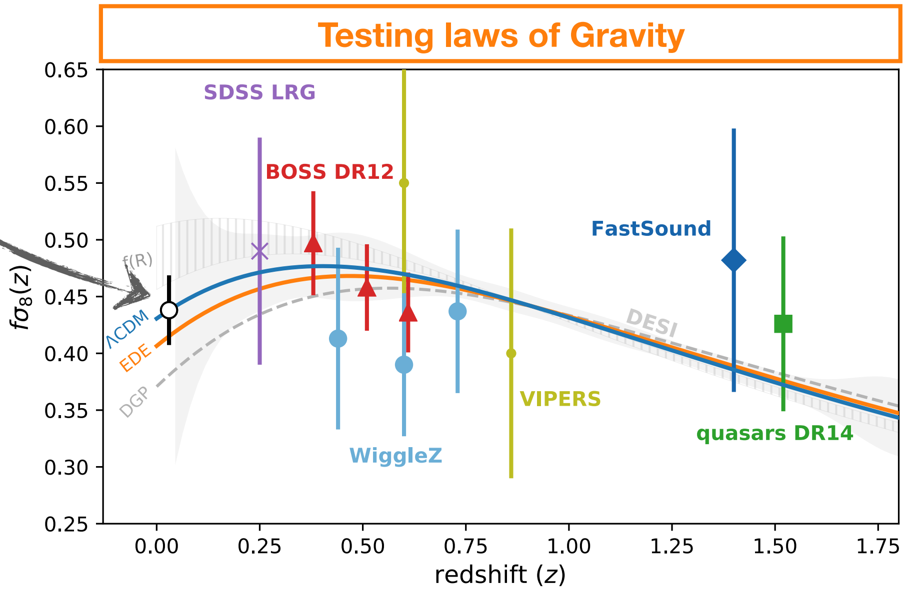
LATINO SNe Ia@z=0.08





x1700/year





UH-88”

ESO VLT Survey Telescope

Tokyo Atacama Observatory Telescope

Galbany & Kim PIs

LBNL Hardware for the PV SNIa Follow-up Network

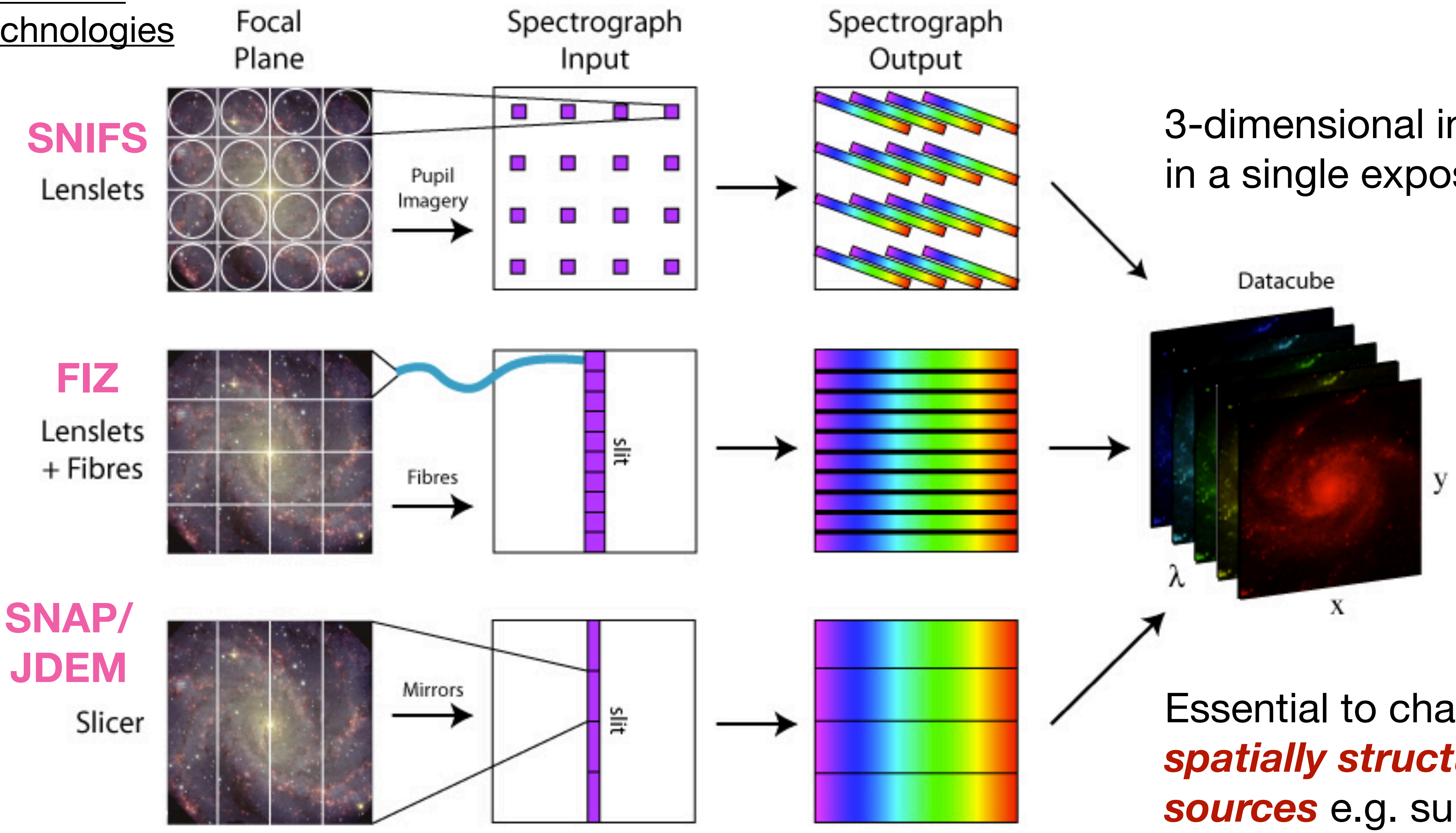
- Need ~3 instrumented 2-m telescopes to follow-up all of the discoveries out to z=0.1

- Need more for z=0.3 for the deeper discoveries of LSST

- Desire an IFU Spectroscopic Instrument design that is easily configurable for different telescopes apertures, focal planes

Integral Field Unit and Integral Field Spectroscopy

Three IFU technologies



SNIFS
Lenslets

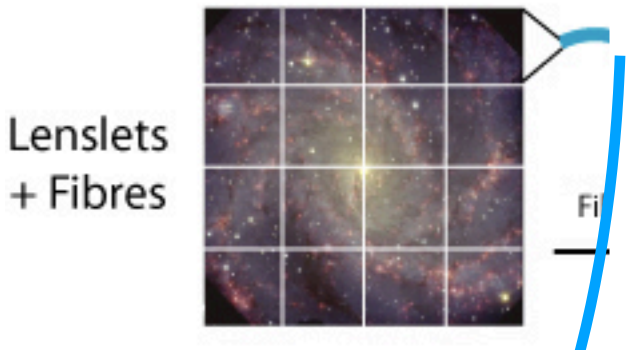
FIZ
Lenslets
+ Fibres

SNAP/ JDEM
Slicer

3-dimensional information in a single exposure

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

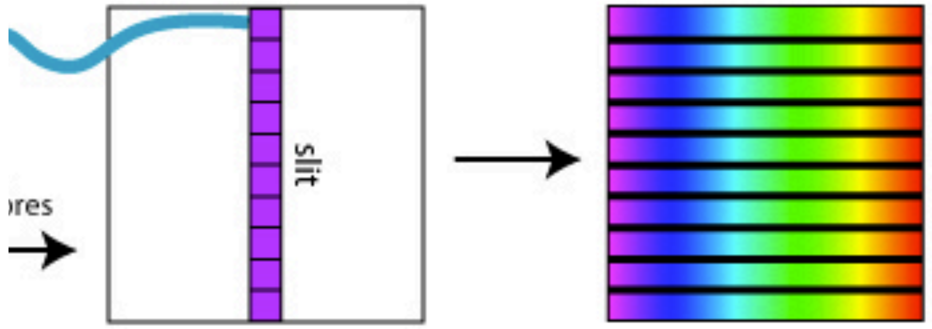
Pros of Fiber IFS



IFU (matched to telescope)

… decoupled …

- Single technology applies to many telescopes - cost savings and design flexibility
  - IFU geometry customized for each focal plane
  - Spectrograph
    - Optics not tailored to telescope, single design applied to many telescopes
    - Put anywhere, not necessarily mounted on telescope



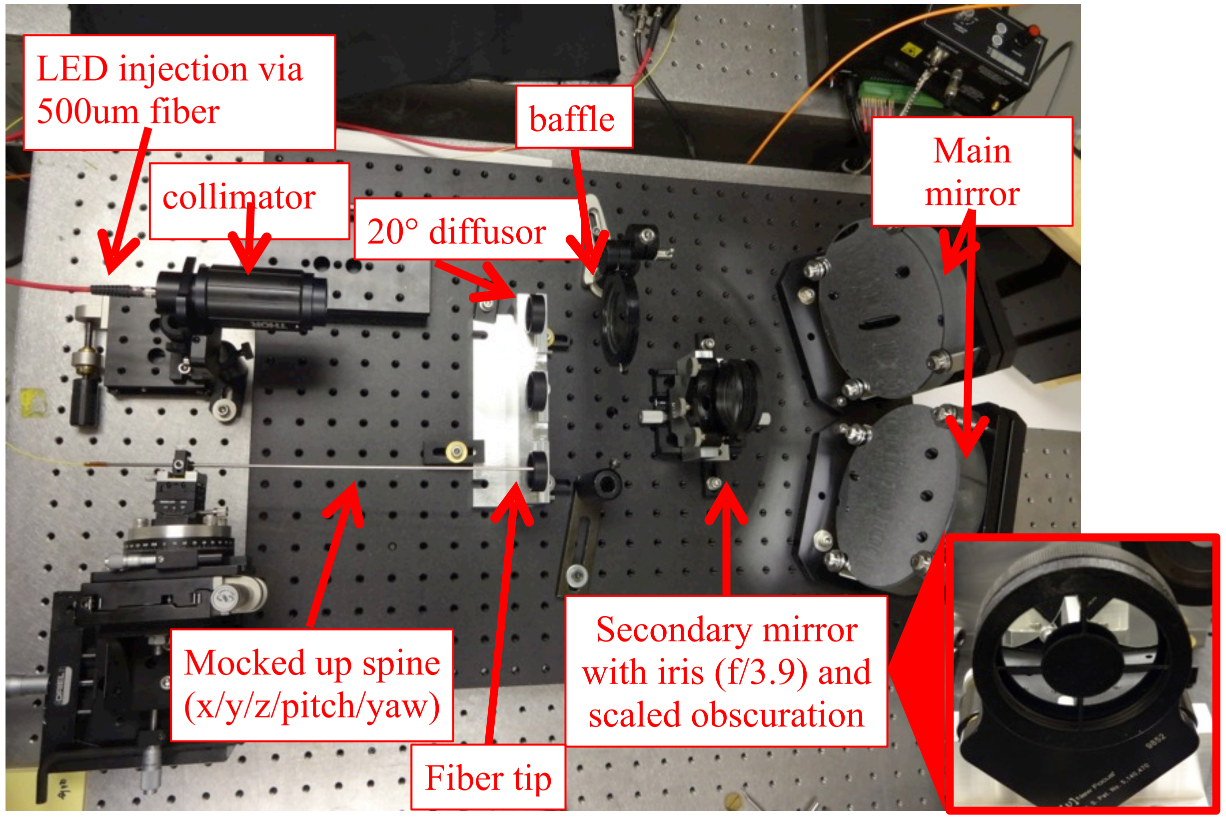
Spectrograph (generic)

LDRD Proposal: Characterize and Mitigate Fiber and Microlens Performance

- For small-core high-NA fibers: measure throughput
- For different input focal ratios and fibers: Measure and mitigate stability
- For microlens arrays: measure energy distribution (PSF)

Build on infrastructure and expertise developed for DESI

Test rig at SSL used for DESI used to measure fiber transmission


LED injection via 500um fiber

baffle

collimator

20° diffusor

Main mirror

Mocked up spine (x/y/z/pitch/yaw)

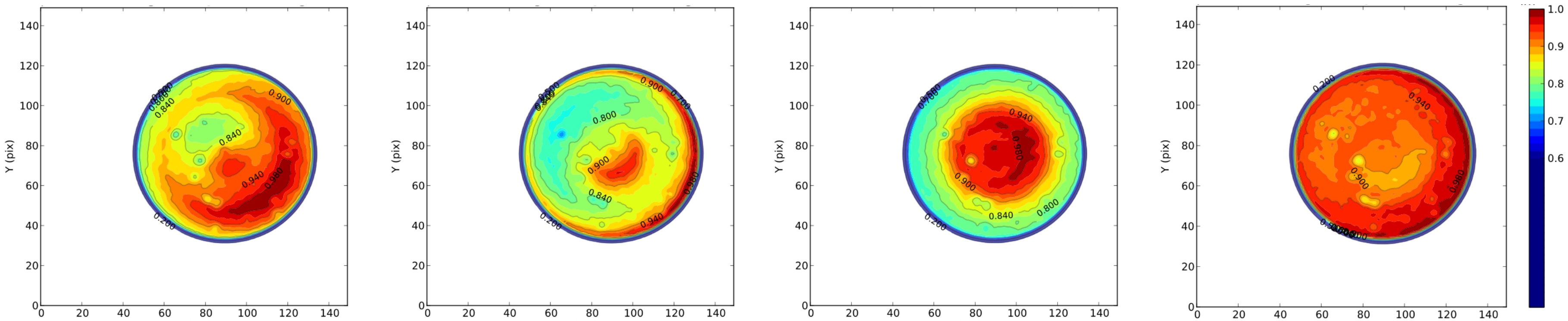
Fiber tip

Secondary mirror with iris (f/3.9) and scaled obscuration

Stability issue as demonstrated by in-house measurements

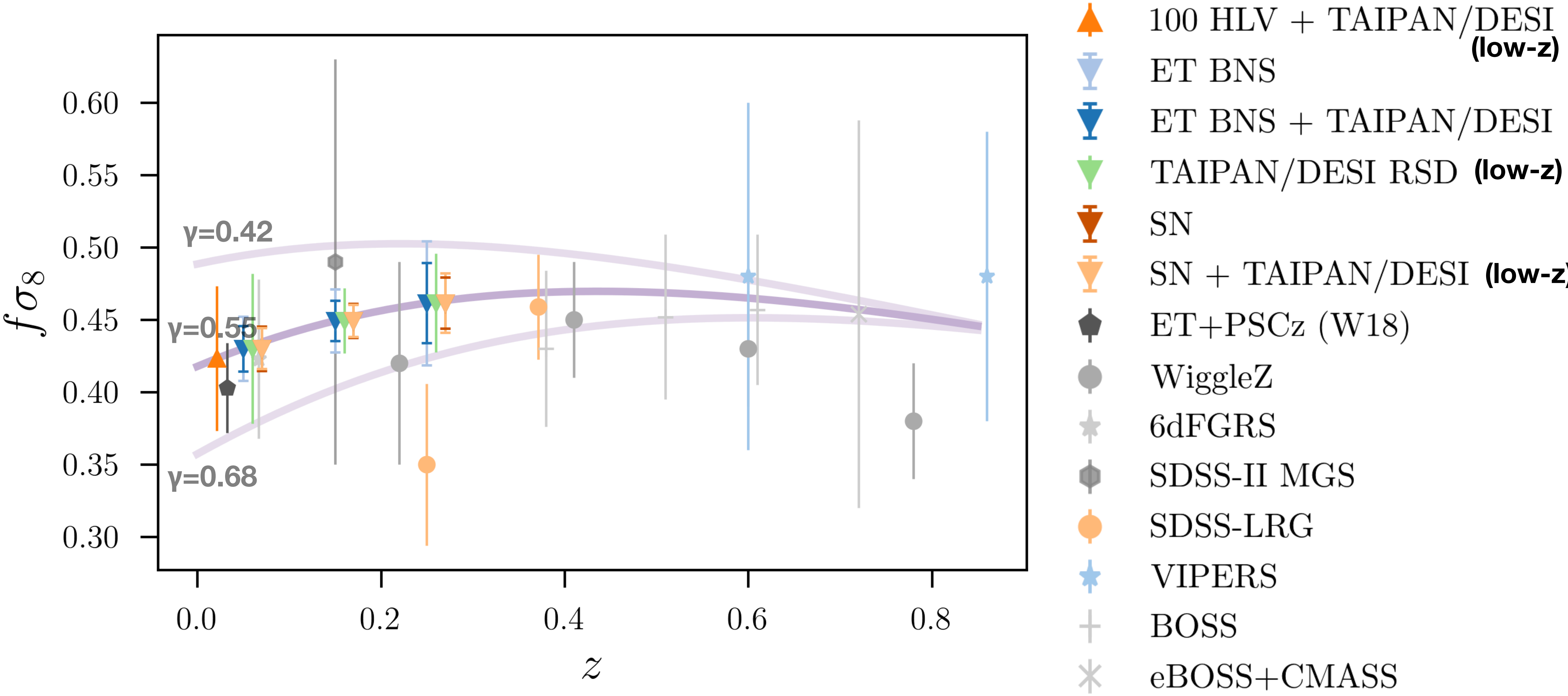
Tilting fiber to different positions changes the near field intensity distribution

2.2° off axis



Kim, Poppett et al.

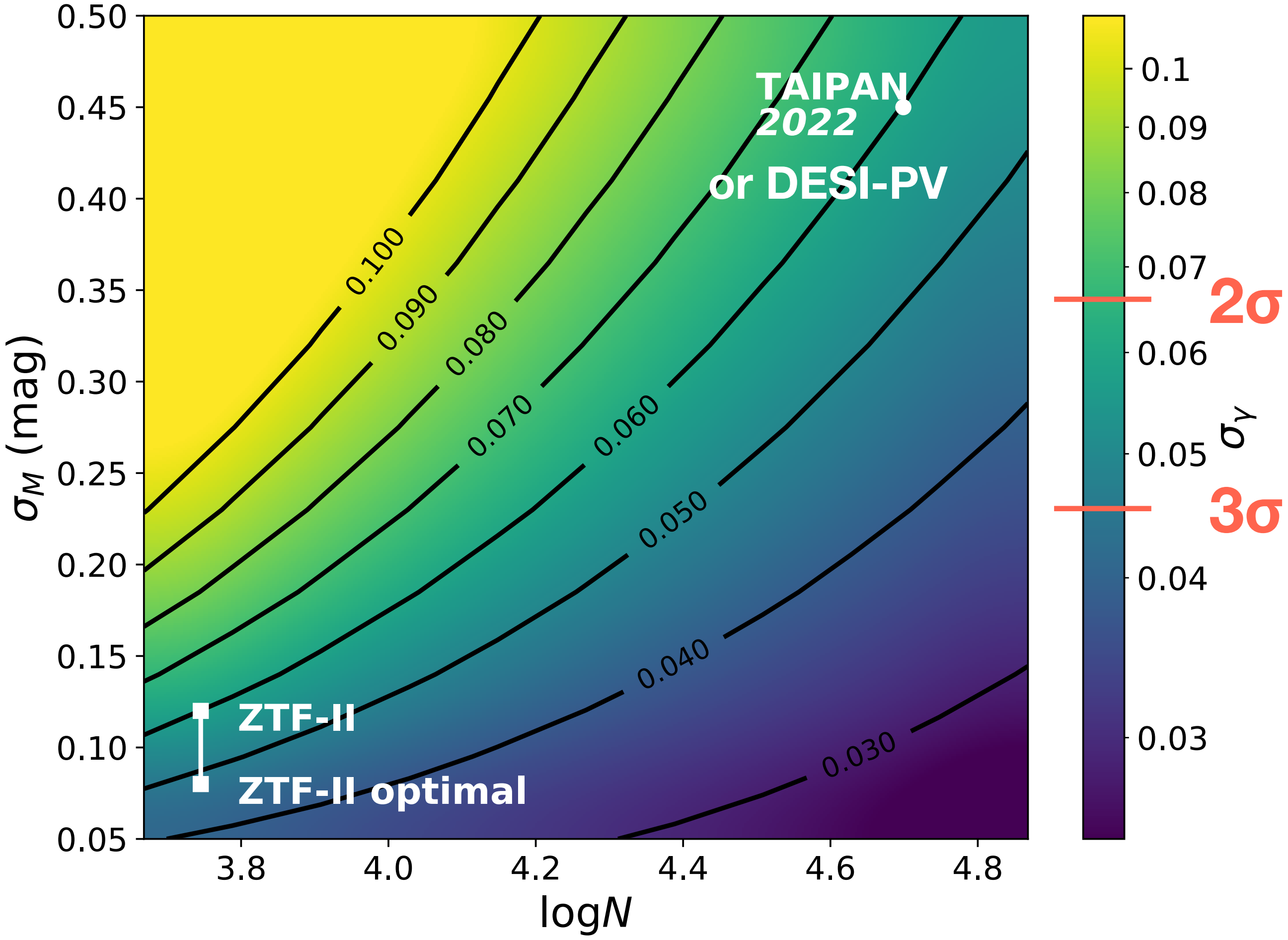
$f\sigma_8$ Measurements and Projections



Palmese and Kim (2020)

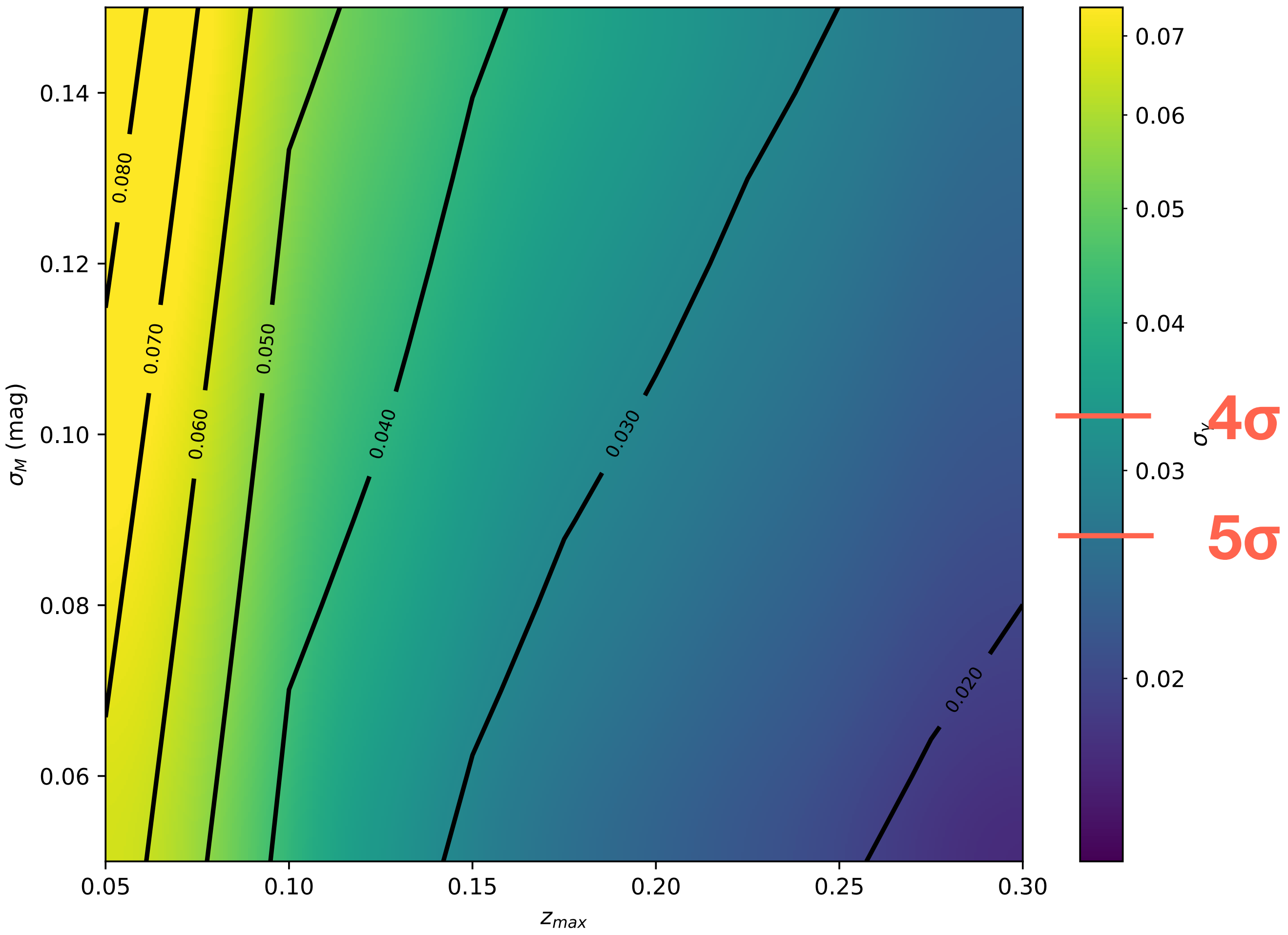
Projections for γ

ZTF2 and DESI
~4 year



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

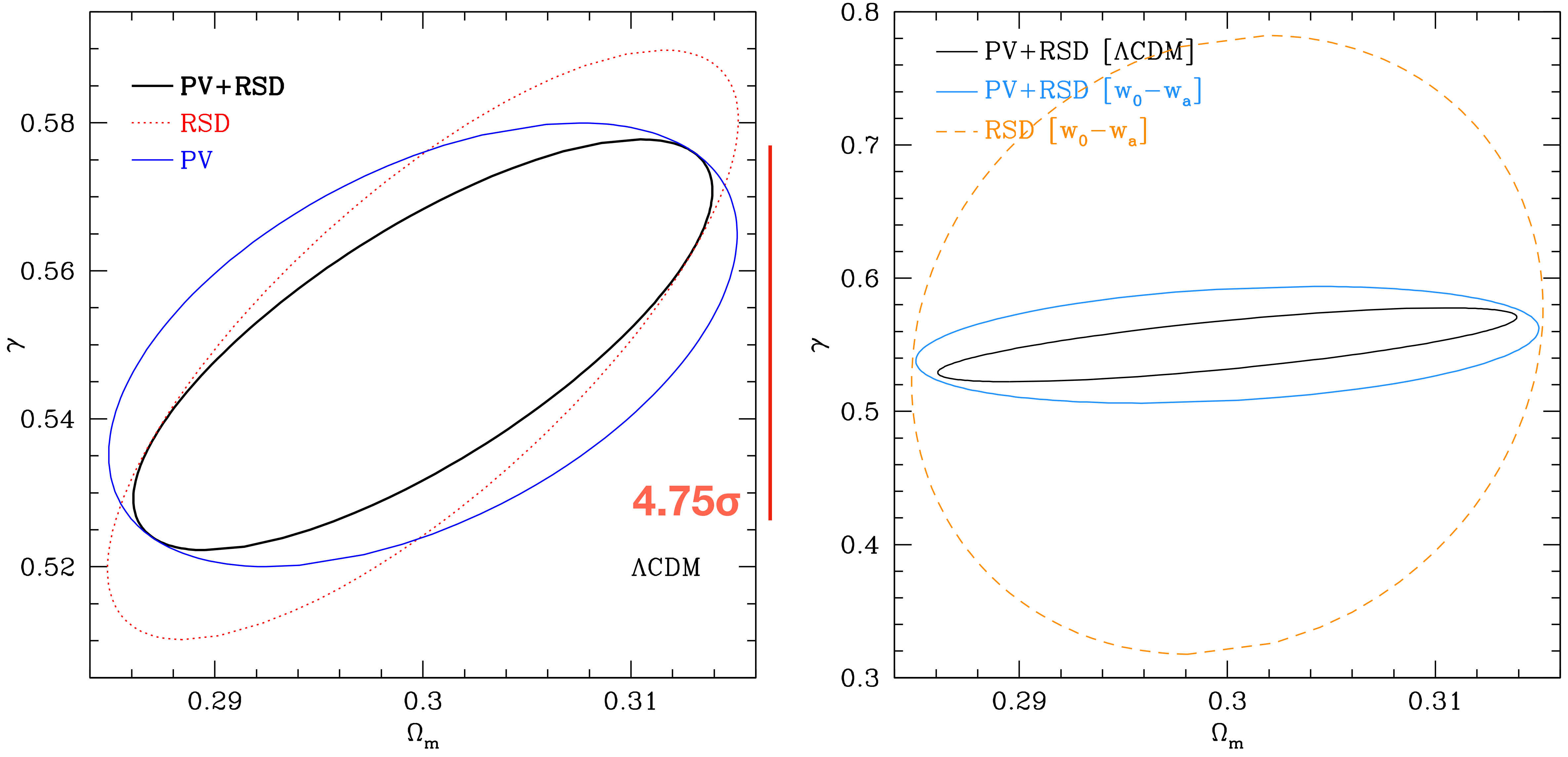
10-year LSST



More sources and going to higher redshift can distinguish models at 4-5σ

PV + RSD Synergy

PV: 0.01<z<0.2



Kim & Linder (2020)

Conclusions

- Peculiar velocities are a powerful probe of the growth of structure and the gravity that drives that growth
- Powerful surveys with increased numbers of objects with improved distance precisions usher in the next generation of science
- SNe Ia soon to be competitive with galaxy distance indicators
- Seminal and current peculiar velocity work led by Berkeley — the opportunity for us to lead into the future

Astro2020 Science White Paper
Testing Gravity Using Type Ia Supernovae Discovered by Next-Generation Wide-Field Imaging Surveys

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Alex Kim
Institution: Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
Email: `agkim@lbl.gov`
Phone: 1-510-486-4621

Co-authors: G. Aldering[1], P. Antilogus[2], A. Bahmanyar[3], S. BenZvi[4], H. Courtois[5], T. Davis[6], H. Feldman[7], S. Ferraro[1], S. Gontcho A Gontcho[4], O. Graur[8,9,10], R. Graziani[11], J. Guy[1], C. Harper[1], R. Hložek[3,12], C. Howlett[13], D. Huterer[14], C. Ju[1], P.-F. Leget[15], E. V. Linder[1], P. McDonald[1], J. Nordin[16], P. Nugent[17], S. Perlmutter[1,18], N. Regnault[15], M. Rigault[11],

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[1] Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
[2] Laboratoire de Physique Nucléaire et de Hautes Energies, Sorbonne Université, CNRS-IN2P3, 4 Place Jussieu, 75005 Paris, France
[3] Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, Ontario, Canada M5S 3H4
[4] Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[5] Université de Lyon, F-69622, Lyon, France; Université de Lyon 1, Villeurbanne; CNRS/IN2P3, Institut de Physique Nucléaire de Lyon, France
[6] School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia
[7] Department of Physics & Astronomy, University of Kansas, Lawrence, KS 66045-7550 USA
[8] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
[9] Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA
[10] NSF Astronomy and Astrophysics Postdoctoral Fellow
[11] Université Clermont Auvergne, CNRS/IN2P3, Laboratoire de Physique de Clermont, F-63000 Clermont-Ferrand, France
[12] Dunlap Institute for Astronomy and Astrophysics, University of Toronto, ON, M5S 3H4
[13] International Centre for Radio Astronomy Research, The University of Western Australia, Crawley, WA 6009, Australia
[14] Department of Physics, University of Michigan, 450 Church Street, Ann Arbor, MI 48109, USA
[15] Laboratoire de Physique Nucléaire et de Hautes Energies, Sorbonne Université, CNRS-IN2P3, 4 Place Jussieu, 75005 Paris, France
[16] Institut fur Physik, Humboldt-Universitat zu Berlin, Newtonstr. 15, 12489 Berlin, Germany
[17] Computational Research Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
[18] Department of Physics, University of California Berkeley, Berkeley, CA 94720

Snowmass Letter of Intent or Contributed Paper

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