Opportunities for Type Ia Supernova Peculiar Velocity Surveys

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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

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

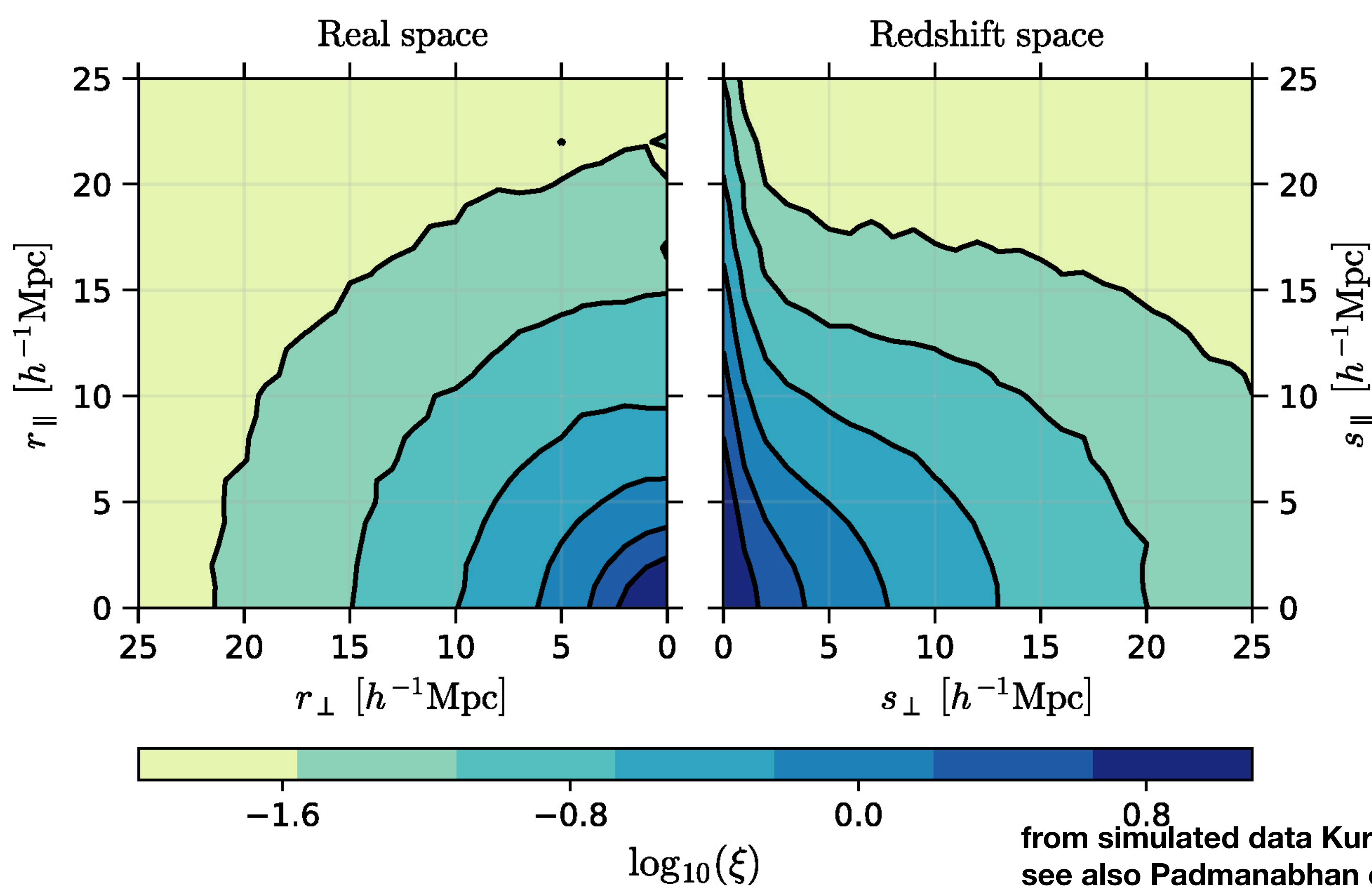
Conservation of Mass

Connection between density overdensities and peculiar velocities

… by the law of transitivity …

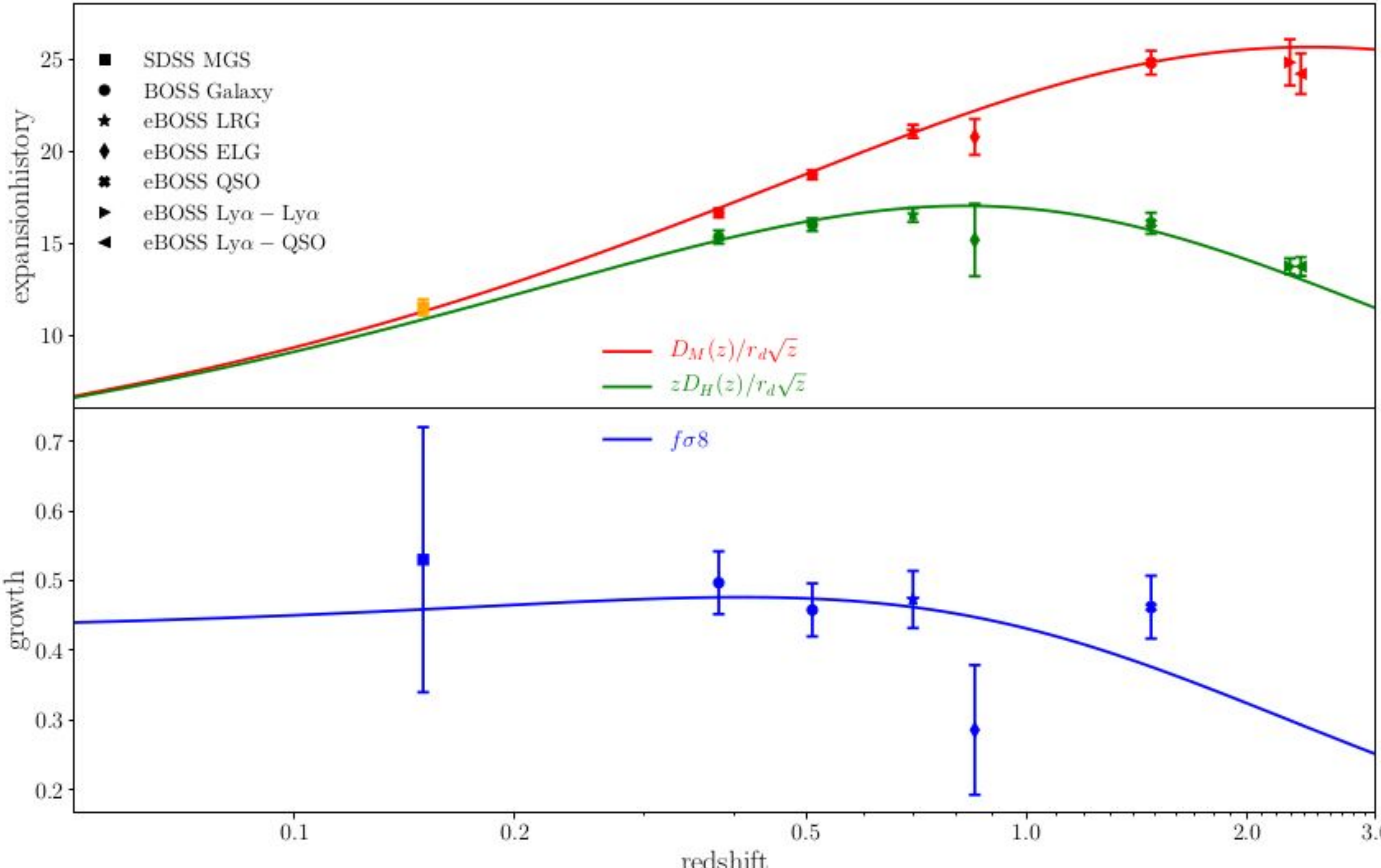
- Peculiar velocities are a powerful probe of the growth of structure, gravity, and the primordial universe, and so should motivate projects and facilities in the next decade

Peculiar Velocities ARE Motivating Projects Today: Redshift Space Distortions



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

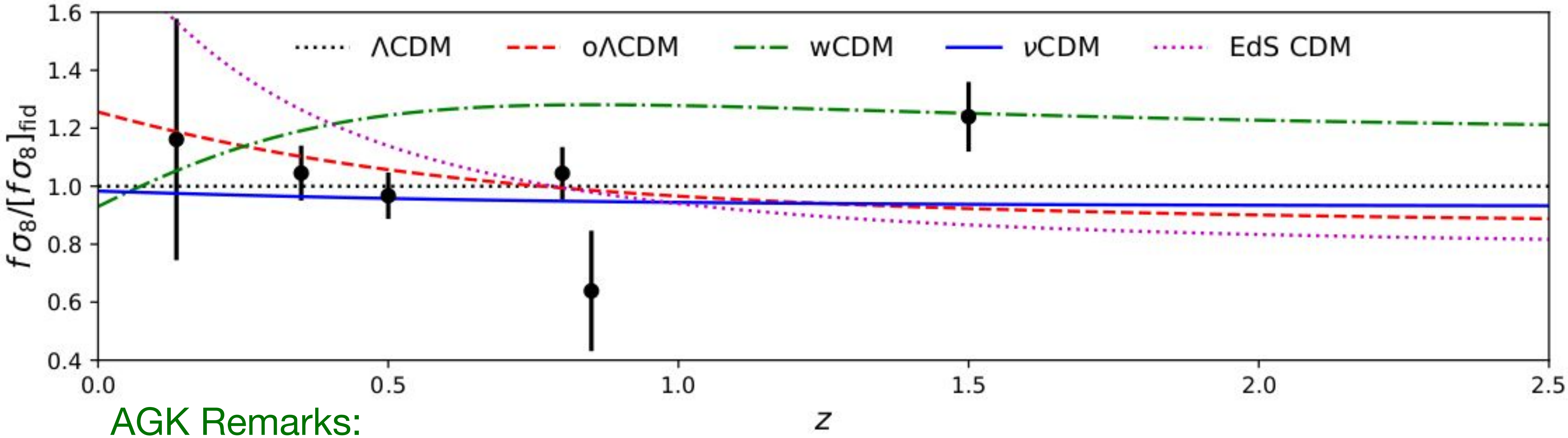
All BAO and RSD Measurements



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)



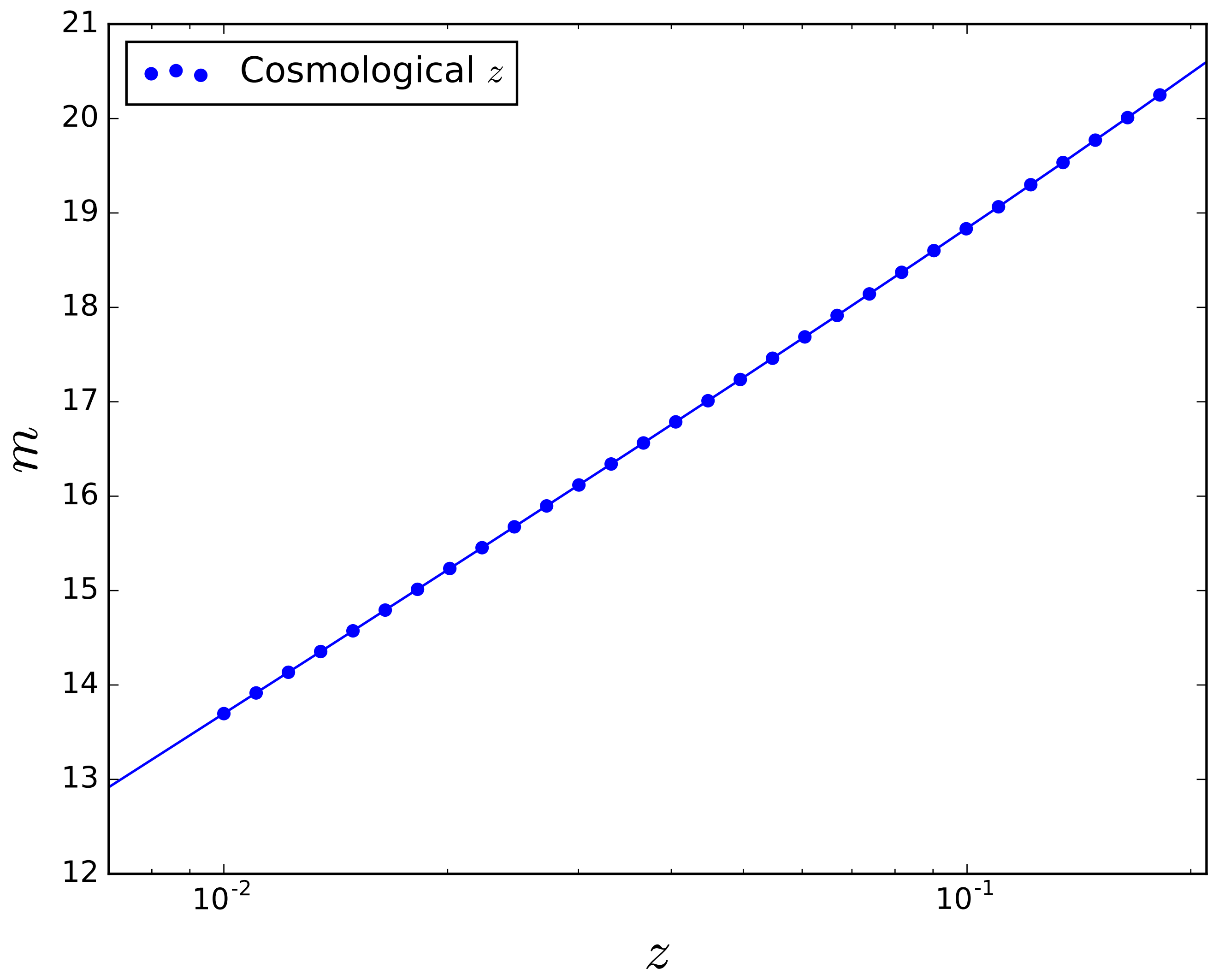
AGK Remarks:

- Models deviate at low redshift
- RSD has poor signal-to-noise at low redshift

https://arxiv.org/abs/2007.08991

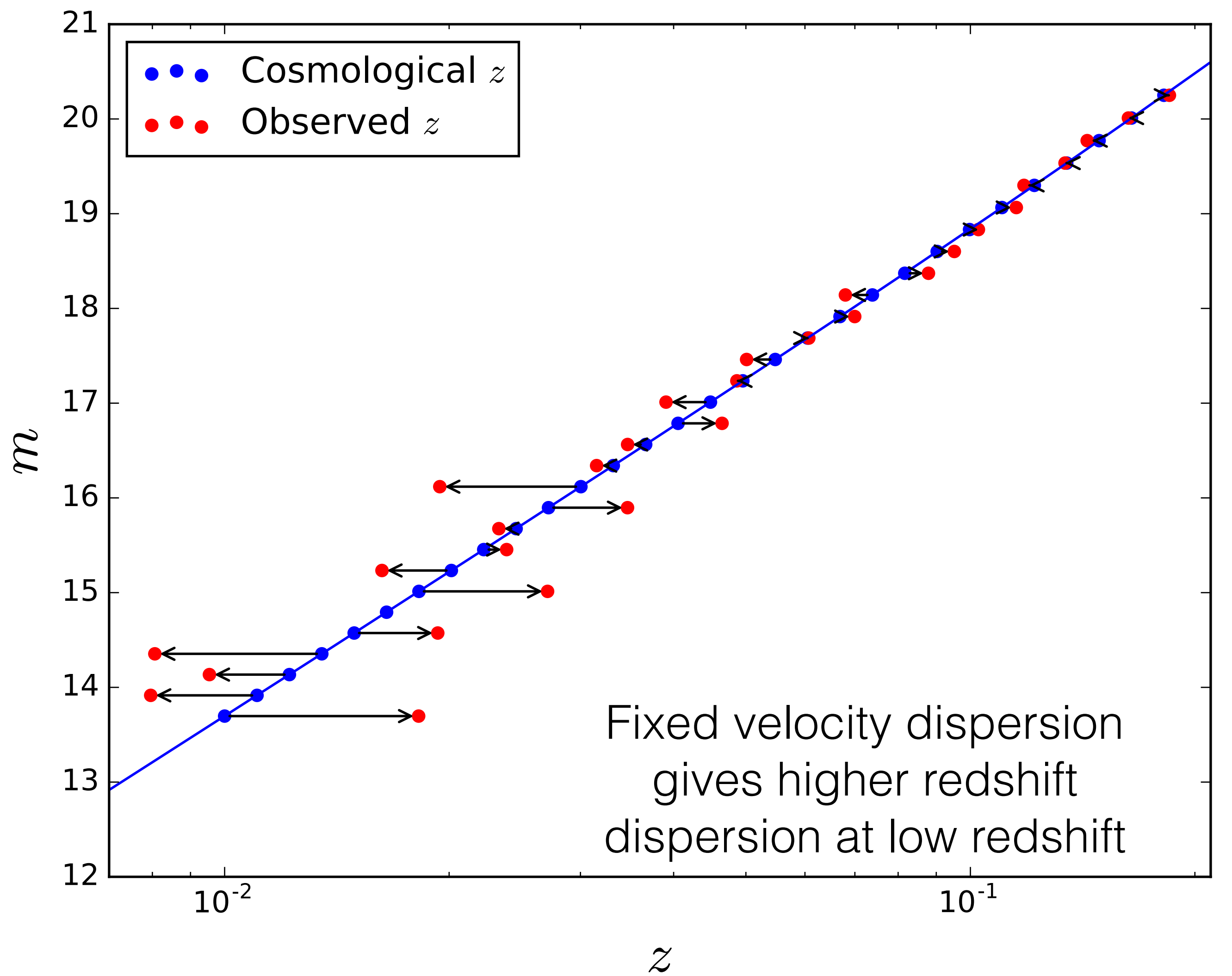
Peculiar Velocities ARE a Motivating Projects Today: Peculiar Magnitudes/Distances

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

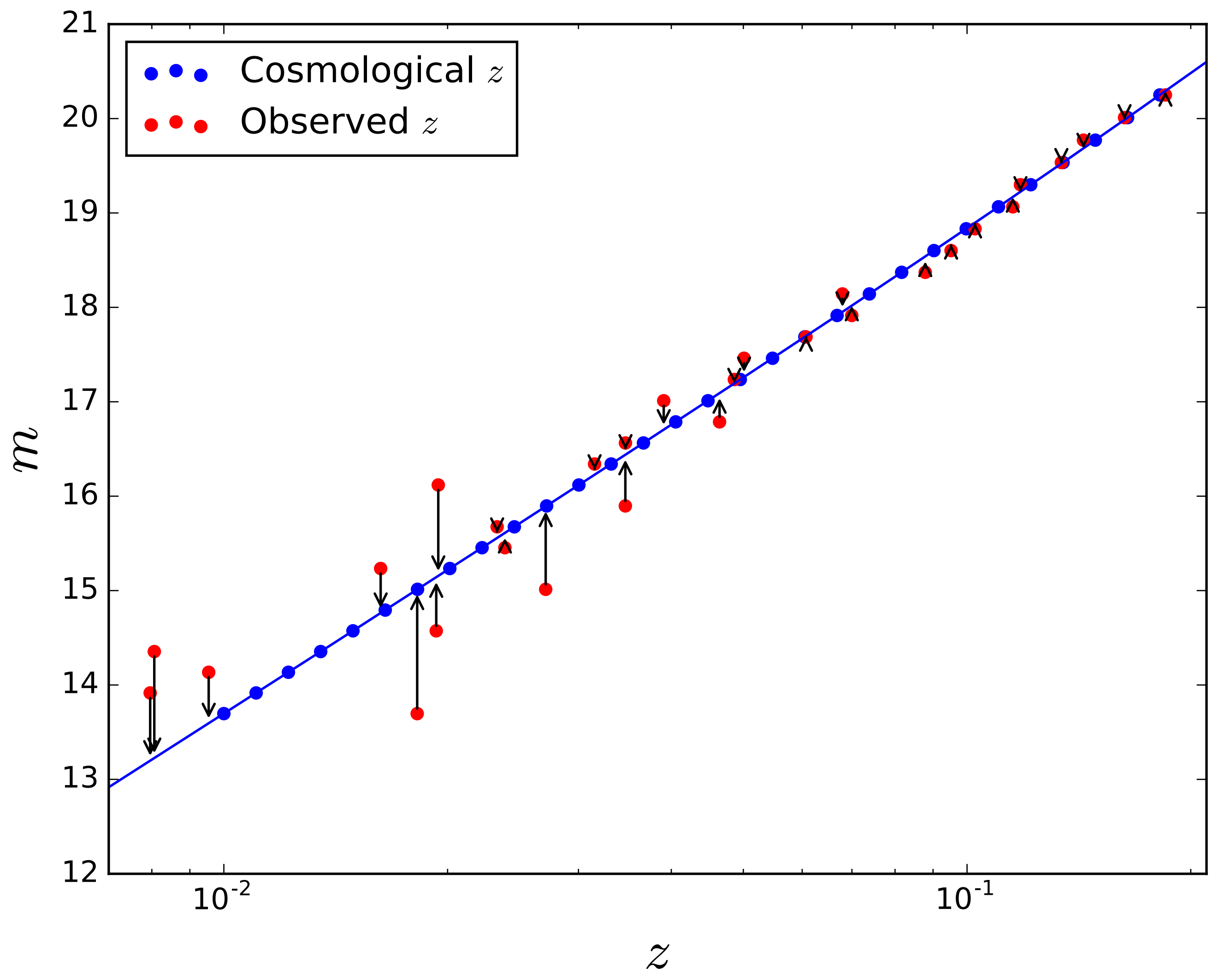


- Perfect standard candles with motion relative to the Hubble flow do not lie on nominal distance-redshift relationship when using the observed redshift

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

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

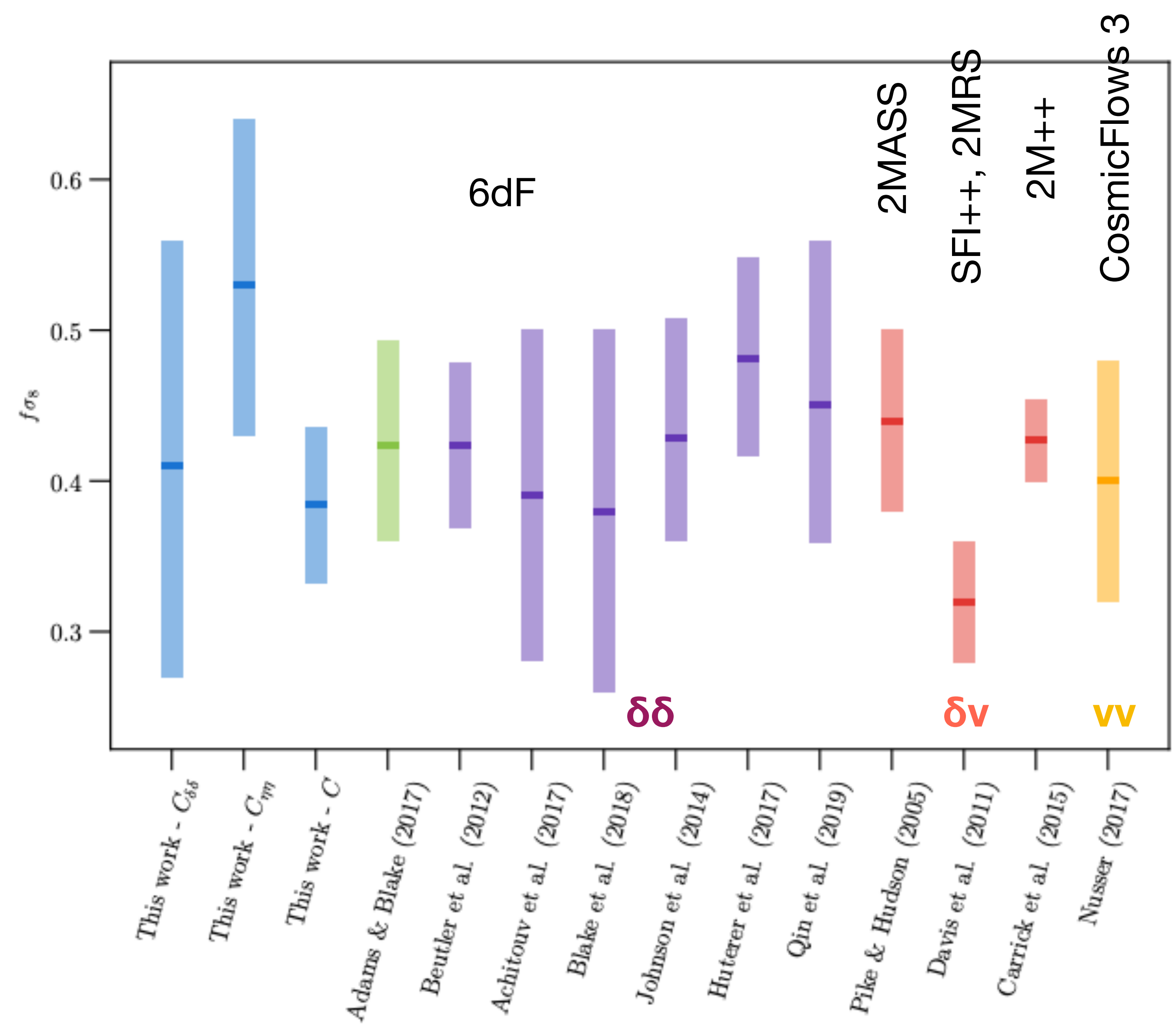
Interpreting Observed Redshift as Cosmological Redshift: Peculiar Magnitude/Distance



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

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
- $f\sigma_8 = 0.384 \pm 0.052(\text{stat}) \pm 0.061(\text{sys})$
- 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

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

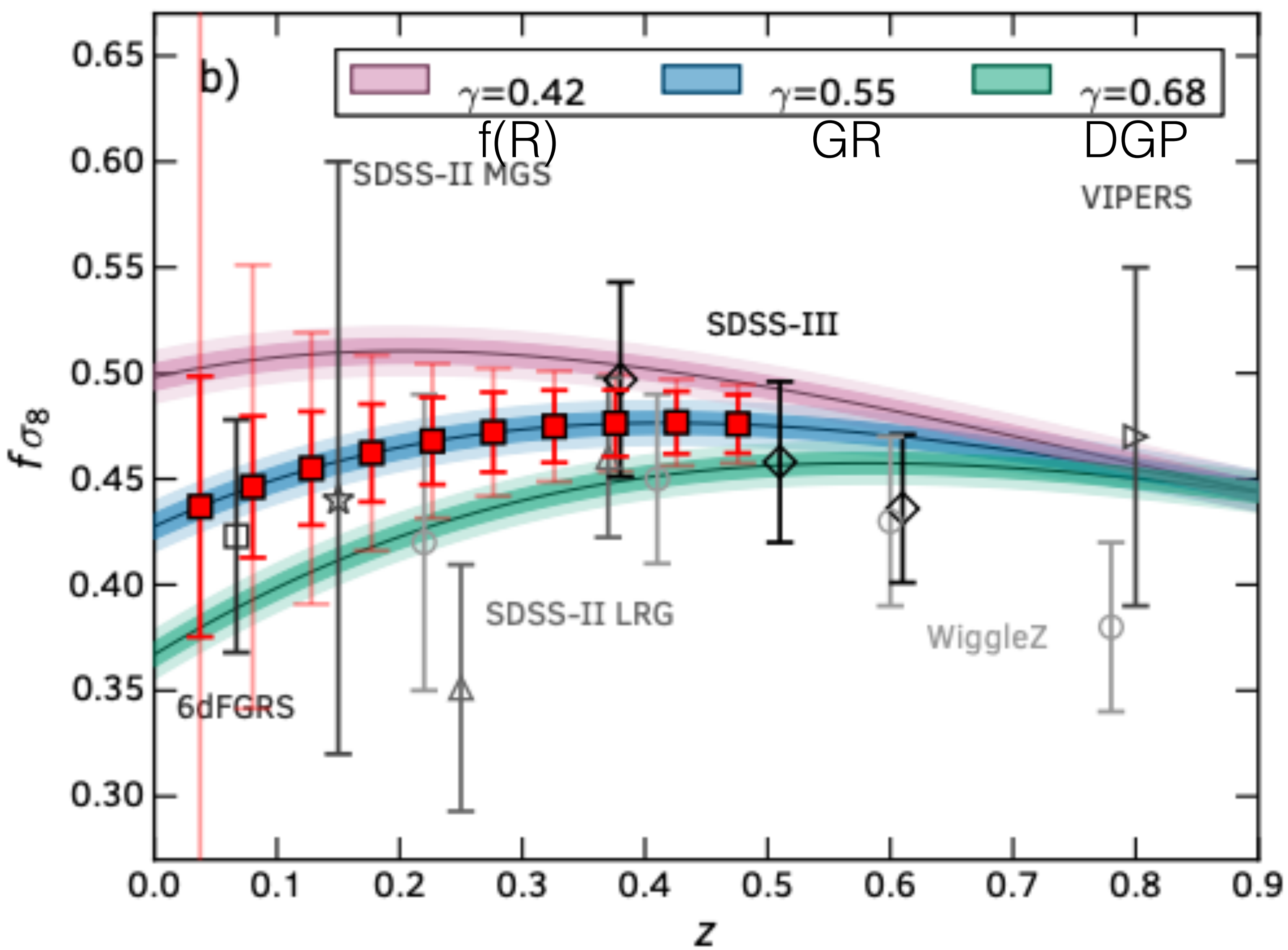
TAIPAN

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

LSST 10-year

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

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

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:

$$f = \Omega_M^\gamma$$

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

γ: growth index

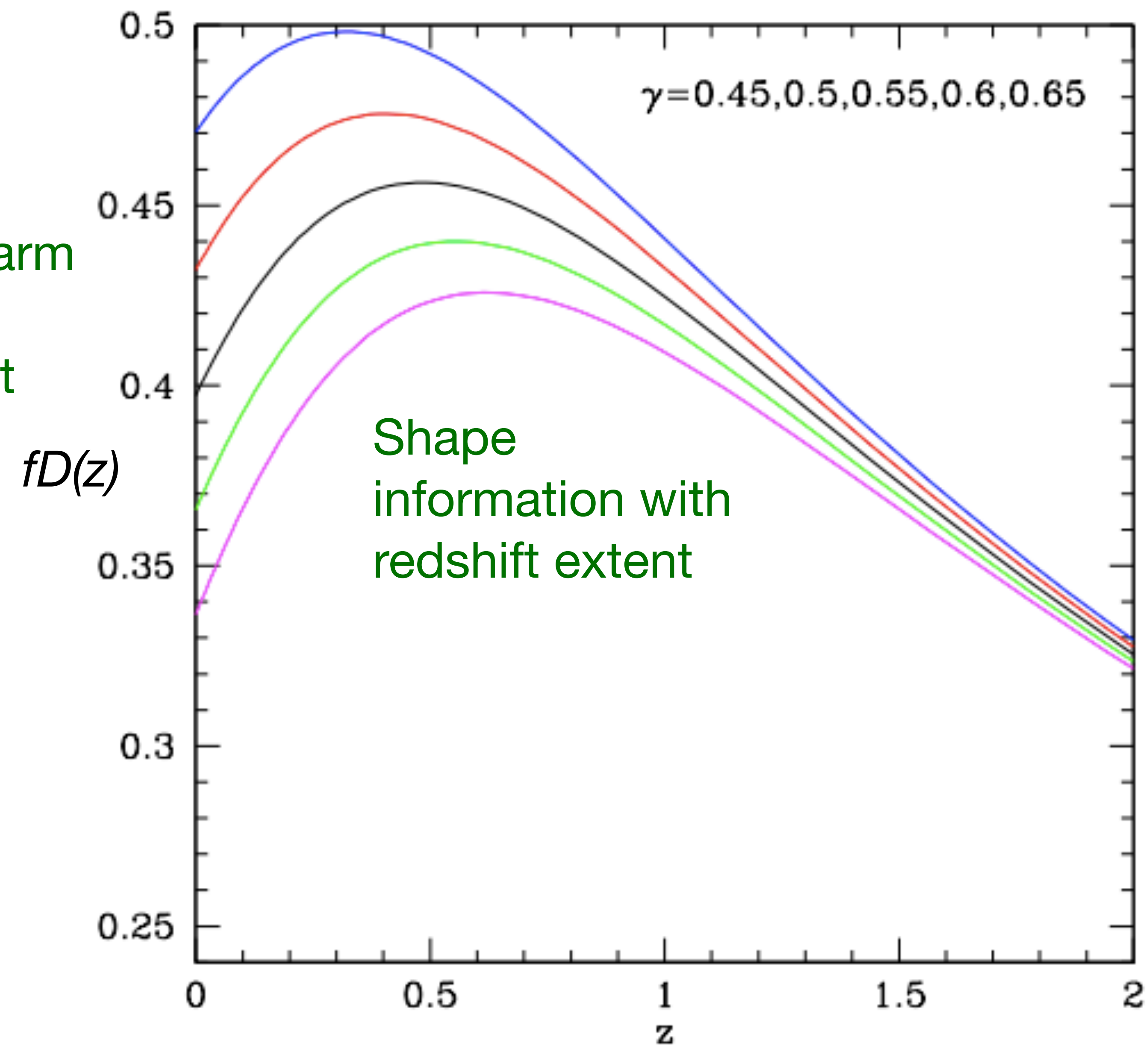
General Relativity, $f(R)$, and DGP gravity predict values of the growth index of $\gamma = 0.55, 0.42, 0.68$

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

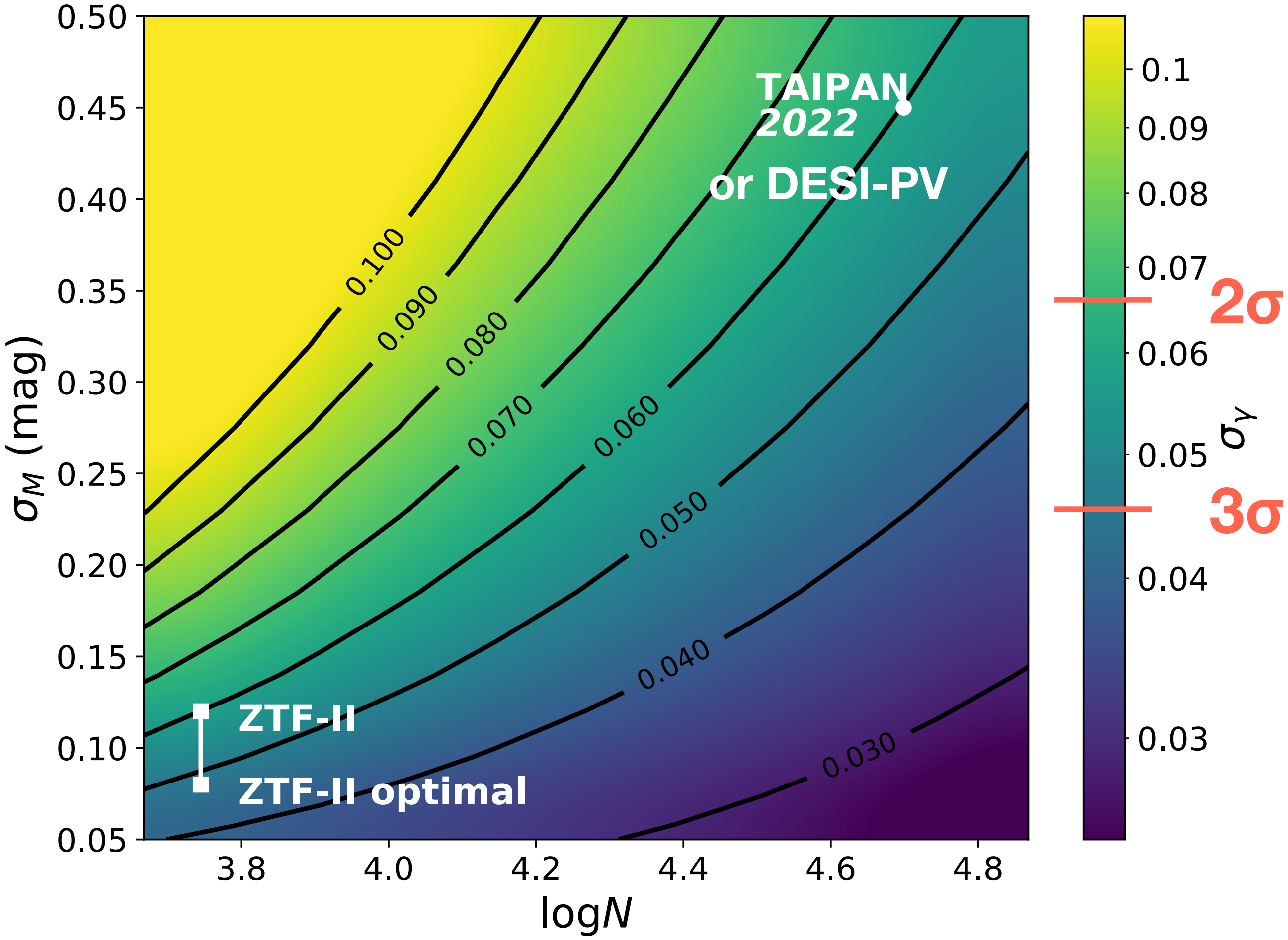


Shape information with redshift extent

Linder (2013)

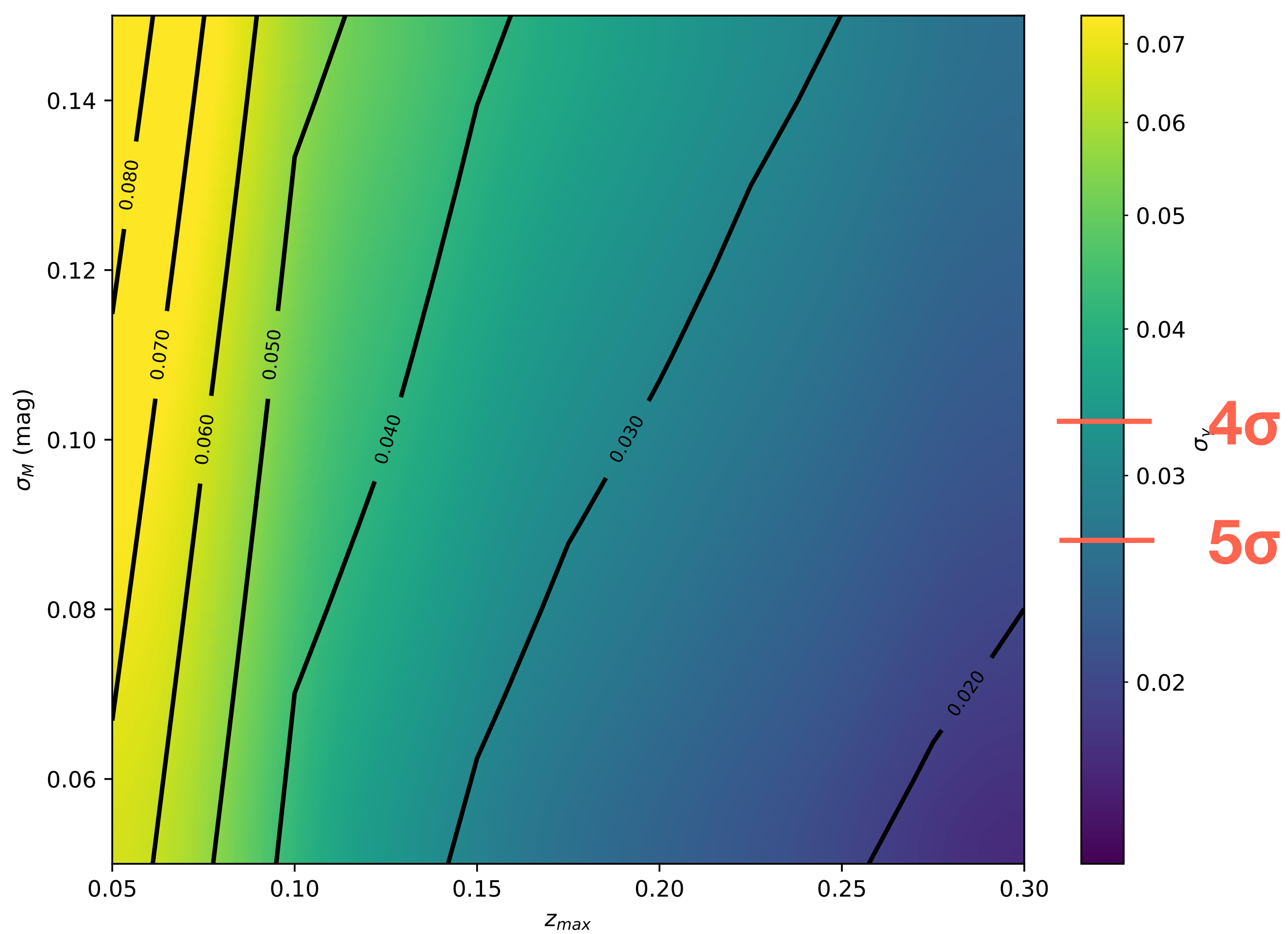
Projections for γ

ZTF2 and DESI z<0.1
~4 year



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

10-year LSST

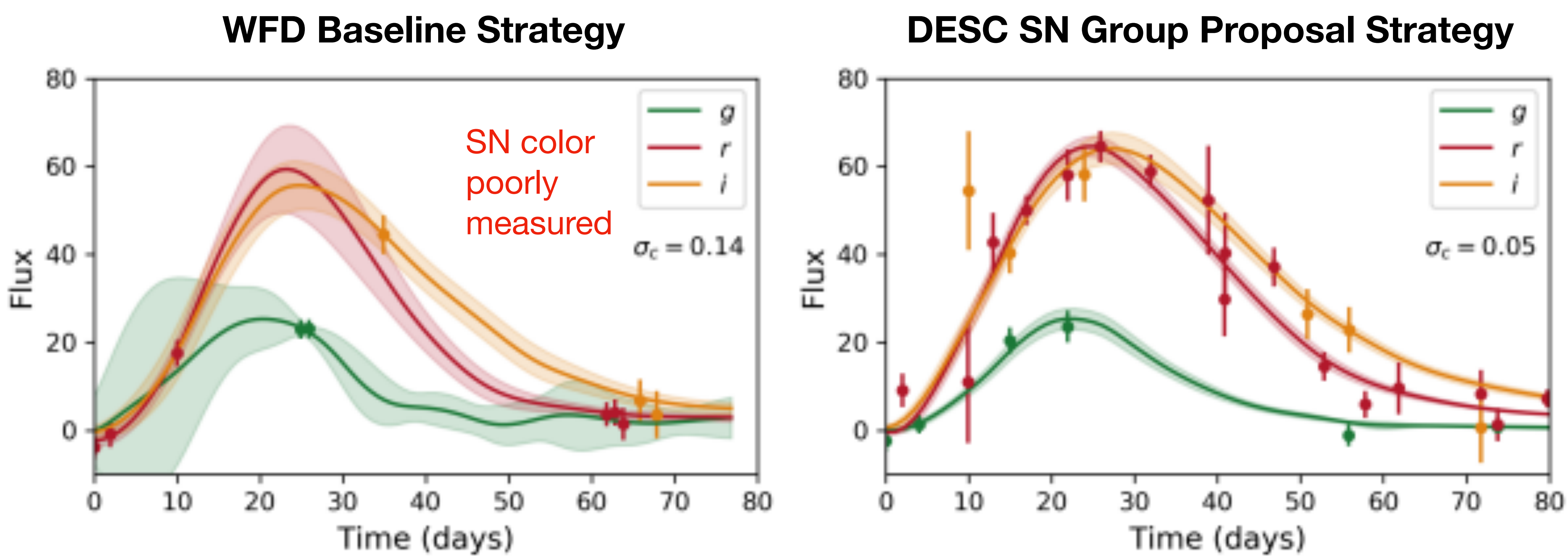


More sources and going to higher redshift can distinguish models up to 5σ depending on follow-up

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

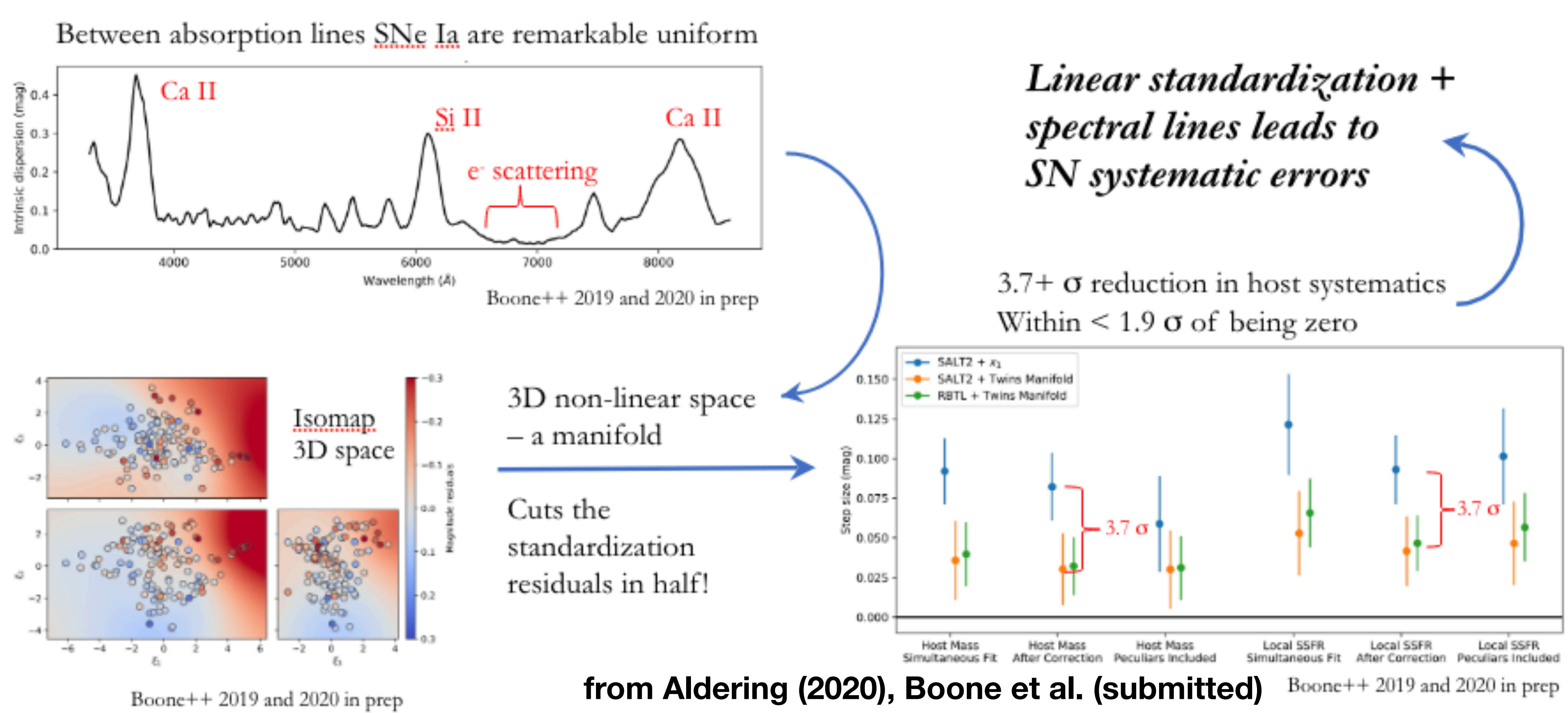


Lochner et al. (2018)

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
  - Good spectrophotometry near peak can give 4% distance precisions



from Aldering (2020), Boone et al. (submitted)

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)

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
- [CF6:] 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

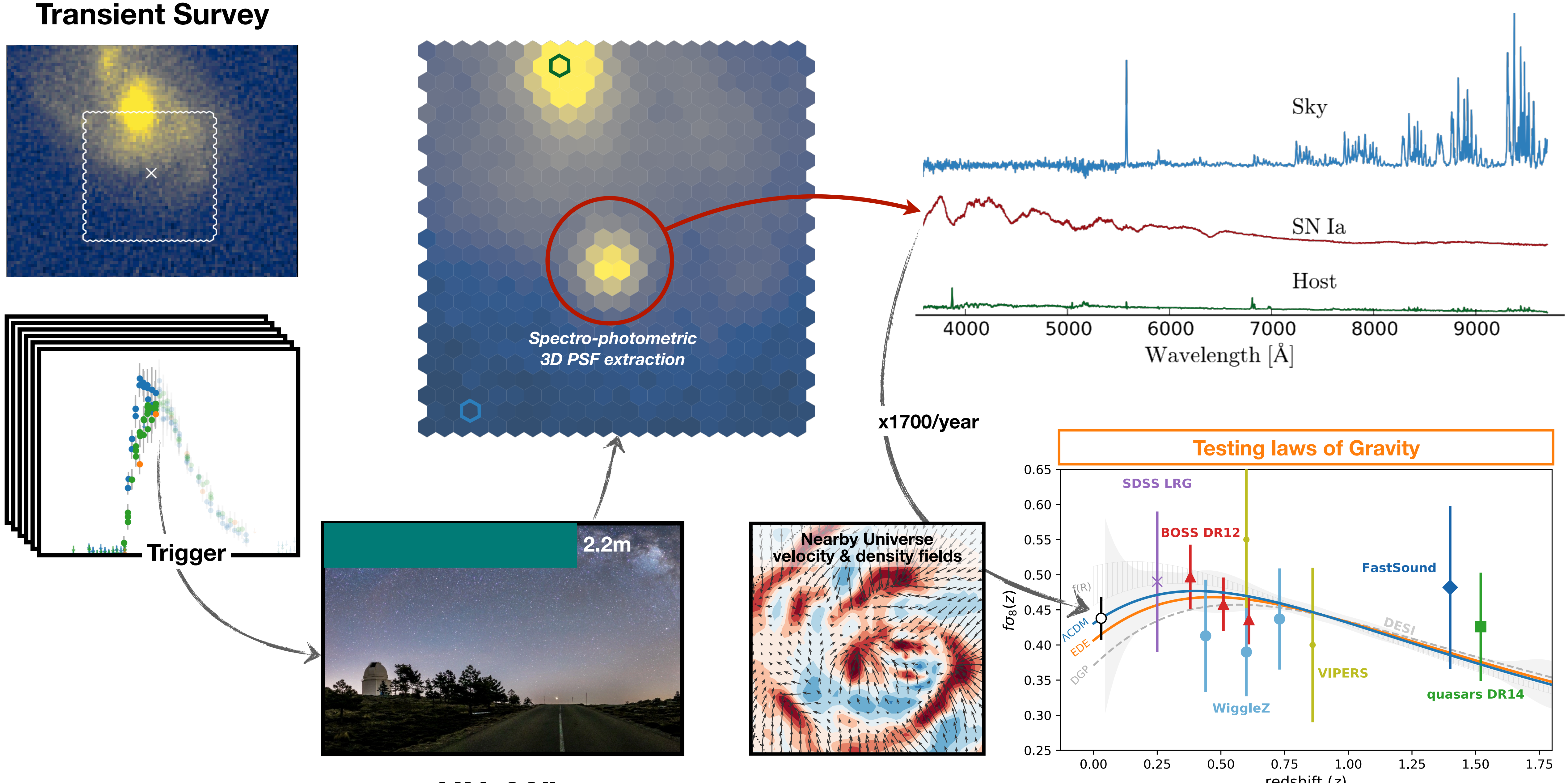
Supplemental Photometry (ZTF - South)

- 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

ESO 1-metre Schmidt telescope

PV SNIa Follow-up Network

ZTF-II, Rubin Obs.
Transient Survey



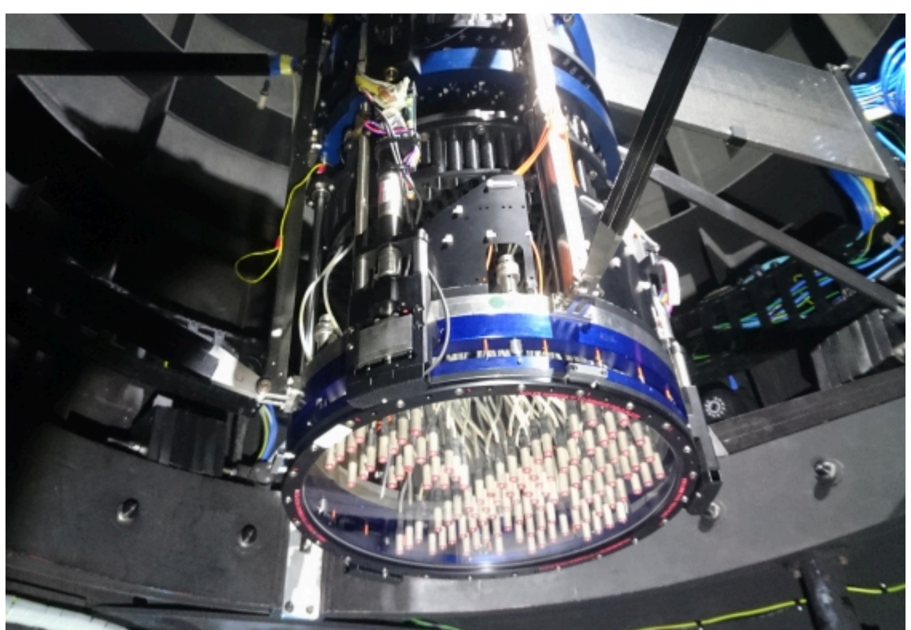
UH-88"
ESO VLT Survey Telescope
Tokyo Atacama Observatory Telescope

adapted from Galbany, Kim, Rigault

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

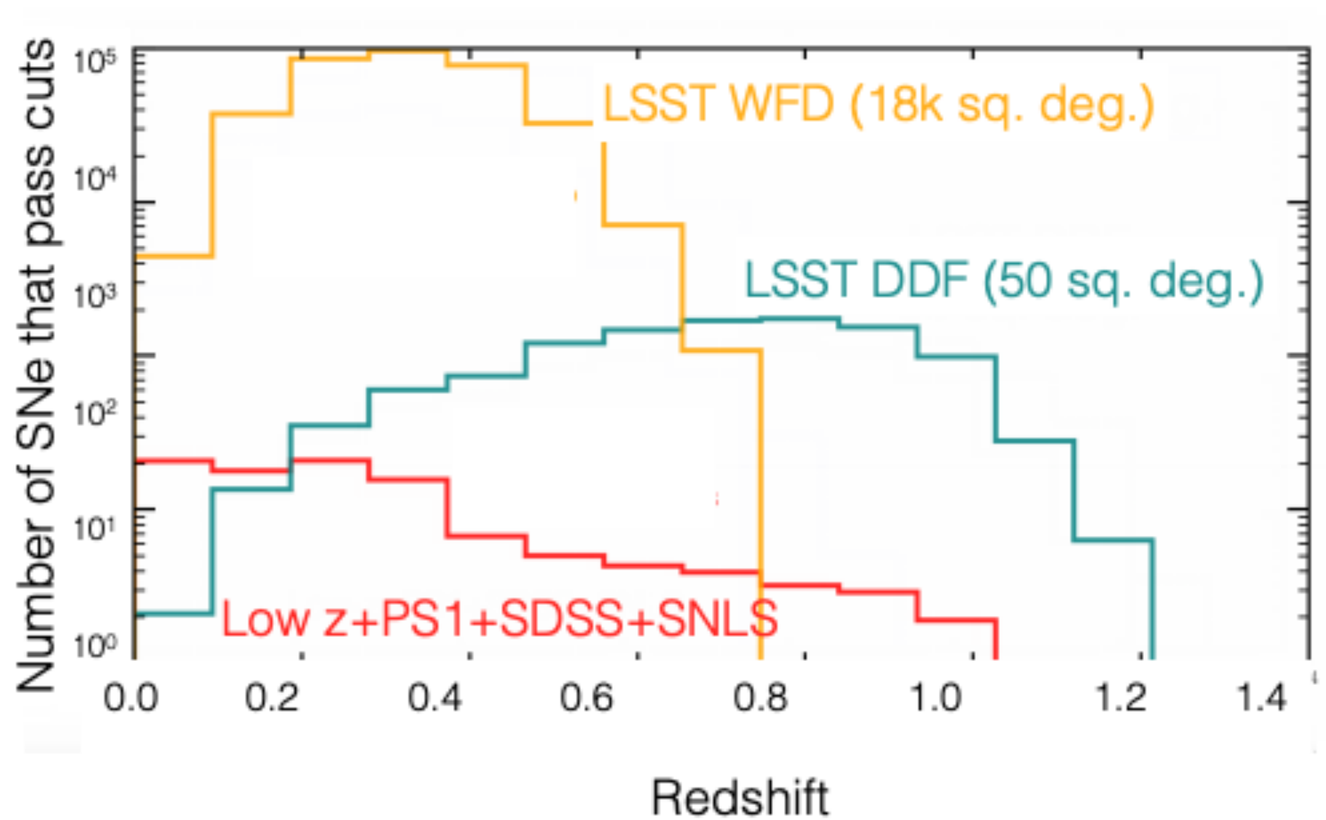
WALLABY

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

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

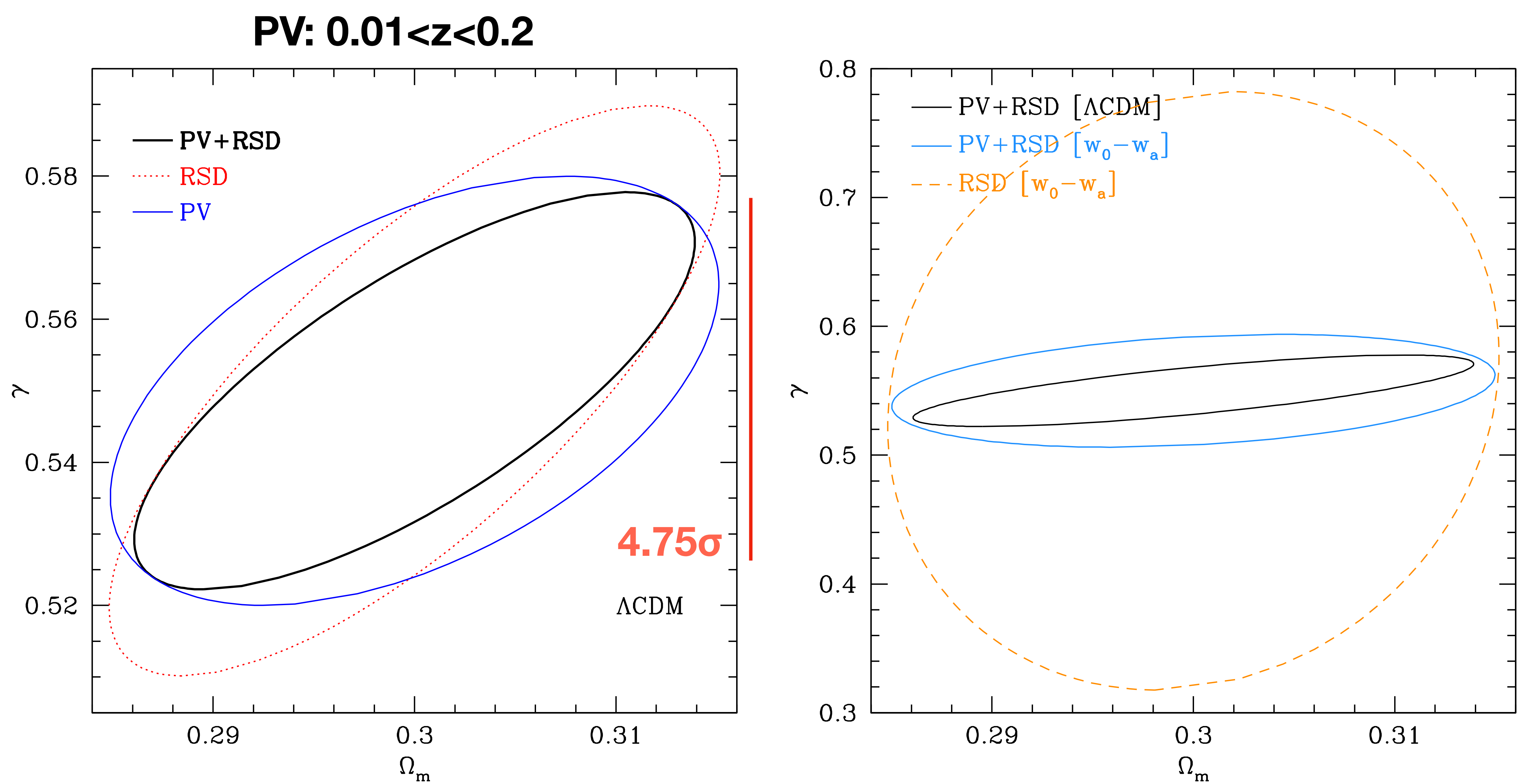
- ZTF-II will continue to be a source of northern sky SNe for 3 years (5000 classified SNe Ia $z<0.09$); ZTF-III?

- 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

PV + RSD Synergy



Kim & Linder (2020)