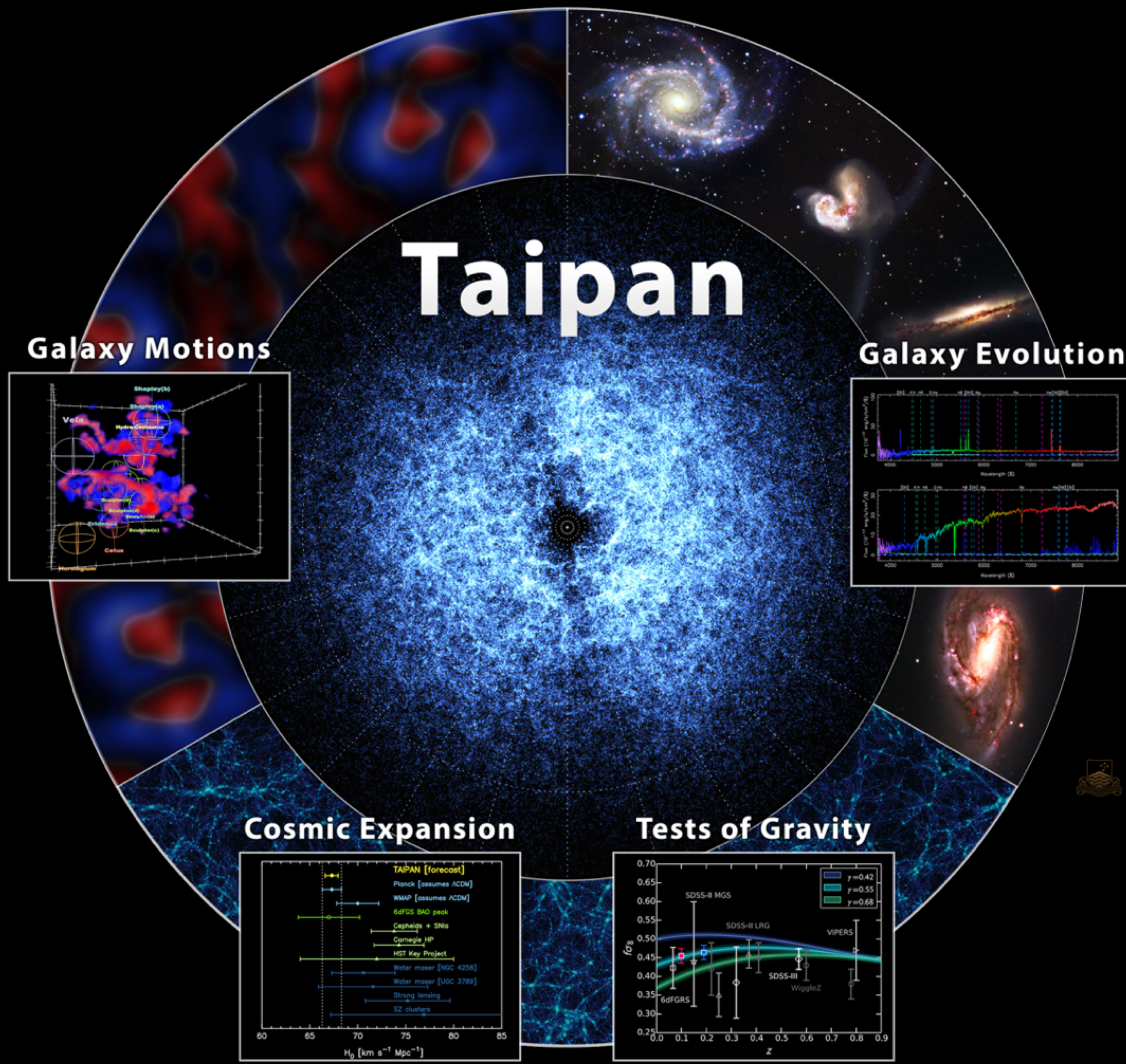
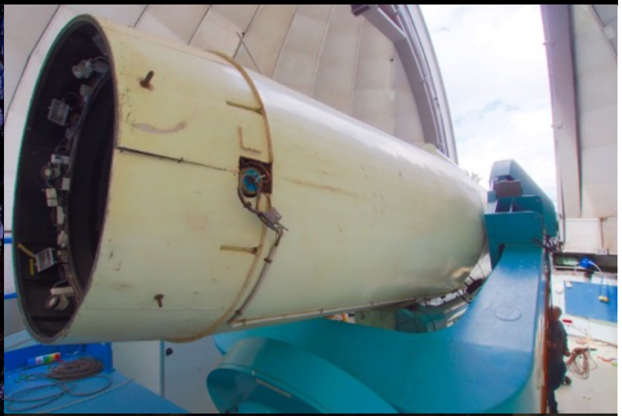
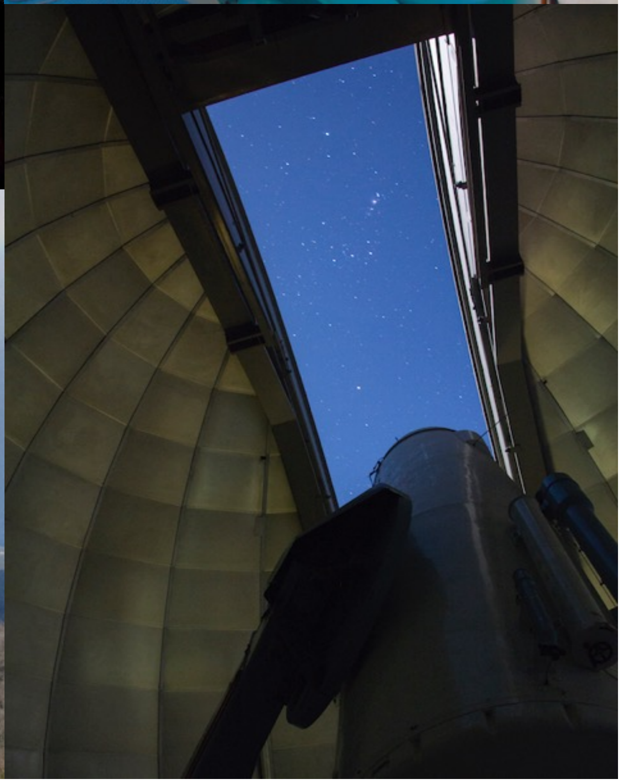

Taipan
Galaxy Motions
Vela
Cetus
Galaxy Evolution
Cosmic Expansion
TAIPAN [forecast]
Planck [assumes ΛCDM]
WMAP [assumes ΛCDM]
6dFGS BAO peak
Cepheids + SNIa
Carnegie HP
HST Key Project
Water maser [NGC 4258]
Water maser [UGC 3789]
Strong lensing
SZ clusters
60 65 70 75 80 85
H0 [km s−1 Mpc−1]
Tests of Gravity
γ=0.42
γ=0.55
γ=0.68
SDSS-II MGS
SDSS-II LRG
VIPERS
SDSS-III
WiggleZ
6dFGRS
fσ8
z

Taipan history

- Dates back to initial concept around 2009, when planning for future use of the UK Schmidt Telescope
- Conceived as next-generation galaxy spectroscopic survey covering the southern hemisphere and significantly extending the 6dF Galaxy Survey
- In 2012, a workshop was held at Macquarie University to develop key science themes; survey team science workshops held annually since, with team video meetings every few weeks to develop key science team components
- Three key technical developments identified as necessary to go beyond 6dF:
  - extensive UKST telescope and dome hardware and software upgrades to allow fully automated survey observations
  - a new purpose-designed, fixed-format, high-efficiency spectrograph
  - a new fibre positioning system using the AAO's Starbug technology (doubling as a prototype for MANIFEST fibre facility on GMT)

UK Schmidt Telescope





Taipan overview

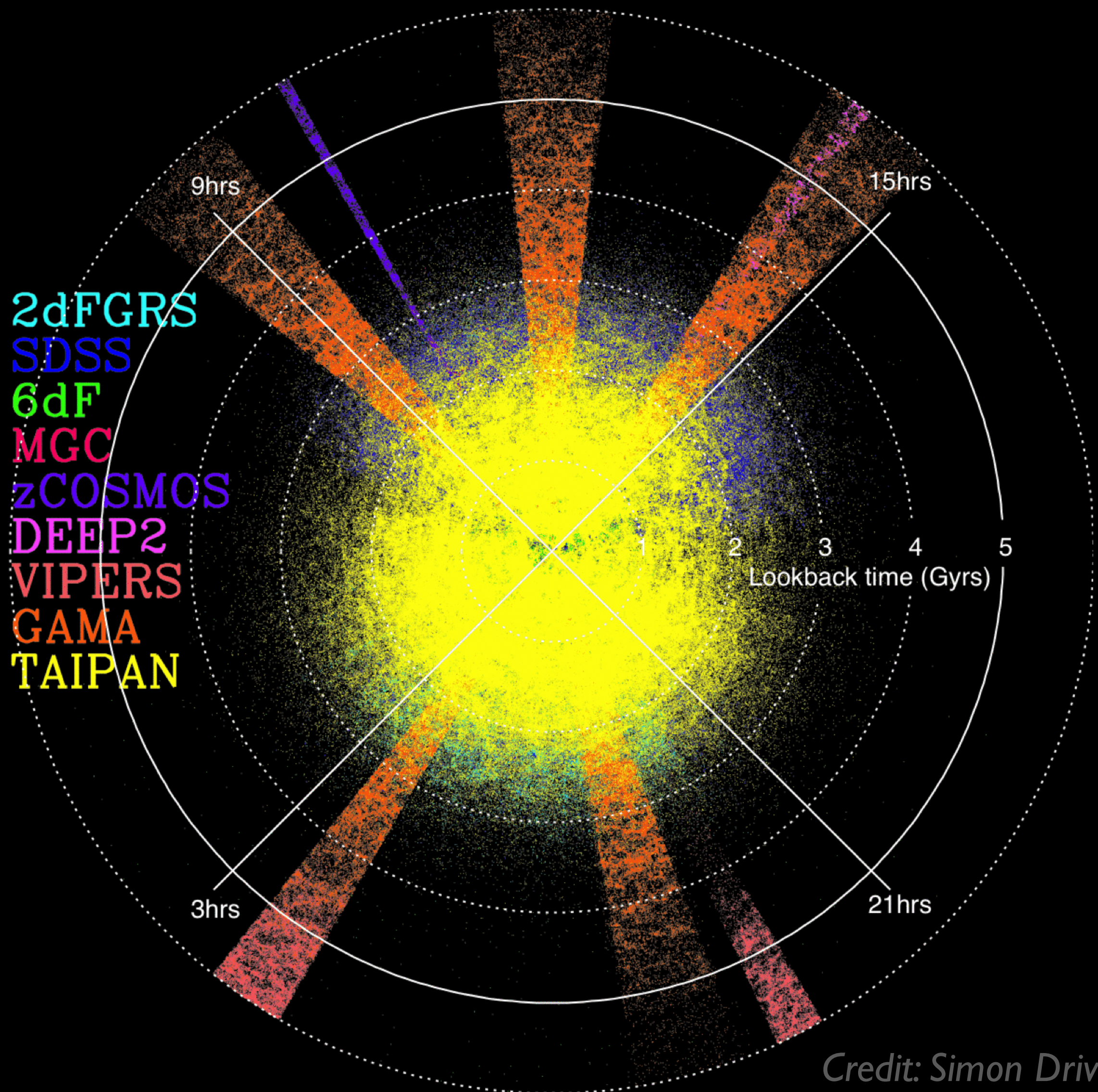
- A spectroscopic survey of galaxies over the southern hemisphere using the 1.2-metre UK Schmidt Telescope
- Observing program will take 4-5 years, from early 2019
- Spectra at R~2100 for 2×10^6 galaxies, complete to $i = 17$
- The survey team comprises more than 70 people
- Survey description: da Cunha et al., 2017, PASA, 34, 47 https://doi.org/10.1017/pasa.2017.41
- More details about survey available on Taipan website https://www.taipan-survey.org/

Taipan science

Taipan has three key science cases:

- Measuring H_0, the present-day expansion rate of the universe, with 1% precision and the growth rate of structure with 5% precision
- Making the most extensive maps of the motions and mass distribution in the local universe using galaxy peculiar velocities
- Understanding the role of mass and environment in the evolution of galaxies

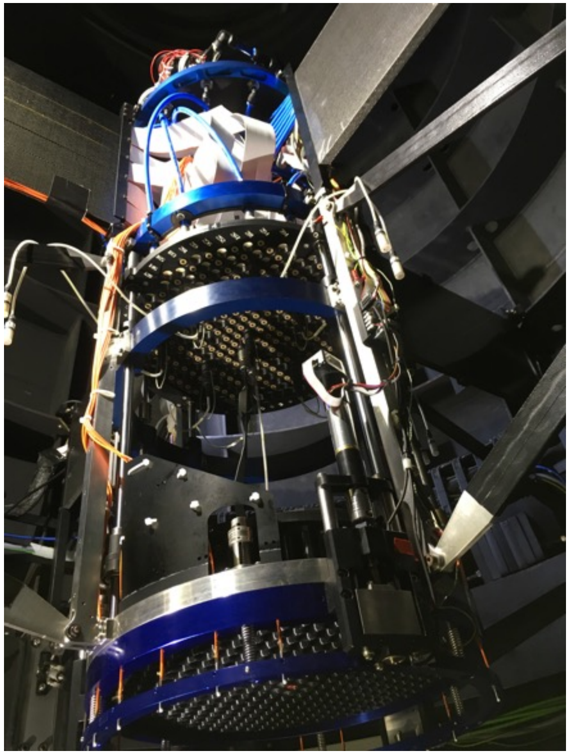
Redshift surveys

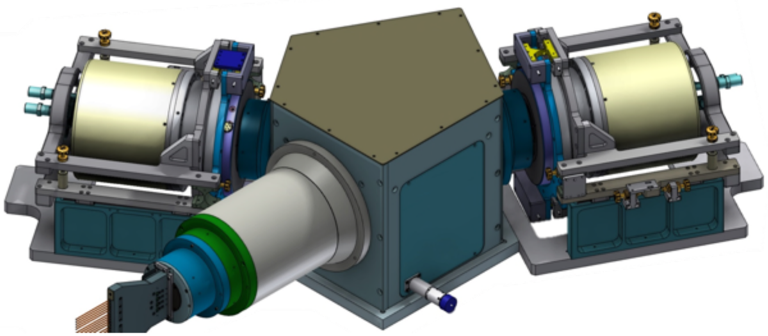


Credit: Simon Driver (UWA)

UKST + TAIPAN system

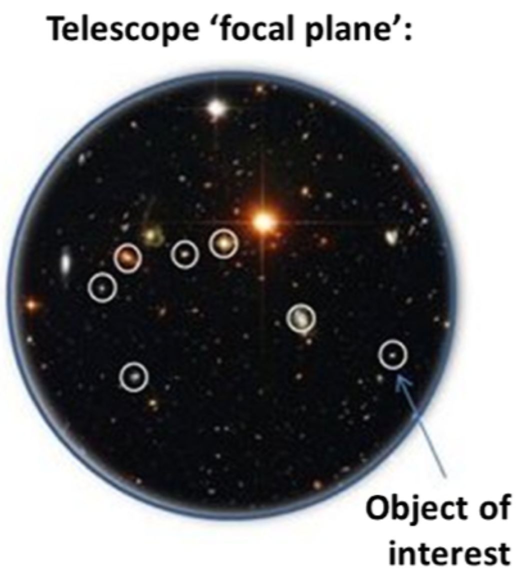
- The Taipan survey will employ the new TAIPAN multi-fibre spectrograph on a rejuvenated UKST…
    - The 1.2-metre UK Schmidt Telescope at Siding Spring Observatory is being fully refurbished so that it can operate in an automated mode, substantially increasing efficiency while reducing operating costs
    - A new 150-fibre Starbugs positioner is being built by AAO to provide rapid automated reconfigurations (prototype for MANIFEST system on GMT); additional funding has now been secured for upgrade to 300 fibres
    - A new TAIPAN spectrograph will provide high-throughput, fixed-format spectroscopy over 370nm to 870nm at R~2100
    - UKST+TAIPAN currently being commissioned; TAIPAN survey expected to start in early 2019

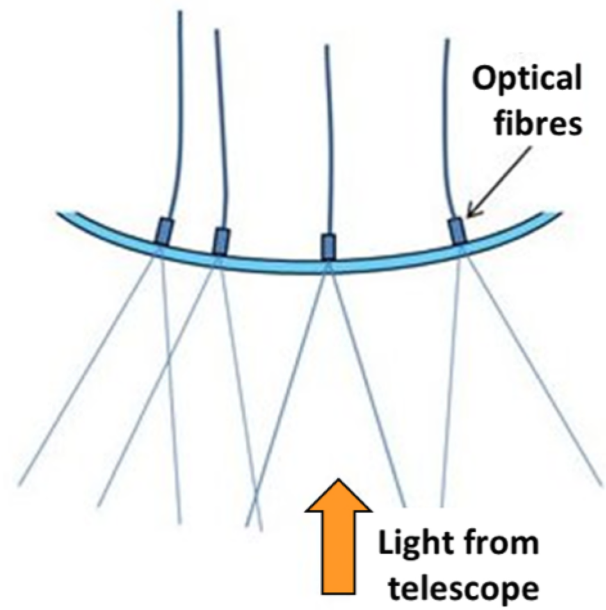




Starbug fibre positioner

- Starbugs are piezoelectric micro-robots providing an elegant way to position fibres in telescope focal planes

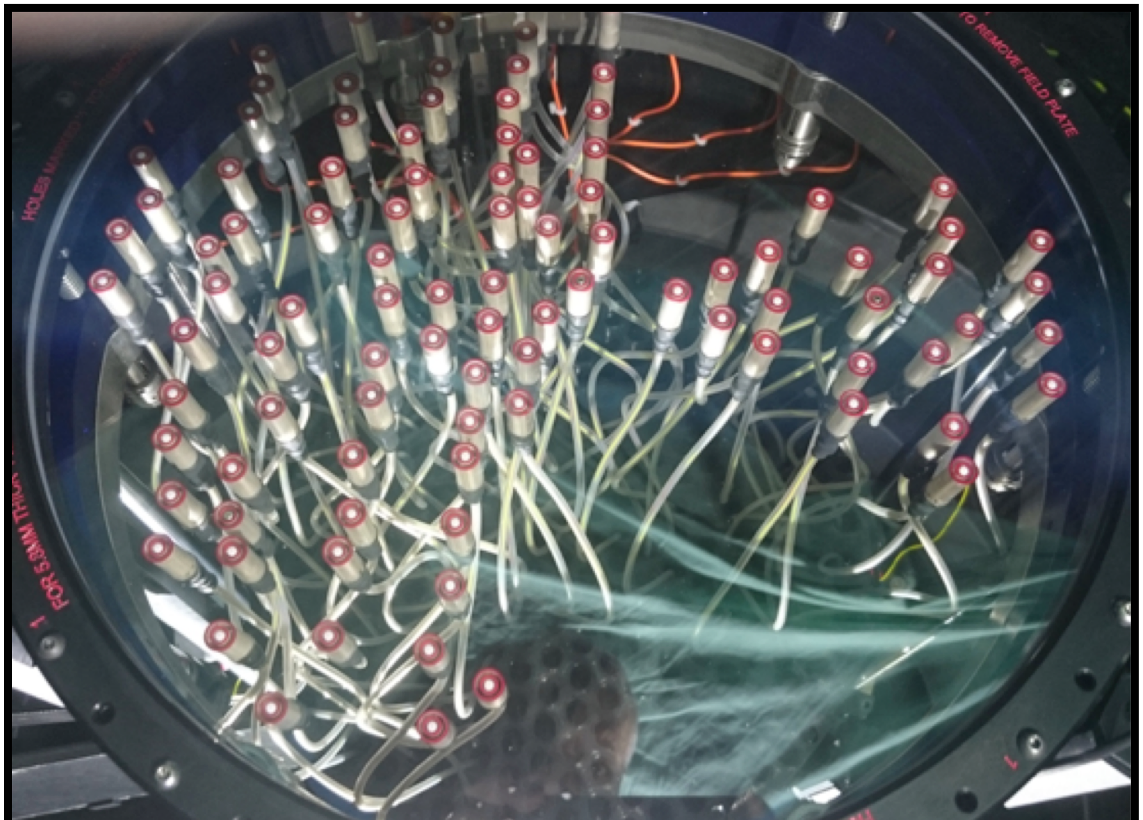


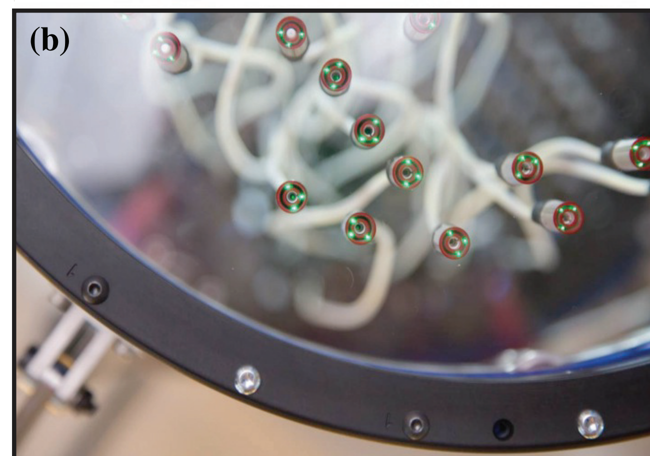


- The 150-starbug TAIPAN system is now being commissioned; the upgrade to the full 300-starbug system will occur in 2019
- Starbugs will also be used in the MANIFEST fibre system that will feed spectrographs on the Giant Magellan Telescope

Starbug fibre positioner

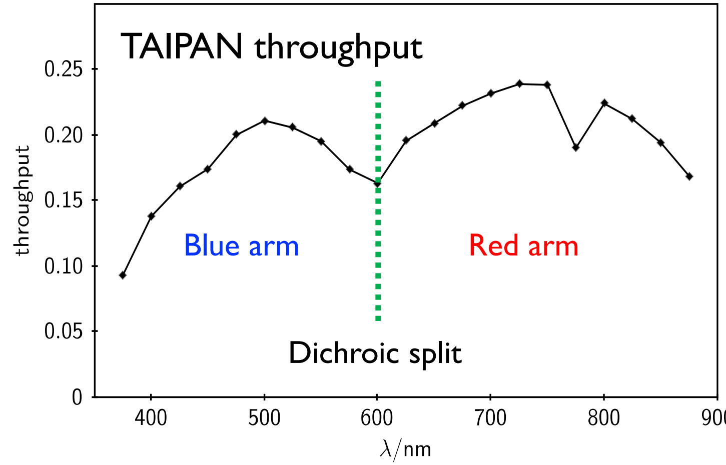
The initial 150-starbug TAIPAN system is now being commissioned; upgrading to the full 300-starbug system will occur in 2019

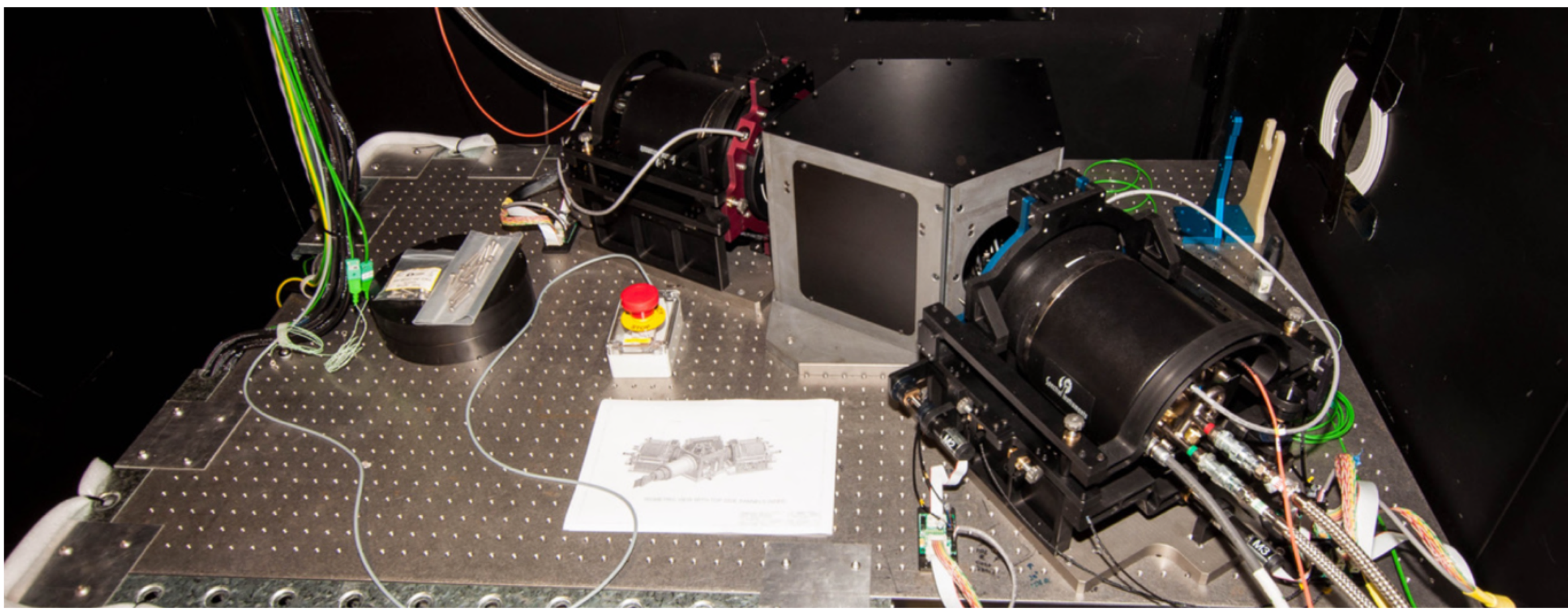




TAIPAN technical specifications

Field of view	6° diameter
# fibres	150 (upgrade to 300 in 2019)
Fibre diameter	3.3 arcsec
Wavelength range	370 nm – 870 nm
Resolving power ($R = \lambda/\Delta\lambda$)	1960 (blue) & 2740 (red)
Instrumental resolution (σ)	65 km/s (blue) & 46 km/s (red)



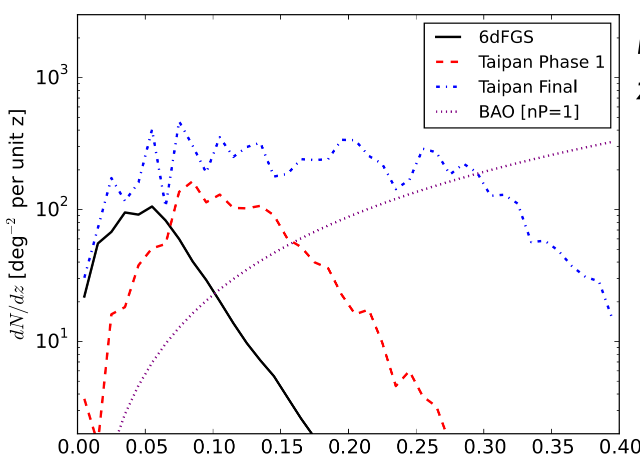


Taipan components & phases

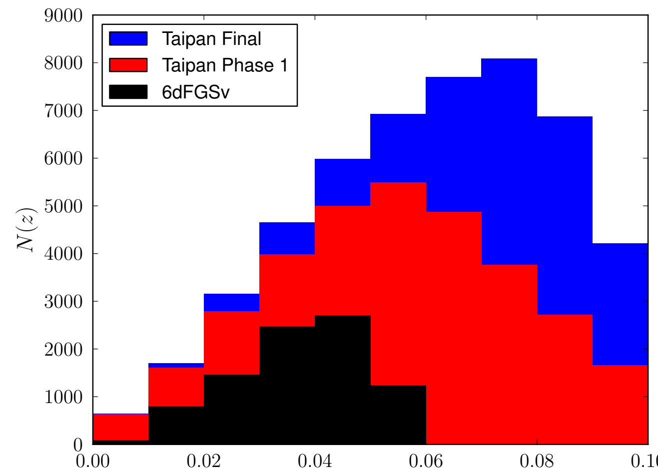
- The Taipan galaxy survey has three components:
  - BAO survey – large-volume z-survey optimized for cosmology
  - Peculiar velocity survey – Fundamental Plane survey optimized for nearby early-type galaxies and measuring peculiar motions
  - Legacy survey – an *i*-band magnitude-limited sample with high completeness optimized for galaxy studies and legacy value
- The survey will be carried out in two phases:
  - Taipan Phase 1 [first ~15 months] will be based on 2MASS (BAO survey), 6dFGS (PV survey) & KiDS-S (*i*-band survey); these are the best available sources at the start of the survey
  - Taipan Final [next ~3 years] will be based on SkyMapper and PanSTARRS (all surveys); best input sources by end of Phase 1

Taipan survey phases

		Magnitude limits	Number of galaxies	Median redshift, $z_{\rm med}$	Sky area / $\deg^2$	Volume at $z_{\rm med}$ / $h^{-3}{\rm Mpc}^3$
Phase I	BAO	$J_{\rm Vega} < 15.4$ $J_{\rm Vega} - K_{\rm Vega} > 1.2$	3.0×10^5	0.110	20, 600	2.0×10^8
	Peculiar velocities	$r_{\rm fibre} < 17.6$	3.3×10^4	0.055	17, 000	2.2×10^7
	i-selected	$i \leq 17$	9.0×10^4	0.086	1, 500	7.2×10^6
Final	BAO	$i \leq 17$ LRG: $17 < i < 18.1$, $g - i > 1.6$	2.0×10^6	0.170	20, 600	1.3×10^9
	Peculiar velocities	$r_{\rm fibre} < 17.6$ $g_{\rm fibre} - r_{\rm fibre} > 0.8$	5.0×10^4	0.065	20, 600	4.3×10^7
	i-selected	$i \leq 17$	1.2×10^6	0.086	20, 600	9.8×10^7



N(z) for *z*-sample



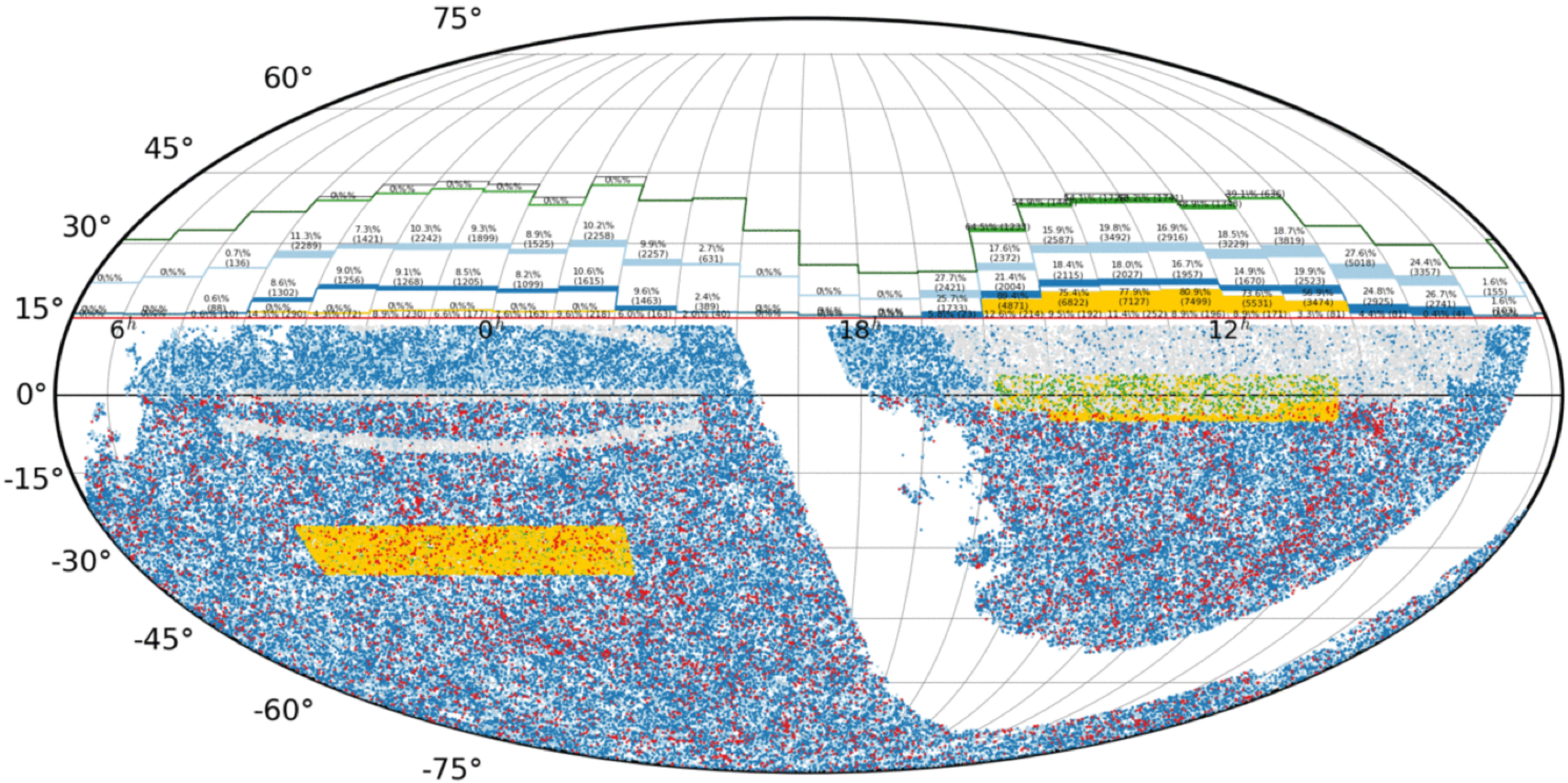
N(z) for *v*-sample

Taipan and other surveys

		Magnitude limits	Number of galaxies	Median redshift, z_{med}	Sky area / deg^2	Volume at z_{med} / $h^{-3}Mpc^3$
	BAO	$J_{Vega} < 15.4$	3.0×10^5	0.110	20, 600	2.0×10^8
		$J_{Vega} - K_{Vega} > 1.2$				
Taipan Phase 1 (Section 4.2)	Peculiar velocities	$r_{fibre} < 17.6$	3.3×10^4	0.055	17, 000	2.2×10^7
	i-selected	$i \leq 17$	9.0×10^4	0.086	1, 500	7.2×10^6
	BAO	$i \leq 17$	2.0×10^6	0.170	20, 600	1.3×10^9
		LRG: $17 < i < 18.1$, $g - i > 1.6$				
Taipan Final (Section 4.3)	Peculiar velocities	$r_{fibre} < 17.6$	5.0×10^4	0.065	20, 600	4.3×10^7
		$g_{fibre} - r_{fibre} > 0.8$				
	i-selected	$i \leq 17$	1.2×10^6	0.086	20, 600	9.8×10^7
6dFGS (Jones et al. 2009)		$K_{Vega} \leq 12.65$	1.3×10^5	0.053	17, 000	2.1×10^7
2dFGRS (Colless et al. 2001)		$b_J \leq 19.45$	2.2×10^5	0.110	1, 600	1.7×10^7
SDSS-DR7 (Abazajian et al. 2009)		$r \leq 17.77$	9.3×10^5	0.100	9, 380	7.6×10^7

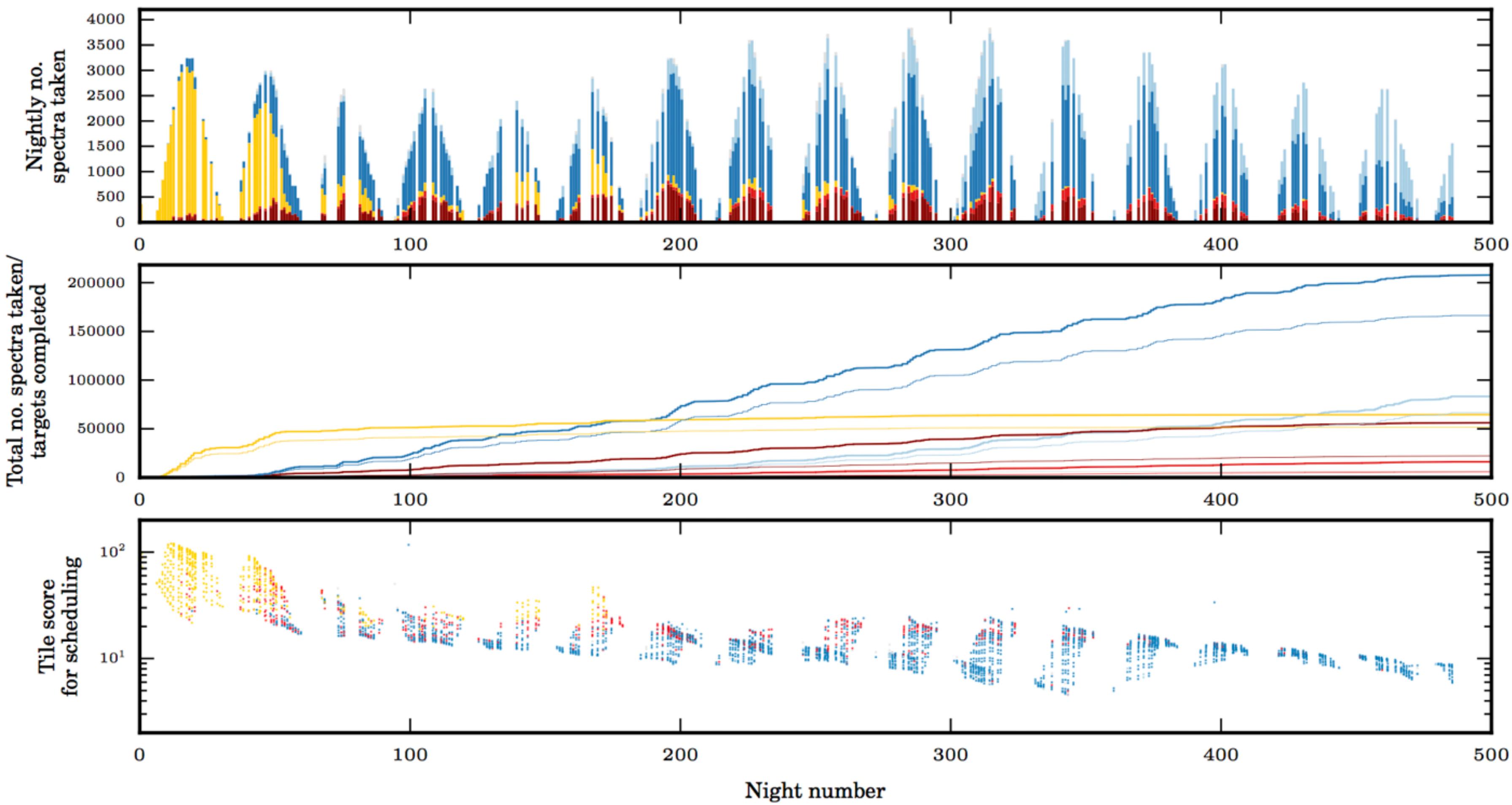
Note: For Taipan Phase 1 and Taipan Final, we divide the survey into three samples: 'BAO' is the redshift sample for BAOs/cosmology science, which includes the magnitude-limited sample and LRG extension; 'Peculiar velocities' refers to the peculiar velocity sample; and 'i-selected' refers to the spectroscopically-complete, magnitude-limited ($i \leq 17$) sample that will be used for galaxy evolution science.

Simulation of Taipan observations



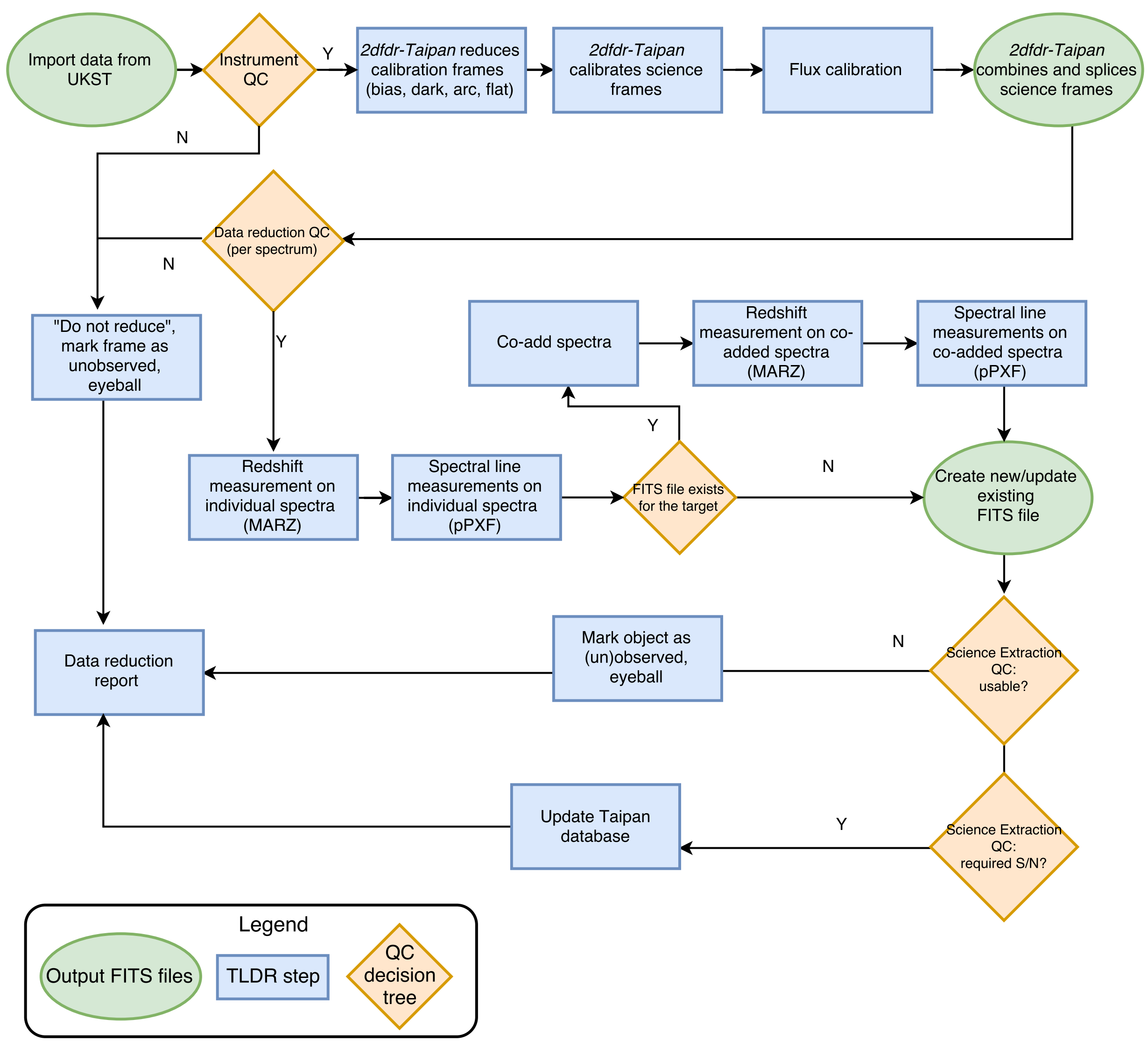
Simulation of Taipan observations

BAO sample: 2MASS LRGs and J_{Vega}<15.4; PV sample: 6dFGS, Taipan; Legacy sample: *i*<17



Taipan Live Data Reduction

TLDR



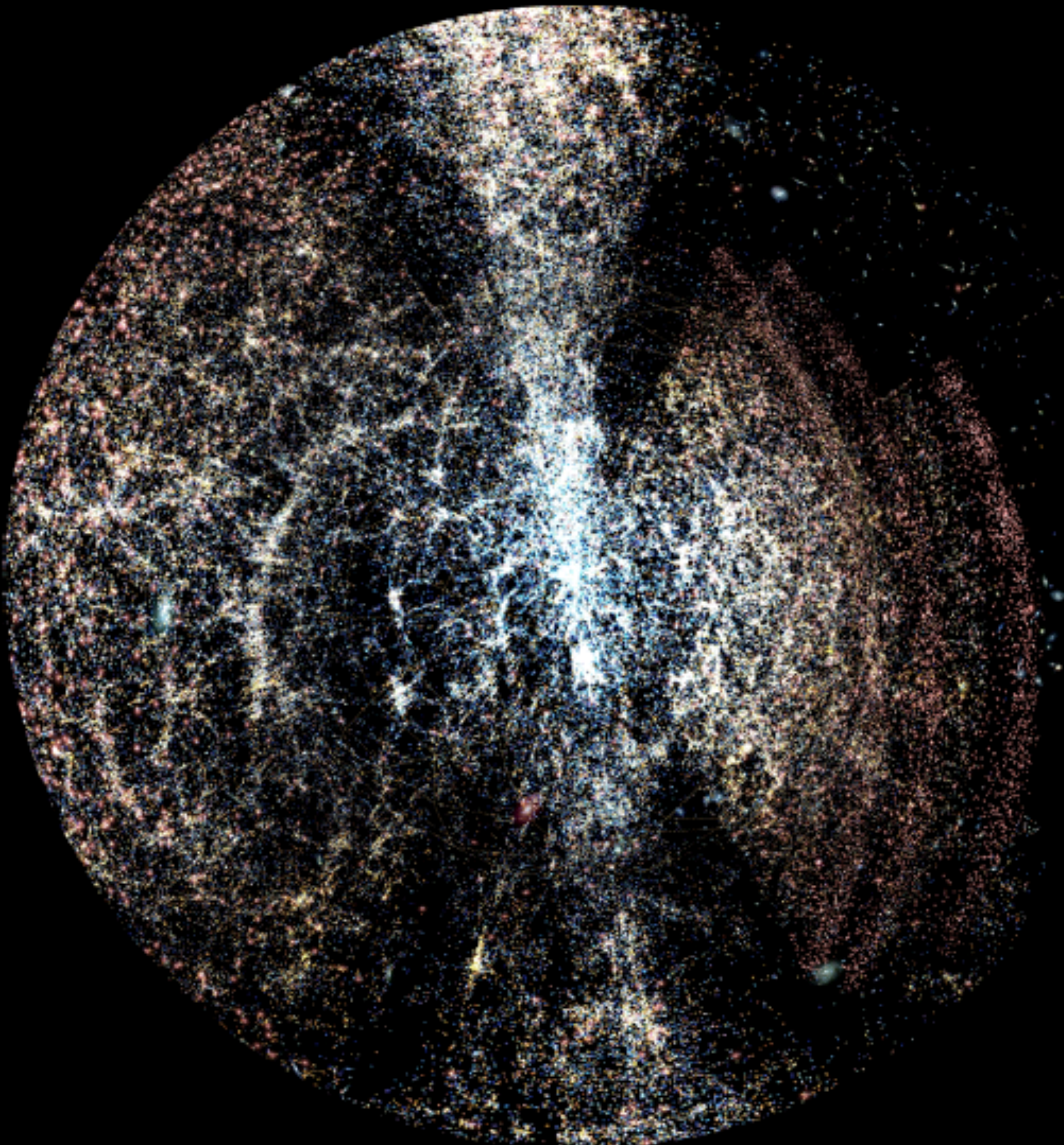
Cosmological goals

1. **What is the current expansion rate of the universe?**
   Directly measure the Hubble constant, H_0, at *low* redshift
   (i.e. with minimal dependence on the cosmological model)
   to a precision of 1% using the large-scale distribution of galaxies
2. **What are the local universe density & velocity fields?**
   Map both *density* & *velocity* fields over a greater volume and with more galaxies than any previous survey, and check consistency
3. **What is the correct theory of gravity on large scales?**
   Test gravity models using both the *peculiar velocities* of galaxies and the *redshift-space distortions* of their large-scale distribution

Taipan will exploit the power of measuring both redshifts & peculiar velocities in the same volume – which is only possible at *low* redshift

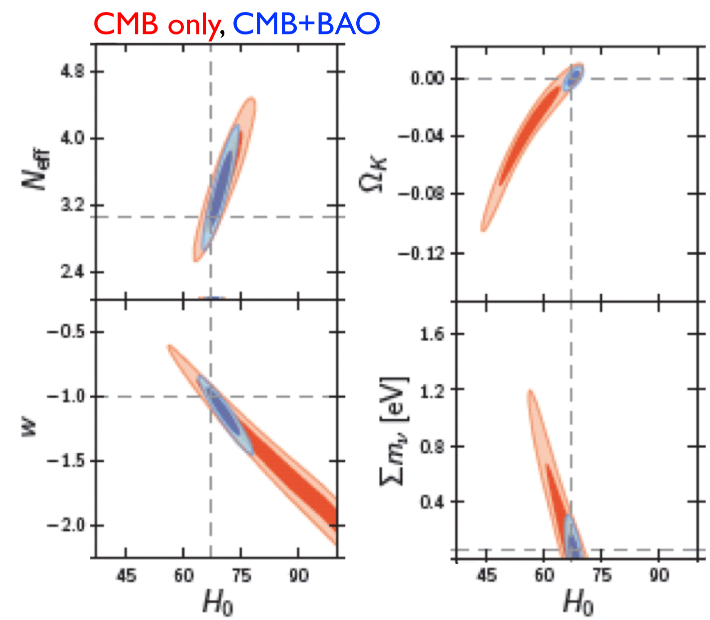
Tests of large-scale gravity

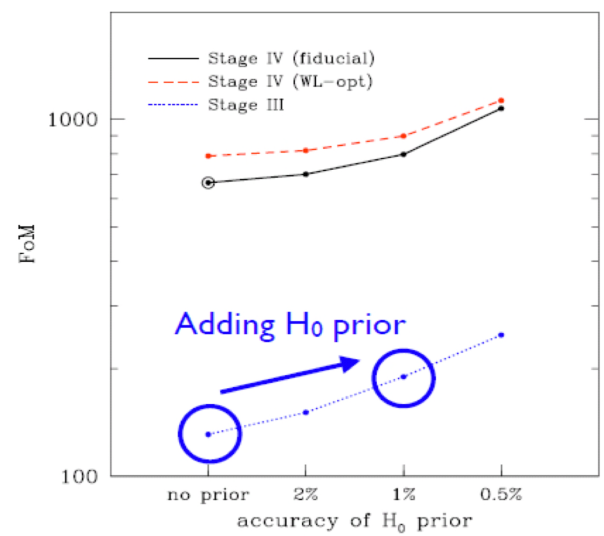
- Is the growth rate of structure consistent with the cosmic expansion history?
- Is the gravitational physics of the homogeneous and inhomogeneous Universe consistent?
- Need to measure galaxy velocities ...



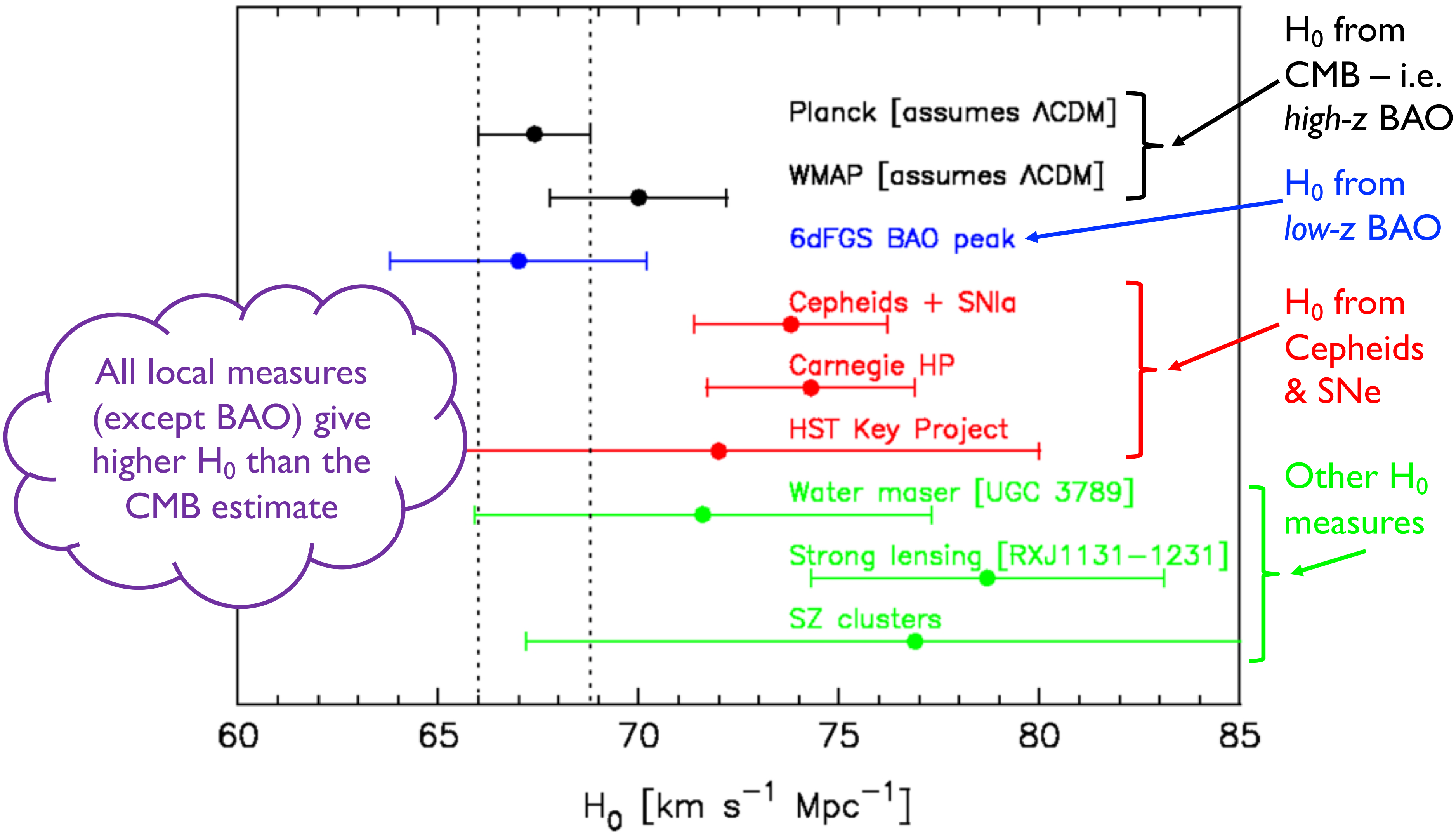
Why measure H_0?

- H_0, the <u>local</u> (i.e. zero-redshift) expansion rate, is a fundamental cosmic parameter defining the age & scale of the universe
- For a flat ΛCDM universe, *Planck* CMB observations alone give H_0 to ~1%, but this is a model-dependent result
- An independent measure of H_0 is a key prior improving constraints on other parameters (e.g. dark energy, neutrino numbers/mass)
- Currently, there is a significant discrepancy between H_0 determined from the CMB and local 'distance ladder' measurements (SNe, Cepheids, masers) with tension at >3σ level



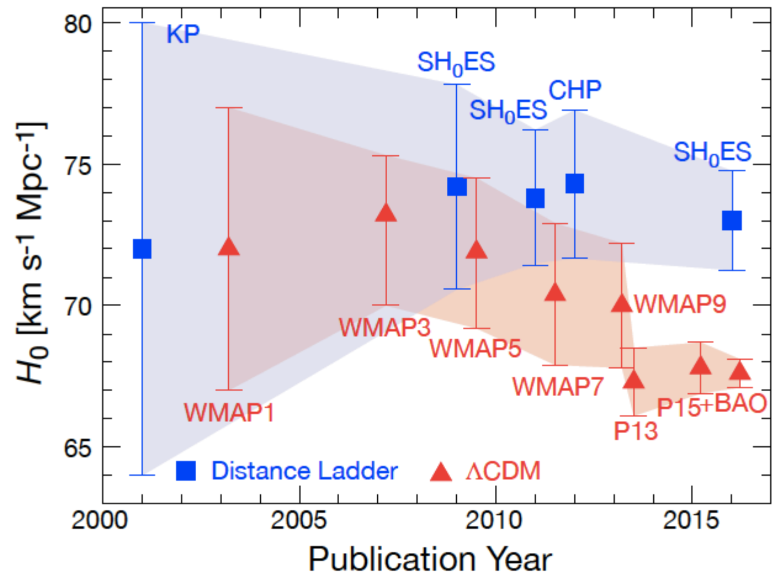


Local & CMB H_0 are discrepant

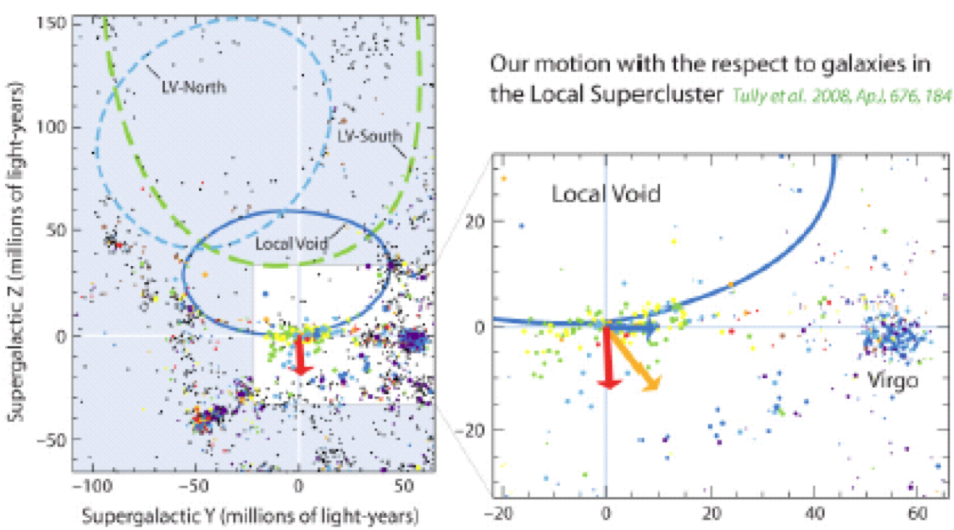


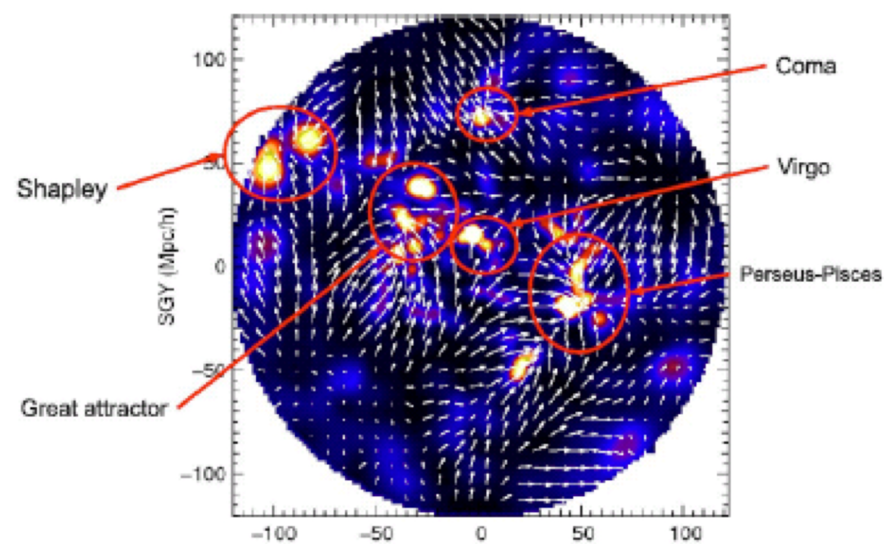
Local & CMB H_0 are discrepant

- Furthermore, the observational discrepancies in H_0 have been sharpening up over time
- These discrepancies could be…
  - … systematic errors in either the local or the CMB measurements
  - … a signature of non-ΛCDM physics in the cosmological model
  - … a signature of gravitational physics due to inhomogeneity and back-reaction



Our motion with the respect to galaxies in the Local Supercluster *Tully et al. 2008, ApJ, 676, 184*

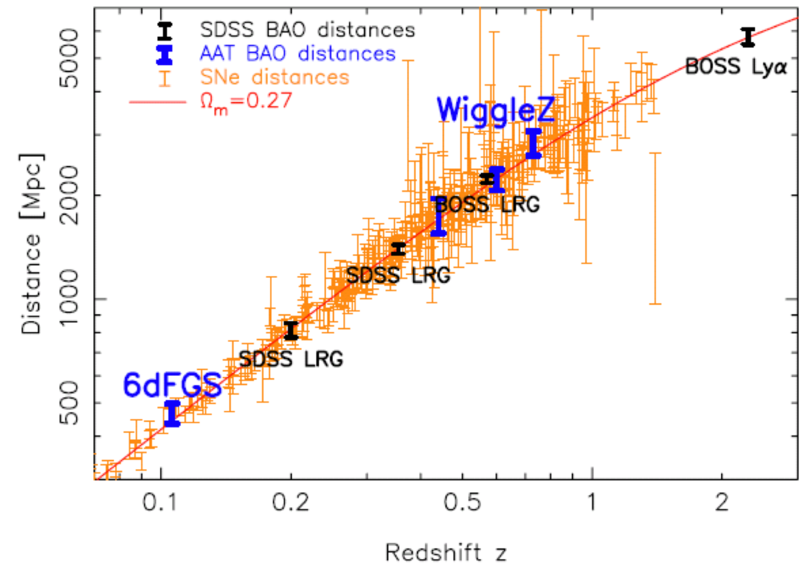


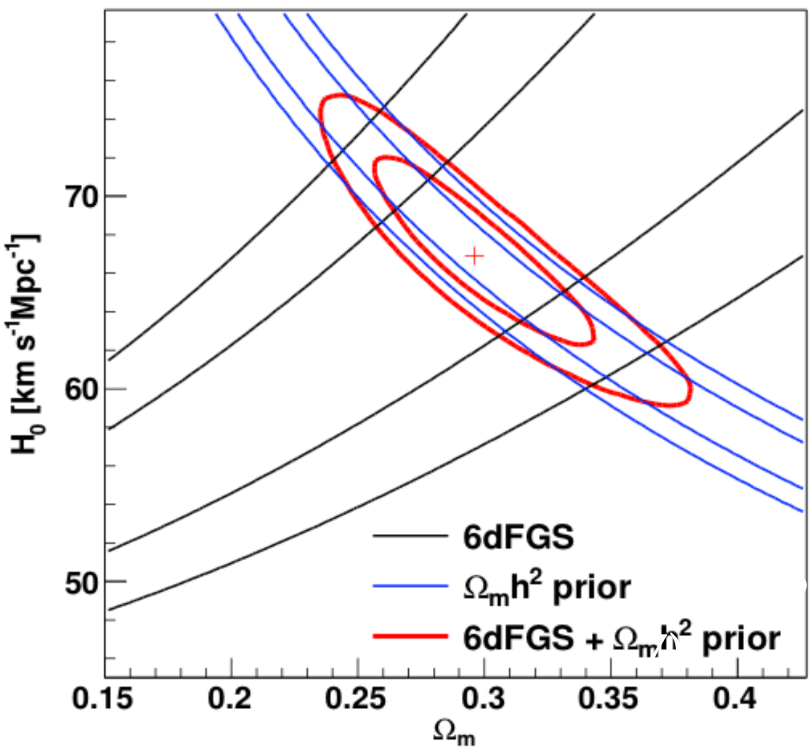


Hubble constant from 6dFGS

At low z, distance measures only constrain H_0 – but such H_0 estimates are (almost) independent of the cosmological model

Local 6dFGS BAO results give lower H_0 like CMB and unlike local distance ladder





low-z

Beutler+ 2011 (6dFGS, BAO)
H_0 = 67 ± 3.2 km/s/Mpc

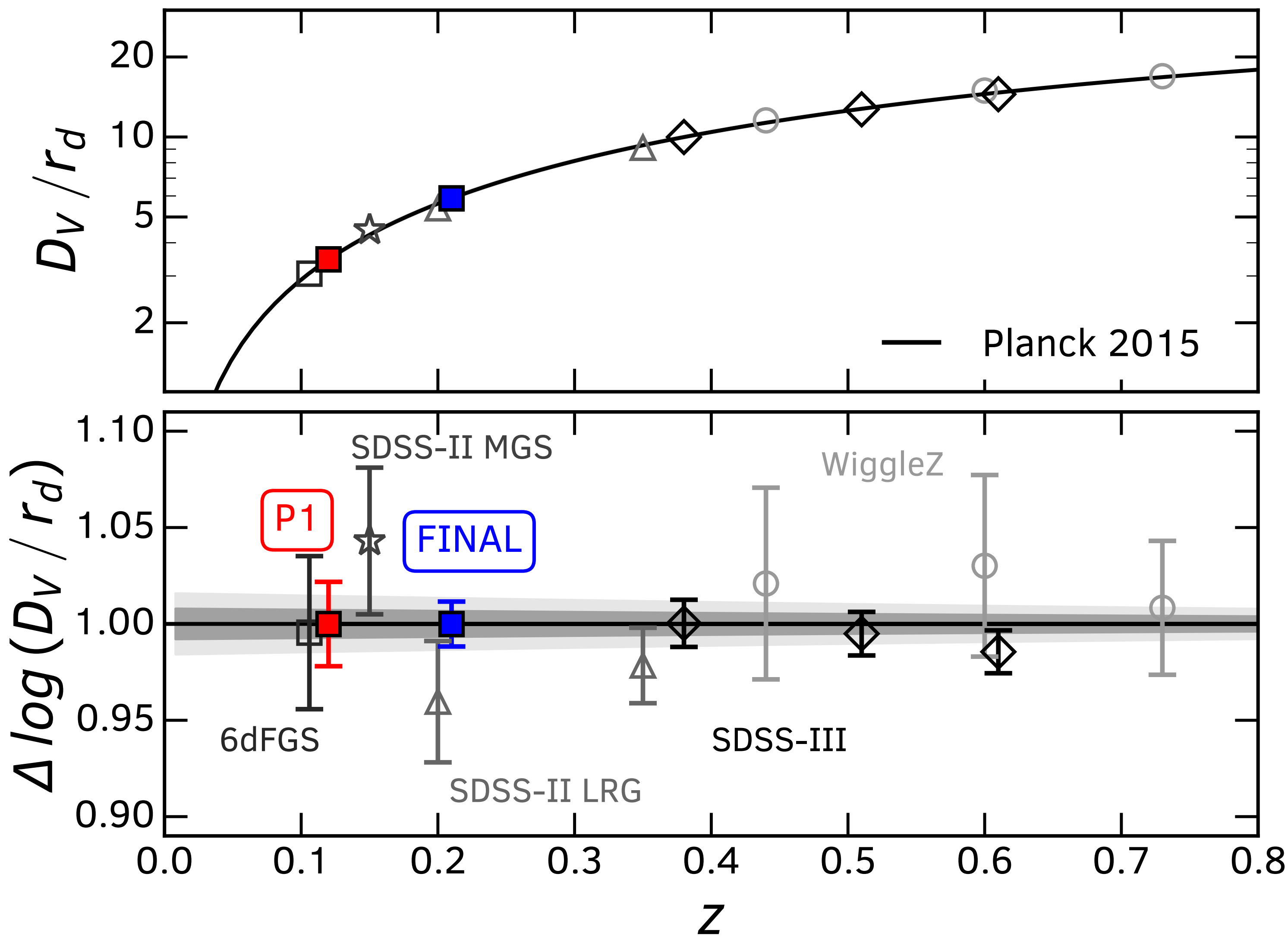
Riess+ 2018 (Cepheids, SNe)
H_0 = 73.5 ± 1.7 km/s/Mpc

high-z

Planck 2016 (CMB, BAO)
H_0 = 66.9 ± 0.6 km/s/Mpc
(*model-dependent*)

3.7σ tension

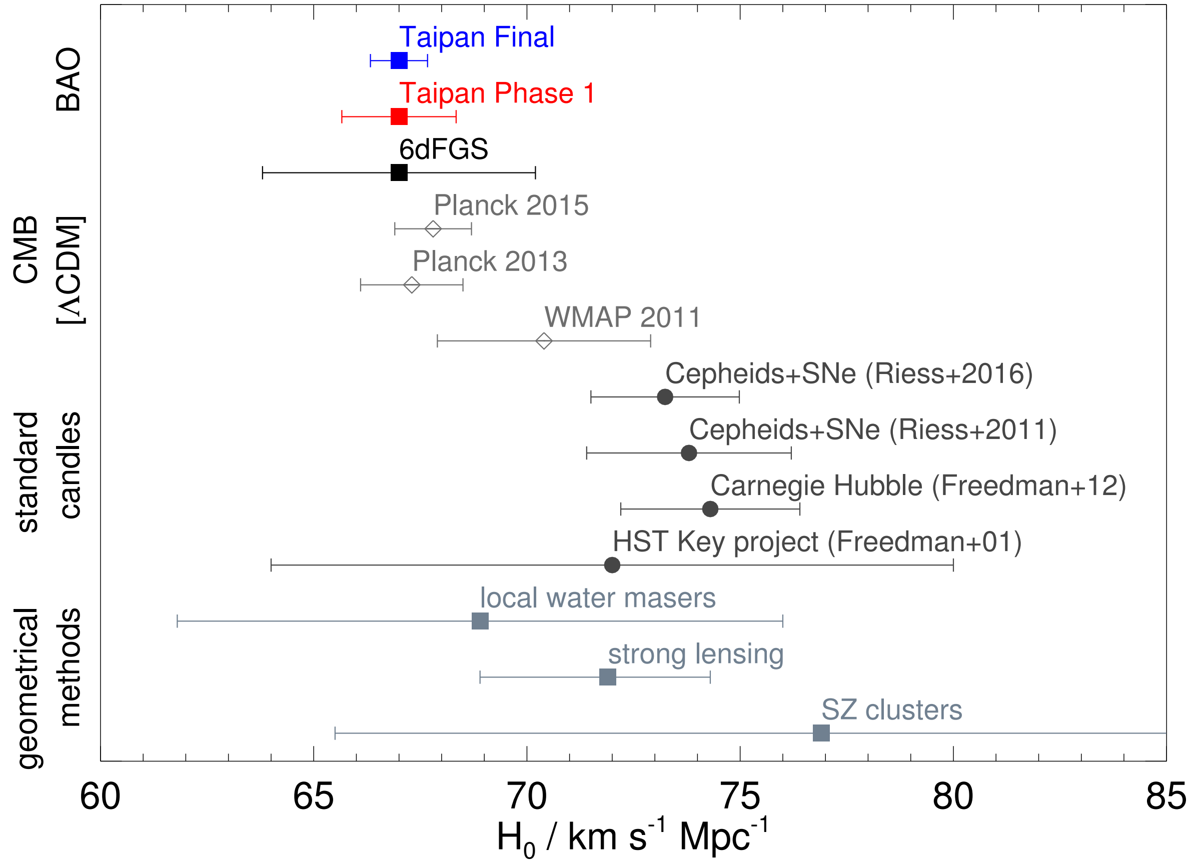
Taipan BAO distances



Hubble constant from Taipan

- With 2,000,000 galaxies at $\langle z \rangle \approx 0.17$ over $V_{eff} \approx 1.3$ Gpc^3, detailed simulations show Taipan Final will measure H_0 to 0.9% precision (with 2.1% precision already by the end of Taipan Phase 1)

- Taipan Final will thus be 5x more precise than 6dFGS:
  - Gain ~2.5x from larger sample size and volume of Taipan *cf.* 6dFGS
  - Gain another ~2x from better BAO reconstruction



H_0 tensions

- Taipan will test the tension in H_0 measurements between high-z CMB and low-z distance ladder estimates by providing a 1% low-z BAO estimate for comparison
  - 2018 status: high-z Planck CMB and low-z SNe distance ladder estimates are in 3.7σ tension
  - 2021 case A: Taipan supports the Planck CMB estimate with a BAO-derived low-z 1% H_0 measurement...
  - 2021 case B: Taipan supports the distance ladder estimate with a BAO-derived, low-z 1% H_0 measurement…
- Less interesting intermediate cases are of course also possible!

2017 status	Direct measure	Distance ladder
High redshift (z~1100)	Planck (2016) CMB 66.9 +/- 0.6	N/A
Low redshift (z<0.1)	6dFGS (2011) BAO 67.0 +/- 3.2	Riess+(2018) SNe 73.5 +/- 1.6

2018 status → 3.7σ 'tension' in direct (CMB) & distance ladder (SNe) results

2021 Case A	Direct measure	Distance ladder
High redshift (z~1100)	Planck (2016) CMB 66.9 +/- 0.6	N/A
Low redshift (z<0.1)	Taipan (2021) BAO 66.9 +/- 0.6	Riess+(2021) SNe 73.5 +/- 0.7

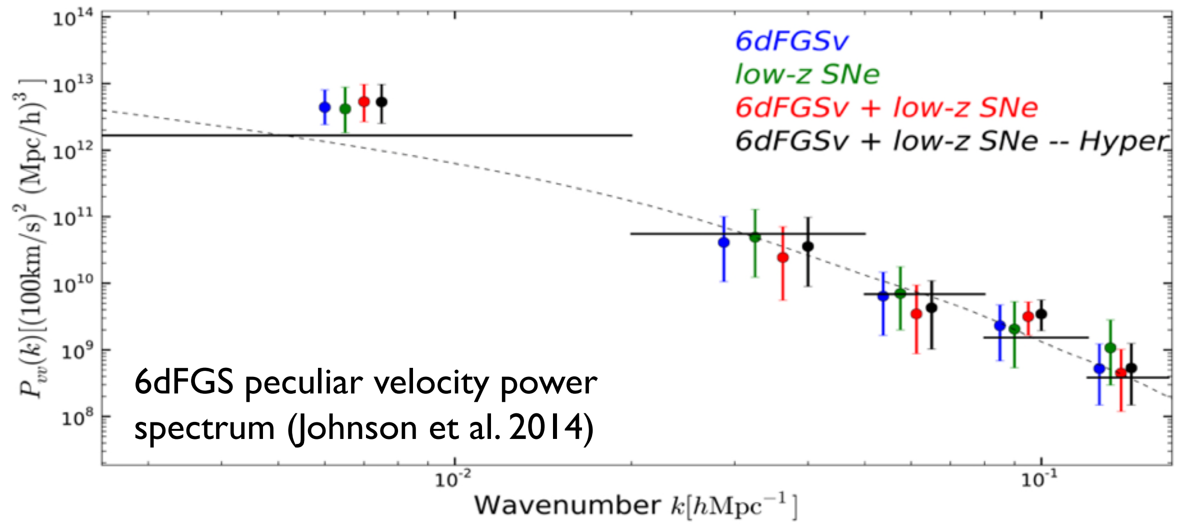
2021 Case A → 7.2σ 'discrepancy' between low-redshift results of two methods
$\Rightarrow$ problem with distance ladder

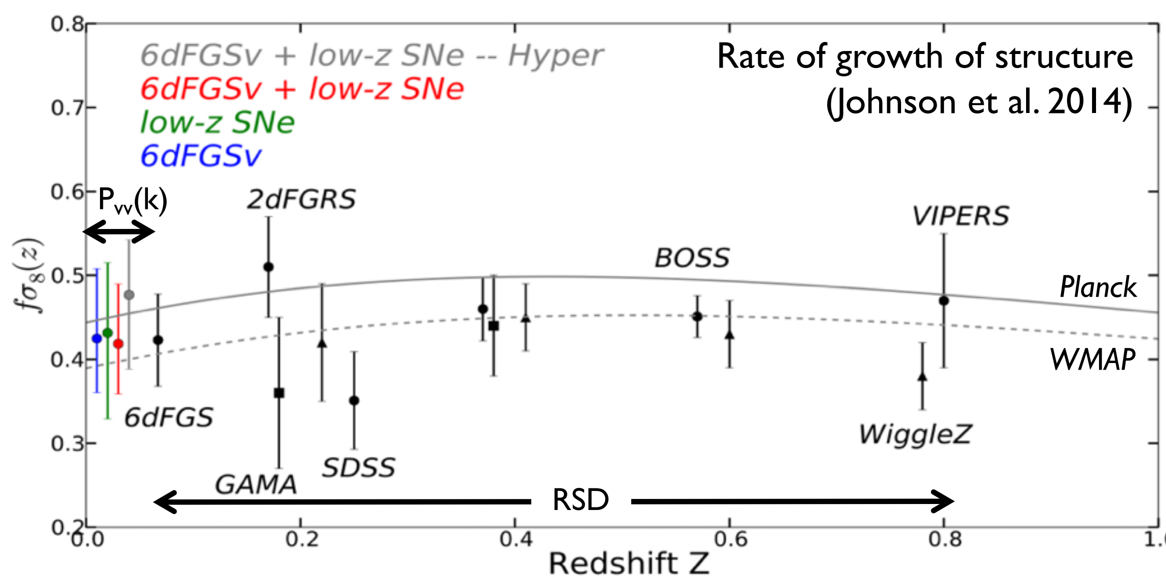
2021 Case B	Direct measure	Distance ladder
High redshift (z~1100)	Planck (2016) CMB 66.9 +/- 0.6	N/A
Low redshift (z<0.1)	Taipan (2021) BAO 73.5 +/- 0.7	Riess+(2021) SNe 73.5 +/- 0.7

2021 Case B → 7.2σ 'discrepancy' between low-z & high-z direct measure results
$\Rightarrow$ problem with cosmology

Cosmology from velocities – 6dFGS

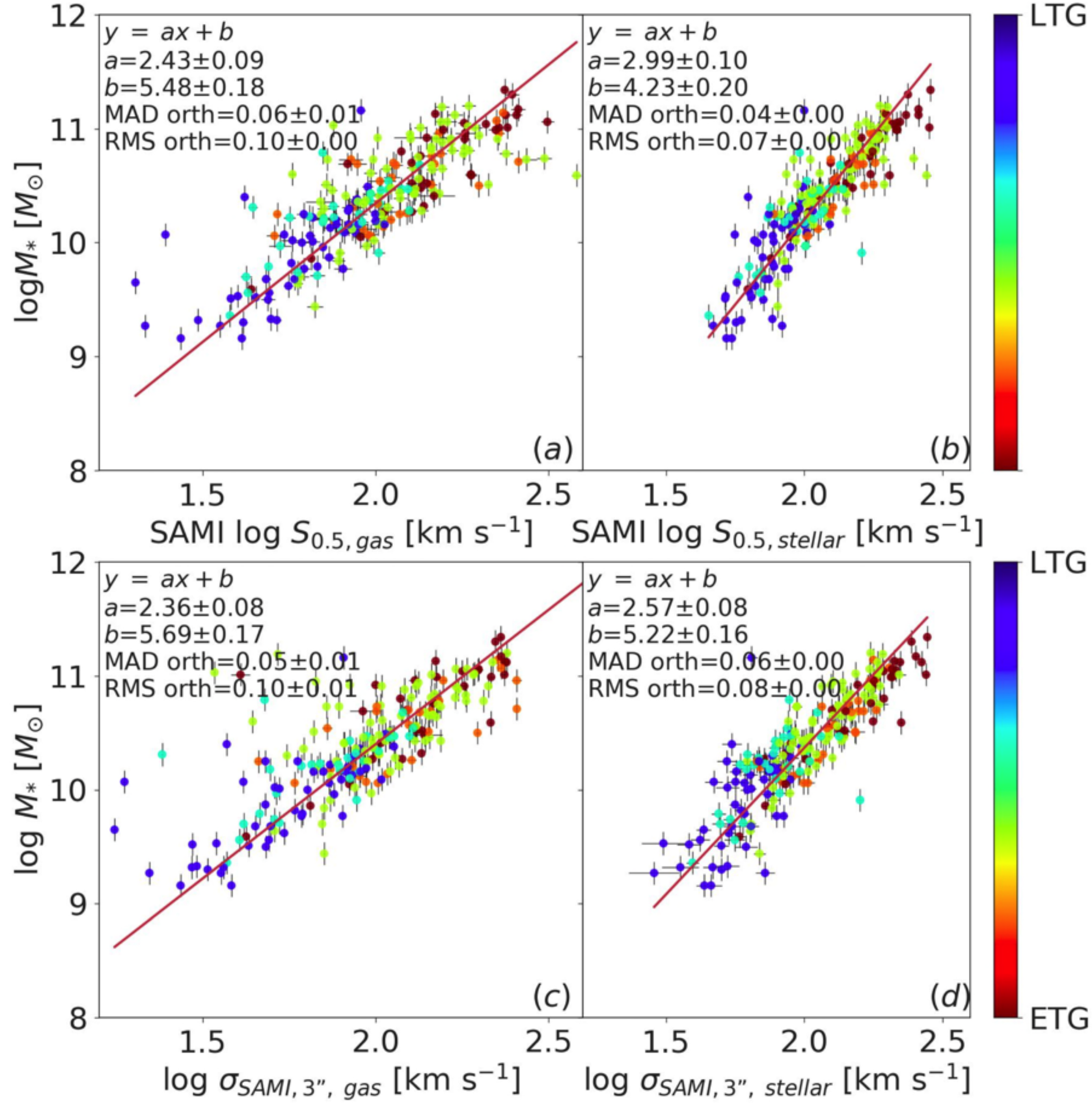
- For parameters that are degenerate in $P_{gg}(k)$, analysis of the peculiar velocity power spectrum $P_{vv}(k)$ & $P_{gv}(k)$ provides additional constraints
- 6dFGS has measured $P_{vv}(k)$ and the growth rate of structure $f\sigma_8$:
  - The growth rate is scale-independent for scales <300 Mpc/h
  - Overall growth rate at z~0 from $P_{vv}(k)$ is consistent with higher-z estimates from RSD, and with Planck/WMAP ΛCDM models



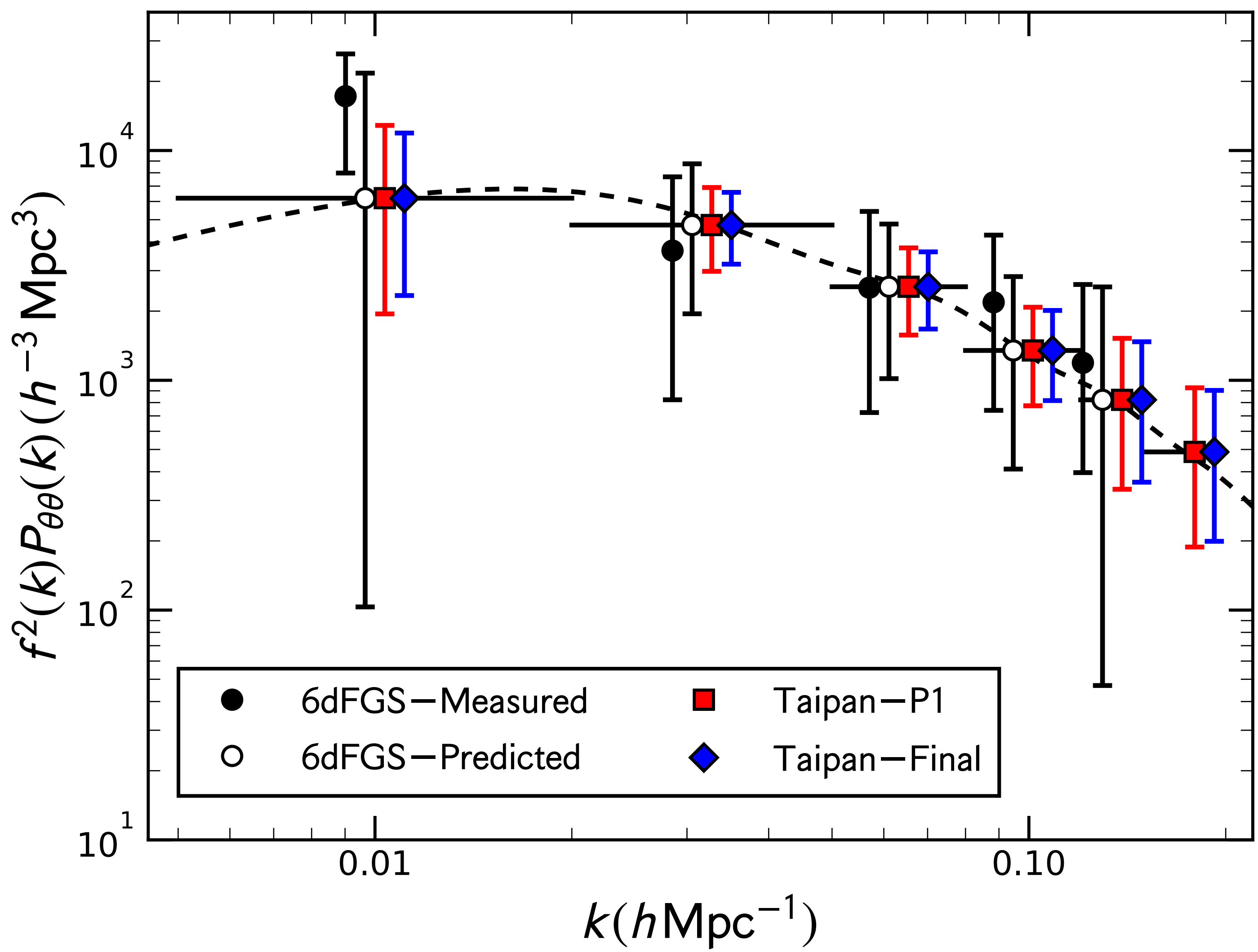


Expanding the Taipan PV sample

- For the mass-kinematics scaling relation, aperture velocity dispersions work nearly as well as kinematic measures from integral field spectroscopy such as $S_{0.5}$
- Aperture velocity dispersions give tight scalings for wide ranges of morphological types
- Exploring aperture velocity dispersions as a way to extend the Fundamental Plane to later-type galaxies offers potential to greatly expand the Taipan sample



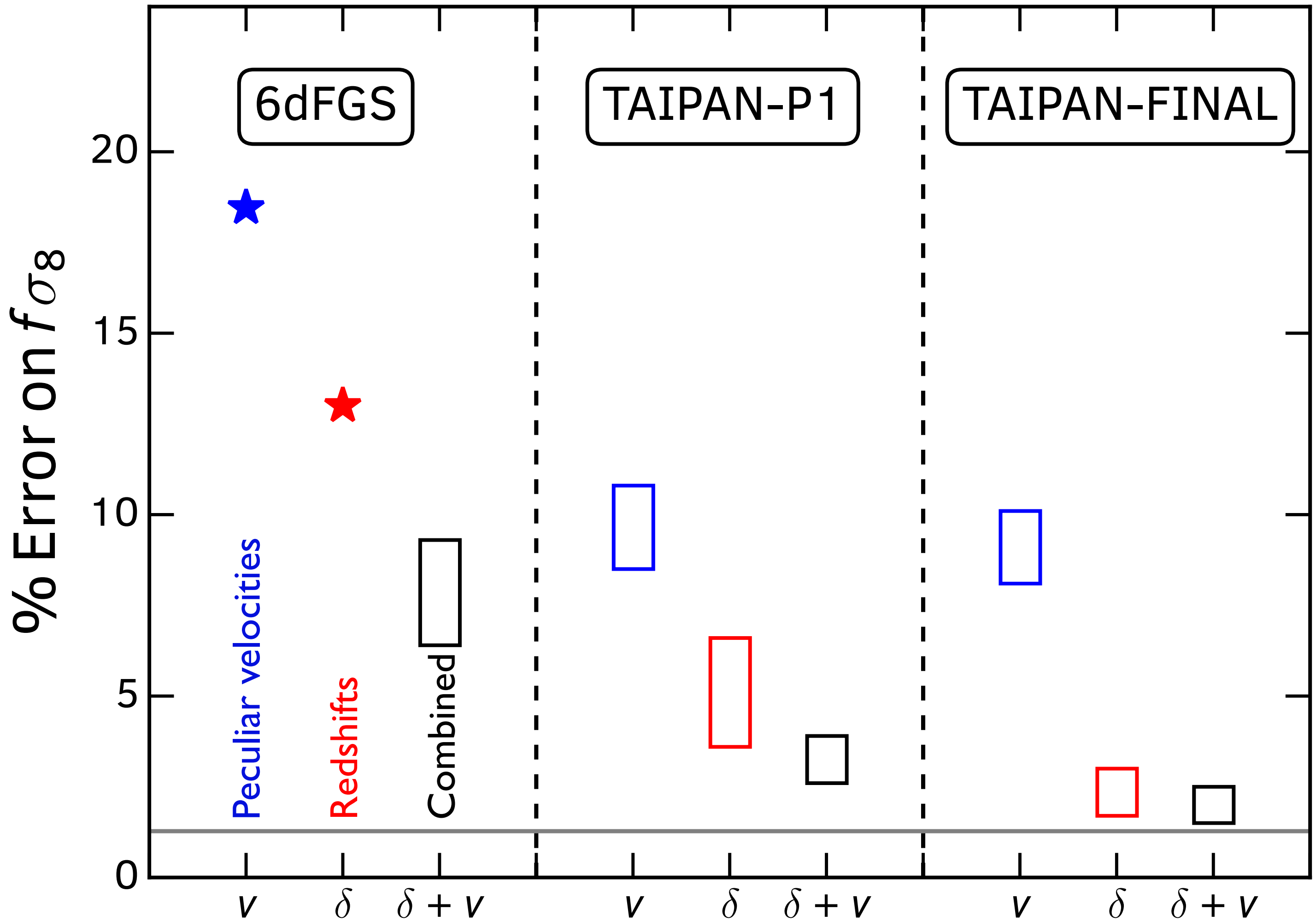
Taipan velocity power spectrum



Joint density & velocity fields

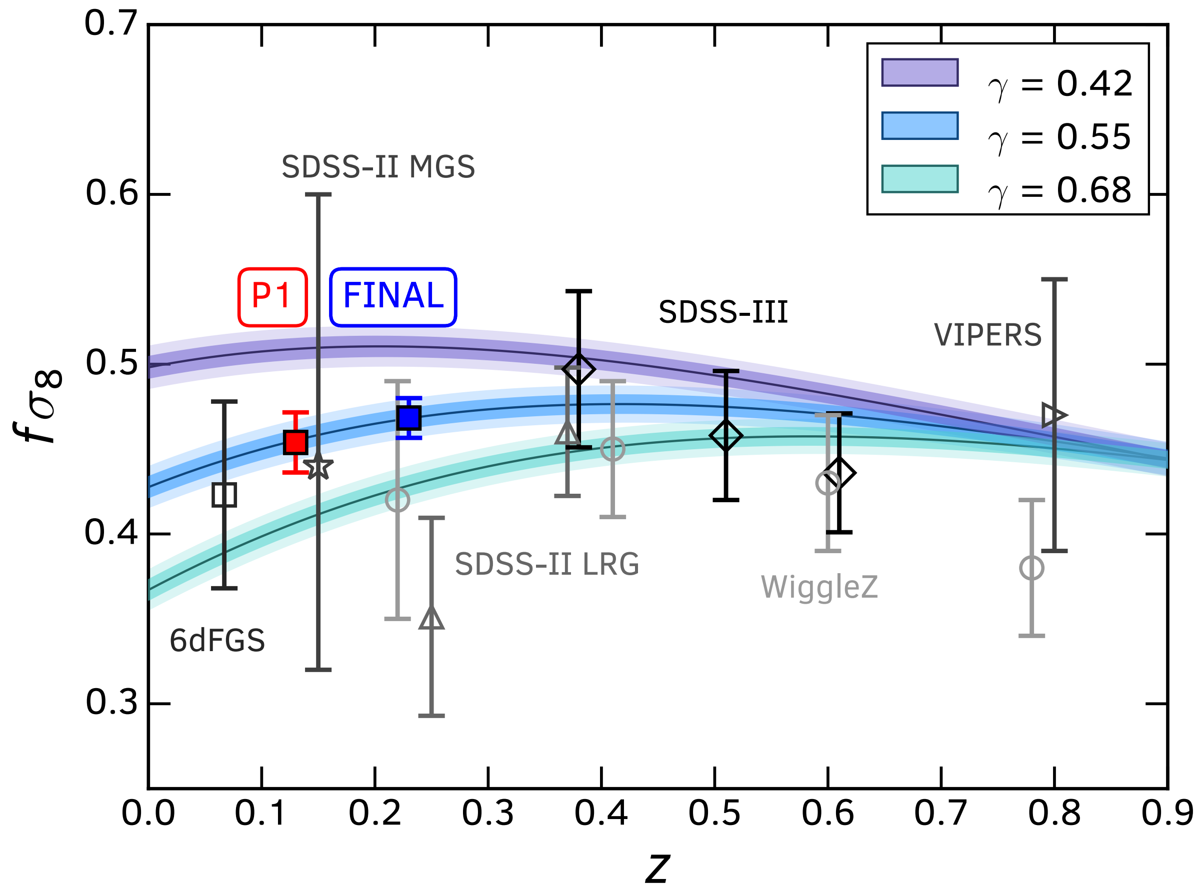
- The density fluctuations source the large-scale velocity field, so sample variance cancels
- Combining z & v tightens constraints on $\beta = f/b = \Omega^{\gamma}/b$
- If β varies on large scales, implies non-standard physics such as non-Gaussianity or modified gravity
- Combining z & v reduces degeneracy due to galaxy bias
- Burkey+Taylor(2004), Koda+(2014) & Howlett+(2016) provide full density & velocity Fisher matrix forecasts for Taipan, both alone & combined with other surveys (including effects of primordial non-Gaussianity, scale-dependent density/velocity biases, and zero-point offsets)

Growth rate of structure



Growth rate of structure

- The Taipan velocity survey improves on the 6dFGS v-survey by having…
  - ~4x the volume
  - ~5x sample size
  - smaller peculiar velocity errors
- Combining RSD & $P_{vv}(k)$, Taipan Final will constrain $f\sigma_8$ at z~0 to 2.7% (and 4.5% in Taipan Phase 1)
- Can distinguish models of gravity with $f\sigma_8 \sim \Omega(z)^\gamma$ and $|\gamma - \gamma_{GR}| > 0.05$ at $>3\sigma$



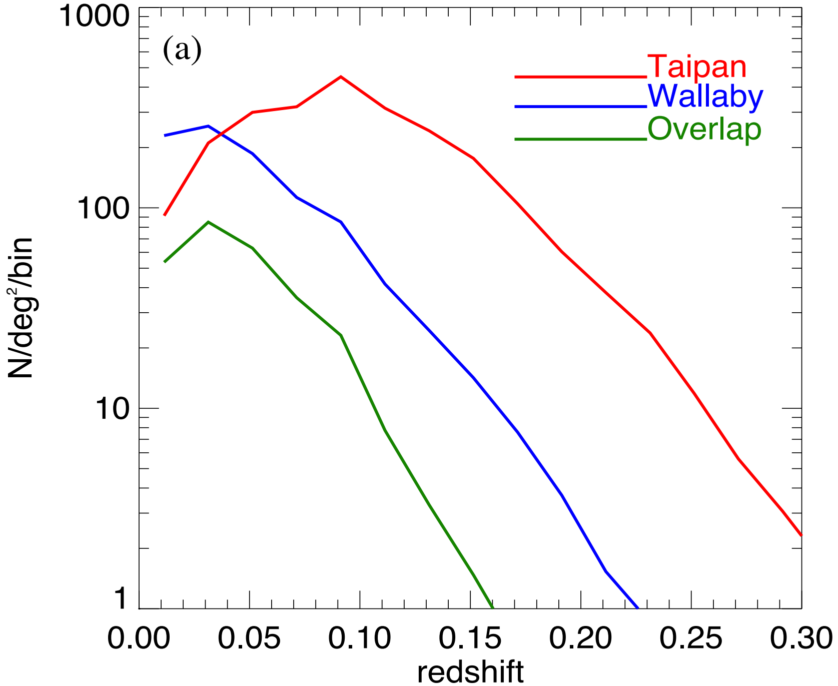
Taipan & WALLABY

- WALLABY is an all-sky HI survey that will measure redshifts for ~500,000 HI galaxies using the Australian SKA Pathfinder:

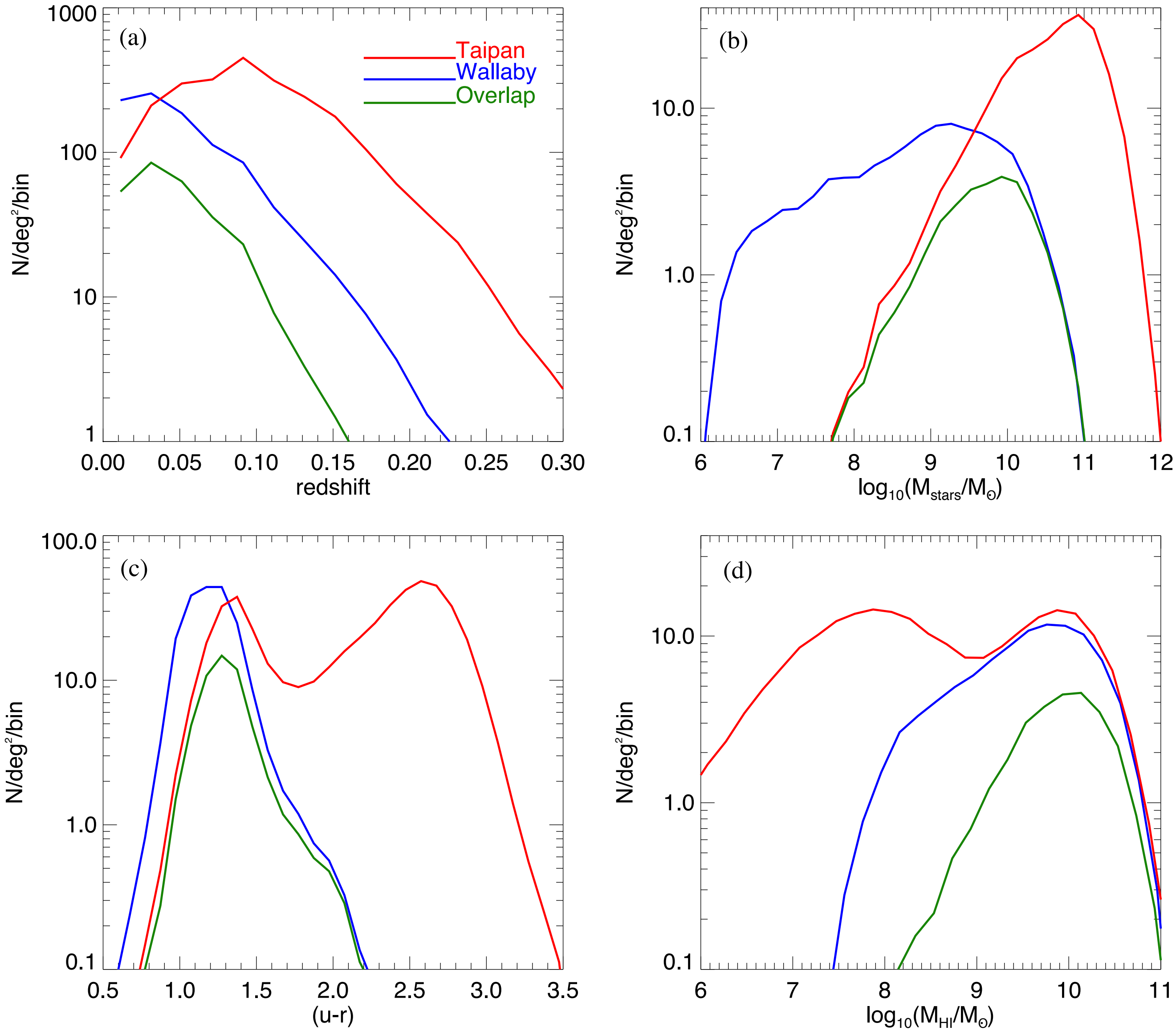
  $b \approx 0.7$, $\langle z \rangle \approx 0.04$, $V_{eff} \approx 0.35$ Gpc^3

- WALLABY will also obtain HI Tully-Fisher distances & peculiar velocities for a large sample of spirals

- WALLABY TF peculiar velocities for spirals will complement the Taipan FP peculiar velocities for early-types, sampling more densely the nearer half of the Taipan survey volume



Taipan–WALLABY overlaps

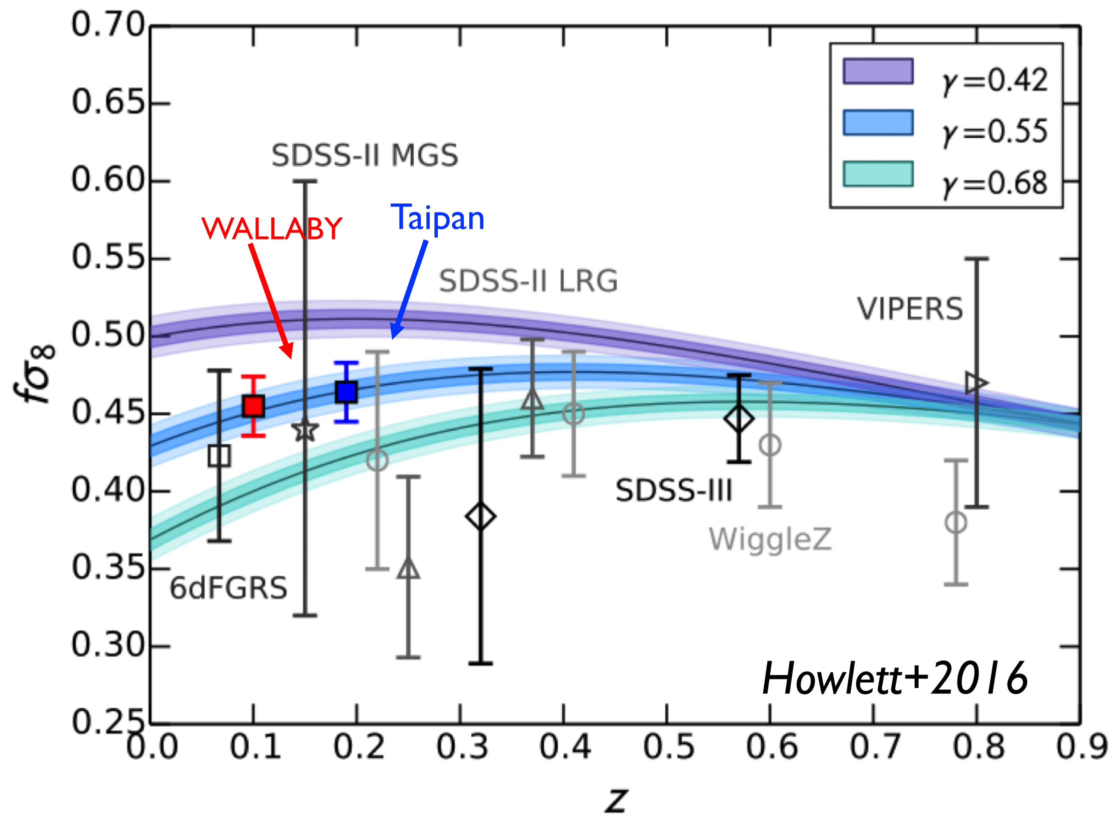


Growth rate of structure

- Taipan and WALLABY jointly provide significantly improved constraints on the growth rate of structure parameter

- The combination of the two surveys can measure $f\sigma_8$ to <2% precision

- The low redshifts of the WALLABY and Taipan samples allow for a much more stringent test of deviations from GR, as it is at low z where differing γ produce the largest changes in $f\sigma_8$



Forecast constraints

Predictions from Fisher matrix analysis by Howlett+(2016) for results from combining various redshift and velocity surveys…

Combined Density and Velocity Fields		$100 \times \sigma(\theta_i) / \theta_i$				
Survey	Parameters	$f\sigma_8$	β	r_g	σ_u	σ_g
						$k_{max} = 0.2\, h\, \mathrm{Mpc}^{-1}$
2MTF	$f\sigma_8$, β	14.8	16.5	-	-	-
	$f\sigma_8$, β, r_g, σ_u, σ_g	20.8	21.2	3.5	27.4	92.6
6dFGSv	$f\sigma_8$, β	12.8	14.0	-	-	-
	$f\sigma_8$, β, r_g, σ_u, σ_g	17.6	17.9	4.7	32.8	45.7
6dFGSv +	$f\sigma_8$, β	8.0	8.9	-	-	-
6dFGRS	$f\sigma_8$, β, r_g, σ_u, σ_g	11.7	12.1	1.8	29.2	21.5
2MTF +	$f\sigma_8$, β	9.7	11.4, 10.6	-	-	-
6dFGSv	$f\sigma_8$, β, r_g, σ_u, σ_g	13.3	14.3, 13.5	3.2, 3.0	23.5, 30.3	71.6, 42.3
2MTF +	$f\sigma_8$, β	6.8	8.6, 7.5	-	-	-
6dFGSv + 6dFGRS	$f\sigma_8$, β, r_g, σ_u, σ_g	9.7	11.2, 10.0	2.6, 1.0	22.0, 28.3	59.5, 20.0
TAIPAN	$f\sigma_8$, β	2.3	2.6	-	-	-
	$f\sigma_8$, β, r_g, σ_u, σ_g	4.1	4.2	2.3	12.1	6.8
WALLABY +	$f\sigma_8$, β	2.7	3.3	-	-	-
WNSHS	$f\sigma_8$, β, r_g, σ_u, σ_g	4.2	4.4	0.3	6.8	12.9
TAIPAN +	$f\sigma_8$, β	1.8	2.2, 2.0	-	-	-
WALLABY + WNSHS	$f\sigma_8$, β, r_g, σ_u, σ_g	2.8	3.0, 3.1	1.1, 0.3	10.9, 6.4	5.7, 9.7

γ constraints	$100 \times \sigma(\gamma) / \gamma$	
Survey	Velocity Only	Velocity + Density
2MTF	40.4	24.0
6dFGSv	37.4	20.3
6dFGSv + 6dFGRS	37.4	13.6
2MTF + 6dFGSv	28.4	15.5
2MTF + 6dFGSv + 6dFGRS	28.4	11.3
TAIPAN	15.2	5.2
WALLABY + WNSHS	16.4	5.3
TAIPAN + WALLABY + WNSHS	11.5	4.0

All-sky survey of local universe

- Strong arguments for an all-sky survey of the local universe…
  - to completely characterize the local velocity field, especially the monopole (local Hubble constant) and dipole terms (bulk flow)
  - to map the foreground large-scale structure for cross-correlation with deeper observations (particularly all-sky CMB surveys)
  - to make a definitive database of optical spectra for local galaxies
- This can be achieved by combining the SDSS, Taipan and other northern surveys into an all-sky ($|b|>10$) survey to $r \approx 17.5$
  - Taipan will cover southern hemisphere and north to at least +10°
  - SDSS/BOSS covers $\gtrsim\pi$ steradians of north (with some overlap in south)
  - These surveys can/will provide good S/N spectra to $r \approx 17.6$ at R~2000
  - A northern survey from CAHA could cover the remaining $\lesssim\pi$ steradians
  - Strong preference for consistent selection criteria (pre-/post-selection of sample) based on SDSS + SkyMapper + Pan-STARRs imaging

Taipan survey – summary

The Taipan galaxy survey is… a multi-object spectroscopic survey starting in 2019 that will cover 2π steradians over the southern sky and obtain optical spectra for about 2 million galaxies out to z=0.4; it will use the refurbished 1.2m UK Schmidt Telescope at Siding Spring Observatory with the new TAIPAN instrument, comprising an innovative 'Starbugs' positioner capable of rapidly deploying 150-300 fibres in parallel over the 6° diameter focal plane and a purpose-built high-performance, fixed-format spectrograph

The main scientific goals of Taipan are…

1. to measure the distance scale of the universe (mainly governed by the local expansion rate, H_0) to 1% precision, and the growth rate of structure to 5%
2. to make the most extensive map yet constructed of the mass distribution and motions in the local universe, using peculiar velocities based on improved Fundamental Plane distances, which will enable sensitive tests of gravitational physics
3. to deliver a legacy sample of low-redshift galaxies that will be the primary redshift and optical spectroscopic reference catalogue for the local universe over the southern sky

For more information see the Taipan survey paper (da Cunha++ 2017, PASA, 34, 47 https://doi.org/10.1017/pasa.2017.41) & the Taipan website (https://www.taipan-survey.org)