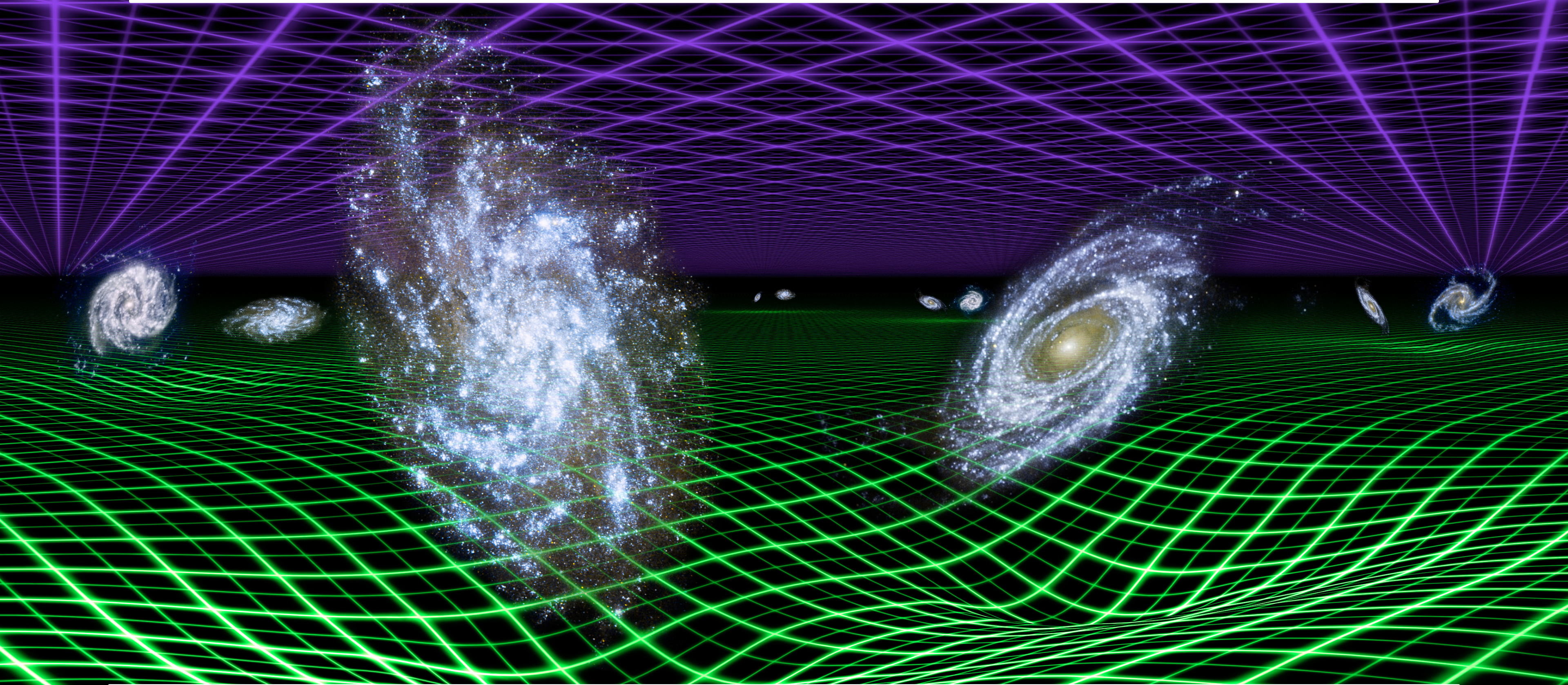
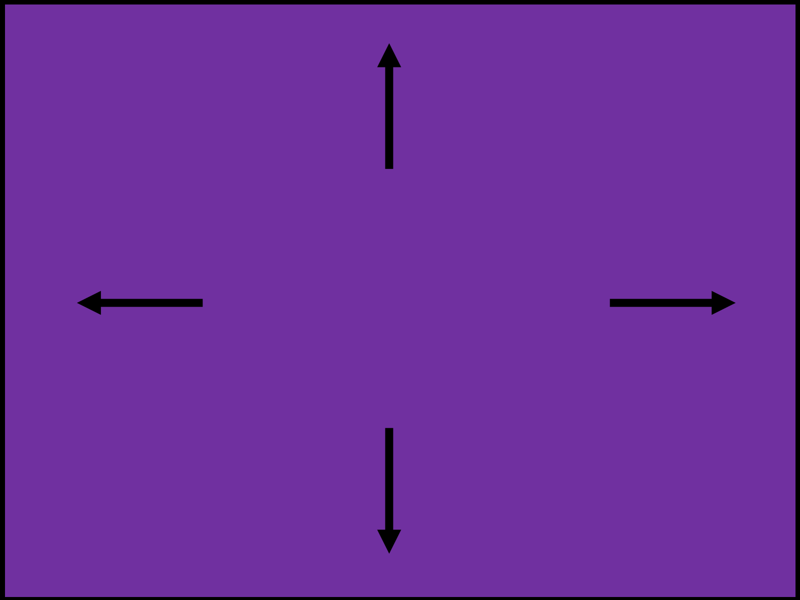
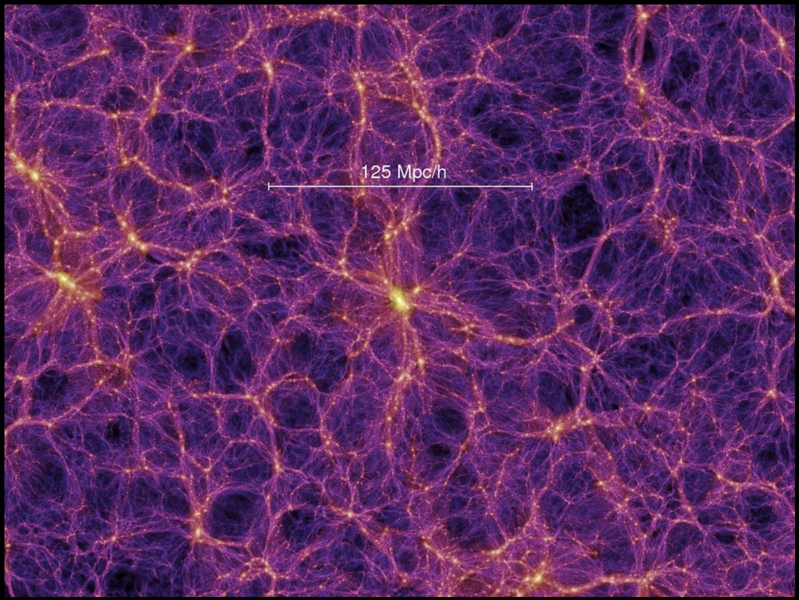
Testing the laws of gravity with combined probes of cosmology



Chris Blake, Ixandra Achitouv, Caitlin Adams, Alexandra Amon,
Andrew Johnson, Shahab Joudaki, Jun Koda

Cosmological observations

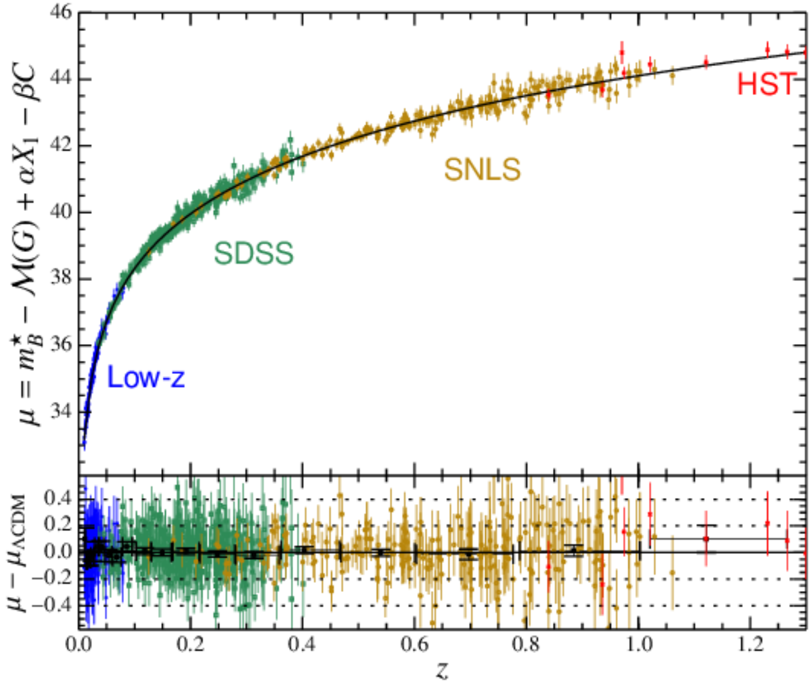


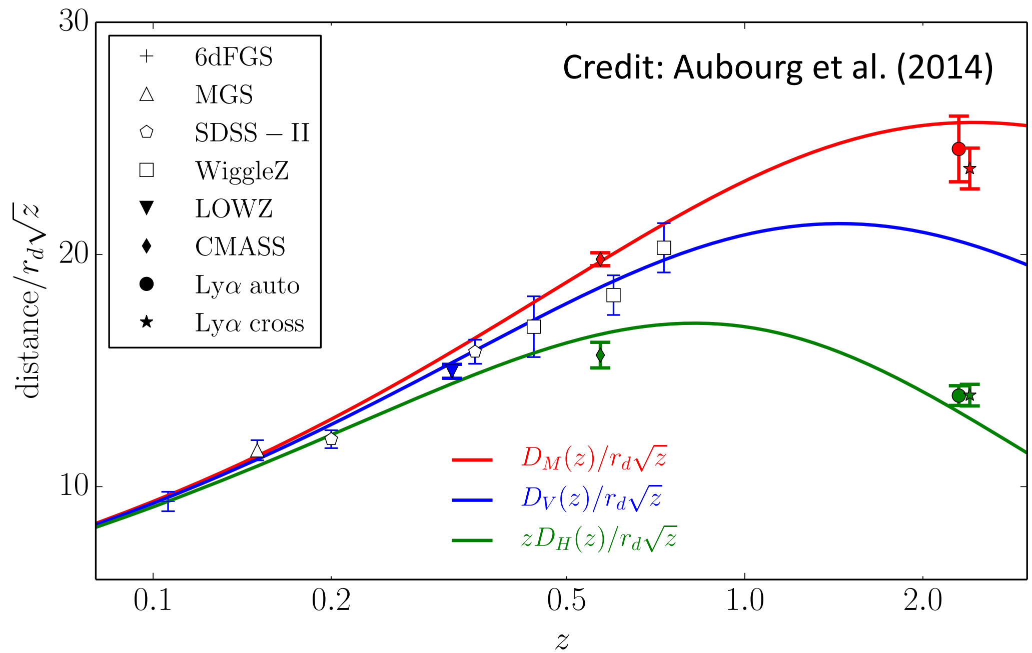


Homogeneous expansion of the Universe

Growth of perturbations within the expanding background

Cosmological observations



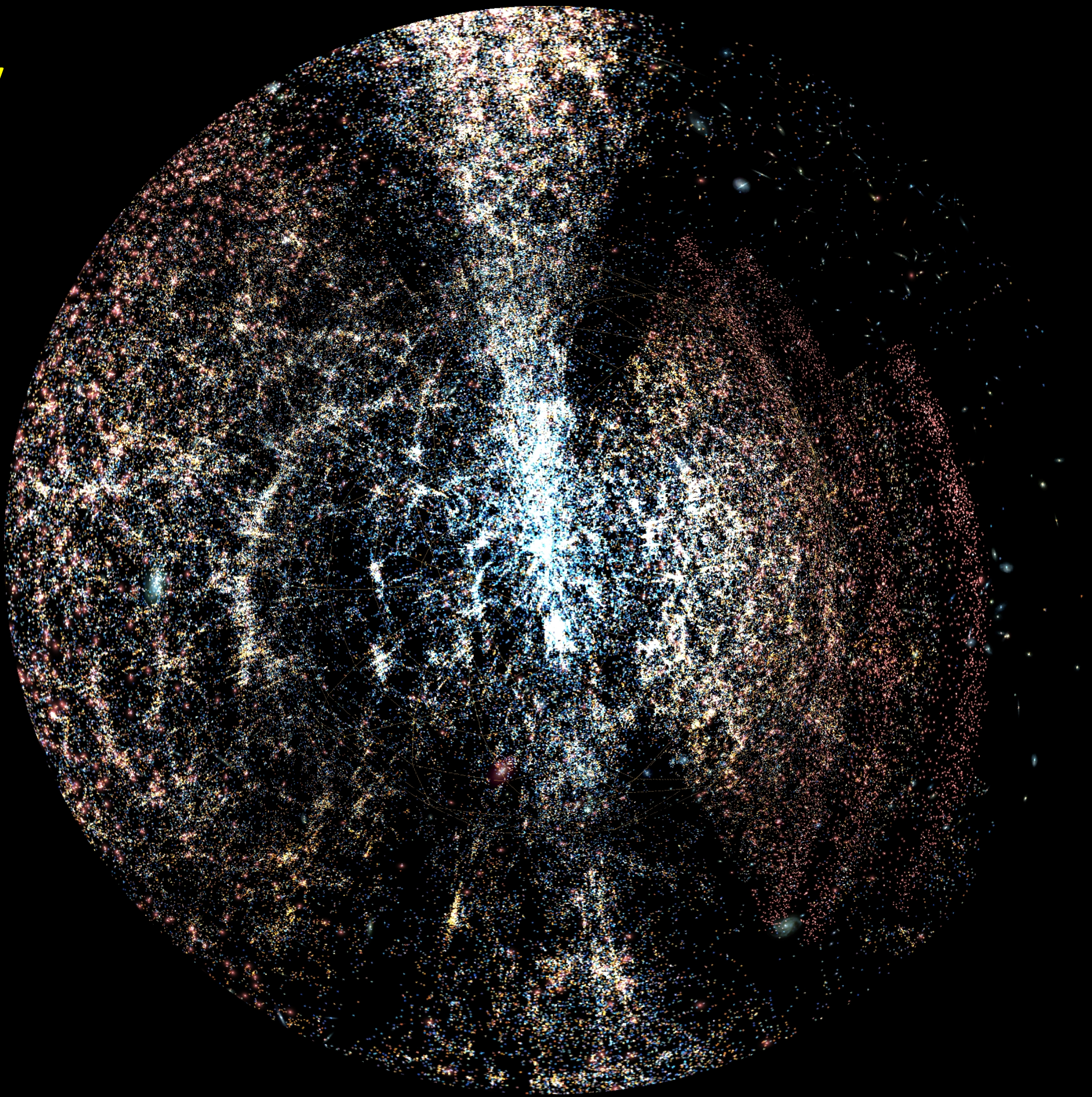


- The **cosmic expansion history** has been measured with ~1% accuracy using supernovae and baryon acoustic oscillations

- The **cosmic growth history** has not yet been measured as accurately, but is crucial for distinguishing physics

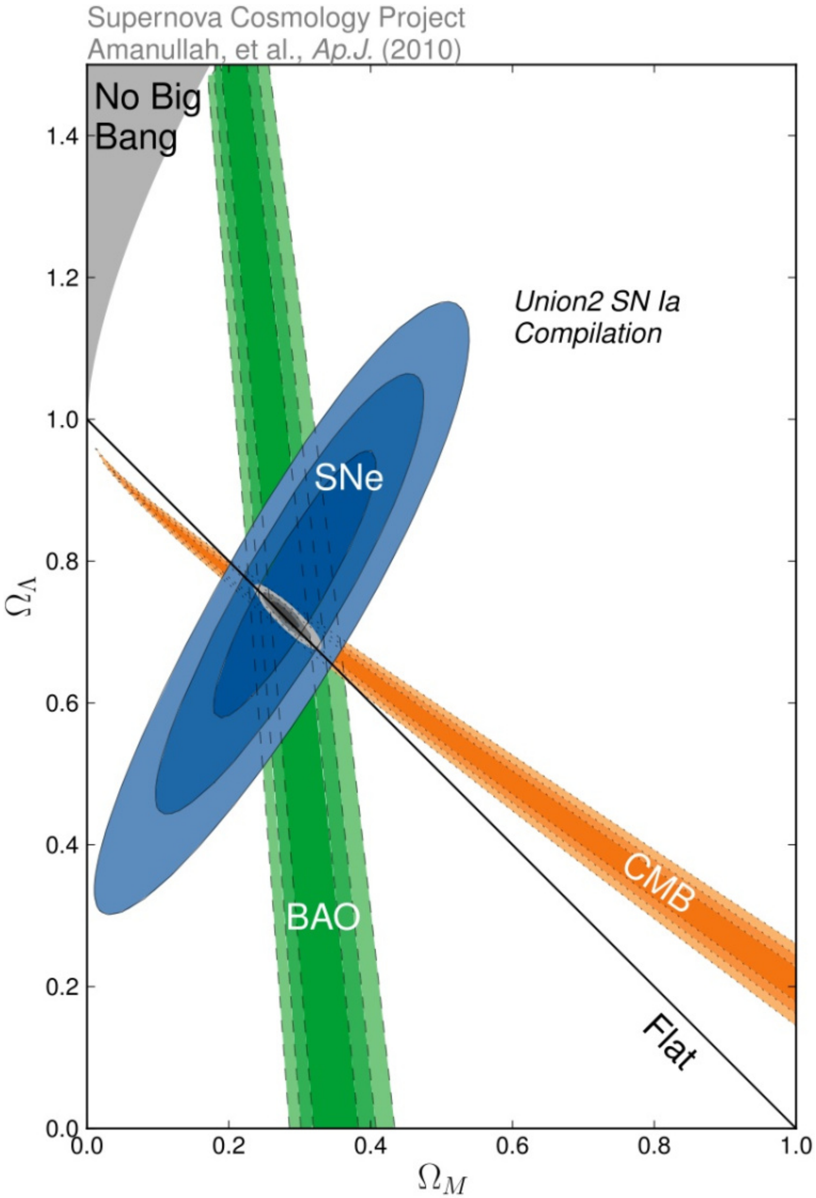
Cosmological observations

- There are a rich variety of observable signatures of the clumpy Universe …
- Clustering of galaxies
- Velocities of objects
- Gravitational lensing
- Abundance/properties of objects
- Environmental effects

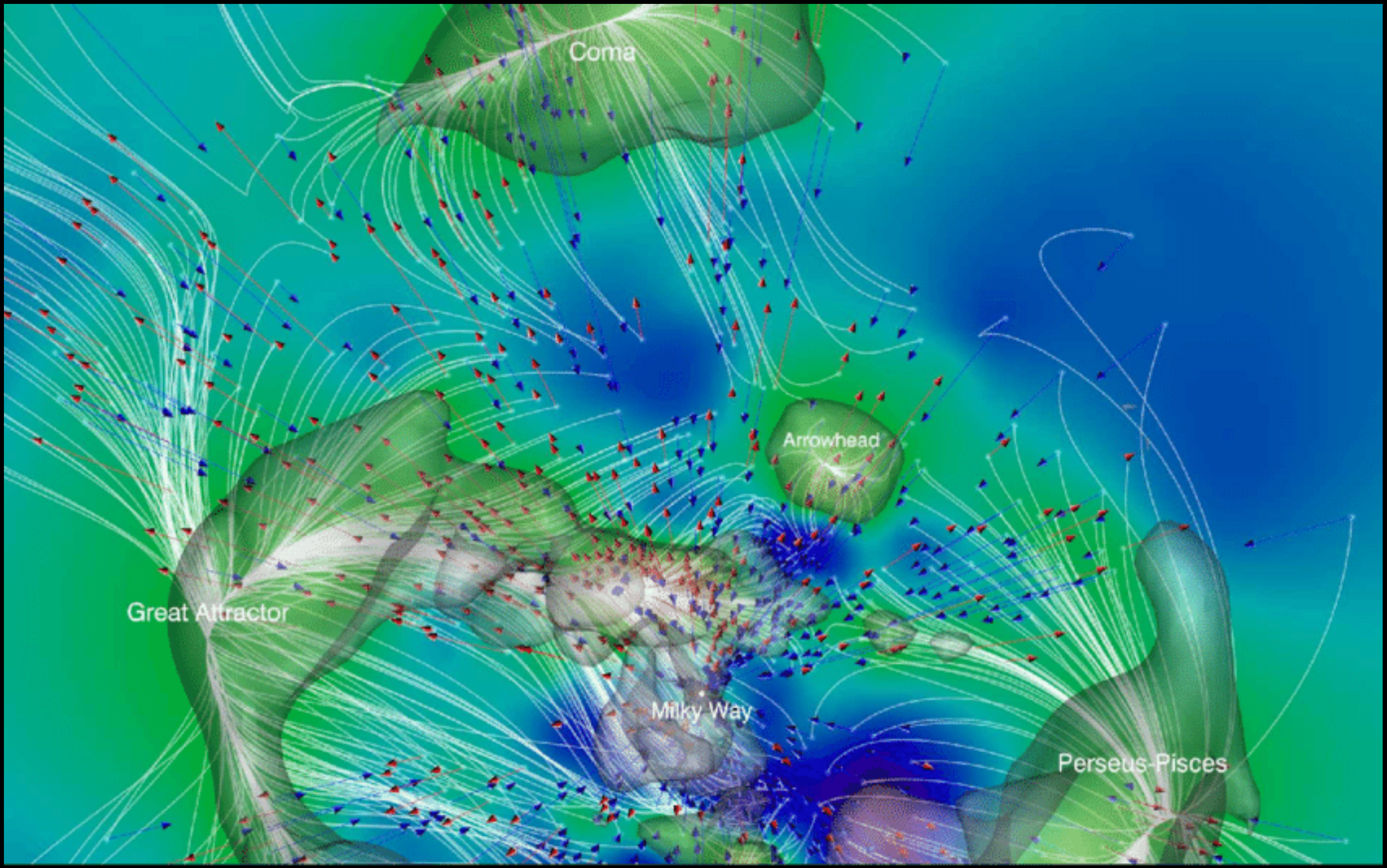


Combined probes

- Different probes are sensitive to different projections of the model (i.e. **break degeneracies**)
- **Statistical errors** can be improved (through extra information, or correlated sample variance)
- **Systematic errors** can be cross-checked or mitigated



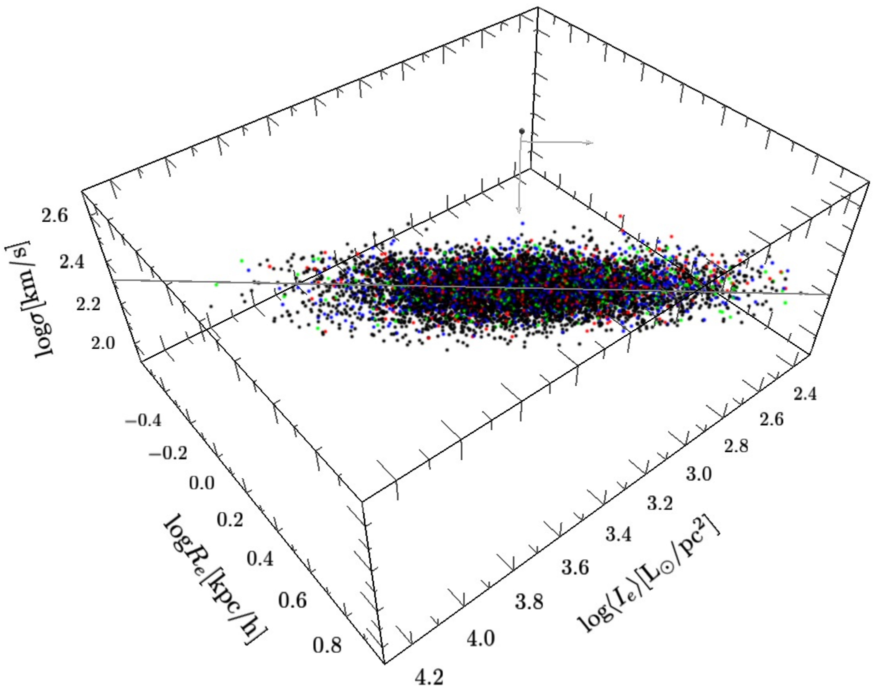
Combined Probes I: Velocities and large-scale structure



Credit: Pomarede et al. (2017) – arXiv:1702.01941

Direct peculiar velocities

- Radial peculiar velocity estimates **for individual galaxies** from distance measurements (e.g. standard candles)



Credit: Christina Magoulas (arXiv:1206.0385)

- **Fundamental plane of elliptical galaxies**: correlation between velocity dispersion σ, size R_e and surface brightness I_e
- $\sim$25% distance measurements
- Obtain radial velocity v_r from $(1 + z_{\text{obs}}) = \left(1 + \frac{v_r}{c}\right)(1 + z_{\text{cos}})$
- Alternatively: SNe, Tully-Fisher

Direct peculiar velocities

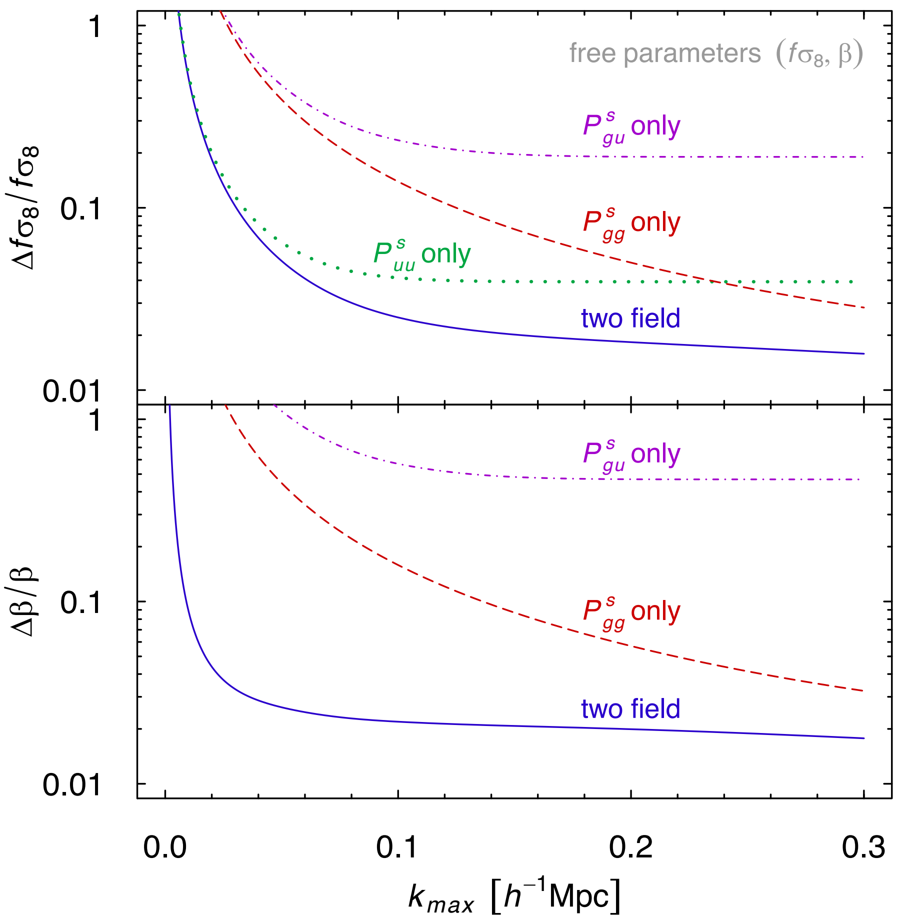
- Direct PVs **improve growth rate measurements** due to direct relationship between velocity and density

- **Common sample variance** imprinted in density/velocity fields improves constraints

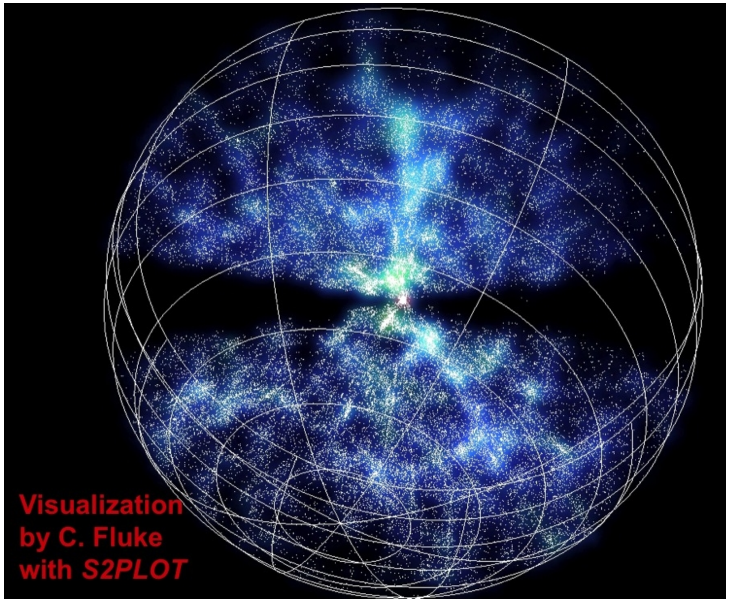
- Velocities driven by **largest-scale density modes**,

$$P_{v_r v_r}(k) \sim \left(\frac{aHf\mu}{k}\right)^2 P_m(k)$$

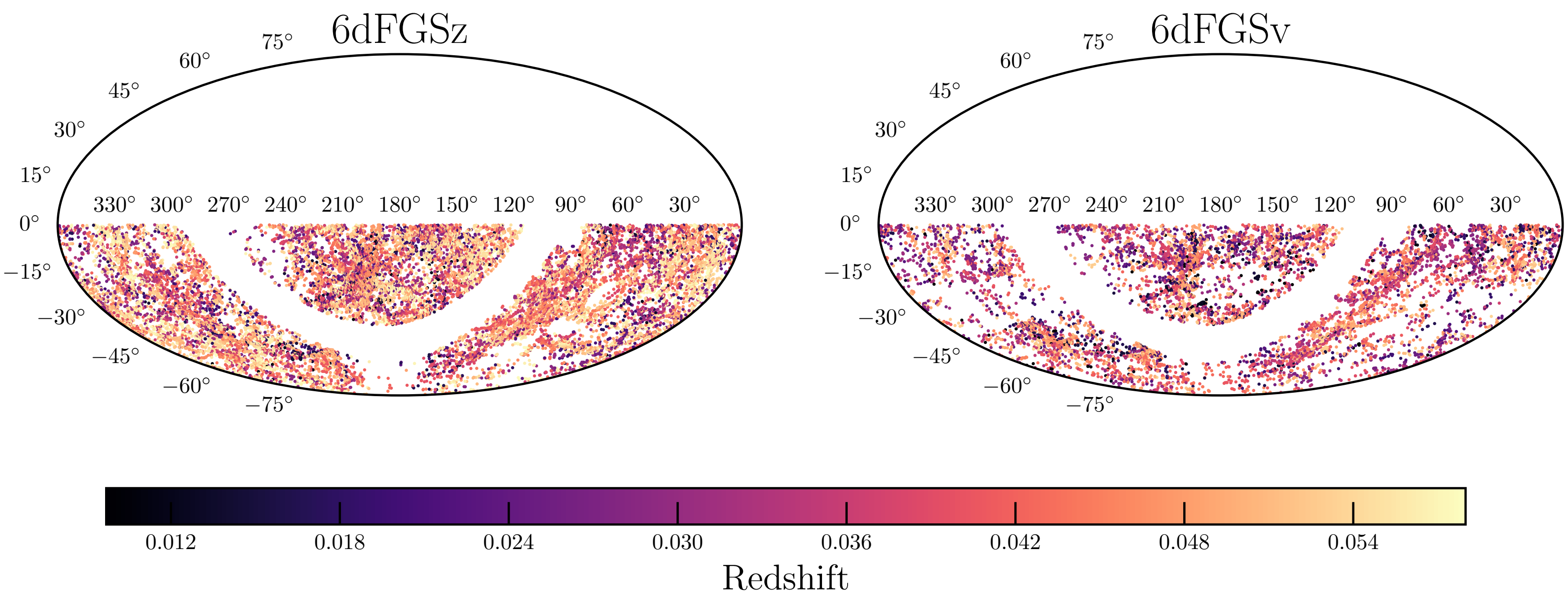
Fisher matrix forecast in Koda et al. (2014) – arXiv:1312.1022



6-degree Field Galaxy Survey



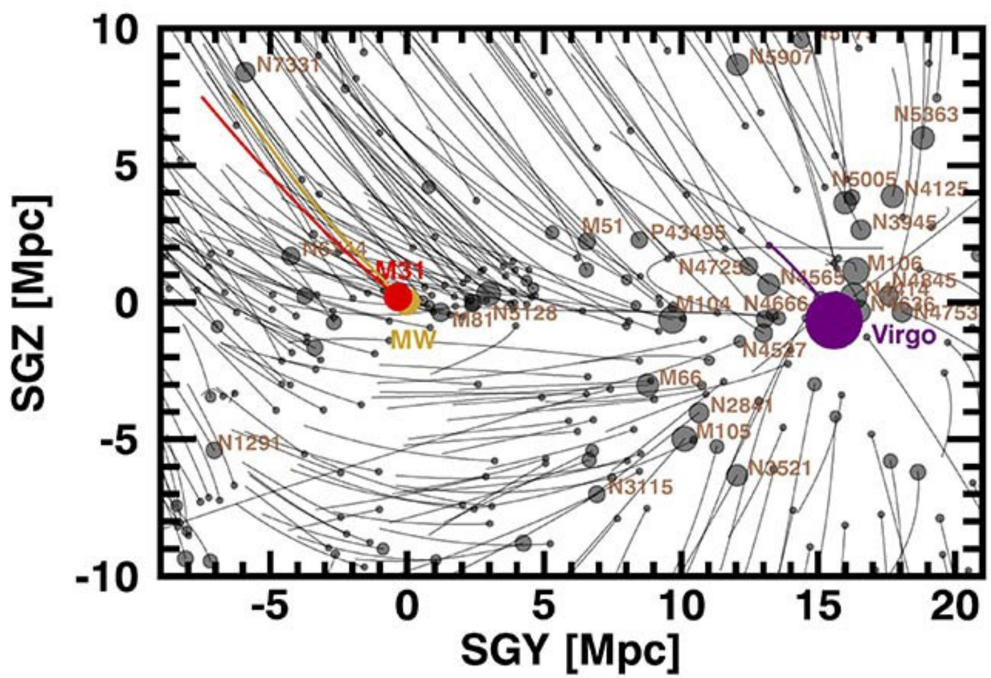
- Southern-sky survey carried out at the UK Schmidt Telescope, 2001-2006
- **125,000 redshifts** with $\bar{z} \sim 0.05$
- **9,000 direct peculiar velocities** from fundamental plane distances (still the largest single sample)

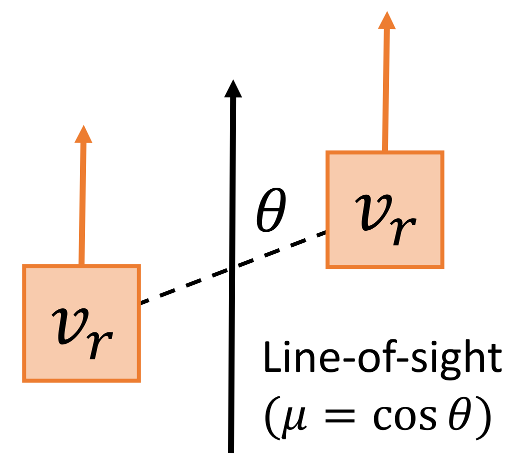


Fits to 6dFGS peculiar velocity data

- First consider fitting to **radial peculiar velocities alone**

- **Peculiar velocities are correlated** by an amount depending on the growth rate of structure (and orientation, scale)





$$P_{v_r v_r}(k) \sim \left(\frac{aHf\mu}{k}\right)^2 P_m(k)$$

Fits to 6dFGS peculiar velocity data

- Model the likelihood in terms of the **observed radial velocities** v_i and a **covariance matrix** C_v

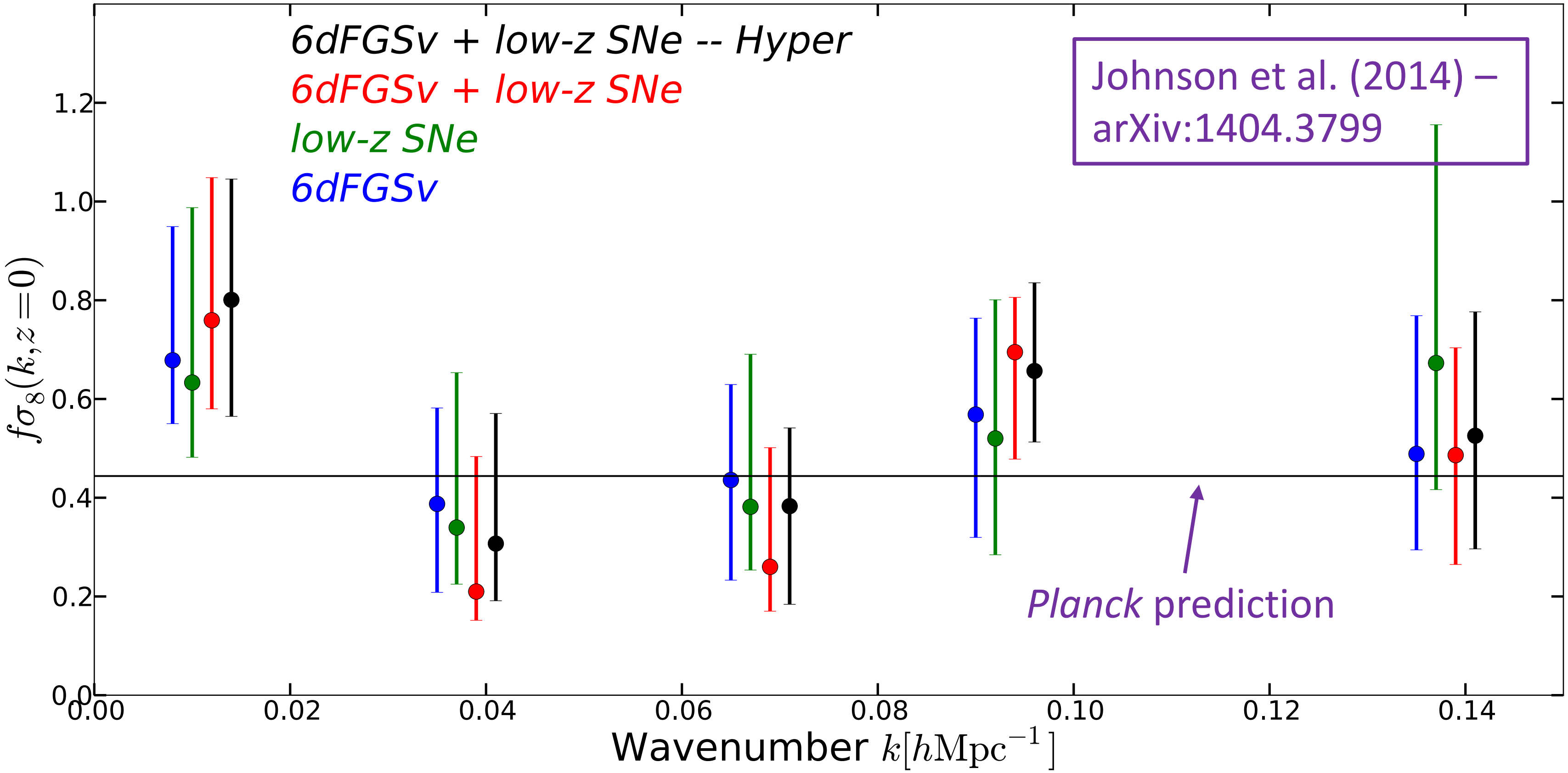
$$L = \frac{1}{\sqrt{2\pi|C_v|}}\ e^{-\frac{1}{2}\sum_{ij} v_i \left({C_v}^{-1}\right)_{ij} v_j}$$

- The covariance matrix C_v depends on the **velocity power spectrum** $\boldsymbol{P_{\theta\theta}(k) = f^2 P_m(k)}$ and the errors in the data

- We do an MCMC fit for the **amplitudes of** $\boldsymbol{P_{\theta\theta}(k)}$ in k-bins, i.e. the growth rate $f\sigma_8(k)$

Johnson et al. (2014) – arXiv:1404.3799

Fits to 6dFGS peculiar velocity data



- The amplitude of the velocity power measures the growth rate on $k \sim 0.01\ h\ \mathrm{Mpc}^{-1}$ ($\sim$Gpc) scales

Phenomenological test of gravity

- Modify **gravitational physics for matter and light** with phenomenological functions $G_{\text{matter}}(k,z)$ and $G_{\text{light}}(k,z)$

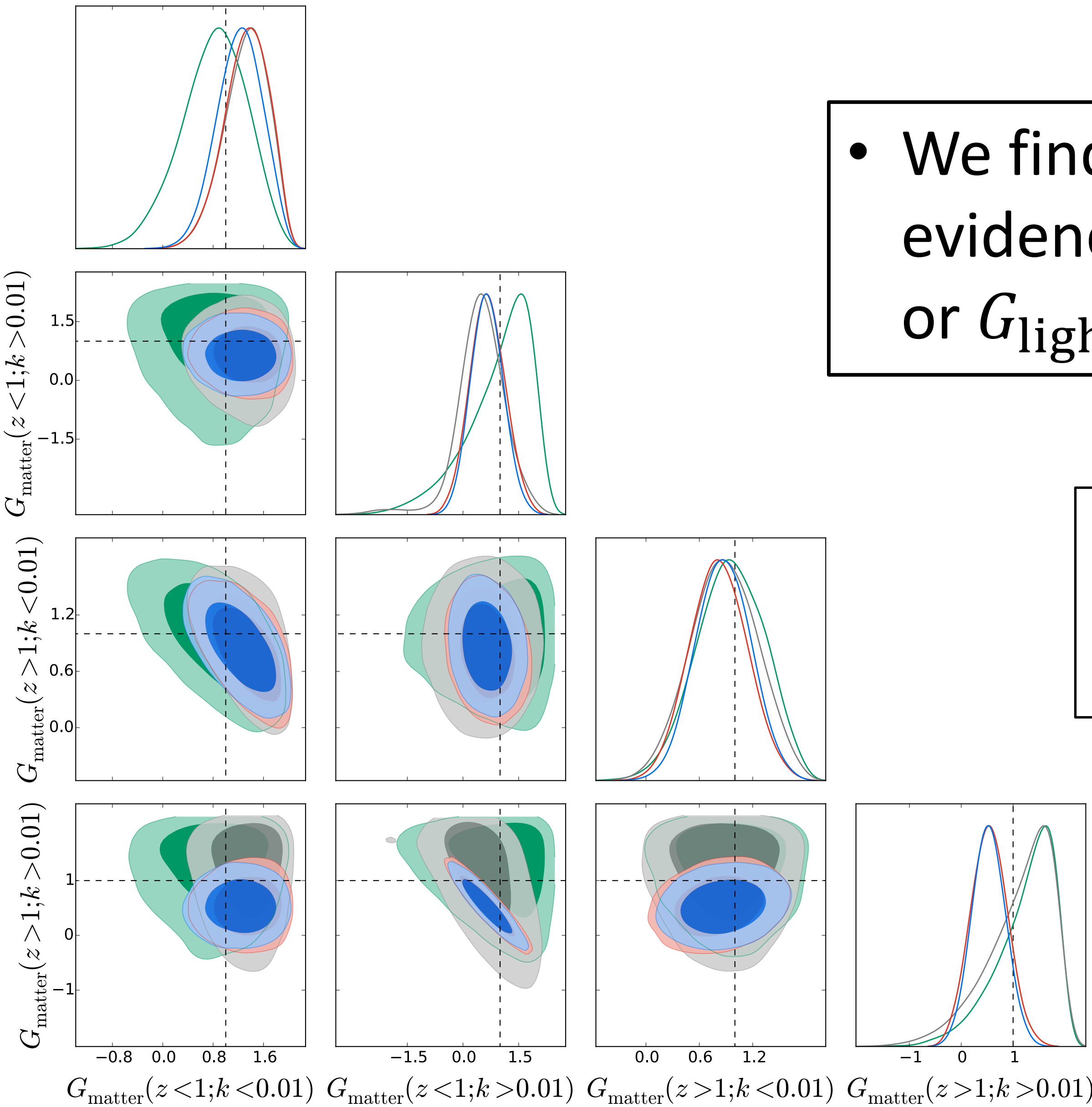
$$\nabla^2\psi = 4\pi G_N a^2 \rho_m \delta_m \times \boldsymbol{G_{\text{matter}}(k,z)}$$

$$\nabla^2(\phi+\psi) = 8\pi G_N a^2 \rho_m \delta_m \times \boldsymbol{G_{\text{light}}(k,z)}$$

- Use **two scale and redshift bins** ($k = 0.01\ h\ \text{Mpc}^{-1}, z = 1$) to fit for 8 MG parameters – implement using ISITGR code

- Fit to a **range of datasets** sensitive to ψ (PVs, RSD), $\phi+\psi$ (lensing, ISW) and background cosmology (CMB, BAO, SNe)

Phenomenological test of gravity



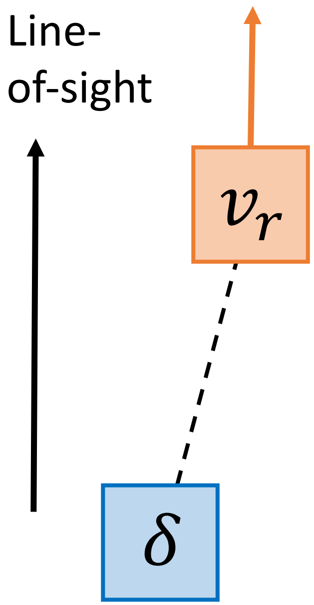
- We find no significant evidence for $G_{\rm matter} \neq 1$ or $G_{\rm light} \neq 1$

Green: CMB+BAO+SNe
Grey: +peculiar velocities
Red: +RSD
Blue: +CMB cross-correlation

Johnson et al. (2015) – arXiv:1504.06885

Including the density field

- As well as correlations between radial velocities, we wish to include **cross-correlations of velocities with the galaxy density field** and **RSD in the density field**



$\delta\delta$-correlations ($\propto b^2$, and RSD)

δv-correlations ($\propto fb$)

$$\vec{x} = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \cdots \\ v_1 \\ v_2 \\ \cdots \end{pmatrix} \qquad C = \left(\begin{array}{ccc|ccc} C_{\delta_1\delta_1} & C_{\delta_1\delta_2} & \cdots & C_{\delta_1 v_1} & C_{\delta_1 v_2} & \cdots \\ C_{\delta_2\delta_1} & C_{\delta_2\delta_2} & \cdots & C_{\delta_2 v_1} & C_{\delta_2 v_2} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ \hline C_{v_1\delta_1} & C_{v_1\delta_2} & \cdots & C_{v_1 v_1} & C_{v_1 v_2} & \cdots \\ C_{v_2\delta_1} & C_{v_2\delta_2} & \cdots & C_{v_2 v_1} & C_{v_2 v_2} & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \end{array}\right)$$

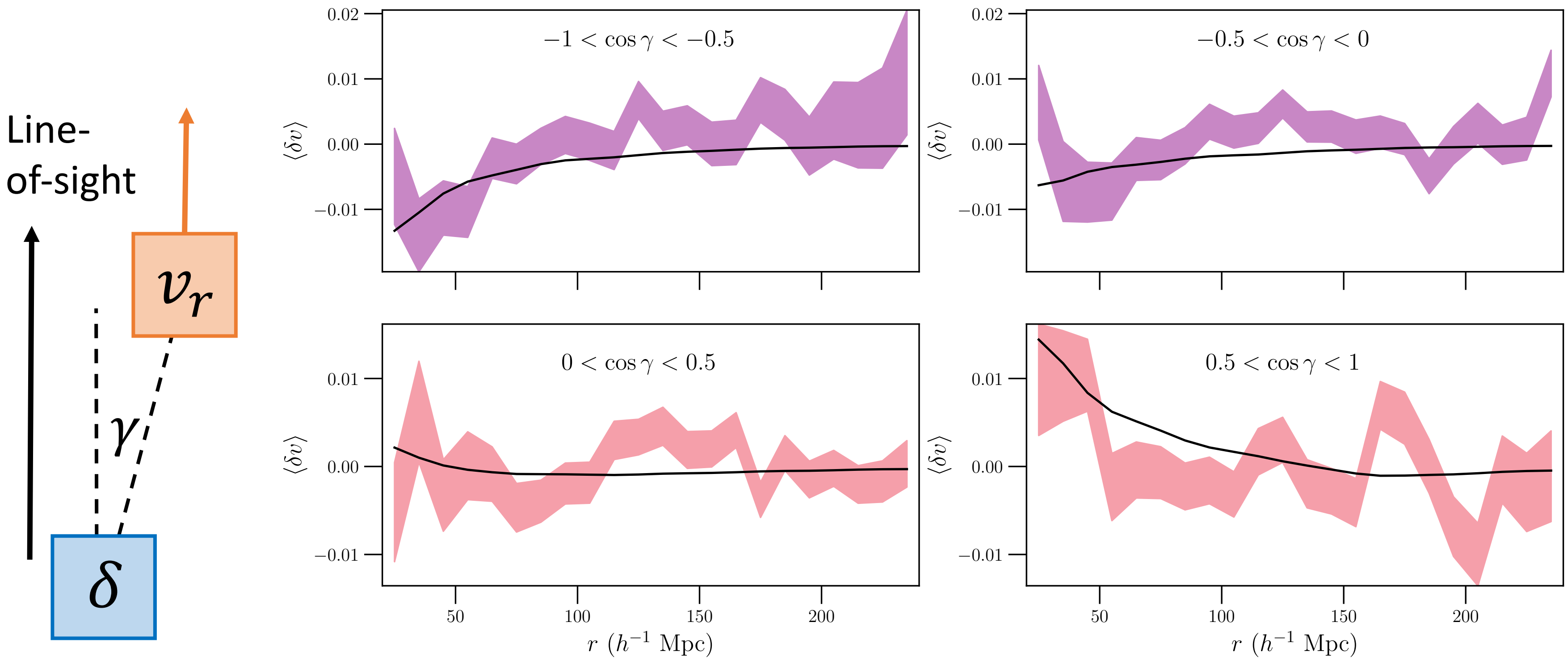
$v\delta$-correlations ($\propto fb$)

vv-correlations ($\propto f^2$)

- Hence obtain **optimal constraints on growth across scales**

Including the density field

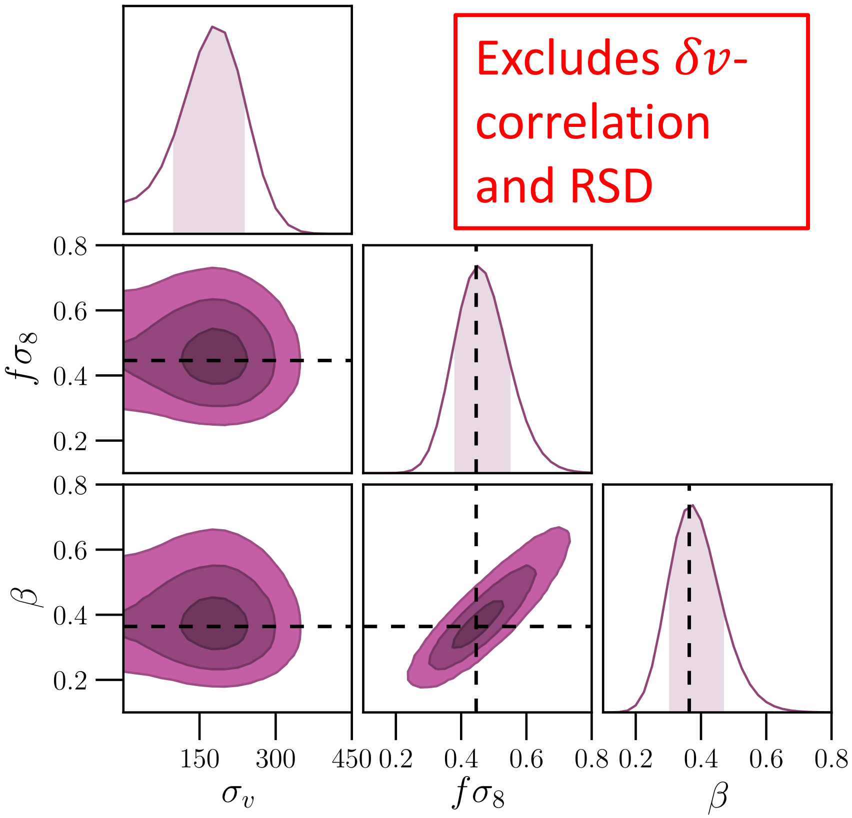
- Visualize the cross-correlation information by plotting $\langle \delta . v \rangle$ against angle to the line-of-sight – **the velocities are produced by the gravitational effect of the densities**!



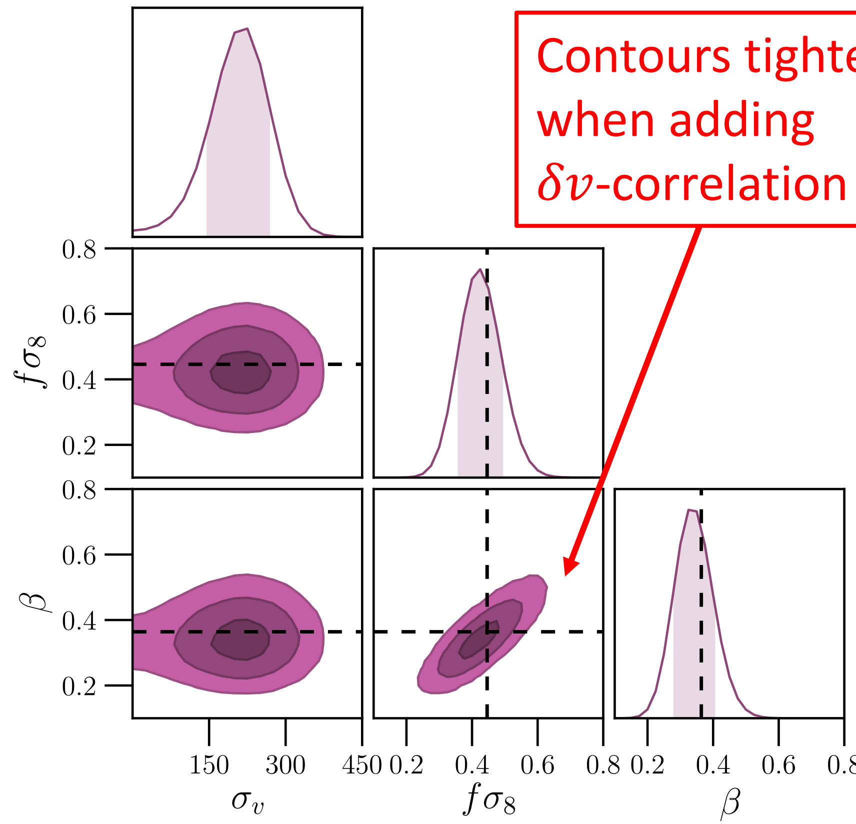
Adams & Blake (2017) – arXiv:1706.05205

Including the density field

- **Add the density-velocity cross-correlations** in the fit for the growth rate (fit for $f\sigma_8, \beta = f/b, \sigma_v$) – excluding RSD for now



Excludes δv-correlation and RSD

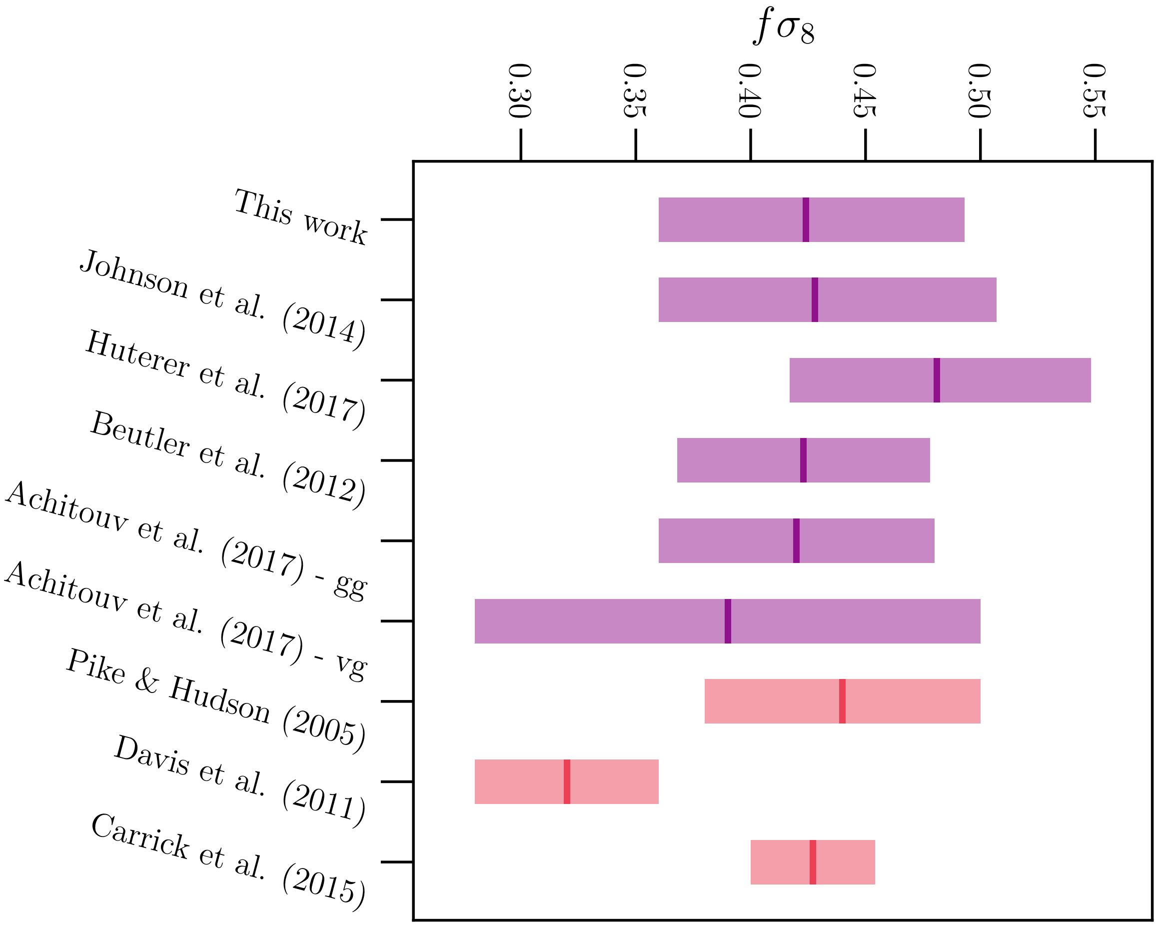


Contours tighten when adding δv-correlation

Adams & Blake (2017) – arXiv:1706.05205

Including the density field

- Growth rate measurement $\boldsymbol{f\sigma_8(z=0) = 0.42 \pm 0.06}$ from vv- and δv-correlations – excluding RSD for now

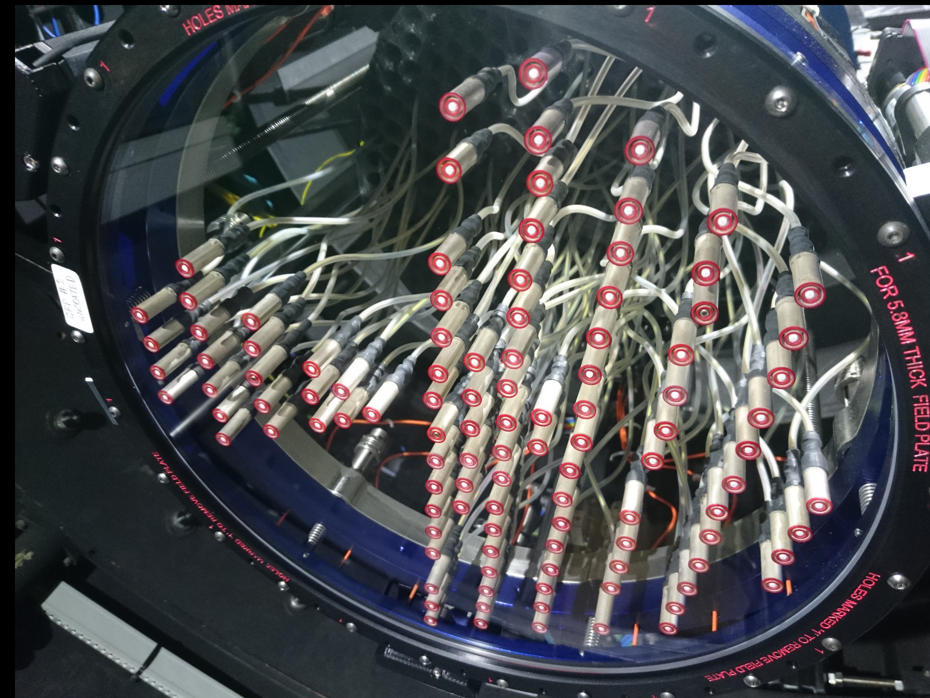


Adams & Blake (2017) – arXiv:1706.05205

Now finalizing adding in RSD information … watch this space!

Taipan Galaxy Survey

Credit: Michael Childress



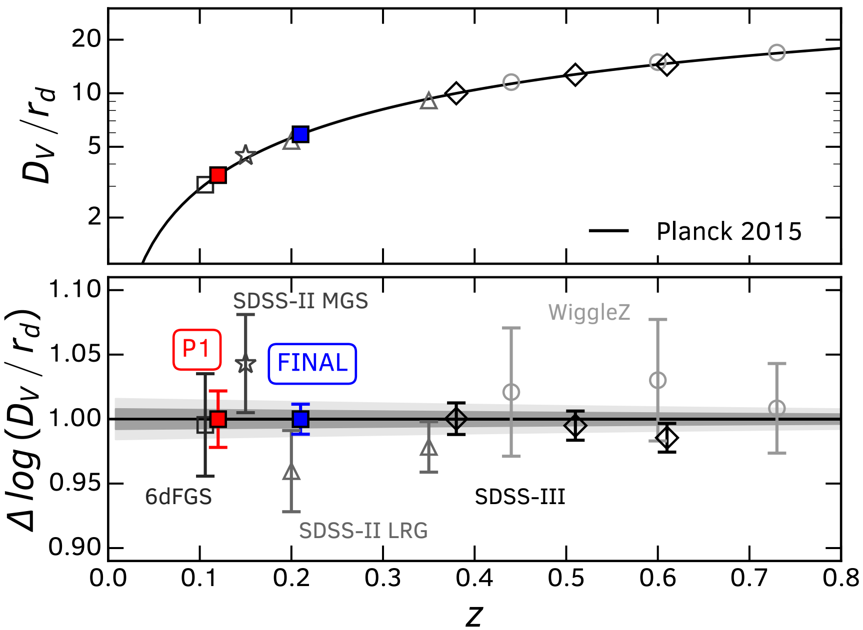
Credit: David Brown, AAO

- Southern-sky survey (20,000 deg^2), 2018-2022
- $\sim 10^6$ galaxy redshifts ($z < 0.3$)
- $\sim 10^5$ direct peculiar velocities ($z < 0.1$)

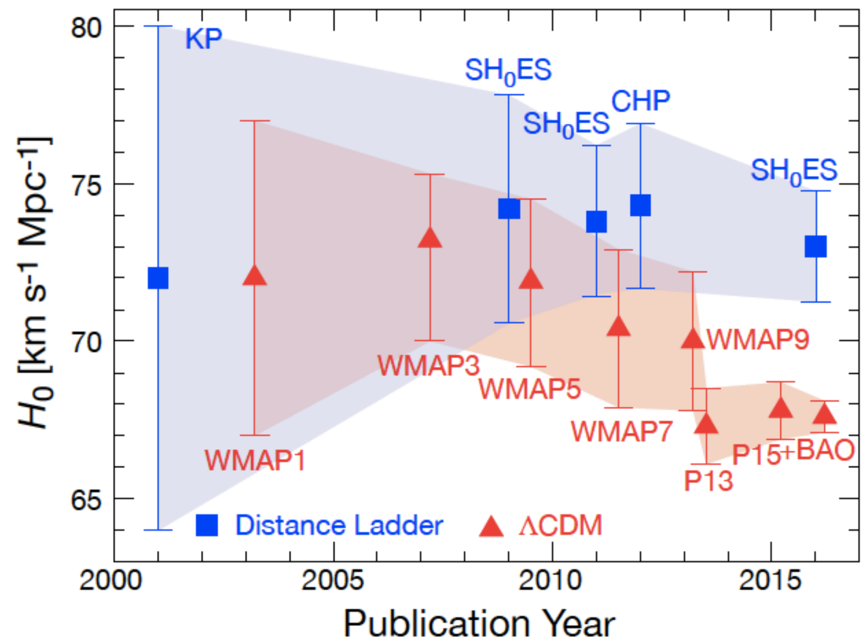
Taipan Galaxy Survey

Distance scale science

Credit: Cullan Howlett (arXiv:1706.01246)



Credit: Wendy Freedman (arXiv:1706.02739)

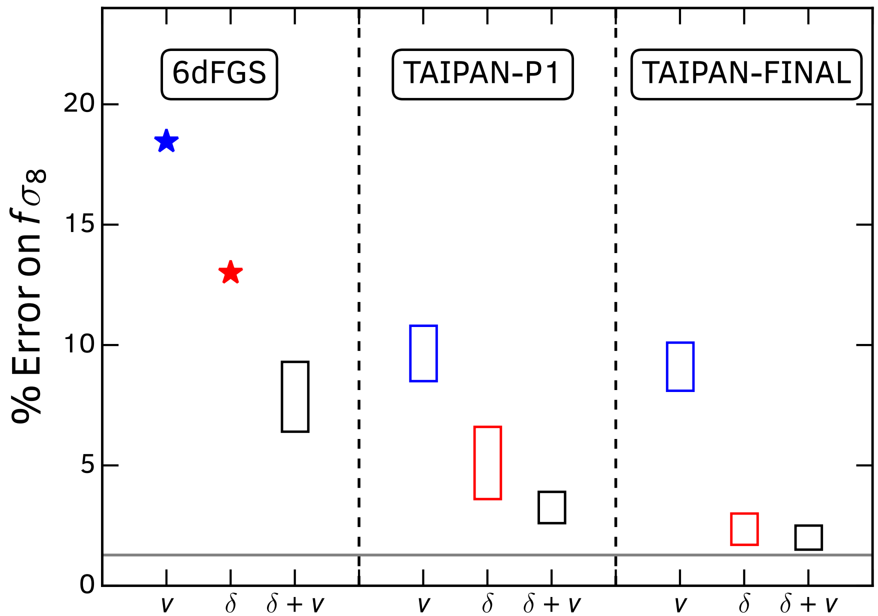


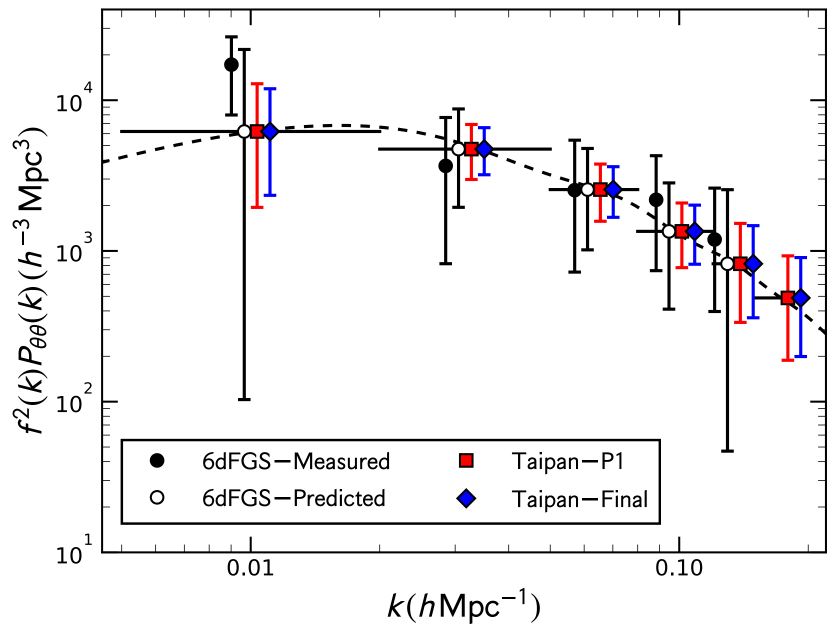
- $\sim 1\%$ **measurement of D_V/r_d** using baryon acoustic peak as a standard ruler ($\sim 2\%$ with Phase 1 data, end-2019)
- Accurate distance constraint may inform H_0 "tension"

Taipan Galaxy Survey

Gravitational growth science

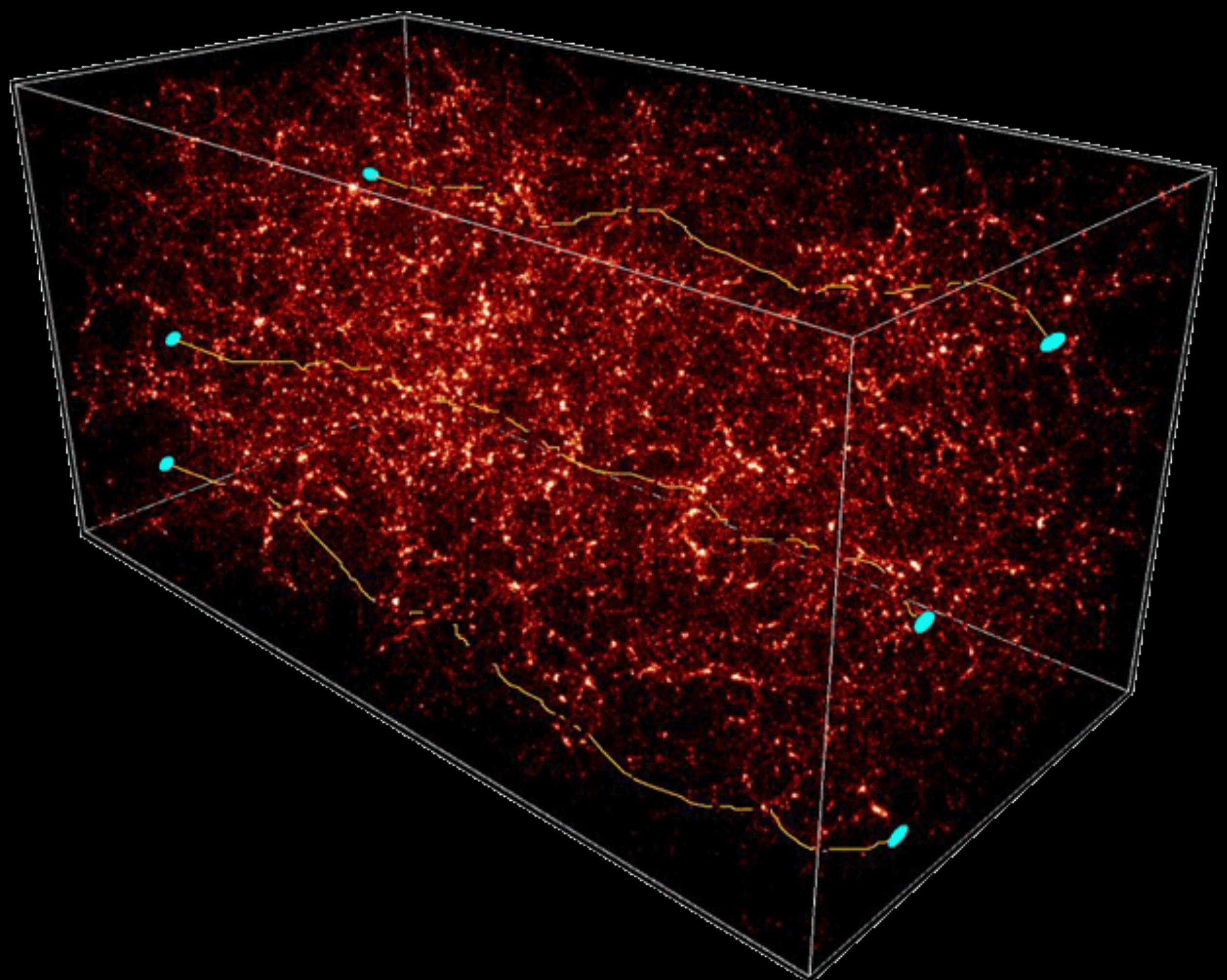
Credit: Cullan Howlett (arXiv:1706.01246)





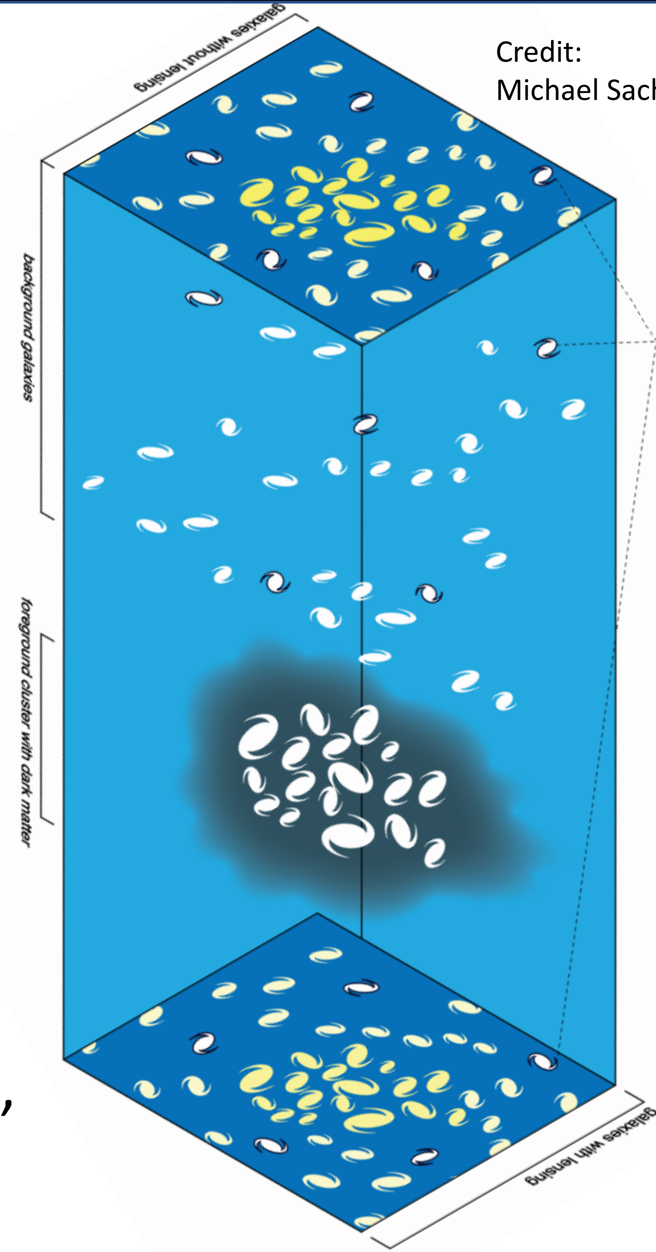
- **~3% measurement of $f\sigma_8$** using RSD and direct peculiar velocities (~5% with Phase 1 data, end-2019)
- Direct PVs tracing large-scale growth ($k < 0.05\ h\ \mathrm{Mpc}^{-1}$)

Combined Probes II: Lensing and large-scale structure



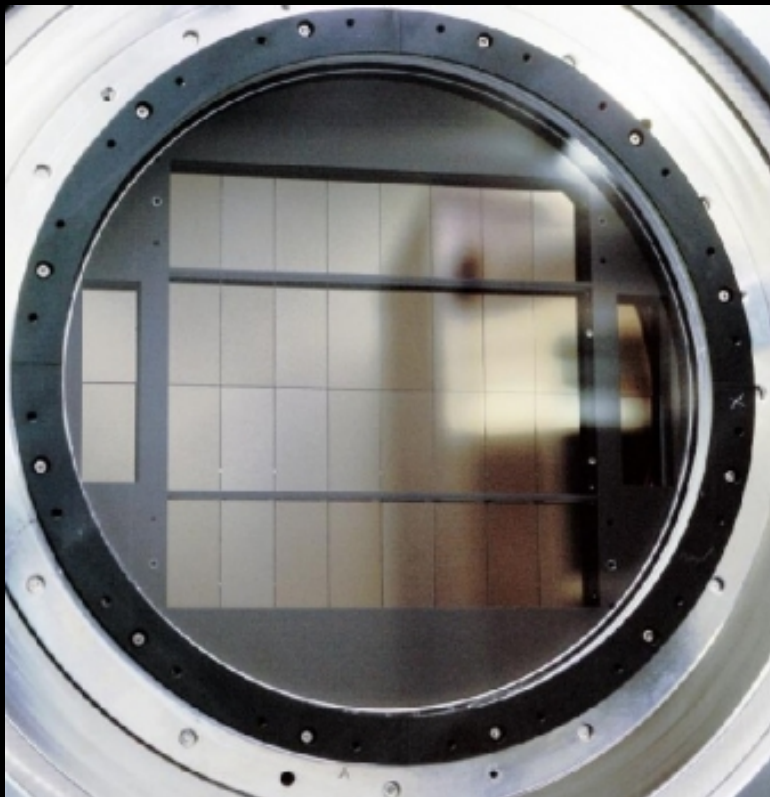
Lensing and large-scale structure

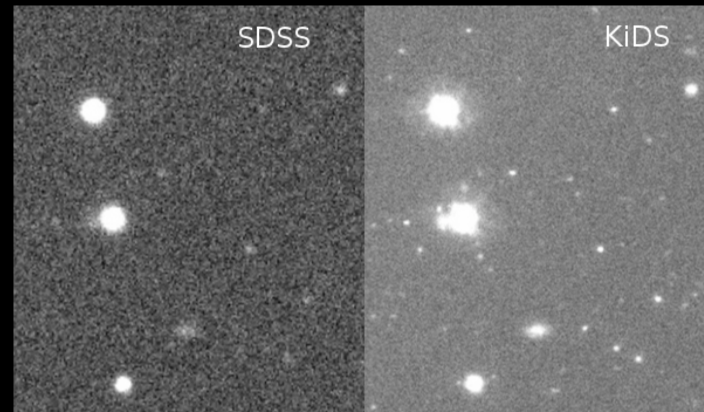
- Compare the effect of density fluctuations on **galaxy velocities** and the **lensing of distant galaxy light**
- Lensing and velocities test **different modifications** to gravitational physics
- Overlapping surveys allow **measurement of new statistics** (i.e. galaxy-galaxy lensing)
- Overlapping surveys allow **mitigation of systematics** (e.g. photo-z calibration, galaxy bias, intrinsic alignments)



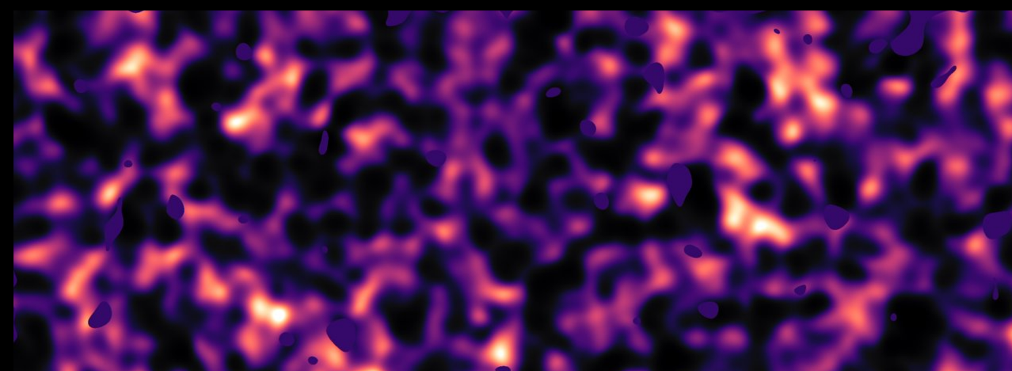
Credit:
Michael Sachs

Kilo-Degree Survey (KiDS)





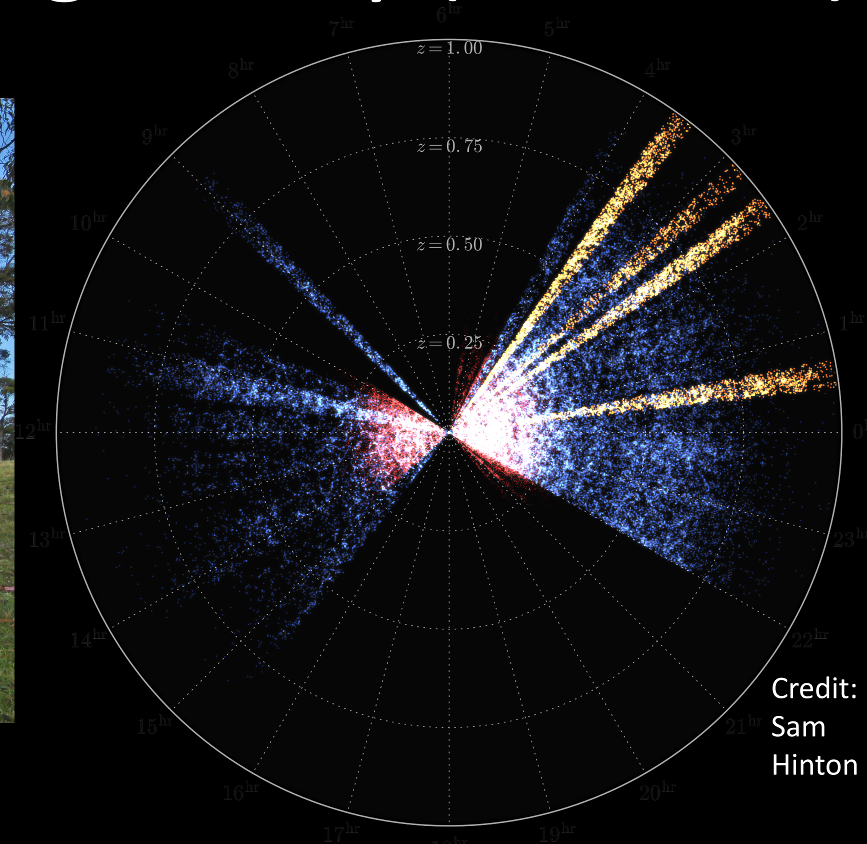
Credit:
H.Hildebrandt



- Multi-band (*ugri*) imaging survey of 1500 deg^2 using the VST's OmegaCAM instrument (450 deg^2 released)
- Optimized for weak gravitational lensing measurements

2-degree Field Lensing Survey (2dFLenS)

Credit: Angel Lopez-Sanchez/AAO

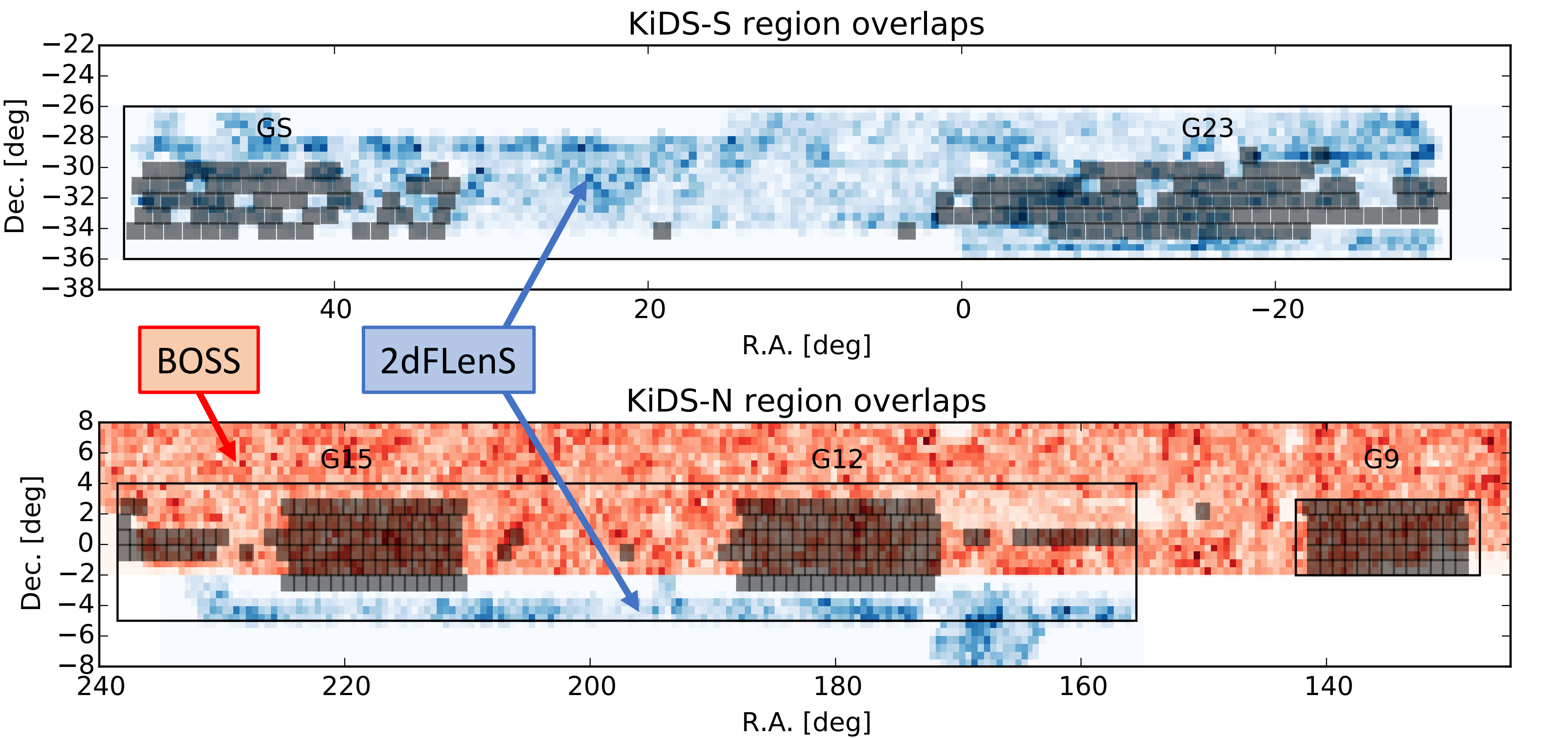


Credit: Sam Hinton

- Spectroscopic follow-up of KiDS and other lensing surveys over 50 AAT nights (Sep 2014 – Jan 2016)
- Sample of 70,000 LRGs/bright galaxies for cross-correlations with weak lensing and photo-z calibration

Combined probes: RSD+lensing

- Analyse lensing/clustering measurements in **overlap areas**



Joudaki et al. (2018) – arXiv:1707.06627

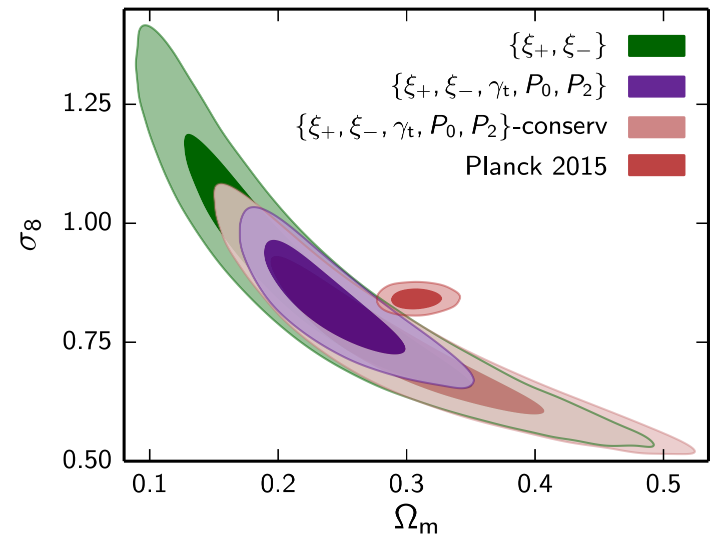
Combined probes: RSD+lensing

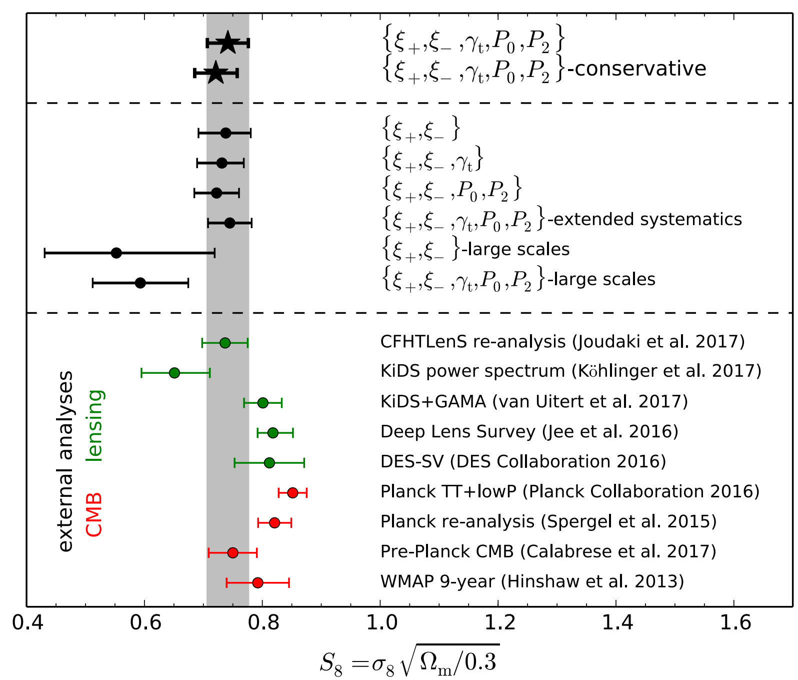
- Cosmological fits to **cosmic shear** (ξ_+, ξ_-), **galaxy-galaxy lensing** (γ_t) and **power spectrum multipoles** (P_0, P_2) in overlap areas

- Combined probes help **determine systematics** (intrinsic alignments, bias)

- Some evidence that lensing prefers lower $\sigma_8\sqrt{\Omega_m}$

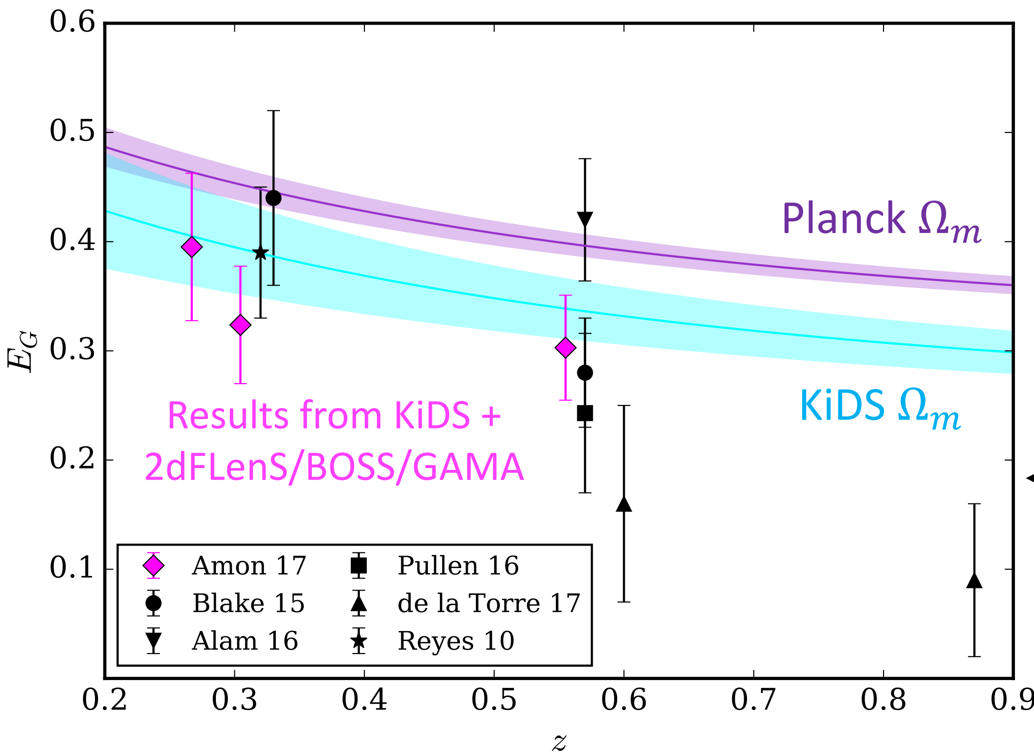
- Will improve as datasets expand! (e.g. KiDS-1000)





Combined probes: gravitational slip

- Overlapping surveys allows tests such as the “gravitational slip”, using **galaxy-galaxy lensing and RSD of lens galaxies**
- $E_G = \frac{\text{Amplitude of galaxy–galaxy lensing}}{\text{Amplitude of galaxy velocities}} = \frac{1}{\beta}\frac{\Upsilon_{gm}(R)}{\Upsilon_{gg}(R)} = \frac{\Omega_m}{f}$



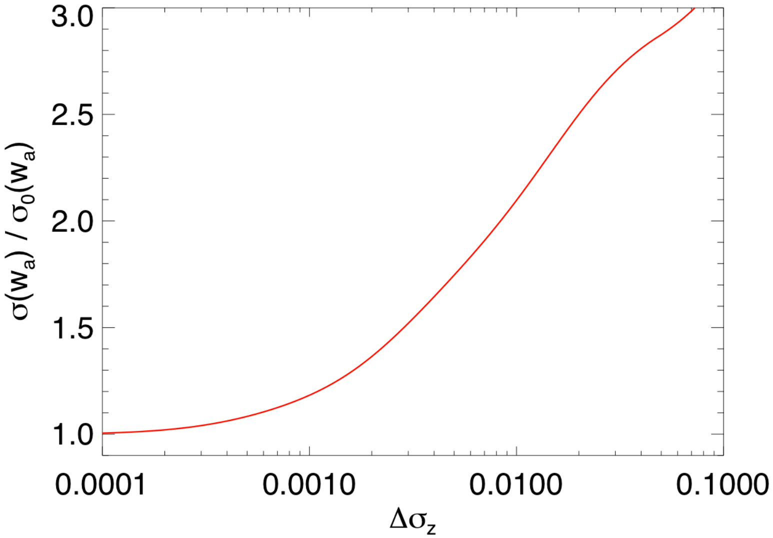
Amon et al. (2018) – arXiv:1711.10999

Lensing signal generally prefers lower matter density

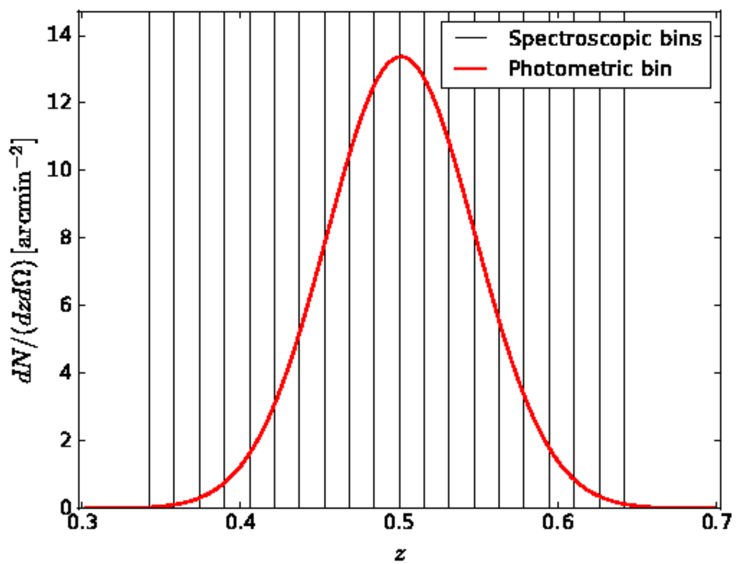
$N(z)$'s from cross-correlations

- **Determining the source redshift distribution** is one of the principal systematics for cosmic shear cosmology
- Direct measurement is challenging due to lack of sufficiently deep and complete spec-z samples
- **Cross-correlation with brighter spec-z samples** offers an alternative approach

Credit: Hearin et al. (2011), Newman et al. (2015)

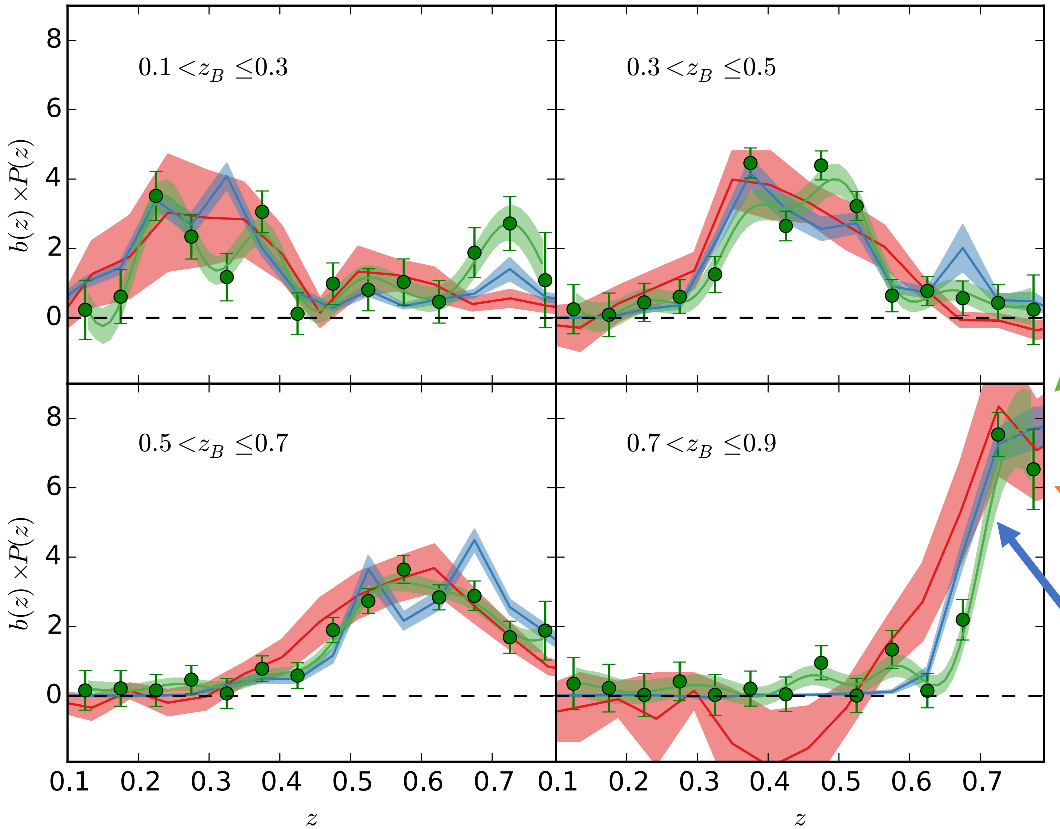


Credit: Alonso et al. (2017)



$N(z)$'s from cross-correlations

- Inference of $b_s(z)P_s(z)$ from angular cross-correlations of KiDS sources in 4 tomographic bins with 2dFLenS spec-z's, using optimal quadratic estimation technique



Johnson et al. (2017) – arXiv:1611.07578

Summary

- Apparent existence of dark energy motivates new tests of large-scale gravitational physics
- Combined probe analyses are pivotal for breaking degeneracies and improving statistics/systematics
- Tests for gravity can be constructed using large-scale structure, peculiar velocities and lensing
- All measurements are so far consistent with the standard cosmological model, but the accuracy will improve significantly in the near future

Credit: Greg Poole