FastSound project: A galaxy redshift survey at z~1.4 with Subaru/FMOS

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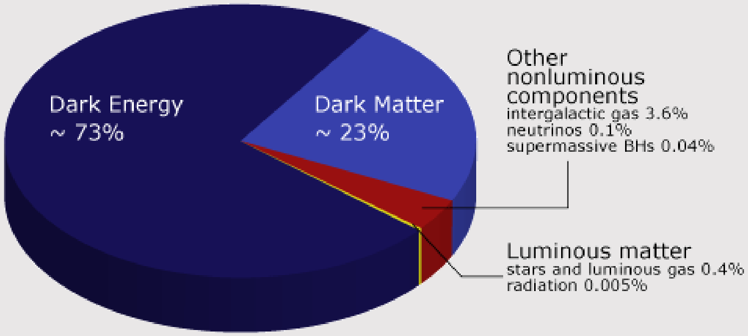
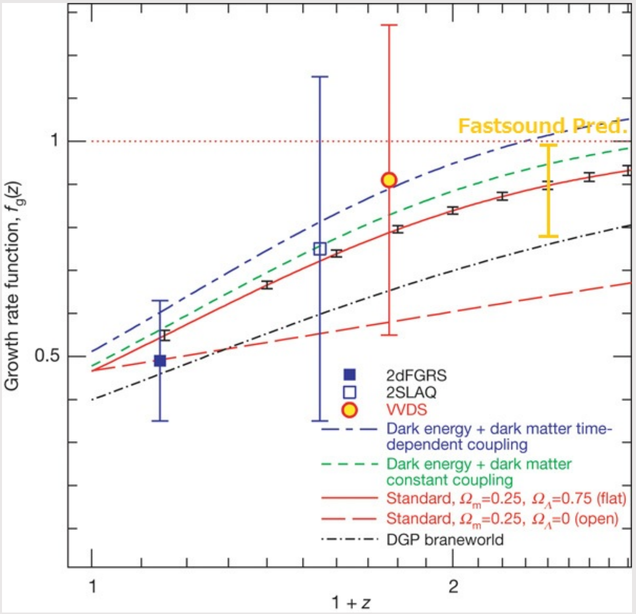
Dark energy

- Accelerating expansion of the Universe
  - Gravitational force is attractive
  - Need the repulsive force
    - Dark energy $p = w\rho \quad (\mathrm{w} < -1/3)$?
    - Modified gravity ?



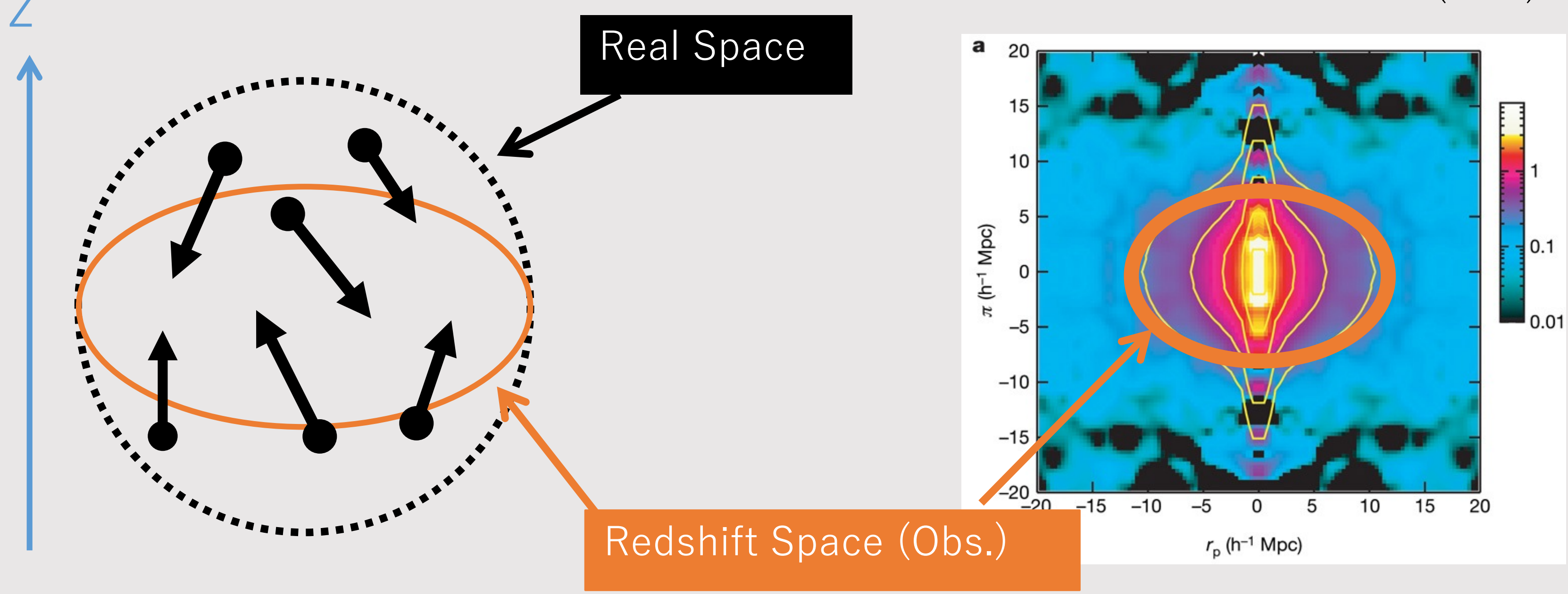
- Growth rate of structure f is a discriminant of gravity theories
  - Redshift space distortion (RSD) gives measurement of f



Redshift Space Distortion (RSD)

- We measure the distance of galaxies from redshifts.
  - redshift = cosmological redshift + Doppler effect (galaxy velocity)
- In redshift space, the galaxy clustering is distorted by the peculiar velocity of galaxies.

Guzzo et al. (2007)



Redshift Space Distortion (RSD)

$$P^{\mathrm{obs}}(k,\mu) = \left(1 + \frac{f\mu^2}{b}\right)^2 P^{\mathrm{real}}(k)$$ (Kaiser formula)

- RSD gives measurement of f as an anisotropy parameter
- f is predicted by gravity theories:

$$f = \frac{d\ln\delta}{d\ln a}$$

$$P(k) = \langle|\delta(k)|\rangle^2$$

$$\delta(k) = \frac{1}{V}\int \delta(x)e^{-ikx}\,d^3x$$

$$\delta(x) = \frac{\rho(x) - \rho}{\bar{\rho}}$$

b: galaxy bias
a: scale factor
$\mu = k_{||} / |k|$
$k = 2\pi / x$

Measurement of f = test of gravity theories on cosmological scale !

Past measurements of RSD

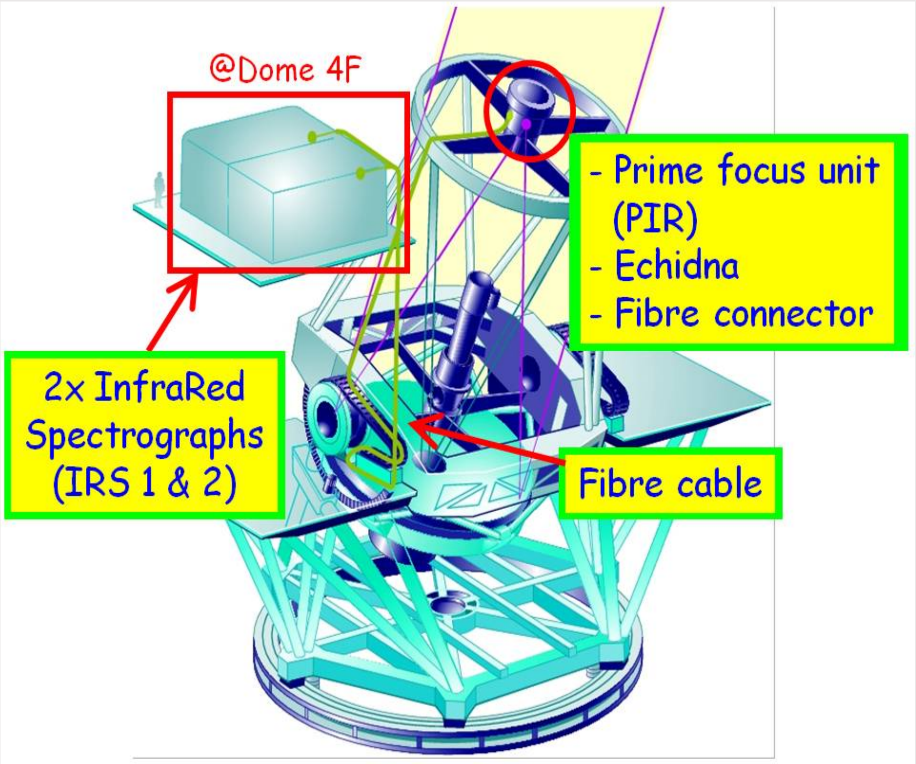
DESI collaboration (2016)

z	$f\sigma_8$	survey	reference
0.067	0.42 ± 0.06	6dFGRS	[80]
0.17	0.51 ± 0.06	2dFGRS	[90]
0.22	0.42 ± 0.07	WiggleZ	[82]
0.25	0.35 ± 0.06	SDSS LRG	[77]
0.37	0.46 ± 0.04	SDSS LRG	[77]
0.41	0.45 ± 0.04	WiggleZ	[82]
0.57	0.45 ± 0.03	BOSS CMASS	[85]
0.6	0.43 ± 0.04	WiggleZ	[82]
0.77	0.49 ± 0.18	VVDS	[91]
0.78	0.38 ± 0.04	WiggleZ	[82]
0.80	0.47 ± 0.08	VIPERS	[92]
1.4	0.48 ± 0.12	FastSound	[93]

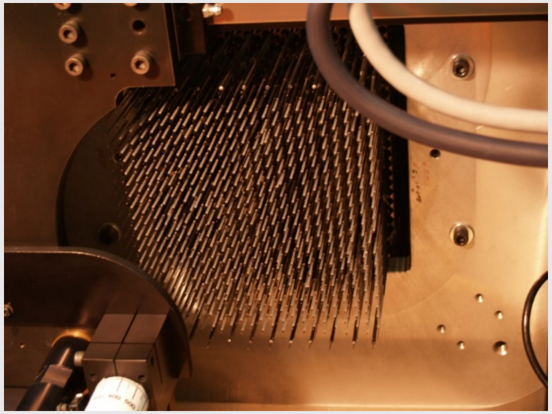
- RSD has been detected up to z~0.8
- All survey has been in optical bands
- FastSound: The first RSD survey at z>1
  - Use FMOS near-infrared spectrograph
  - FAST = FMOS Ankoku Sekai Tansa (暗黒世界探査 meaning "dark universe survey" in Japanese), or FMOS Acceleration Sampling Test
  - SOUND = Subaru Observation Understanding Nature of Dark energy

FastSound

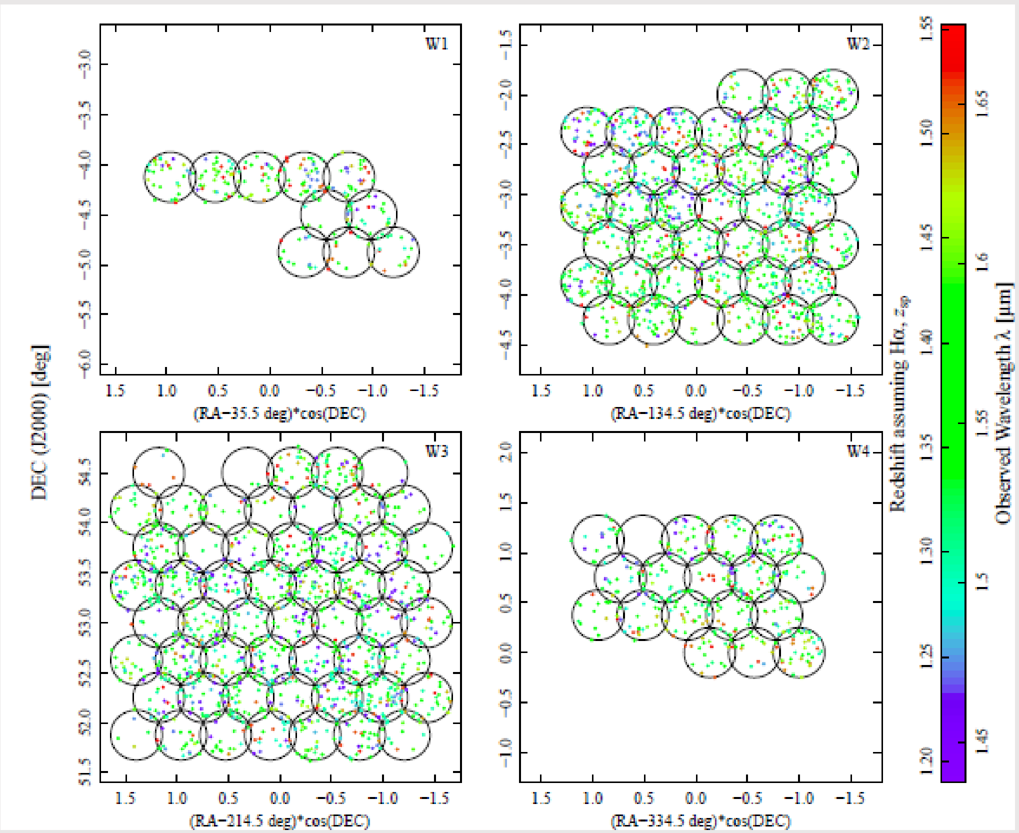
FastSound with Subaru/FMOS



- Fiber Multi-Object Spectrograph
  - 400 fibers in 30’ diameter
  - NIR spectrograph
    - Low-resolution(LR) : 0.9 – 1.8 um, R~500
    - High-resolution(HR) : R~2200
  - FastSound uses HR mode
    - 1.43--1.68 um
    - Hα λ6563 @ z ~ 1.4
- OH mask suppression by the mask mirror
- NIR observation = reach z>1!



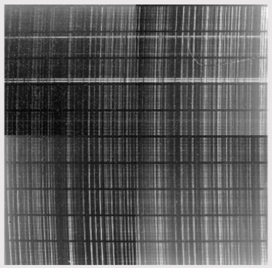
Observations

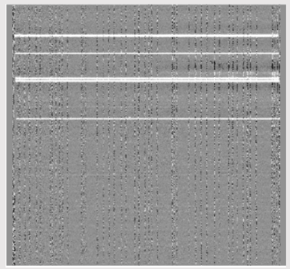


Okada et al. (2015)

- Observation
  - March. 2012 – July. 2014
- Target selection
  - Use CFHTLS Wide 5 bands (u*g’r’I’z)
  - Based on redshift and Hα flux estimates using LePhare
- Survey field
  - W1: 10 FoVs (2deg^2)
  - W2: 39 FoVs (8deg^2)
  - W3: 54 FoVs (11deg^2)
  - W4: 18 FoVs (4deg^2)

Data Reduction / Line detection





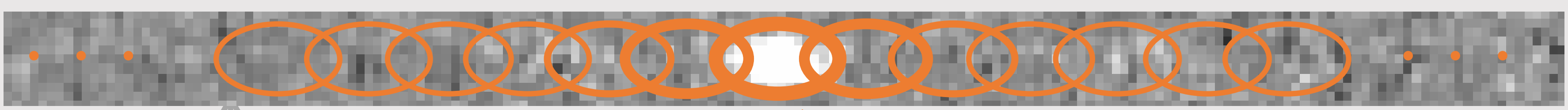
select candidates by given S/N threshold

Raw image → Reduced → Redshift Catalog

FIBRE-pac
(Iwamuro et al. 2012)

FIELD
(Tonegawa et al. 2015)

Fiber Aperture

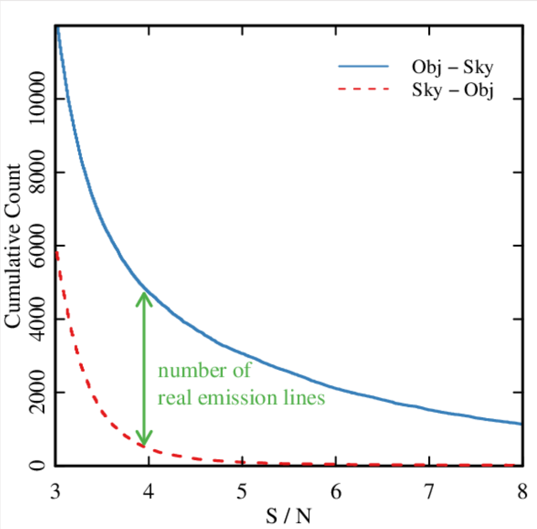


Wavelength

Kernel of Emission line
$\sigma_x = 4.26$ pix (175km/s velocity dispersion)
$\sigma_y = 2.5$ pix

Line Candidate
(Peak of convolved S/N)

Suppression of false detections



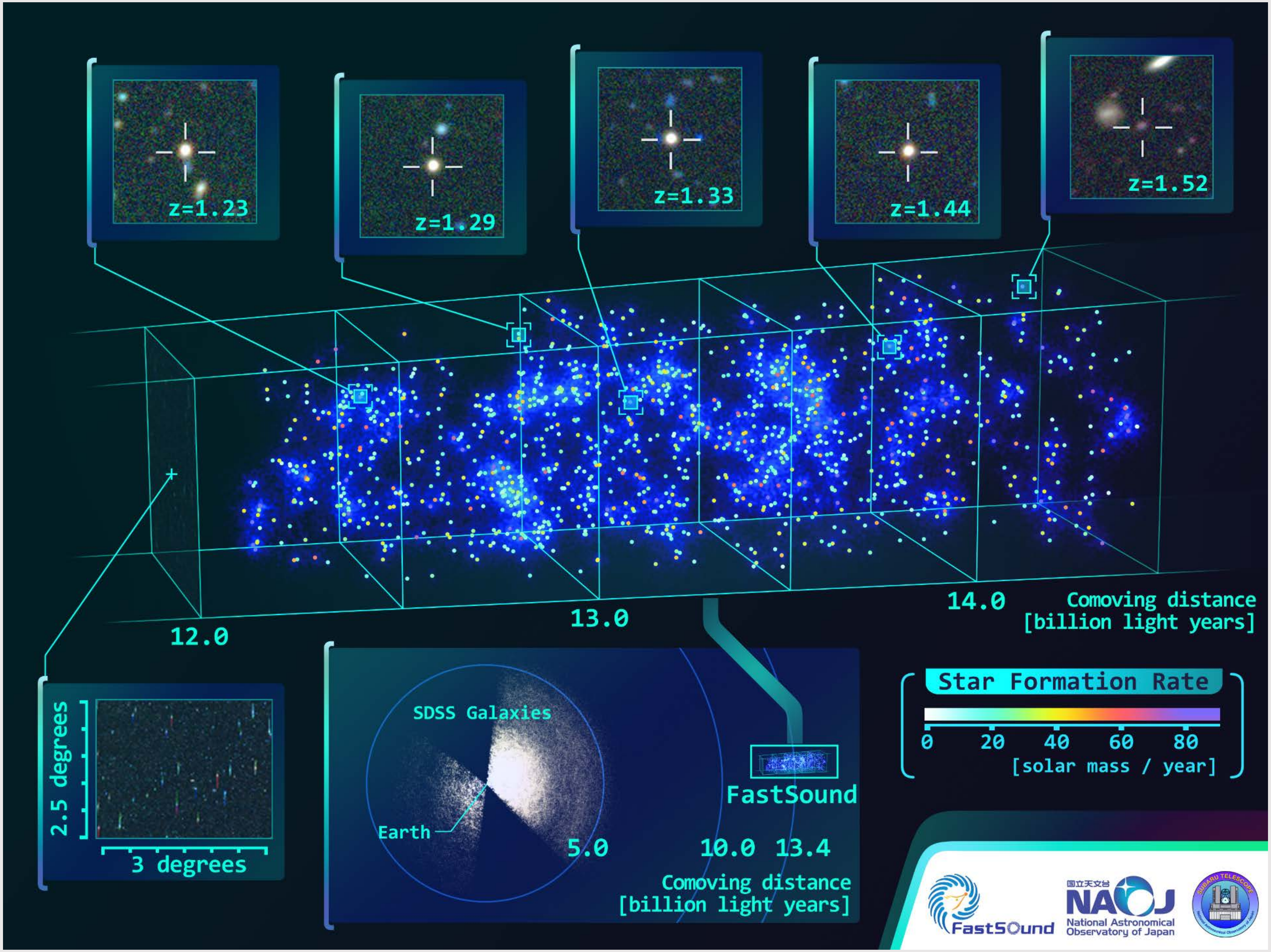
- False detection rate estimates
  - Line search on “inverted” image
  - 4.5% (S/N>4.5), 9.2% (S/N>4.0)
- Line confusion
  - We have typically only 1 emission line, because of limited wavelength coverage: is it really Ha line ?
  - Using multiple line objects, the line confusion rate is estimated (Okada et al. 2015).
  - [OIII] λ 5007 @ z~2 is the largest contamination (4.4%).
  - Used for correction of the power spectrum

Emission line statistics

- Emission lines：~4,000 (S/N>4.5) ~5,000 (S/N>4.0)

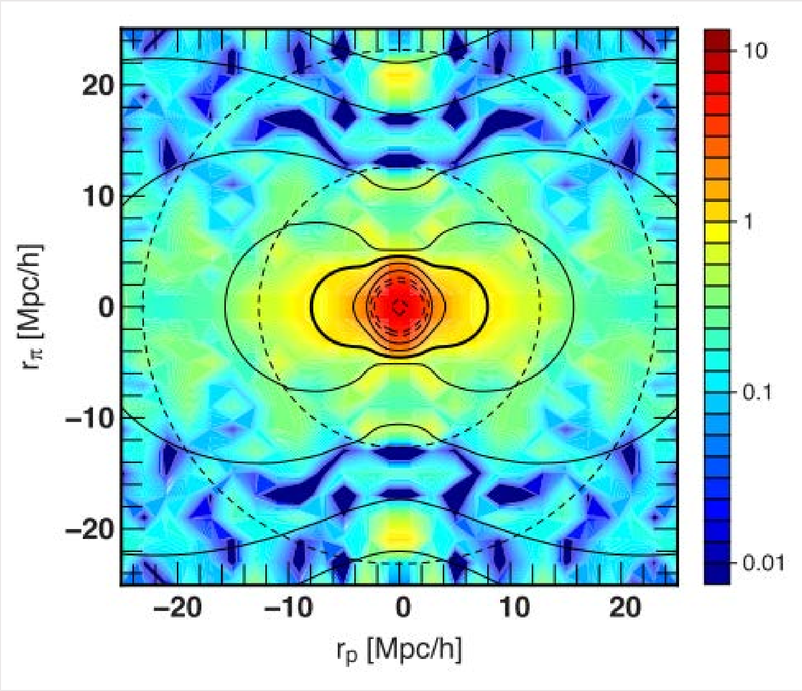
Emission lines	S/N > 4.5	S/N > 4.0
W1	239 (14)	318 (27)
W2	1535 (75)	1950 (185)
W3	1528 (98)	1929 (224)
W4	436 (26)	557 (75)
Total	3769 (170)	4797 (441)

( ) : number of detections in inverted frames



https://www.youtube.com/watch?v=RAiPZ_oUPI4

2D correlation function



Paper IV, Okumura et al. (2015)

- About 3,000 conservatively selected galaxies (S/N > 4.5)
- Landy-Szaley estimator

$$\xi = \frac{DD - 2DR + RR}{RR}$$

- Fiber allocation failure corrected
- Decrease of detection rate near OH mask corrected

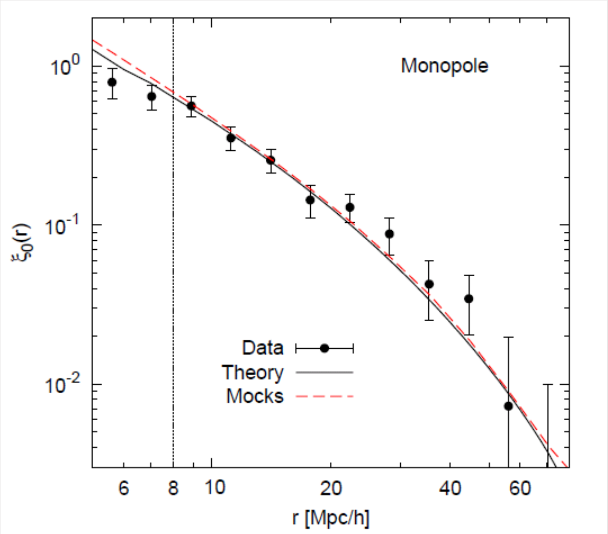
Correlation function

- Legendre expansion

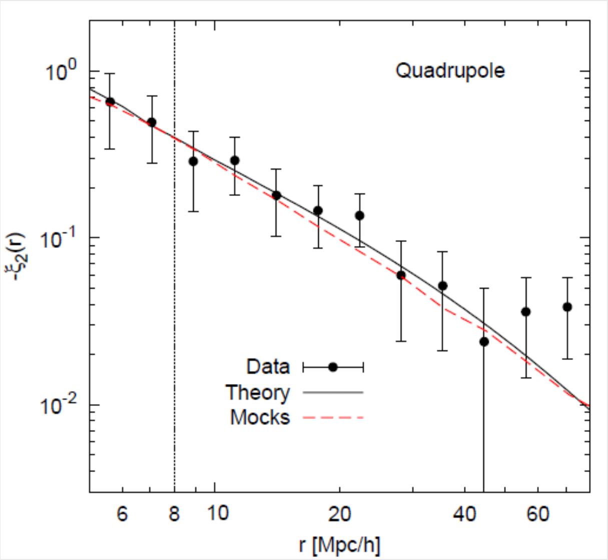
$$\xi_l = \frac{2l+1}{2}\int_{-1}^{1}\xi(r,\mu)L_l(\mu)d\mu$$

$L_l(\mu)$: Legendre polynomials

- Model fitting
  - Use $8 < r < 80h^{-1}$Mpc
  - Kaiser model + nonlinear P_m
  - Two parameters $(f\sigma_8, b\sigma_8)$
  - False detection and line confusion effects considered
- RSD is seen!



monopole component (l=0)

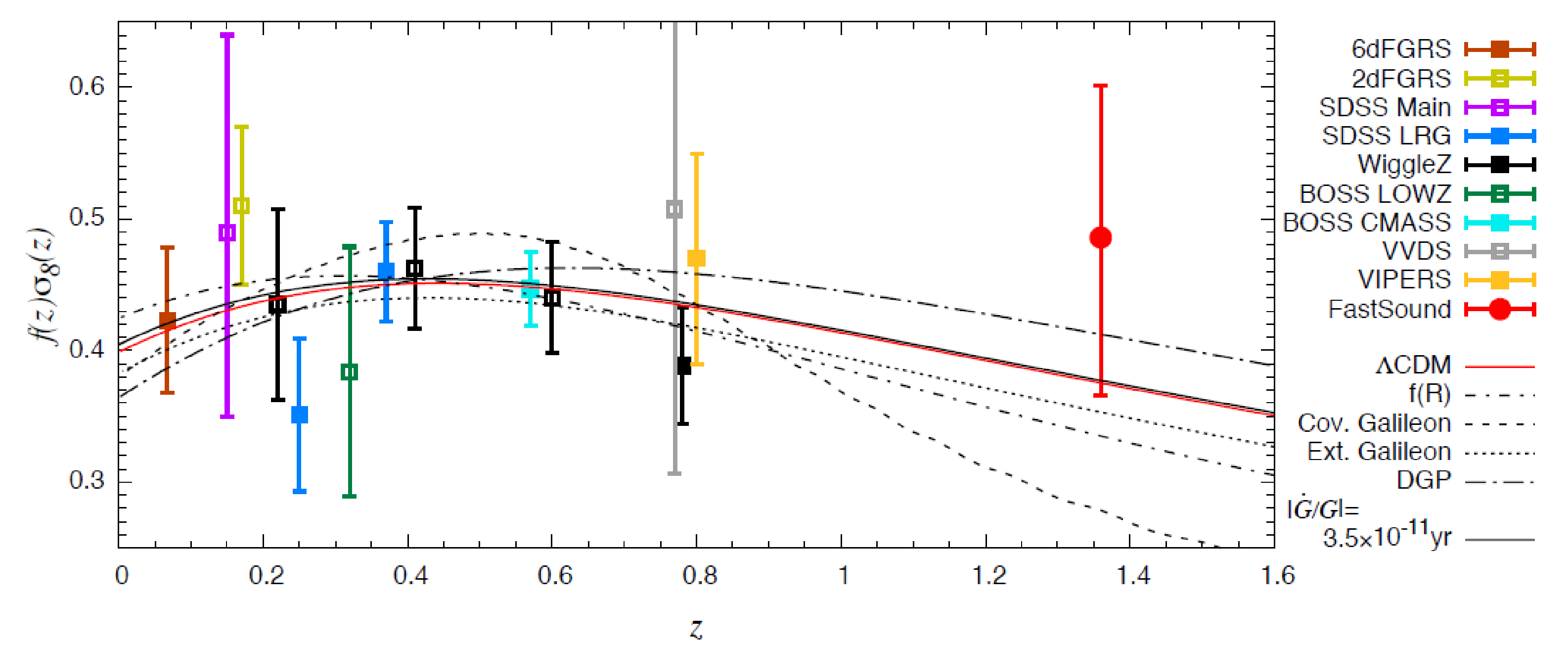


quadrupole component (l=2, RSD)

$f\sigma_8$ measurement at z~1.4

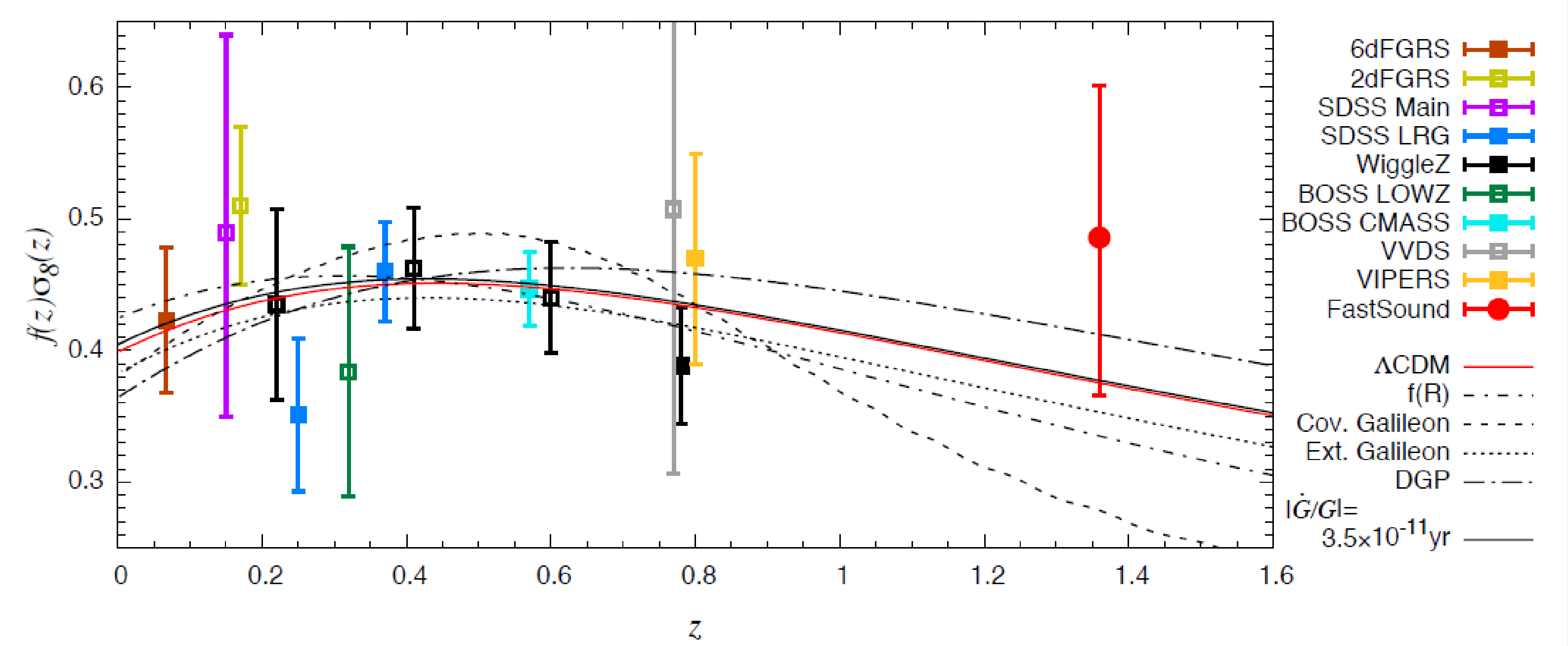
- 4.2 σ detection of RSD
- First significant detection of RSD at z>1
- Consistent with ΛCDM within 1 σ

	$f\sigma_8$
FastSound	0.482 ± 0.116
ΛCDM	0.392



Constraint on gravity theories

- Covariant Galileon model can be distinguished.
- High-z galaxy surveys, combined with the low-z constraints, is useful to distinguish gravity theories, independently of CMB experiments.

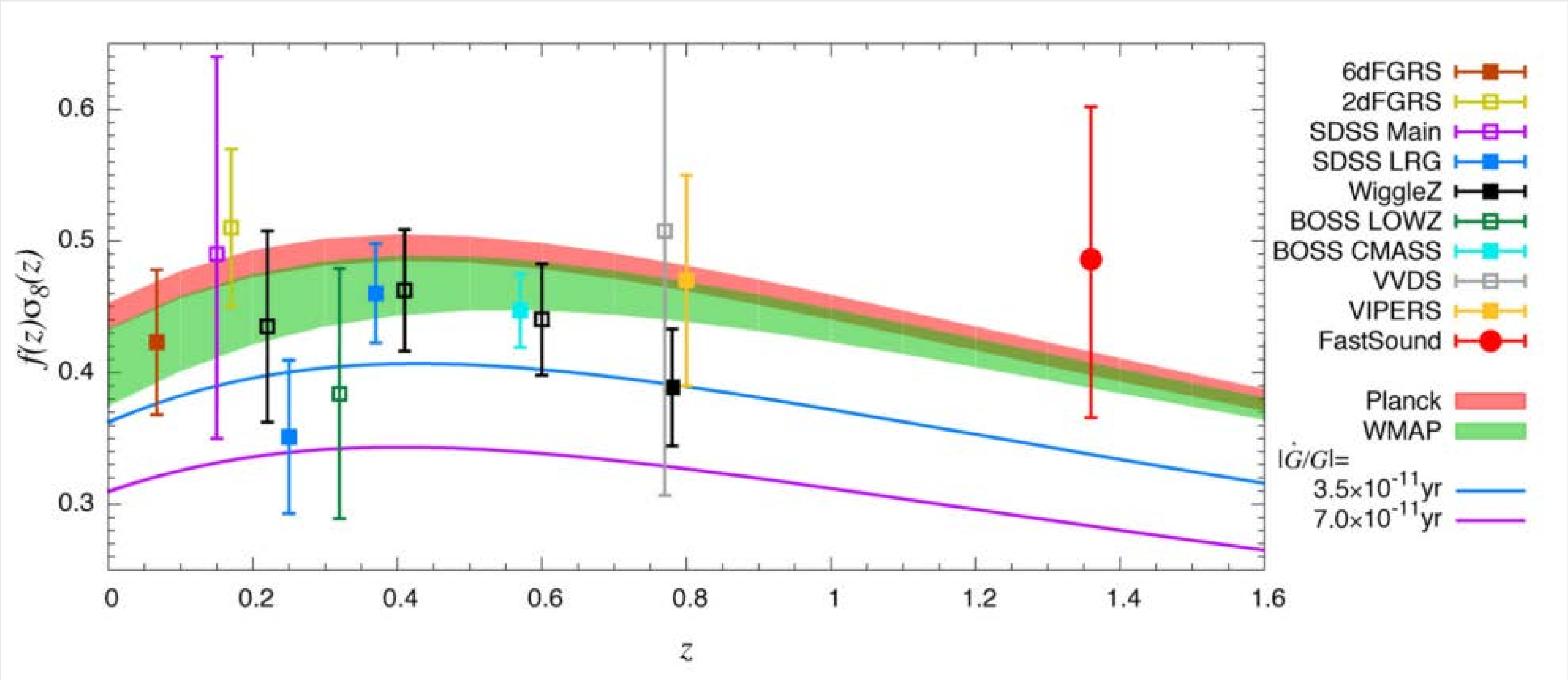


Summary

- FastSound project: the first RSD survey beyond z > 1
- ~5,000 redshifts of star-forming galaxies were collected by Subaru/FMOS
- RSD is detected at z~1.4 for the first time and the constraint on the growth rate $f\sigma_8 = 0.482 \pm 0.016$ is obtained. This is consistent with the prediction of the ΛCDM model.
- Measuring $f\sigma_8$ at various redshifts can be useful to distinguish modified gravity theories, without relying on CMB experiments.

Comparison with CMB results

- FastSound and almost all results from RSD are consistent with CMB results from WMAP and Planck



FastSound project

- FastSound：cosmological redshift survey using Subaru/FMOS
  - ~25 deg^2, ~5,000 redshifts of Hα galaxies
  - 35 nights observation from Mar. 2012 to Jul. 2014
- Scientific Goal
  - Reveal 3D distribution of Hα Galaxies at z=1.2-1.6
  - Detect Redshift Space Distortion (RSD) beyond z=1
  - Measure $f\sigma_8$ from RSD → test of General Relativity

Dark energy vs. Modified Gravity

- Λ on right-hand side or left-hand side?
  - right: the energy of the Universe (“dark energy”)
  - left: physical law of gravity (“modified gravity”)

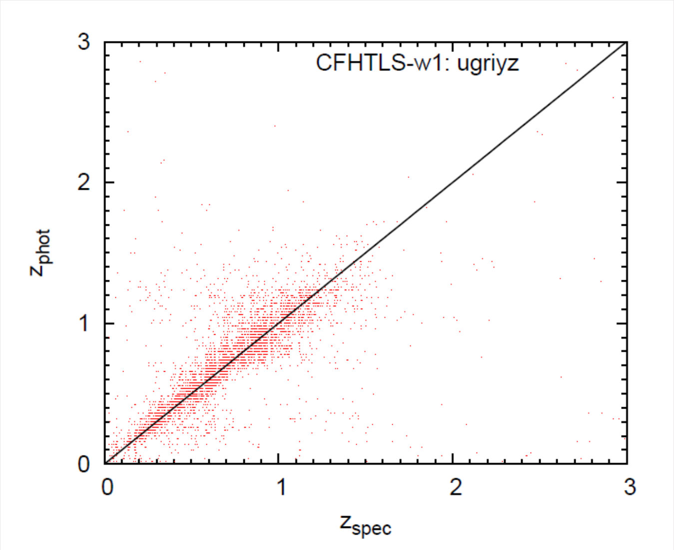
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

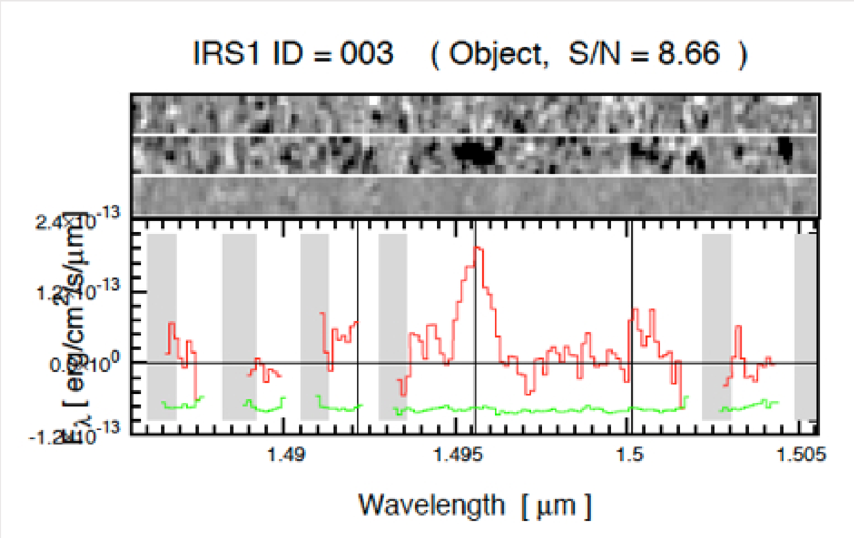
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

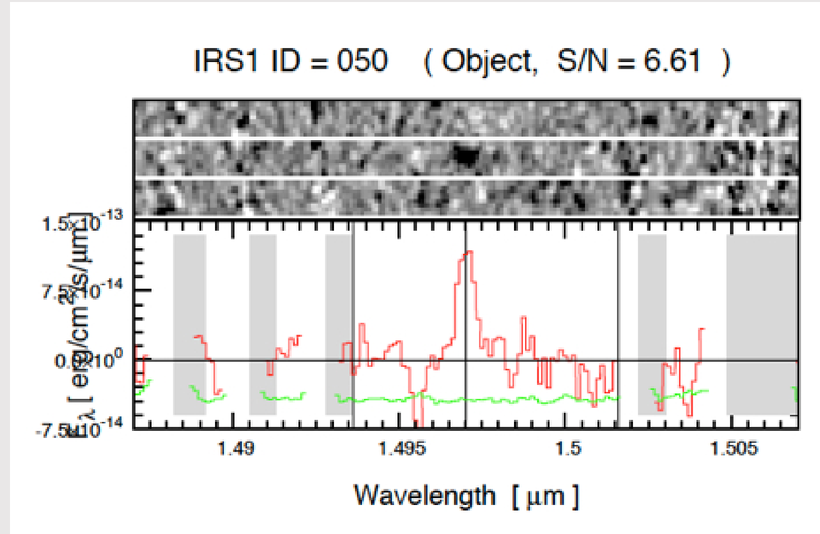
- Observational approaches are different

Target Selection

- Redshift and H α flux estimates using LePhare
  - CFHTLS optical 5 bands (u*, g', r,' i', z')
  - Empirical templates for redshift estimates z_{ph}
  - Population synthesis model (PEGASE2) for Ha flux estimates
- Selection criteria
  - $1.18 < z_{\mathrm{ph}} < 1.54$
  - H α flux > 1.0 x 10^{-16} [erg/cm^2/s]
  - 20.0 < z' mag < 23.0
  - g' – r' < 0.55

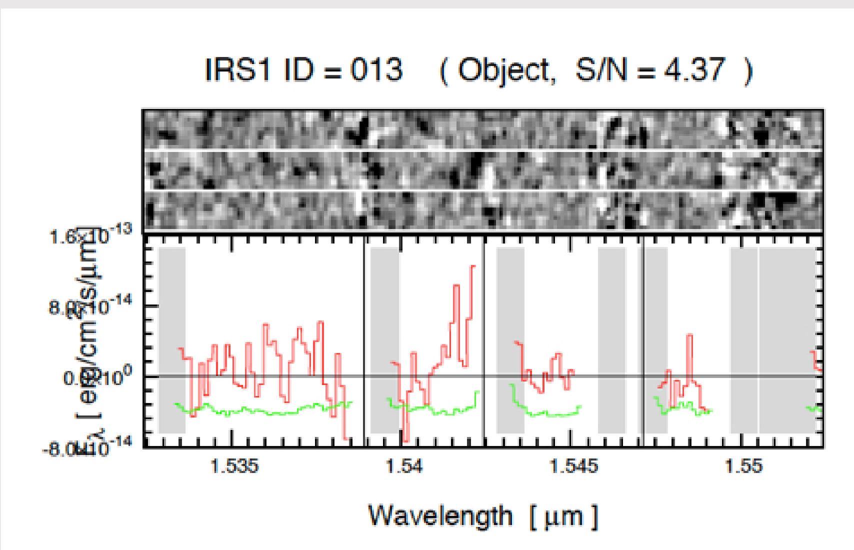


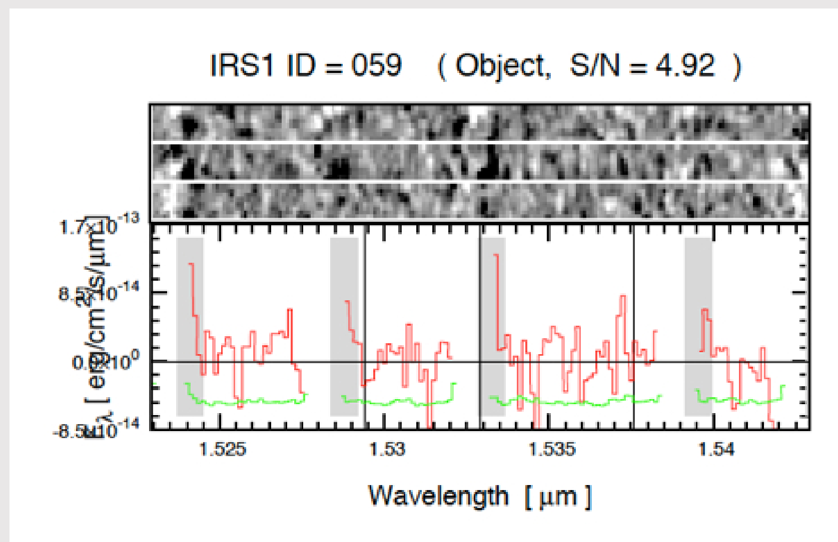


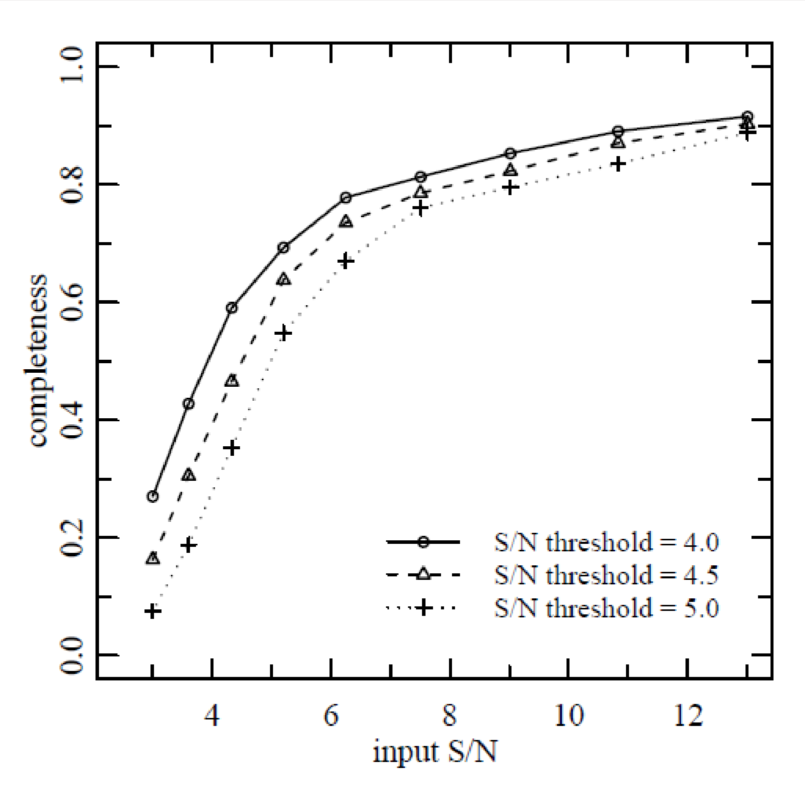


↑ True lines

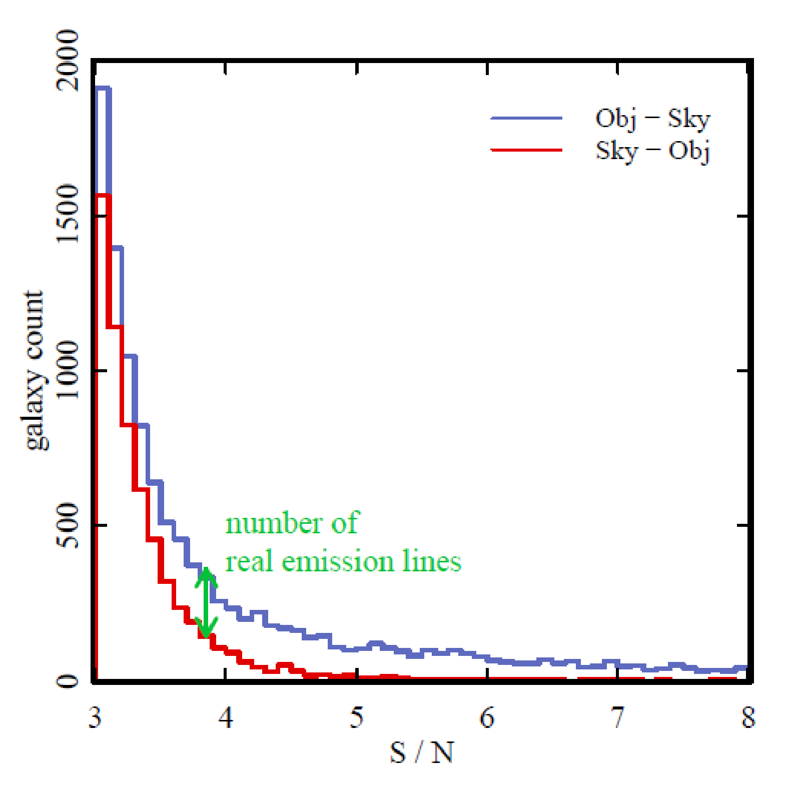
↓ Spurious objects







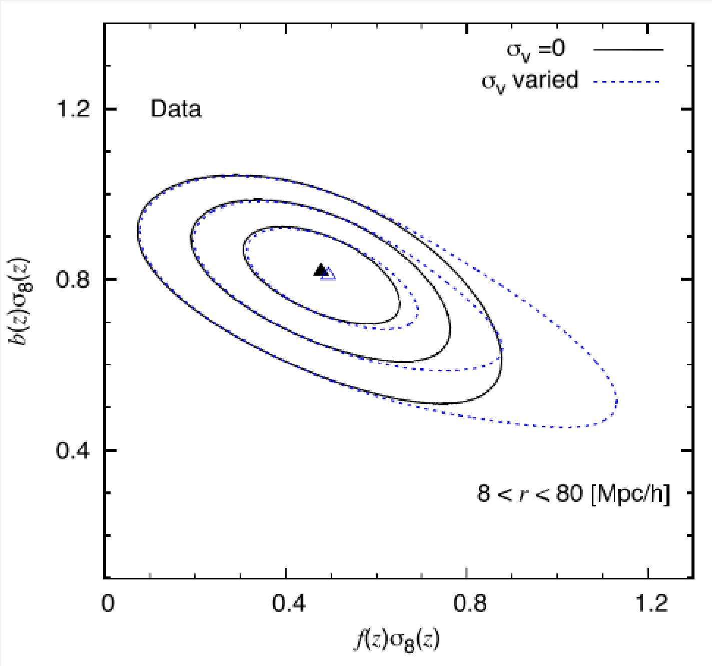
completeness
input S/N
0.0
0.2
0.4
0.6
0.8
1.0
4
6
8
10
12
S/N threshold = 4.0
S/N threshold = 4.5
S/N threshold = 5.0



galaxy count
S / N
0
500
1000
1500
2000
3
4
5
6
7
8
Obj − Sky
Sky − Obj
number of
real emission lines

Varying σ_v

- We also allow σ_v to vary, for a check.
- The best-fit value on $f\sigma_8$ does not change significantly
- $\sigma_v = 0$ is preferred: our spectroscopic targets are likely to be central galaxies, residing in small haloes



	$f\sigma_8$
FastSound	0.482 ± 0.116
σ_v varied	$0.494^{+0.126}_{-0.120}$