FastSound: A Near-Infrared Galaxy Redshift Survey for Cosmology at z~1.3 using Subaru/FMOS

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2016 Jan. 19
Subaru User's Meeting, Atami, Shizuoka

Scientific Background: RSD as a Probe of Cosmic Acceleration

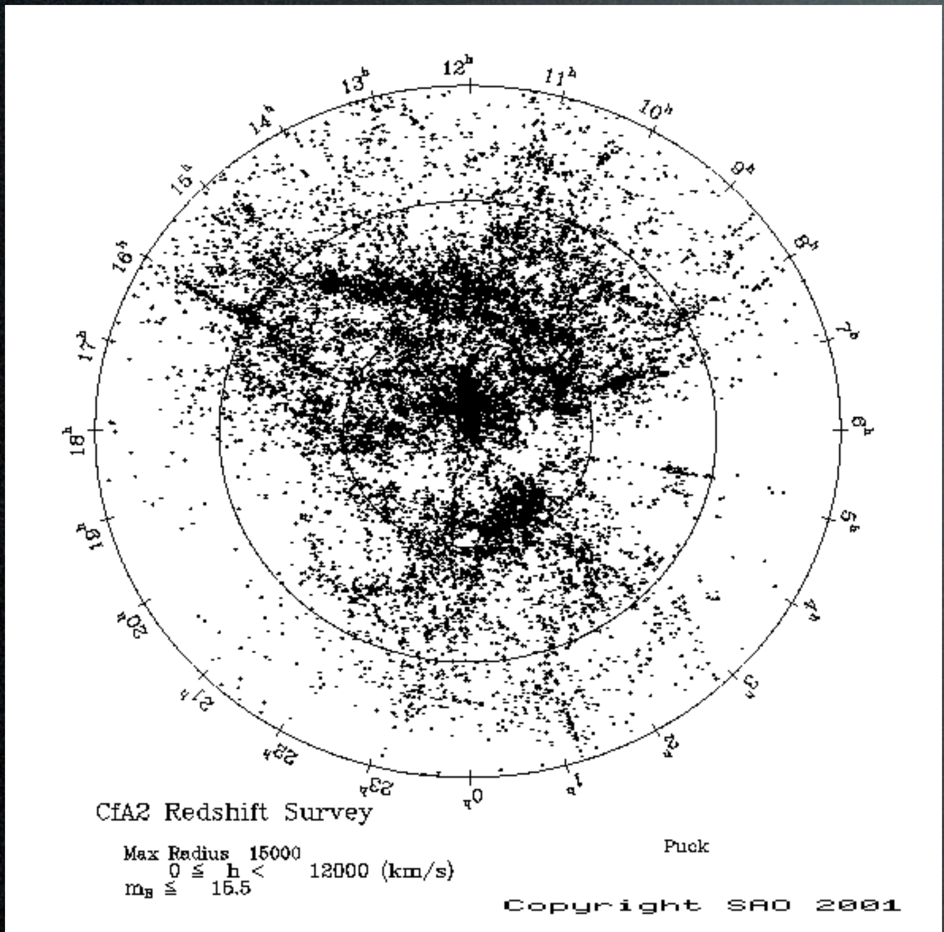
- The origin of the acceleration of the cosmic expansion?
  - dark energy?
  - breakdown of general relativity on cosmological scales?

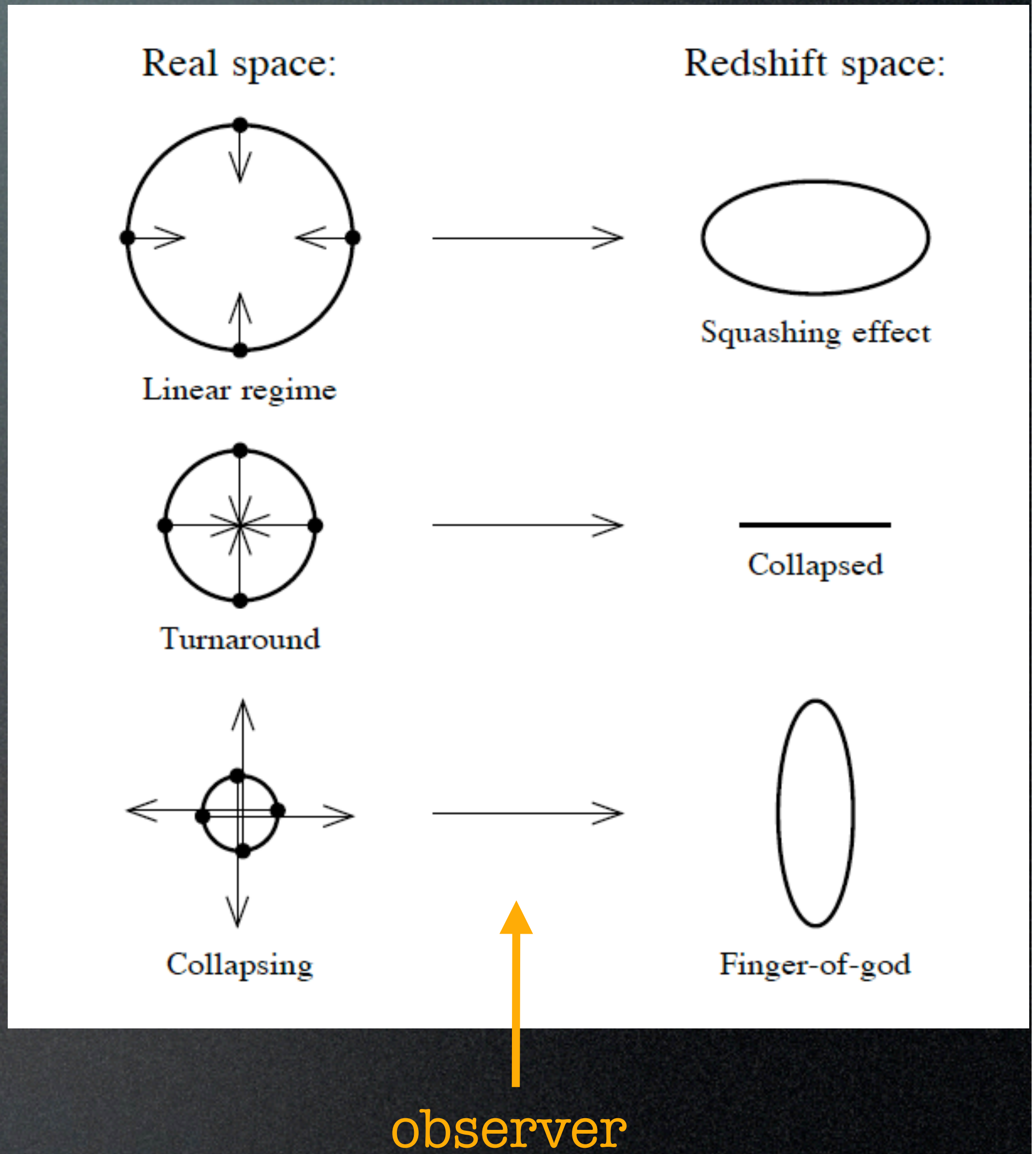
- Measurement of large-scale structure growth rate gives constraints on the theory of gravity
  - redshift space distortion (RSD) observed in galaxy redshift surveys gives such a test

Redshift Space Distortion (RSD)

- observed P(k) or ξ(r) is distorted by line-of-sight peculiar velocity of galaxies

Hamilton '98





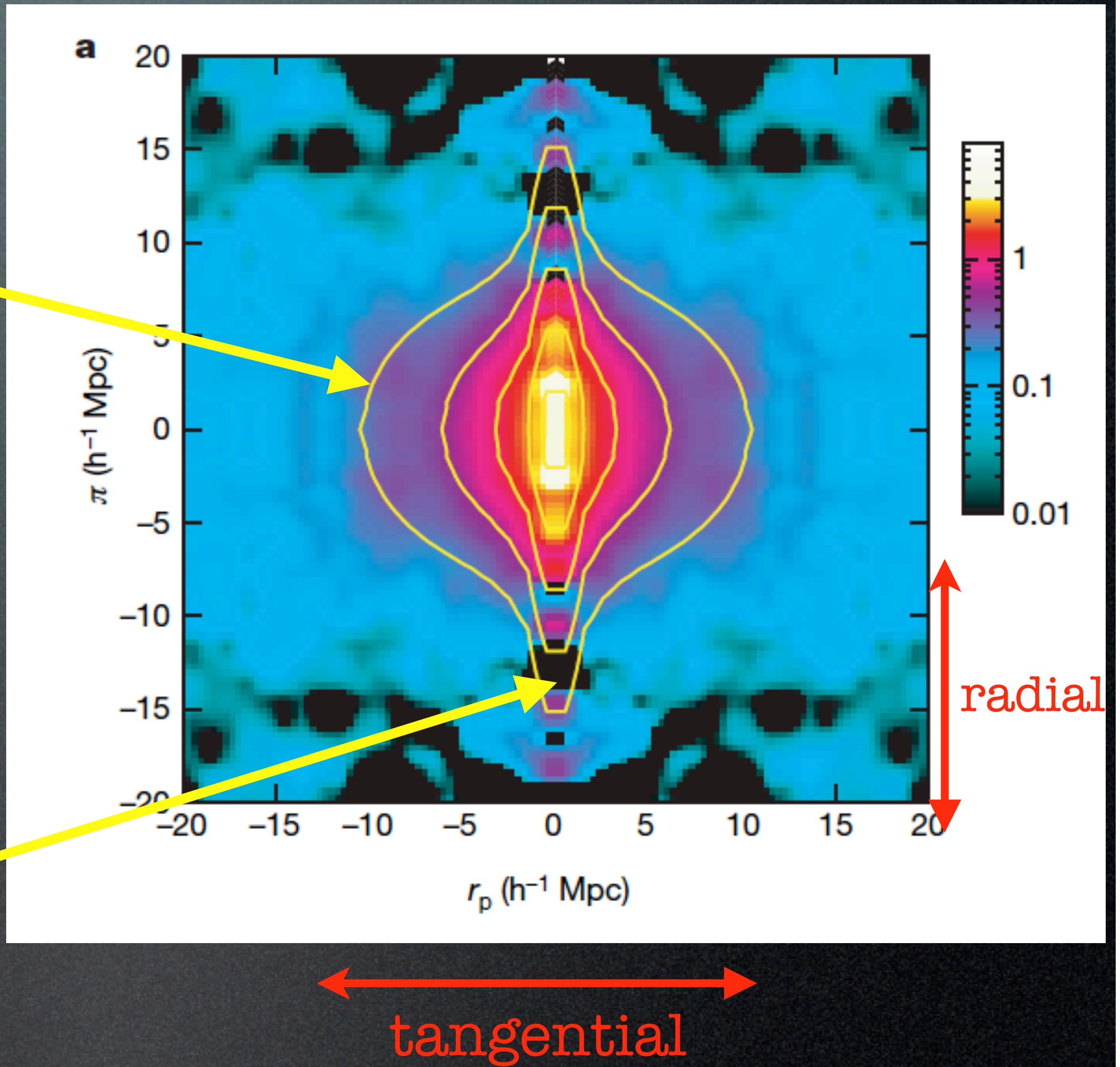
RSD in P(k) or ξ (x)

2D contour of galaxy correlation func. ξ (r)

- In the linear regime:
  - the Kaiser effect

$$P^s(\boldsymbol{k}) = (1+\beta\mu_{\boldsymbol{k}}^2)^2 P(k)$$

  - β : the anisotropy parameter
  - μ =cos θ （θ : angle to line-of-sight)
  - scale independent



- In the non-linear regime:
  - Fingers of God

Guzzo+’08

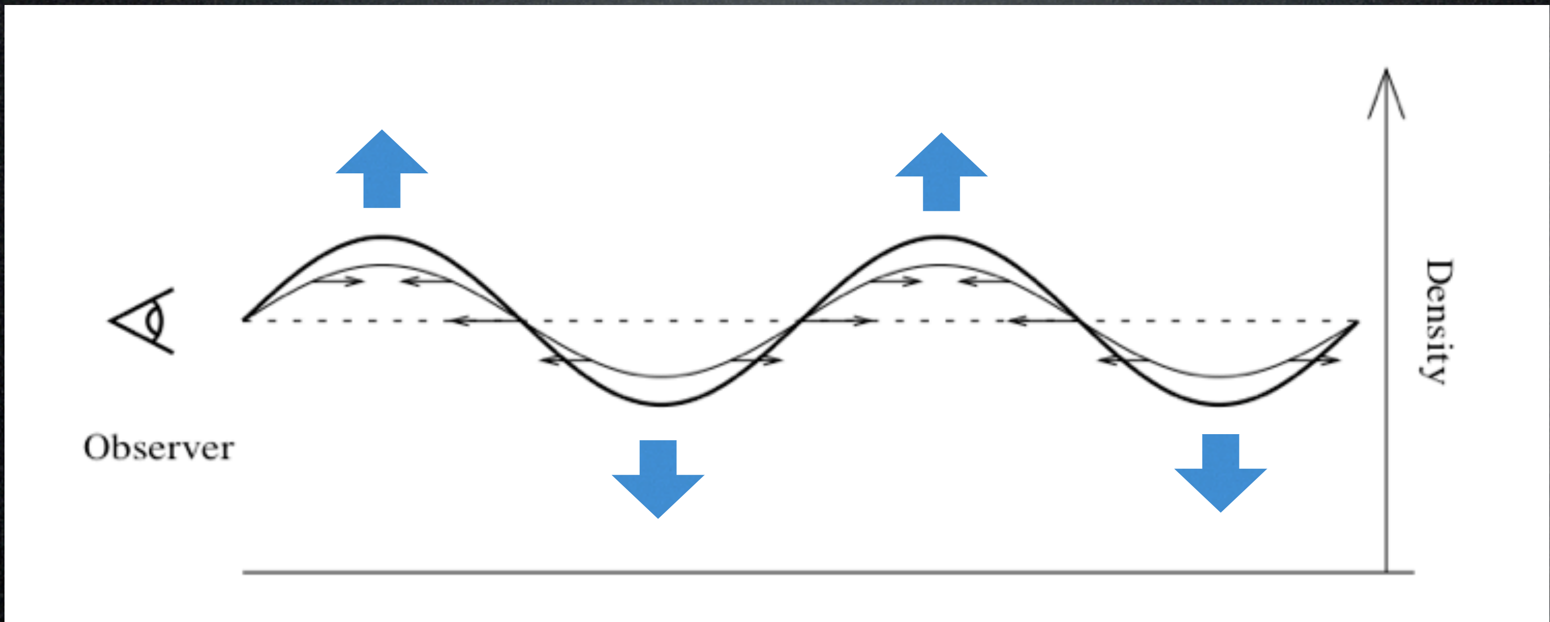
RSD gives a measure of structure growth rate

- anisotropy parameter β = infall velocity of large scale structure
- related to the speed of density fluctuation growth
  - simply by mass conservation, independent of gravity theory

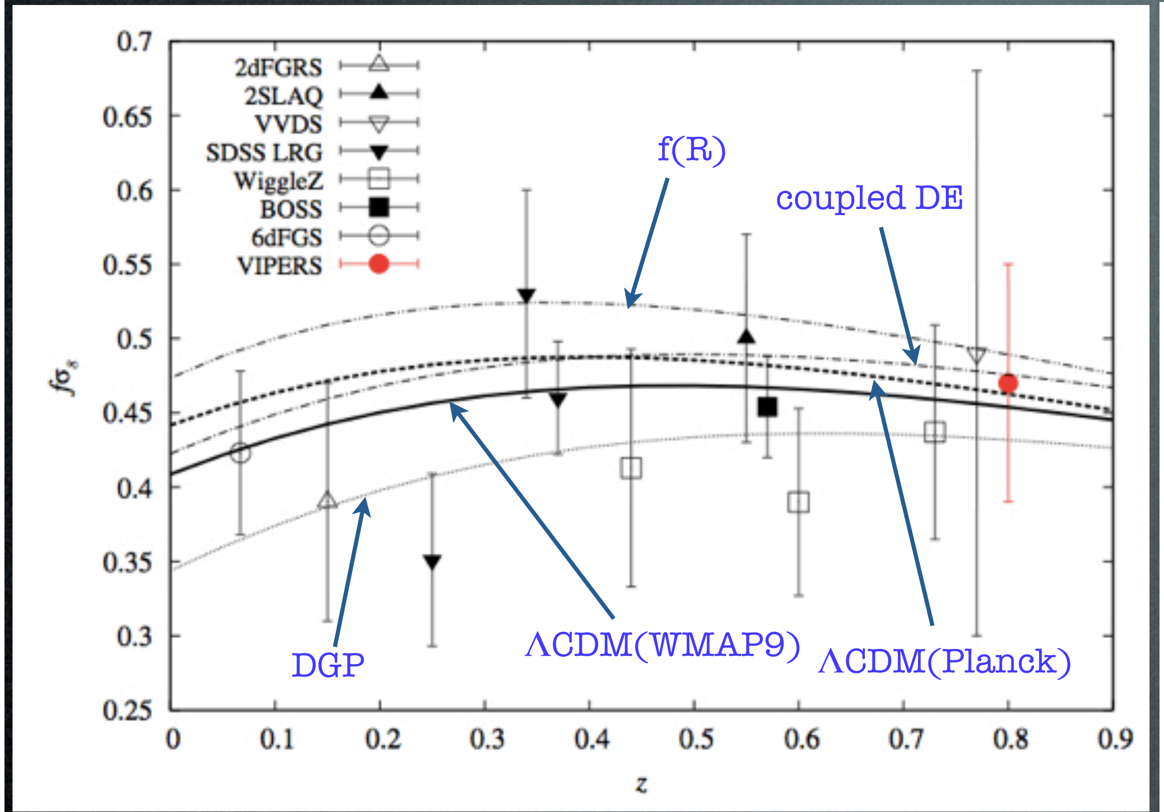
$$f \equiv \frac{H_0 a_0}{H a} \frac{d \ln D}{d\tau} = \frac{d \ln D}{d \ln a} \, .$$

structure growth rate,
$D(t) \propto \delta(t)$

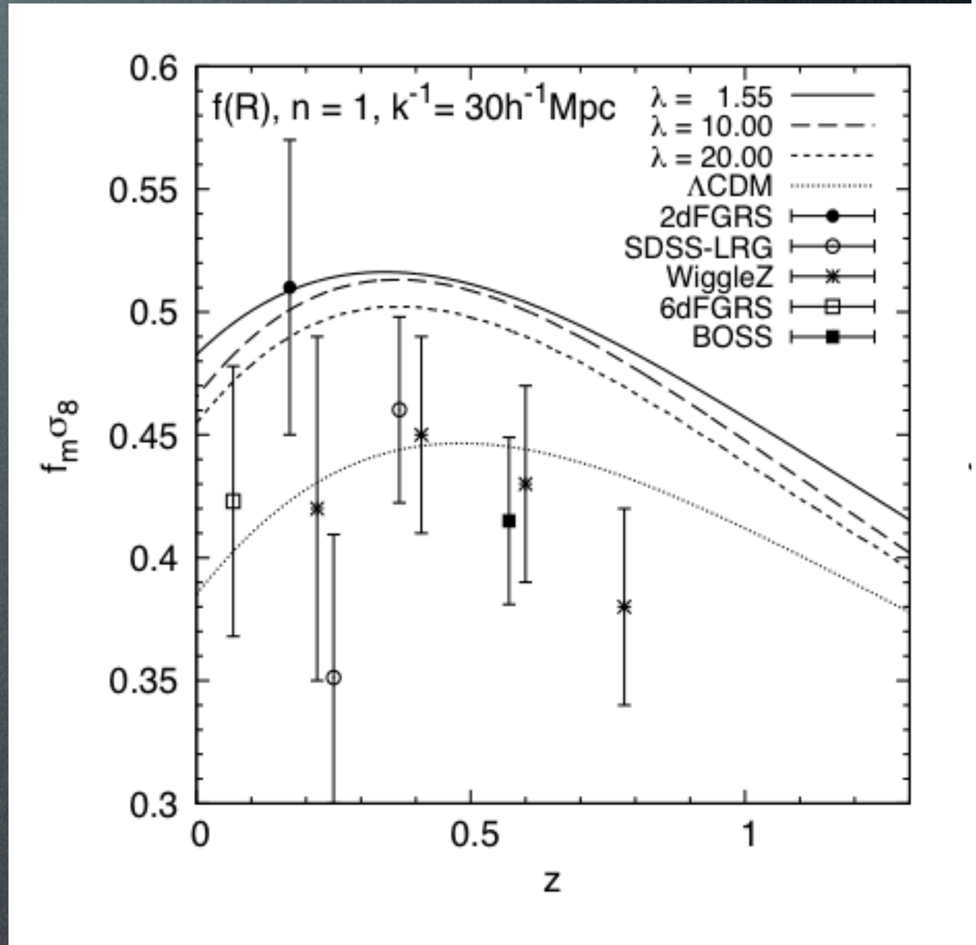
- β = f/b within the linear theory
- $\beta \rightarrow$ f/b or $f(z)\sigma_8(z) \rightarrow$ test of gravity on cosmological scale!



RSD testing Gravity Theory



de la Torre+'13

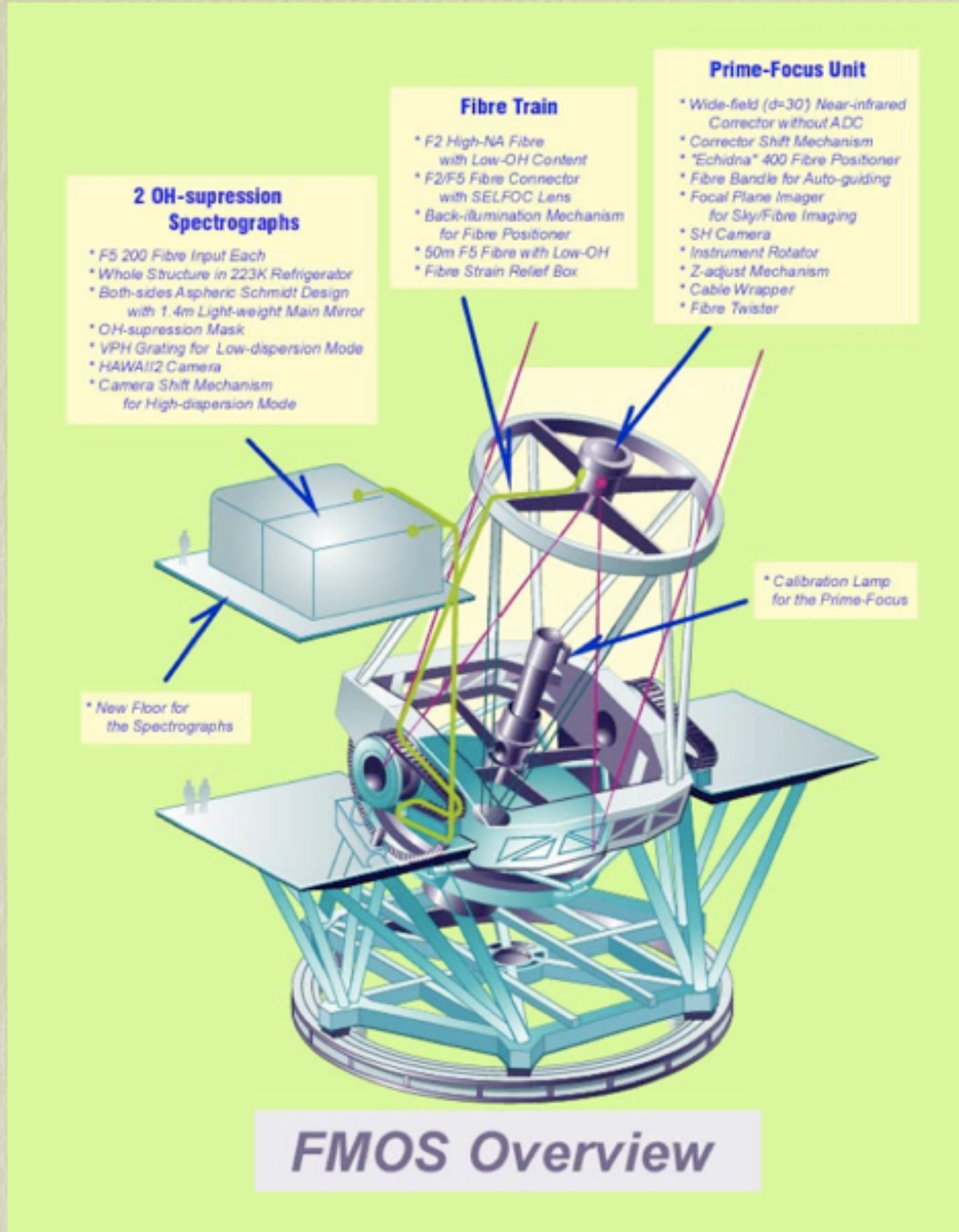


Okada+'13

- Next step:
  - more precise measurements at z < 1
  - go beyond z = 1: FastSound!

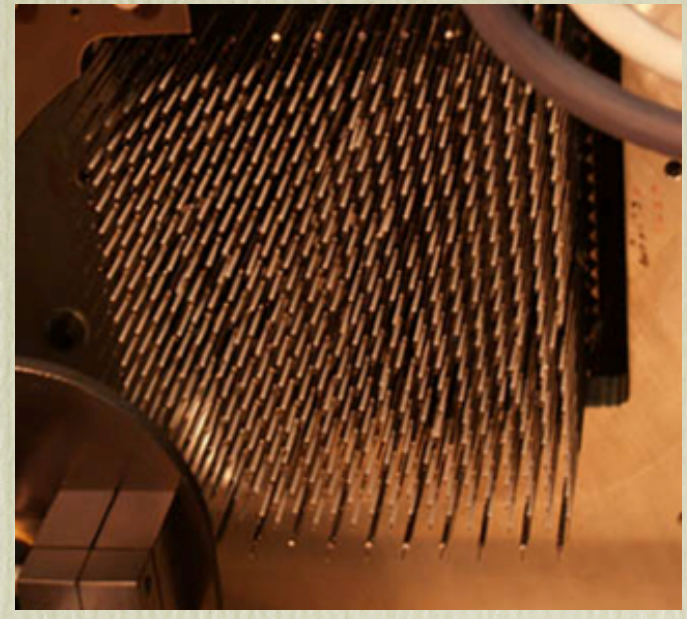
Subaru/FMOS

- Fiber Multi-Object Spectrograph in NIR for Subaru
  - constructed by Japan-UK collaboration
- 400 fibres in circular FOV (30’ Φ)
  - hexagonal arrangement with 1.4’ separation
  - fiber aperture 1.25” ϕ
- wavelength coverage: 0.9um - 1.8um
- Spectral resolution
  - Low resolution mode: R=500
  - High resolution mode: R=2200
- Limiting magnitude (1 hr, S/N=5)
  - J ~ 22.0
  - H ~ 20.0
  - Line ~ 1 x 10^{-16} erg/s/cm^2
  - OH airglow suppression system



FMOS highlights

- multi-fiber NIR spectroscopy using Subaru prime-focus
  - 400 fibers in 30' diameter field of view
  - large photon collecting power by 8m Subaru
  - efficient fiber allocation by the Echidna system
  - two spectrographs (IRS1, 2) cover 200 fibers



Echidna

- OH airglow suppression system using mask mirror

mask mirror

FastSound

- The name comes from…
  - FMOS 暗黒世界探査 (Ankoku Sekai Tansa = Dark World Survey)
  - Subaru Observation Understanding Nature of Dark energy
- The team ~40 members from Japan, UK + Int’l:

PI & Co-PI

- Tomonori Totani (PI, Kyoto University)
- Naruhisa Takato (Co-PI, NAOJ/Subaru)

Japan:

- Masayuki Akiyama (Tohoku)
- Tomotsugu Goto (IfA, Univ. Hawaii)
- Chiaki Hikage (Princeton)
- Masatoshi Imanishi (NAOJ/Subaru)
- Takashi Ishikawa (Kyoto)
- Yoichi Itoh (Hyogo)
- Fumihide Iwamuro (kyoto)
- Tsutomu Kobayashi (Tokyo)
- Toshinori Maihara (Kyoto)
- Takahiko Matsubara (Nagoya)
- Takahiro Nishimichi (Tokyo)
- Kouji Ohta (Kyoto)
- Hiroyuki Okada (Kyoto)
- Teppei Okumura (IEU, Ewha Womans Univ., Korea)
- Shinki Oyabu (Nagoya)
- Shun Saito (JSPS, UC Berkeley)
- Masanao Sumiyoshi (Kyoto)
- Ryuichi Takahashi (Hirosaki)
- Naoyuki Tamura (Tokyo)
- Atsushi Taruya (Tokyo)
- Motonari Tonegawa (Kyoto)
- Shinji Tsujikawa (Tokyo Sci. Univ.)
- Kiyoto Yabe (NAOJ)
- Naoki Yoshida (Tokyo)

UK:

- Andrew Bunker (Oxford Univ.)
- Gavin Dalton (Oxford Univ.)
- Pedro Ferreira (Oxford Univ.)
- Carlos Frenk (Durham Univ.)
- Edward Macaulay (Oxford Univ.)
- Will Percival (Univ. Portsmouth)
- Tom Shanks (Durham Univ.)

International Members:

- Stephane Arnouts (CFHT)
- Chris Blake (Swinburne)
- Jean Coupon (Taiwan)
- Richard Ellis(Caltech)
- Karl Glazebrook (Swinburne)
- Henry McCracken (Terapix)
- Lee Spitler (Swinburne)
- Istvan Szapudi (IfA, Hawaii)

FastSound

FastSound: Quick Summary

- Cosmology-purpose redshift survey by FMOS (near-IR fiber-fed spectrograph) of Subaru Telescope, approved as the second "Subaru Strategic Program"
- 20 deg^2, ~4000 galaxy redshifts in 4 CFHTLS Wide fields
  - targeting Hα emitting galaxies at z~1.2-1.5 (=wavelength coverage)
  - target selection: photo-z & Hα flux est. by five optical (ugriz) bands
  - 30 min. on-source exposures for each field-of-view (0.2 deg^2)
  - ~10% detection efficiency for 400 FMOS fibers
  - ~40 nights for 2 years from Mar. 2012 - Jul. 2014

FastSound: Quick Summary (contd.)

- primary science goal: test of gravity theory about structure growth rate, by measuring redshift space distortion (RSD)
  - measurement of $f\sigma_8$ at z~1.35 (~25% stat. error)
  - the first significant detection of RSD at z > 1
- Other various science topics, e.g.
  - Hα luminosity function and cosmic SFR at z ~ 1.3
  - metallicity study for star forming galaxies at z ~ 1.3
  - environmental dependence of star-forming galaxies at z~1.3
  - ...

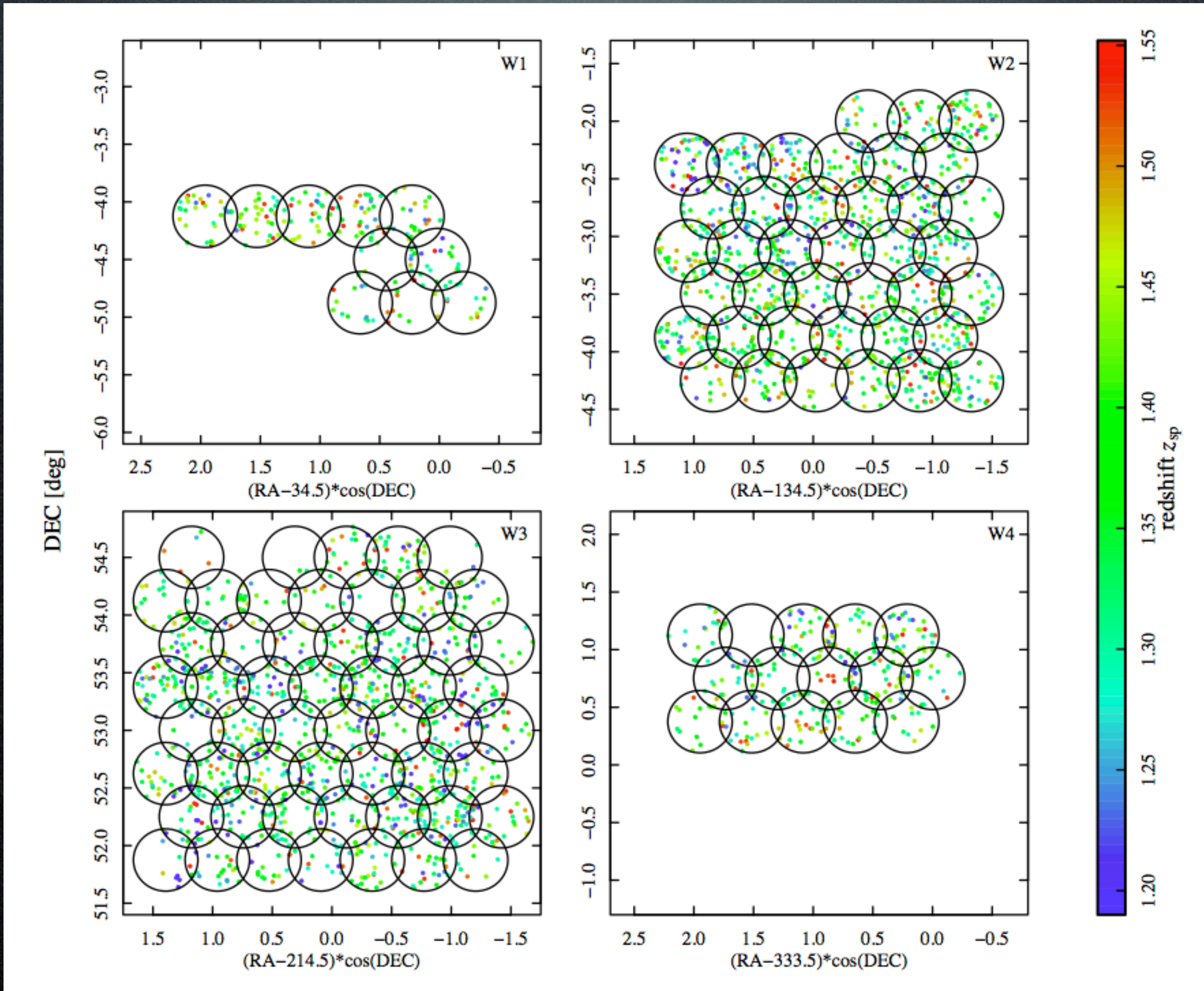
Project Status

- All observations finished (July 2014).
- The emission line catalog already open to public on the webpage
  - including ~4,000 galaxies (S/N >~ 4)
  - by far the largest spectroscopic sample in NIR at z > 1
  - >~90% should be Hα at z ~ 1.2-1.5
- Main series papers published/submitted to PASJ (all available on arXiv)
  - Paper I (Tonegawa et al.) for survey overview
    - PASJ, 67, 81 (2015)
  - Paper II (Okada et al.) for catalog description and basic properties of emission line galaxies
    - re-submitted to PASJ, arXiv:1504.05592
  - Paper III (Yabe et al.) for metallicity study
    - PASJ, 67, 102 (2015)
  - Paper IV (Okumura et al.) for RSD and cosmology
    - submitted to PASJ, arXiv:1511.08083

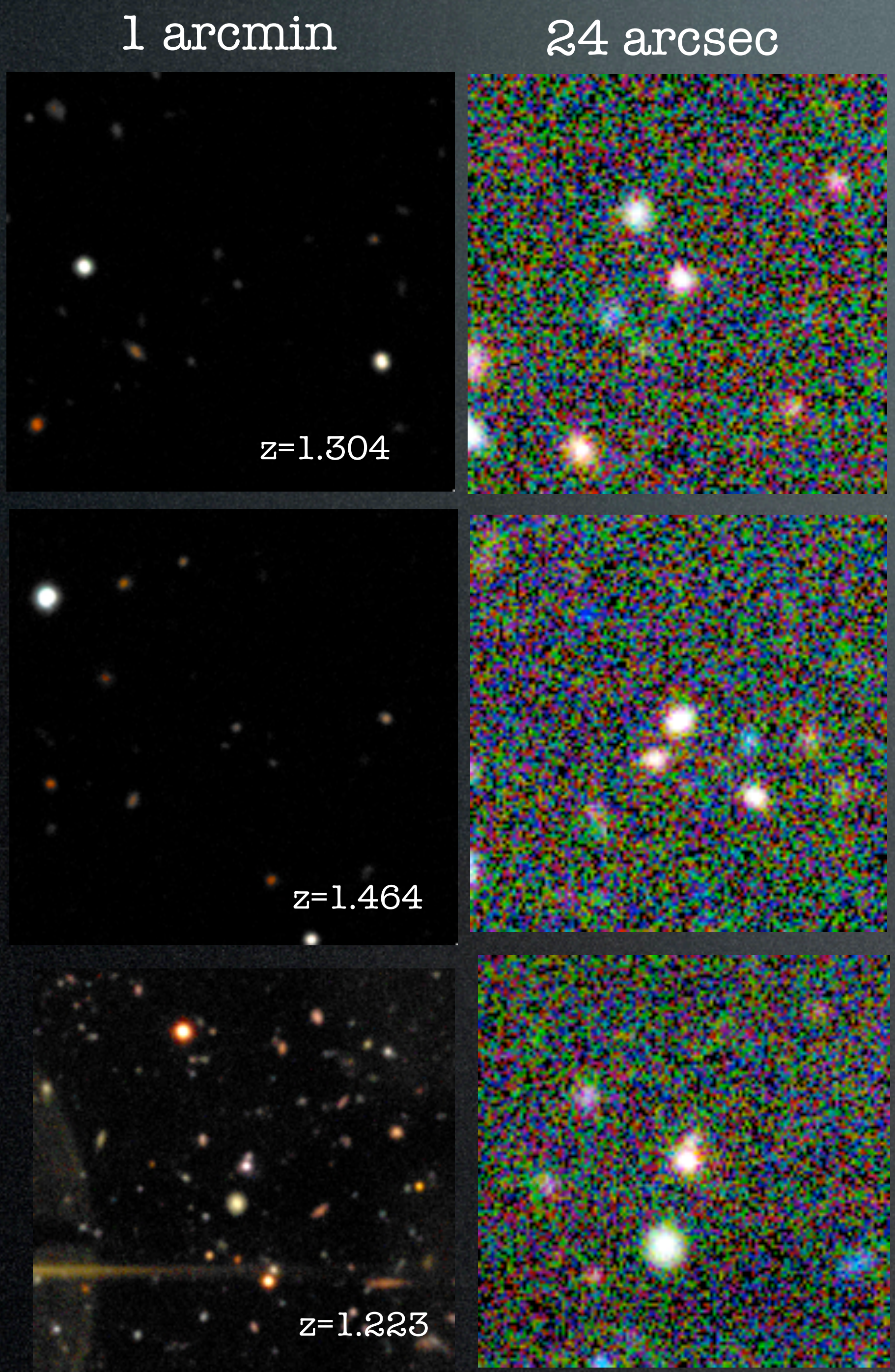
FastSound Results Highlights

galaxy distribution map in 4 CHFHTLS-W fields

- 121 FMOS FoVs, 20.6 deg^2 in total



Example CFHTLS Images of FastSound Galaxies



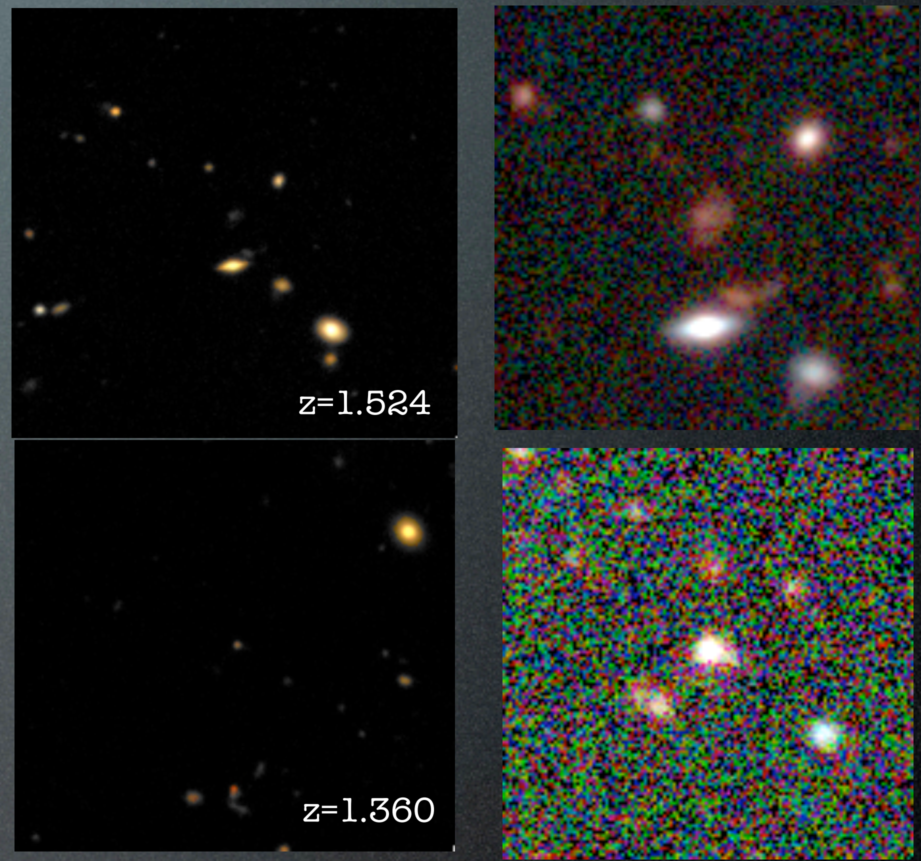
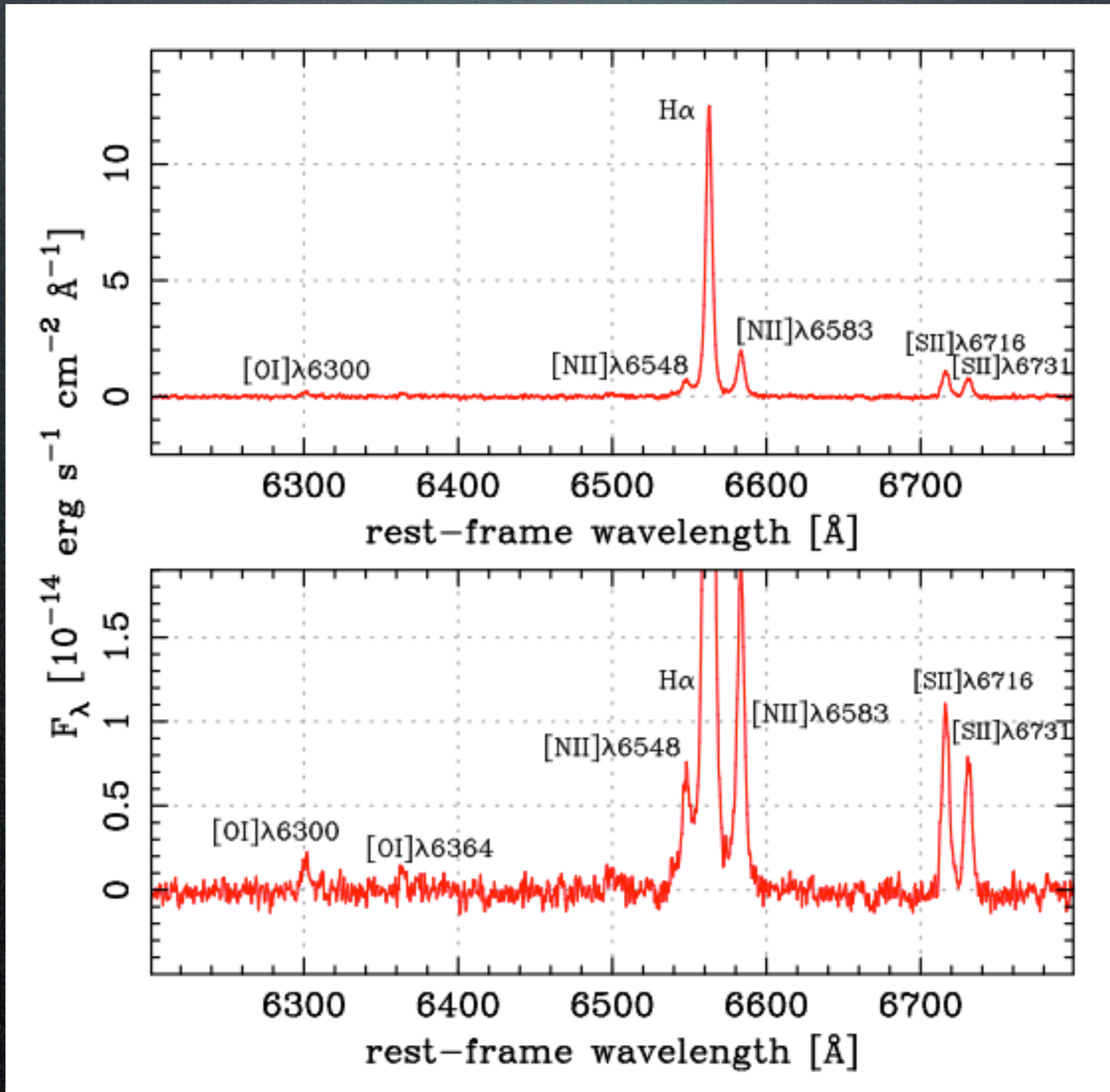


Image credit: CFHTLS, CFHTLenS, CDAC

Stacked FastSound Spectra

- assuming that the strongest line is always Hα



Are these mostly Hα ?

- multiple-line galaxies are
  - Hα-NII-SII system
  - OIII doublets at z~2 (estimated to be ~4% in all single-line galaxies)
  - no significant detection of other line pairs
- Stacked spectrum indicates that OIII doublets are ~5% of all FastSound emission line galaxies
  - consistent result from multiple line statistics

Okada+'15

Table 6. The result of the line identification for the emission line pairs found in the 1,105 FastSound galaxies.

	line (shorter)	line (longer)	wavelength ratio	number n	noise* n_{n}	number (corrected)†	chance probability‡
(1)	[SII]λ6717	[SII]λ6731	1.00214§	35	10.9	$24.1^{+7.0}_{-5.9}$	$< 10^{-5}$
(2)	[NII]λ6548	Hα	1.00225§	37	10.9	$26.1^{+7.1}_{-6.1}$	$< 10^{-5}$
(3)	Hα	[NII]λ6583	1.00315	226	10.9	$215.1^{+16.1}_{-15.0}$	$< 10^{-5}$
(4)	[NII]λ6548	[NII]λ6583	1.00541	6	10.7	< 3.78	0.95
(5)	[OIII]λ4959	[OIII]λ5007	1.00966	50	10.3	$39.7^{+8.1}_{-7.0}$	$< 10^{-5}$
(6)	Hβ	[OIII]λ4959	1.02007‖	6	9.5	< 3.78	0.91
(7)	[NII]λ6583	[SII]λ6717	1.02020‖	5	9.5	< 3.78	0.96
(8)	[NII]λ6583	[SII]λ6731	1.02238	5	9.3	< 3.78	0.95
(9)	Hα	[SII]λ6717	1.02341	67	9.2	$57.8^{+9.2}_{-8.2}$	$< 10^{-5}$
(10)	Hα	[SII]λ6731	1.02560#	26	9.0	$17.0^{+6.2}_{-5.1}$	$< 10^{-5}$
(11)	[NII]λ6548	[SII]λ6717	1.02572#	24	9.0	$15.0^{+6.0}_{-4.9}$	0.00002
(12)	[NII]λ6548	[SII]λ6731	1.02791	11	8.8	$2.2^{+4.4}_{-2.2}$	0.27
(13)	Hβ	[OIII]λ5007	1.02993	15	8.6	$6.4^{+5.0}_{-3.8}$	0.031
(14)	[SIII]λ9069	[SIII]λ9531	1.05094	12	6.8	$5.2^{+4.6}_{-3.4}$	0.046

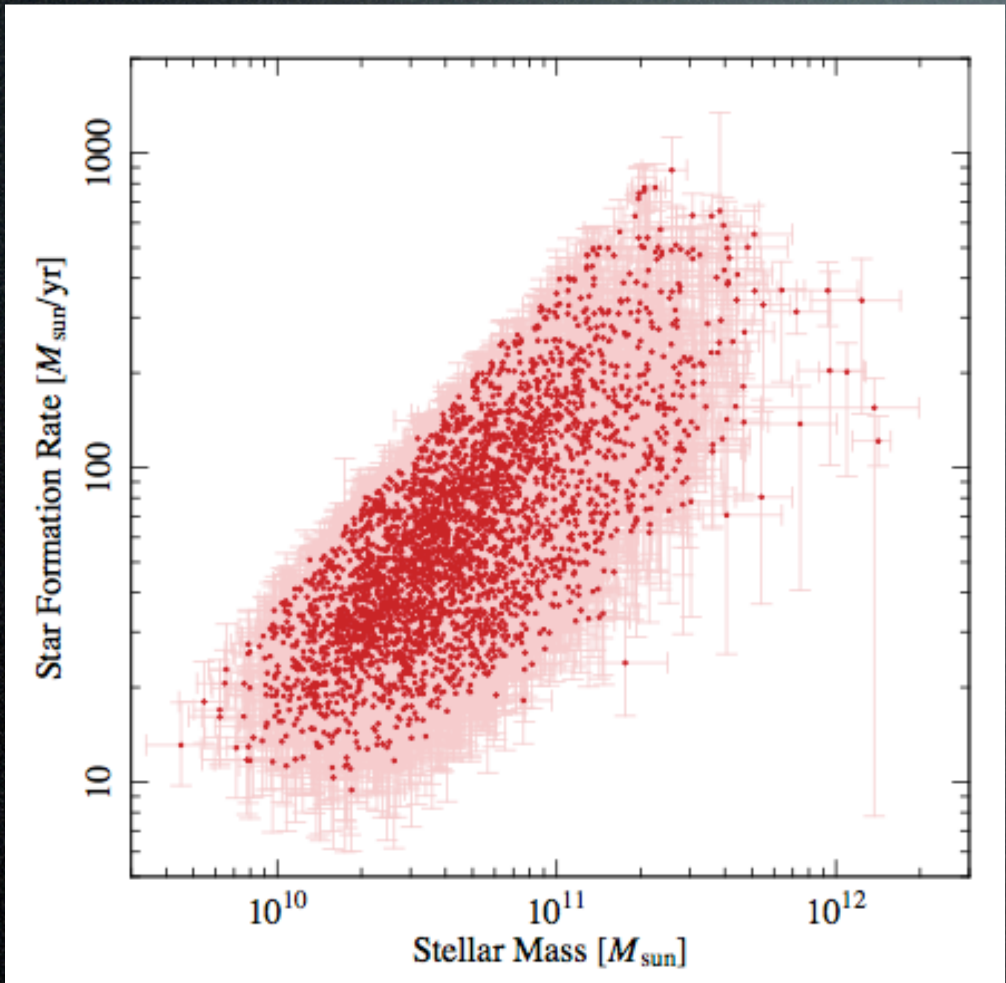
* The expected number of spurious pairs originating from noise.

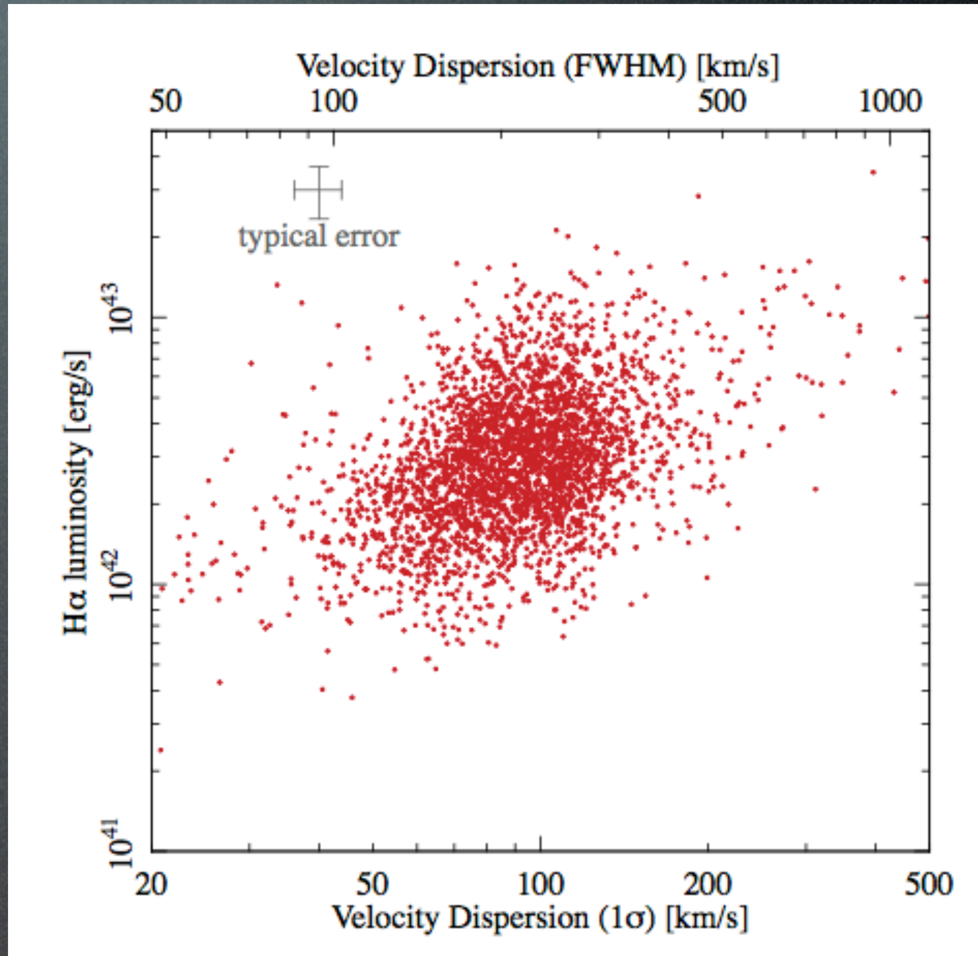
† The number corrected for the spurious pair detection rate, i.e., $n - n_{\mathrm{n}}$, with 1σ statistical errors. The upper bound is given at 2σ.

‡ The probability of finding the observed number of pairs only by noise events under the Poisson statistics.

§,‖,# These pairs are indistinguishable due to the very close values of wavelength ratio.

Some Galaxy Properties

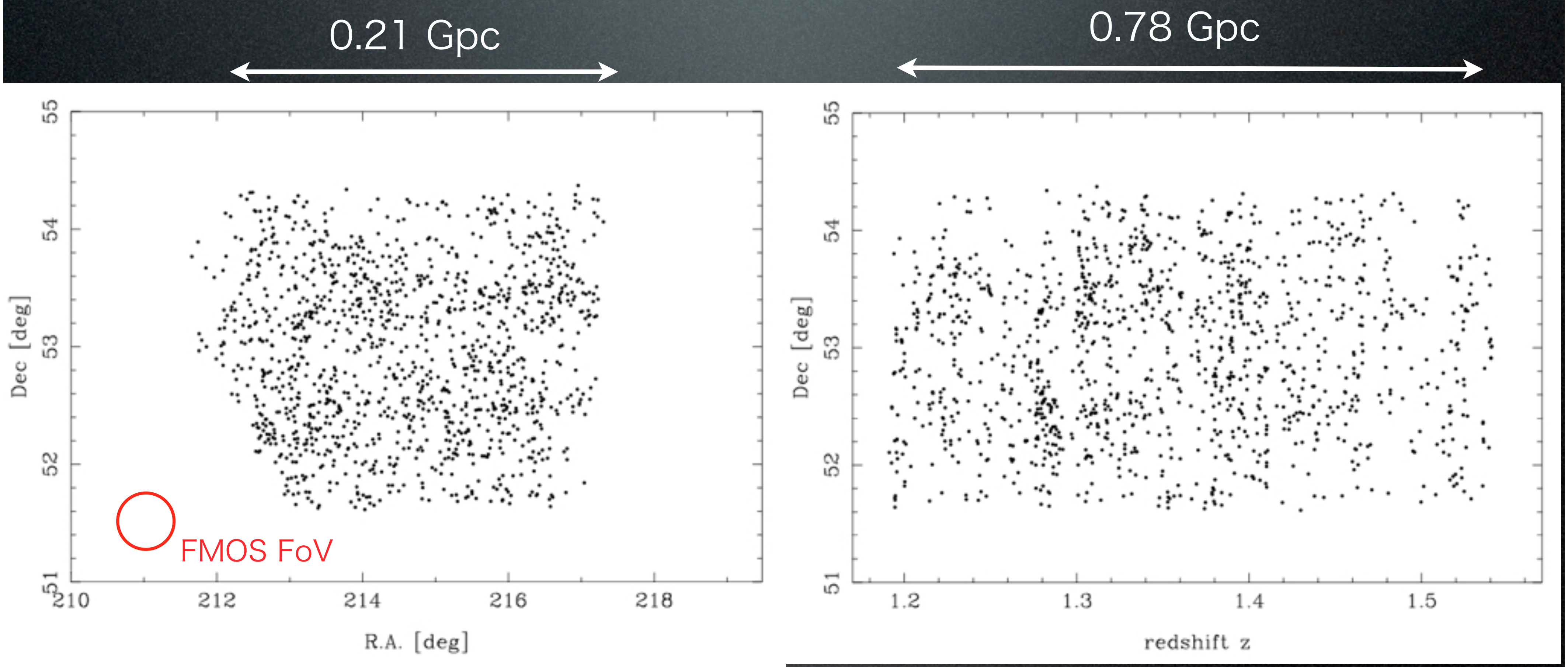




- FastSound Paper II (Okada+'15)

The FastSound Real Galaxy 3D Map

- >1200 galaxies in 7 deg^2, z ~ 1.2-1.5 in CFHTLS W3 field
  - comoving distance = 4.0 Gpc
  - age at this redshift = 4.7 Gyr
  - comoving volume = 0.04 Gpc^3



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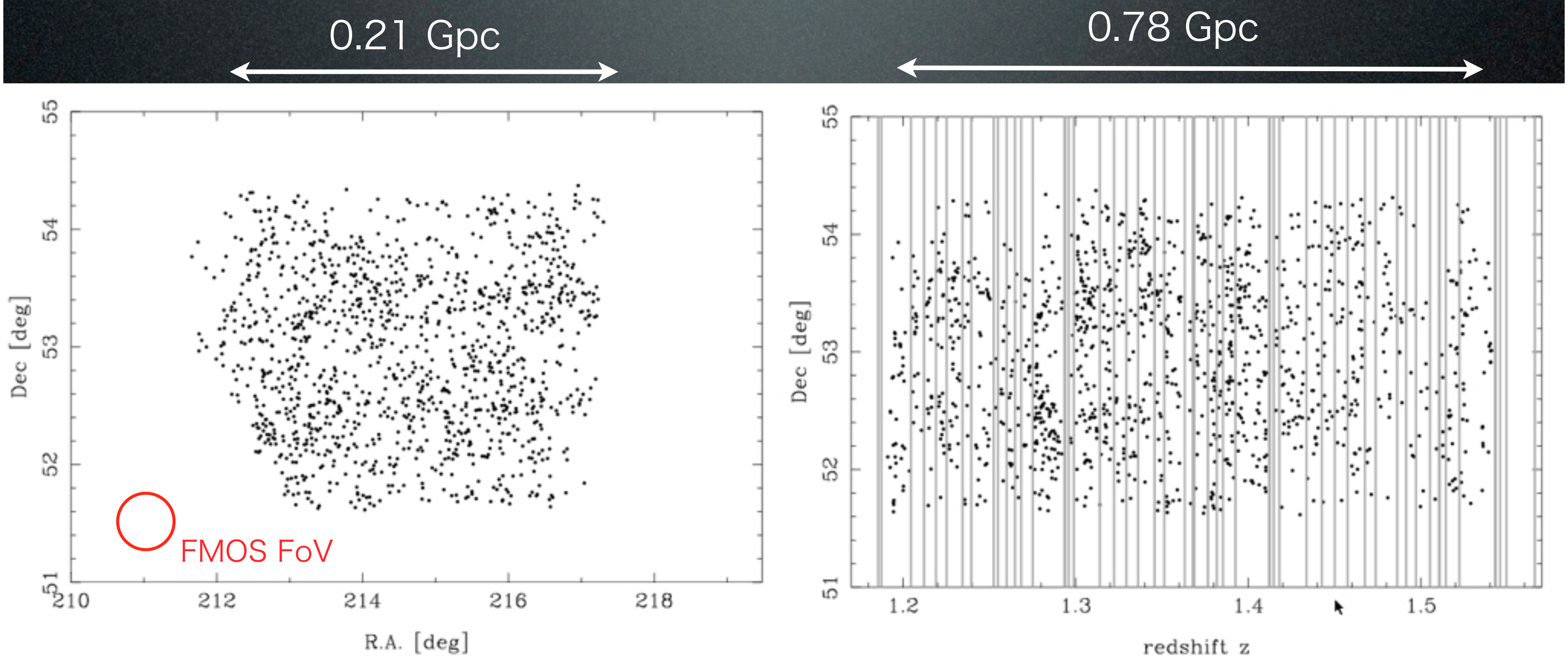
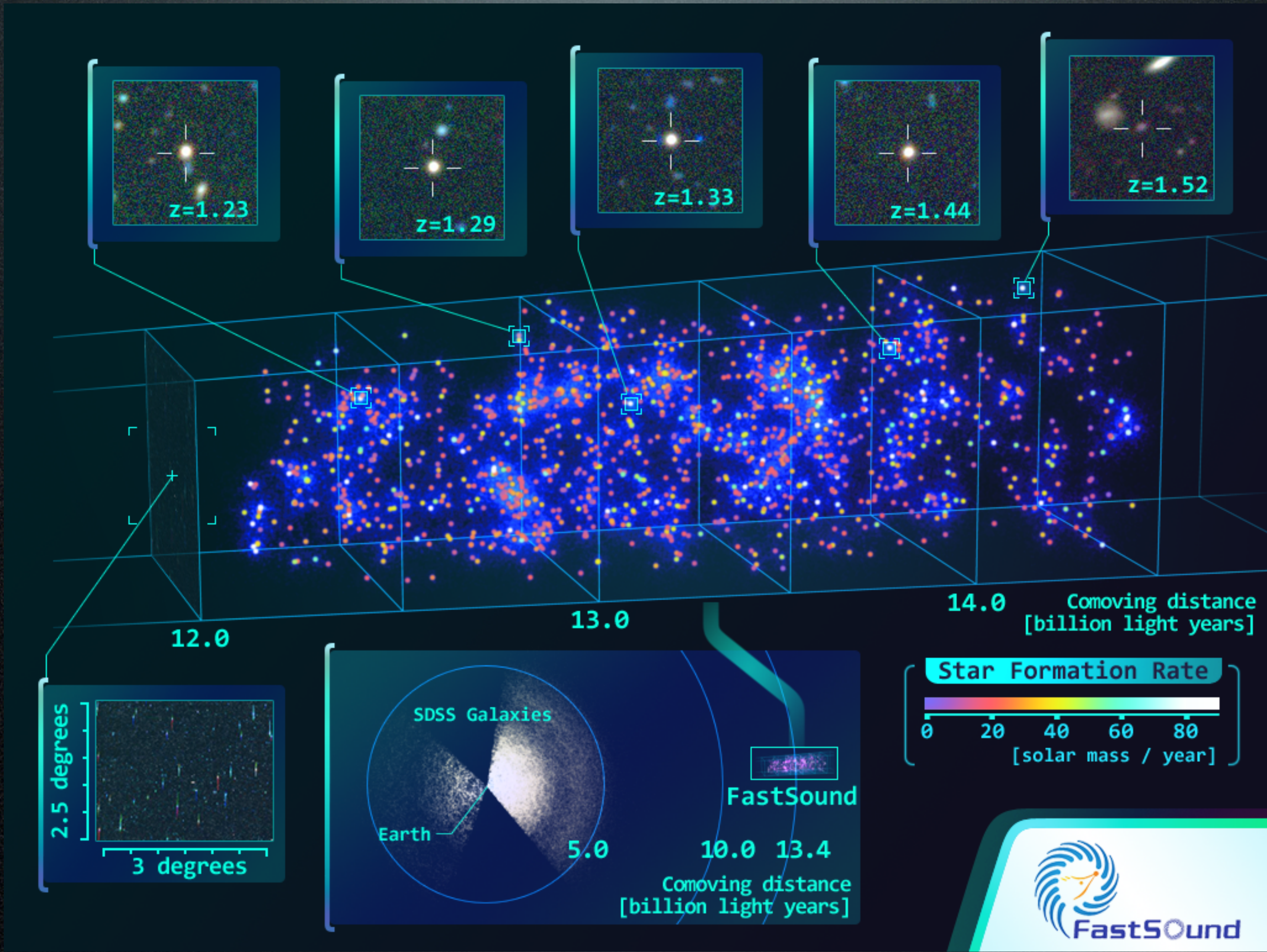
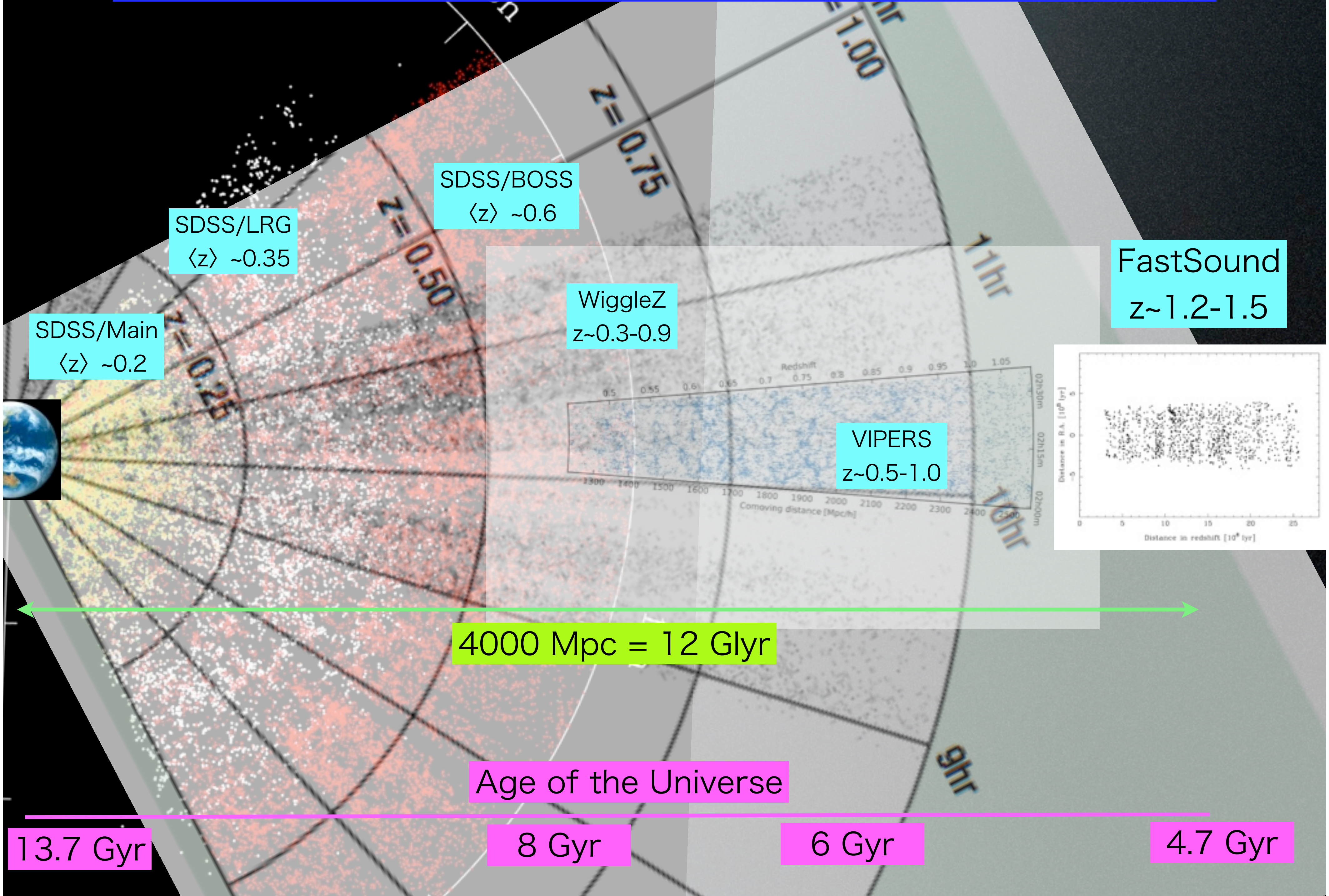


FastSound 3D map in W3 field



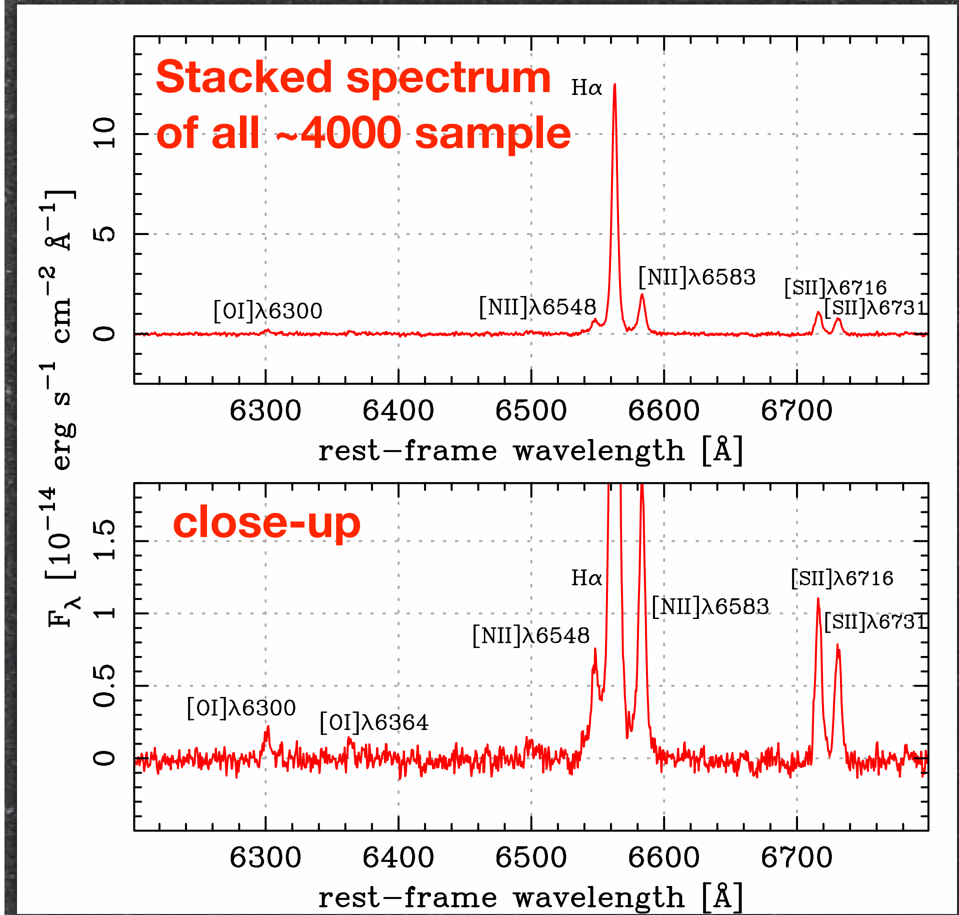
3D galaxy maps by various surveys



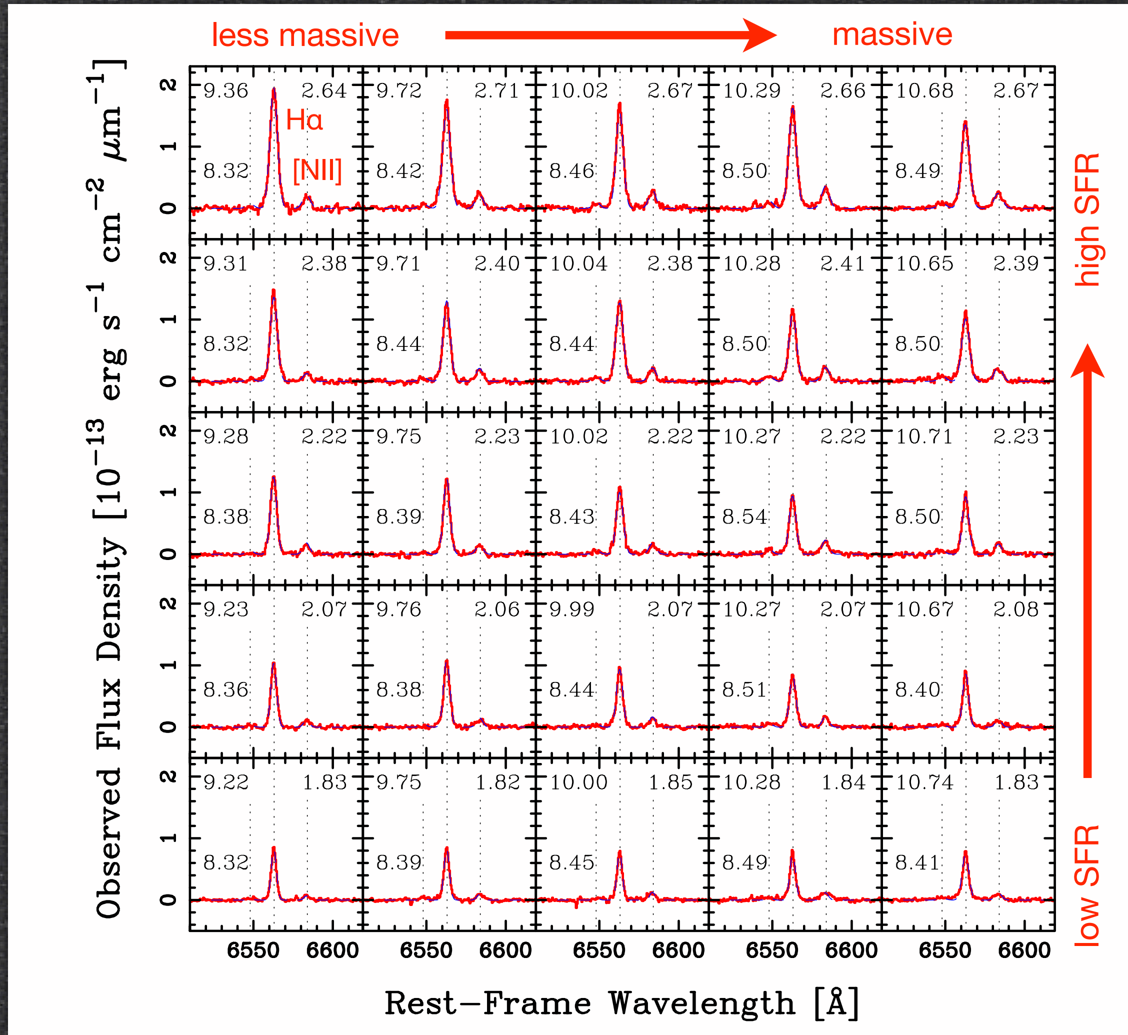
Scientific Results Highlights

“The Subaru FMOS Galaxy Redshift Survey (FastSound) - The mass-metallicity relation and the fundamental metallicity relation at z~1.4”

Yabe et al. 2015 PASJ in press (arXiv: 1508.01512)



- Quality of individual spectrum is not so good, and thus, a spectral stacking analysis is applied in this study



- Stacking analysis dividing sample into stellar mass and SFR bin (5 masses x 5 SFRs). The number of galaxies in each bin is ~160

Stacked spectra around Hα line (6563Å)

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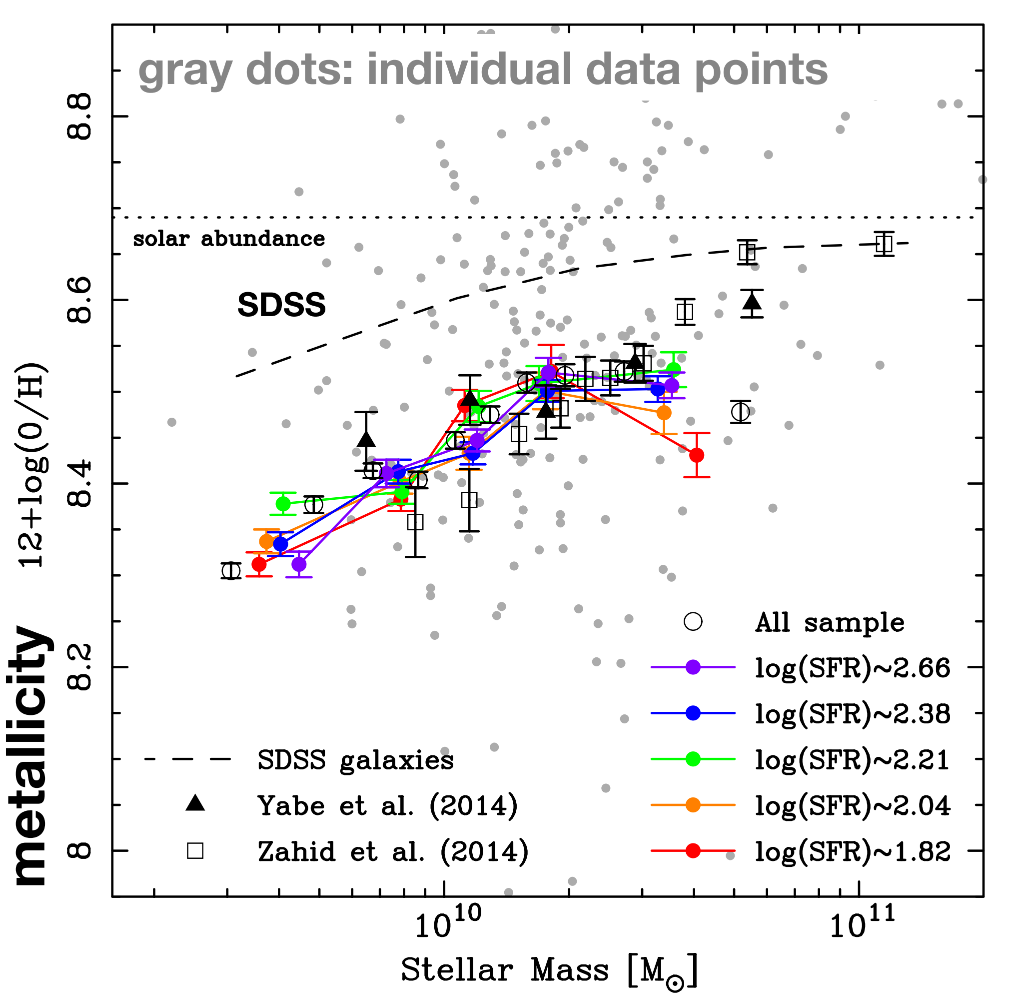
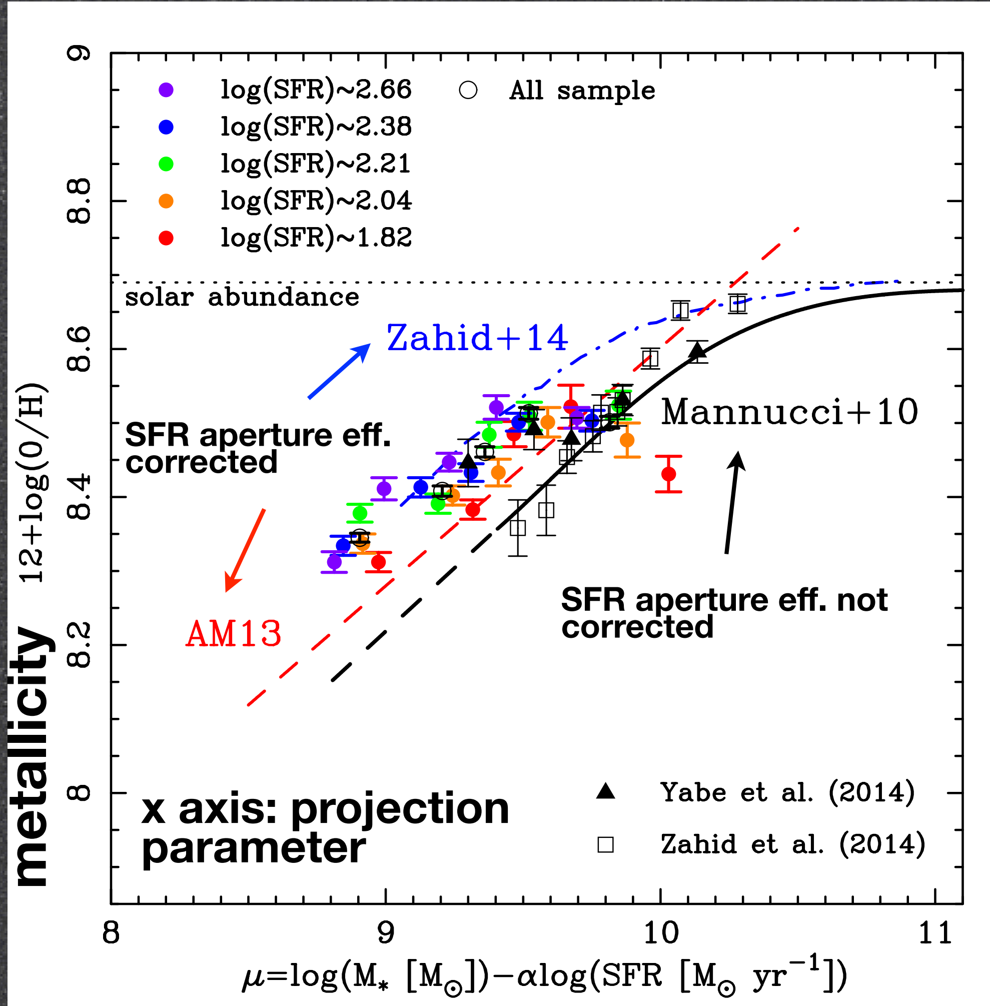
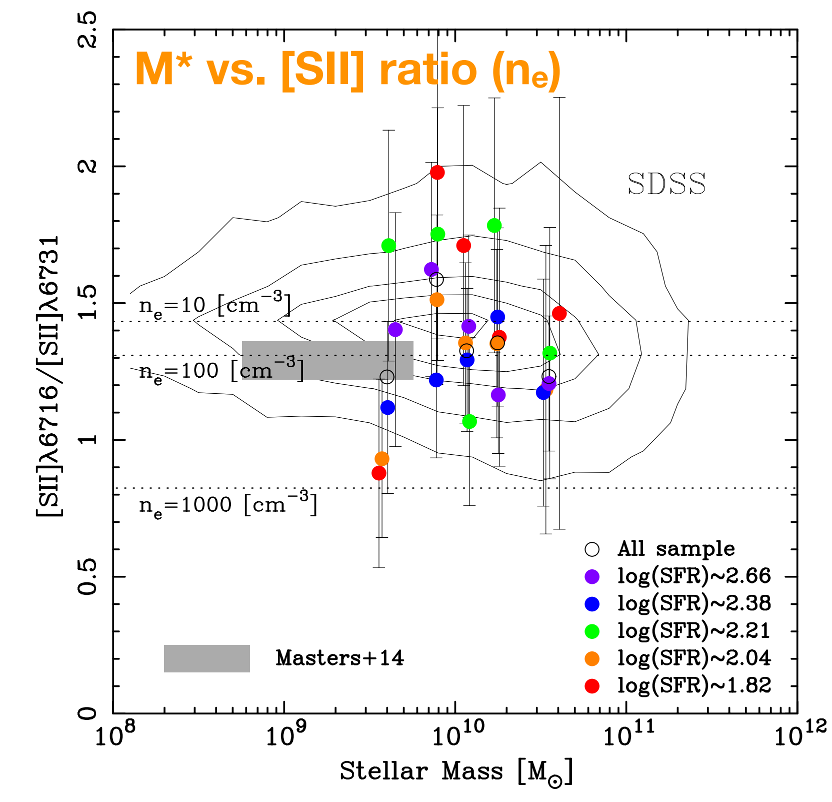




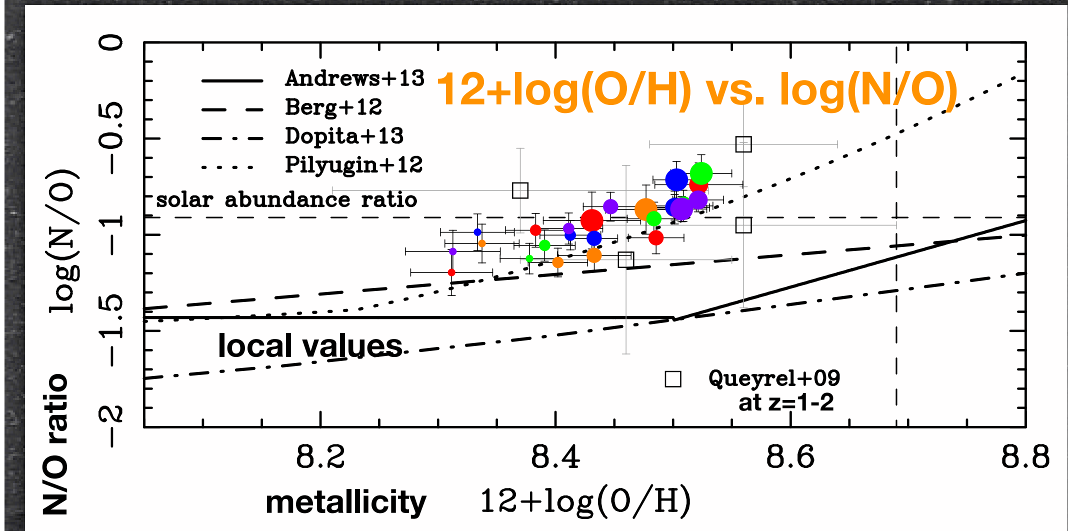
Metallicity is derived from [NII]λ6584/Hα (N2 method; Pettini & Pagel 04) of the stacked spectra (5 mass x 5 SFR bins) and the mass-metallicity relation (left) and the fundamental metallicity relation (right) at z~1.4 are constructed by using ~4,000 sample (the largest sample in this redshift range ever)

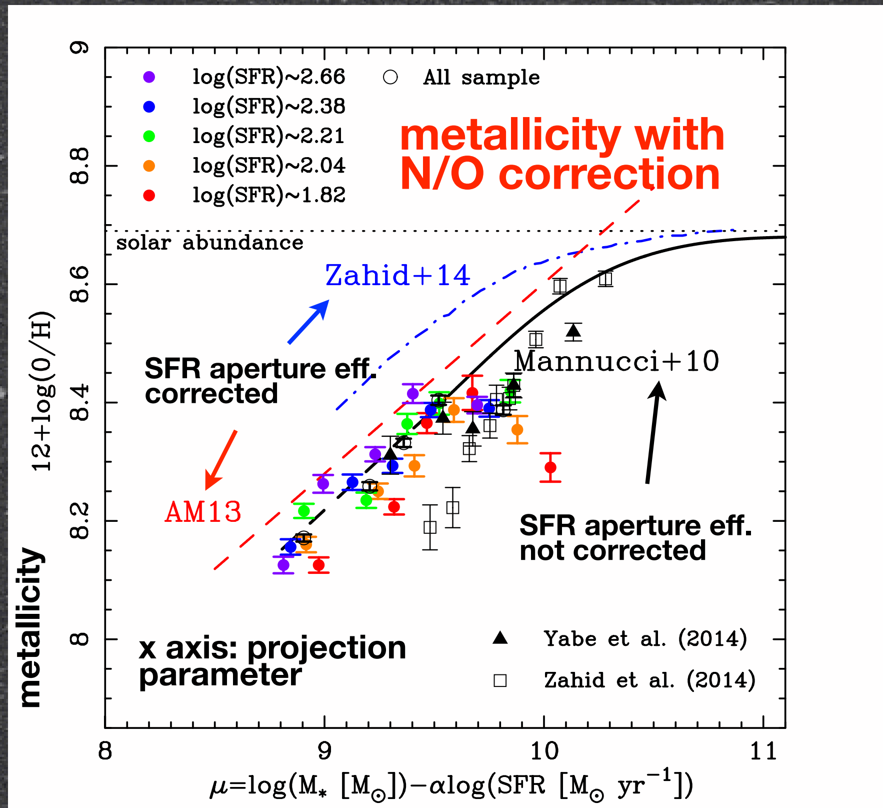
“The Subaru FMOS Galaxy Redshift Survey (FastSound) - The mass-metallicity relation and the fundamental metallicity relation at z~1.4”

Yabe et al. 2015 PASJ in press (arXiv: 1508.01512)

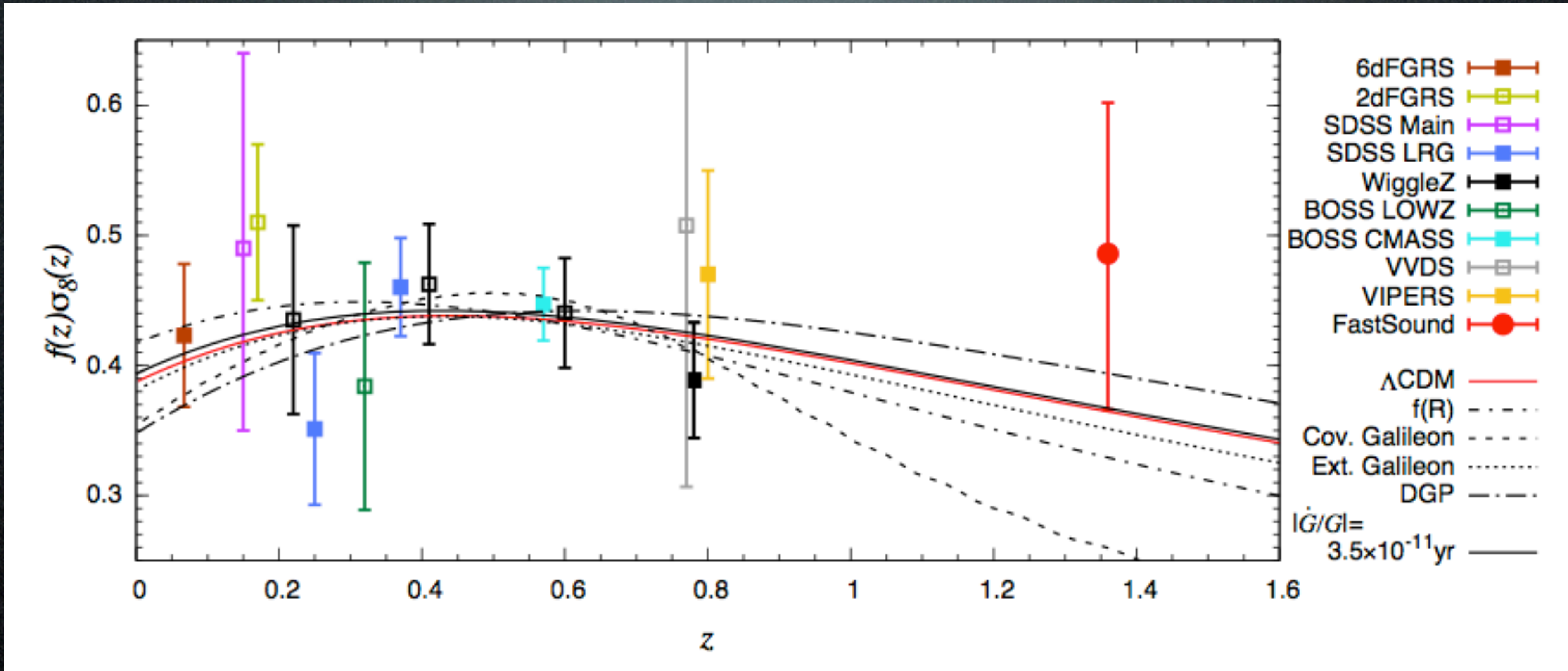


- [SII]λλ6717, 6731 detected significantly in the stacked spectra.
- [SII]λ6717/[SII]λ6731 line ratio (top left) a good tracer of **electron density**) is comparable to that of SDSS galaxies at z~0.1 (n_e ~ 10 - 500 cm^{-3})
- **N/O abundance ratio** (bottom left) is measured from [NII]λ6584/[SII]λλ6717,6731 (N2S2 index), showing higher value at z~1.4 than local values





RSD & Cosmology



- Paper IV (Okumura+'15)
  - paper submitted on 2015 Nov. 25 --- the 100th anniversary of general relativity!
  - we got a positive referee report on 2015 Dec. 25, i.e., the birthday of ...
- wait for Okumura-san's talk later!

Summary

- FastSound: a galaxy redshift survey in near-infrared, targeting Hα emitters at z = 1.2-1.5
  - to deliver RSD measurement at ~4 sigma using ~4000 Hα emitters in 20 deg^2 fields
- Survey observations already finished. The emission line catalog open to public.
- galaxy clustering and RSD clearly detected.
- The main series four papers already on arXiv.
  - Paper I, III already published in PASJ
  - Paper II, IV will appear soon in PASJ