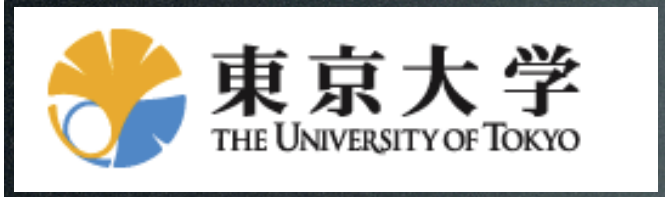


FastSound: Testing modified gravity by redshift-space distortion beyond z=1

TOTANI, Tomonori
(Dept. Astron., Univ. of Tokyo)

Return of de Sitter II @ MPA, Munich, Germany
2013 Oct. 16

FastSound: Quick Summary

- Cosmology-purpose redshift survey by FMOS (near-IR fiber-fed spectrograph) of Subaru Telescope
  - approved as the second “Subaru Strategic Program”

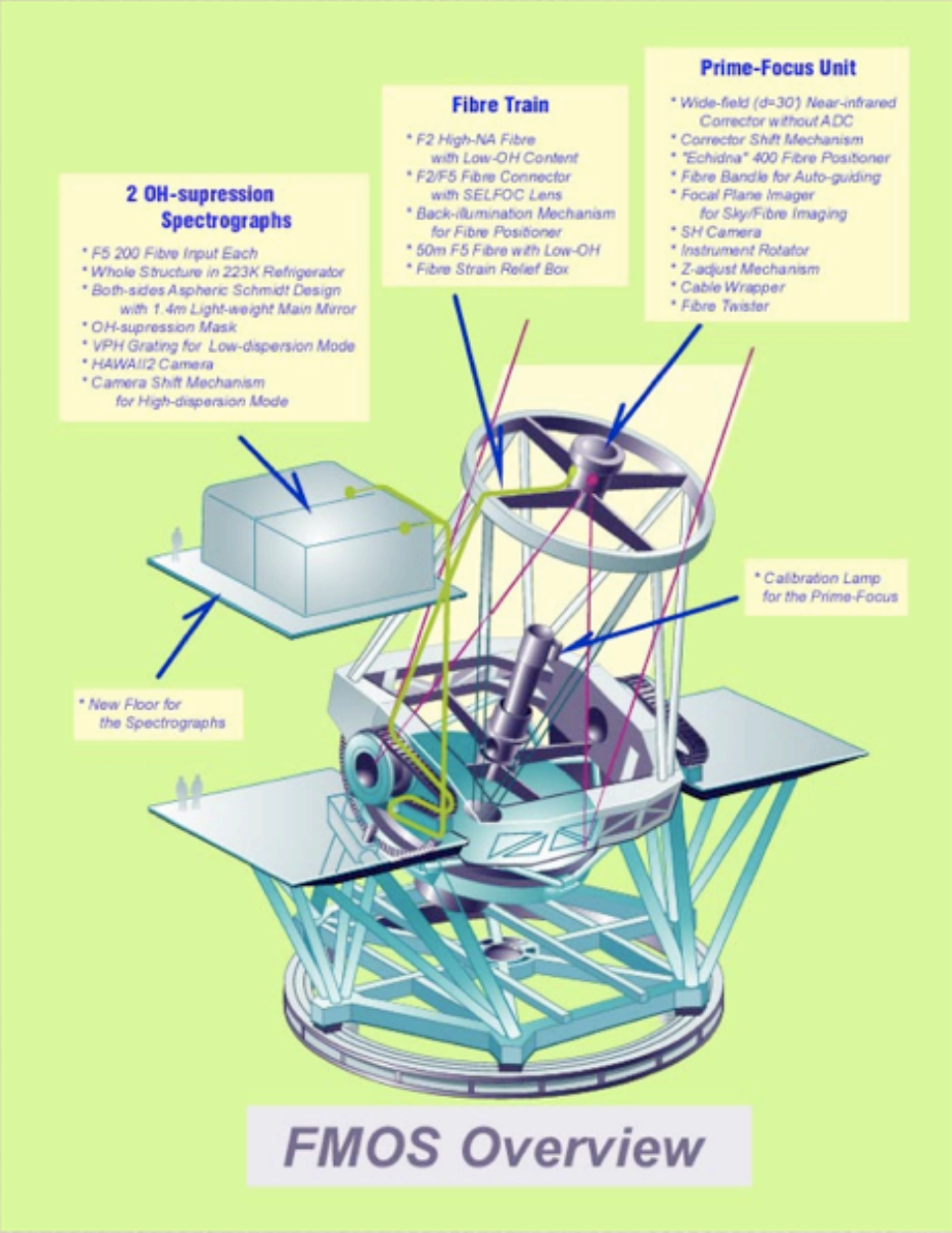
- targeting Hα emitting galaxies at z~1.2-1.5

- 30 deg^2, ~5000 galaxy redshifts using ~40 nights for 2 years from Mar. 2012 - Dec. 2014
  - about 2/3 of the planned fields completed
  - preliminary redshift catalog and 3D map for 1/4 of all fields

- primary science goal: test of gravity theory about structure growth rate, by measuring redshift space distortion (RSD)
  - ~20% measurement of $f\sigma_8$ at z~1.35
  - the first significant detection of RSD at $z > 1$

Subaru/FMOS

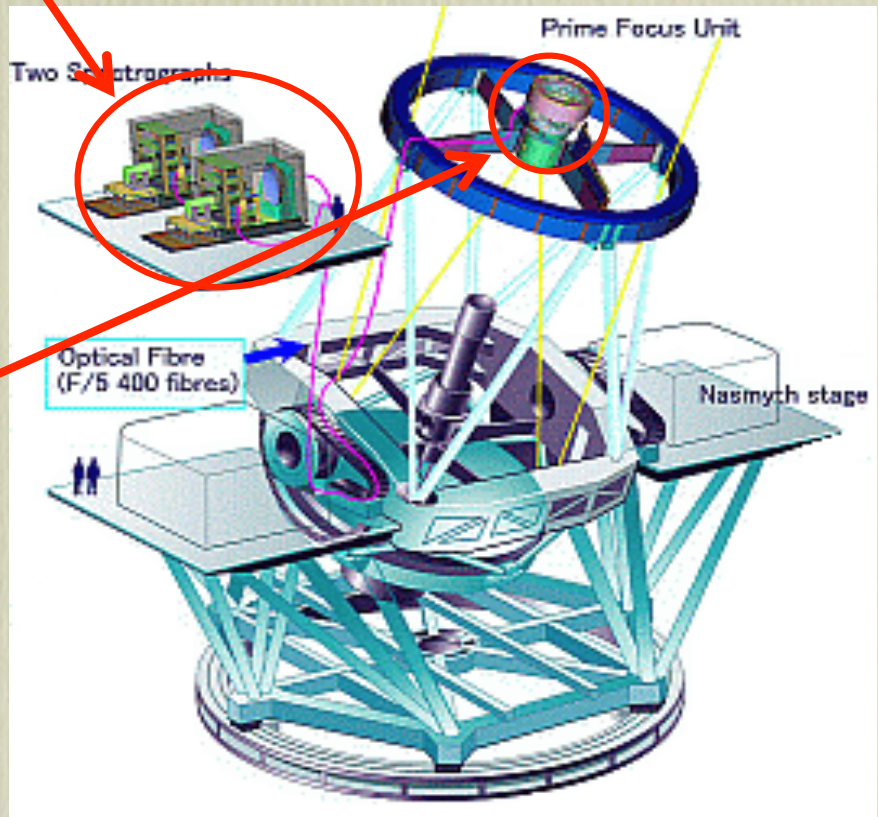
- Fiber Multi-Object Spectrograph in NIR for Subaru
  - constructed by Japan-UK collaboration
- 400 fibres in circular FOV (30' Φ)
  - hexagonal arrangement with 1.4' separation
  - fiber aperture 1.25" ϕ
- wavelength coverage: 0.9um - 1.8um
- Spectral resolution
  - Low resolution mode: R=500
  - High 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 pictures

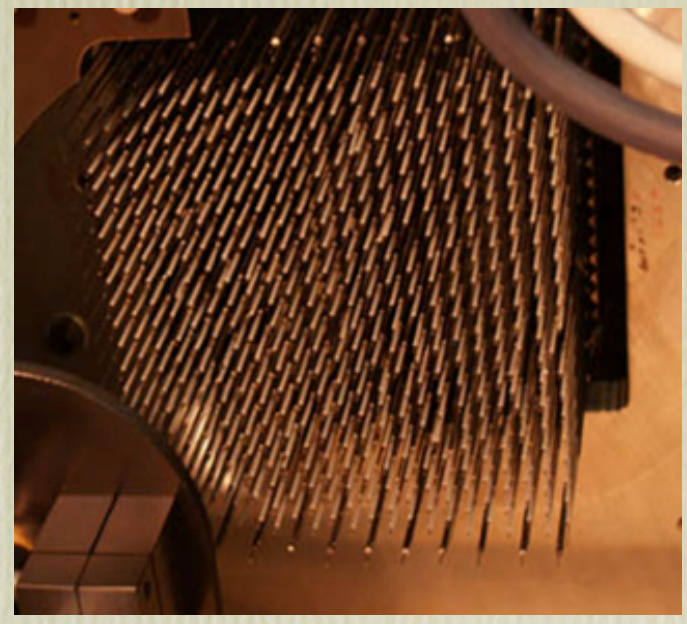
spectrometer
分光器(IRS1)

(IRS2)



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
- OH airglow suppression system using mask mirror



Echidna

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

About the Logo

+

FastSound

FastSound: a brief history

- ~2000- FMOS project started
  - (original science objectives: mostly galaxy science)
- cosmological survey proposed to detect baryon acoustic oscillation (BAO) at z~1 around 2005
- FMOS comission in 2010
- call for the Subaru Strategic Program (SSP) using FMOS (2010)
- FastSound reorganized as a survey mainly targeting RSD, rather than BAO
  - >300 nights will be necessary to detect BAO...
- Originally, the FMOS consortium submitted one single SSP proposal including galaxy science and FastSound
- SAC (Subaru Advisory Committee) forced us to split, allowing only one accepted
  - “Your friend yesterday is enemy today!”
- FastSound selected as FMOS-SSP (2011, May)
- Survey started in Mar. 2012 (40 nights in 2 years)

Primary Science Goal of FastSound: RSD

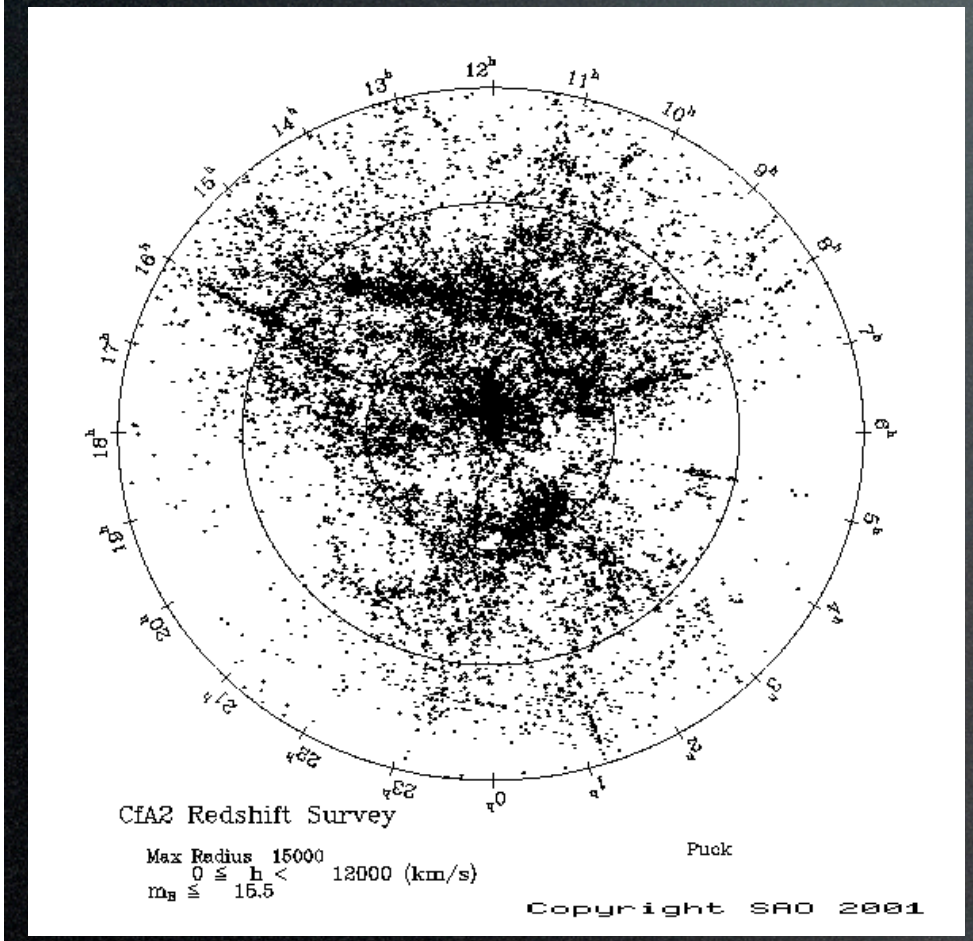
- The origin of the acceleration of the cosmic expansion?
  - dark energy?
  - breakdown of general relativity on cosmological scales?

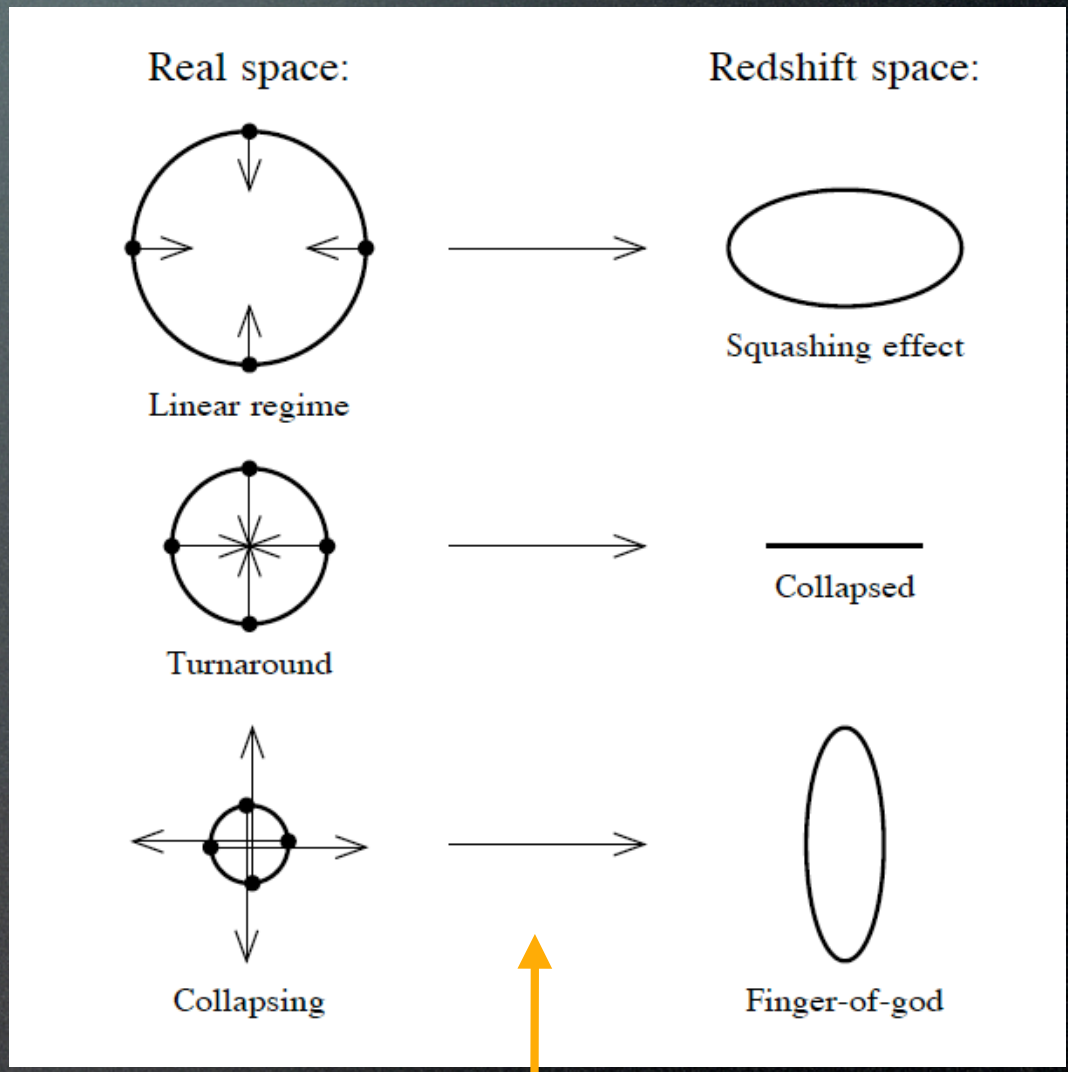
- Measurement of large-scale structure growth rate gives constraints on the theory of gravity
  - redshift space distortion (RSD) observed in galaxy redshift surveys gives such a test

Redshift Space Distortion (RSD)

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

Hamilton '98





RSD in P(k) or ξ(x)

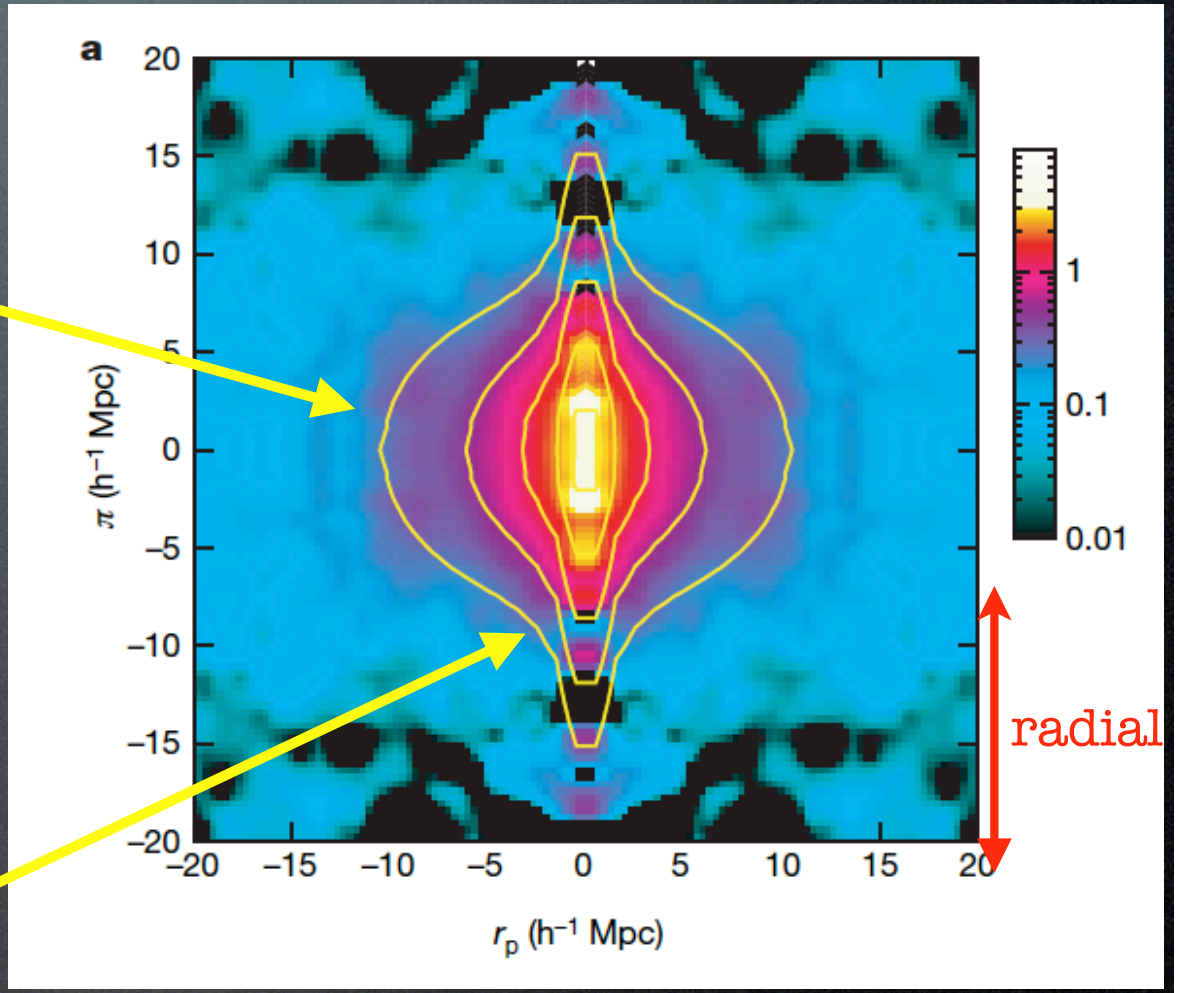
- In the linear regime:
  - the Kaiser effect

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

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

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

2D contour of ξ(r)



Guzzo+'08

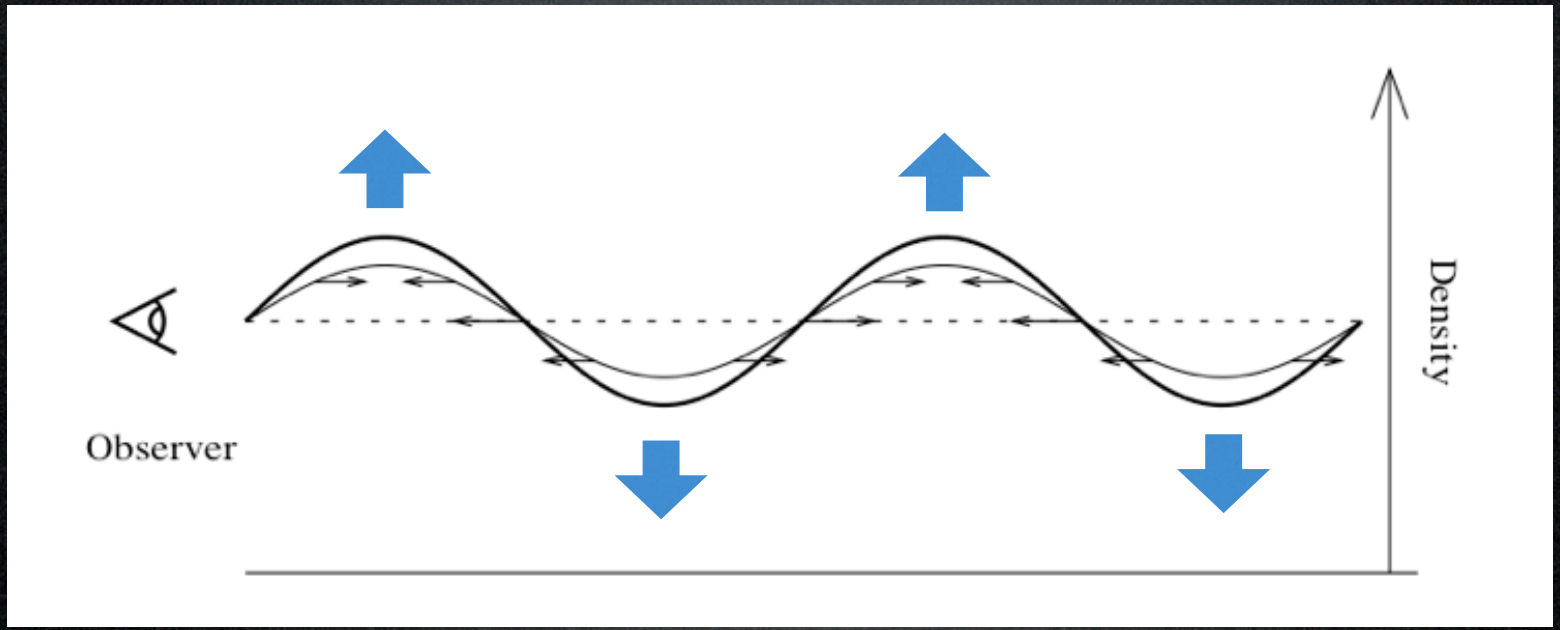
RSD gives a measure of structure growth rate

- 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

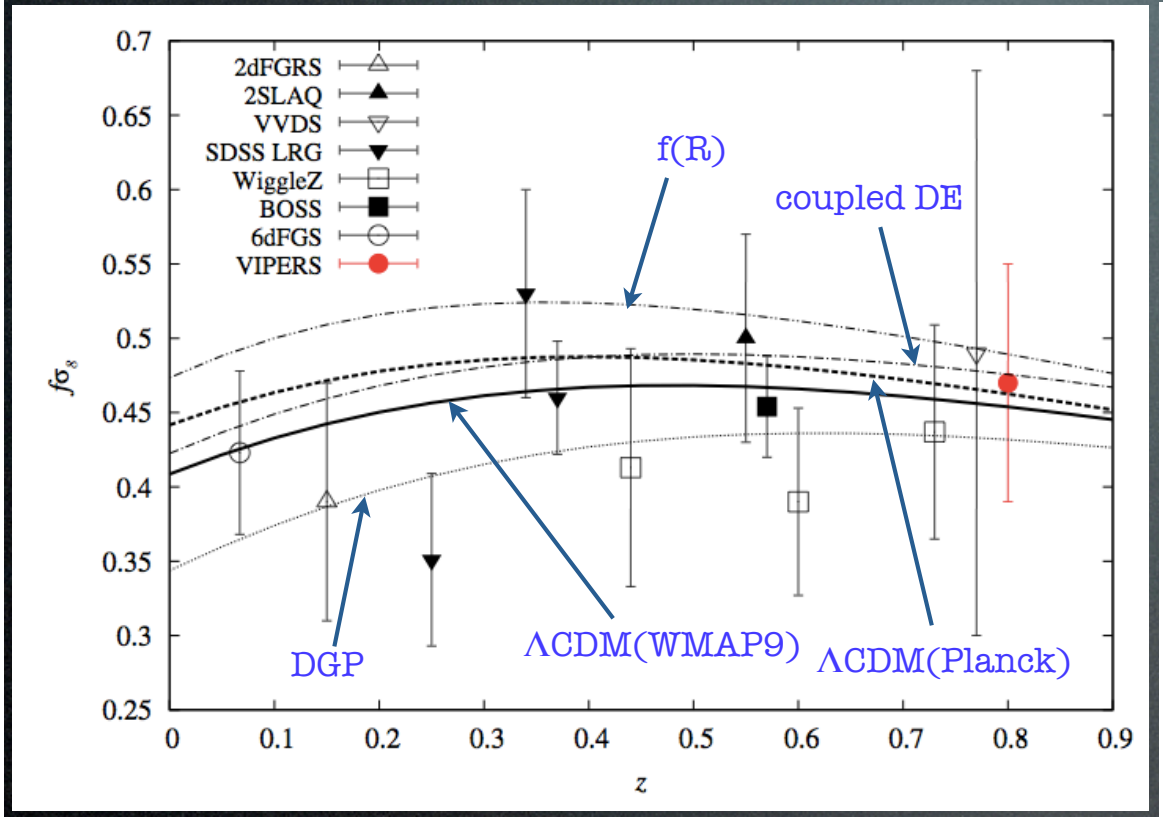
$$f \equiv \frac{H_0 a_0}{Ha}\frac{d\ln D}{d\tau} = \frac{d\ln D}{d\ln a}\,.$$

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

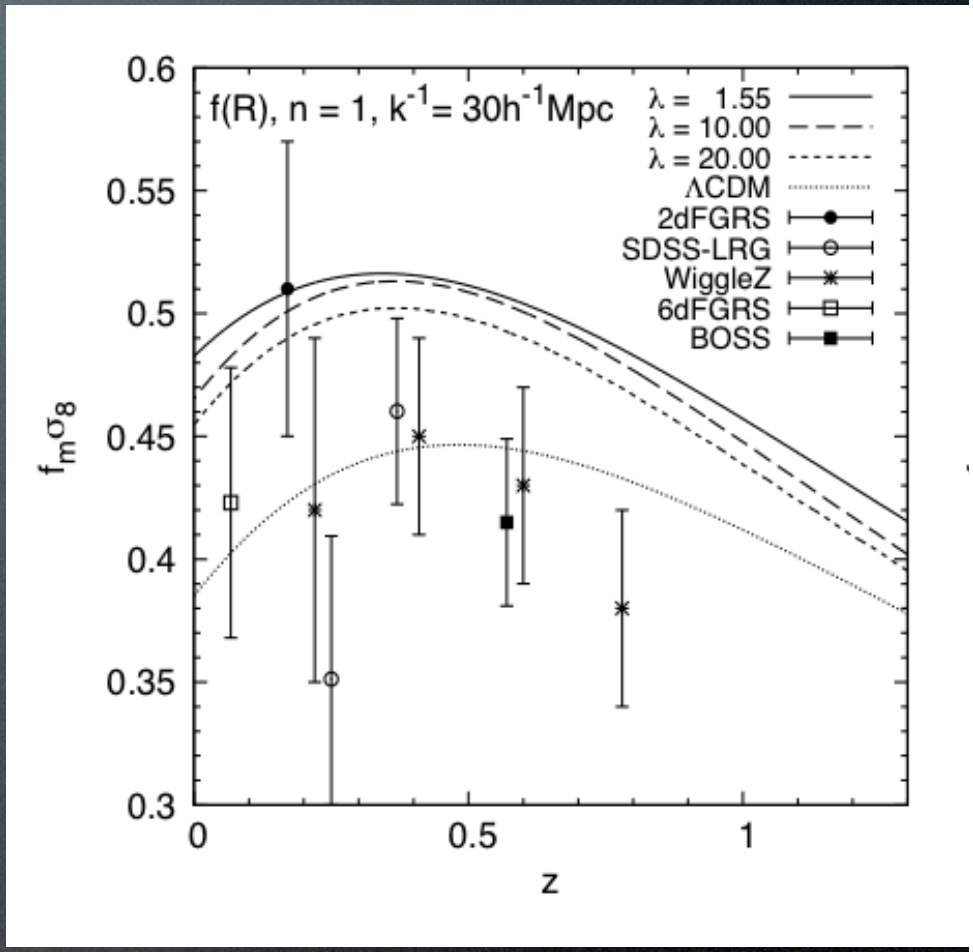
- β = f/b within the linear theory
- $\beta \rightarrow$ f/b or $f(z)\,\sigma_8(z) \rightarrow$ test of gravity on cosmological scale!



RSD testing Gravity Theory



de la Torre+'13



Okada+'13

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

The FastSound Project

- using high-resolution (HR) mode of FMOS (because of better throughput of HR)
- Hα emitting galaxies at z~1.2-1.5
- 30 deg^2 in total, for 4 CFHTLS Wide fields
- ~30 min exposure on source per field-of-view (0.2 deg^2), 1.4 hr including overhead
- ~40 Subaru nights in 2 years
- target selection: ugriz photo-z calculation of z_{phot} and Hα flux
- ~10% emission line detection rate for 400 fibers

Main Science Goal of FastSound

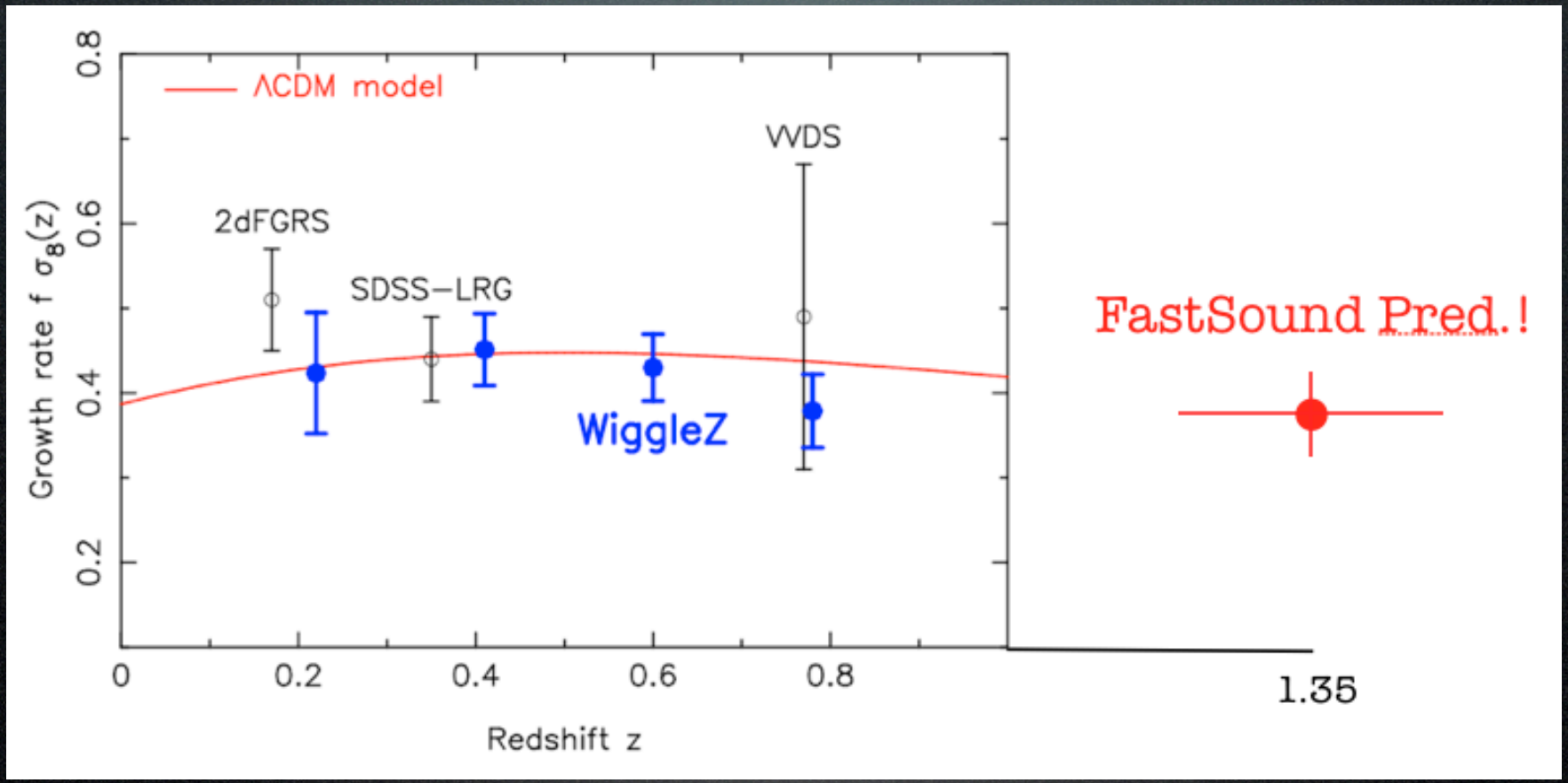
- ~5,000 galaxy redshifts in 0.12 Gpc^3 volume
  - 780 Mpc in radial direction
  - Four 7.5 deg^2 (= 210x210 Mpc^2) fields in CFHTLS W1-4
  - z ~ 1.2-1.5, age of the universe: 4.7 Gyr (9 Gyr ago)

- Aiming at the first significant detection of RSD at z > 1
  - current expectation of the final $f\sigma_8$ accuracy ~20%
    - c.f. $f\sigma_8$ = 0.26±0.13 @z=3 by VLT LBG RS (Bielby+'13)
  - constraints on modified gravity scenario as the origin of dark energy

- a path finder for future planned emission-line galaxy redshift survey at z > 1

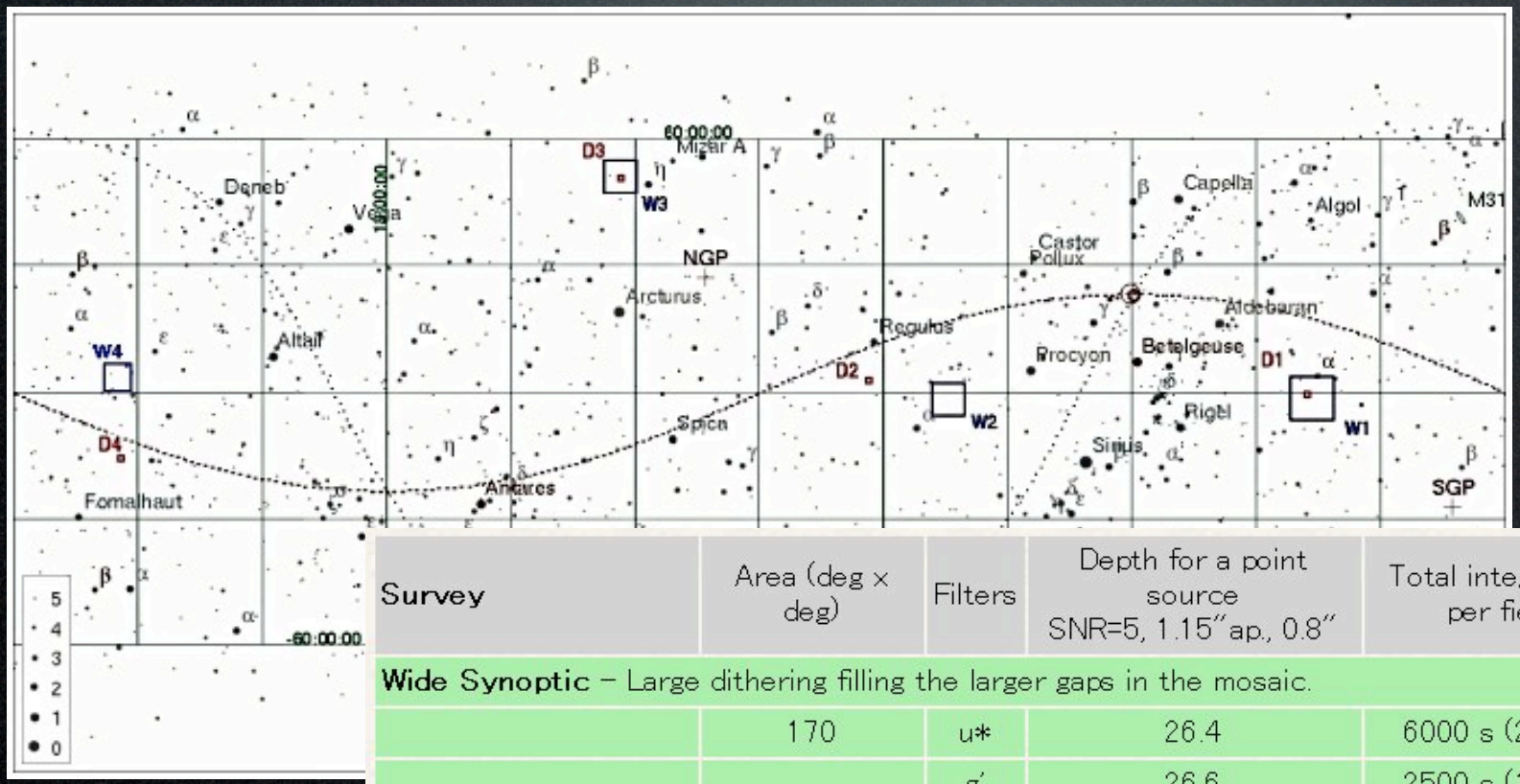
- many other "astronomical" science topics using Hα
  - cosmic star formation rate, SF activity in different environments, Hα luminosity function, halo occupation distribution, ...

$f\sigma_8$ from RSD: Expected Impact



Survey Field: CFHTLS-Wide

- 4 fields, 170 deg^2 available in total
  - u*g'r'i'z' 5 bands
- 7.5 deg^2 will be covered by FastSound in each of the 4 fields



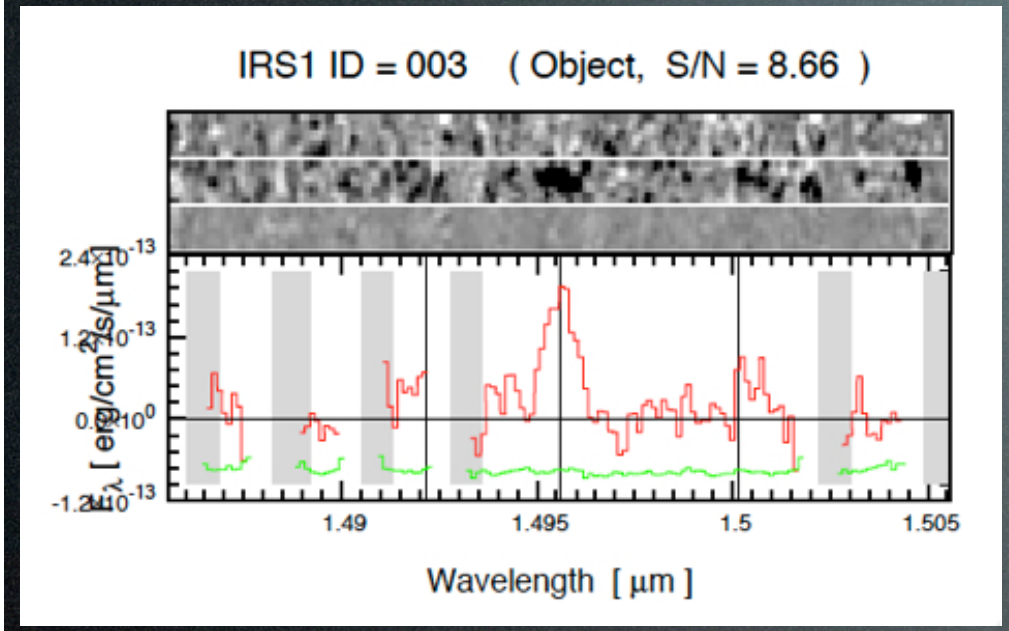
Survey	Area (deg × deg)	Filters	Depth for a point source SNR=5, 1.15″ap., 0.8″	Total integration per field	Observing strategy
Wide Synoptic – Large dithering filling the larger gaps in the mosaic.					
	170	u*	26.4	6000 s (27.2%)	7×850 s
		g′	26.6	2500 s (11.3%)	5×500 s
		r′	25.9	2000 s (9.1%)	Twice 2×500 s 3 years apa
		i′	25.5	4300 s (19.5%)	7×620 s
		z′	24.8	7200 s (32.7%)	9×800 s

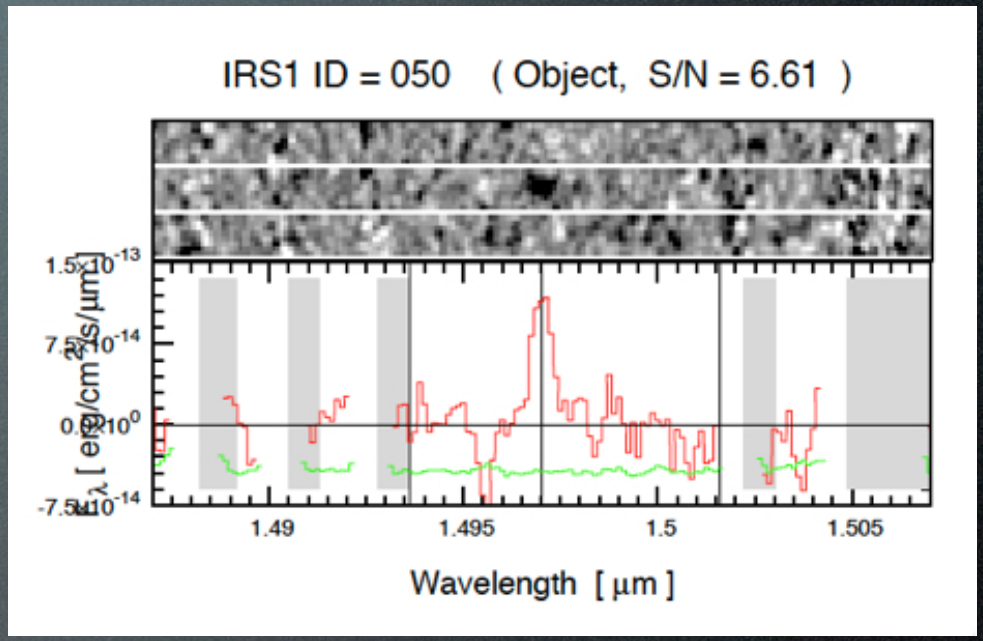
Survey Status

- W1: 3 / 37 FMOS FoVs completed
- W2: 28 / 37 completed
- W3: 52 / 37 completed
- W4: 11 / 37 completed

- about ~2/3 completed overall

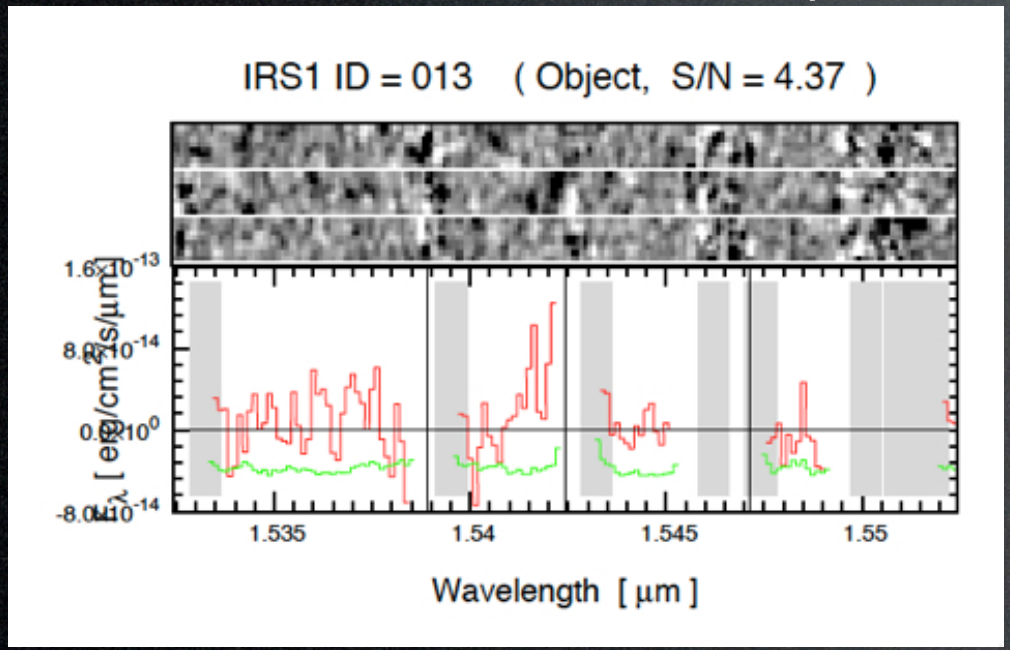
A tough issue: line detection in noisy NIR!

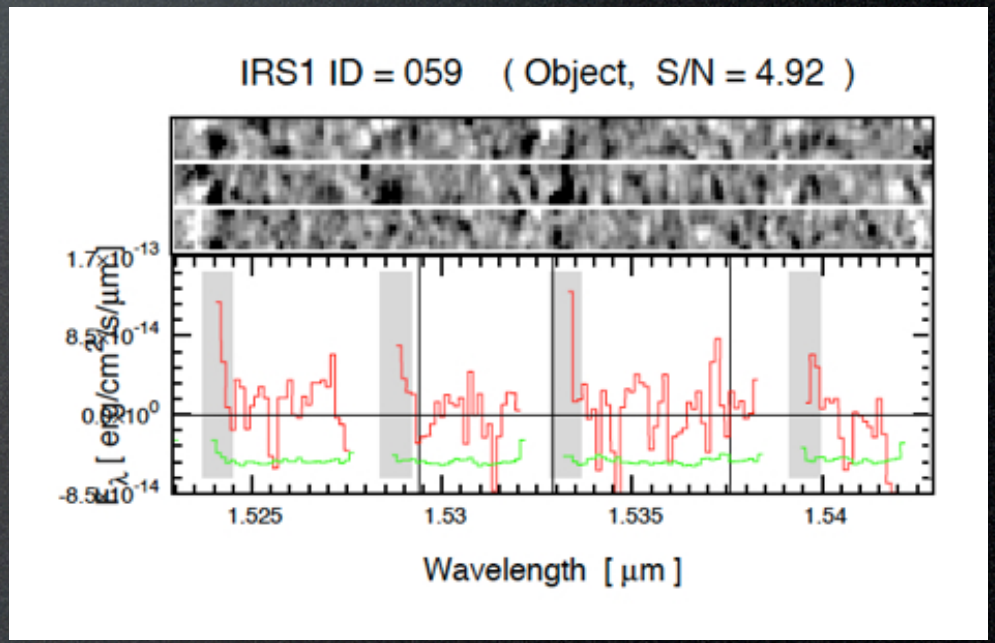




↑ our friends

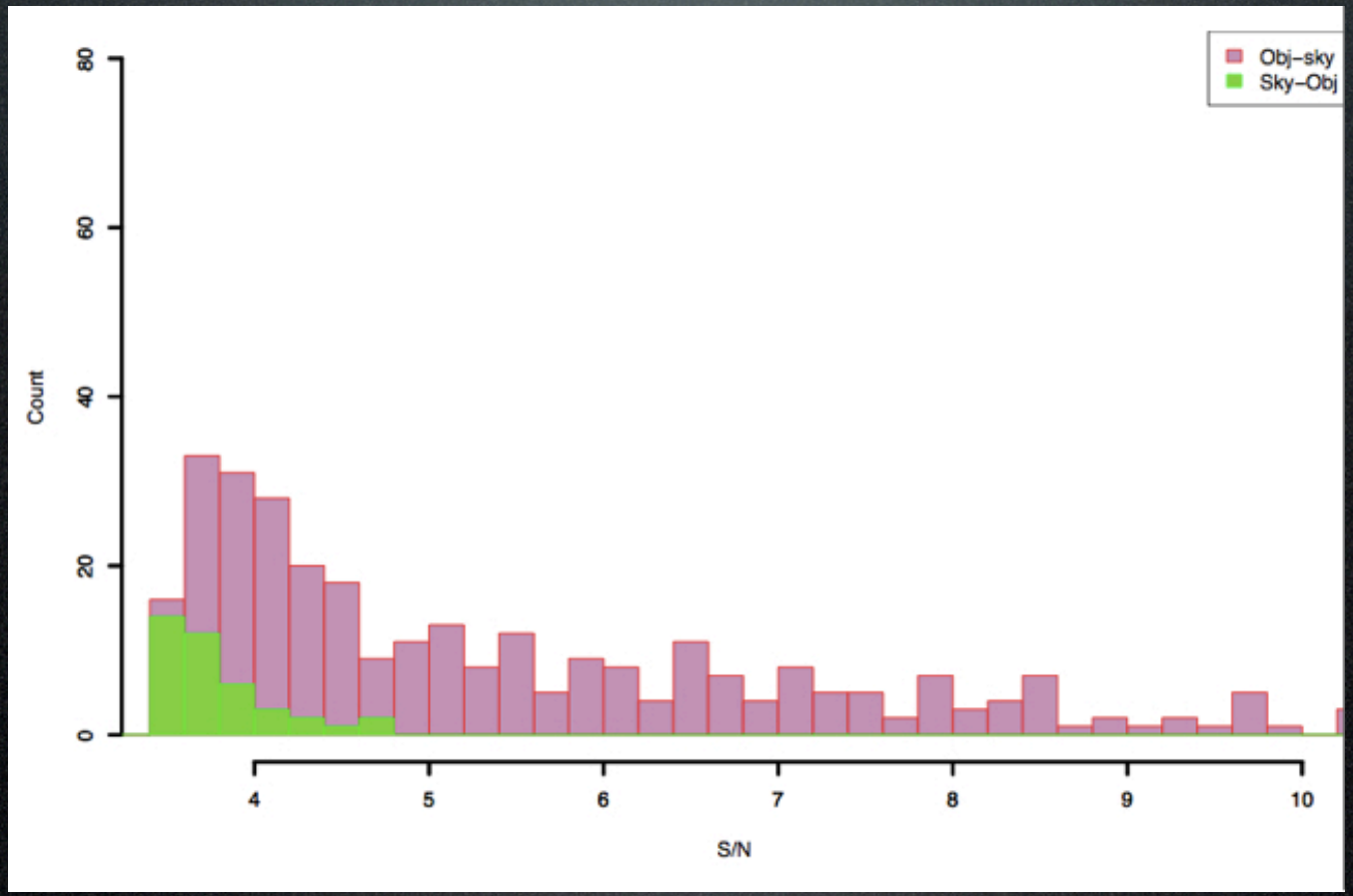
↓ our enemies





Emission Line Detection Software Development

- A large effort has been made to automatically detect real emission lines, avoiding spurious objects
  - NIR spectra are very noisy e.g. by OH airglow/mask!
- Our software has achieved a satisfactory quality
  - practically no contamination at line S/N > 5 (tested by inverted frames)

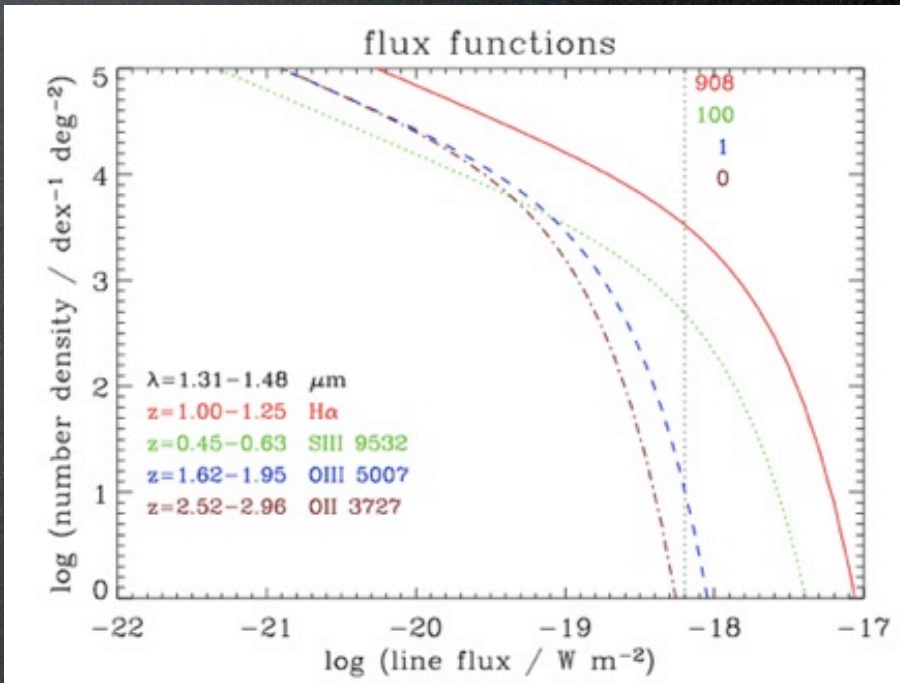


Is a line really Hα ?

- In most case, we have only one emission line in HR mode
- possibility of lines other than Hα 6563Å ?
  - expectation from luminosity function of star-forming galaxies: ~10%
  - examination using HiZELS data (H band narrow band emitters, z~1.47 for Hα): ~10% (Tonegawa+ '13)
  - further investigation underway using real FastSound galaxies with multiple lines
- x% contamination = x% fractional error on $f\sigma_8$ measurement
  - ~10% systematic in the worst case < statistical error

by I.K. Baldry

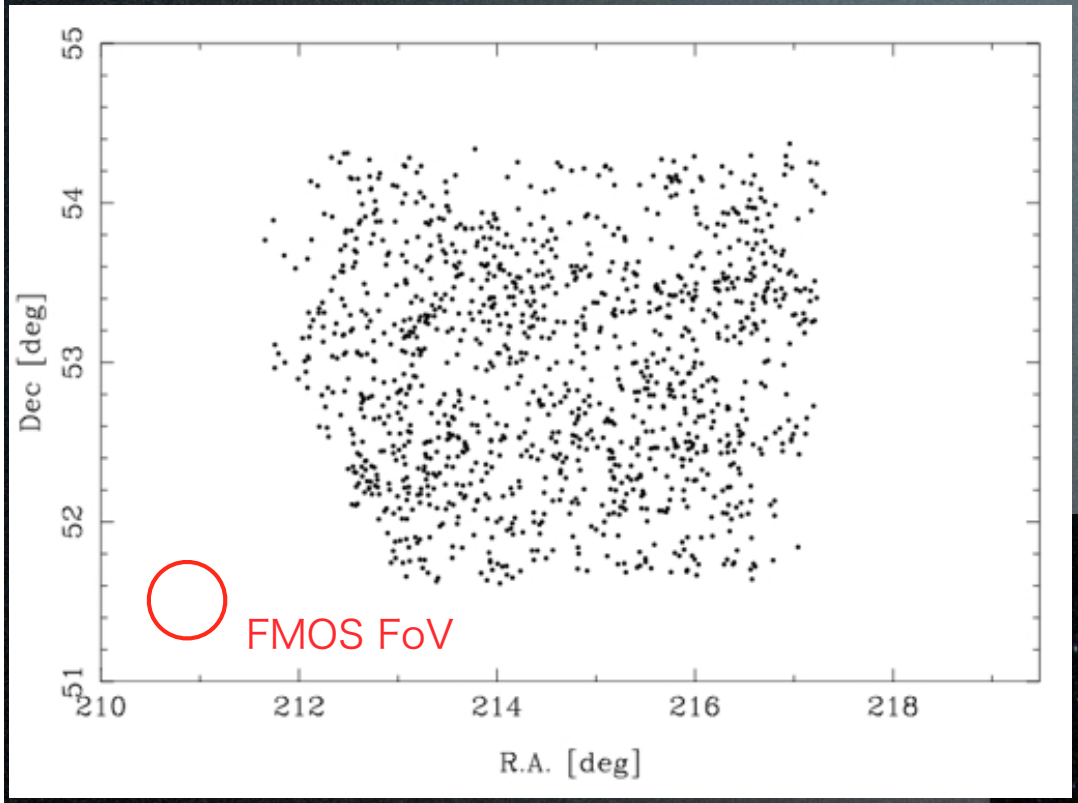
line	wavelength (μm)	flux (relative)	redshift range (obs. $\lambda = 1$–$2\,\mu$m)
OII	0.3727	0.47	1.68–4.37
Hβ	0.4861	0.15	1.06–3.11
OIII	0.4959	0.07	1.02–3.03
OIII	0.5007	0.27	1.00–2.99
NII	0.6548	0.17	0.53–2.05
Hα	0.6563	1	0.52–2.05
NII	0.6583	0.46	0.52–2.04
SII	0.6716	0.19	0.49–1.98
SII	0.6731	0.14	0.49–1.97
SIII	0.9069	0.1	0.10–1.21
SIII	0.9532	0.2	0.05–1.10
Paβ	1.2818	0.1	0.00–0.56
Paα	1.8751	0.2	0.00–0.07

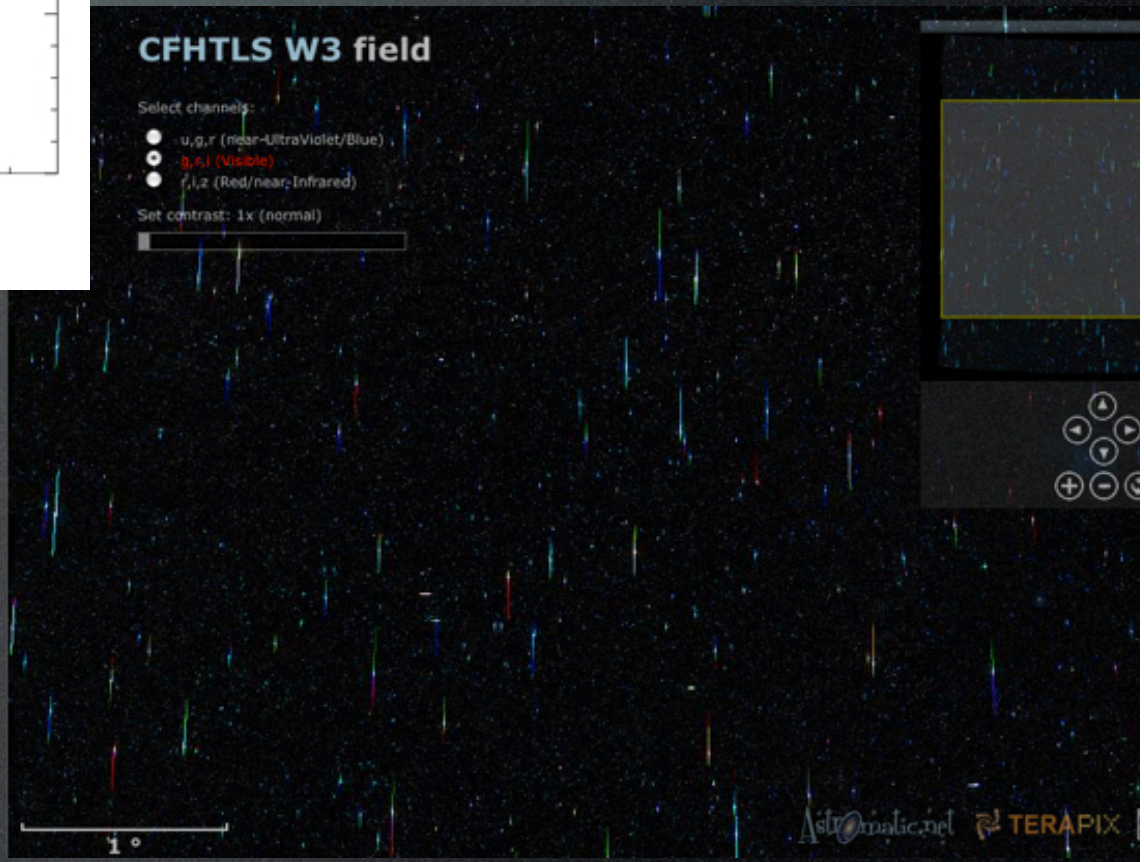


Preliminary Redshift Catalog in W3

- 47 FMOS FoVs in W3 (observed in 2012 Mar.-Jun.) have been reduced, and line detection analysis completed
  - about 1/4 of the total survey plan
- 1226 objects detected at S/N > 4.5. The first version redshift catalog produced assuming that they are all Hα
- Line detection rate: 8.2% per fiber on average.
  - at best performance, rate is ~10%
  - worse by instrumental troubles in some observing runs

FastSound Galaxies in CFHTLS W3





Example Images of FastSound Galaxies

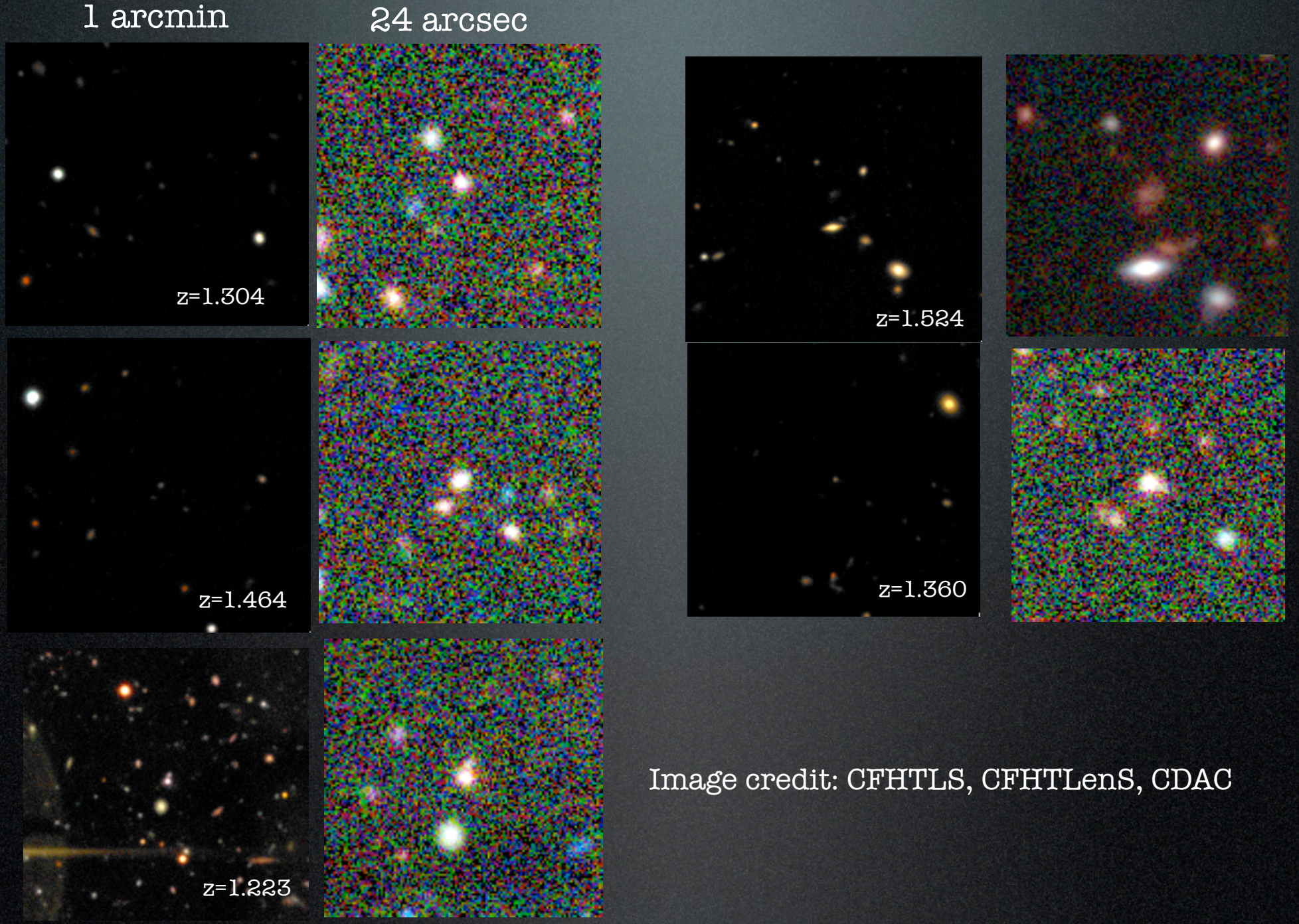
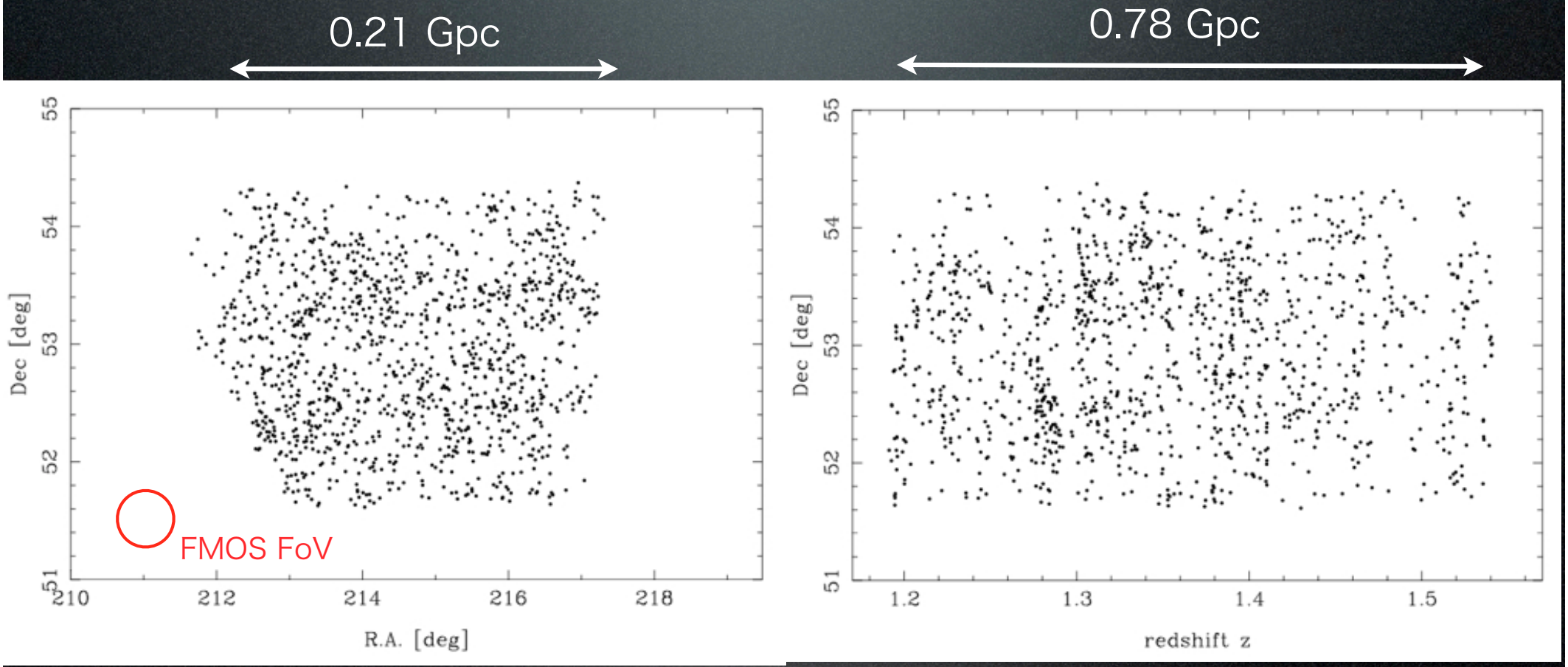


Image credit: CFHTLS, CFHTLenS, CDAC

The FastSound Real Galaxy 3D Map!

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

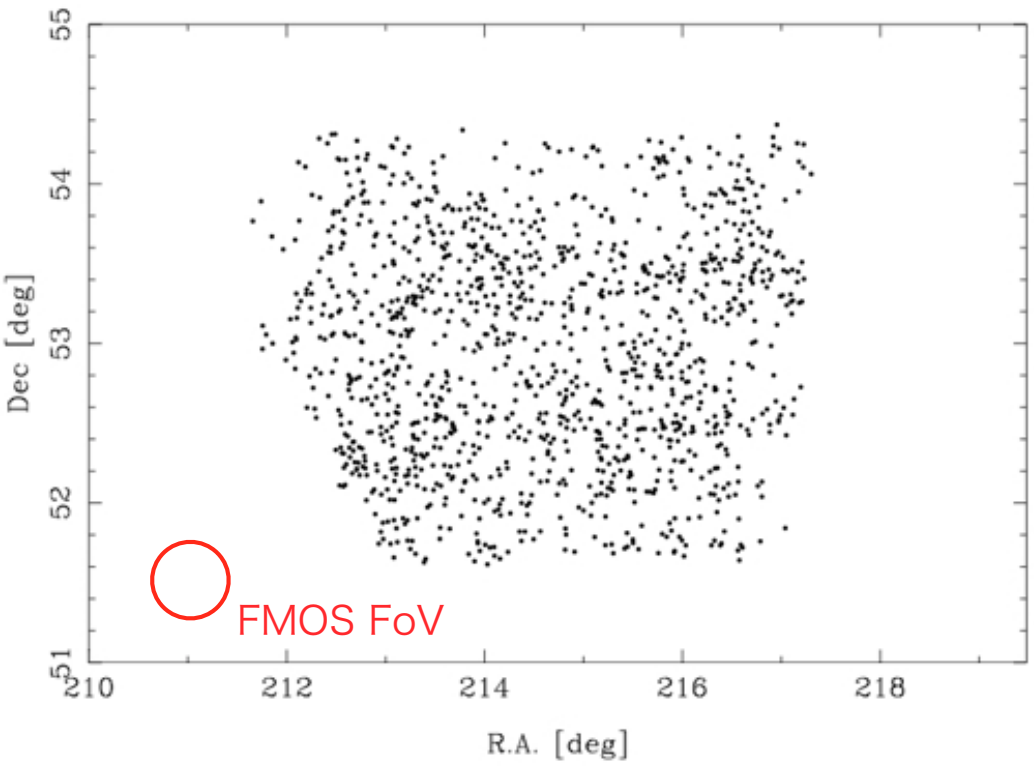


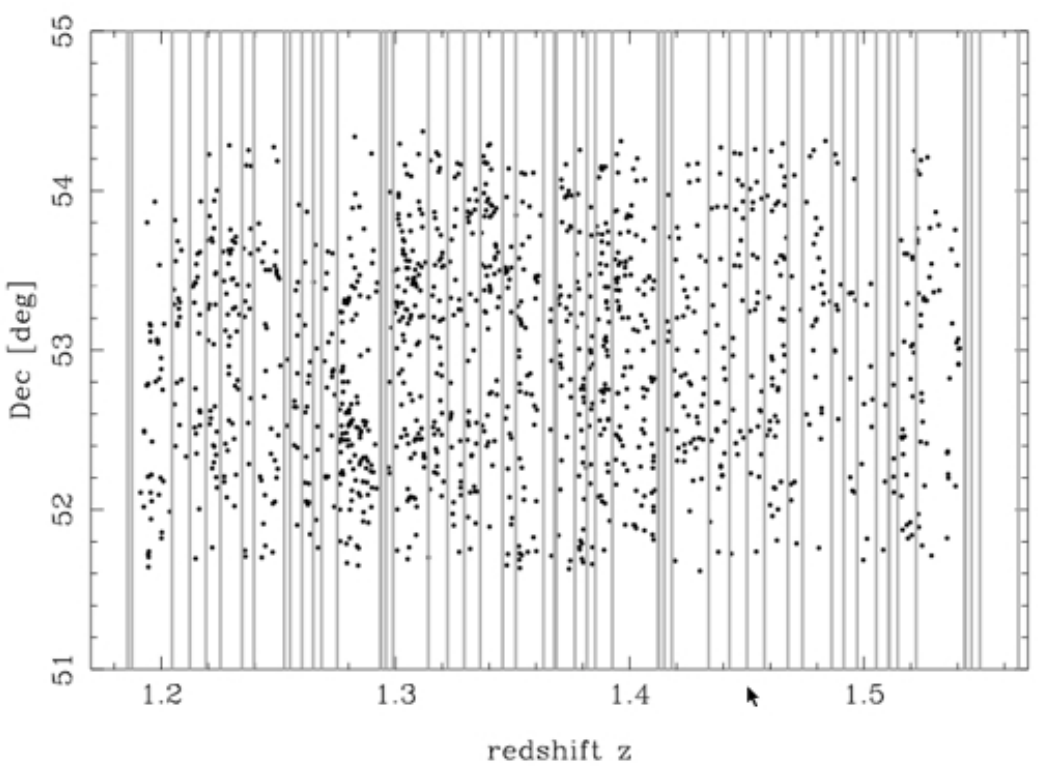
The FastSound Real Galaxy 3D Map!

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

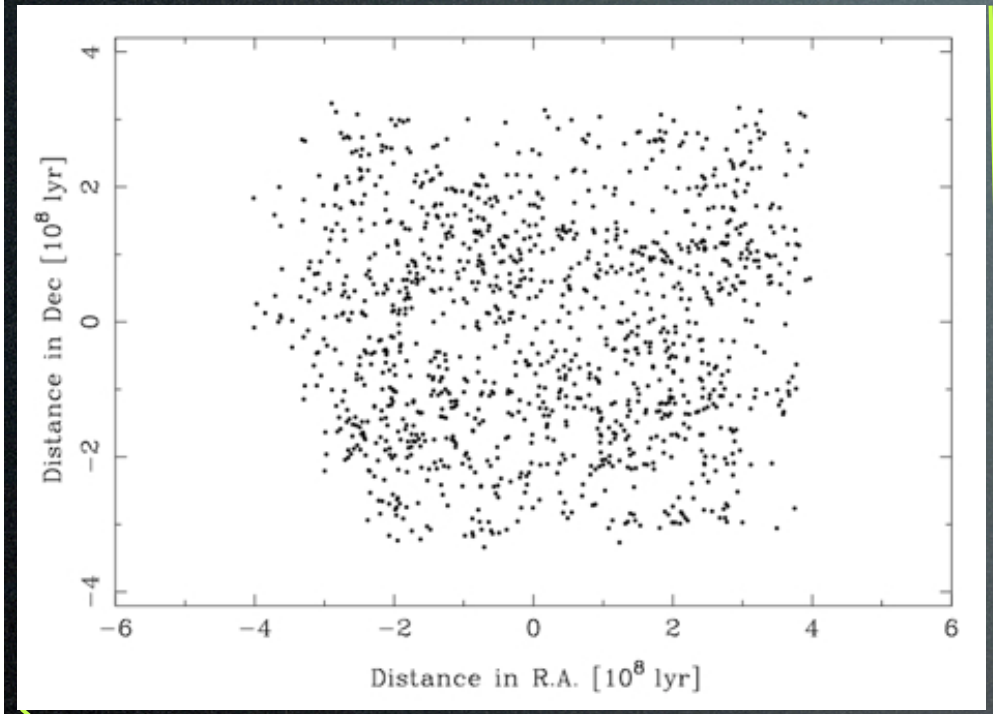
0.21 Gpc

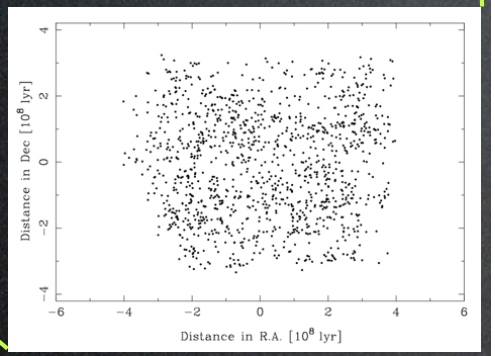
0.78 Gpc

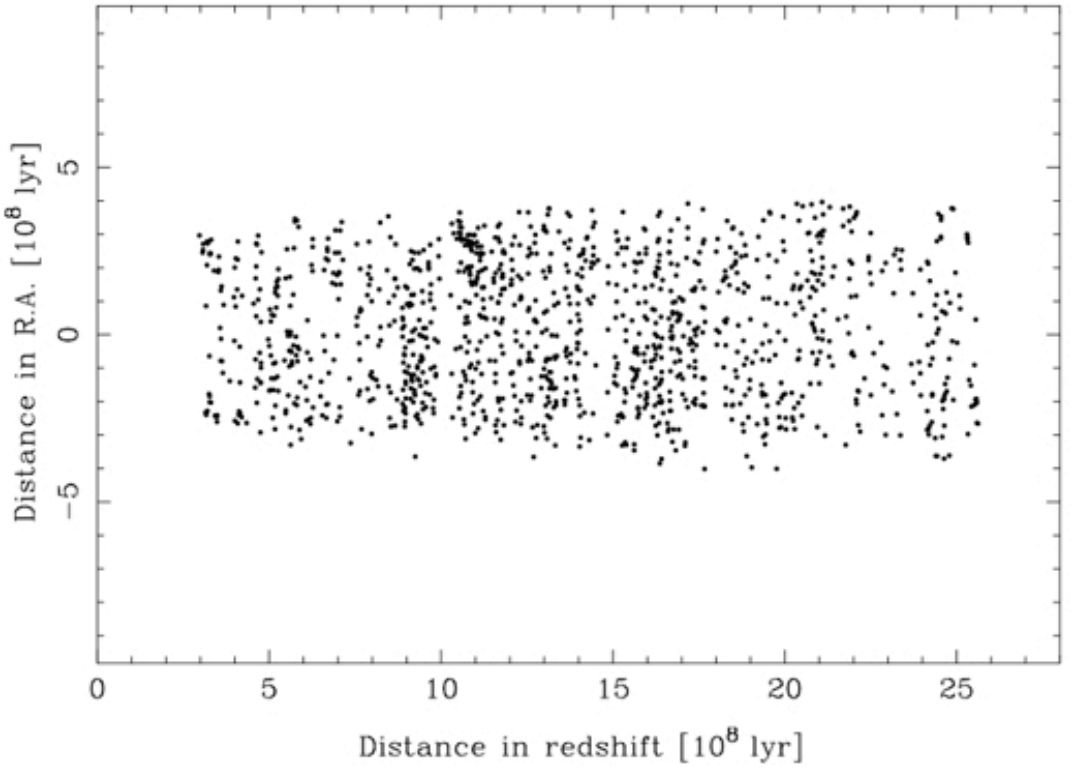


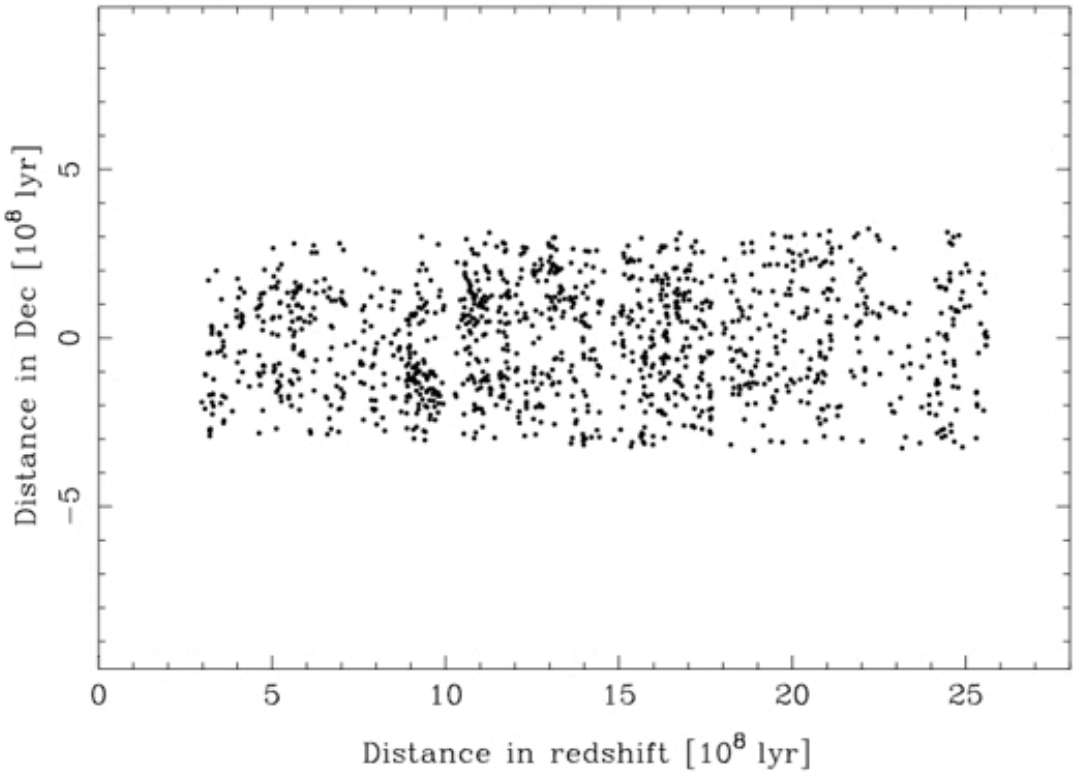


3D map in comoving coordinate









3D galaxy maps by various surveys

SDSS/BOSS
⟨z⟩ ~0.6

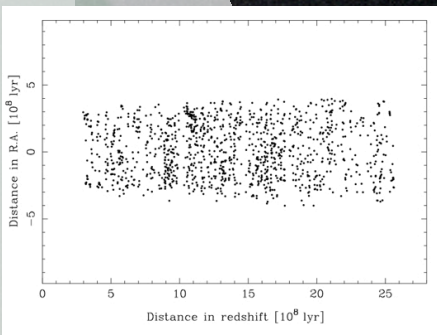
SDSS/LRG
⟨z⟩ ~0.35

SDSS/Main
⟨z⟩ ~0.2

WiggleZ
z~0.3-0.9

VIPERS
z~0.5-1.0

FastSound
z~1.2-1.5



4000 Mpc = 12 Glyr

Age of the Universe

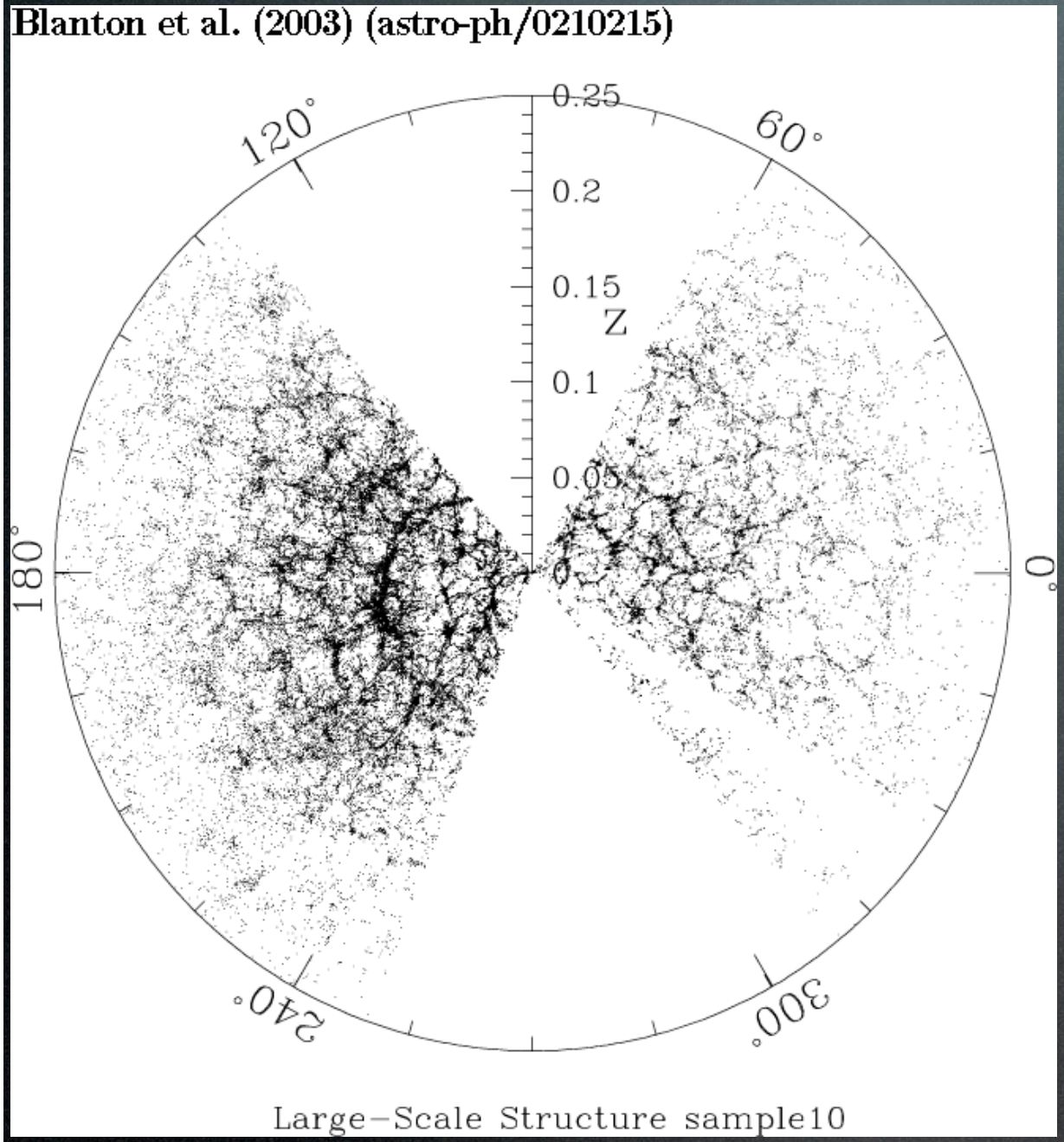
13.7 Gyr

8 Gyr

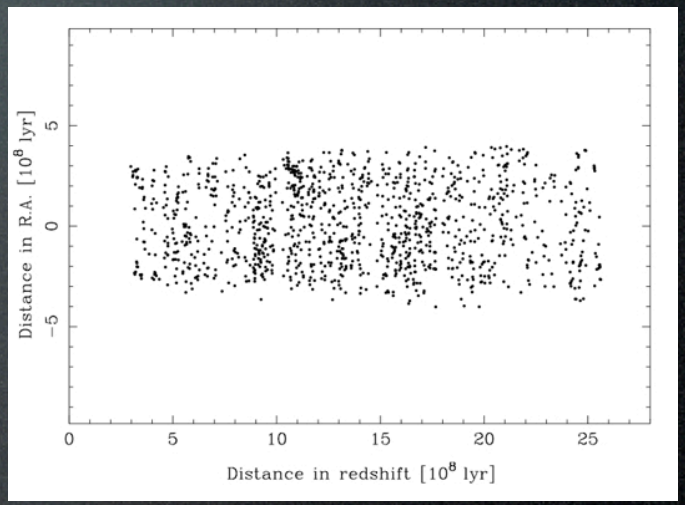
6 Gyr

4.7 Gyr

Large Scale Structure: Past vs. Present

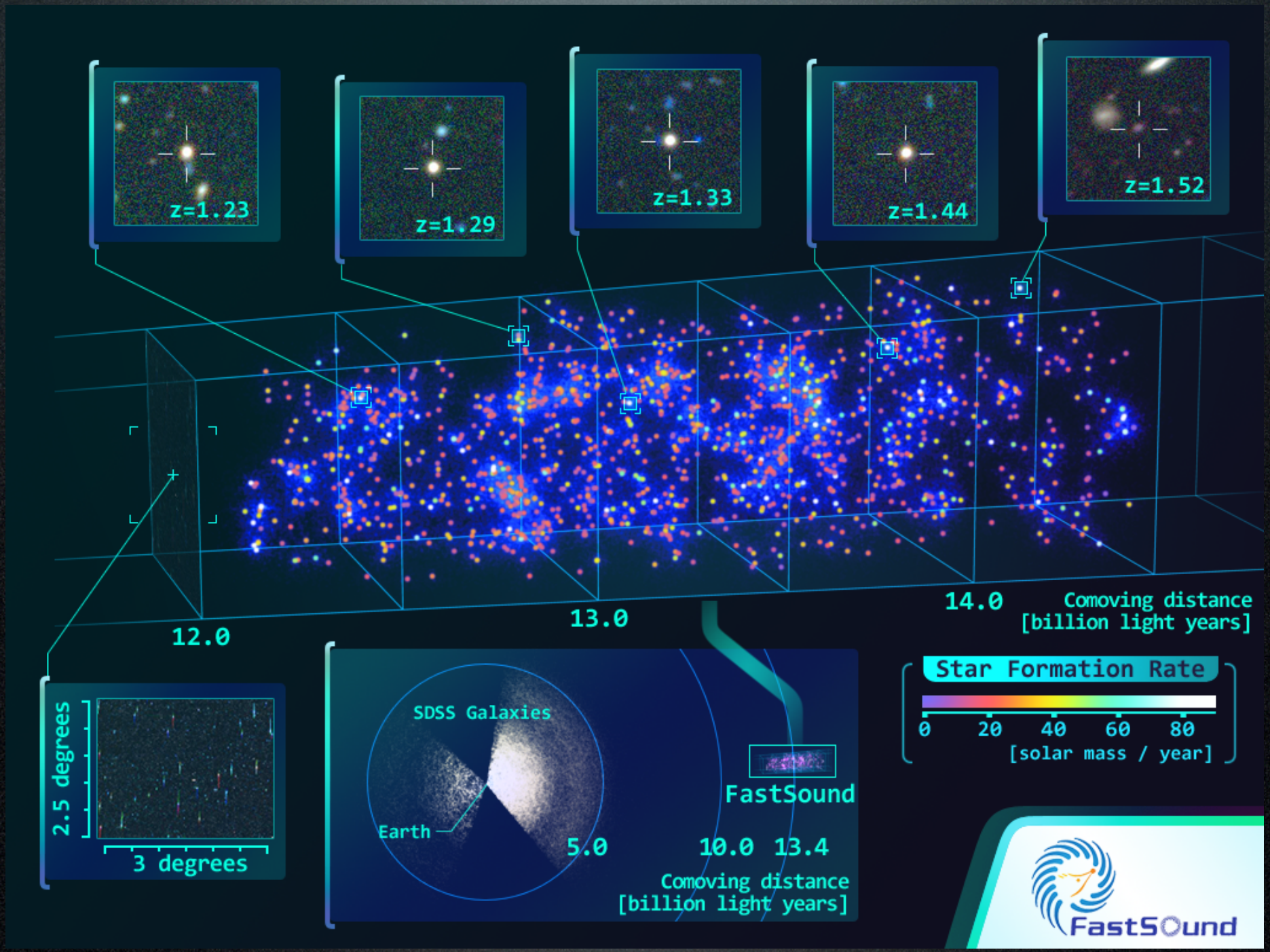


13.7 Gyr old



4.7 Gyr old

FastSound 3D map in W3 field



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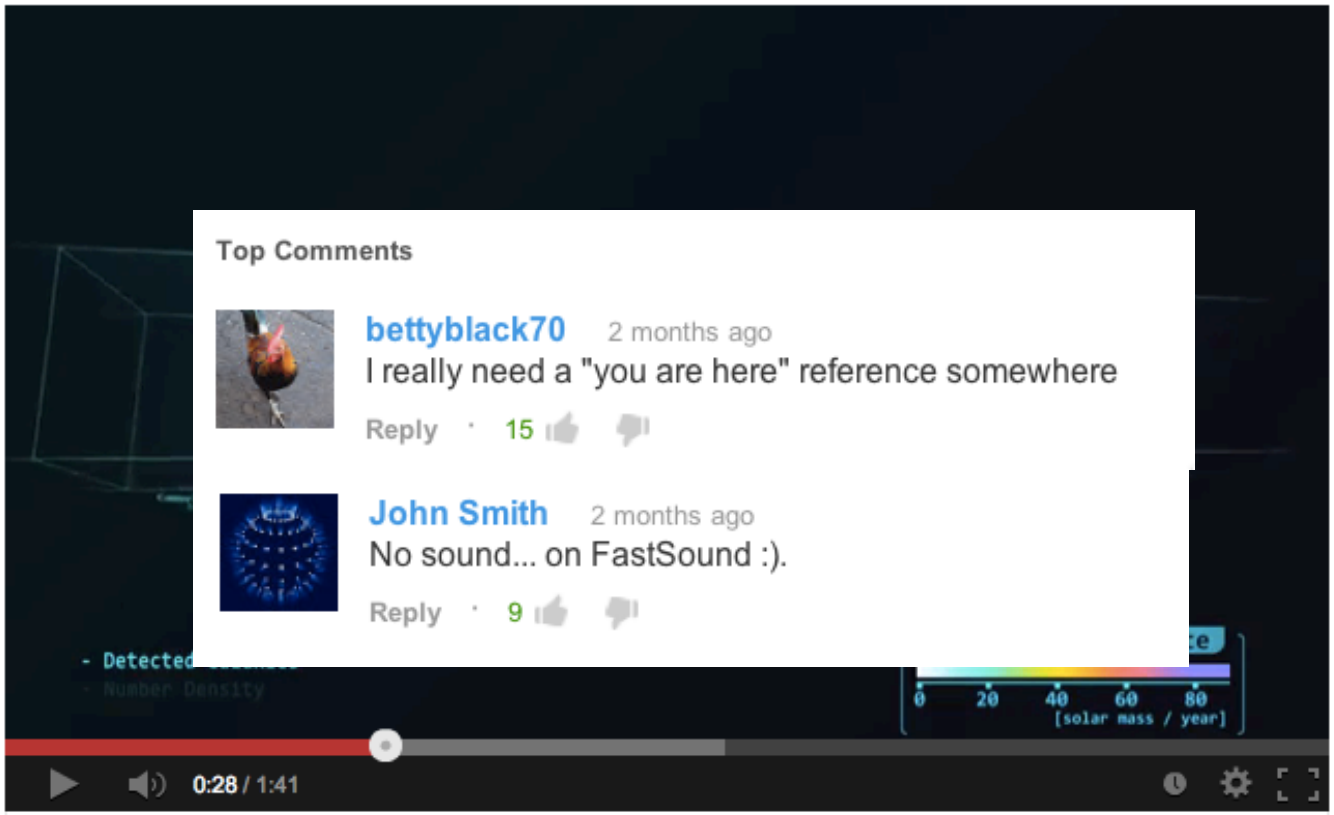

First Version of a 3D Map of Universe from the FastSound Project

SubaruTelescopeNAOJe · 8 videos

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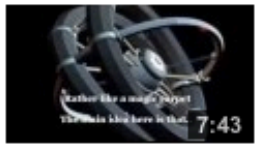
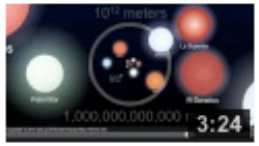
by AncesthroneTV
30,839 views



NASA Warp Drive Project - "Speeds" that Could Take
by nemesis maturity
139,552 views

The Observable Universe (accurately scaled zoom o
by Equiinox1989
35,777 views

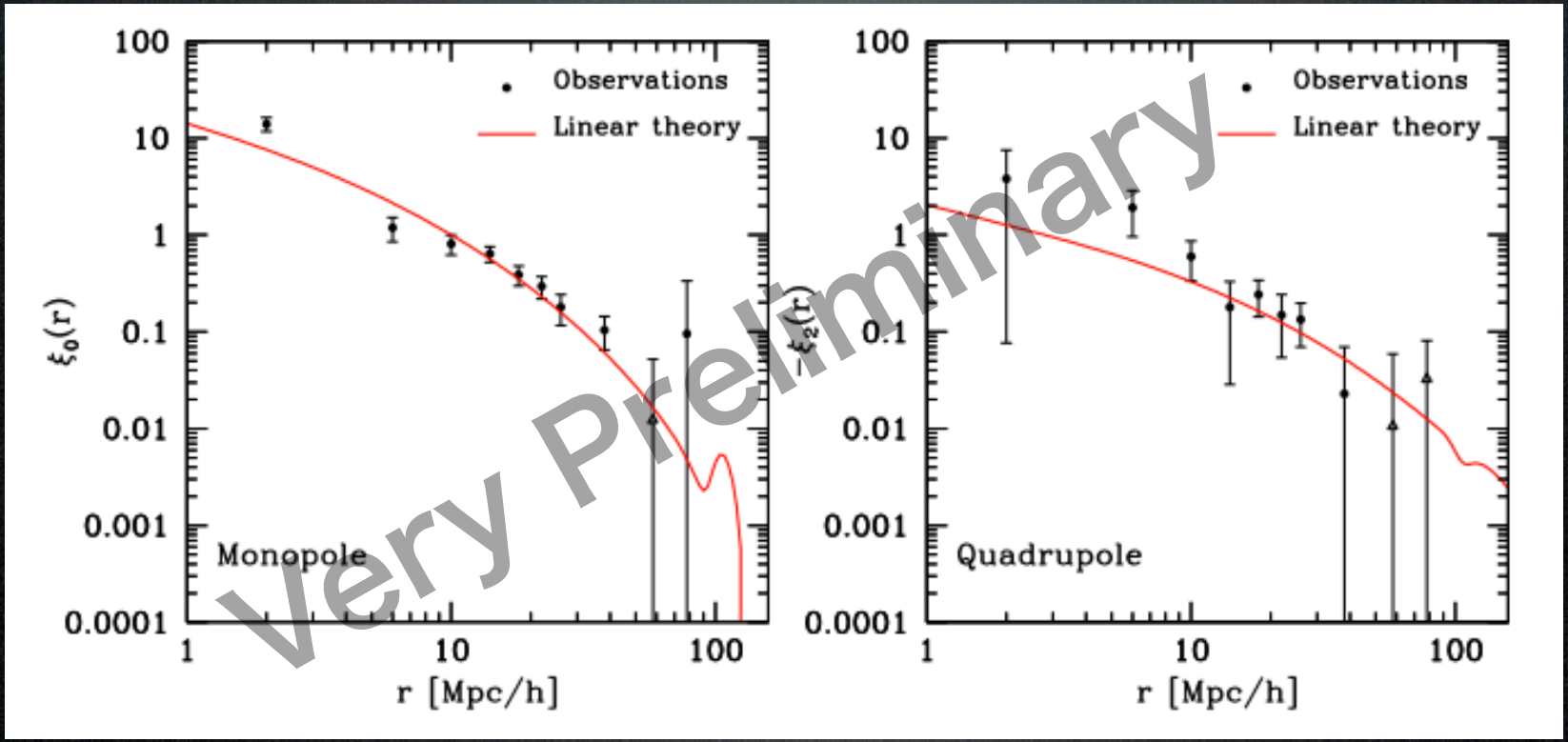


The Scale of the Universe
by carykh
208,307 views

Making a custom knife for an Infantryman
by Gough Custom

Test Calculation of correlation function $\xi(r)$

- monopole & quadrupole component of $\xi(r)$ clearly detected
- roughly consistent with linear theory + b~3
- anisotropy is mainly by RSD rather than the Alcock-Paczynski effect
- fractional error of $f\sigma_8$ = 44%
  - → ~4-5σ detection expected by the final catalog (x4 than now)



Calculations done by C. Hikage, also by T. Okumura

Summary/Future Plan

- FastSound: a galaxy redshift survey in near-infrared, targeting Hα emitters at z = 1.2-1.5
  - to deliver RSD measurement at 4-5 sigma using ~5000 Hα emitters in 30 deg^2 fields
- about 2/3 of the survey completed, all the survey will be completed in Dec. this year
- RSD has already been detected in the first version preliminary catalog by using 1/4 of the total data expected
- Detailed studies underway for the final catalog
  - automatic line detection
  - examination of other line contamination
- Publications will follow after we complete the final catalog production

back up slides

様々な銀河分光サーベイによる立体地図

SDSS/BOSS
〈z〉~0.6

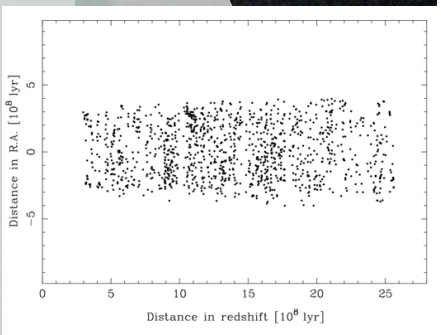
SDSS/LRG
〈z〉~0.35

SDSS/Main
〈z〉~0.2

WiggleZ
z~0.3-0.9

VIPERS
z~0.5-1.0

FastSound
z~1.2-1.5



4000 Mpc = 120億光年

宇宙年齢

137億年

80億年

60億年

47億年