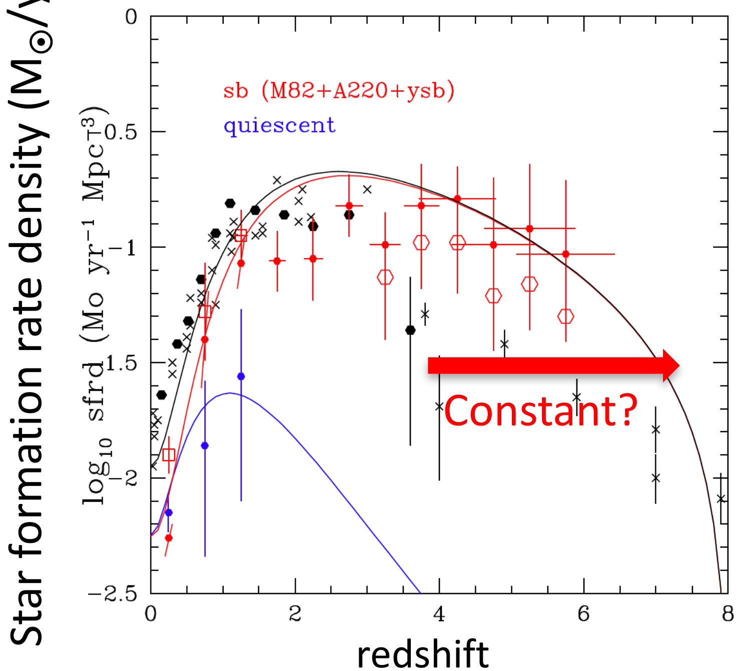
AtLAST workshop@ESO
17 – 19 January 2018

Blind spectroscopic galaxy surveys using an ultra-wide-band imaging spectrograph on AtLAST and LST (and LMT)

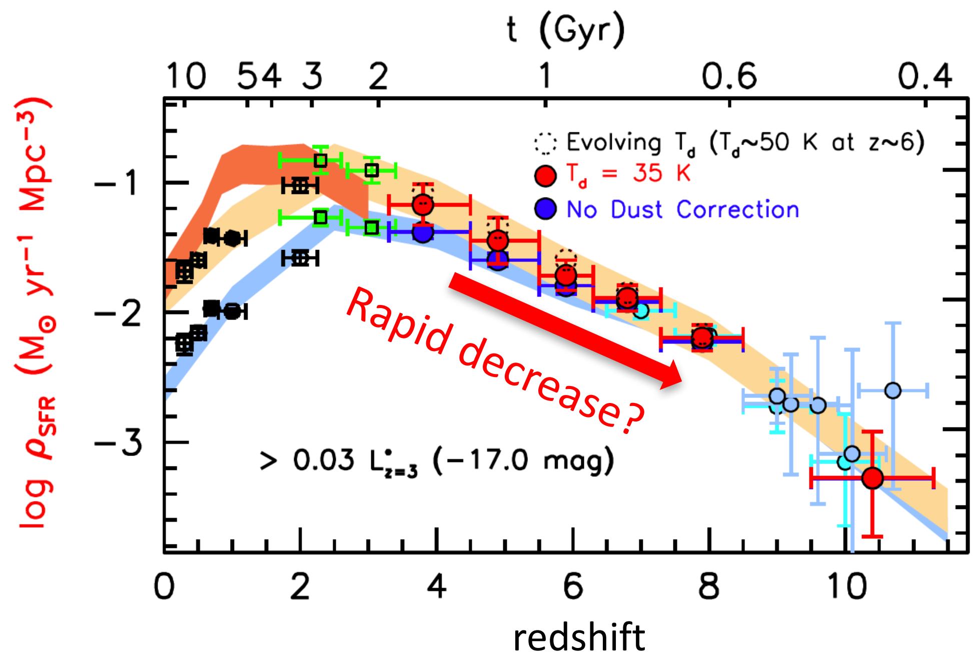
Kotaro Kohno, Yuki Yamaguchi, Yuki Yoshimura, Bunyo Hatsukade (IoA/Univ. of Tokyo), Yoichi Tamura, Tsutomu Takeuchi (Nagoya Univ.), Ryohei Kawabe (NAOJ) and LST science WG + Akira Endo (TU Delft), Jochem Baselmans (SRON) and DESHIMA/MOSAIC collaboration

What is the role of the dust-enshrouded star-formation activities in z>3-6 and beyond?

Rowan-Robinson et al. 2016, MNRAS, 461, 1100



Bouwens et al. 2016, ApJ, 833, id. 72

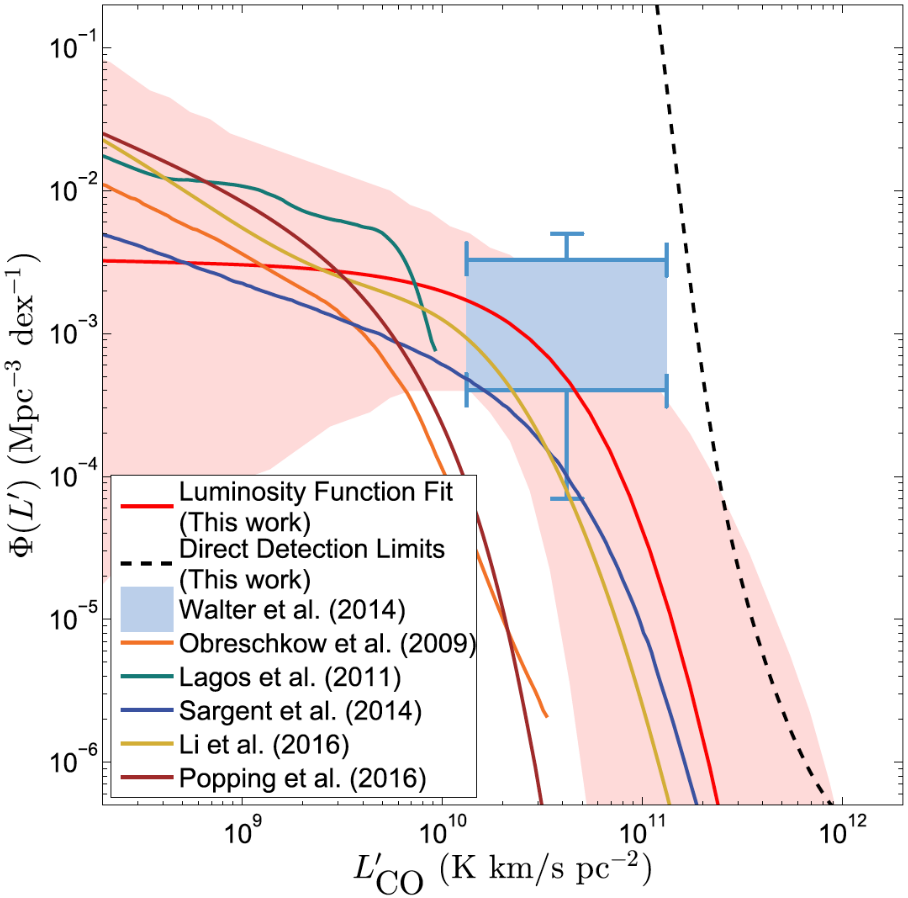


- Herschel wide area surveys of red submm sources ➔ significant amount of dust-obscured star formation up to z~6?
- An ALMA deep survey @HUDF(ASPECS): Dust-observed star-formation plays minor roles on the rest-frame-UV-selected galaxies

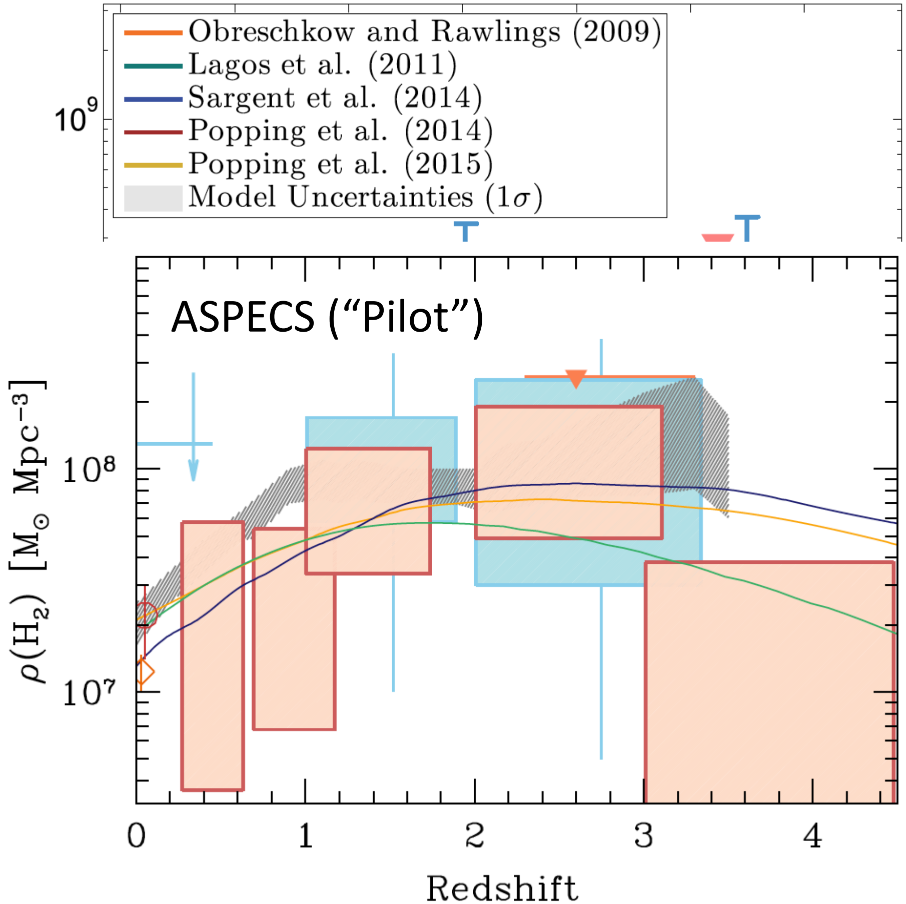
What is the physical cause for the cosmic SFRD evolution? ➔ constraints on CO LF and H_2 mass density evolution

The Sunyaev-Zeldvich Array
Kavli Institute for Cosmological Physics
Univ. of Chicago

19 fields, 0.7 deg^2, f_{obs} = 27 – 35 GHz ➔ aggregate CO(1-0) emission from z=2.3 – 3.3 galaxies



Keating et al. 2016, ApJ, 830, 34



Decarli et al. 2016, ApJ, 833, id. 69

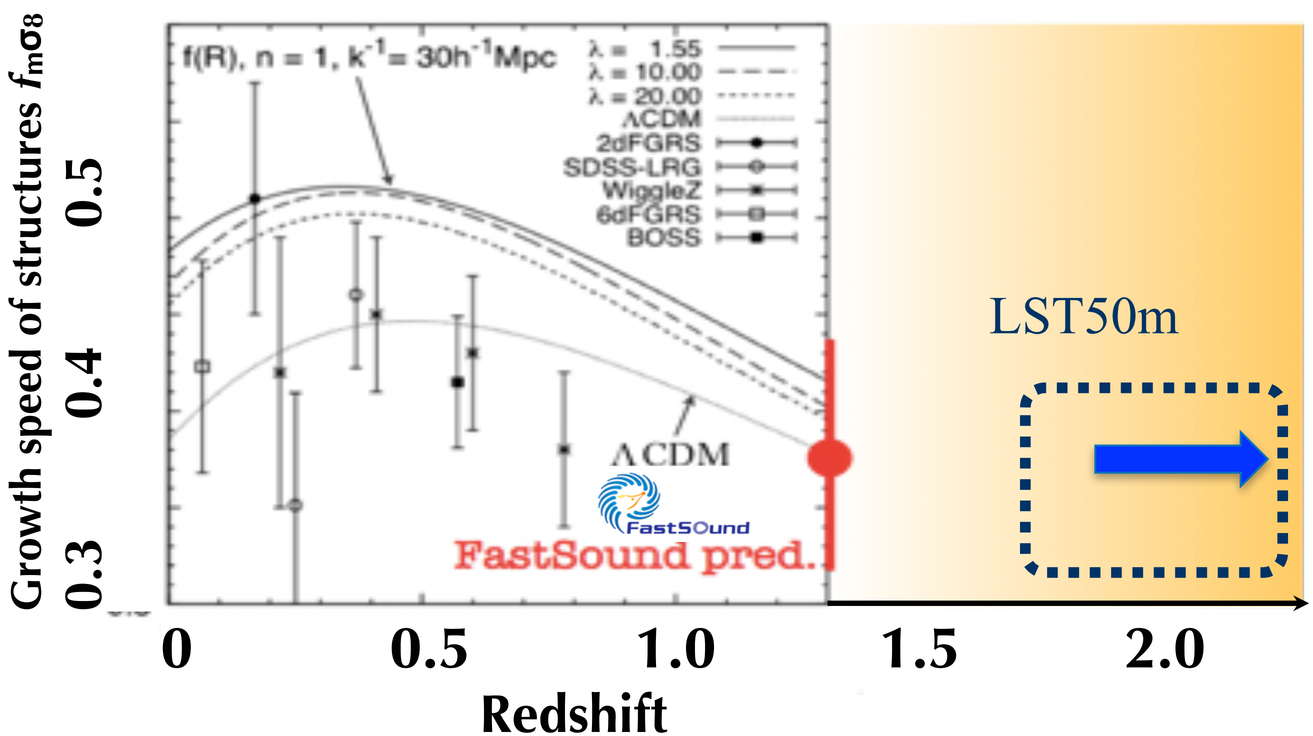
Does the growth rate of structures agree with the gravity theory (or require new physics)? ➔ **R**edshift **S**pace **D**istorsion

- To estimate the growth speed of structures in the universe ➔ cosmological test of gravity theory (or dark energy)
- verification of gravity theory based on RSD: can be competitive to others even in a (relatively) small survey, if we go a unique redshift range ➔ Can LST detect >10,000 spec-z galaxies in CO (or [CII]) at z=2 and beyond?

– **FastSound**

(P.I. T. Totani)

- Subaru / FMOS (40 nights, 2012-14)
- 30 deg^2, 10,000 redshifts at z_spec ~ 1.5

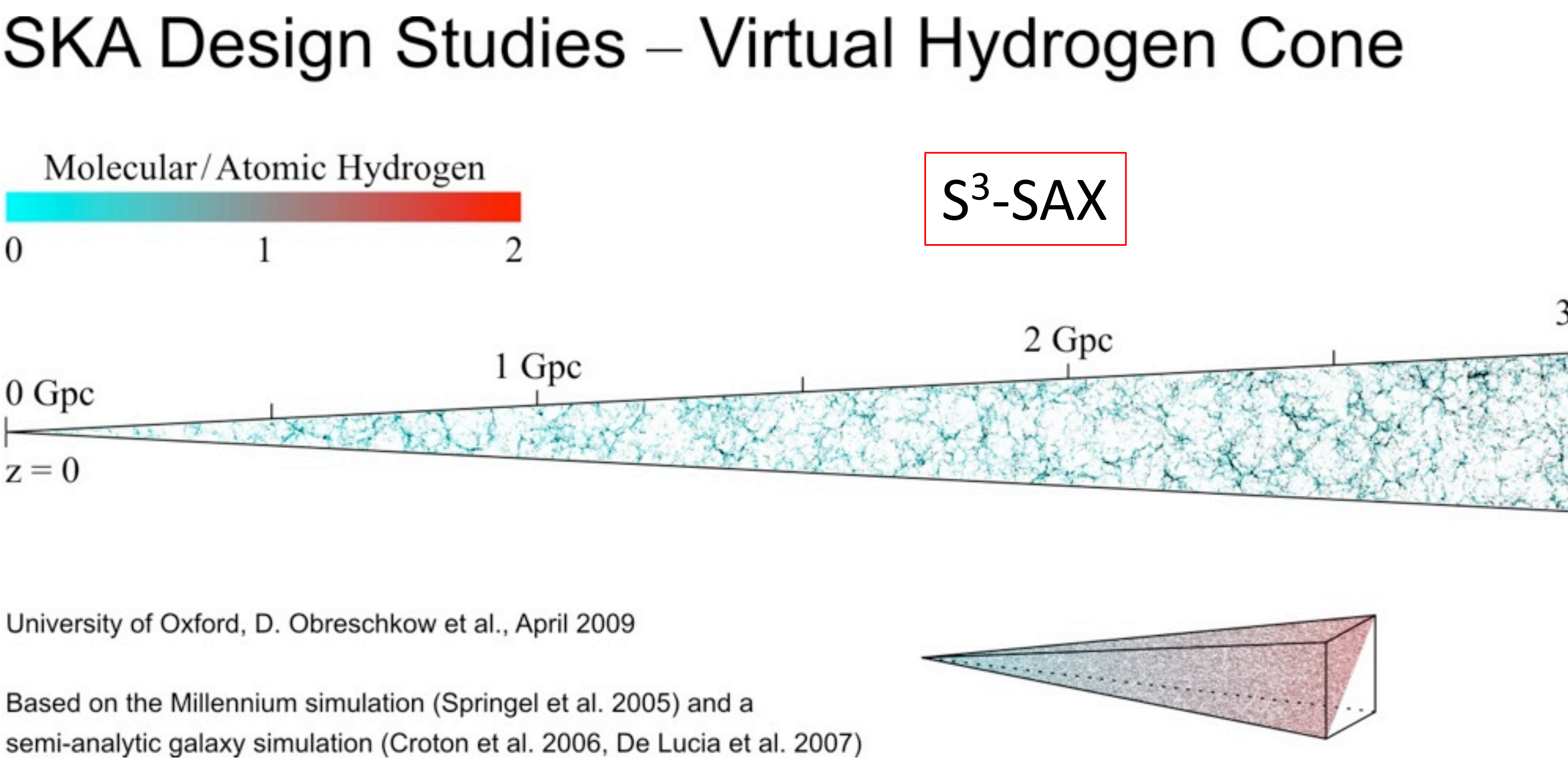


Large scale spectroscopic survey is really new:

A feasibility study of blind spectroscopic survey:

How can we build a SDSS-like data set, $>10^6$ CO emitting galaxies and >10,000 [CII] emitting galaxies ?

For a feasibility study of CO/[CII] tomography:



S^3-SAX

Obreschkow et al.
2009, ApJ, 702, 1321

Unbiased spectroscopy survey using **LST** (or a hypothetical) **50m** equipped with "**super-DESHIMA**" (or a hypothetical) imaging spectrograph

- **100 pix, dual-pol.** receiver array which instantaneously covers the **70-370 GHz** wavebands ("MUSE"-like instrument)
- t(on-source) = **1,000 hr (~several months)**

Tamura, Y., + in prep.

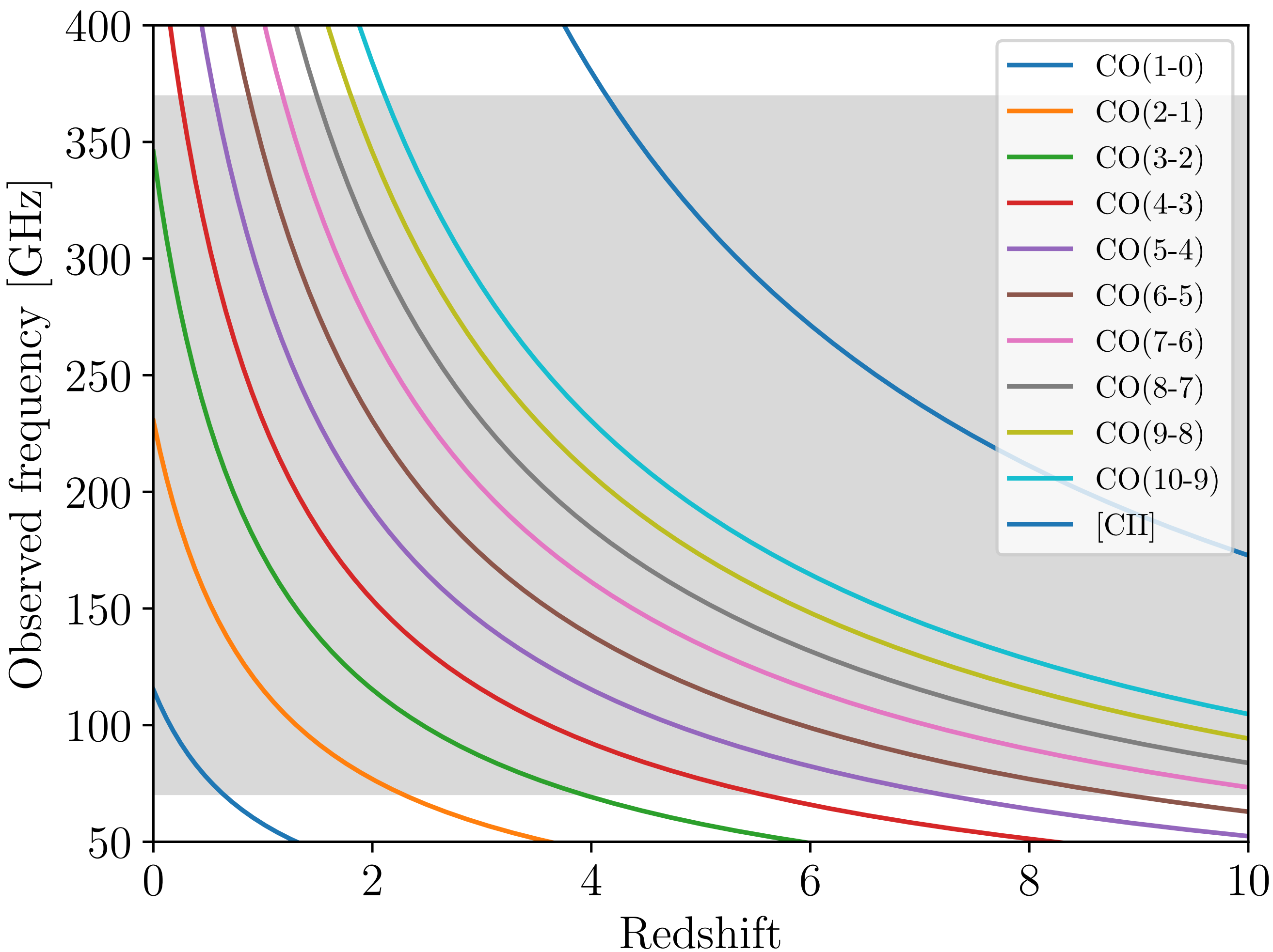
- **Area = 2 deg^2**
- extracting galaxies with at least 1 line detected at >4σ.
- Assumptions
  - T_{sys} (PWV, $T_{receiver}$, $\eta_{aperture}$): same as the ALMA median condition.
  - scaling a result from the 45m OTF calculator (Sawada+08)

- Parent sample (retrieved from the S^3-SAX/MySQL webpage)
  - 1.4M objects with $S_{CO}\Delta V \geqq 0.02$ Jy km/s for all transitions up to J =10 from the "Milli-Millennium" Simulation (1/64 of the full simulation)
  - [CII]158μm is considered using the scaling relation between $L_{CO(1-0)}$ and $L_{[CII]}$ of ~4,100 (Stacey+10)

Mock observation

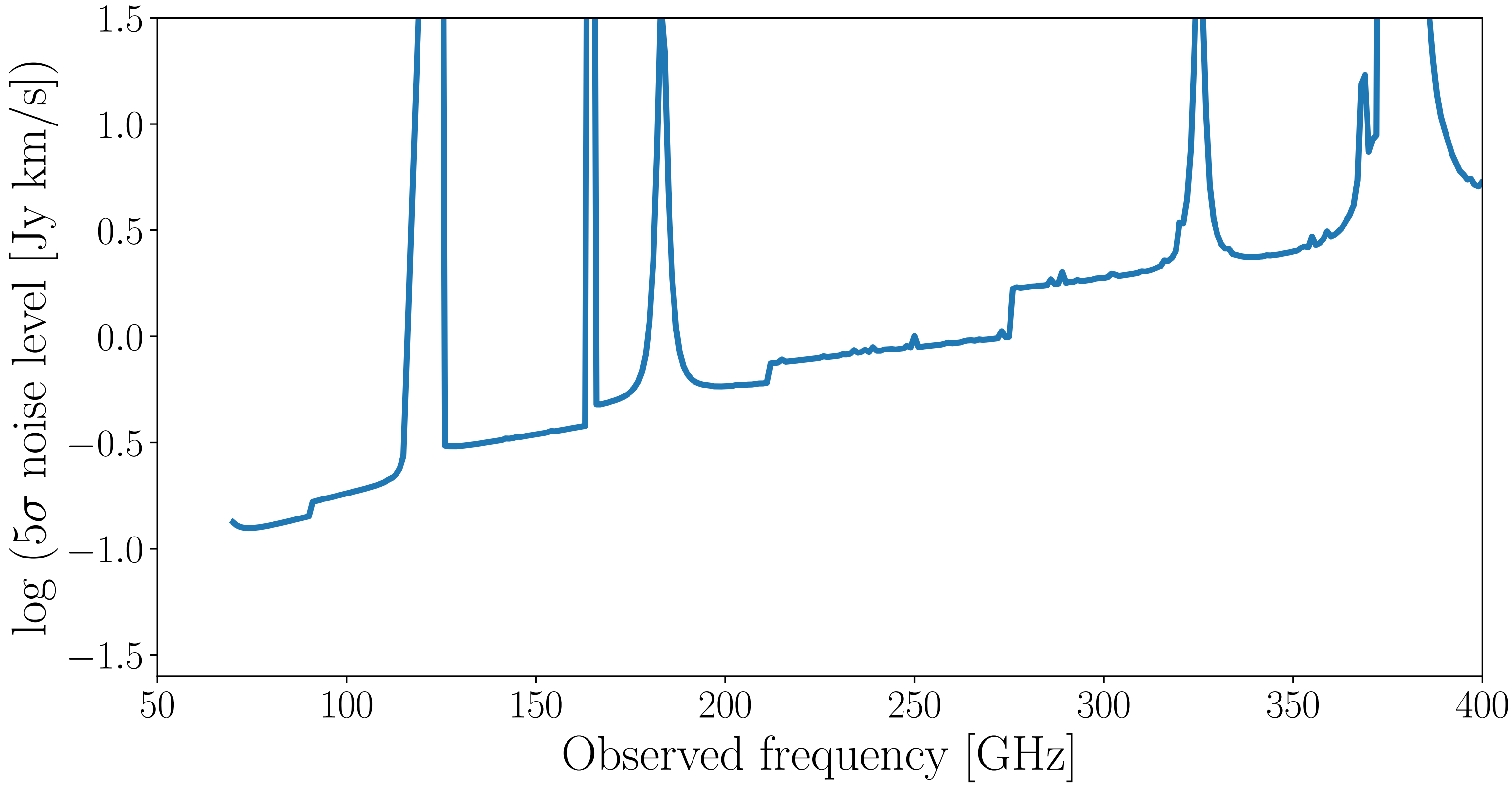
- Observable redshift range

Slides by Yamaguchi, Y.



line	z_{min}	z_{max}
CO1-0	0	0.65
CO2-1	0	2.29
CO3-2	0	3.94
CO4-3	0.25	5.59
CO5-4	0.56	7.23
CO6-5	0.87	8.88
CO7-6	1.18	10
CO8-9	1.49	10
CO9-8	1.80	10
CO10-9	2.11	10
[CII]	4.14	10

Mock observation

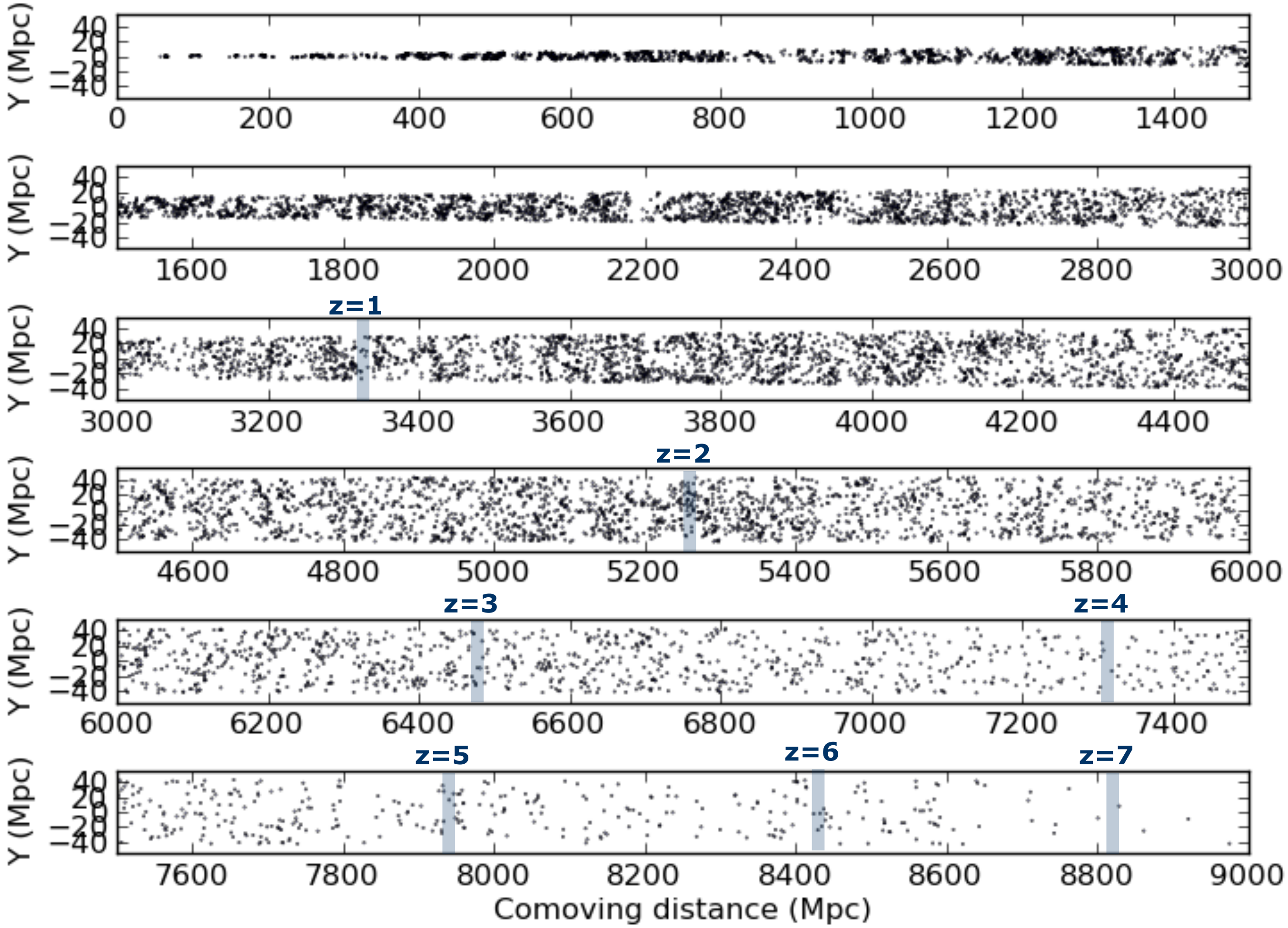


- The 1σ noise level achieved in the 2 deg^2 survey is comparable to that obtained in a single track of ALMA, but the survey area is ~13,000 times larger than the ALMA FoV.
- The survey can detect MW-like galaxies at z ~ 2.

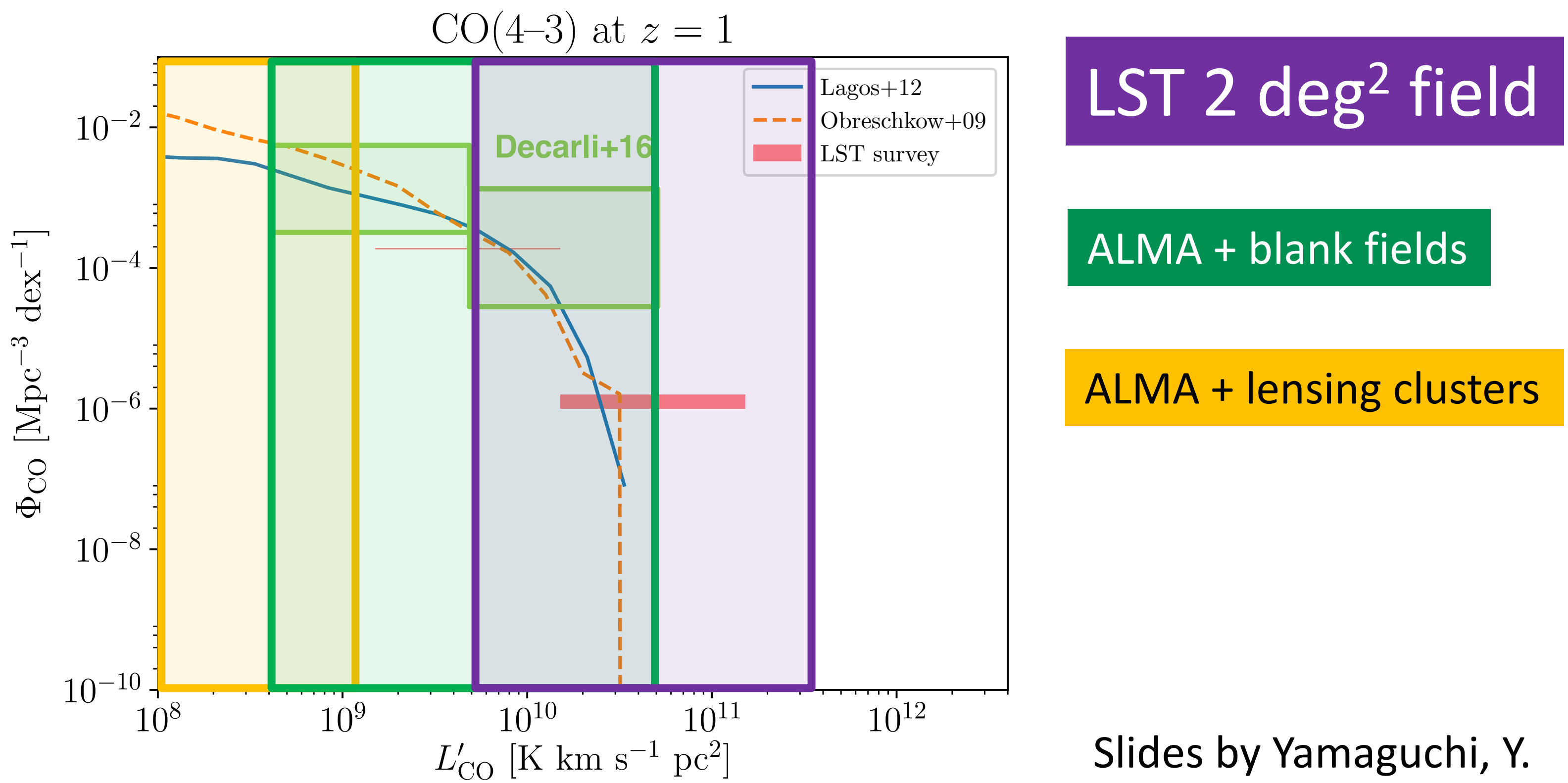
2 deg^2 Light cone (Super-DESHIMA/LST 50m)

Tamura, Y., + in prep.

Kawabe+ 2016, SPIE



CO luminosity functions



Slides by Yamaguchi, Y.

- The proposed 2 deg^2 survey will
  - Drastically improve the statistics of ALMA constraints
  - put a significant constraint on the bright-end of CO luminosity functions for the first time ➔ essential for the formation of the massive galaxies

Reference survey results
(2 deg^2, 1,000 hr, 100 pixels, 5σ)

- CO emitters: 21,776 galaxies (at least 1 CO line)
  - 17,481 of them will have >2 CO lines
- [CII] emitters: 1,217

100 deg^2, 5,000 hrs
w/ 1,000 pixels
➔ 10^6 CO emitters,
50,000 [CII] emitters

line	ALL	2	3	4	5	6	7	8
1-0	3489	788	2088	450	33	-	-	-
2-1	12158	3507	4454	1780	507	69	7	3
3-2	15479	5520	5394	2484	719	149	25	3
4-3	11277	2639	3890	2792	798	164	29	3
5-4	7219	1595	2217	2319	749	163	29	3
6-5	3447	197	746	1487	781	173	28	3
7-6	1250	11	258	416	359	170	26	3
8-7	420	1	26	86	159	112	29	3
9-8	130	-	4	18	24	58	23	3
10-9	12	-	-	-	1	4	7	-

Slides by Yamaguchi, Y.

Redshift Space Distorsion (RSD)

- Redshift z = expansion + peculiar velocity
- Peculiar velocity → speed of structue formation
  - Linear regime → Kaiser effect (galaxies fall down to higher density region)

linear growth rate Scale factor

- Observable: "linear growth rate" f = dln D/dln a
- How to forecast parameter constraining the power of the LST blind survey?
- ➔ Fisher forecast
- Feasibility study done by Yuki Yoshimura

Fisher forecast

- ✏ Fisher information
  $I(\hat{\theta}) := \mathrm{var}[\frac{\partial \ln L(\theta)}{\partial \theta}]$, L is likelihood function

- ✏ Statistics version of "uncertainty relation"
  $\mathrm{var}(\hat{\theta}) \geq I(\hat{\theta})^{-1}$ (Cramer - Rao's relation)

- ✏ Often used for estimating statistical uncertainty of future cosmological mesurement (Tegmark 97; Seo & Eisenstein 03, Majerotto+12,...)

- ✏ Approxmated Fisher matrix for cosmology (Tegmark 97)

$$F_{ij} = \int_{k_{min}}^{k_{max}} \frac{\partial \ln P(k)}{\partial p_i} \frac{\partial \ln P(k)}{\partial p_j} V_{eff}(k) \frac{dk^3}{2(2\pi)^3}$$

Slides by Yuki Yoshimura

Fisher Forecast for LST survey

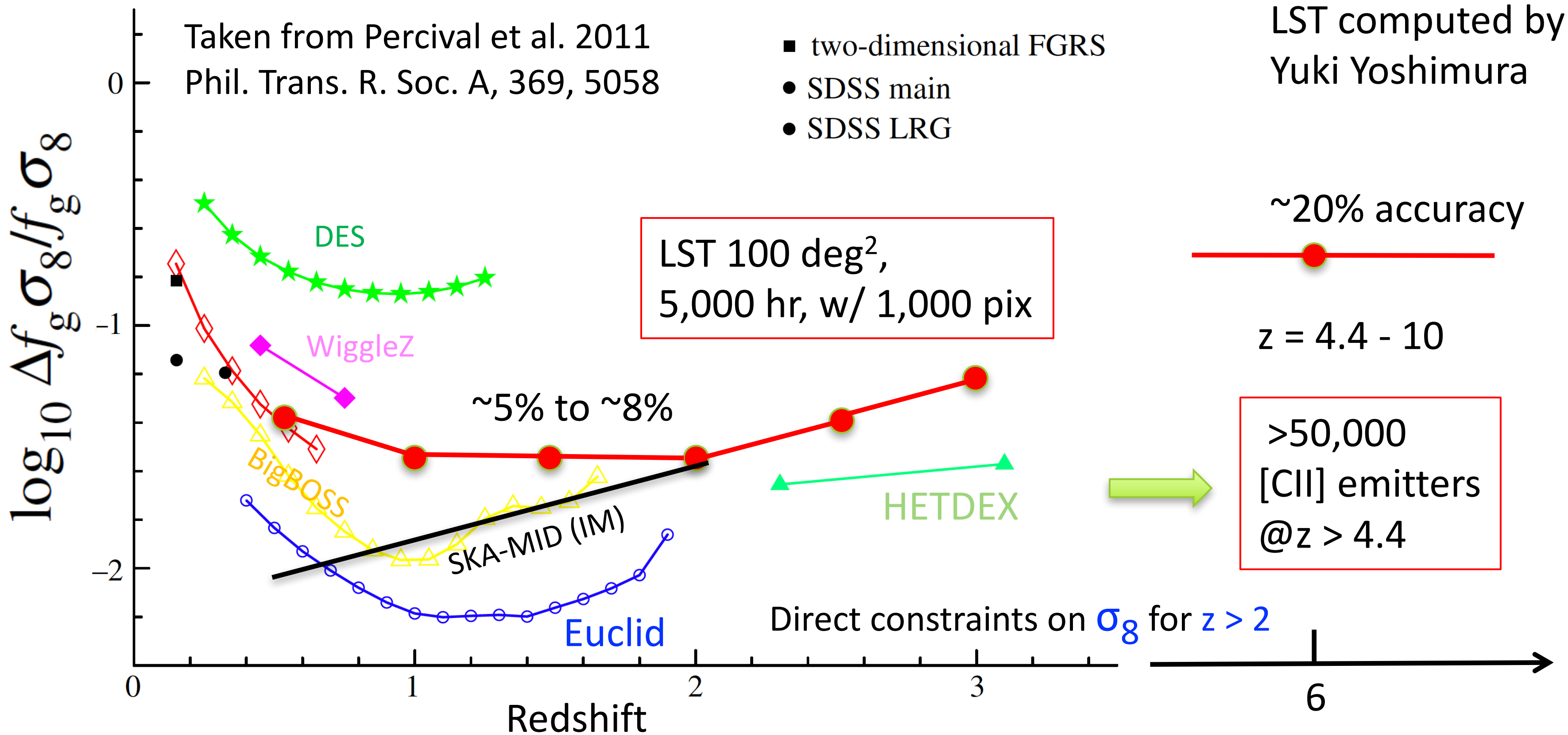
- Total integration time per area (= 500 hr/deg^2) is fixed
- fractional errer for $f(z)\sigma_8(z)$, $\Delta z = 0.5$

z	2 deg^2	10 deg^2	20 deg^2	100 deg^2
0.5	43 %	19 %	13 %	6 %
1.0	33 %	14 %	10 %	5 %
1.5	38 %	15 %	10 %	5 %
2.0	44 %	17 %	12 %	5 %
2.5	45 %	20 %	14 %	6 %
3.0	57 %	26 %	18 %	8 %

Slides by Yuki Yoshimura

Comparison to optical cosmology surveys

σ_8: The rms amplitude of density fluctuation with a comoving radius of 8/h Mpc



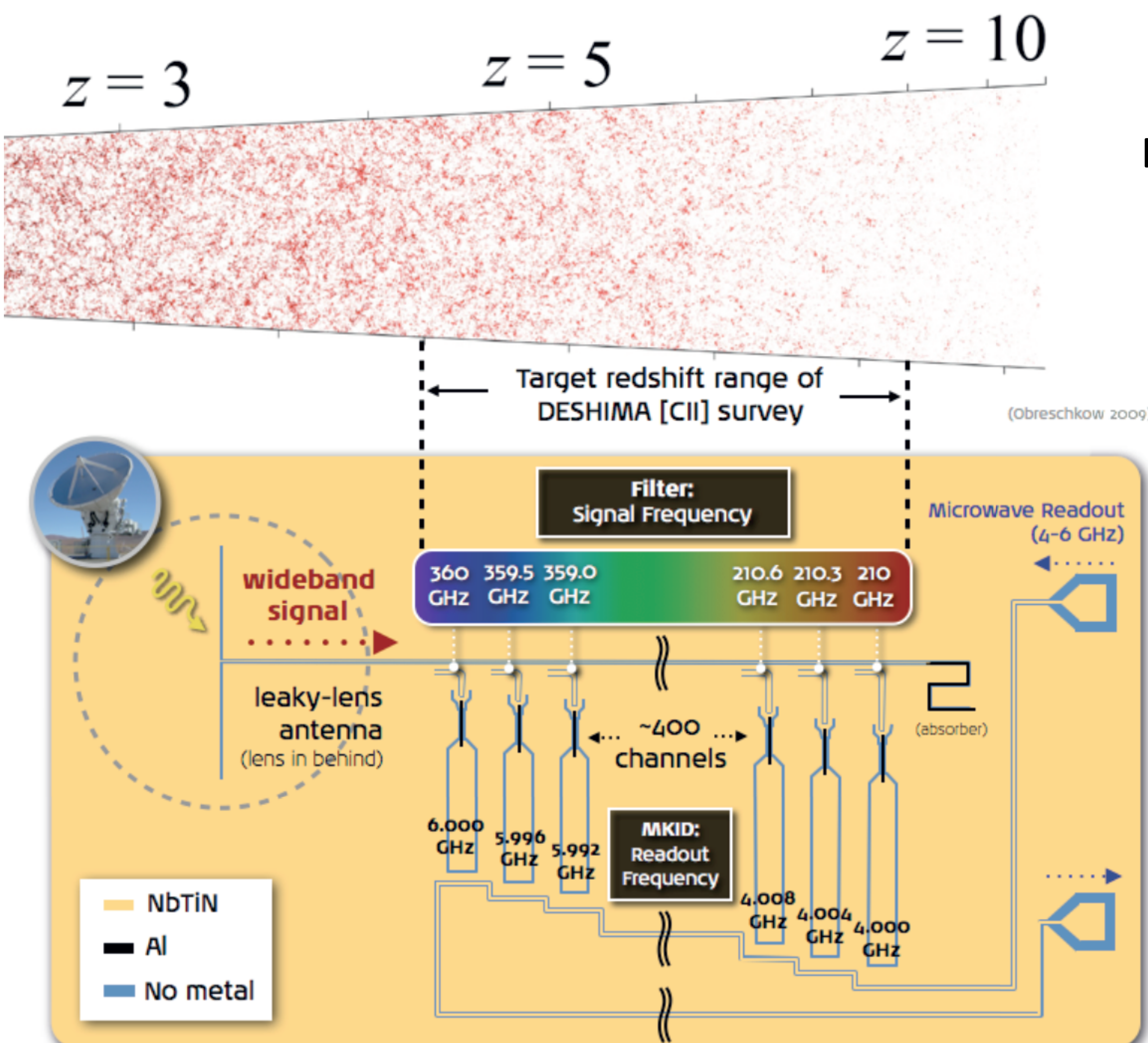
- If we think a hypothetical super-DESHIMA (1,000 spatial pixel), the LST 100 deg^2 survey can be competitive to HETDEX (Lyα-based) ➔ "multi-tracer" can defeat cosmic variance (e.g., Seljak+09) ➔ RSD measurements by using mm/submm line emitters is still unique even z=2-3 and purely new at z>4.4

Such a hypothetical (crazy?) imaging-spectrograph can become available in ~N years (N>5) ?

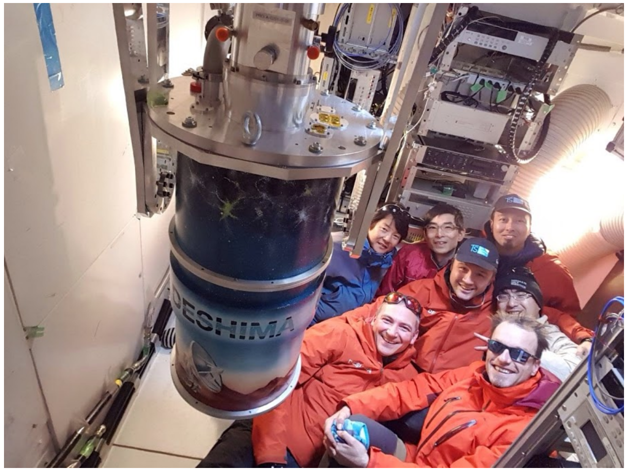
On-chip superconducting spectrograph DESHIMA (does exist)

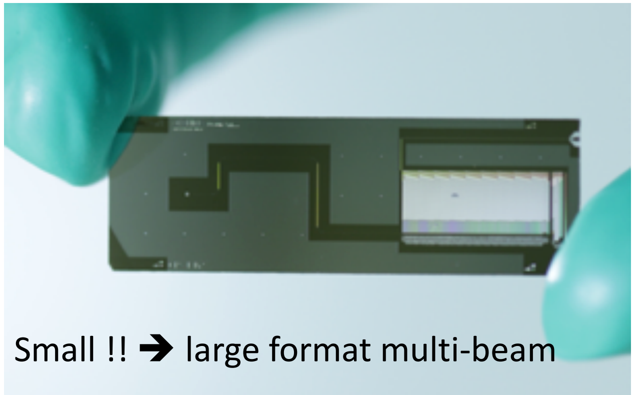
See also Noroozian's talk

Endo et al. 2012, JLTP, 167, 341



DESHIMA on ASTE 10m in Atacama

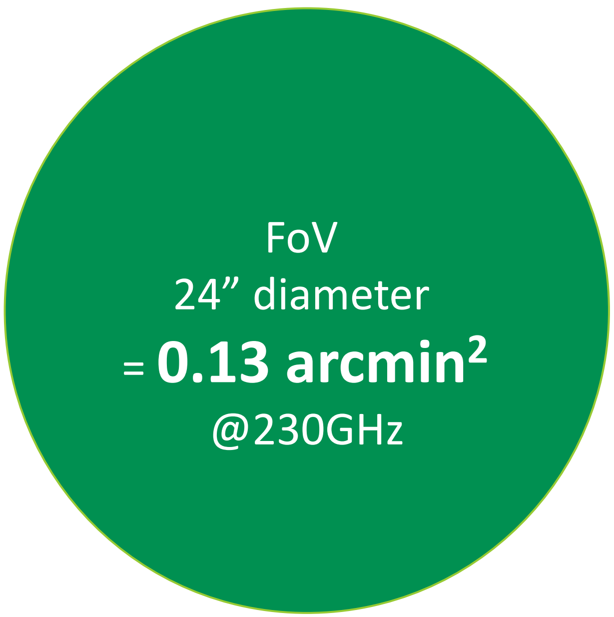




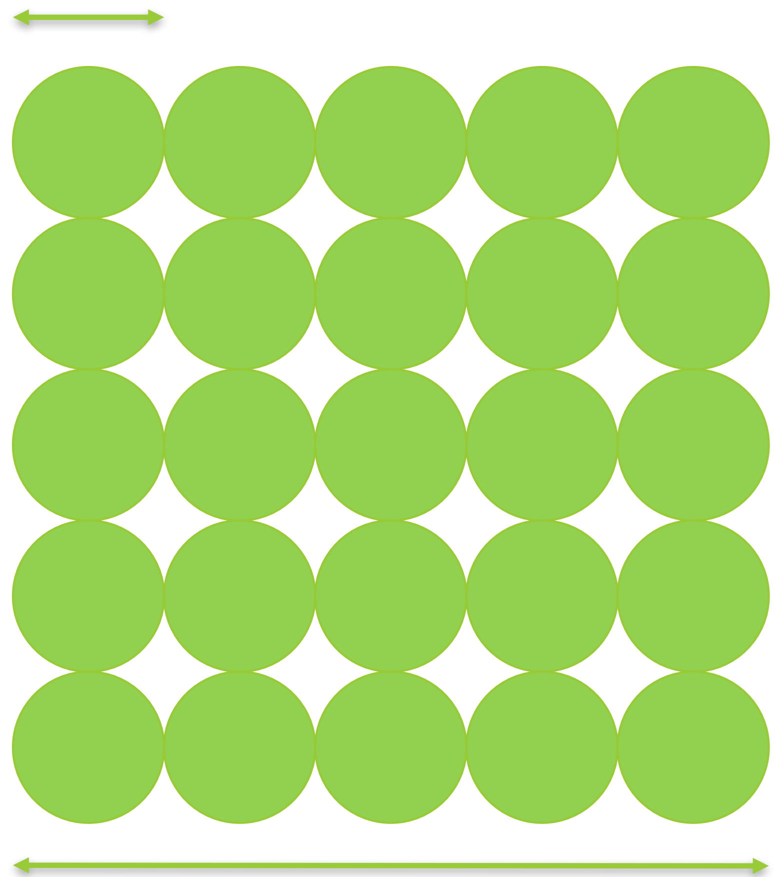
Small !! ➔ large format multi-beam

An imaging spectrograph on LMT versus ALMA

ALMA Band-6



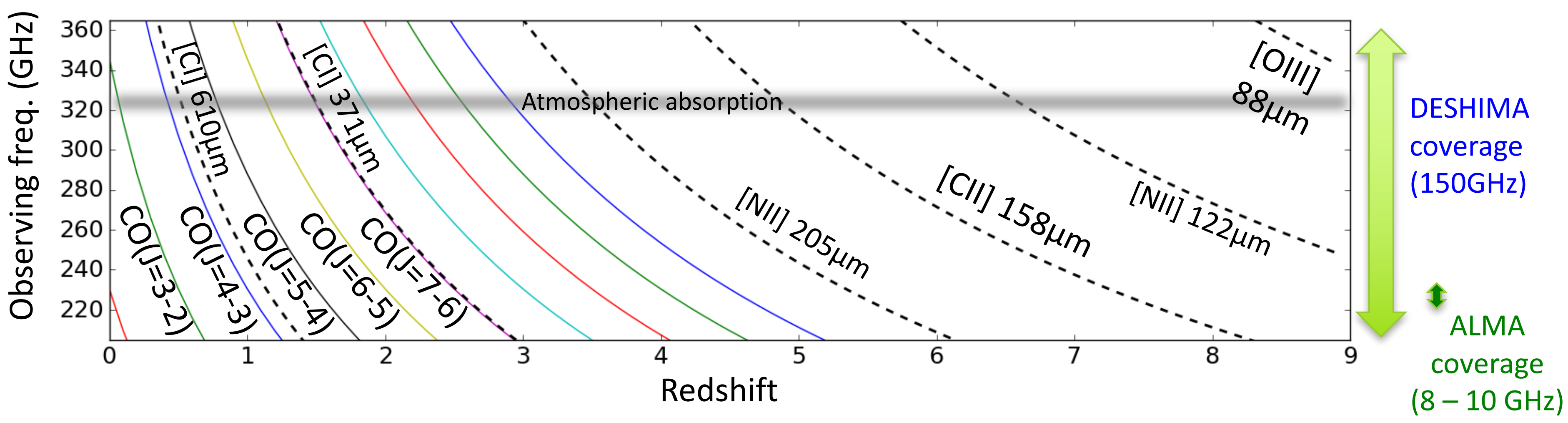
LMT beam @230GHz ➔ 6” (HPBW)



30” x 30” ➔ **0.25 arcmin^2** @230GHz

An imaging spectrograph on LMT versus ALMA

- It covers from 210GHz to 360GHz (df = 150GHz ; >15 times wider than ALMA) with a moderate resolution (R=f/df～500)
- 25 spatial pixels, covering ~0.25 arcmin^2 (~2 times wider FoV than ALMA)
- ➔ It results in (collecting area) 0.4 x (FoV) 2 x (bandwidth) 15 = 12 times more efficient than ALMA (equivalent to D = 70 m) when it resides on LMT 50m

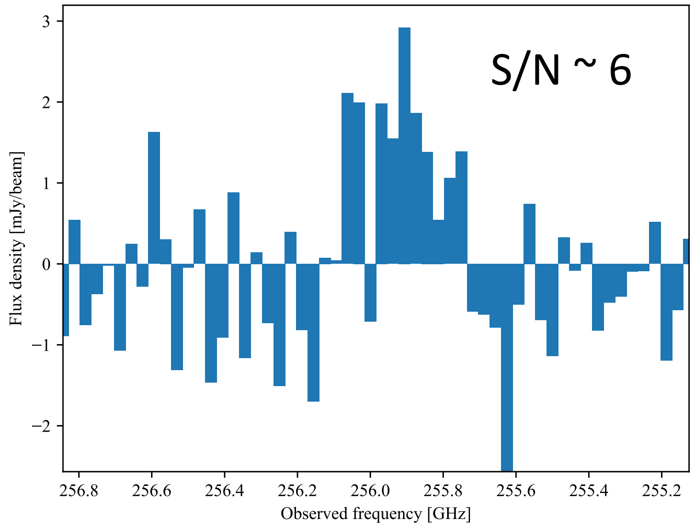


Conclusions

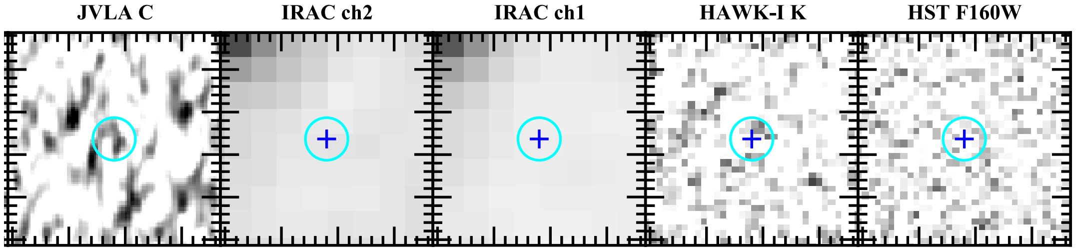
- Question: can we build a SDSS-like data set at mm/submm band, with 10^6 CO emitters and > 10,000 [CII] emitters?
- An answer: a 100 deg^2 survey (5,000 hrs) using a hypothetical 50m (LST 50m) equipped with a hypothetical imaging spectrograph (super-DESHIMA), covering 70 – 370 GHz in one shot having 1,000 spatial pixels within ~100 $arcmin^2$ FoV)
  - Assume ~600 channels (R = 600@300GHz) x 1,000 pix = 600,000 detectors (readout looks OK already; data rate and processing is ?)
- It yields ~10^6 CO emitters and ~50,000 [CII] emitters (z>4.4)
- Put unique constraints on the bright-end of CO and [CII] luminosity functions, which is inaccessible with ALMA
  - Synergies with MIR missions like SPICA, OST, etc. → Spinoglio's talk
- Put unique constraints (~5%) on the growth rate of the universe (RSD) at z = 2-3 *even after Euclid* and a purely new constraint (~20%) on RSD at z = 4 – 6 and beyond
- Perhaps extremely wide FoV is not essential for this case (practically limited by the number of detectors) .. ?

Unbiased surveys vs pre-selected spectroscopy?

- Do we really need unbiased surveys, rather than a targeted spectroscopy of pre-selected galaxies?
- ➔ On-going deep unbiased surveys using ALMA will tell us if a significant discovery space remains (such as new mm/submm emitters which are invisible in deepest optical/near-infrared surveys)
- May also depend on the progress of configurable multi-object spectrograph, in mm/submm, though



ALMA 45-hr deep survey of GOODS-S
(ASAGAO; PI. = K. Kohno)
ALMA Band-6, 2 tunings, 26 arcmin^2,
Continuum sensitivity down to 1σ = 60 μJy



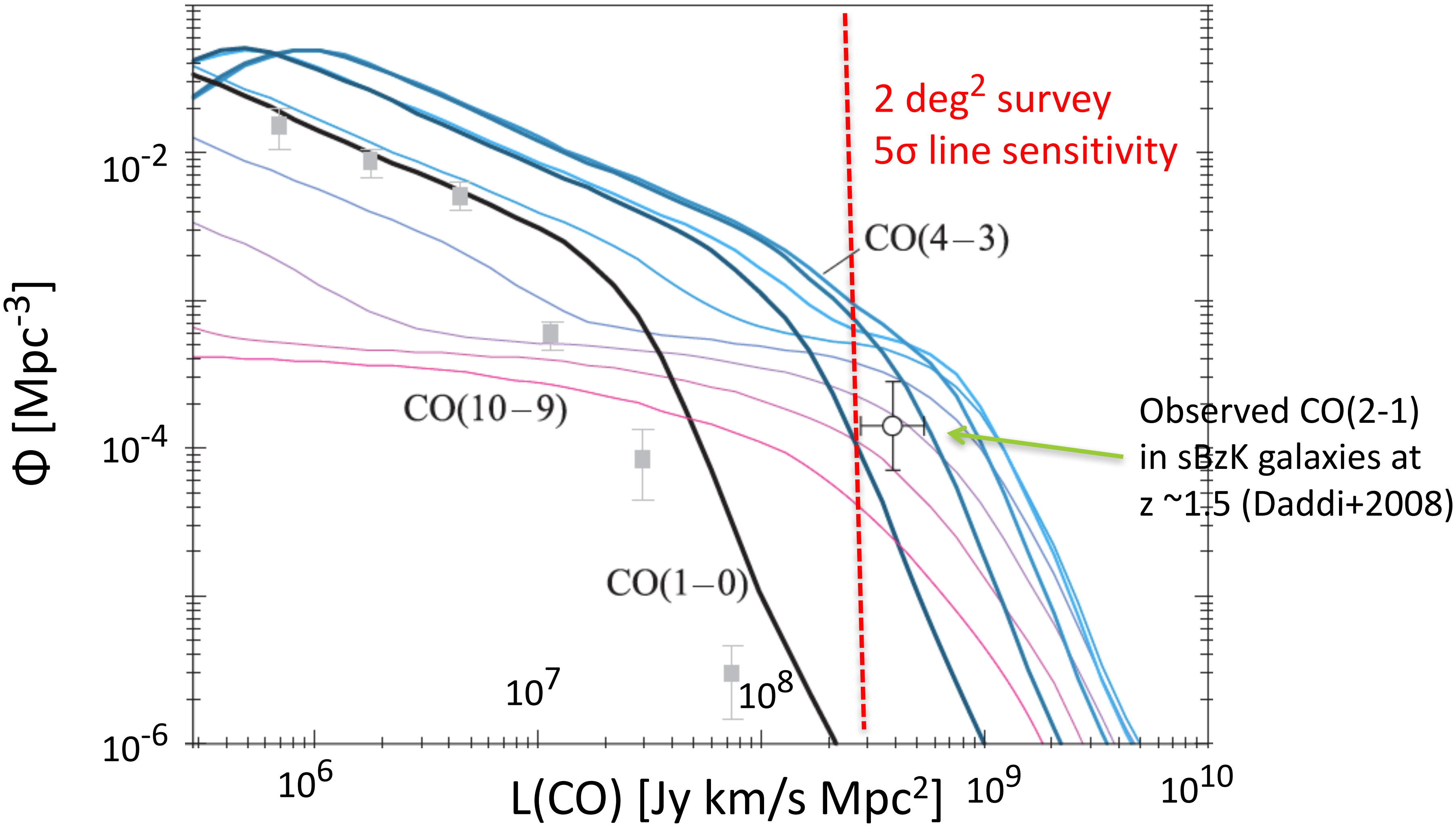
Yamaguchi, Y., Hayatsu, N., Ivison, R., et al., in prep.

Back-up slides

Predicted CO luminosity functions: a case for z = 2

Obreschkow et al. 2009, ApJ, 702, 1321

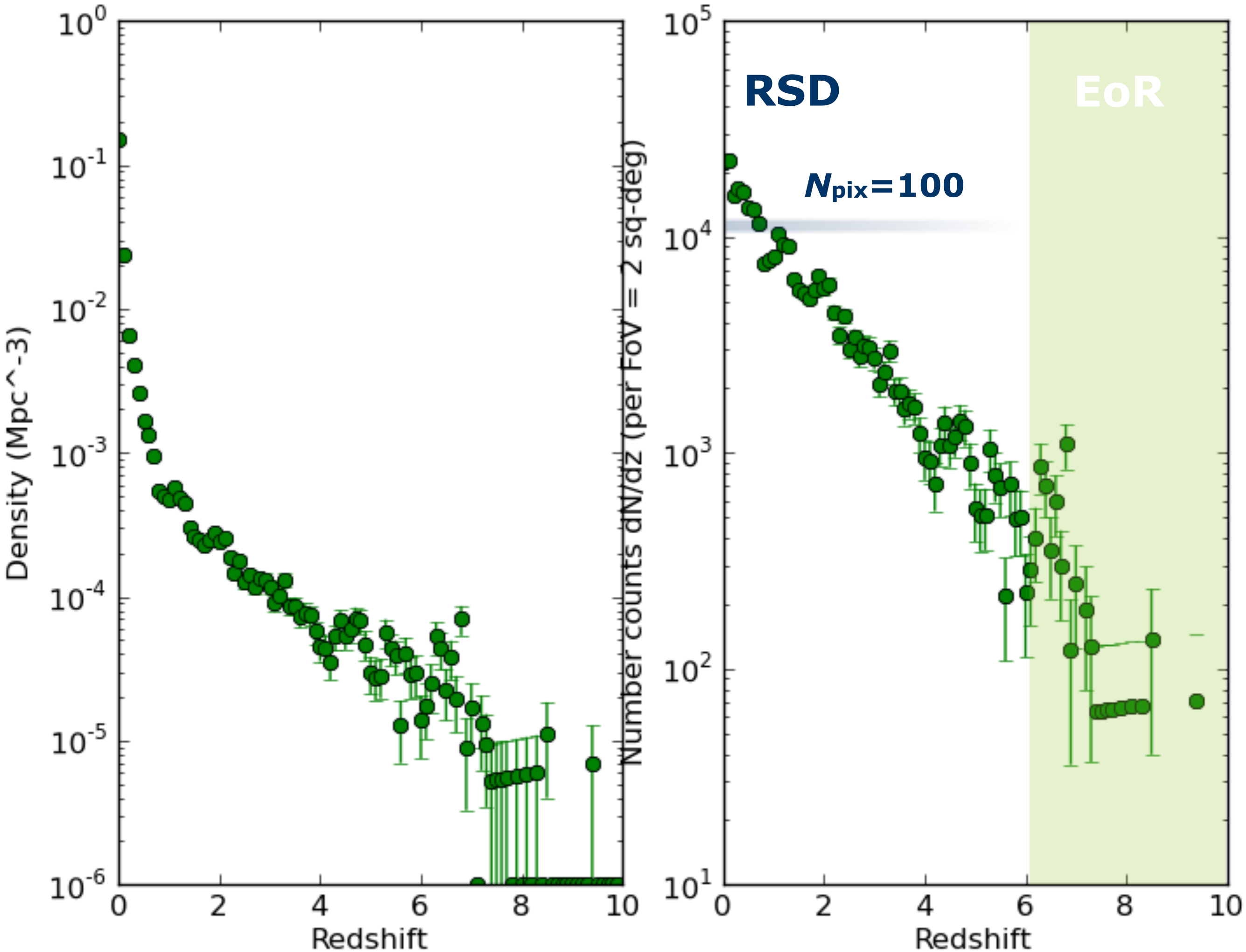
http://s-cubed.physics.ox.ac.uk/s3_sax



Number counts (Super-DESHIMA/LST 50m)

Tamura, Y., + in prep.

Kawabe+ 2016, SPIE



Assumptions for this feasibility study

✏ Fiducial cosmology

- $\Omega_{m,0} = 0.25$, $h = 0.73$, $\sigma_8 = 0.84$
- $k_{max} = 0.2\, h\mathrm{Mpc}^{-1}$
- $b(z) = \sqrt{1+z}$ (~ normal SFG's bias)

✏ Alcock-Paczynski effect → neglect

- Incorrect assumption for $D_A(z)$ and $H(z)$ causes distortion
- Note that this effect can make constraint ~ facter looser

✏ Run HALOFIT code (Smith+03) for DM power spectorum

Slides by Yuki Yoshimura

Opt/NIR cosmological galaxy surveys

https://indico.cern.ch/event/617679/contributions/2567910/attachments/1478584/2292986/sanchez.pdf

Project	Dates	Area/deg2	Data	Redshift	Methods
BOSS	2008-2014	10000	Opt-S	0.3-0.7 (gal) 2-3.5 (Lyα Forest)	BAO/RSD
DES	2013-2018	5000	Opt-I	0.2-1.5	WL/CL/BAO/SN
eBOSS	2014-2020	7500	Opt-S	0.6-2.0 (gal/QSO) 2-3.5 (Lyα Forest)	BAO/RSD
SuMIRE	2014-2024	1500	Opt-I Opt-NIR-S	0.2-1.5 0.8-2.4 (gals)	WL/CL/ BAO/RSD
HETDEX	2014-2019	300	Opt-S	1.9-3.5 (gals)	BAO/RSD
DESI	2019-2024	14000	Opt-S	0-2 (gals) 2-3.5 (QSO/Lyα Forest)	BAO/RSD
LSST	2020-2030	20000	Opt-I	0.2-2	WL/CL/BAO/SN
Euclid	2020-2026	15000	Opt-I NIR-S	0.2-2 0.7-2.2 (gals)	WL/CL/BAO/RSD
WFIRST	2024-2030	2200	NIR-I NIR-S	1.0-3.0 (gals)	WL/CL/SN/BAO/RSD

From PDG 2016