Log-Normal Simulation of Intensity Mapping: Lyman α in HETDEX

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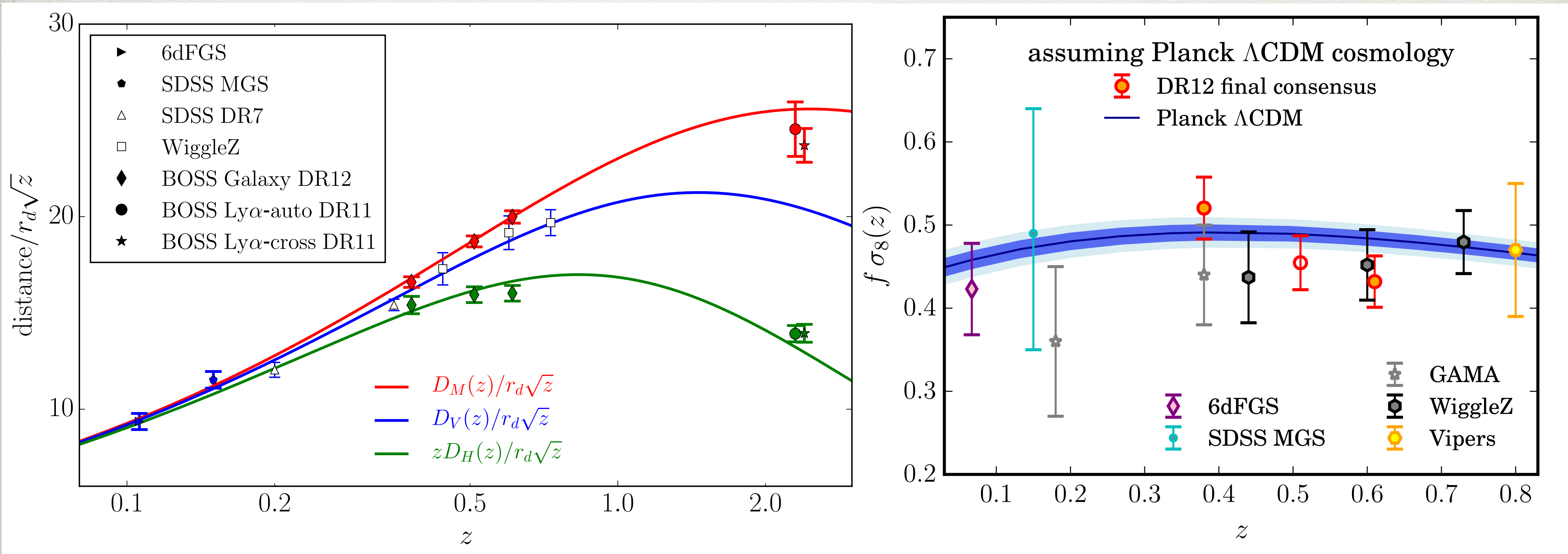
collaborating with
E. Komatsu, R. Makiya*, I. Kayo*, K. Takahashi
A. Agrawal & HETDEX collaboration

Why does the Universe accelerate? @ KEK
Friday, 15th Mar 2017

<u>*D01加速王者</u>

BOSS DR12 BAO & RSD results

Alam,**SS**+ (2016)



✔ Galaxy redshift surveys are ***DONE at low z***.

✔ Future surveys go ***towards higher z***,
to map out expansion & growth history in detail.

What will future surveys observe?

- Future surveys weigh ***high redshift***
  → galaxies with ***strong emission line***

$$1 + z = \frac{\lambda_0}{\lambda_{\rm line}}$$

Fonseca+(2016)

Emission line	Wavelength range	Redshift range	Spectral class	Galaxy Survey
Lyα	122-679 nm	0.0-4.58	UV/Optical	**HETDEX**
OII	679-1131 nm	0.82-2.03	Optical/NIF	PFS
Hα	1.25-3.94 μm	0.9-5	NIF	EUCLID, WFIRST
CII	249-948 μm	0.57-5	FIR	
CO(3-2)	1.24-4.06 mm	0.43-3.69	Radio(Millimetre)	
CO(2-1)	4.06-7.8 mm	2.12-5	Radio(Millimetre)	
CO(1-0)	8.48-15.6 mm	2.60-5	Radio(Millimetre)	
21cm in HI			**Radio**	**SKA**

- There shall be ***another probe of the 3D Galaxy Clustering*** in such emission line surveys.

3D Galaxy Clustering

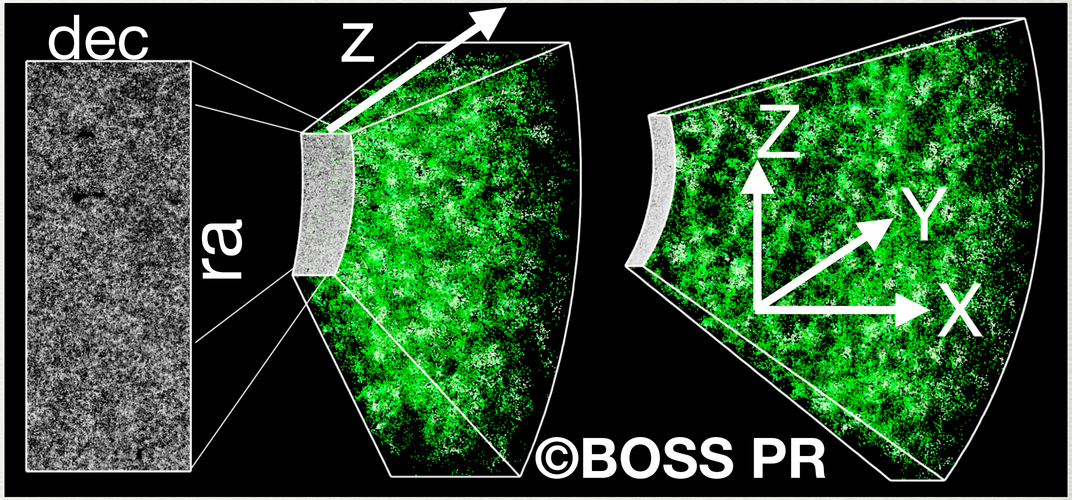
- If the emission line is ***significantly*** detected (e.g., S/N > 5)

3-dimensional galaxy map

(ra, dec, **z(↔λ_{obs})**)

→ distance-redshift relation

→ **x** = (X, Y, Z)



- fluctuation in **number count**

$$\delta_{\rm g}(\mathbf{x}) = \frac{n_{\rm g}(\mathbf{x}) - \bar{n}_{\rm g}}{\bar{n}_{\rm g}}$$

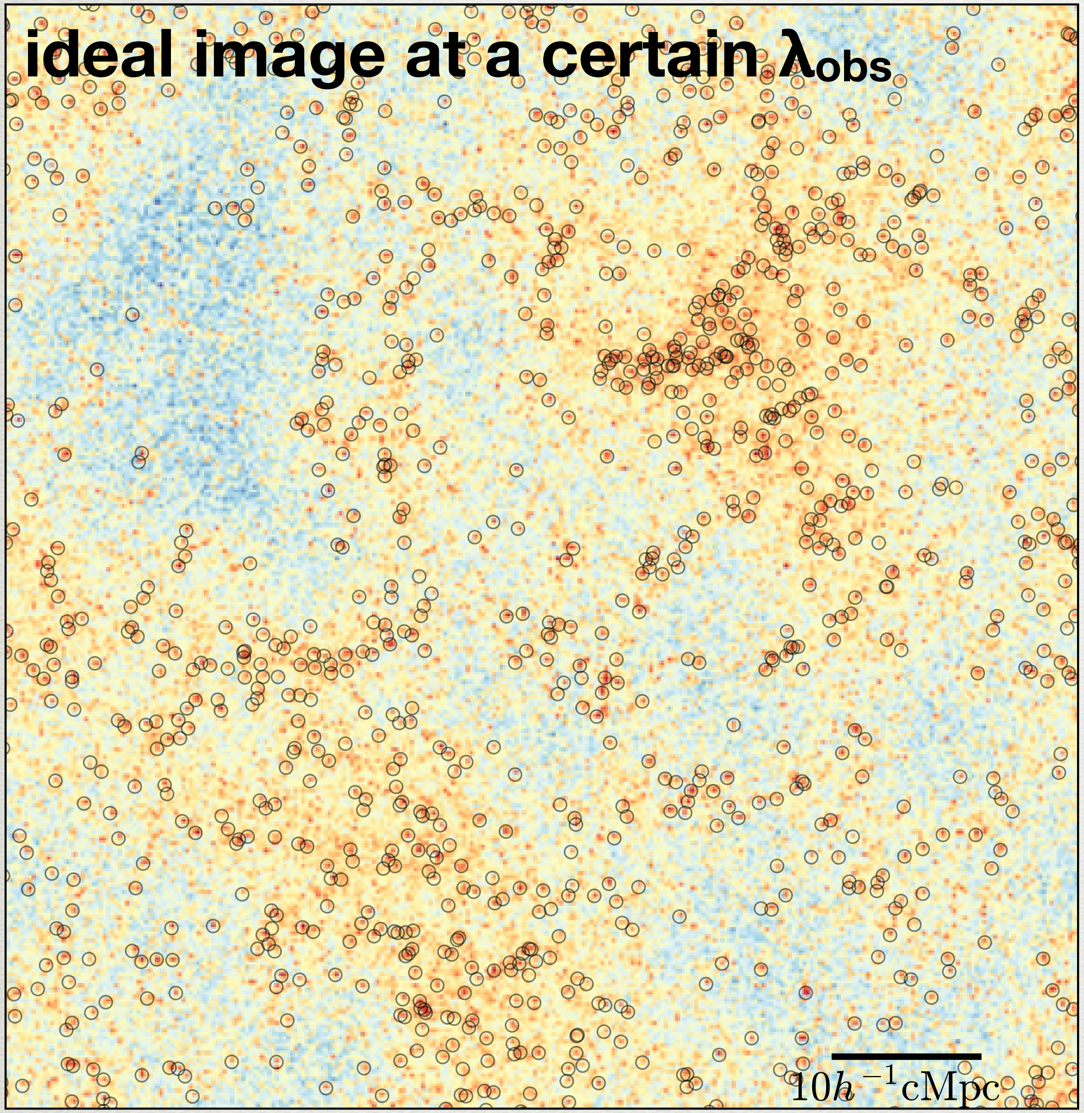
- **Two-point statistics → e.g., BAO & RSD → Dark Energy etc.**

Power Spectrum in Fourier Space

$$\langle \delta_{\rm g}(\mathbf{k}) \delta_{\rm g}(\mathbf{k}') \rangle = (2\pi)^3 \delta_D(\mathbf{k} + \mathbf{k}') P_{\rm g}(\mathbf{k})$$

Intensity Mapping as another probe

- Galaxy clustering ***only*** with number count with high S/N? → **No!**



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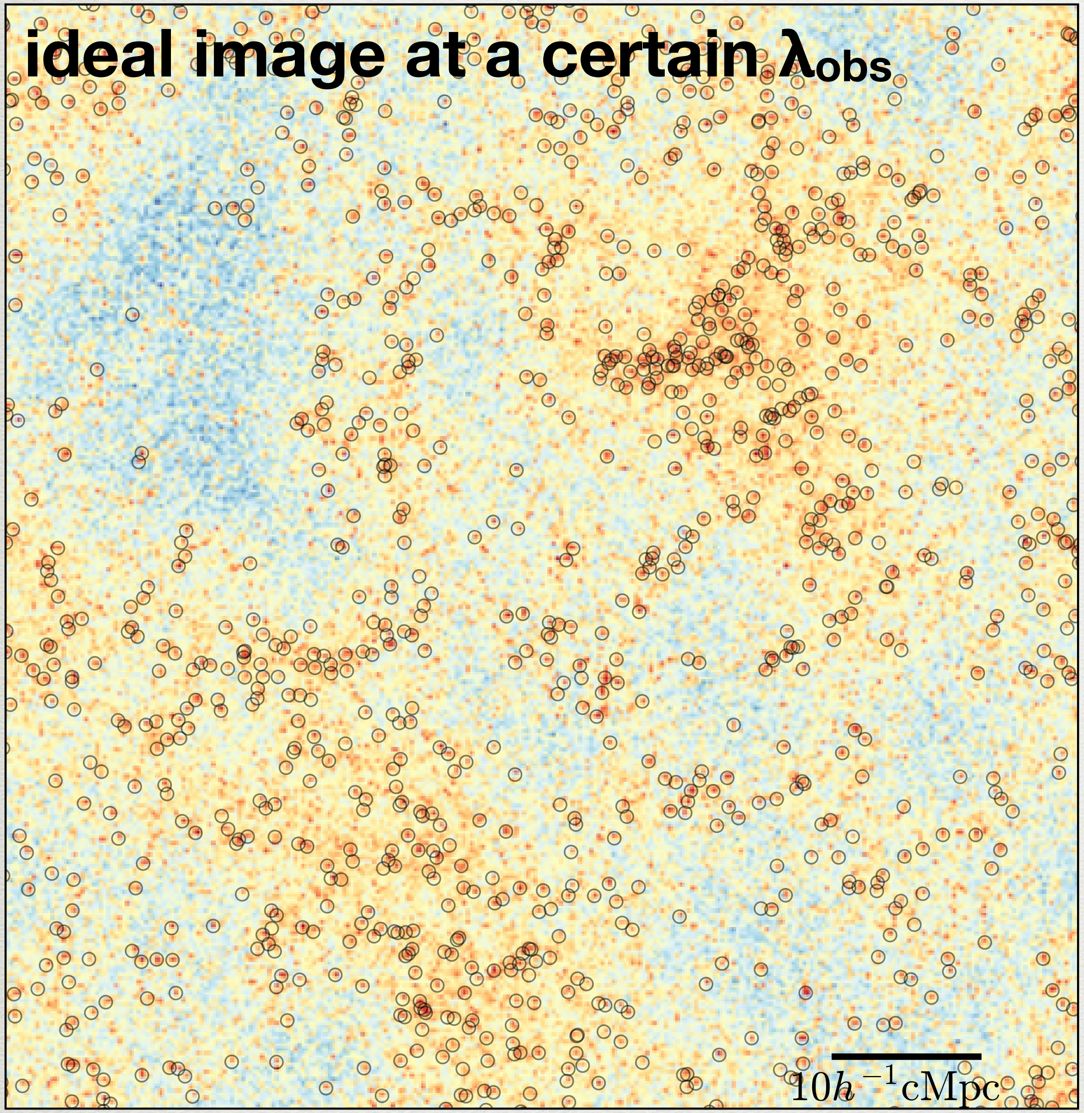

any pixels include signal

= *"Intensity Map"*

Pros

- can be cheap
- additional information

Cons

- noisy by definition
- severer systematics

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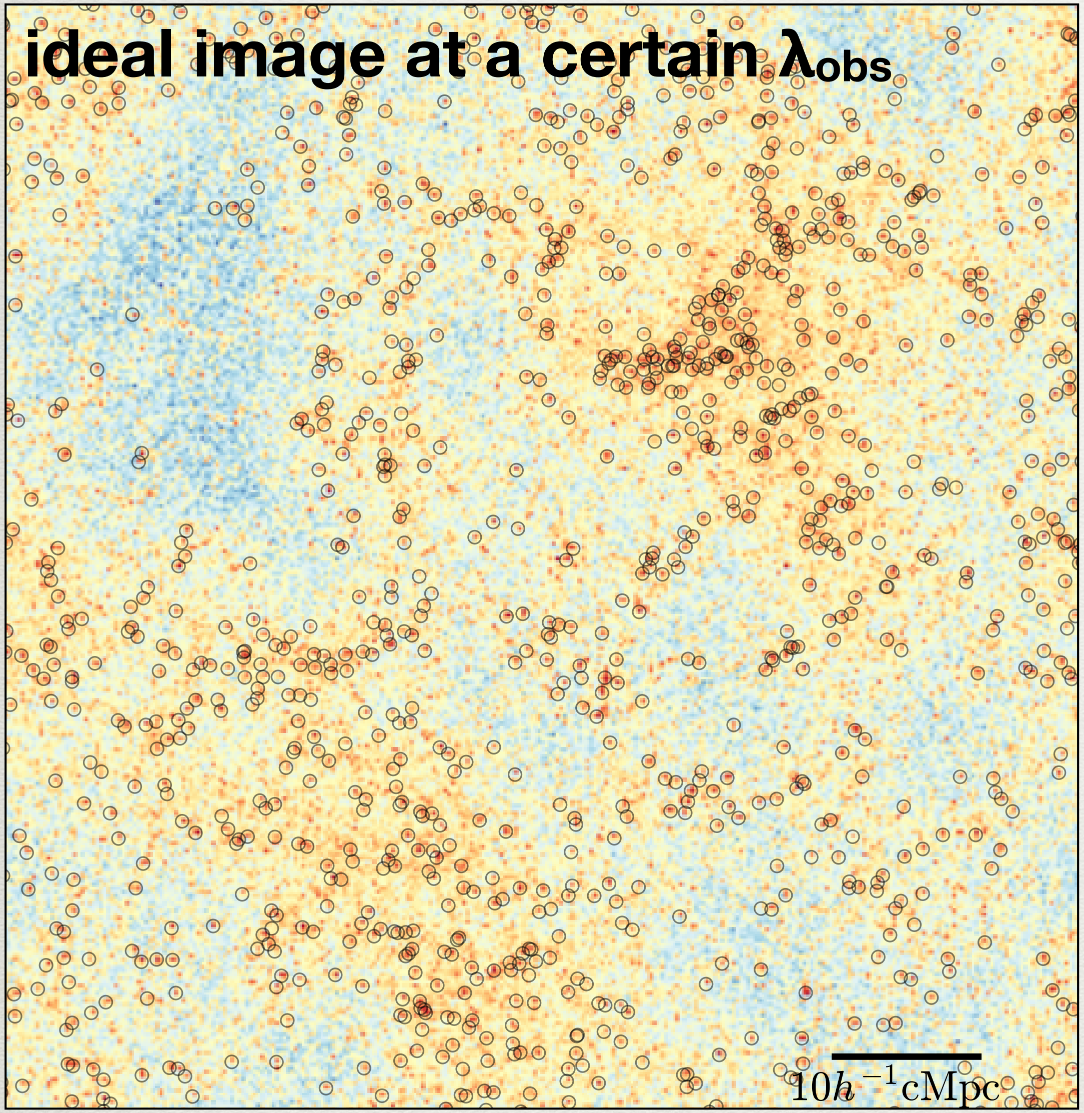

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= *"Intensity Map"*

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Cross Correlation should help!!

Already detected for 21cm

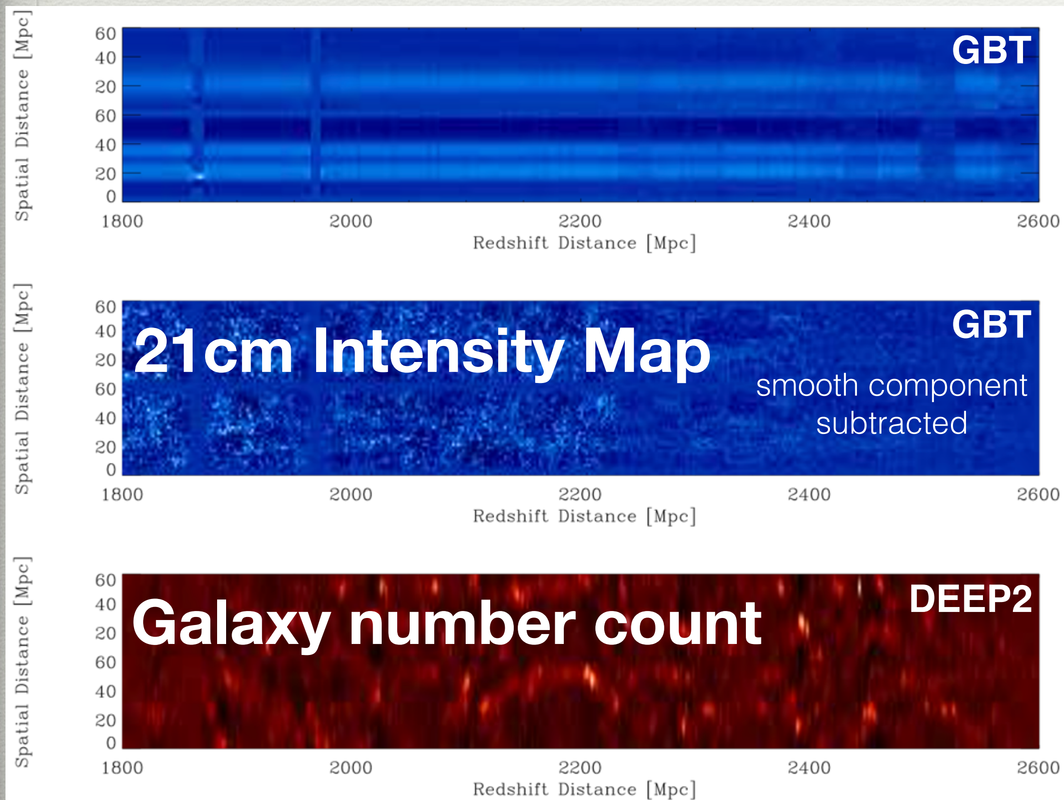
Chang et al. (2010)

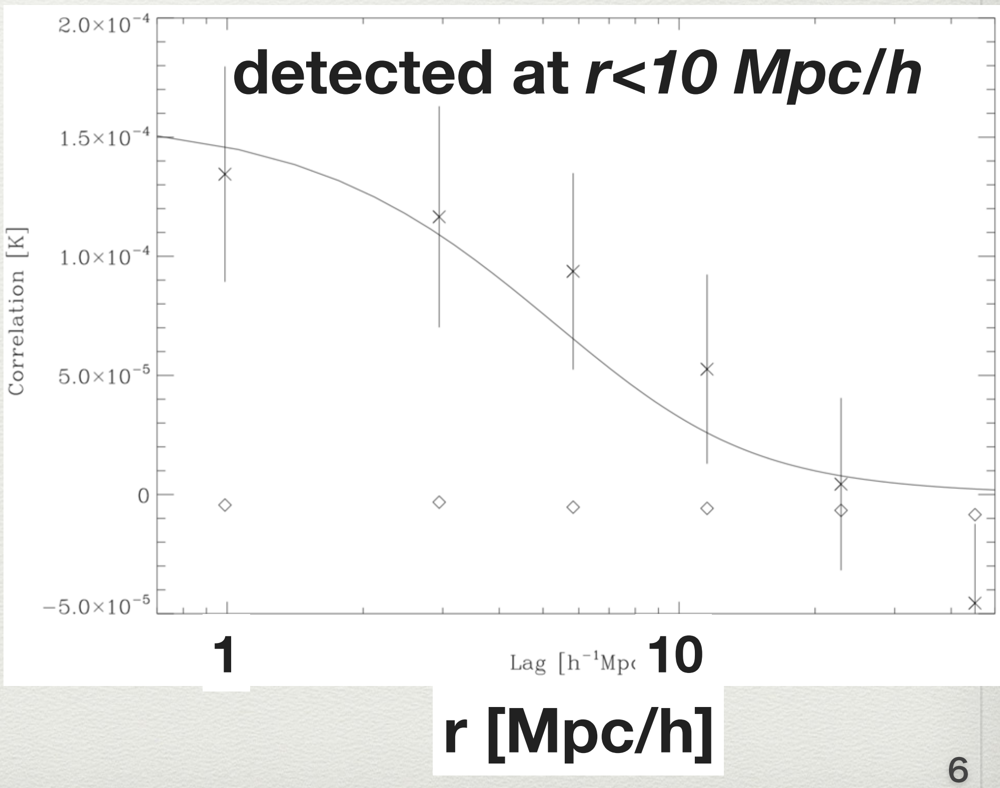
nature International weekly journal of science

An intensity map of hydrogen 21-cm emission at redshift $z \approx 0.8$

Tzu-Ching Chang, Ue-Li Pen, Kevin Bandura & Jeffrey B. Peterson

Nature **466**, 463–465 (22 July 2010) | doi:10.1038/nature09187

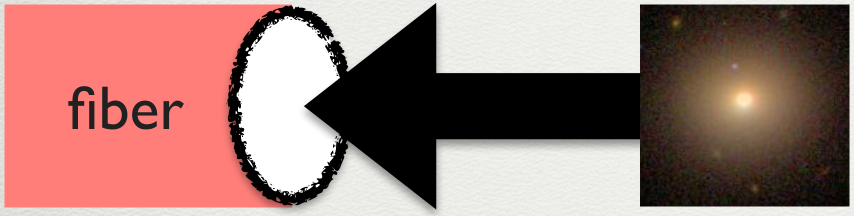




Detection of Lyα IM in Croft+(2016)

- Lyα Intensity Mapping from BOSS in Croft+, MNRAS (2016)

~1M galaxies at $0.15 < z < 0.70$



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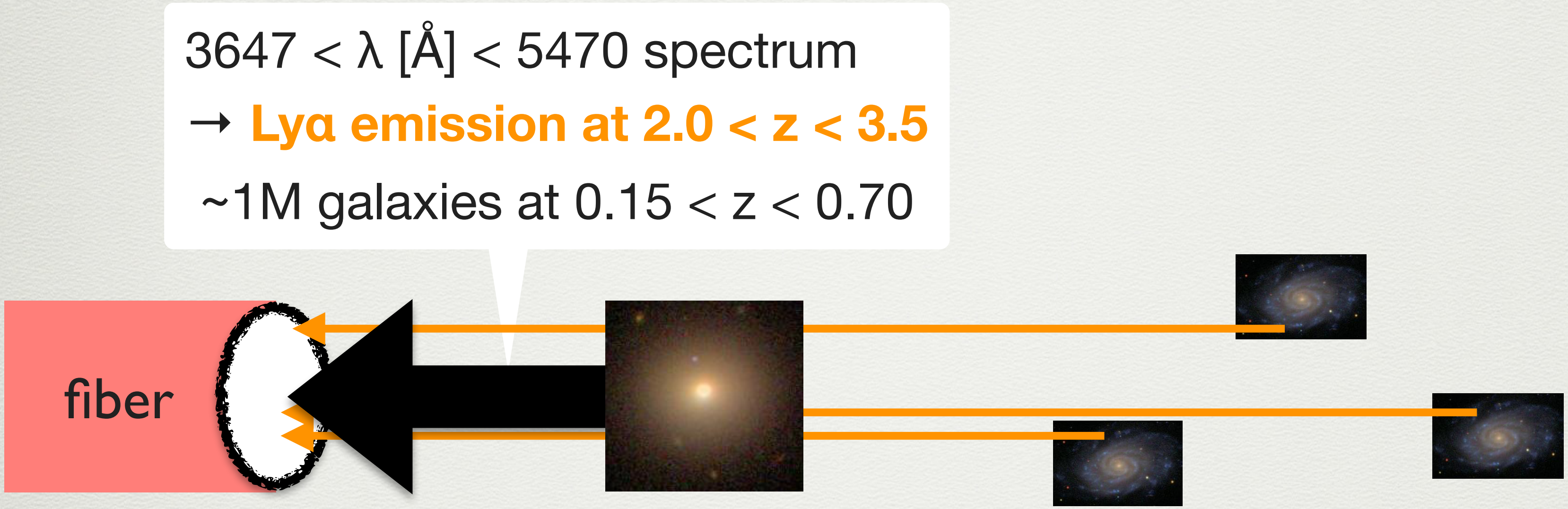

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3647 < λ [Å] < 5470 spectrum

→ **Lyα emission at 2.0 < z < 3.5**

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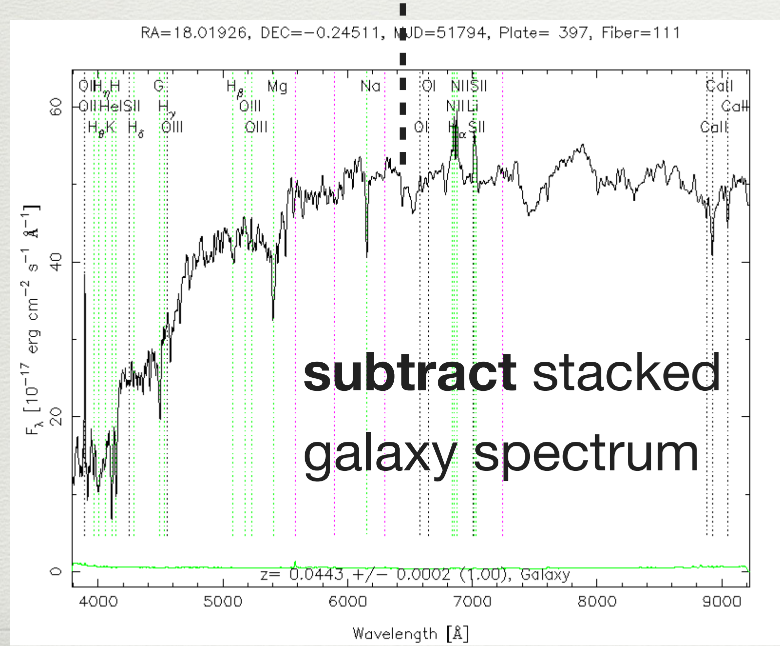

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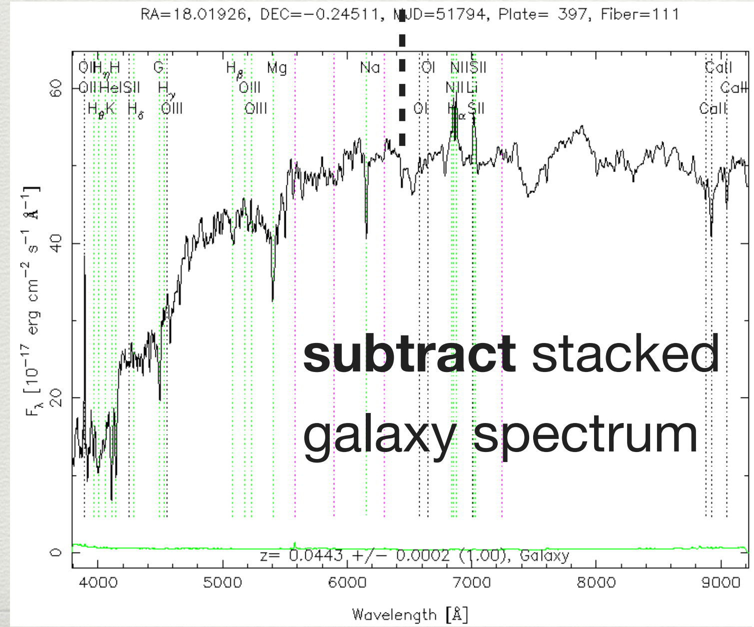

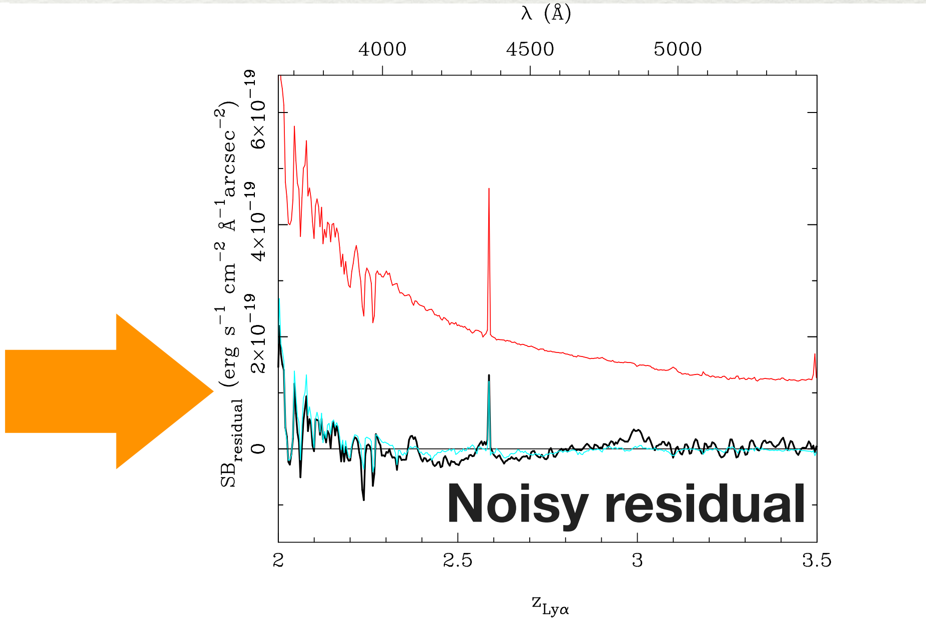

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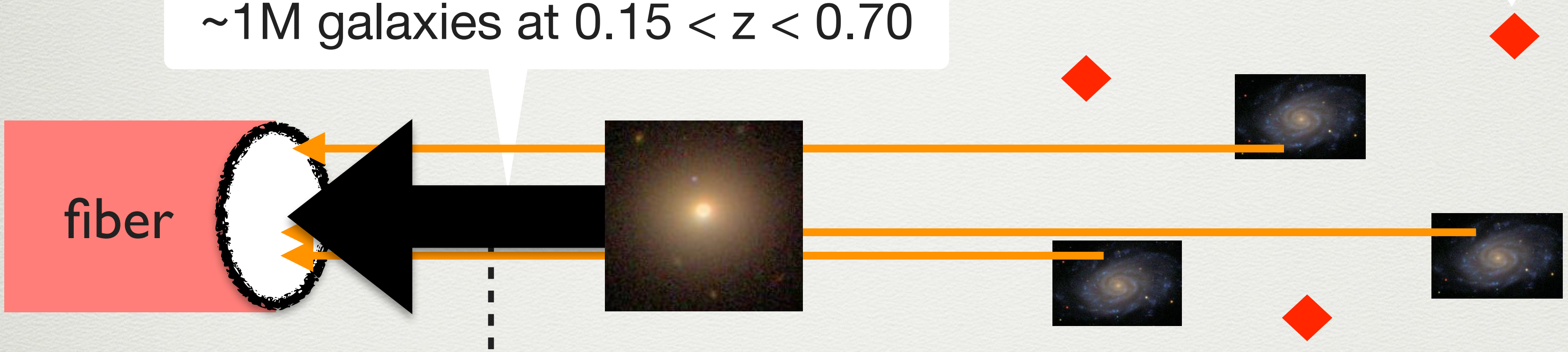
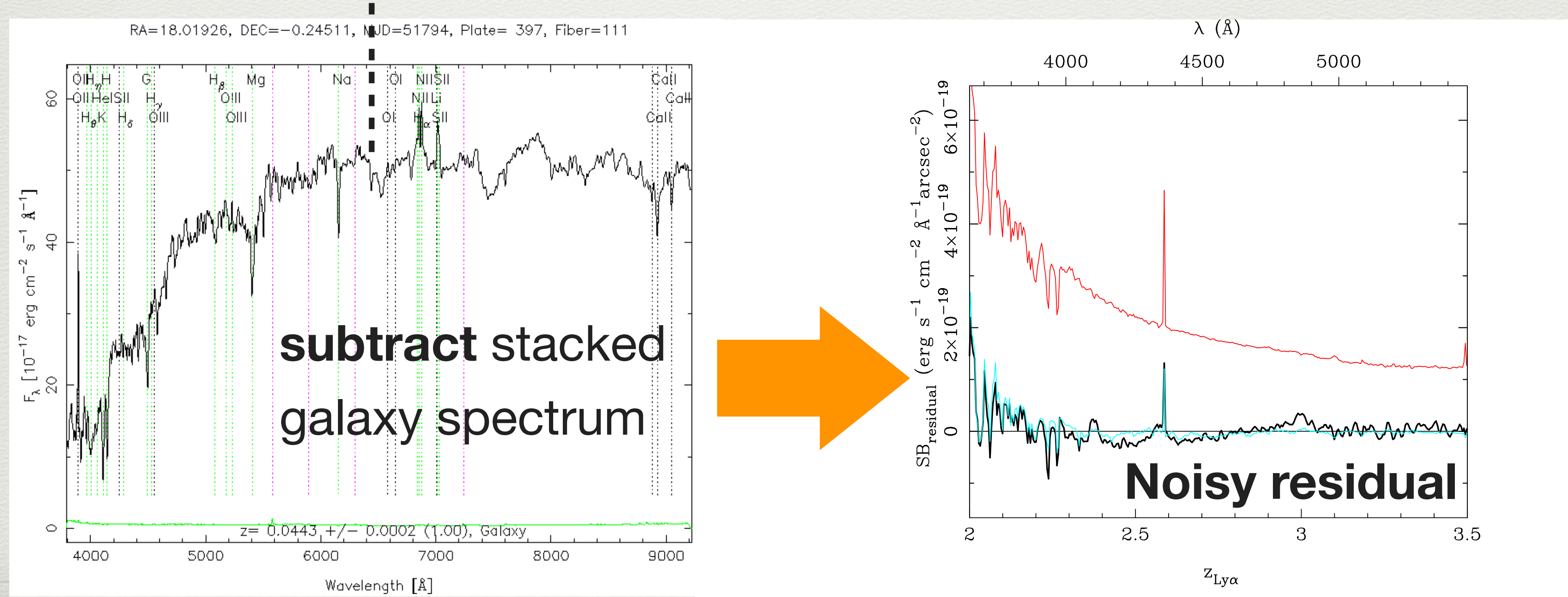
~100,000 QSOs over ~10,000deg^2
at 2.0 < z < 3.5





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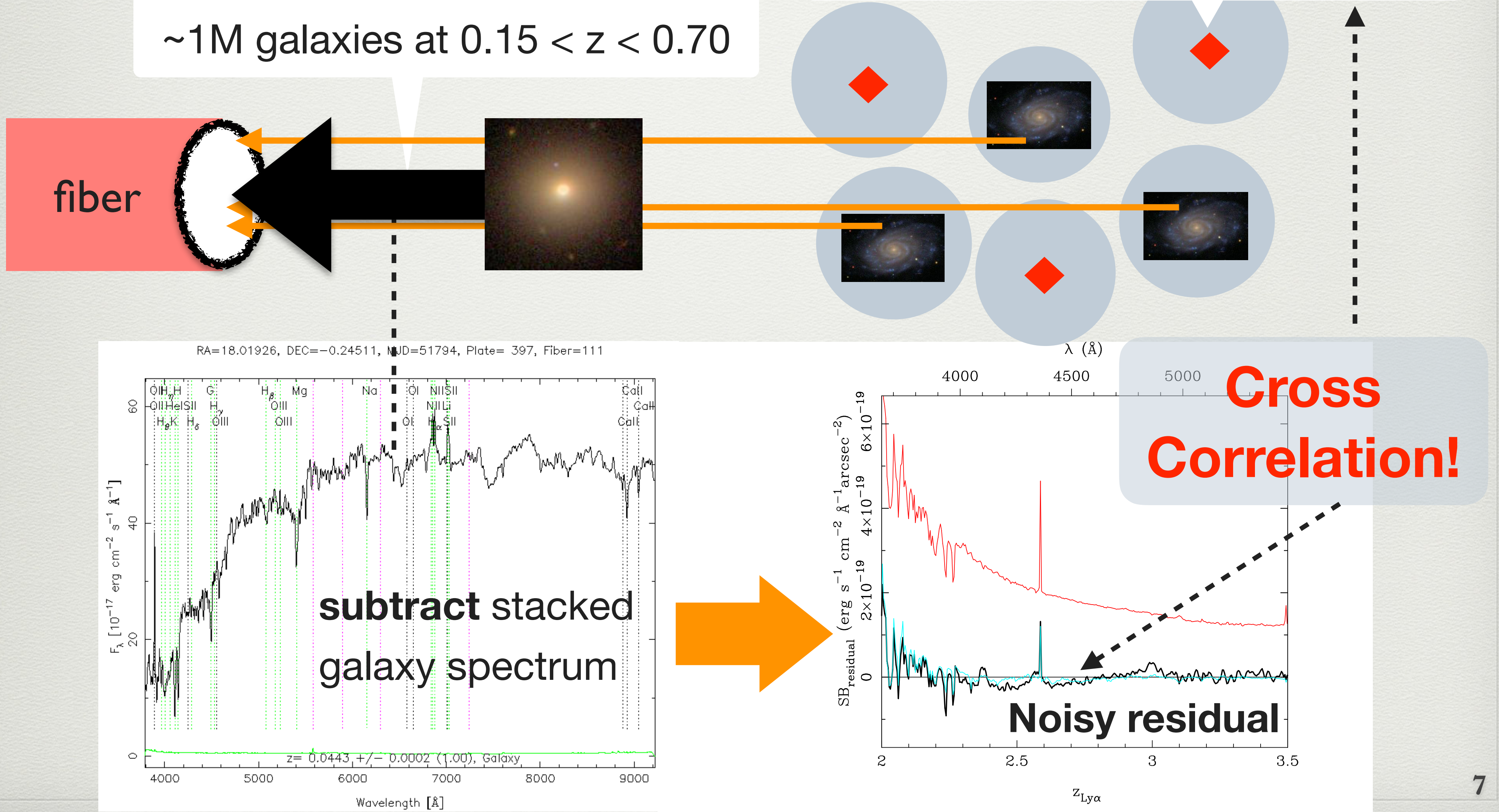

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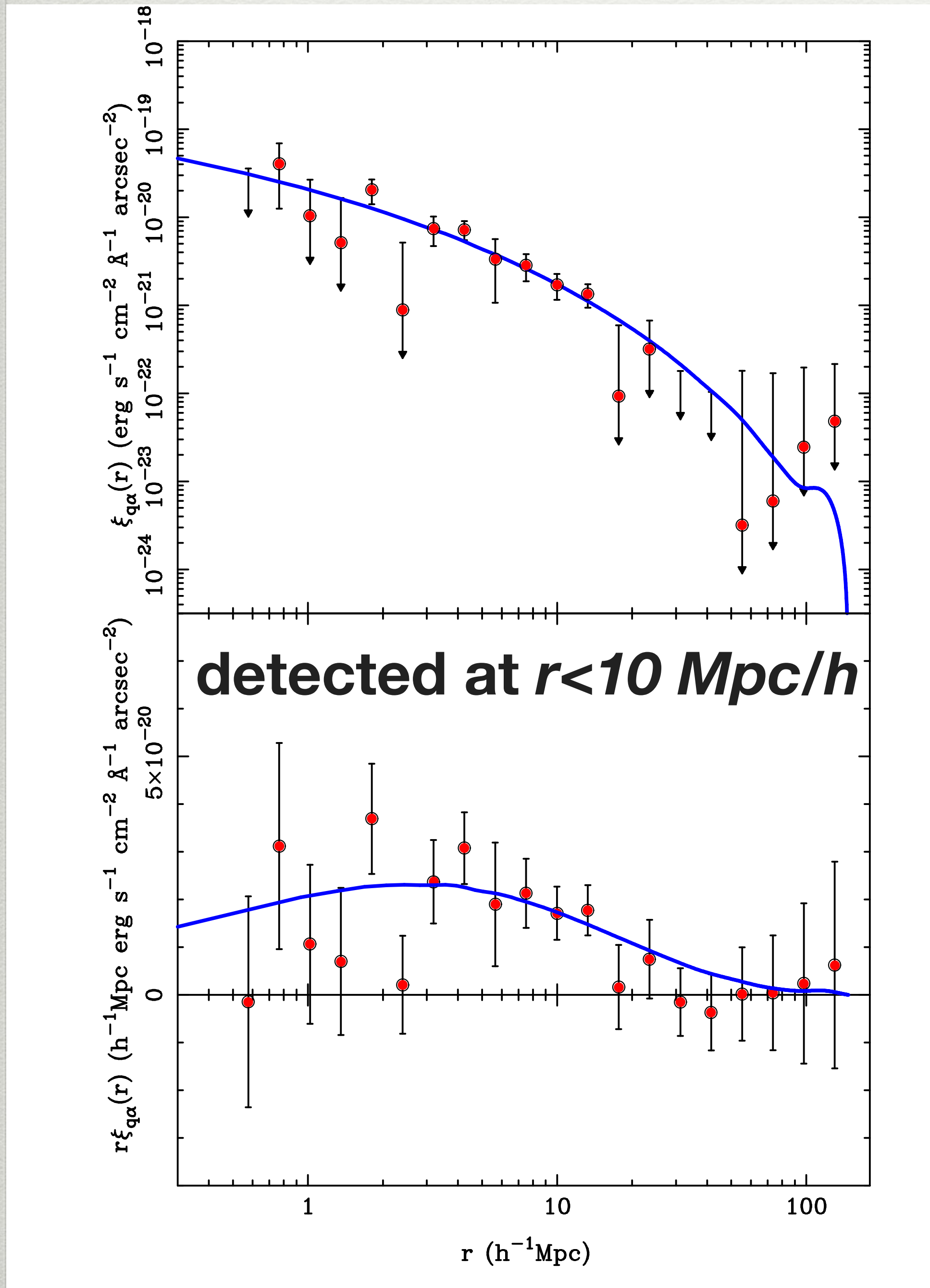
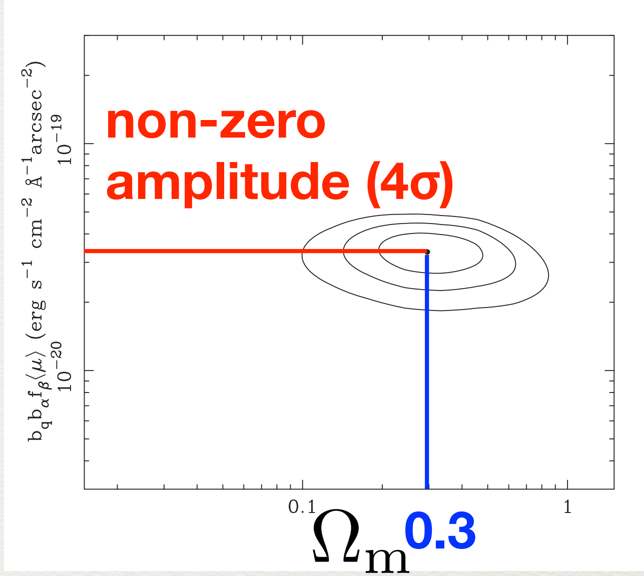
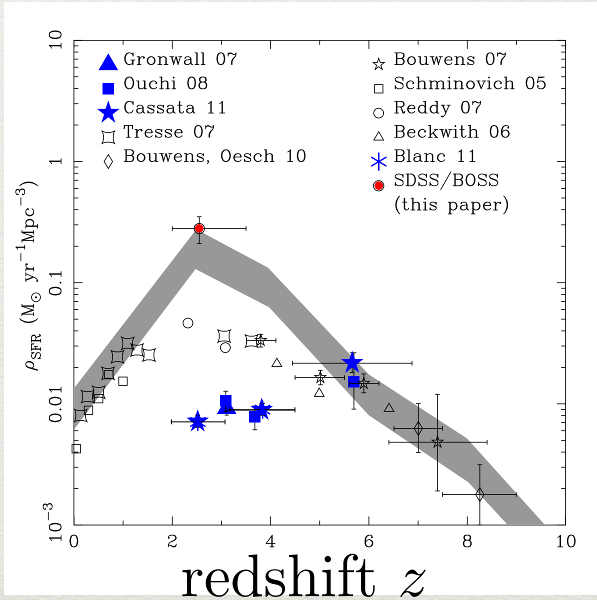


- its shape consistent with LCDM.



- amplitude **x30 higher** than expected



What is measured in IM?

- Intensity or flux is related to **luminosity density**

$$\lambda_{\rm obs} = \lambda_{\rm Ly\alpha}(1+z), \quad \lambda_{\rm Ly\alpha} = 1216\,\text{Å}$$

$$F(\vec{\theta}, \lambda_{\rm obs}) = \int dL \, \frac{dn}{dL} \frac{L(\vec{x})}{4\pi D_L^2(z)} V_{\rm vox} = \frac{V_{\rm vox}}{4\pi D_L^2(z)} \rho_L(\vec{x})$$

$$\lambda I_\lambda(\vec{\theta}, \lambda_{\rm obs}) = \frac{c}{4\pi(1+z)H(z)} \rho_{\rm L}(\vec{x}) \quad [\mathrm{erg/s/cm^2/Sr}]$$

- difference is the **luminosity weighting**

$$\delta\rho_L(\vec{x}) = \int dL \frac{dn}{dL} L \, b(L) \delta_m(\vec{x}) = \bar{\rho}_L b_\alpha \delta_m(\vec{x})$$

$$\delta n_g(\vec{x}) = \int dL \frac{dn}{dL} b(L) \delta_m(\vec{x}) = \bar{n}_g b_g \delta_m(\vec{x})$$

- **Cross Correlation**

$$\langle \delta n_g(\vec{x}) \delta\rho_L(\vec{x}+\vec{r}) \rangle \Rightarrow \boxed{\xi_{g\rho_L}(\vec{r}) = \bar{n}_g b_g \bar{\rho}_L b_\alpha \xi_m(\vec{r})}$$

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measurable via

auto $\xi_{gg}(\vec{r})$ $(P_{\rm gg}(\vec{k}))$

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measurable via auto $\xi_{gg}(\vec{r})$ $(P_{\rm gg}(\vec{k}))$

target

The HETDEX Survey

◆ ***The Hobby-Eberly Telescope Dark Energy Experiment (2016-2019)***

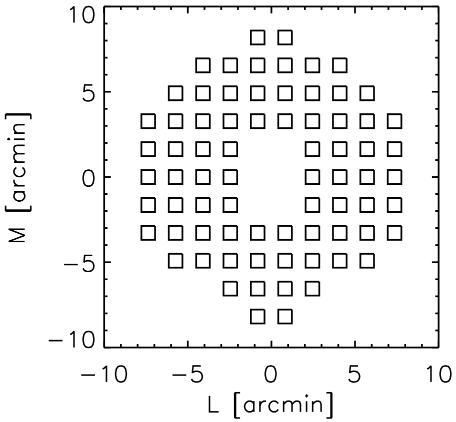
- Collaboration
  - PI: Gary J. Hill (Univ. of Texas)
  - **~50** people: U Texas, McDonald Obs, Penn State, Texas A&M
    LMU, AIP, MPE/MPA, Gottingen, Oxford
- Instrument
  - **10m** Hobby-Eberly Telescope at McDonald Observatory
  - **33k** spectra **(448 fibers/IFU x 75 units)** at one 20mins exposure
  - λ=350–550nm, R~700, a flux sensitivity~a few x 10^{-17} erg/cm^2/s

➡ **~0.8M** Lyman Alpha Emitters (LAEs) over **400deg^2** & **1.9 < z < 3.5**

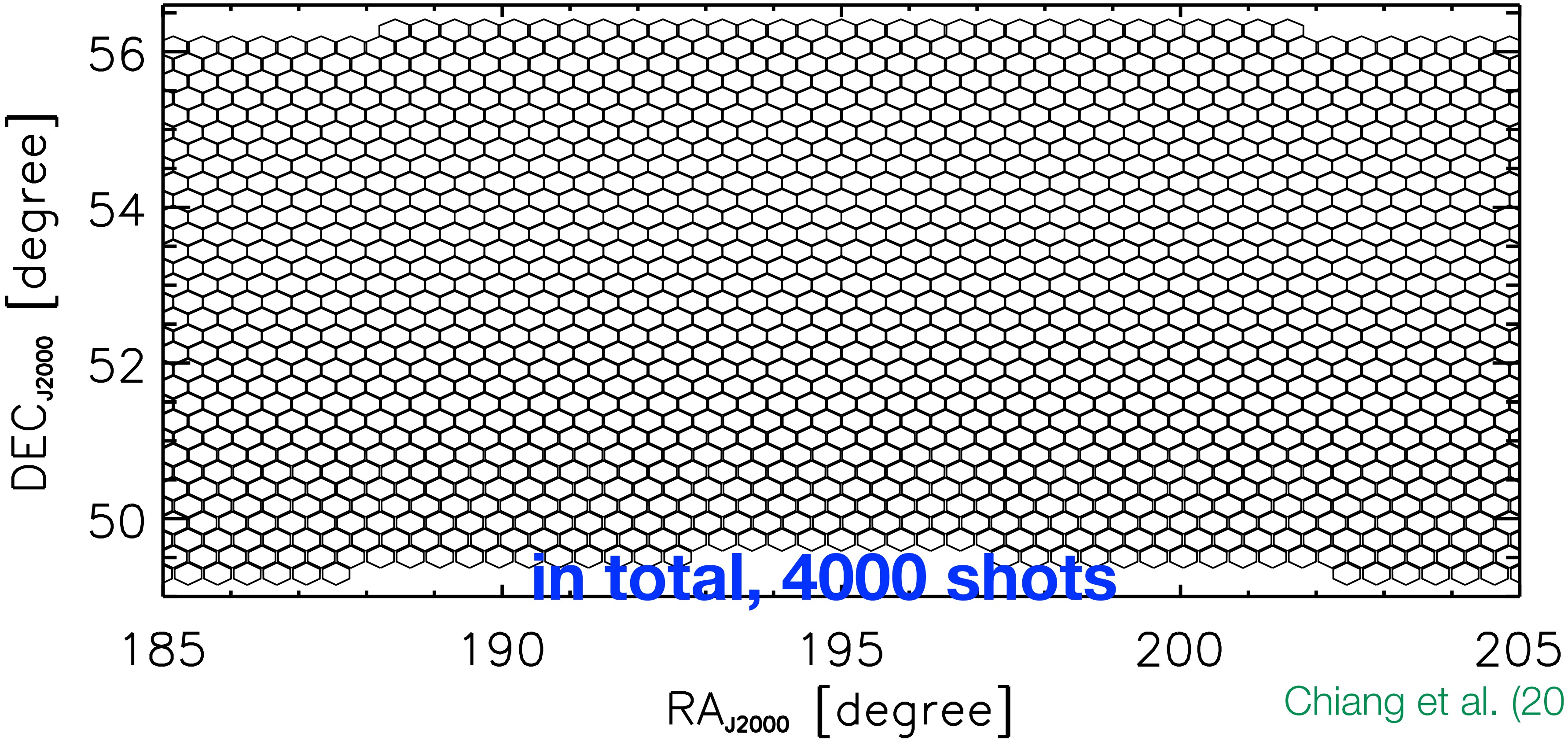
+ 1M OII-emitters at z < 0.5

First blind survey & First 10Gpc^3-class survey at high z

Blind Survey & Sparse Sampling



- Each "shot" in the sky contains 75 IFUs
  - Spending 20 minutes per shot ~ 200 LAEs
- We do not completely fill the focal plane (if only we had more IFUs...)
- This is the "sparse sampling" method



Chiang et al. (2016)

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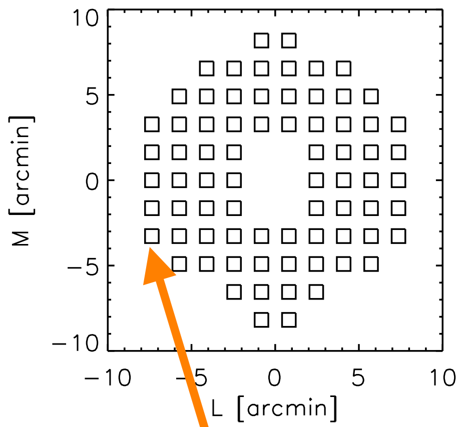

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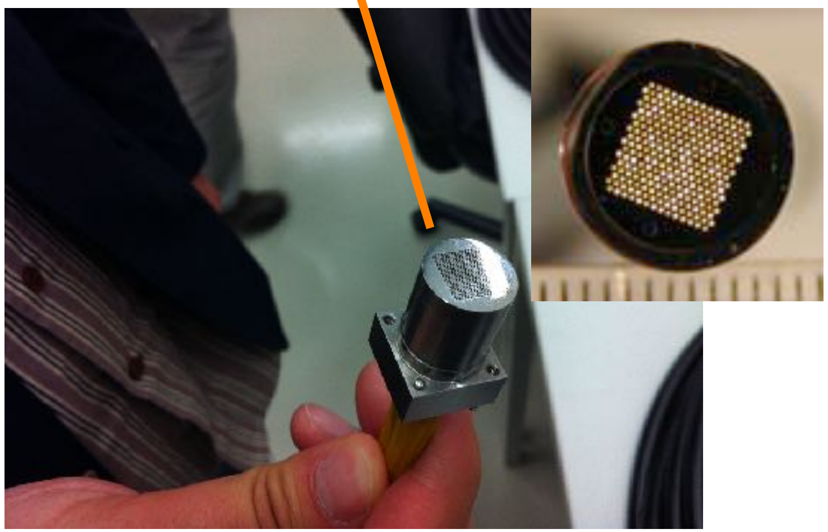
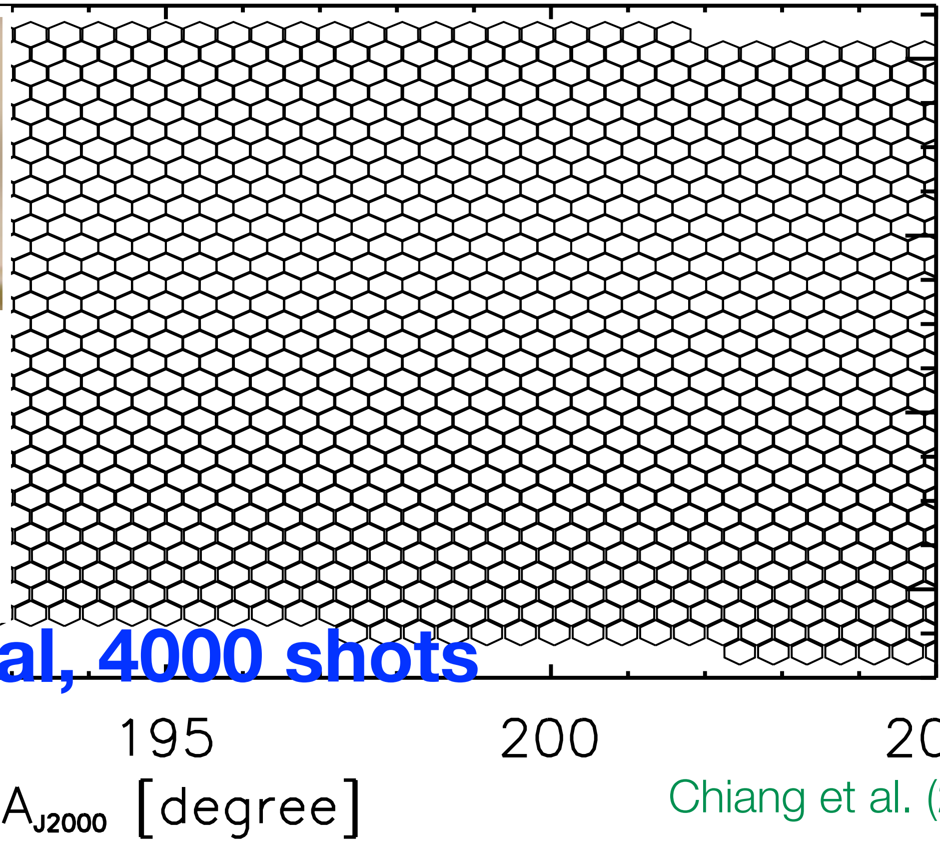


448 fibers per IFU



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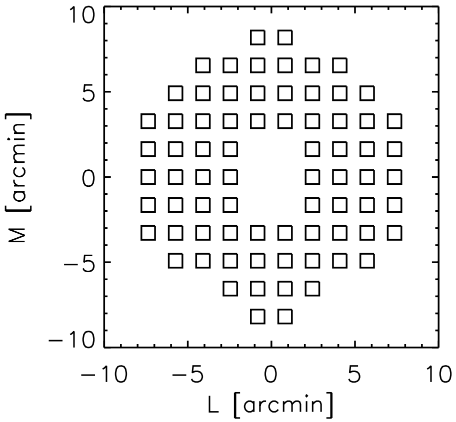

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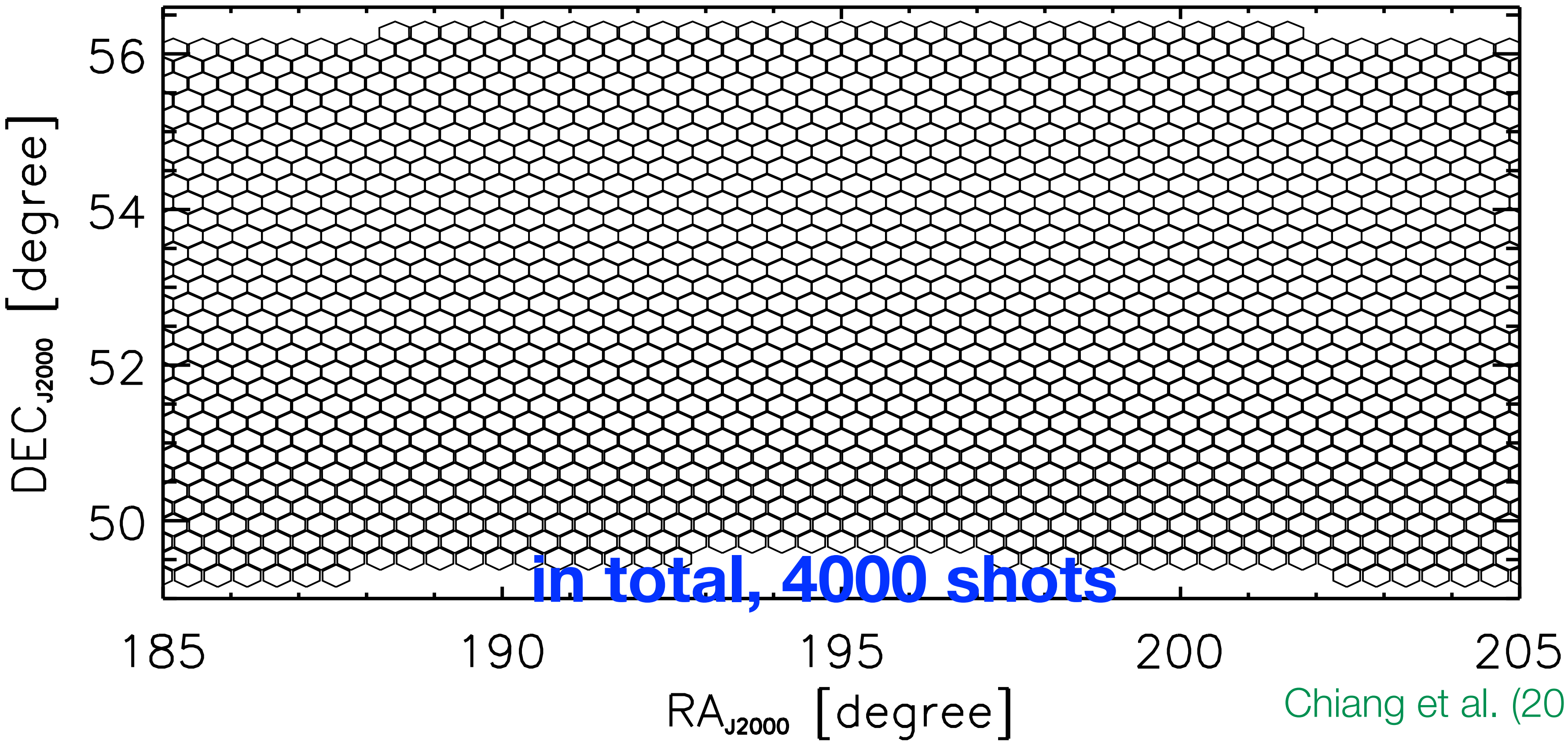

Chiang et al. (2016)

HETDEX as the IM survey

- Original survey design

- **33k** spectra **(448 fibers/IFU x 75 units)** at one 20mins exposure

- **4000** shots over 400 deg^2

- will find ~0.8M LAEs + ~0.9M OIIEs = **~1.7M** objects detected

- ***BUT we can do better!***

- More importantly, the ***first blind*** large-scale survey with ***IFU***

➡ 1.7M/(33k x 4000) ~ **only 1%** is used in the original design

➡ ***Intensity Mapping***: propose to extract information from 99%.

HETDEX is a unique survey to perform the Intensity Mapping.

How much ***cosmological information*** can we obtain?

Log-Normal simulation of IM

- We developed a c++ code to generate **logN distribution of IM.**

  - given luminosity function, generate luminosity density

  - **RSD** is implemented!

  - separate python script to convert $\rho_L(\vec{x})$ into $\lambda I_\lambda(\vec{\theta}, \lambda)$ w/ **noise**

  - To-Do-List includes b(L) & sparse sampling.

- simple feasibility study for HETDEX ($300\mathrm{deg}^2$, $1.9<z<2.5$)

  - $V_{box} = 0.874\ (\mathrm{Gpc}/h)^3$, $z = 2.2$, $N_{grid}=512^3$ ($L_{grid}=5.63\ \mathrm{Mpc}/h$), $b(L) = 1.5$

$$\delta n_g(\vec{x}) = \int_{L_{g,\min}}^{L_{g,\max}} dL \frac{dn}{dL} b(L)\delta_m(\vec{x}) = \bar{n}_g b \delta_m(\vec{x})$$

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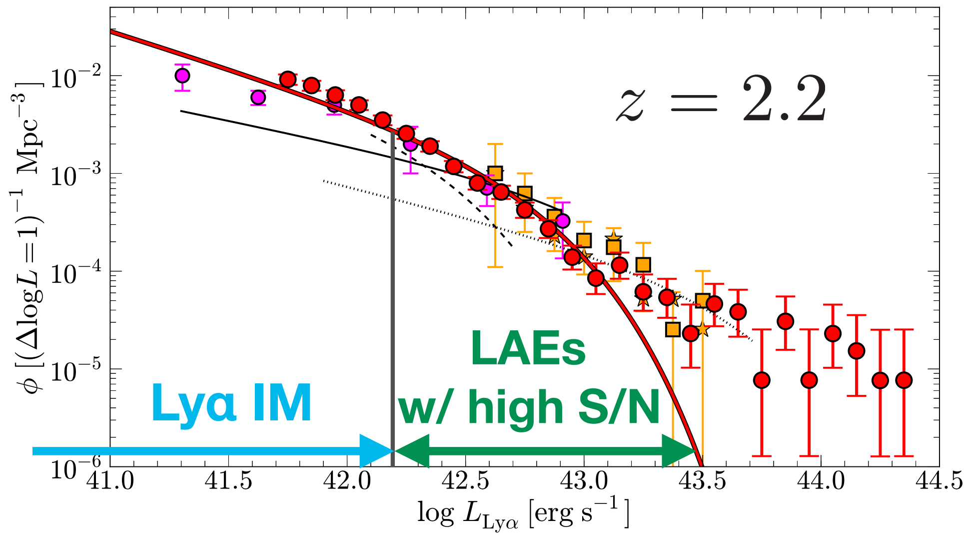
$$P_{g\rho_L}(k) = \langle \delta n_g \delta \rho_L \rangle = \bar{n}_g \bar{\rho}_L b^2 P_m(k)$$

$$P_{\rho_L \rho_L}(k) = \langle \delta \rho_L \delta \rho_L \rangle = \bar{\rho}_L^2 b^2 P_m(k)$$

Lya Luminosity Function

◆ Taken from Konno+ (2015)



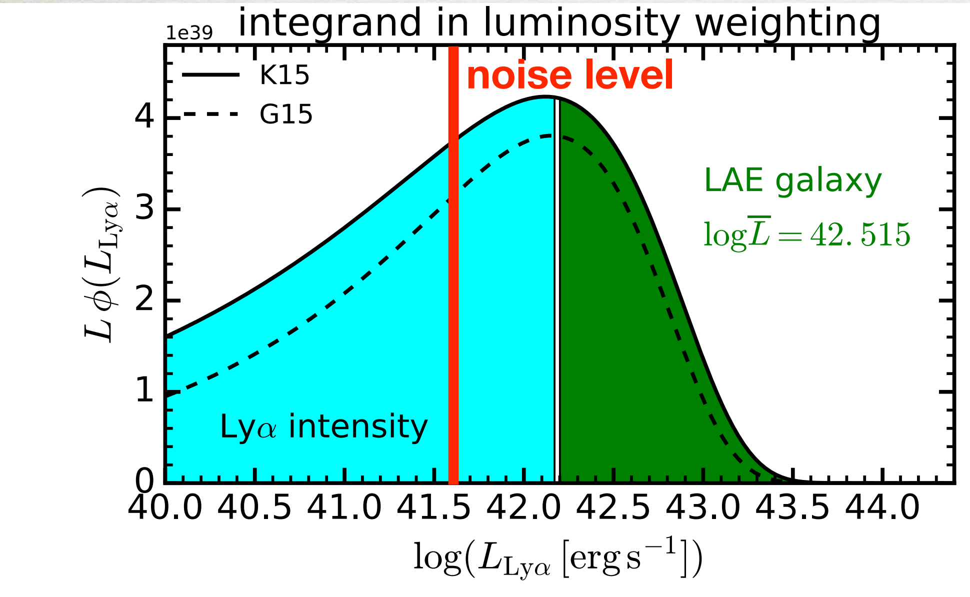
- Subaru deep NB survey
- 3,137 LAEs over ~1.5 deg^2
- Best-fitting Schechter parameters

$$L^*_{\mathrm{Ly}\alpha} = 5.29^{+1.67}_{-1.13} \times 10^{42}\ \mathrm{erg\ s^{-1}}$$

$$\phi^*_{\mathrm{Ly}\alpha} = 6.32^{+3.08}_{-2.31} \times 10^{-4}\ \mathrm{Mpc^{-3}}$$

$$\boxed{\alpha = -1.75^{+0.10}_{-0.09}}$$

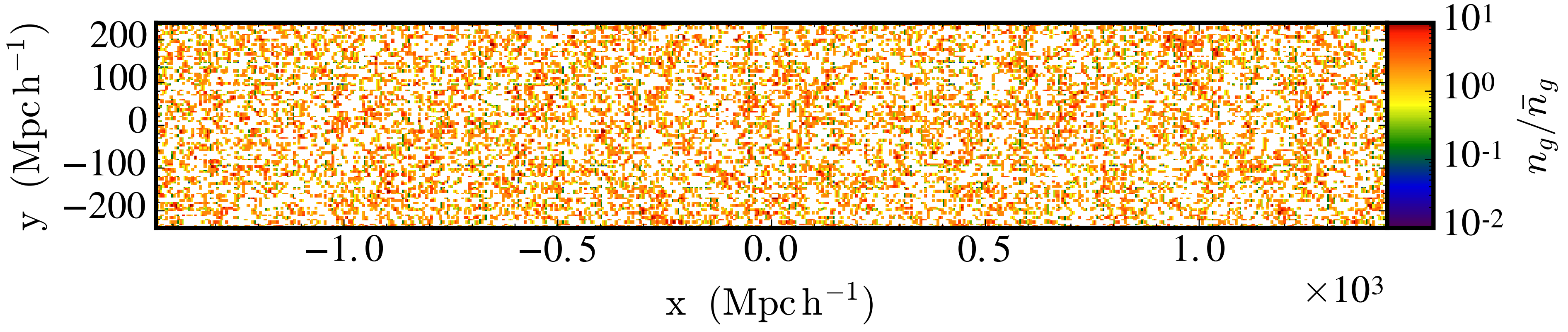
◆ information in luminosity density



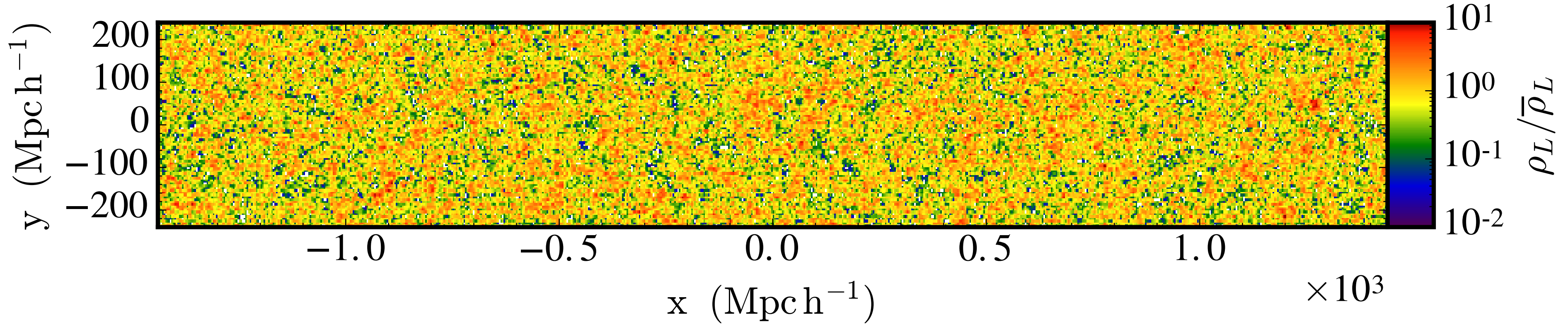
- Here estimate the contribution from faint-end LAEs.
- Croft+(2016) found much larger mean $\overline{\rho}_L$ by a factor of ~30(3/b_{LAI}).

Visual Impression of slice at z=2.2

- LAE number density field (on a grid with L_{grid}=5.625 Mpc/h)



- LA luminosity density field



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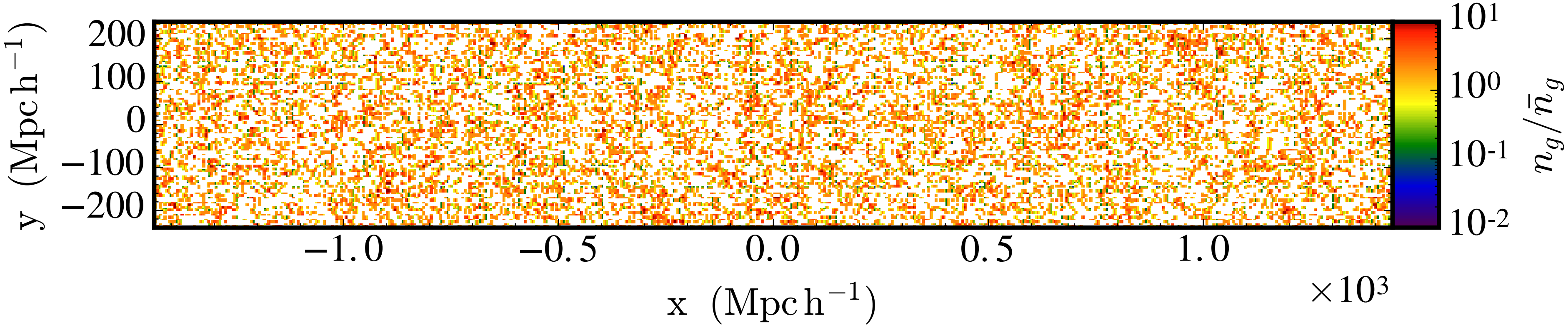
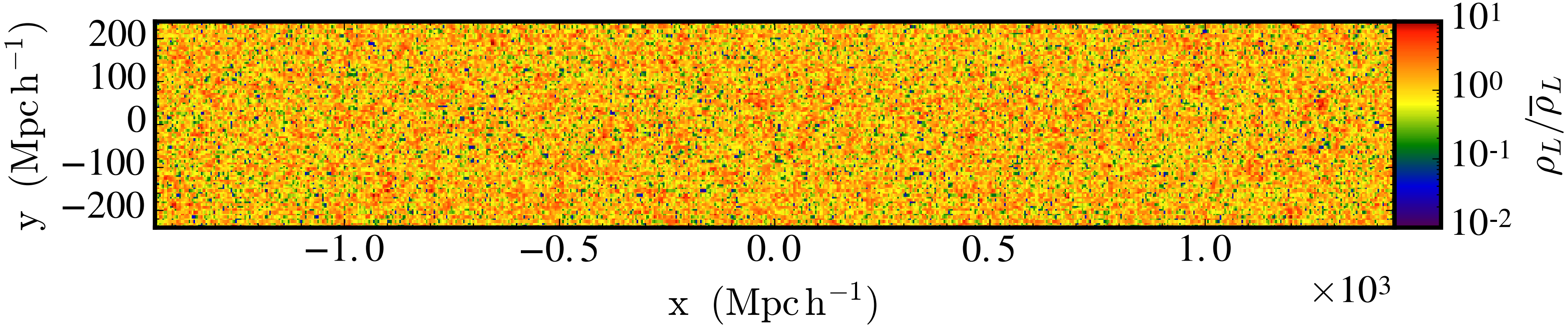
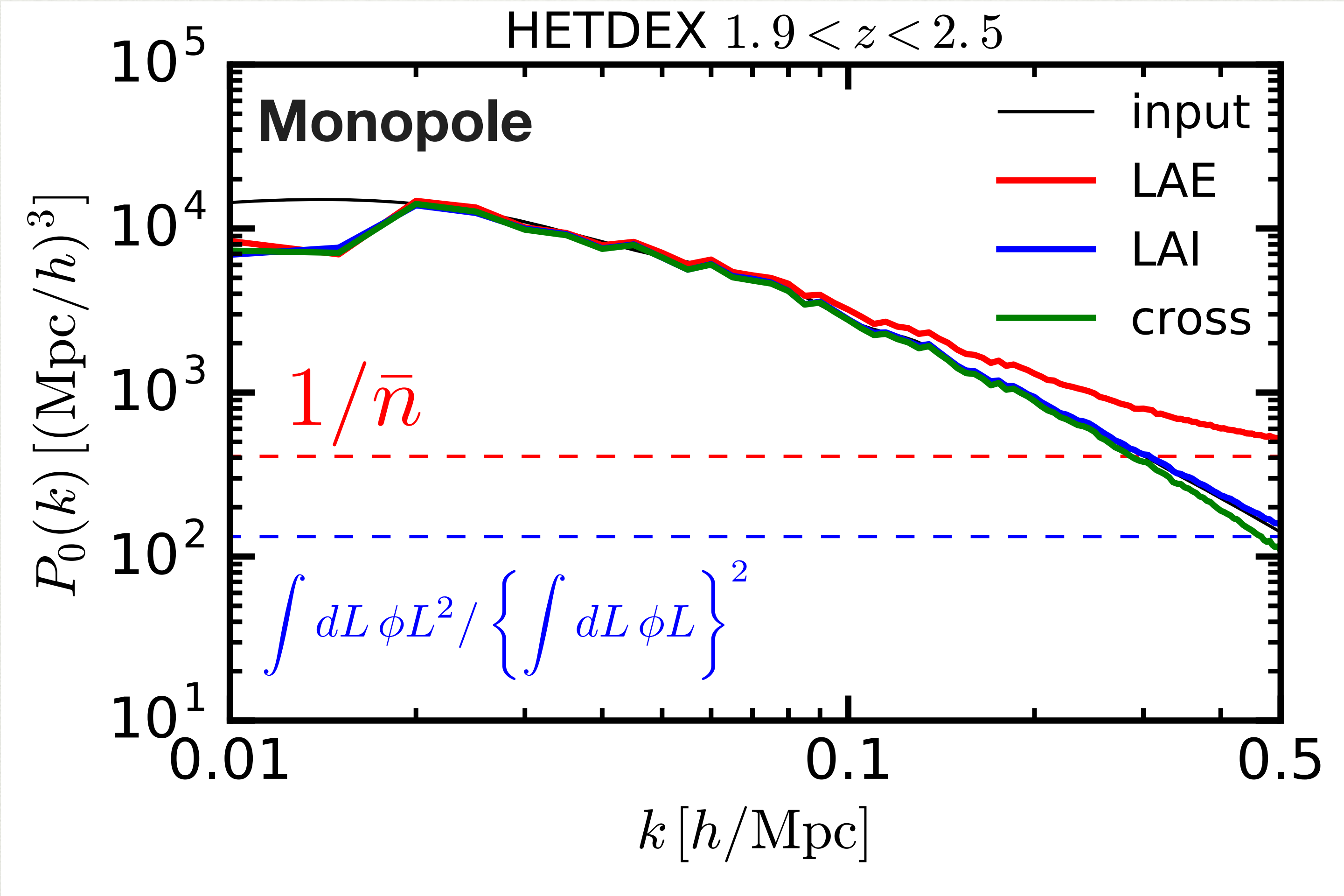


- LA luminosity density field **with HETDEX instrumental noise (x100)**



Auto & Cross Power Spectrum

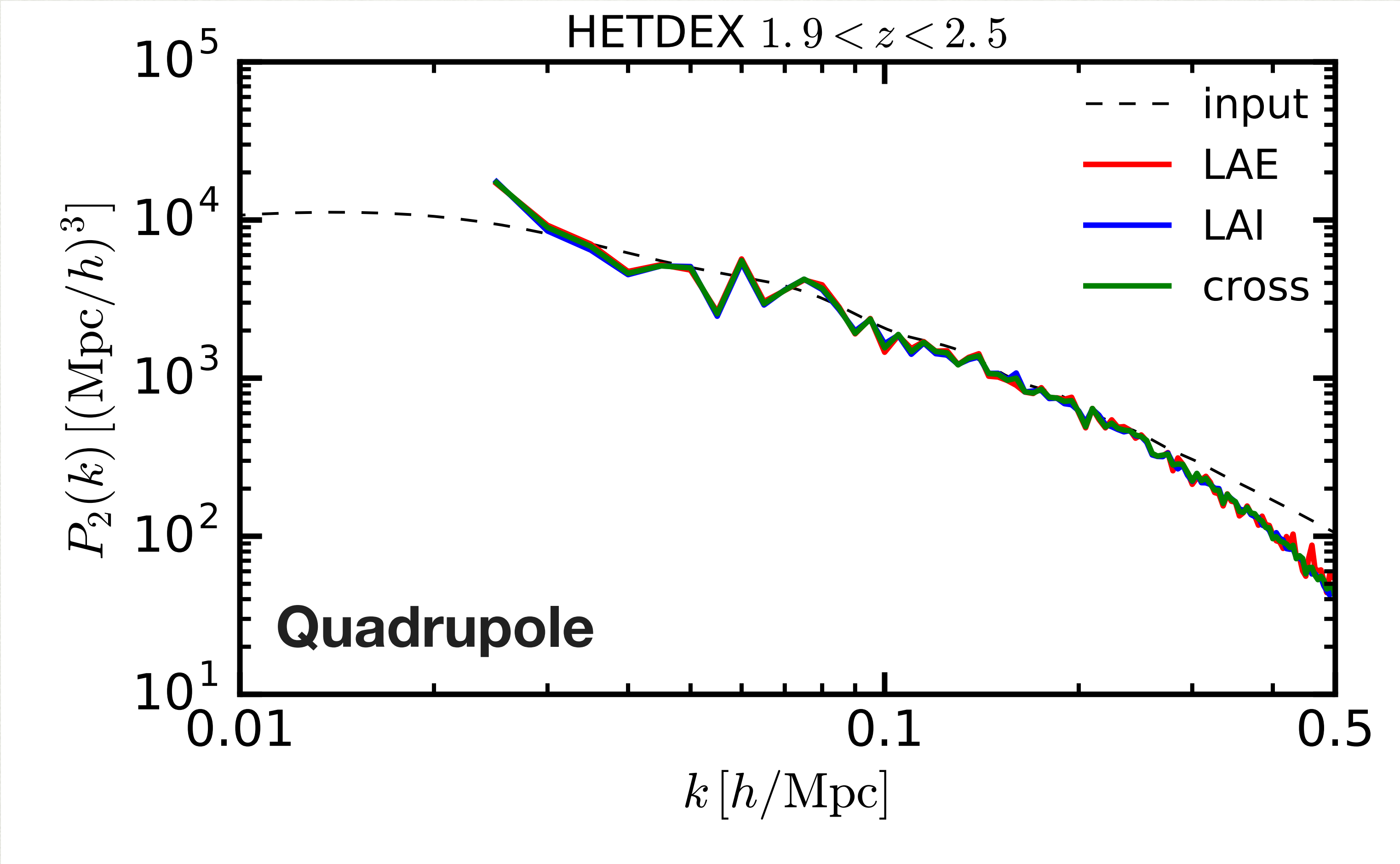


- **LAE P(k)** still dominated by Poisson shot noise.

- **LyA IM P(k)** has ***L^2-weighted*** Poisson shot noise.

- high S/N measurement of the **cross P(k)**!!

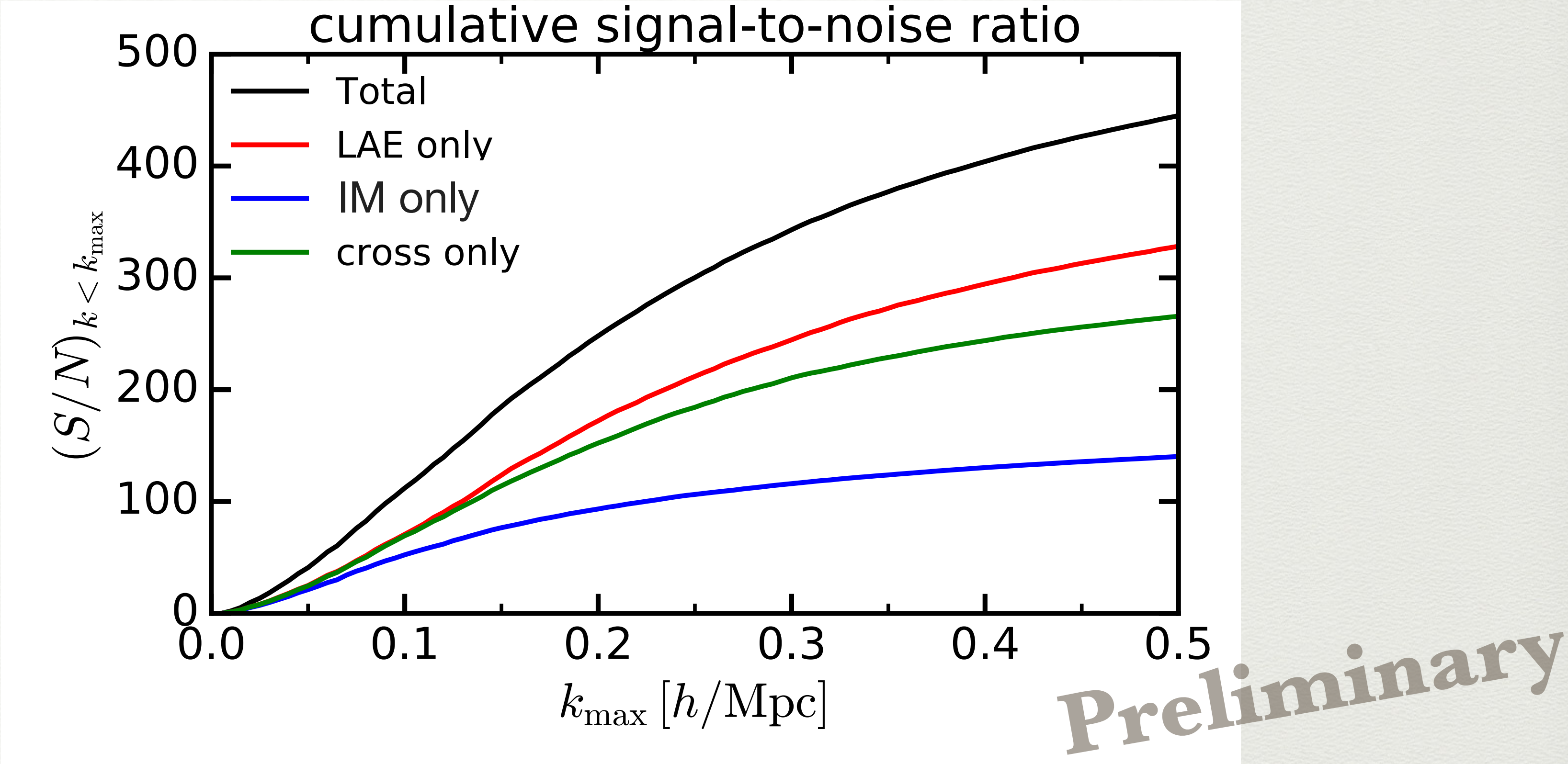
Auto & Cross Power Spectrum



- RSD can be measured similarly to LAEs.

Improvement on Cosmological Constraints

IM contribution only from $41 < \log_{10}(L\,/\mathrm{ergs}^{-1}) < 42.2$.



- including IM → larger (S/N) by a factor of **~1.35** @k_{max}=0.5h/Mpc
- translated to **~35%** improvement on cosmological constraints
- additional ~HETDEX LAE survey is available ***FOR FREE***

Summary & Prospects

- ***Lya Intensity Mapping in HETDEX*** is a promising probe of the large-scale structure. In particular, it will be the first high-S/N measurement **at large scales, O(100Mpc)**.

→ aim at the first detection of BAO using IM (*Nature paper?*)

- First year result [w/ 0.6deg^2] will come out in 2017-2018!

- Our IM logN code will become publicly available soon!
  - can be easily applied to e.g., **21cm in MWA/ASKAP/SKA**
  - would be worth planning future surveys
  - useful to study how well IM can test your theory!