D01:
Ultimate Physics Analysis

Eiichiro Komatsu
(Max-Planck-Institut für Astrophysik / Kavli IPMU)
“*Cosmic Acceleration*” Symposium, Yukawa Institute
March 3, 2019

Goals of the D01 team [1]

- To develop and provide necessary analysis tools for the “B-teams” (experiments) of the proposal
  - B01: **CMB** (Simons Array, LiteBIRD)
  - B02: **Weak gravitational lensing survey** (HSC)
  - B03: **Galaxy redshift survey** (PFS)
  - B04: **Redshift drift** (TMT)

「宇宙の加速膨張」：領域代表　村山　斉

領域事務　片山伸彦

[X00]総括班 村山 (IPMU)	[A01]Inflation 佐々木 (京都)	[A02]構造と揺らぎ 高橋 (東北)	[A02]dark energy 杉山 (名古屋)
[B01]CMB偏光 羽澄 (KEK)	$\delta\rho/\rho$, r, n_s 直接検証	CMB lensing isocurv, m_ν	cosm. params CMB lensing
[B02]imaging 宮崎 (NAOJ)	b(k)測定→ $P_{\mathrm{primord}}(k)$	weak lensing m_ν	weak lensing SNe-Ia, γ
[B03]spectroscopy 高田 (IPMU)	*primord. NG,* n_s, α_s, Ω_k	dSph, isocurv $P(k)$, m_ν	BAO $\Omega_\Lambda(z)$, γ
[B04]将来計画 臼田 (NAOJ)	varying α	Lyman α	加速直接測定
[C01]究極理論 大栗 (Caltech/IPMU)	mod. grav $>M_{Pl}$? BD?	non-Std DM	models mod. grav.

[D01]データ解析班　小松 (MPA/IPMU)

Goals of the D01 team [2]

- To develop novel analysis tools that go **beyond** B01–04:
  - Tomography of **hot gas** in the Universe: SZ-galaxy cross-correlation
  - **Intensity mapping**
    - Lyman-alpha and 21-cm lines, cross-correlated with galaxies and CMB

LSS = Large-scale Structure; CMB = Cosmic Microwave Background

D01: The Core Team





I. Kayo — Tokyo Univ. of Tech

R. Makiya, E. Komatsu — Kavli IPMU / MPA

S. Saito — Missouri S&T

K. Takahashi — Kumamoto Univ.

- LSS
- Lensing

- LSS
- Hot Gas

- LSS
- CMB

- LSS
- Ly-alpha

- LSS
- 21cm

***Joint analysis*, fully taking into account the mutual cross-correlation**

LSS = Large-scale Structure; CMB = Cosmic Microwave Background

D01: The Core Team

Will give talks today

I. Kayo
Tokyo Univ. of Tech

R. Makiya
E. Komatsu
Kavli IPMU / MPA

S. Saito
Missouri S&T

K. Takahashi
Kumamoto Univ.

- **LSS**
- **Lensing**

- **LSS**
- **Hot Gas**

- **LSS**
- **CMB**

- **LSS**
- **Ly-alpha**

- **LSS**
- **21cm**

***Joint analysis*, fully taking into account the mutual cross-correlation**

LSS = Large-scale Structure; CMB = Cosmic Microwave Background

D01: Collaborators

H. Kanai
YNU

- **CMB** (B01)

Y. Minami
IPMU

- **CMB** (B01)

K. Ichiki
Nagoya

- **CMB** (B01)

T. Inoue
Doshisha

- **Redshift drift** (B04)

from Facebook

T. Hiramatsu
Rikkyo

- **Inflation** (A01)

LSS = Large-scale Structure; CMB = Cosmic Microwave Background

D01: Collaborators

Gave a talk **Will give talks today**

from Facebook

H. Kanai
YNU

- **CMB** (B01)

Y. Minami
IPMU

- **CMB** (B01)

K. Ichiki
Nagoya

- **CMB** (B01)

T. Inoue
Doshisha

- **Redshift drift** (B04)

T. Hiramatsu
Rikkyo

- **Inflation** (A01)

Science Goals

- The main scientific motivations for the "ultimate physics analysis" are three-folds:

B02,03,04 Falsify the ΛCDM model by **ruling out Λ**

B01,02,03 Detect, or rule out, the inverted mass hierarchy of the neutrino mass by **measuring $\sum m_\nu < 0.1$ eV** [95% CL]

B01 Find definitive evidence for inflation by **measuring primordial gravitational waves in the CMB**

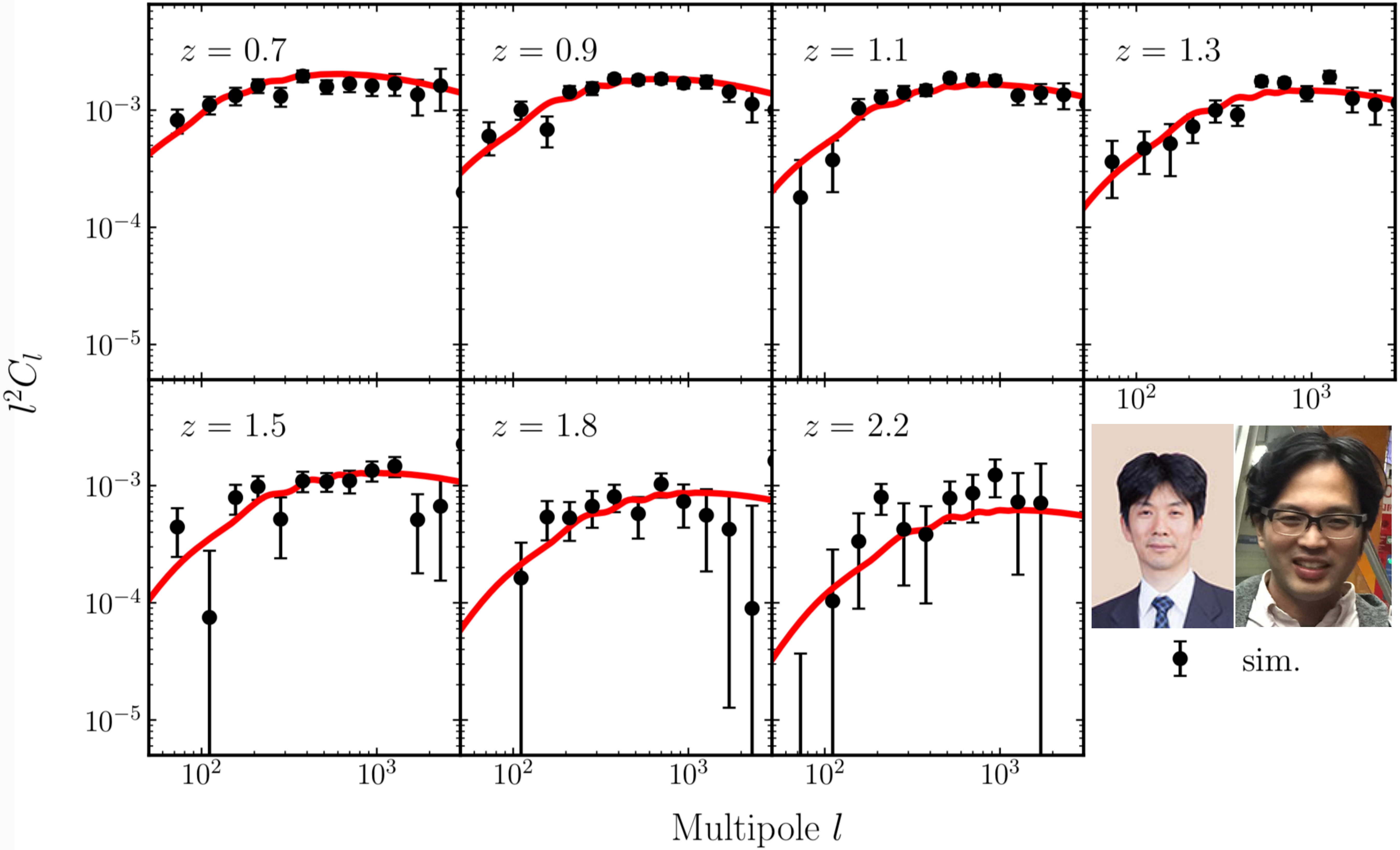
Fundamental Contributions to B01, 02, 03, 04


- **B01: Foreground removal** (Ichiki) **and polarisation angle calibration** (Minami)
  - For LiteBIRD. See Minami's and Ichiki's talks

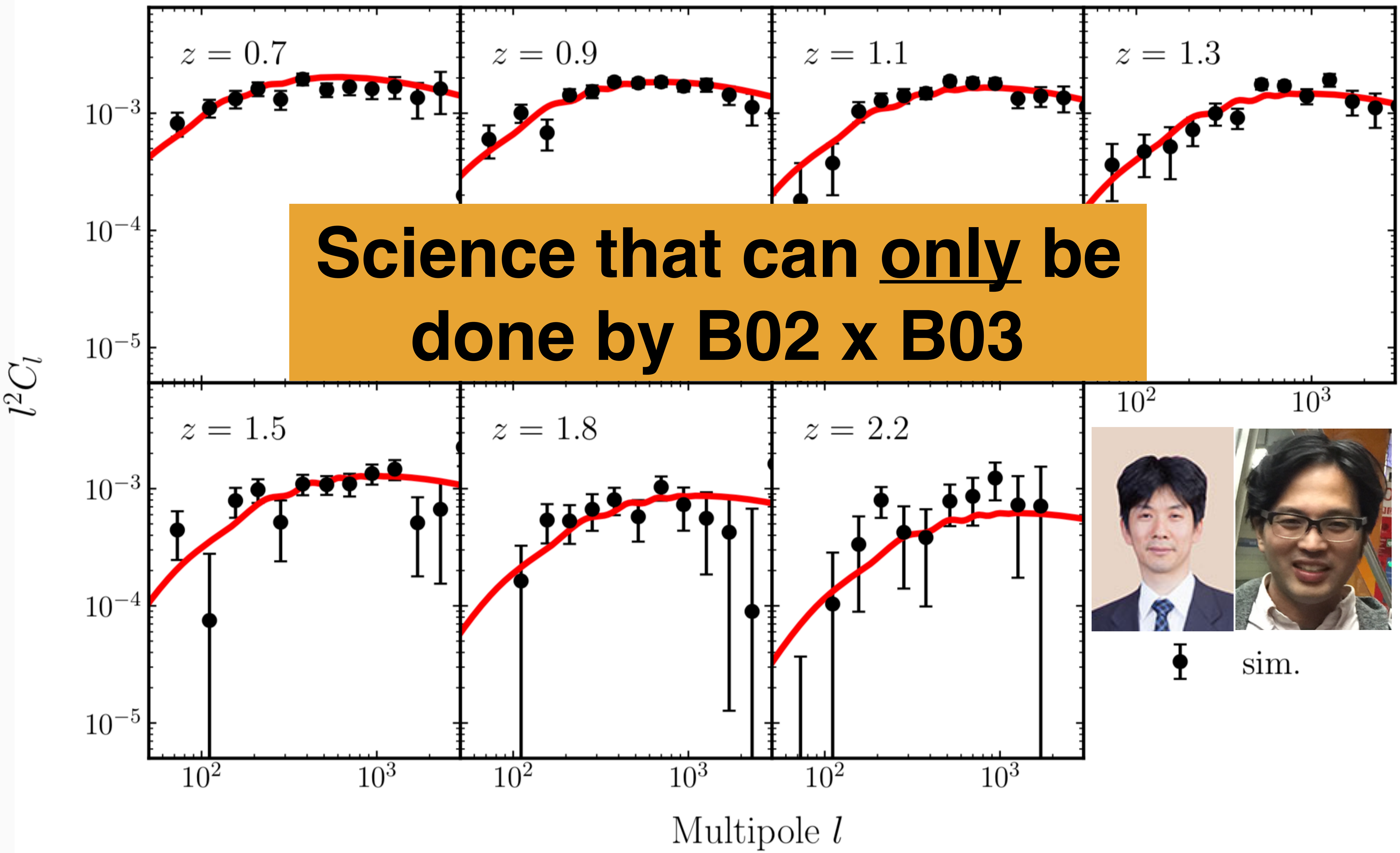
  - The foreground simulation code "*GM100*" (Kanai)
- **B02: Cross-correlation science for HSC and PFS**


  - Testing modified gravity
  - The lens simulation code "*lognormal_lens*" (Kayo/Makiya)

Simulated cross-correlation power spectra of HSC shear and PFS galaxies at z=0.7–2.2!



Simulated cross-correlation power spectra of HSC shear and PFS galaxies at z=0.7–2.2!



Science that can <u>only</u> be done by B02 x B03

Fundamental Contributions to B01, 02, 03, 04

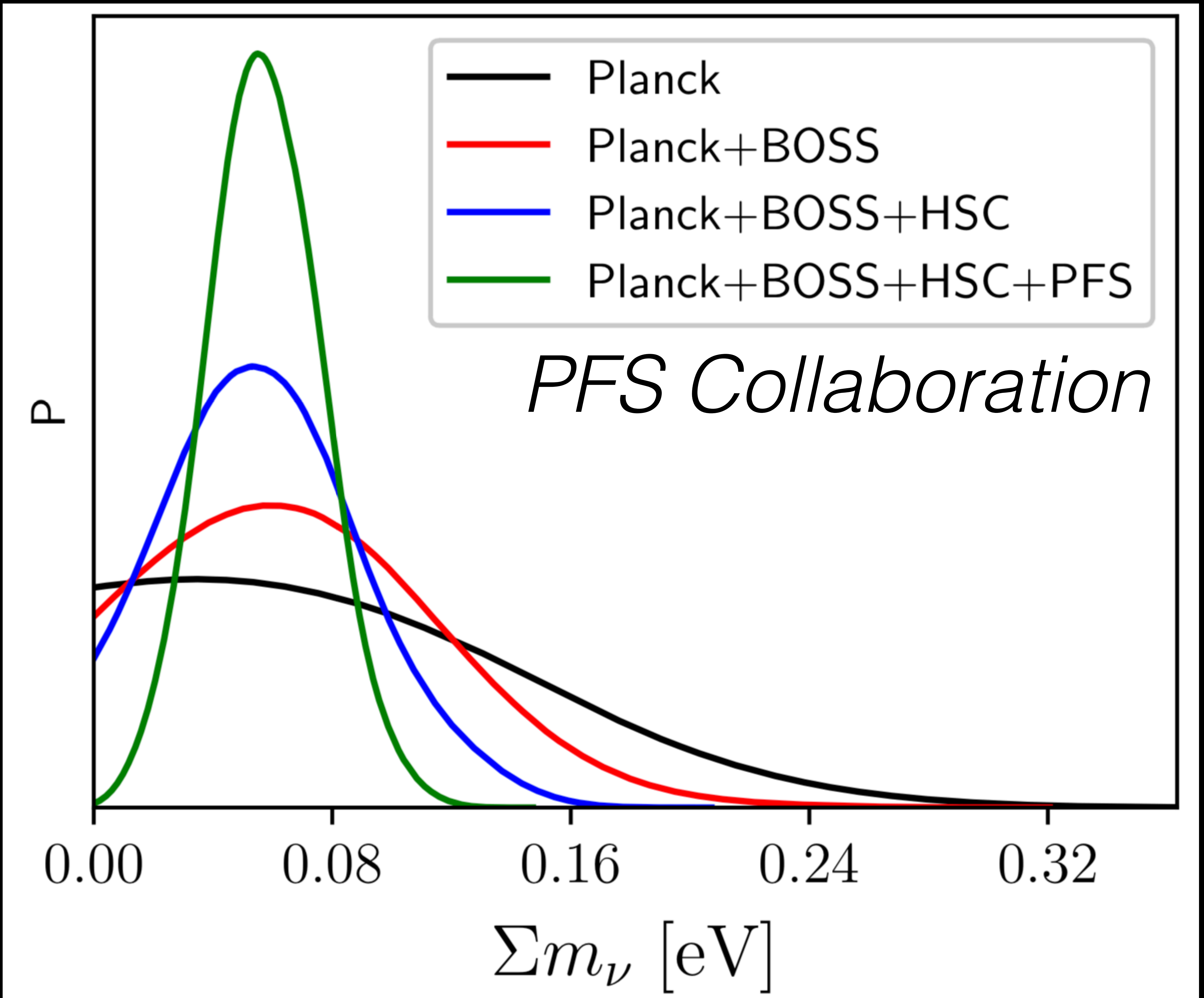
- **B04: Effect of our local motion on the redshift drift measurement**

  - For TMT, or any other measurements (e.g., E-ELT). See Inoue's talk

- **B03: Cosmology proposal for PFS**

  - Majority of the study for the cosmology proposal of PFS was done by the members of D01
  - The galaxy simulation code "*lognormal_galaxy*" (Makiya/Kayo/Saito)

HSC and PFS will constrain the mass of neutrinos with unprecedented precision!



Going beyond B01, 02, 03, 04

- **Tomography of Hot gas: SZ-galaxy cross-correlation**

  - See Makiya's talk on **Tuesday** during the next symposium

- **Intensity mapping**

  - Lyman-alpha: See Saito's talk

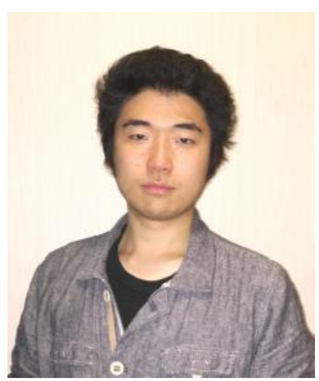
  - 21-cm: See Takahashi's talk

Summary

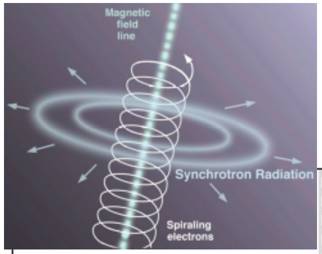
- Over the last 3.5 years of the grant period, we have made fundamental contributions to the progress of B01, B02, B03, and B04
  - <u>We should make sure to let the reviewers know this!</u>
- We are going beyond B01–04 by extending the cross-correlation techniques to hot gas and intensity mapping
- ***Many publications in refereed journals have resulted and more are being written. Most led by junior scientists***
- ***It has been a wonderful, productive 3.5 years! (And one more year to come.)***

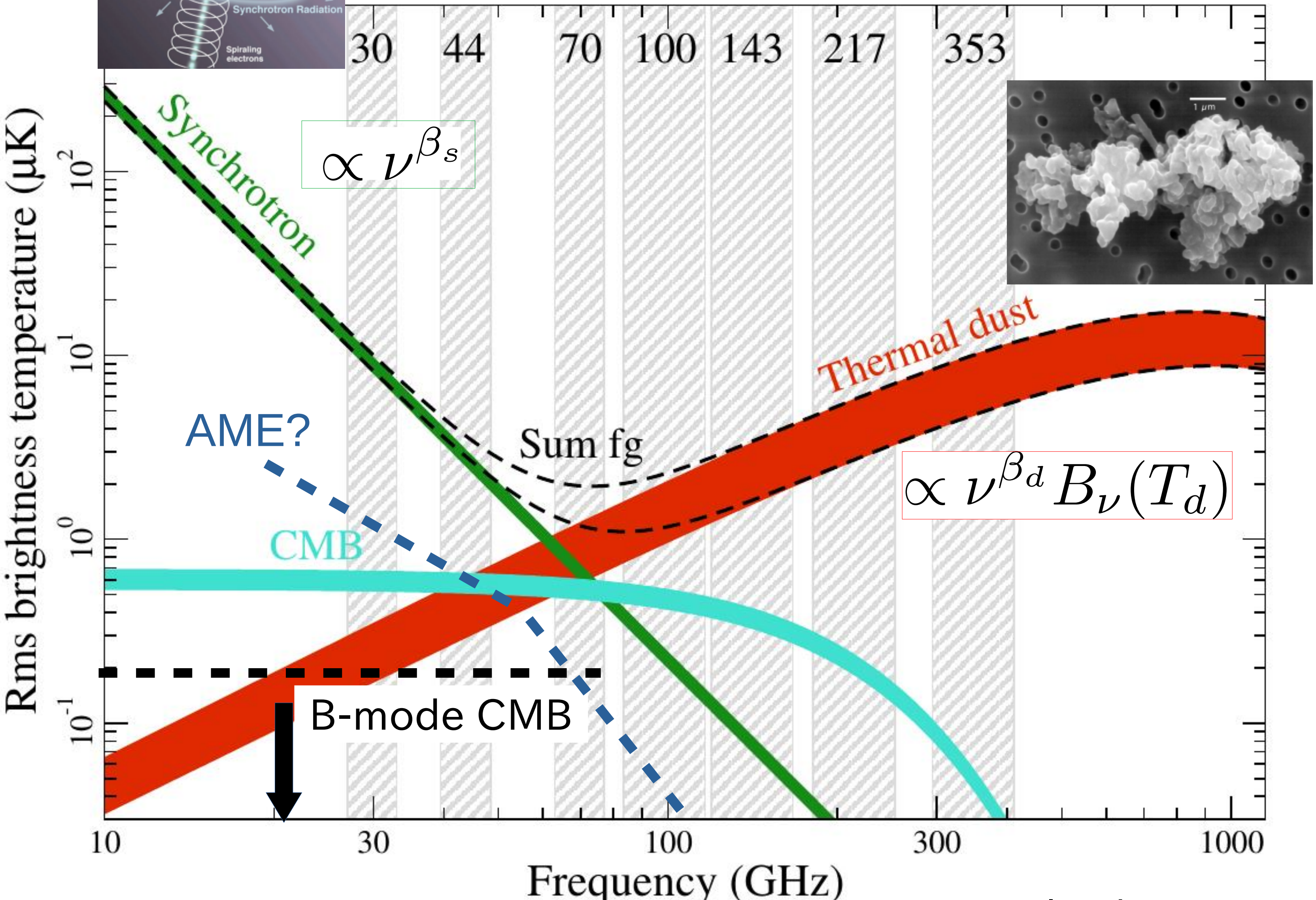
Delta-map method to remove CMB foregrounds with spatially varying spectra

K. ICHIKI, H. Kanai, E. Komatsu and N. Katayama



CMB and foregrounds

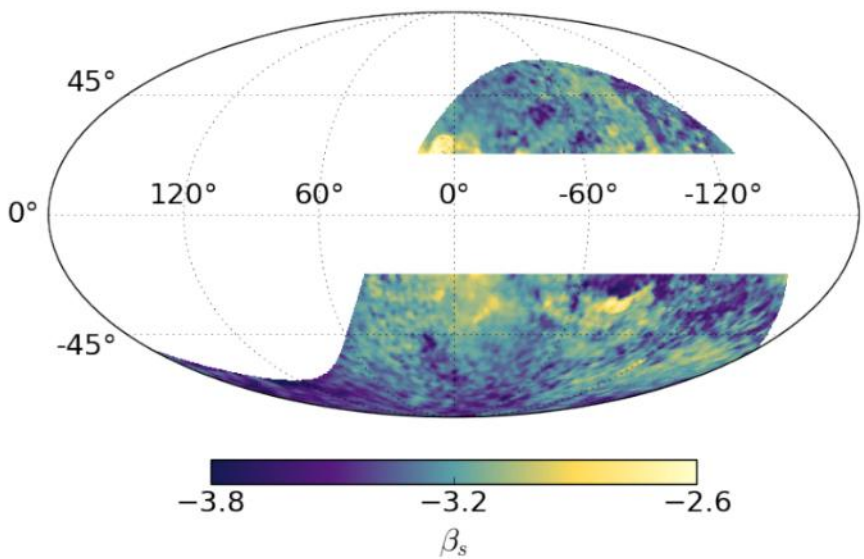


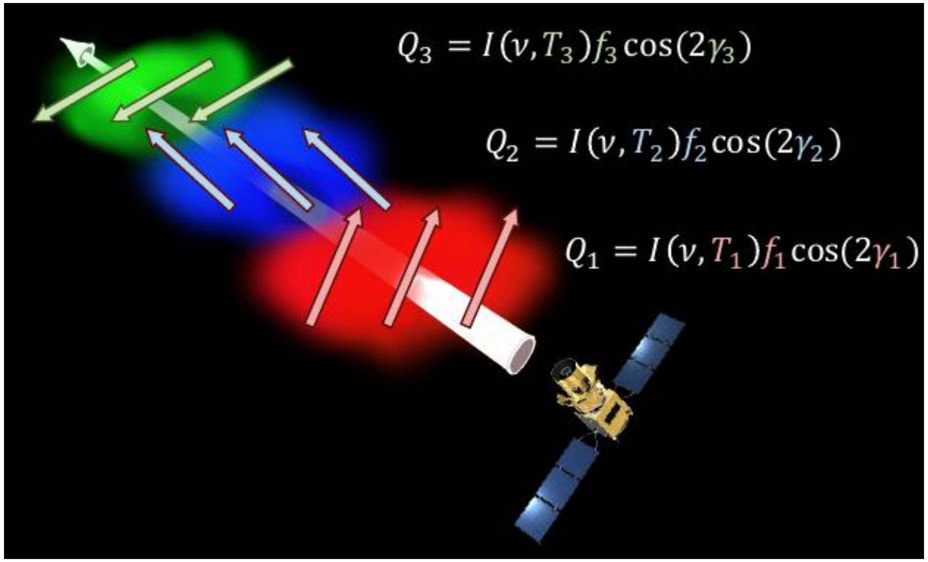


Planck 2015 results. X

KK2011 からの宿題

S-PASS (Krachmalnicoff+, arxiv: 1802.01145)





Internal template 法では **map** の線型結合によって **CMB** を取り出すが各放射成分の周波数依存性が方向に依存しないことを仮定していた
(e.g. Katayama&Komatsu, ApJ, 2011)

が、実際はそうではないという問題

他にも

AME および
De-correlation effect (Tassis+, MNRAS, '15)
をどう考慮するかという問題

Delta-map method

$$Q^{\rm synch}(\nu,\hat{n}) = g_\nu \left(\frac{\nu}{\nu_*}\right)^{\beta_{\rm s}(\hat{n})} Q^{\rm synch}(\nu_*,\hat{n})$$

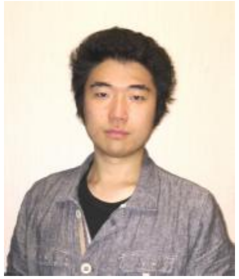
$\beta_{\rm s}(\hat{n}) = \beta_{\rm s}(\hat{n}) + C(\hat{n})\ln(\nu/\nu_*)$ をテイラー展開

$$\begin{aligned} Q^{\rm total}(\nu,\hat{n}) \approx \mathrm{CMB}(\hat{n}) + g_\nu \left(\frac{\nu}{\nu_*}\right)^{\bar{\beta}_{\rm s}} \Bigg[& Q^{\rm synch}(\nu_*,\hat{n}) \\ & + \ln\left(\frac{\nu}{\nu_*}\right) \delta\beta_s(\hat{n}) Q^{\rm synch}(\nu_*,\hat{n}) \\ & + \left[\ln\left(\frac{\nu}{\nu_*}\right)\right]^2 \underbrace{C(\hat{n}) Q^{\rm synch}(\nu_*,\hat{n})} \Bigg] \end{aligned}$$

Delta-map: 方向依存性を差分のテンプレートで考慮

Synchrotron running:
→ **AME** 成分を吸収

Foreground modeling (gm100)



- simple python script to generate sky maps with CMB, white noise, and foregrounds
- Foregrounds include

component	base map	params
synch	SynchrotronPol-commander_0256_R2.00 (30GHz)	MAMD2008, no curvature
dust	DustPol-commander_1024_R2.00 (353GHz)	Meisner-Finkbeiner two component model
point source	PCCS_xxx_R2.xx	uniform 5 % pol. fraction

- options
  - de-correlation of dust pol, one component model

code available> git clone https://h_kan@bitbucket.org/h_kan/gm100.git

Results

Work in Nside=4 resolution

6 or 7 bands used

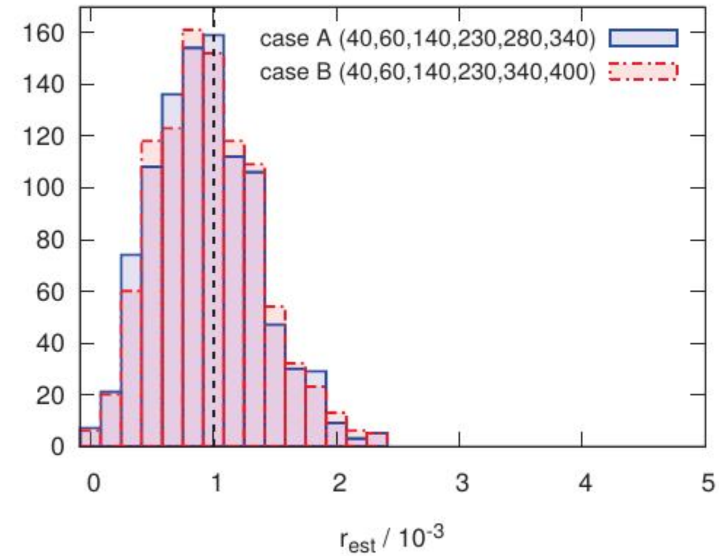
\# of parameters = 4 $(r, \bar{\beta}_{\mathrm{s}}, \bar{\beta}_{\mathrm{d}}, \bar{T}_{\mathrm{d}})$

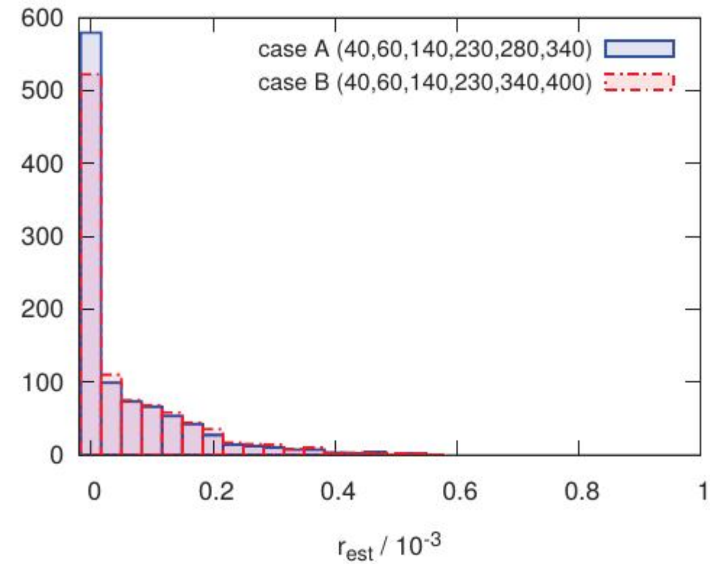
Appealing points

- **internal & simple**
- **accounting for spatially varying foreground params to 1st order**
- **AME is supported**
- **decorrelation is supported**
- **unbiased**

$$\sigma(r) \simeq 0.9 \times 10^{-3} \text{ (LiteBIRD noise)}$$

$$\sigma(r) \simeq 0.2 \times 10^{-3} \text{ (noiseless)}$$

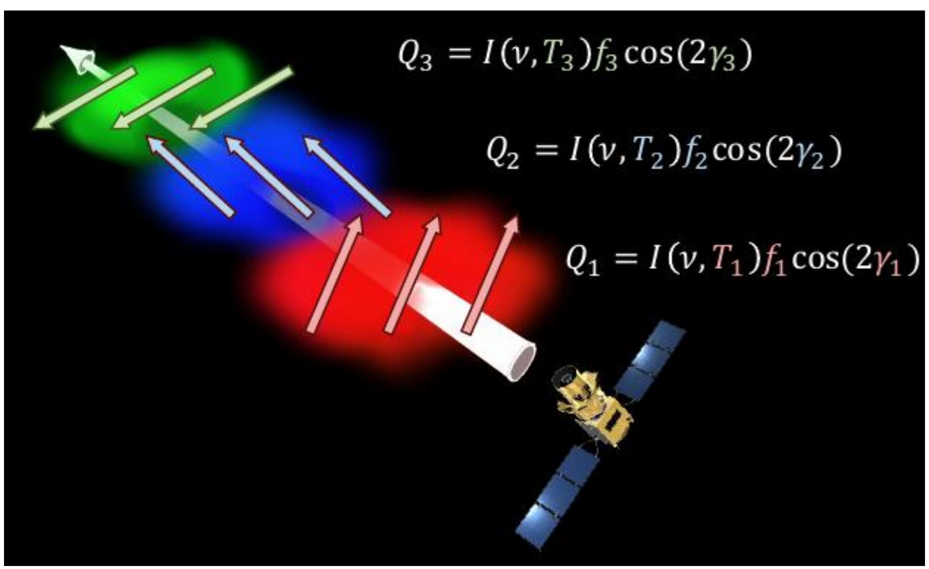


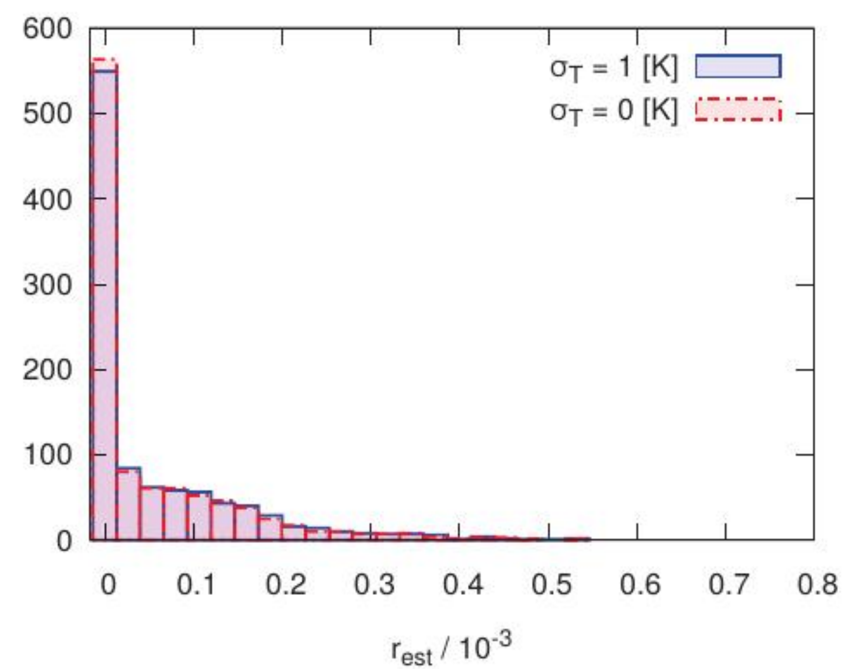


Results (de-correlation)　B01 班向け

De-correlation の効果は、各ダスト雲の温度の違いの1次のオーダーで **Q,U** が異なる温度の周波数依存を持つものとして表現できる

$(r, \bar{\beta}_{\mathrm{s}}, \bar{\beta}_{\mathrm{d}}, \bar{T}_{\mathrm{d}}) \Rightarrow (r, \bar{\beta}_{\mathrm{s}}, \bar{\beta}^{\mathrm{Q}}_{\mathrm{d}}, \bar{T}^{\mathrm{Q}}_{\mathrm{d}}, \bar{\beta}^{\mathrm{U}}_{\mathrm{d}}, \bar{T}^{\mathrm{U}}_{\mathrm{d}})$ とすればよい





PTEP, in press arxiv:1811.03886

Methodology paper is now available

observed map

signal map (CMB,dust,..)

$$-2\ln\mathcal{L}(\vec{m}|\vec{s},\boldsymbol{D}) = (\boxed{\vec{m}} - \boxed{\boldsymbol{D}}\vec{s})^{\mathrm{T}}\,\boldsymbol{N}^{-1}\,(\vec{m} - \boldsymbol{D}\boxed{\vec{s}}) + \ln|2\pi\boldsymbol{N}|\,. \tag{40}$$

mixing matrix (frequency dependence)

PTEP, in press arxiv:1811.03886

Methodology paper is now available

observed map

signal map (CMB,dust,..)

$$-2\ln\mathcal{L}(\vec{m}|\vec{s},\boldsymbol{D}) = (\boxed{\vec{m}} - \boxed{\boldsymbol{D}}\vec{s})^{\mathrm{T}}\,\boldsymbol{N}^{-1}\,(\vec{m} - \boldsymbol{D}\boxed{\vec{s}}) + \ln|2\pi\boldsymbol{N}|\,. \tag{40}$$

mixing matrix (frequency dependence)

Marginalize over gaussian CMB

$$\begin{aligned}-2\ln P(\vec{p}^{I},\vec{s}_f,\boldsymbol{S}|\vec{m}) \;&=\; \left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right)^{\mathrm{T}}\left(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N}\right)^{-1}\left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right)\\ &\quad+\ln\left|2\pi(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})\right| - 2\ln P(\vec{s}_f,\boldsymbol{S}^{f}) + \mathrm{constant}\,,\end{aligned}$$

PTEP, in press arxiv:1811.03886

Methodology paper is now available

observed map

signal map (CMB,dust,..)

$$-2\ln\mathcal{L}(\vec{m}|\vec{s},\boldsymbol{D}) = (\boxed{\vec{m}} - \boxed{\boldsymbol{D}}\vec{s})^{\mathrm{T}}\boldsymbol{N}^{-1}(\vec{m} - \boldsymbol{D}\boxed{\vec{s}}) + \ln|2\pi\boldsymbol{N}|\,. \tag{40}$$

mixing matrix (frequency dependence)

Marginalize over gaussian CMB

$$-2\ln P(\bar{p}^I,\vec{s}_f,\boldsymbol{S}|\vec{m}) = \left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right)^{\mathrm{T}}\left(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N}\right)^{-1}\left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right) + \ln\left|2\pi(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})\right| - 2\ln P(\vec{s}_f,\boldsymbol{S}^f) + \mathrm{constant}\,,$$

Maximum likelihood solution (foreground)

$$\vec{s}_f^{\,\mathrm{ML}} = \left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\tilde{\boldsymbol{D}}\right]^{-1}\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m}\,.$$

PTEP, in press arxiv:1811.03886

Methodology paper is now available

observed map

signal map (CMB,dust,..)

$$-2\ln\mathcal{L}(\vec{m}|\vec{s},\boldsymbol{D}) = (\boxed{\vec{m}} - \boxed{\boldsymbol{D}}\vec{s})^{\mathrm{T}}\,\boldsymbol{N}^{-1}\,(\vec{m} - \boldsymbol{D}\boxed{\vec{s}}) + \ln|2\pi\boldsymbol{N}|\,. \qquad (40)$$

mixing matrix (frequency dependence)

Marginalize over gaussian CMB

$$\begin{aligned} -2\ln P(\bar{p}^I,\vec{s}_f,\boldsymbol{S}|\vec{m}) \;=\;& \left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right)^{\mathrm{T}}\left(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N}\right)^{-1}\left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right) \\ &+\ln\left|2\pi(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})\right| - 2\ln P(\vec{s}_f,\boldsymbol{S}^f) + \text{constant}\,, \end{aligned}$$

Maximum likelihood solution (foreground)

$$\vec{s}_f^{\mathrm{ML}} = \left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\tilde{\boldsymbol{D}}\right]^{-1}\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m}\,.$$

$$\begin{aligned} -2\ln P(\bar{p}^I,\vec{s}_f^{\mathrm{ML}},\boldsymbol{S}|\vec{m}) =& \;\vec{m}^{\mathrm{T}}\left(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N}\right)^{-1}\vec{m} \\ &- \left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m}\right]^{\mathrm{T}}\left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\tilde{\boldsymbol{D}}\right]^{-1}\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m} \\ &+\ln\left|2\pi(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})\right| - 2\ln P(\vec{s}_f^{\mathrm{ML}},\boldsymbol{S}^f) + \text{constant}\,. \qquad (61) \end{aligned}$$

PTEP, in press arxiv:1811.03886

Methodology paper is now available

observed map

signal map (CMB,dust,..)

$$-2\ln\mathcal{L}(\vec{m}|\vec{s},\boldsymbol{D}) = (\boxed{\vec{m}}-\boxed{\boldsymbol{D}}\vec{s})^{\mathrm{T}}\boldsymbol{N}^{-1}(\vec{m}-\boldsymbol{D}\boxed{\vec{s}}) + \ln|2\pi\boldsymbol{N}|\,. \quad (40)$$

mixing matrix (frequency dependence)

Marginalize over gaussian CMB

$$\begin{aligned}-2\ln P(\vec{p}^{I},\vec{s}_f,\boldsymbol{S}|\vec{m}) &= \left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right)^{\mathrm{T}}\left(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N}\right)^{-1}\left(\vec{m}-\tilde{\boldsymbol{D}}\vec{s}_f\right)\\ &\quad+\ln\left|2\pi(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})\right|-2\ln P(\vec{s}_f,\boldsymbol{S}^f)+\text{constant}\,,\end{aligned}$$

Maximum likelihood solution (foreground)

$$\vec{s}_f^{\mathrm{ML}} = \left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\tilde{\boldsymbol{D}}\right]^{-1}\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m}\,.$$

$$\boxed{\begin{aligned}-2\ln P(\vec{p}^{I},\vec{s}_f^{\mathrm{ML}},\boldsymbol{S}|\vec{m}) &= \vec{m}^{\mathrm{T}}\left(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N}\right)^{-1}\vec{m}\\ &\quad-\left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m}\right]^{\mathrm{T}}\left[\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\tilde{\boldsymbol{D}}\right]^{-1}\tilde{\boldsymbol{D}}^{\mathrm{T}}(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})^{-1}\vec{m}\\ &\quad+\ln\left|2\pi(\boldsymbol{S}^{\mathrm{CMB}}+\boldsymbol{N})\right|-2\ln P(\vec{s}_f^{\mathrm{ML}},\boldsymbol{S}^f)+\text{constant}\,. \quad (61)\end{aligned}}$$

The above expression is exactly the same as our likelihood used when the number of observation bands is just enough to solve for one CMB map. This formula will enable us to find the optimal combination of multi-frequency bands of the LiteBIRD, reducing σ(r) further (under investigation).

The Effect of our local motion on the Sandage-Loeb test of the cosmic expansion

D01: Takuya Inoue

Mechanical Engineering department

Doshisha University (同志社大学)

ctwc0518@mail4.doshisha.ac.jp

2019 新学術領域シンポジウム
Kyoto University, Japan; March 4th, 2019

Introduction

Redshift drift & Sandage-Loeb test

The cosmic expansion rate is not constant with time

The redshift from the distant sources like quasars changes with time

« Redshift drift »

$$\frac{\Delta z}{\Delta t_0} = H_0(1+z) - H(z)$$

$e.g., z = 3 \;\; \Delta t_0 = 10\ years$

$\Delta v \approx -2.5\ cm/s$

The order of this drift should be a few cm/s after 10 years

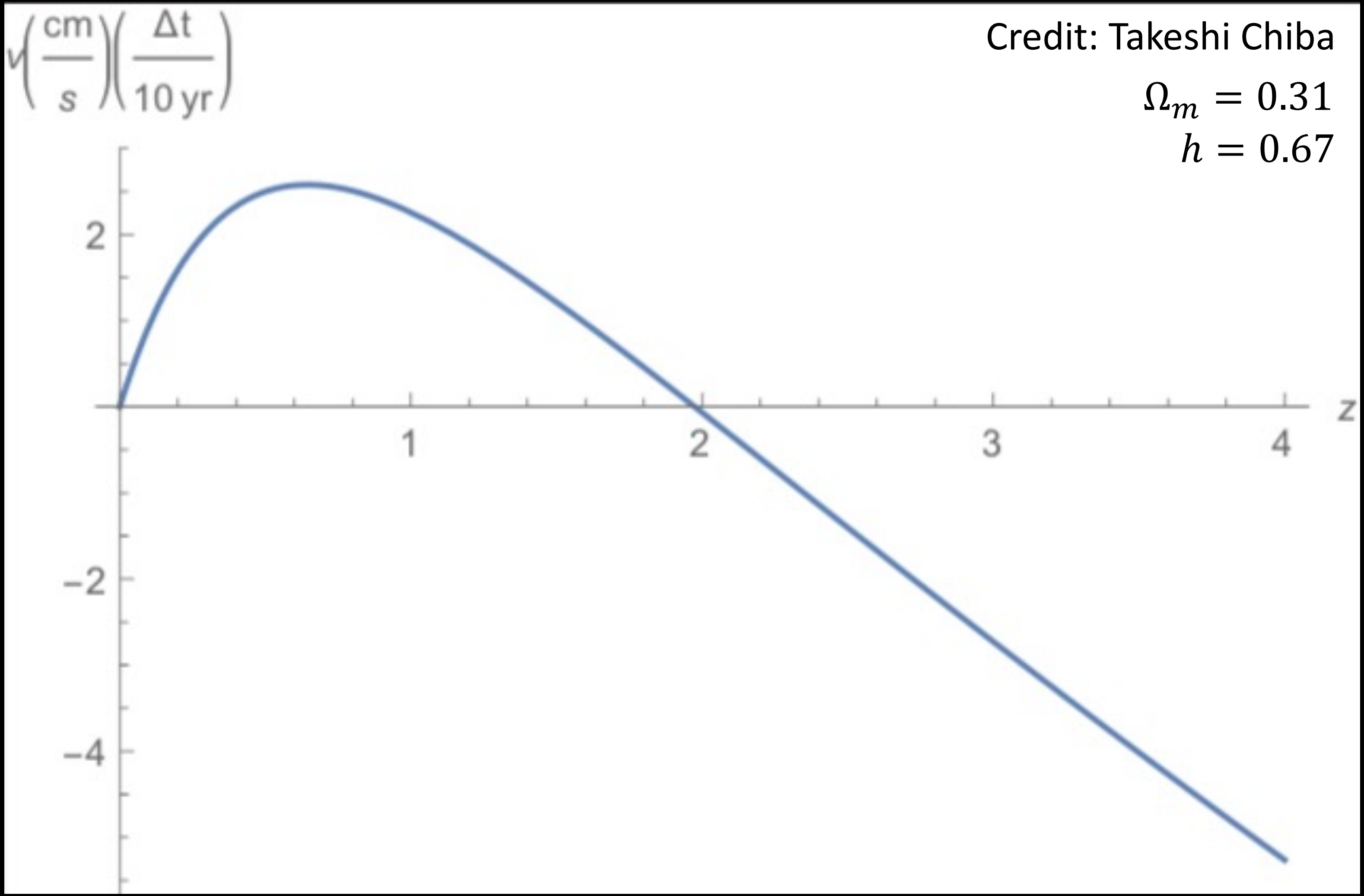
« Sandage-Loeb test »

Alan Sandage (1962): Direct measurement of the expansion rate of the universe by detecting the redshift at two different times

Abraham Loeb (1998): Measurement of the spectra of absorption line from high redshift quasars by using large telescopes with high-resolution spectrographs

Introduction

Cosmic velocity shift



Objective

Our research objective

In reality, our local motion which is determined by the proper motion of the Solar System also contributes to the changes in redshift

Analysis of the effect of our local motion on the redshift drift by calculating the difference in velocity of the Solar System for 10 years in any line-of-sight direction.

Our research goal

- Calculation of the difference in velocity of the Solar System for 10 years

$$\vec{a}_{sun-LG} * 10\ years = \vec{a}_{sun-mw}(2\ body) * 10\ years + \vec{a}_{mw-LG}(3\ body) * 10\ years$$

- Creation of the all-sky maps as a form of the Mollweide projection

Method

2-body problem (sun-mw)

Acceleration of the Solar System with respect to the GC

$$a_{sun-mw} = \frac{GM(r)}{D^2_{sun-mw}} \Rightarrow \boxed{a_{sun-mw} = \frac{V^2}{D_{sun-mw}}}$$

From the balance between centrifugal force and gravity,

$$\frac{V^2}{r} = \frac{GM(r)}{r^2} \Rightarrow M(r) = \frac{rV^2}{G}$$

In our research,

D_{sun-mw} **= r = 8.2±0.1 kpc, (Distance of sun-mw)**

V = 238±15 km/s (Circular velocity)

(Bland-Hawthon & Gerhard 2016)

Acceleration	Velocity difference for 10 years
$a_{sun-mw}(cm/s^2)$	$\Delta v_{sun-mw}(cm/s)$
$(2.25 \pm 0.28)\times10^{-8}$	7.09 ± 0.90 **This is big!!**

Method

3-body problem (MW-LG)

- **Other contributions to our local motion**

➢ **The contribution of the massive galaxies in the Local Group (MW, M31)**

- **According to current research finding (Pennarubia, J. et al. 2016), the Large Magellanic Cloud (LMC) also has a large total mass. (1/4 mass of the MW)**
- **In this research, we include the LMC in the Local Group dynamics**

$$\vec{a}_{mw-LG}(3\ body) * 10\ years$$

The MW dominates but we find that the contributions of the M31 and the LMC are also important

Results

Acceleration of each galaxy of the Local Group (3-body problem)

	MW	M31	LMC
$a_x(cm/s^2)$	$(-2.72 \pm 1.25)\times10^{-11}$	$(1.40 \pm 0.30)\times10^{-11}$	$(3.88 \pm 4.62)\times10^{-11}$
$a_y(cm/s^2)$	$(-1.13 \pm 0.40)\times10^{-9}$	$(-2.29 \pm 0.49)\times10^{-11}$	$(4.81 \pm 1.19)\times10^{-9}$
$a_z(cm/s^2)$	$(-7.68 \pm 2.65)\times10^{-10}$	$(1.03 \pm 0.22)\times10^{-11}$	$(3.14 \pm 0.78)\times10^{-9}$

$$\vec{a}_{mw-LG}(3\ body) * 10\ years$$

	X component	Y component	Z component
$\Delta v_{mw-LG}(cm/s)$	-0.009 ± 0.004	-0.355 ± 0.127	-0.242 ± 0.084

$$\vec{a}_{sun-LG} * 10\ years = \vec{a}_{sun-mw}(2\ body) * 10\ years + \vec{a}_{mw-LG}(3\ body) * 10\ years$$

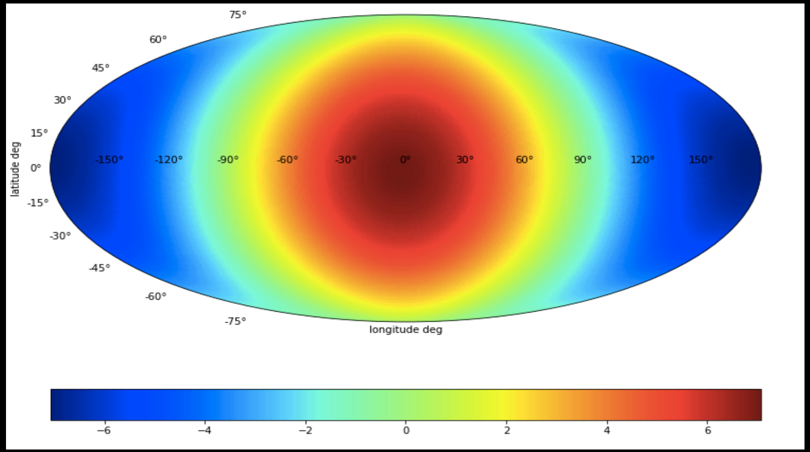
	X component	Y component	Z component
$a_{sun-LG}(cm/s^2)$	$(2.25 \pm 0.29)\times10^{-8}$	$(-1.13 \pm 0.40)\times10^{-9}$	$(-7.68 \pm 2.65)\times10^{-8}$
$\Delta v_{sun-LG}(cm/s)$	7.08 ± 0.90	-0.36 ± 0.13	-0.24 ± 0.08

Results

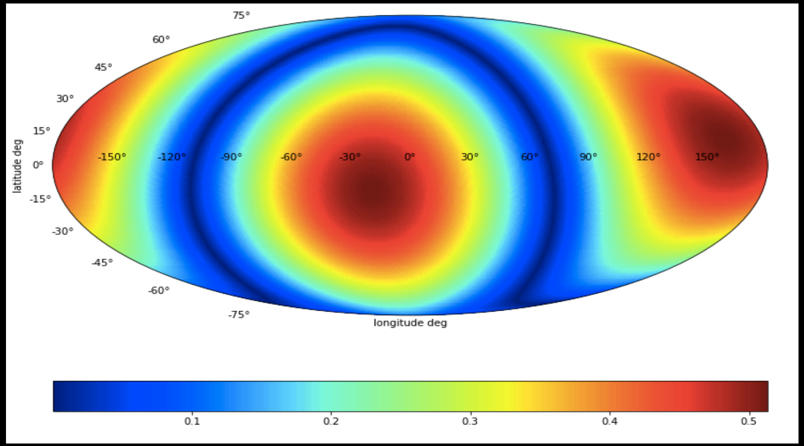
l= [-pi, pi], b= [-pi/2, pi/2]

All-sky maps (Mollweide projection method)

Δv_{sun-LG}

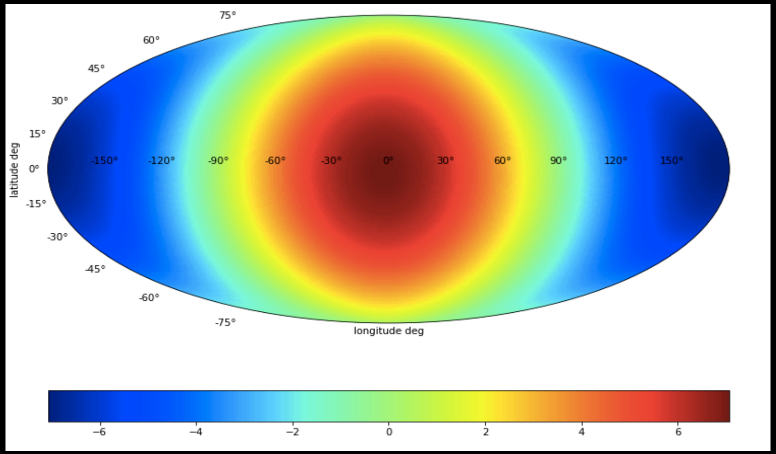


Δv mean **max = 7.16 cm/s**

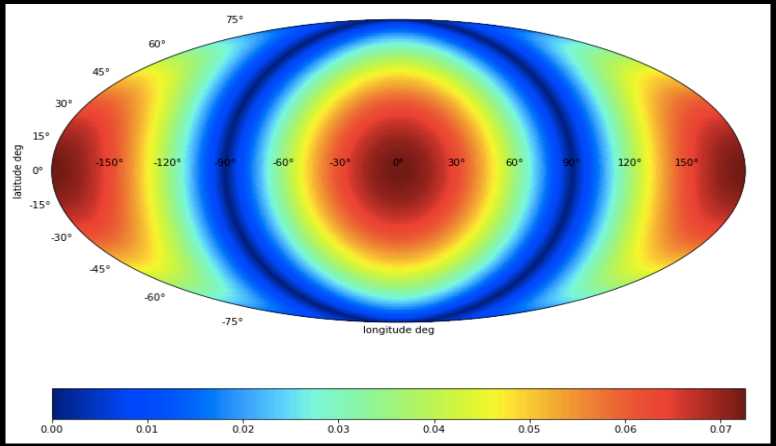


Δv std **max = 0.51 cm/s**

Δv_{sun-mw}

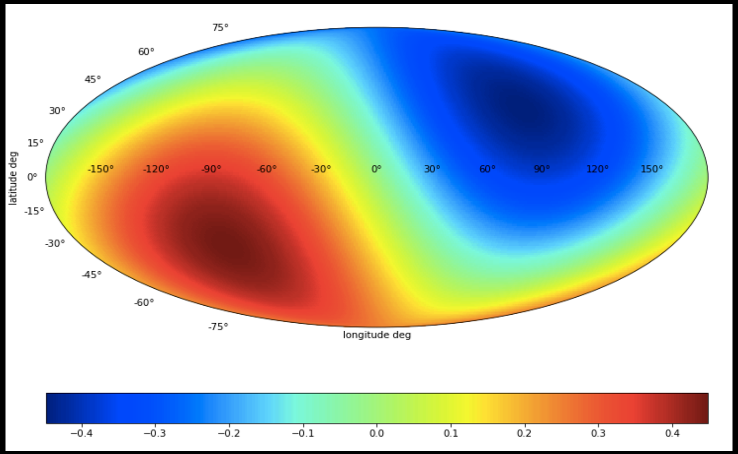


Δv **mean max = 7.15 cm/s**

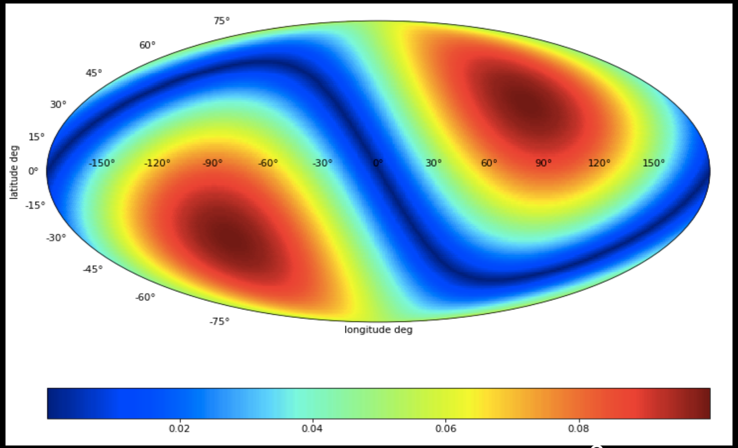


Δv std **max = 0.49 cm/s**

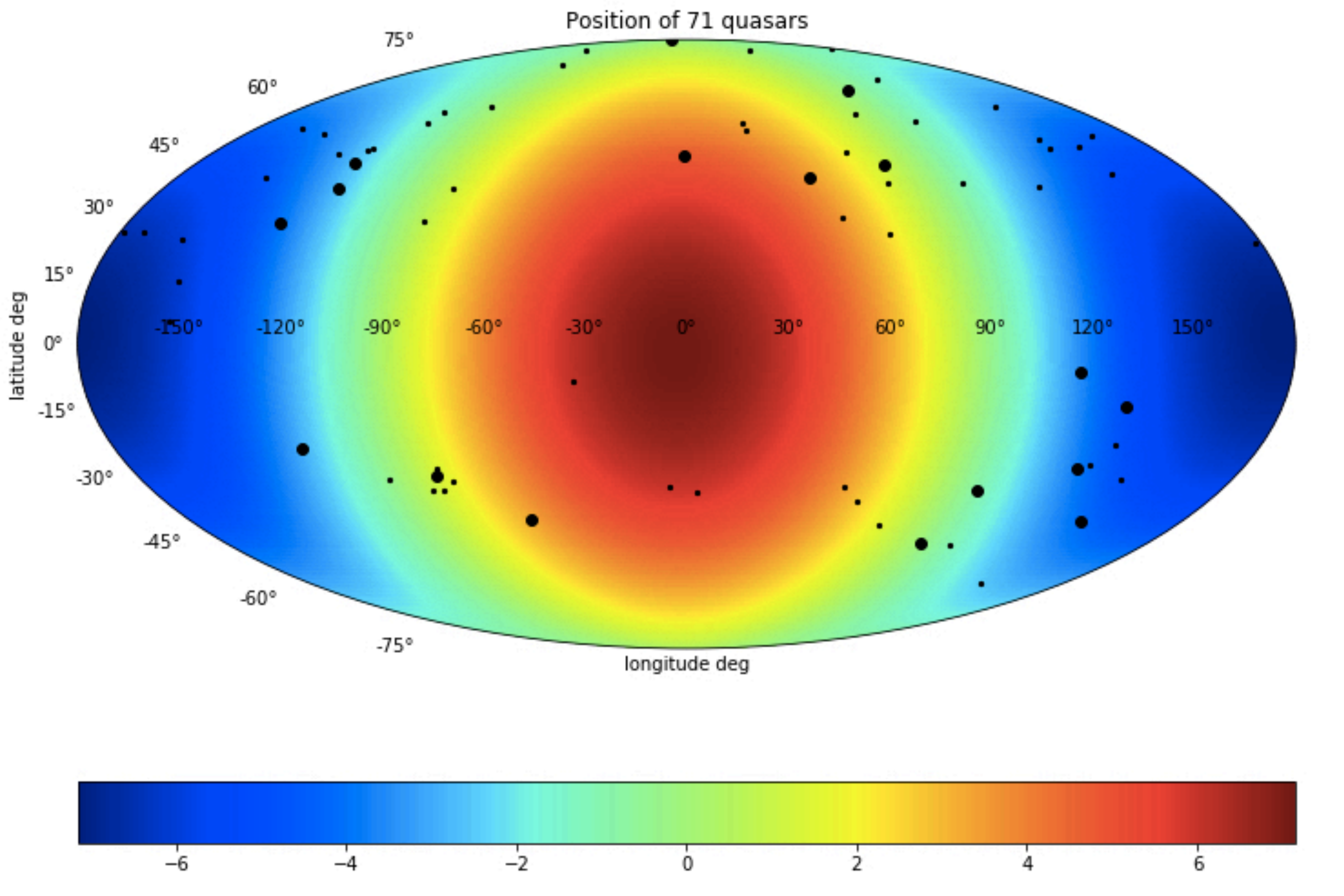
Δv_{mw-LG}



Δv **mean max = 0.46 cm/s**



Δv std **max = 0.20 cm/s**



Position of 71 quasars
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°
latitude deg
longitude deg
−6
−4
−2
0
2
4
6

Conclusions

- Our local motion yields the maximum redshift drift signal of 7.2 cm/s over 10 years in the direction of Galactic Center
  - ➢ The maximum uncertainty is 0.5 cm/s

- 7.2 cm/s is comparable to the expected cosmological signal of order a few cm/s; thus, correcting for the effect of local motion is essential!

- Dominated by the acceleration toward Galactic Center, but the contributions from M31 and LMC cannot be ignored, especially in the direction of LMC

References

Parameters	Values	References
Solar mass	$(1.9884 \pm 0.0002)\times 10^{30}\ kg$	IAU 2009/2012
Gravitational constant	$(6.67428 \pm 0.00067)\times 10^{-11}\ m^3/kg/s^2$	IAU 2009/2012
Circular velocity	$238 \pm 15\ \text{km/s}$	Bland-Hawthon & Gerhard 2016

Galaxy	Mass (Msun)	Dsun (kpc)	L (degree)	B (degree)
MW	$1.04^{+0.26}_{-0.23}\times 10^{12}$ Jorge P. et al. 2016	8.2 ± 0.1 Bland-Hawthon & Gerhard 2016	0	0
M31	$1.33^{+0.39}_{-0.33}\times 10^{12}$ Jorge P. et al. 2016	783 ± 25 Jorge P. et al. 2016	121.17432 simbad	21.573311 simbad
LMC	$0.25^{+0.09}_{-0.08}\times 10^{12}$ Jorge P. et al. 2016	51 ± 2 Jorge P. et al. 2016	280.4652 simbad	32.8884 simbad

Annex

$$a_{mw-LG}\ (3 - body)$$

$$\ddot{x}i = -Gmj * \frac{(xi - xj)}{Dij^3} - Gmk * \frac{(xi - xk)}{Dik^3}$$

$$\ddot{y}i = -Gmj * \frac{(yi - yj)}{Dij^3} - Gmk * \frac{(yi - yk)}{Dik^3}$$

$$\ddot{z}i = -Gmj * \frac{(zi - zj)}{Dij^3} - Gmk * \frac{(zi - zk)}{Dik^3}$$

Right-handed galactic coordinate system

$$x_i = D_{sun} \times cos(l) \times cos(b) - D_{sun-mw}$$

$$y_i = D_{sun} \times sin(l) \times cos(b)$$

$$z_i = D_{sun} \times sin(b)$$

$$D_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}$$

Simulating Lyman-α emitting galaxies for HETDEX

Shun Saito

MPA → **Missouri S&T** (since Jan 2019)

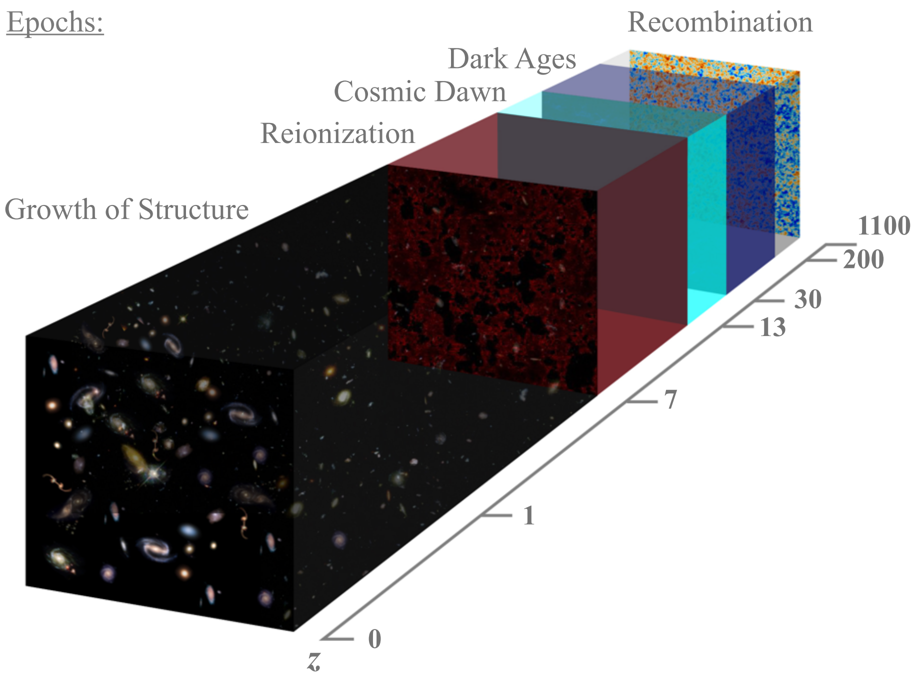
"Cosmic Acceleration" Symposium

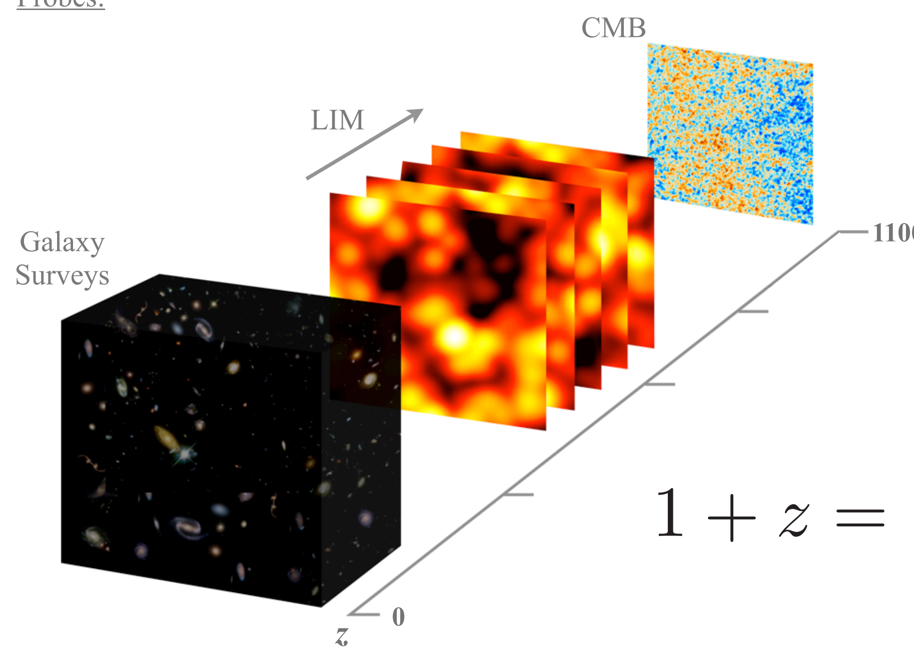
Yukawa Institute, Kyoto, Japan

Mar 4th 2019

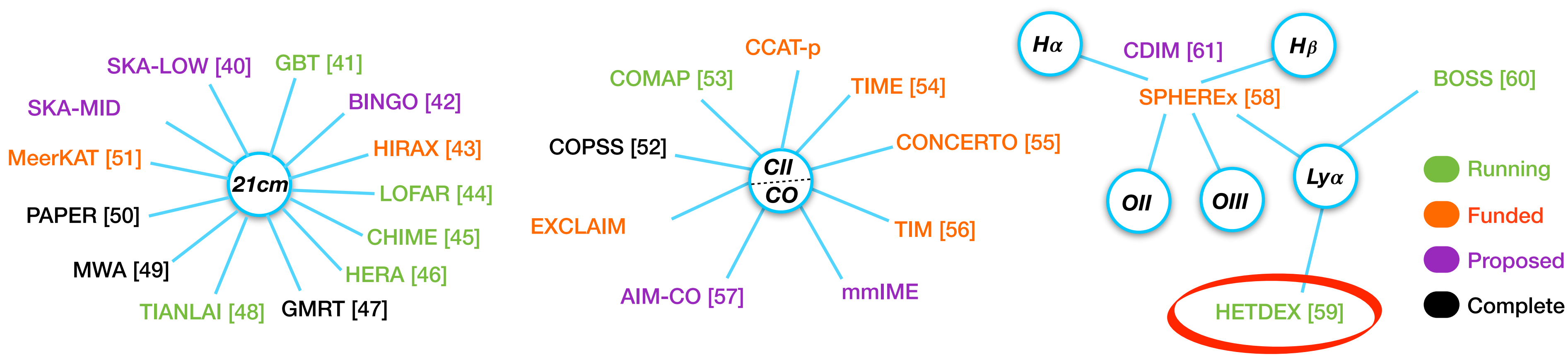
Intensity Mapping is Future

Kovetz, **SS**+, Astro2020, coming soon





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



$\lambda_{Ly\alpha}$=1215Å

HETDEX as a DE survey

- ***The Hobby-Eberly Telescope Dark Energy Experiment (2019-2022)***

- 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, **[*Missouri S&T*]**
- Instrument
  - **10m** Hobby-Eberly Telescope at McDonald Observatory
  - **35k** spectra **(448 fibers/IFU x 78 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

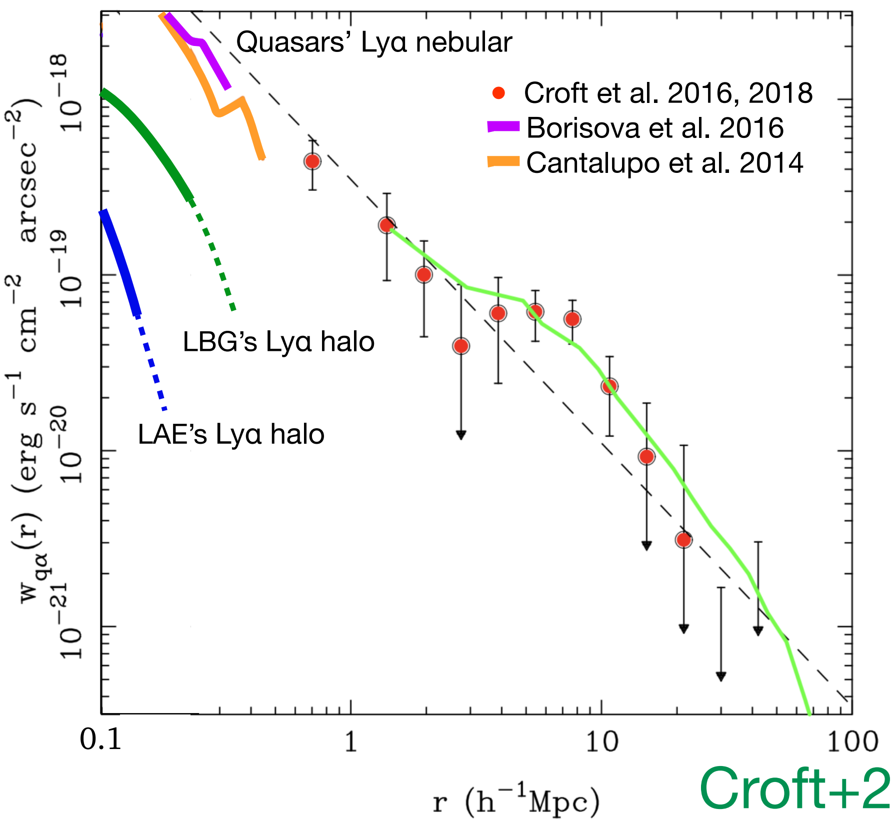
HETDEX as a Lyα IM survey

- ***We can do better than the original plan!***

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

➡ Original design: 1.7M/140M fibers, i.e., only 1.2% is used

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



Croft+2018 & modified by R.Momose

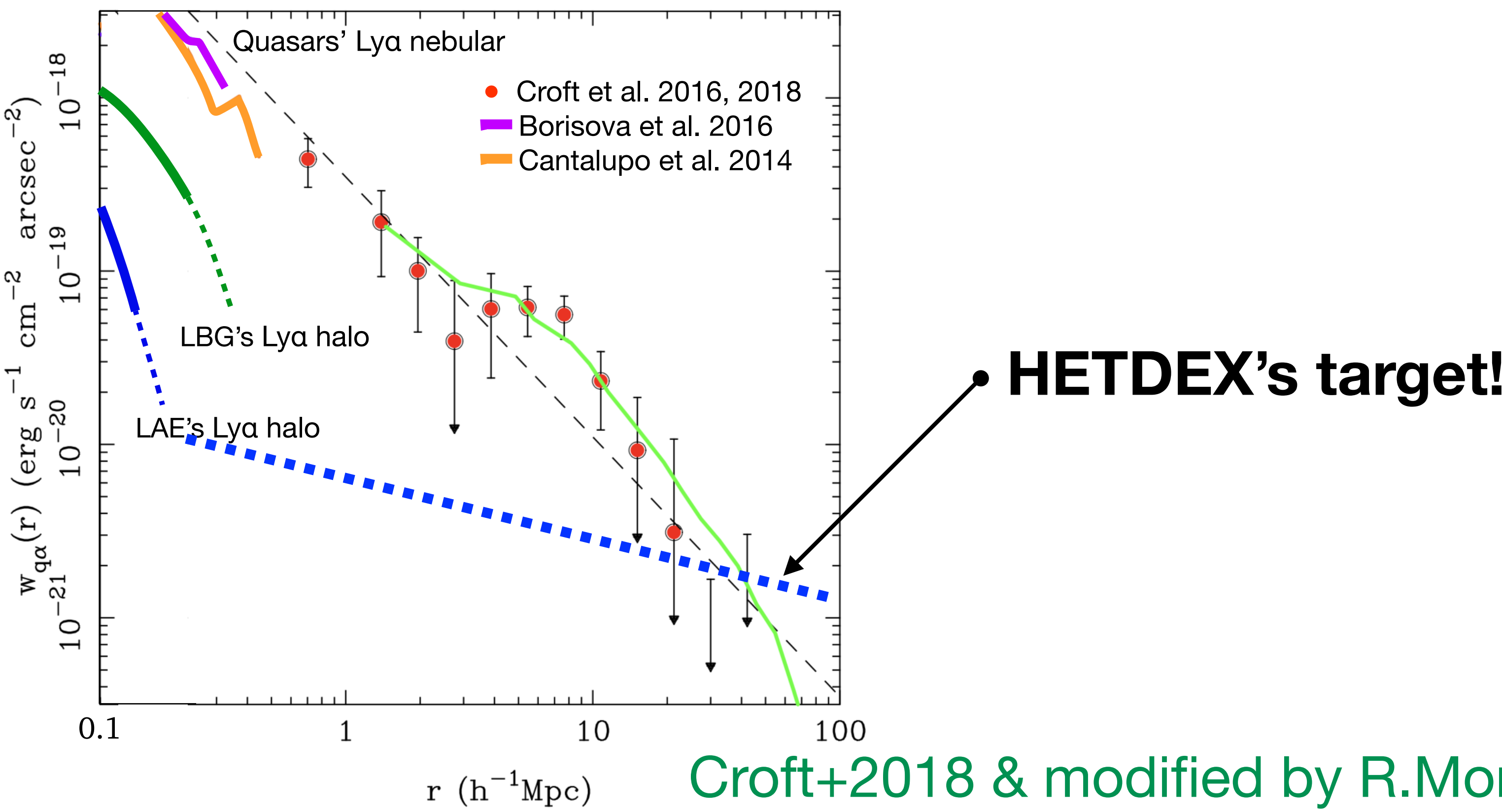
HETDEX as a Lyα IM survey

◆ ***We can do better than the original plan!***

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

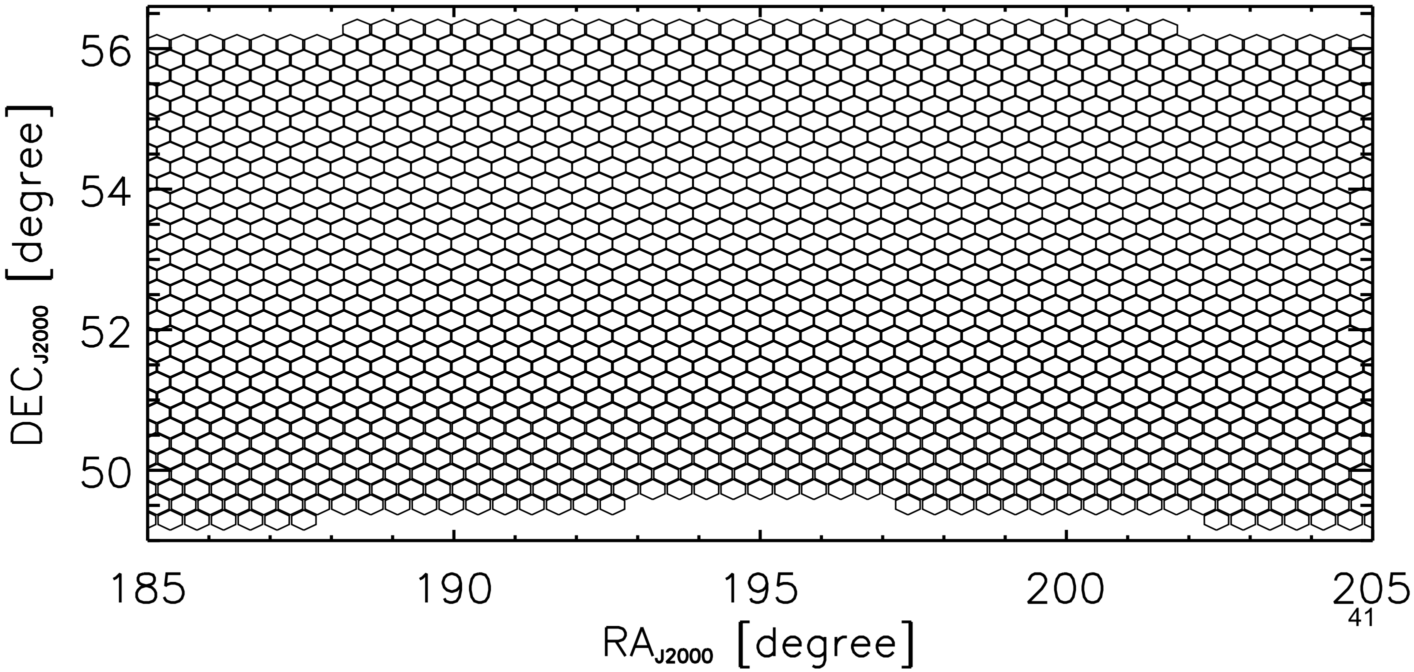
➡ Original design: 1.7M/140M fibers, i.e., only 1.2% is used

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

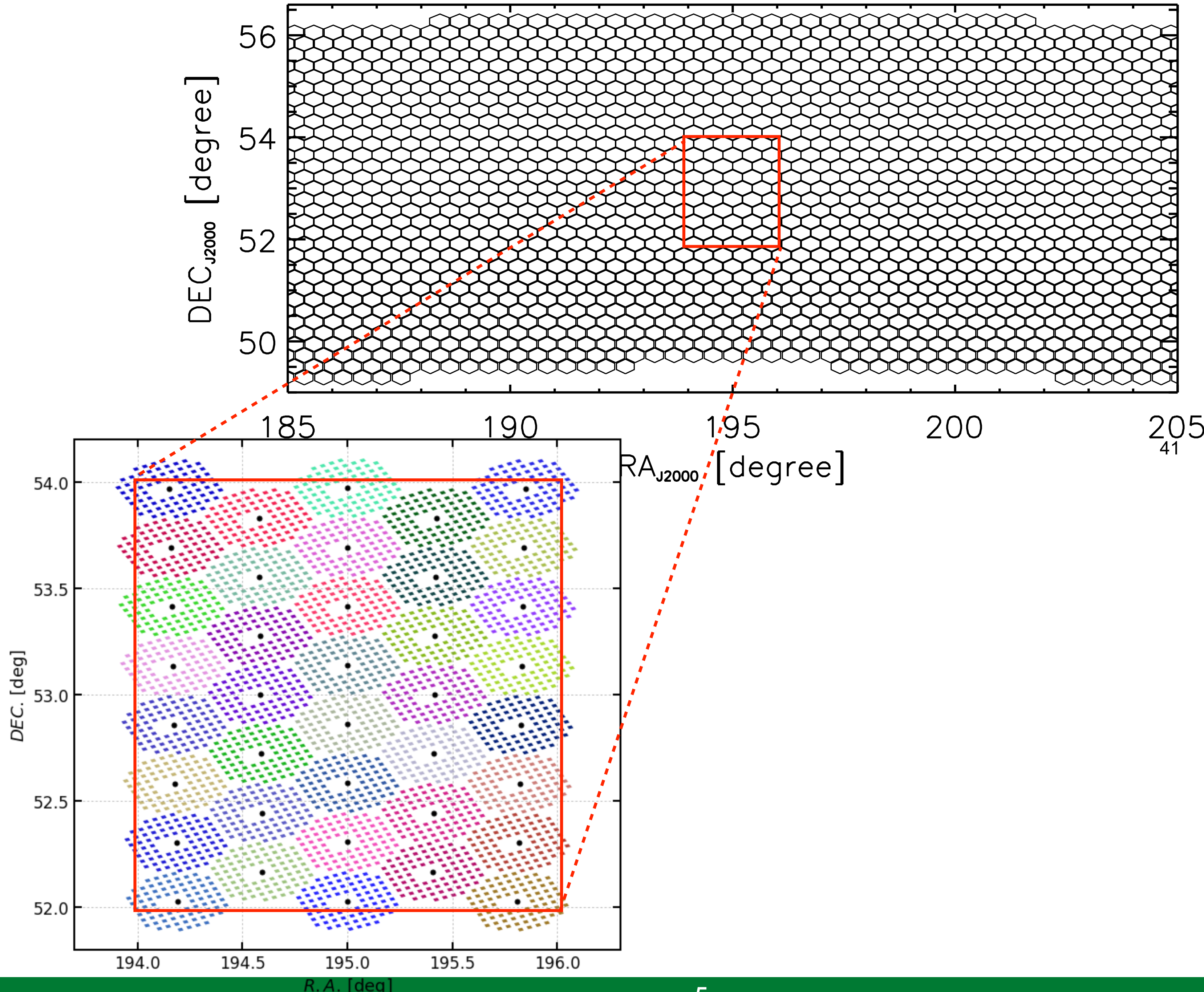


Croft+2018 & modified by R.Momose

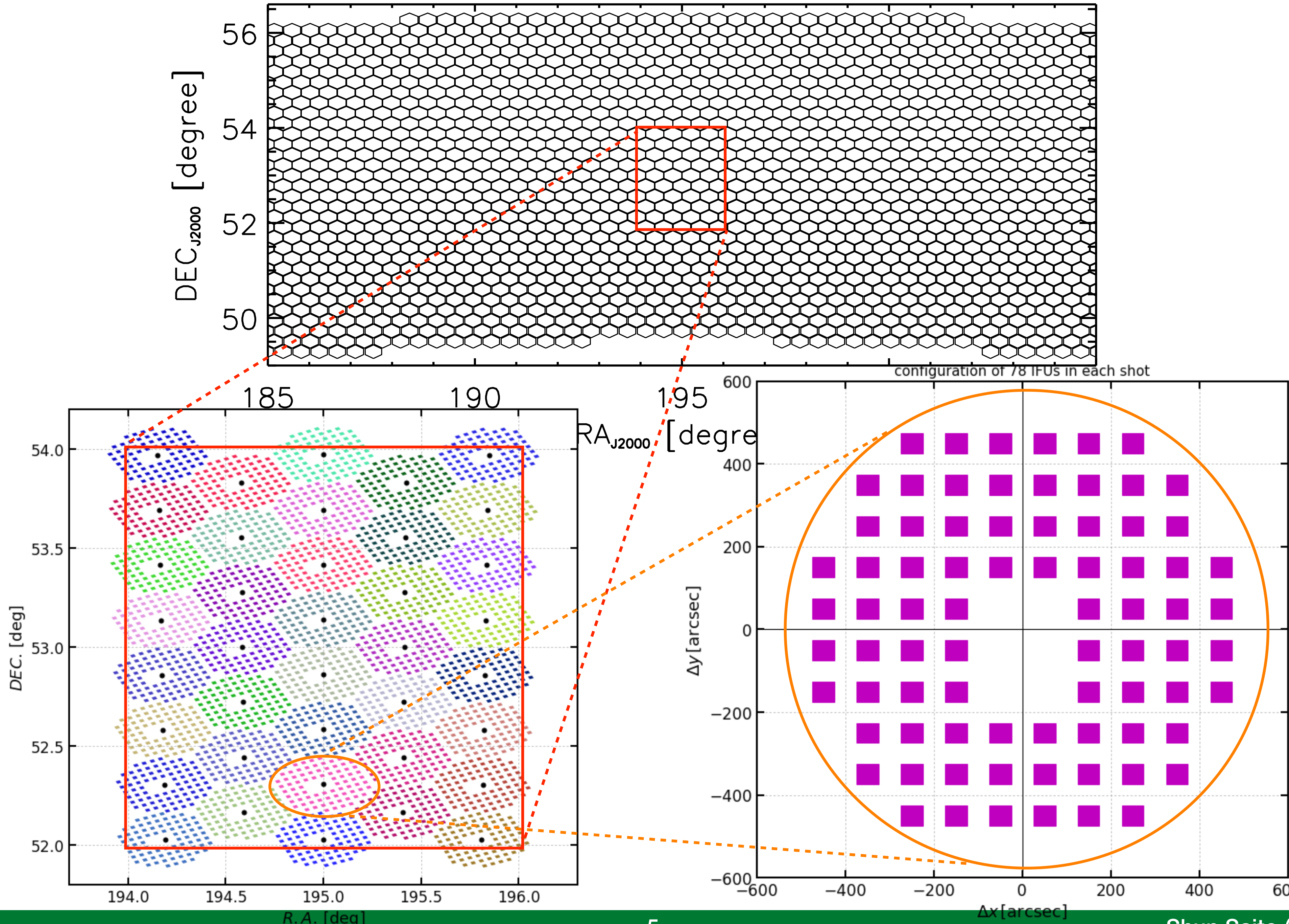
Simulating LogN LAE IM



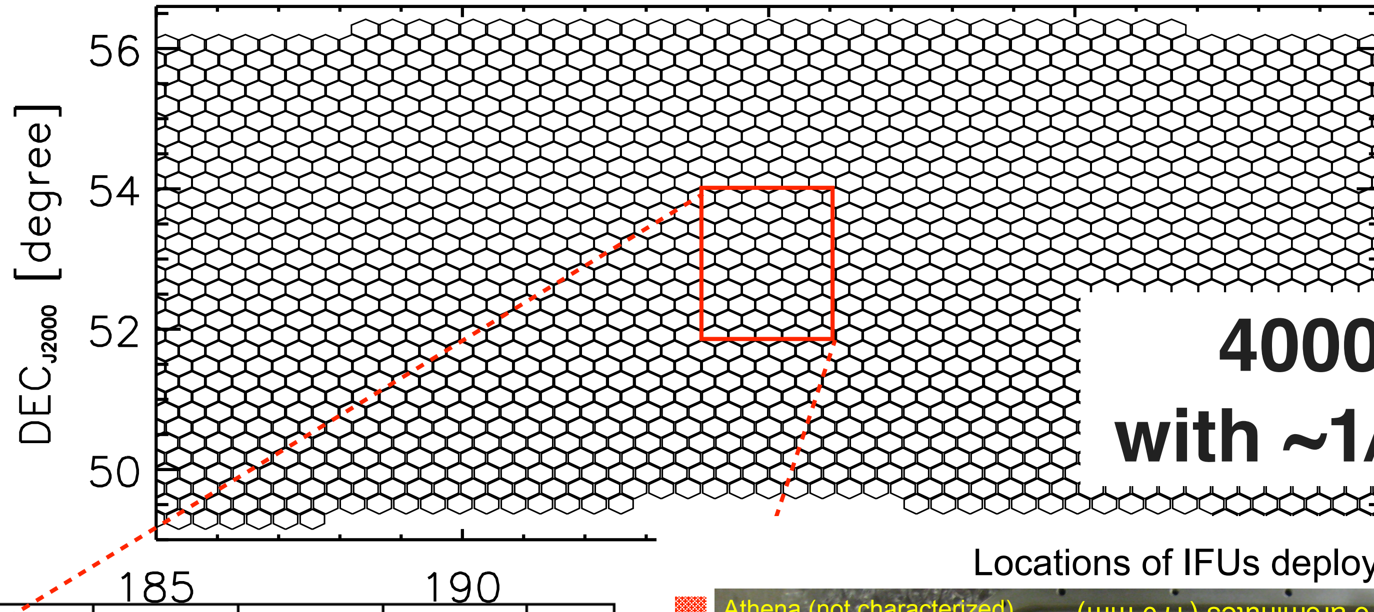
Simulating LogN LAE IM



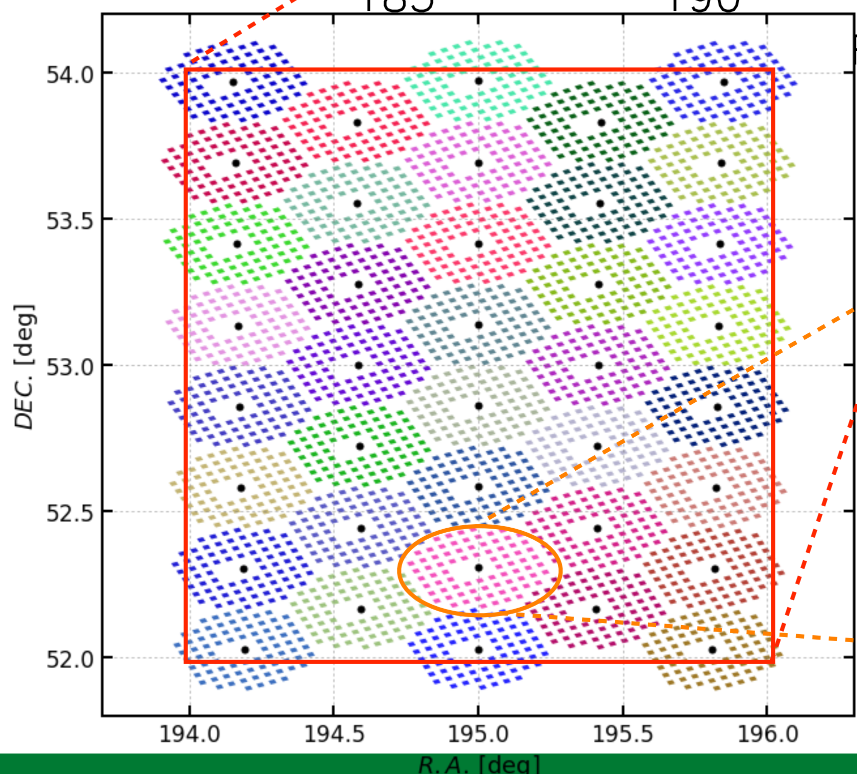
Simulating LogN LAE IM



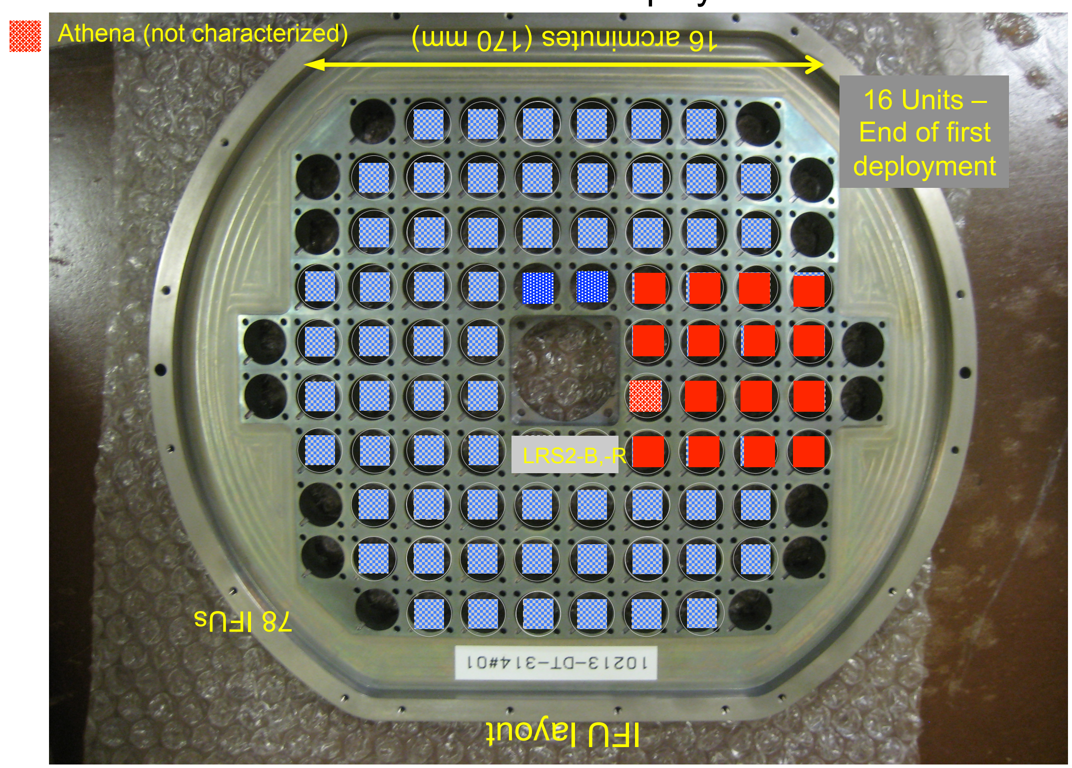
Simulating LogN LAE IM



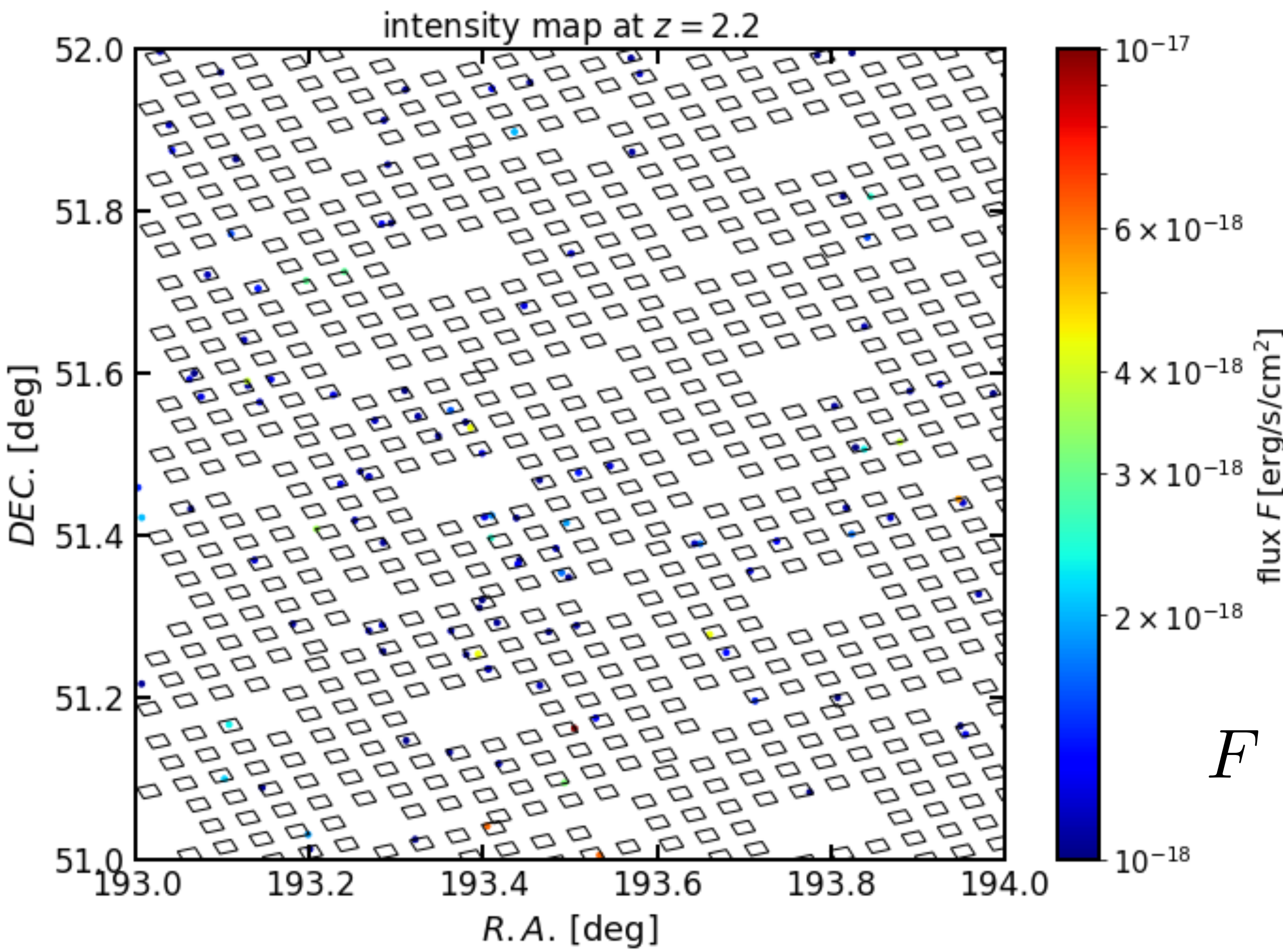
4000 shots with ~1/4.5 filling



Locations of IFUs deployed in IHMP



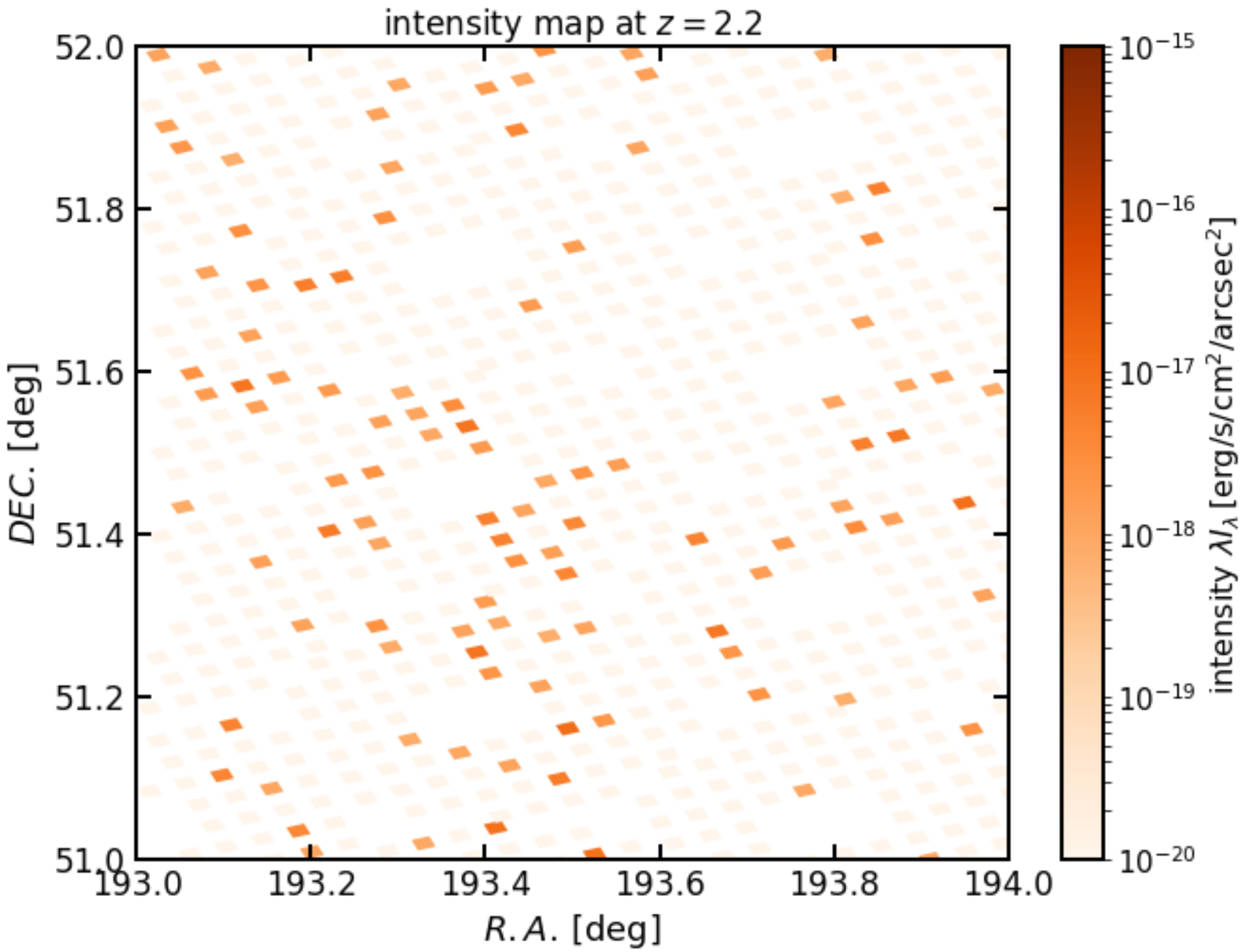
Simulating LogN LAE IM



$$F = \frac{L}{4\pi D_L^2}$$

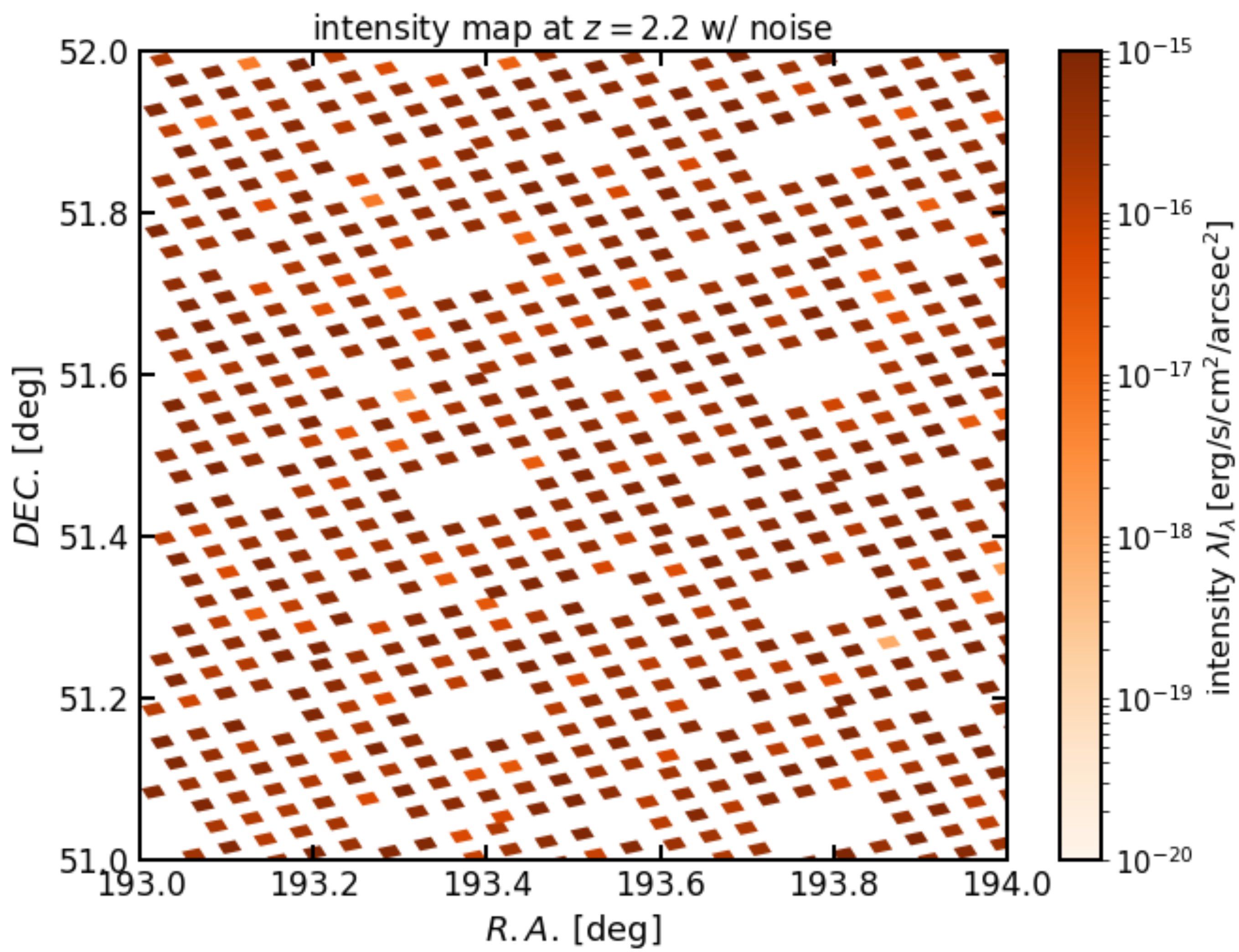
- Luminosity and positions are assigned so that the simulated LogN galaxies recovers ***the input LF & P(k)***.

Simulating LogN LAE IM



$$\lambda I_\lambda = \Delta F \times \frac{\lambda \Delta V_{\rm pix}}{\Delta\Omega\Delta\lambda} = \int dL \frac{dn}{dL}\frac{L}{4\pi D_L^2} \times (1+z)^3 D_A^2 \frac{c}{H}$$

Simulating LogN LAE IM



$d\Omega_{\mathrm{fiber}} = (1.5''/2)^2 \times \pi$

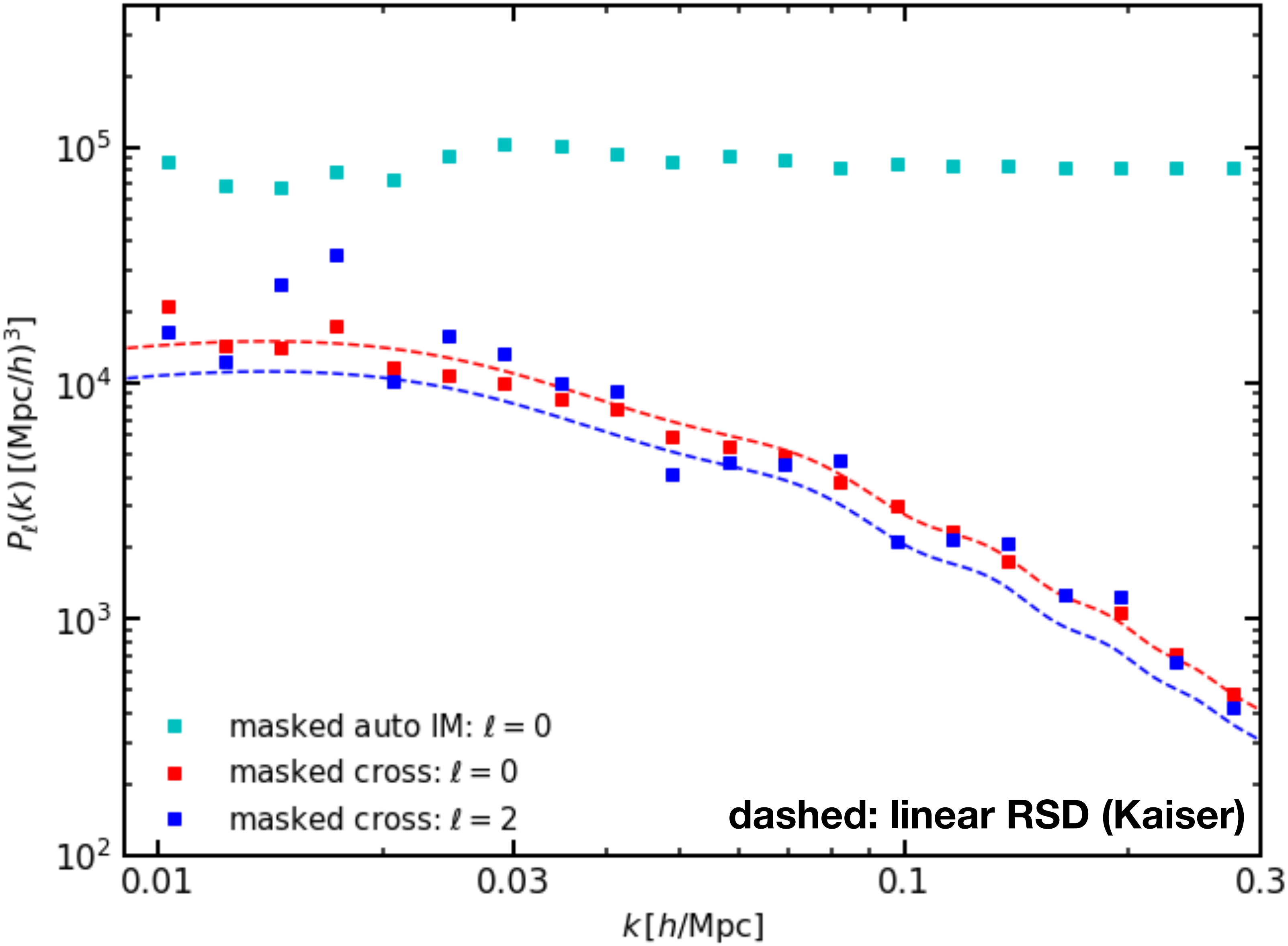
$d\Omega_{\mathrm{IFU}} = (48.96'')^2$

+ HETDEX noise

$$\sigma_{\lambda I_\lambda}^{\mathrm{IFU}} = \sigma_{\lambda I_\lambda}^{\mathrm{fiber}} \sqrt{\frac{d\Omega_{\mathrm{fiber}}}{d\Omega_{\mathrm{IFU}}}}$$

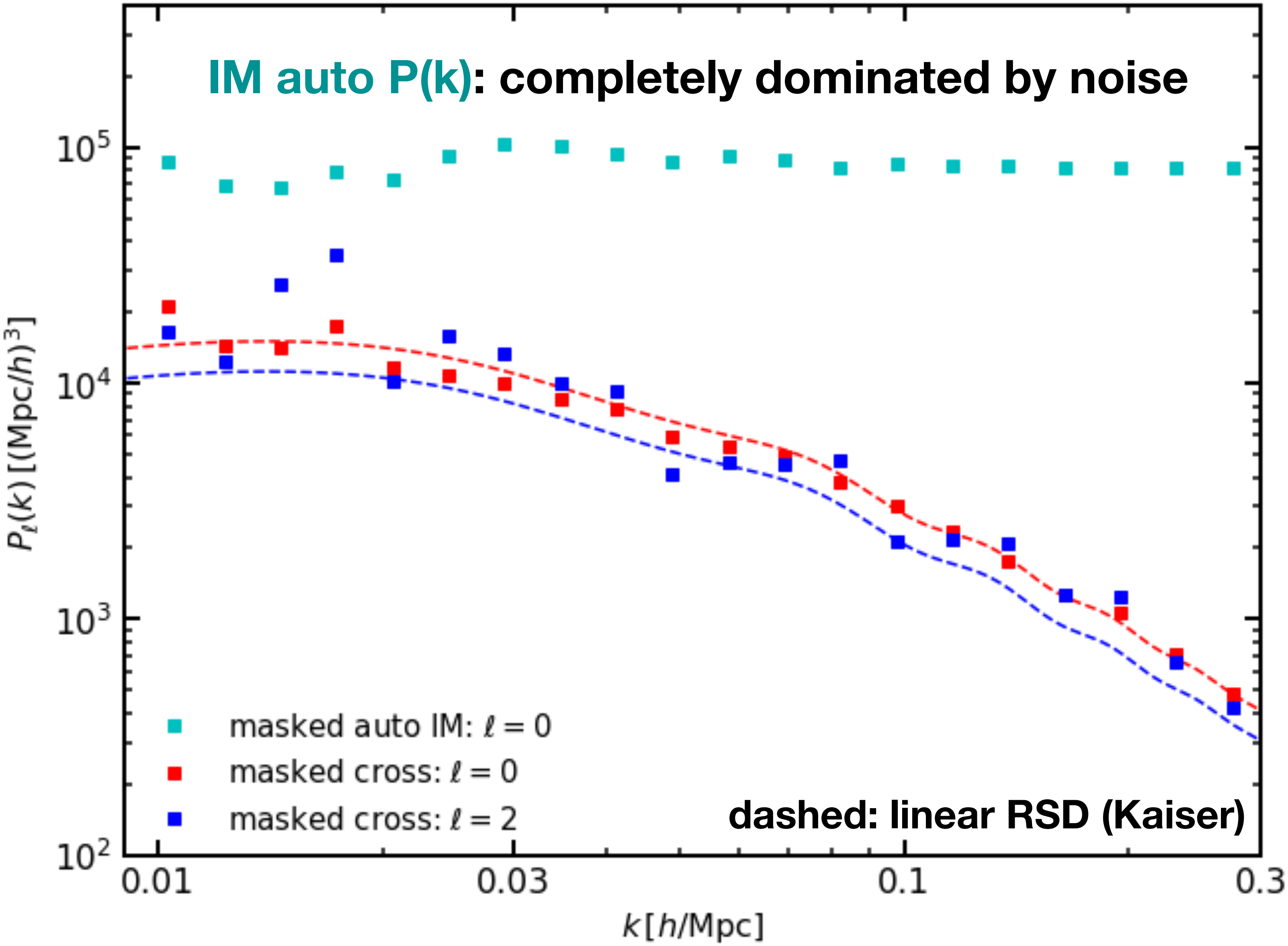
Simulating LogN LAE IM

➤ Developed P(k) estimator code



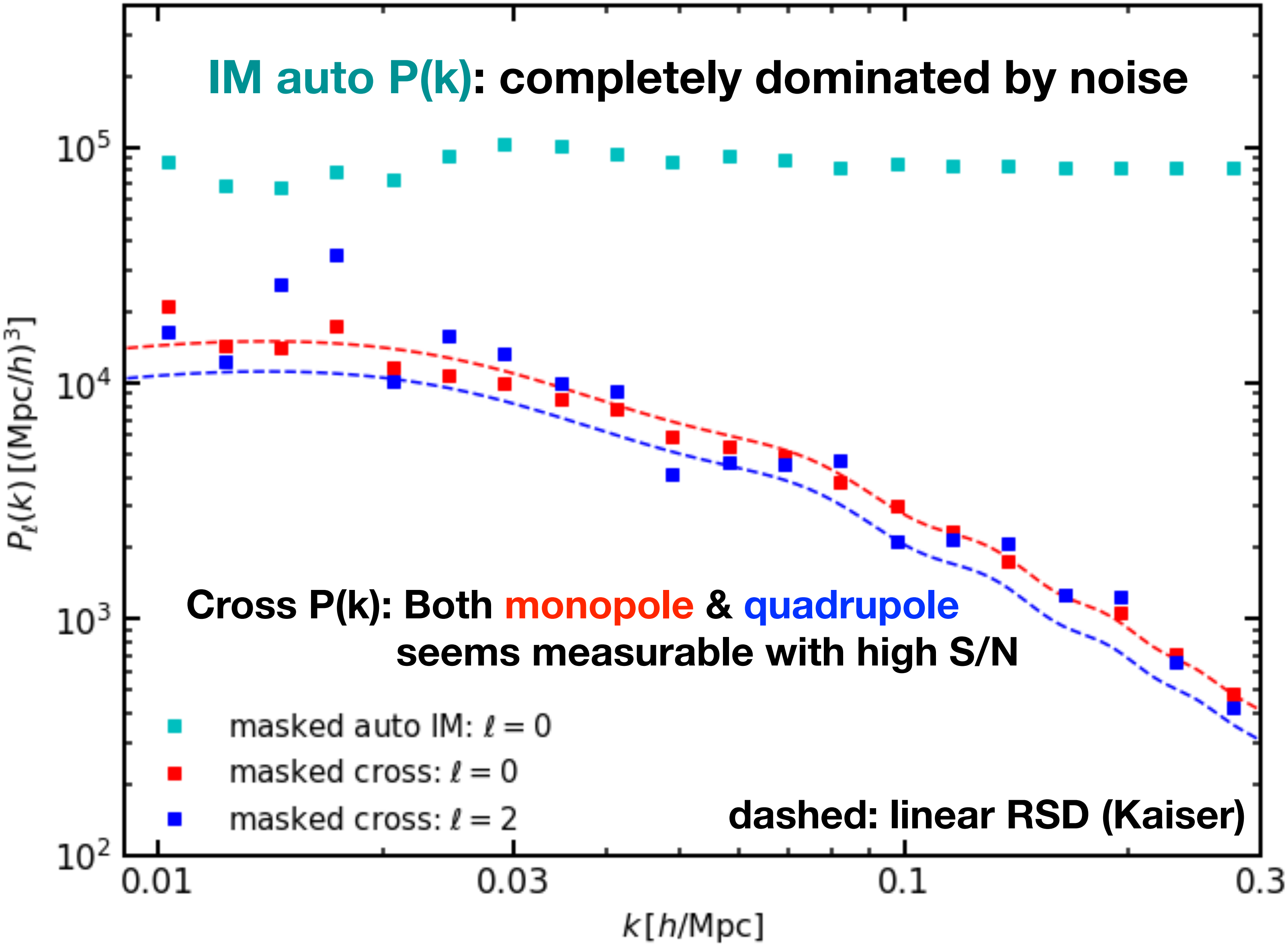
Simulating LogN LAE IM

- Developed P(k) estimator code



Simulating LogN LAE IM

- Developed P(k) estimator code

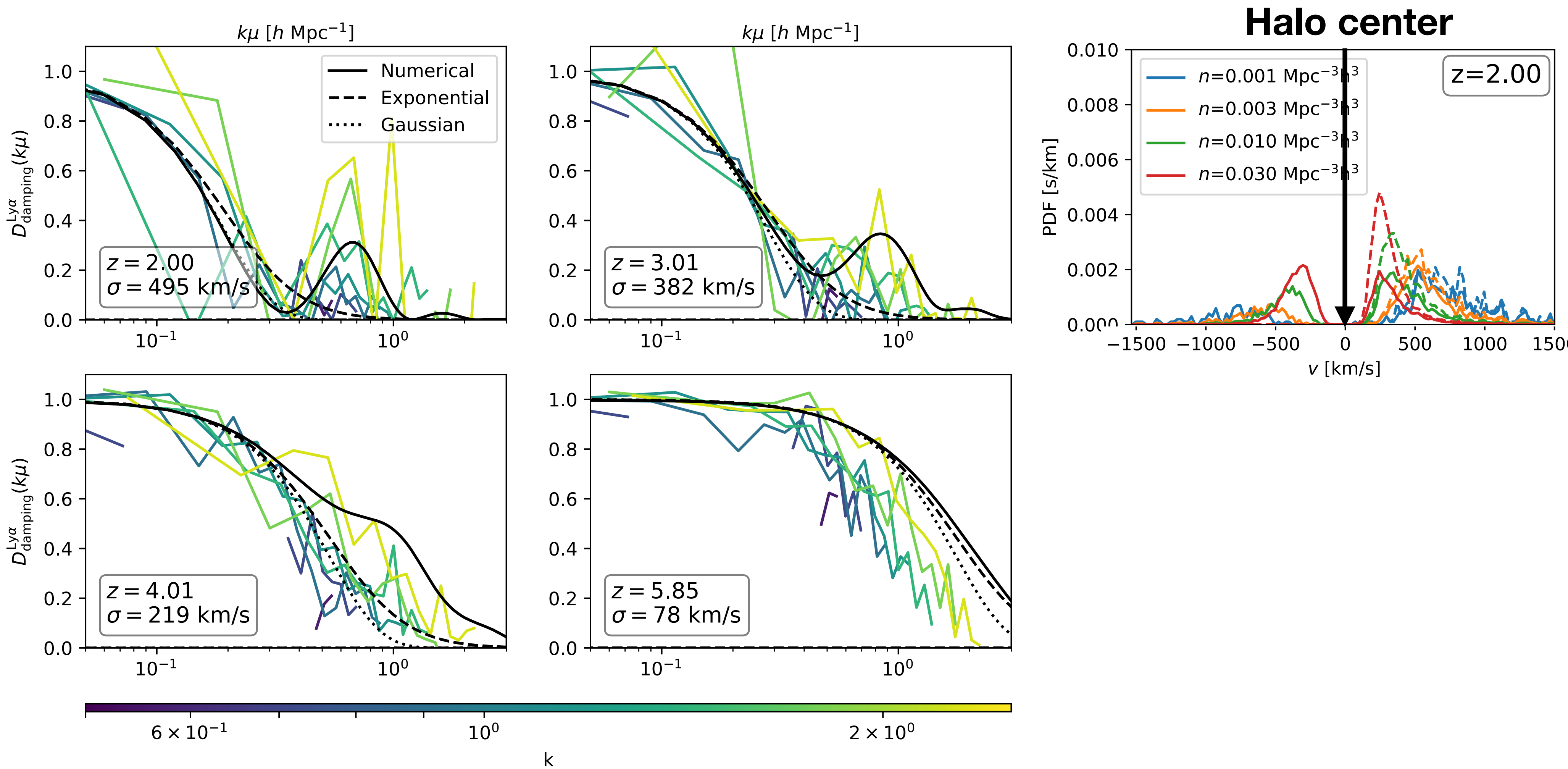


Physical RT Simulation

Behrens, **Byrohl**, ***SS***, **Niemeyer**, A&A (2018), **Byrohl**, ***SS***, Behrens, in prep.

- Run Lyα Radiative Transfer code on the ***Illustris***

  - find a new *Finger-of-God* damping due to RT.



Summary

- ***HETDEX as a Lyα IM survey***

  - Fully make use of its **blind** nature.

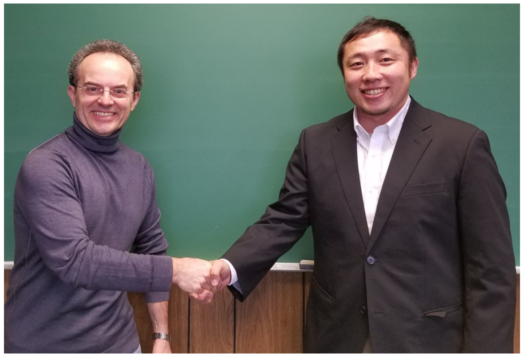
  - First results coming soon! Hopefully pioneering IM cosmology.

- ***Preparing analysis & simulation pipeline***

  - End-to-End Log-Normal simulation

  - Physical Radiative Transfer simulation

S&T Physics opens a window to the sky



Marco Cavaglia, Shun Saito

Starting in January, two new faculty, Marco Cavaglia and Shun Saito, will work to unravel the mysteries of the universe at S&T. Cavaglia, who joins the department after 15 years at the University of Mississippi, is an expert on gravitational physics and multi-messenger astrophysics. Saito, from the Max Planck-Institute for Astrophysics in Germany, works on observational cosmology. They will collaborate to develop a new astrophysics program at S&T. Detailed faculty profiles for Marco Cavaglia and Shun Saito will be published in the next edition of the newsletter.

Multi-messenger astrophysics and precision cosmology are research areas at the forefront of today's physics. Multi-messenger astrophysics studies celestial phenomena through different physical carriers (electromagnetic waves, gravitational waves, particles and cosmic rays). Cosmology studies the origin and large-scale structure of the Universe.

Join our new astro group if interested in working on *HETDEX* and/or *LIGO*!

S&T Physics News Letter 2019