Cosmology with Subaru Hyper Suprime-Cam

Masahiro Takada

On behalf of asrtro/cosmology group at IPMU

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

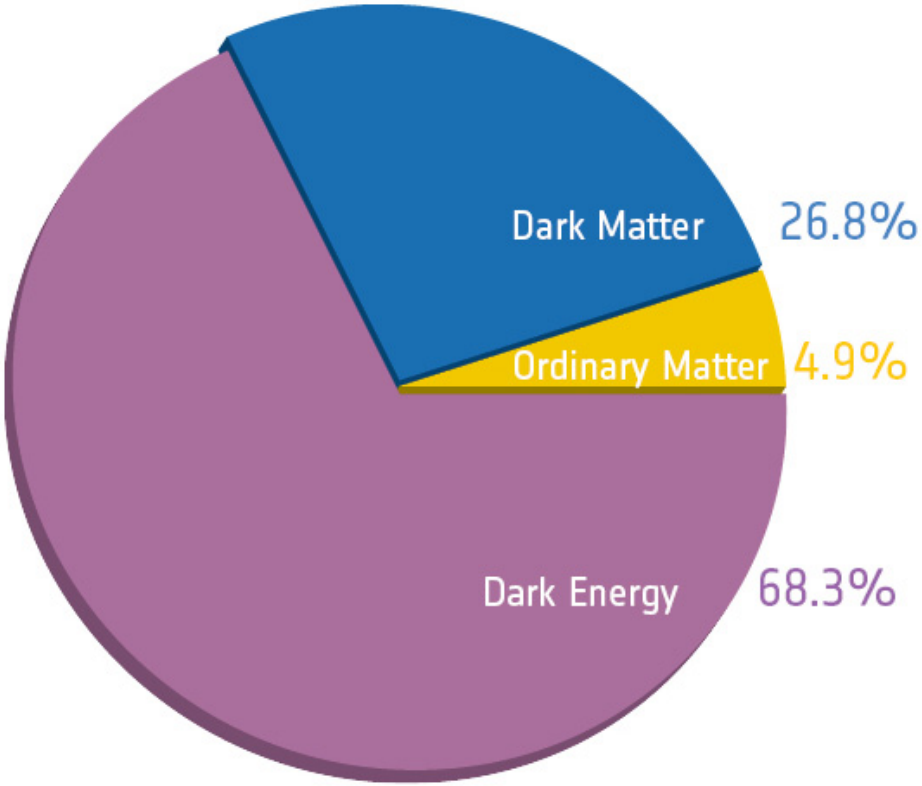
東京大学 THE UNIVERSITY OF TOKYO

wpi

IPMU zoo!

physicists, astronomers, mathematicians

Big Questions



- What is the universe made of?
  - the nature of **dark matter**
- What is the fate of the universe?
  - the nature of **dark energy**
- Why do we exist?
  - **Baryonic** processes (astrophysics, the origin of Milky Way and other galaxies)

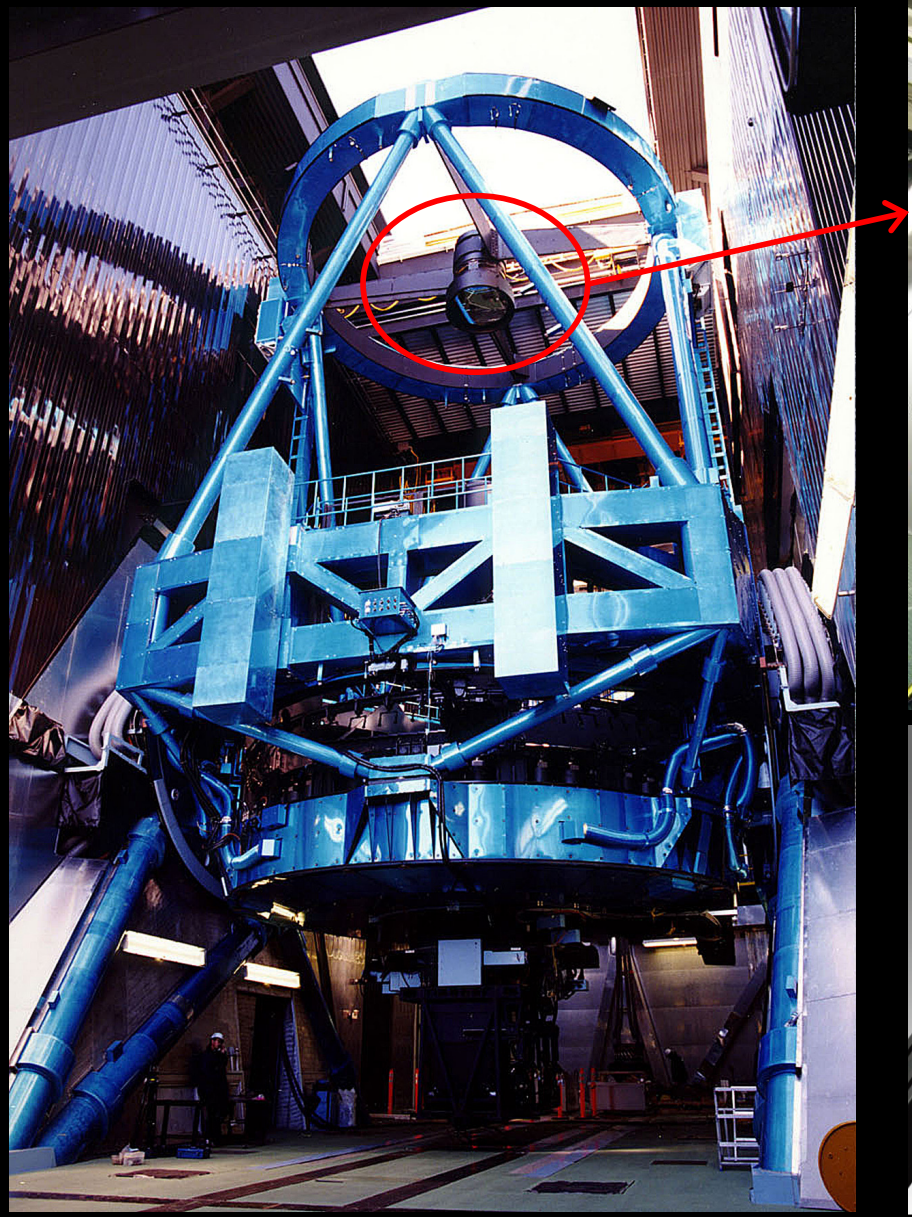
Subaru Telescope

Prime-Focus Instrument

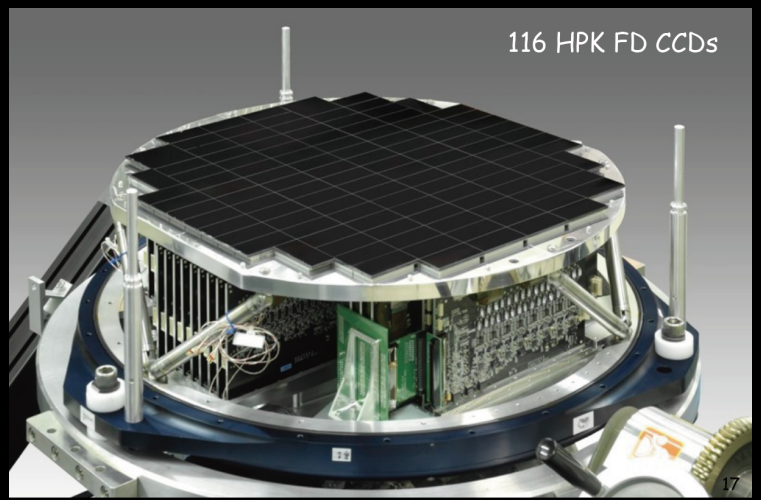
Subaru Telescope
(NAOJ)

@ summit of Mt. Mauna Kea (4200m), Big Island, Hawaii

Hyper Suprime-Cam

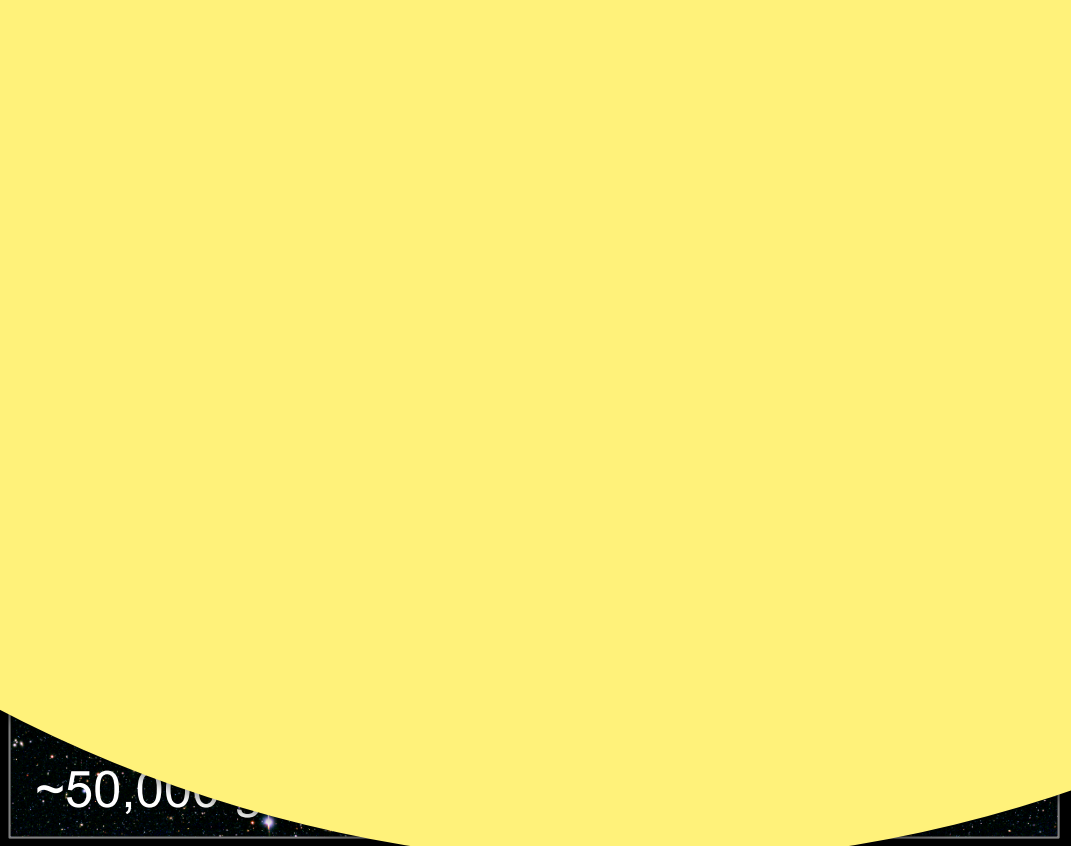


- largest camera
- 3m high
- weigh 3 ton
- 104 CCDs (~0.9B pixels)



Hyper Suprime-Cam FoV

- **Fast**
- a cos



すばる望遠鏡に搭載された Hyper Suprime-Cam

2012年8月16日撮影 (180倍速)

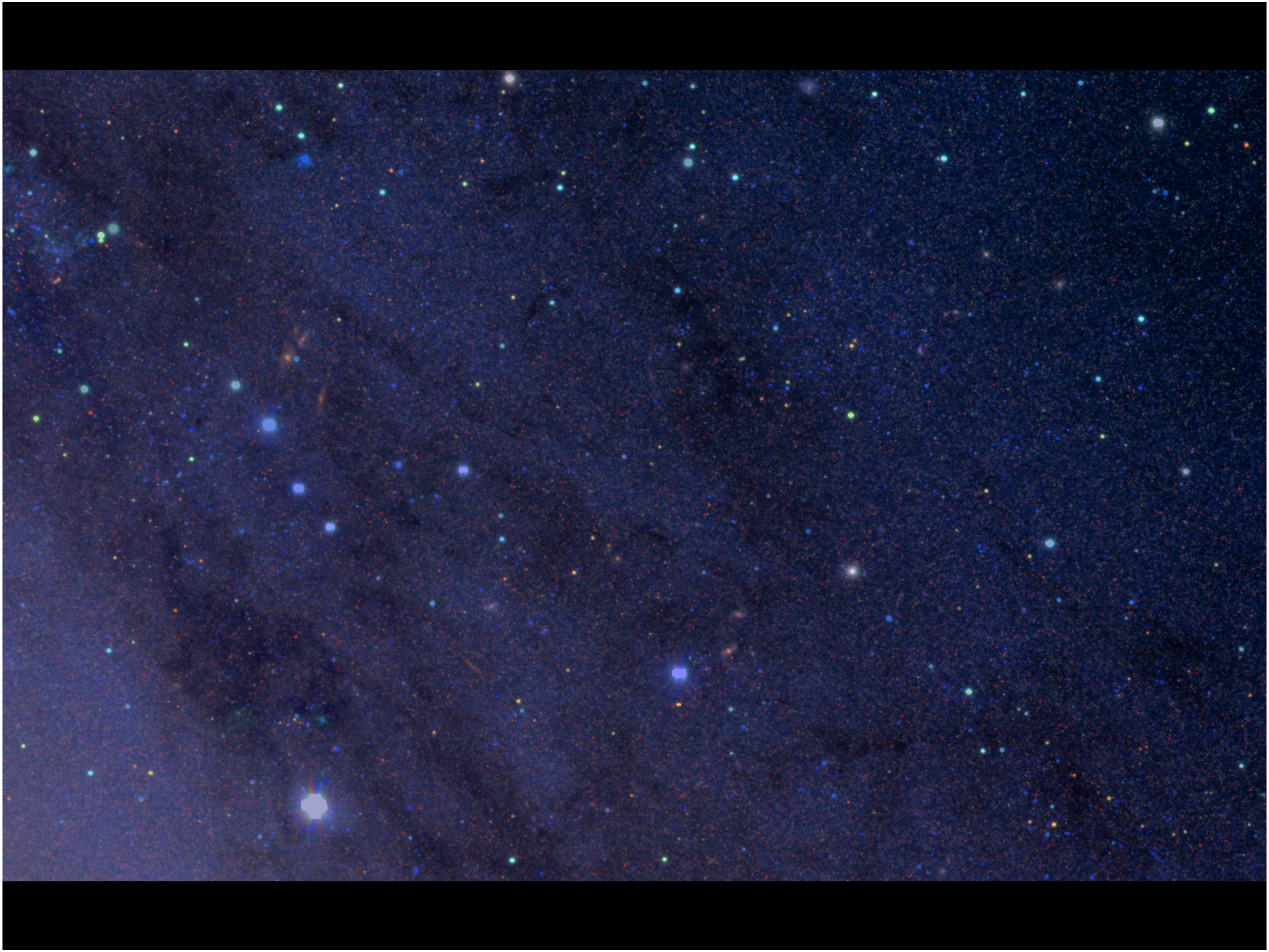
Installing Hyper Suprime-Cam on the Subaru Telescope

HSC Image of M31 (HSC FoV=1.8 sq. degrees)

Naoki Yasuda

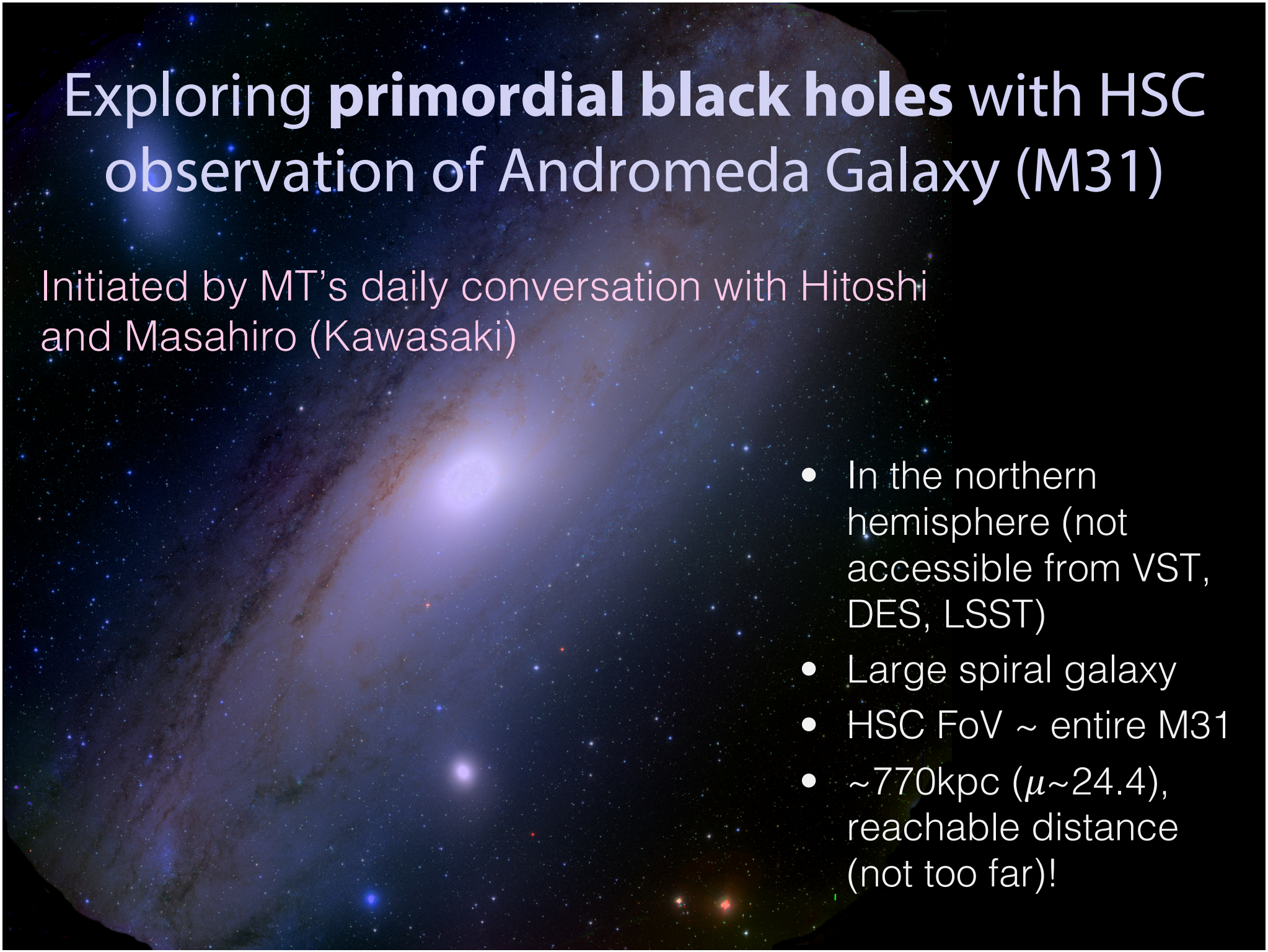
Steven Bickerton
(former IPMUer)

Robert Lupton
(Princeton)



Exploring **primordial black holes** with HSC observation of Andromeda Galaxy (M31)

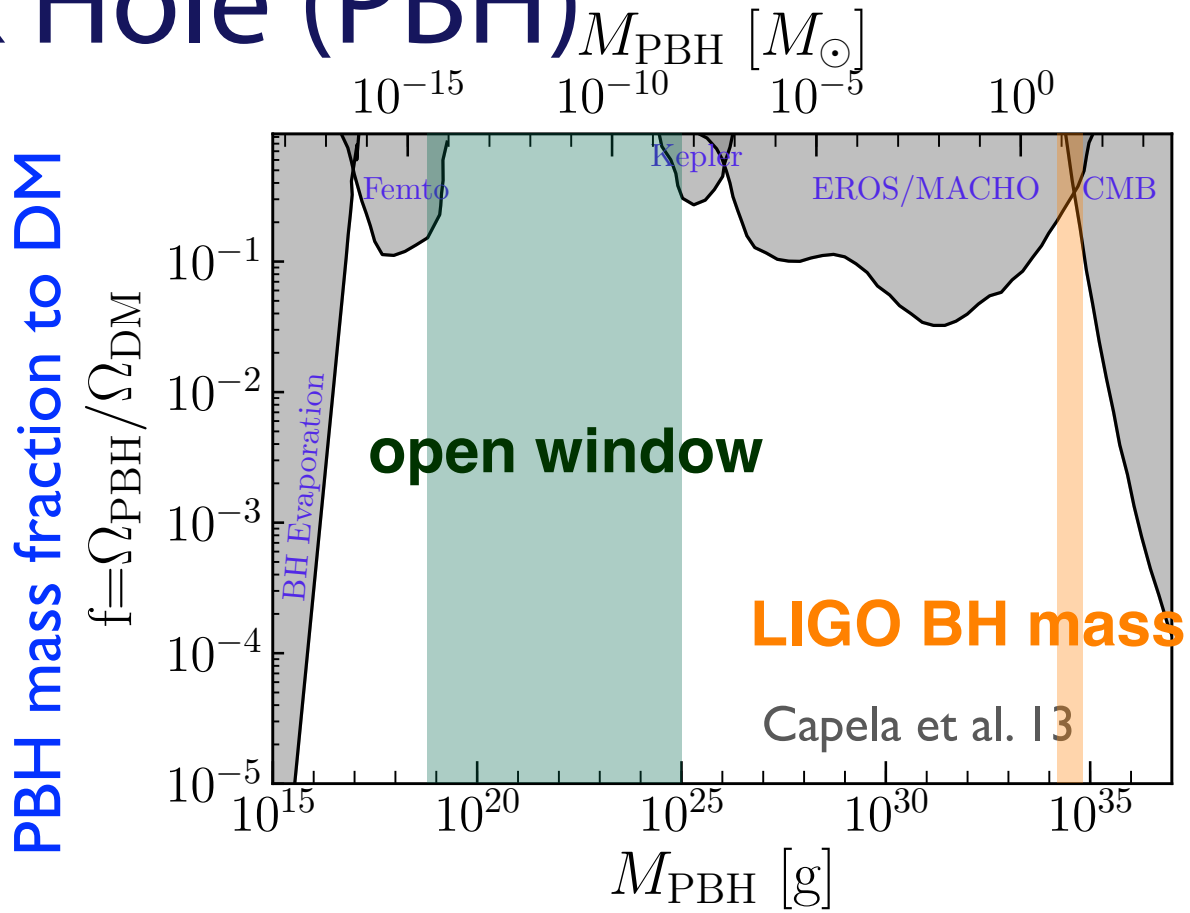
Initiated by MT's daily conversation with Hitoshi and Masahiro (Kawasaki)



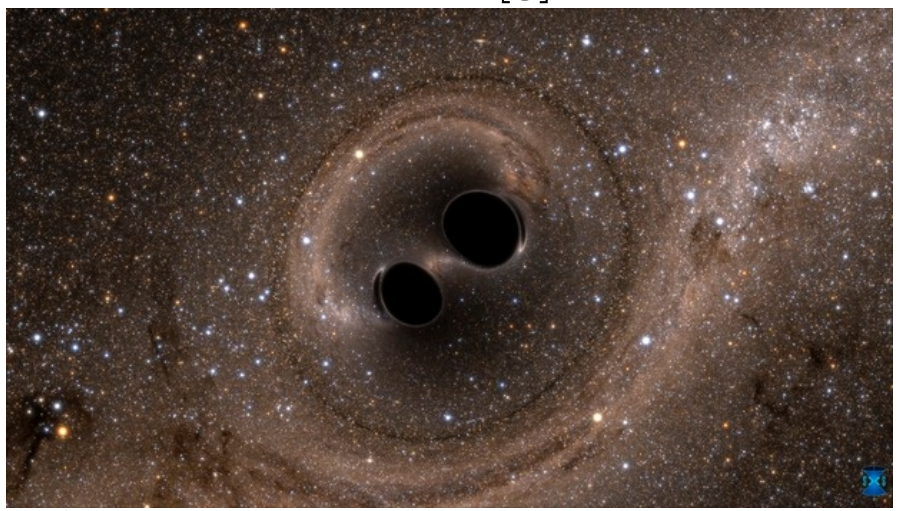
- In the northern hemisphere (not accessible from VST, DES, LSST)
- Large spiral galaxy
- HSC FoV ~ entire M31
- ~770kpc (μ~24.4), reachable distance (not too far)!

Primordial Black Hole (PBH)

- Can be formed in the early universe (Zel'dovich & Novikov67; Hawking1971); not from any astrophysical processes
- A viable candidate of (cold) DM
- Progenitor of LIGO GW binary BHs? (Sasaki, Suyama, Tanaka & Yokoyama, PRL 2016)



$M_{\rm PBH} \sim 10^{24}{\rm g} \sim M_H \ @\ T \sim 10\ {\rm TeV}$



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Physics Prizes 2017

▼ About the Nobel Prize in Physics 2017

The Nobel Prize in Physics 2017

Rainer Weiss, Barry C. Barish, Kip S. Thorne

Share this: ?

The Nobel Prize in Physics 2017

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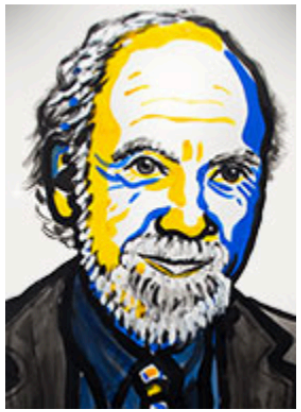
Rainer Weiss

Prize share: 1/2



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Barry C. Barish

Prize share: 1/4

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Kip S. Thorne

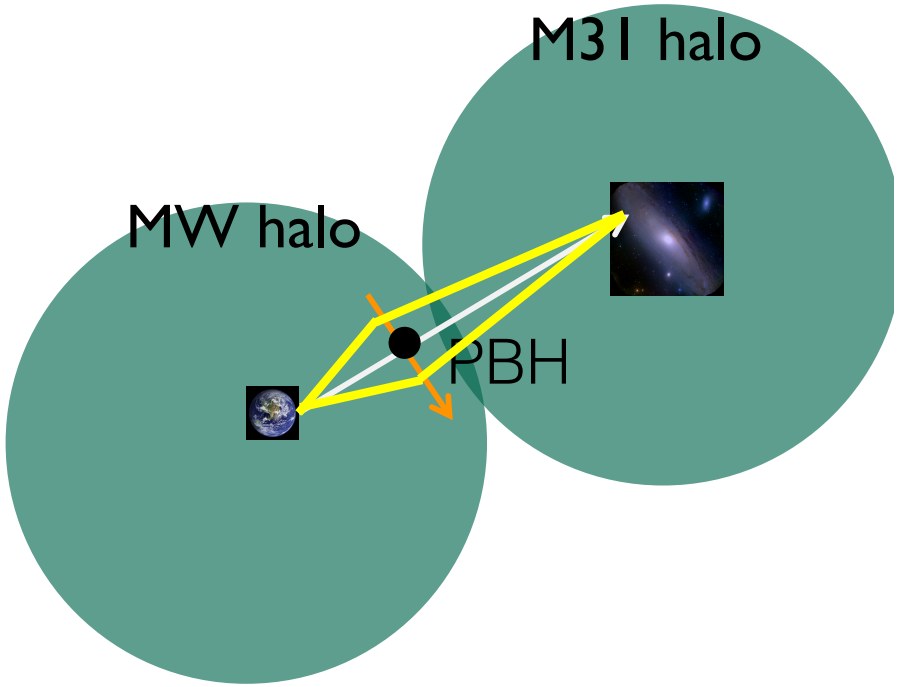
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

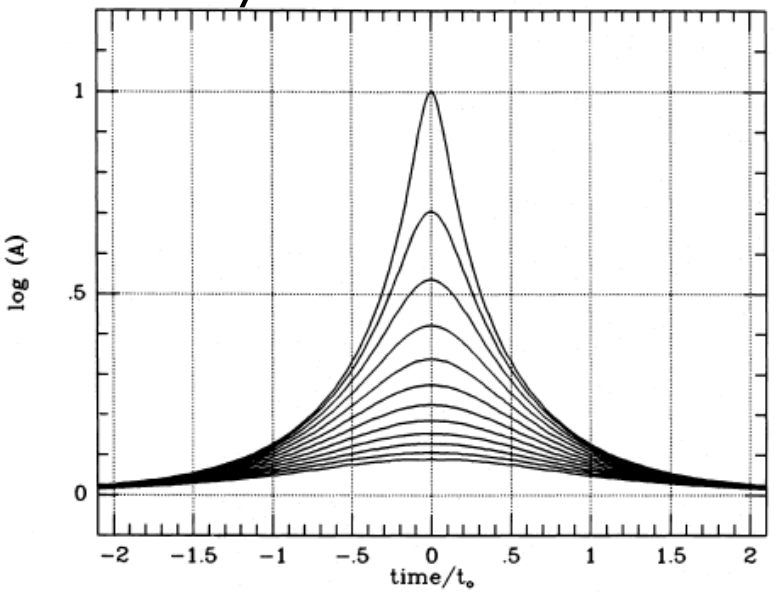
PBH microlensing on M31 star

- Lensed image can't be resolved with optical resolution (~10^{-8} arcsec) ⇒ only light curve is a signal
- Huge volume
- MW/M31 halo **~ 10^{12}Msun** (we assumed NFW models)
- PBH has a peculiar velocity of **~200km/s**
- Need to **monitor** brightness of the same star as a function of **"time"** (time domain astronomy)

$$R_E = \sqrt{\frac{4\pi G M_{\rm PBH} d(1-d/d_s)}{c^2}}$$

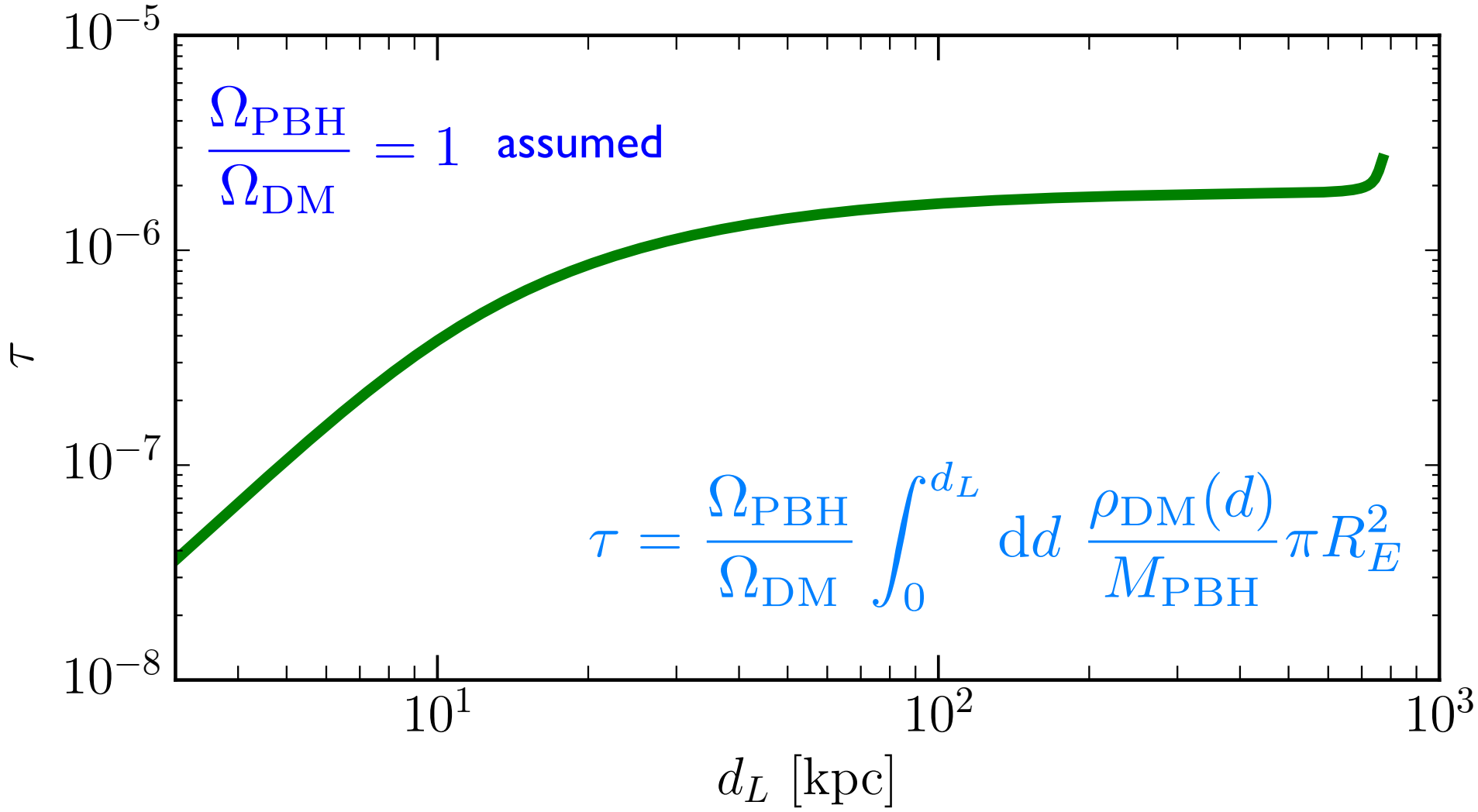


Paczynski 86



PBH microlensing on M31 star

Cumulative optical depth of PBH microlensing for a **single** star in M31

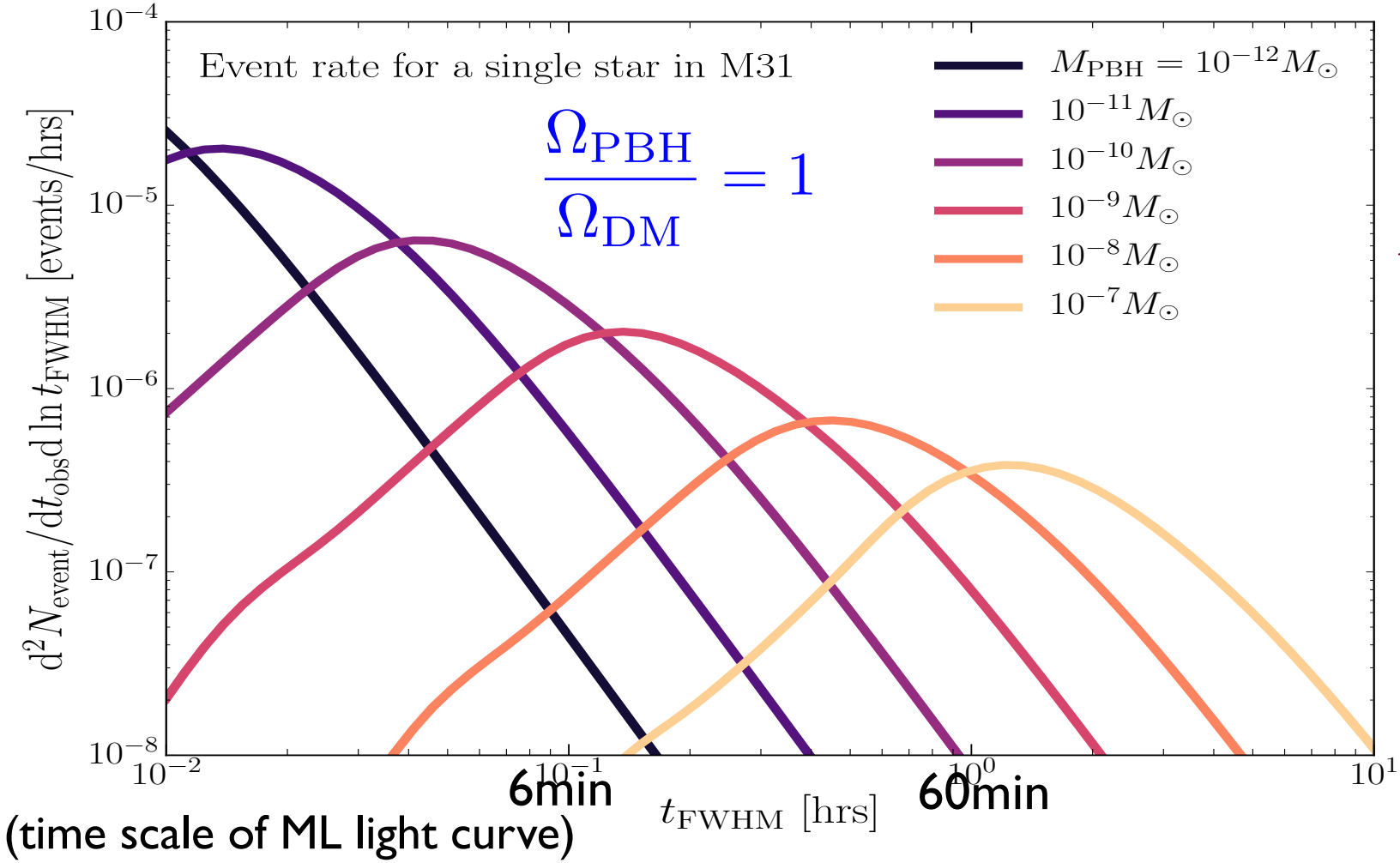


If we observe **~10^6 stars** at one time, **one star at least** should be micro-lensed if PBHs are DM

PBH microlensing event rate

source star

$$t_E \sim \frac{d_L \theta_E}{v_{\rm PBH}} \sim 34\ {\rm min} \left(\frac{M_{\rm PBH}}{10^{-8} M_\odot}\right)^{1/2} \left(\frac{d_L}{100\ {\rm kpc}}\right) \left(\frac{v_{\rm PBH}}{200\ {\rm km/s}}\right)^{-1}$$



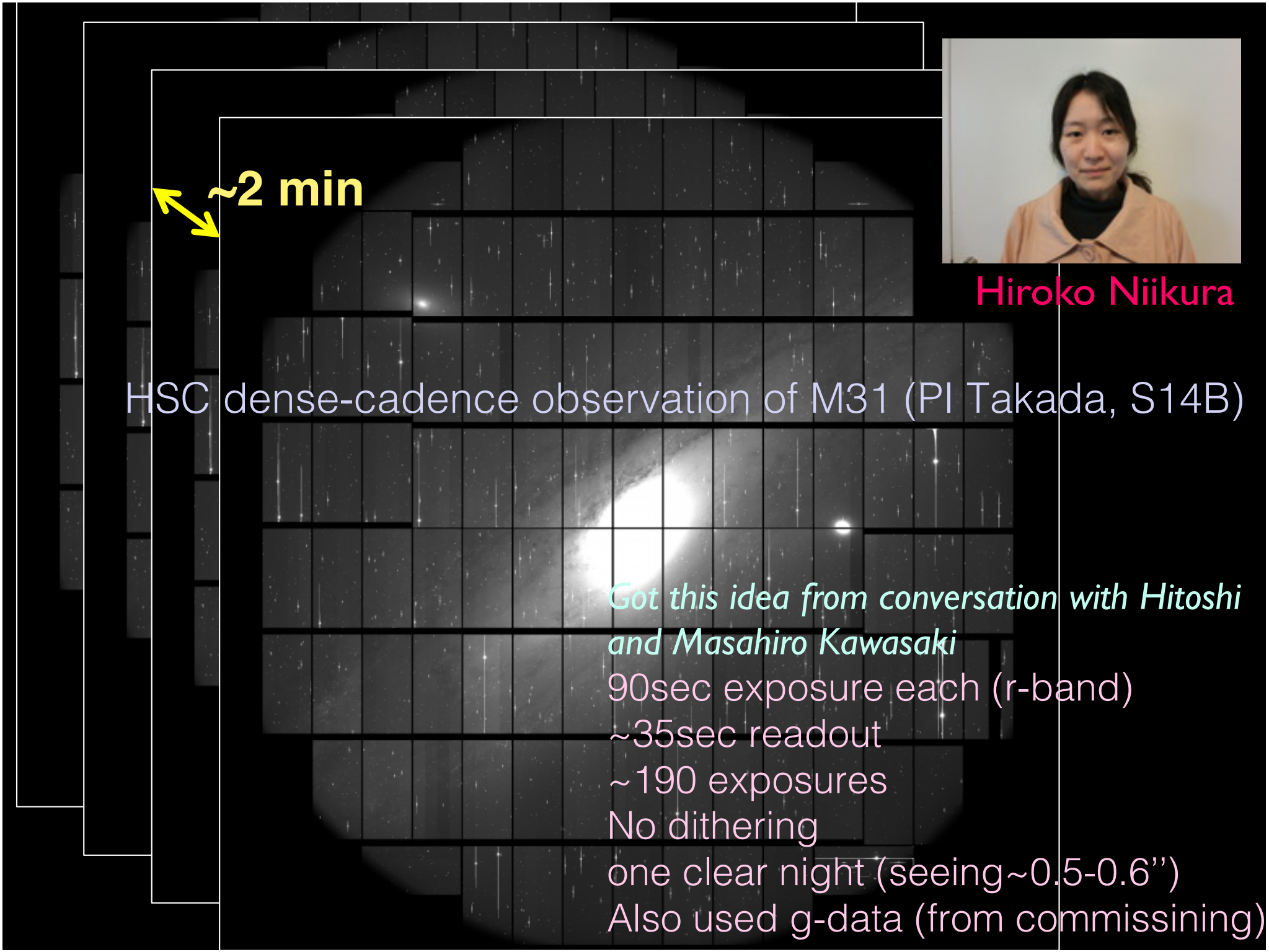
(time scale of ML light curve)

$R_E \propto M_{\rm PBH}^{1/2}$

lens (PBH)

observer

Event rate per **unit obs. time** and per **a single star** in M31 for **a given timescale of light curve (we monitored ~10^8 stars)**



Hiroko Niikura

HSC dense-cadence observation of M31 (PI Takada, S14B)

Got this idea from conversation with Hitoshi and Masahiro Kawasaki

90sec exposure each (r-band)

~35sec readout

~190 exposures

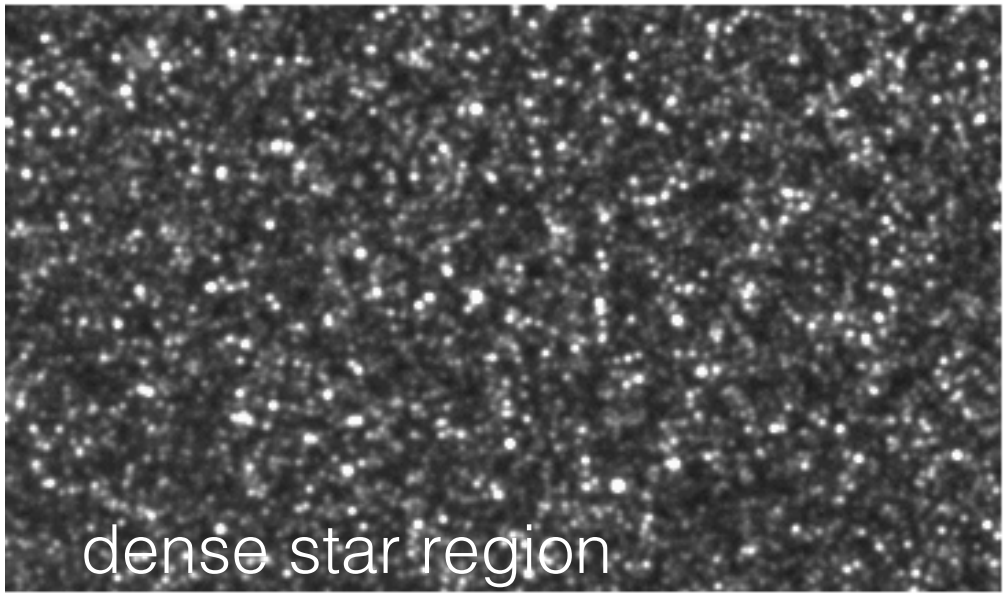
No dithering

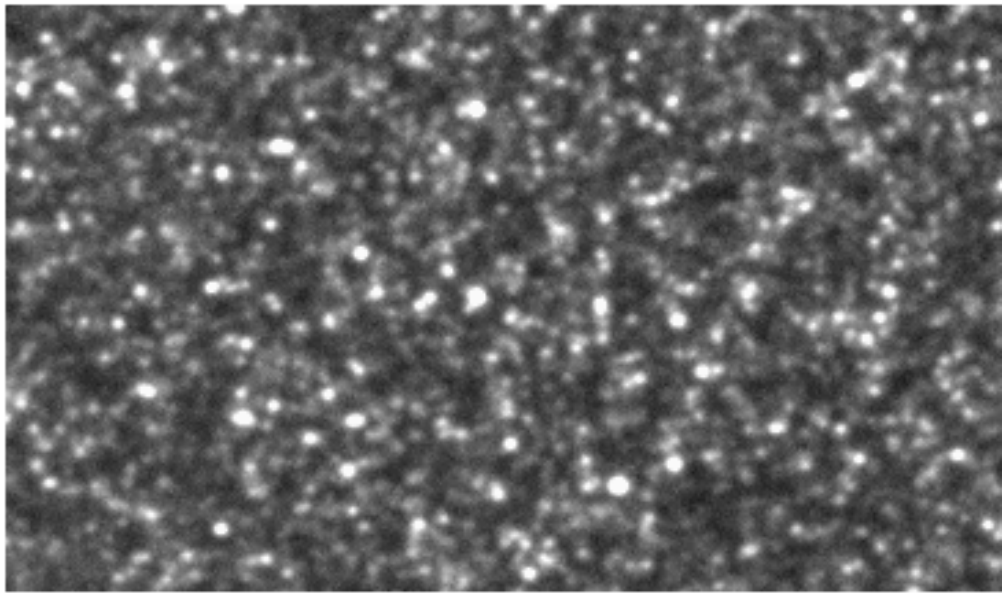
one clear night (seeing~0.5-0.6")

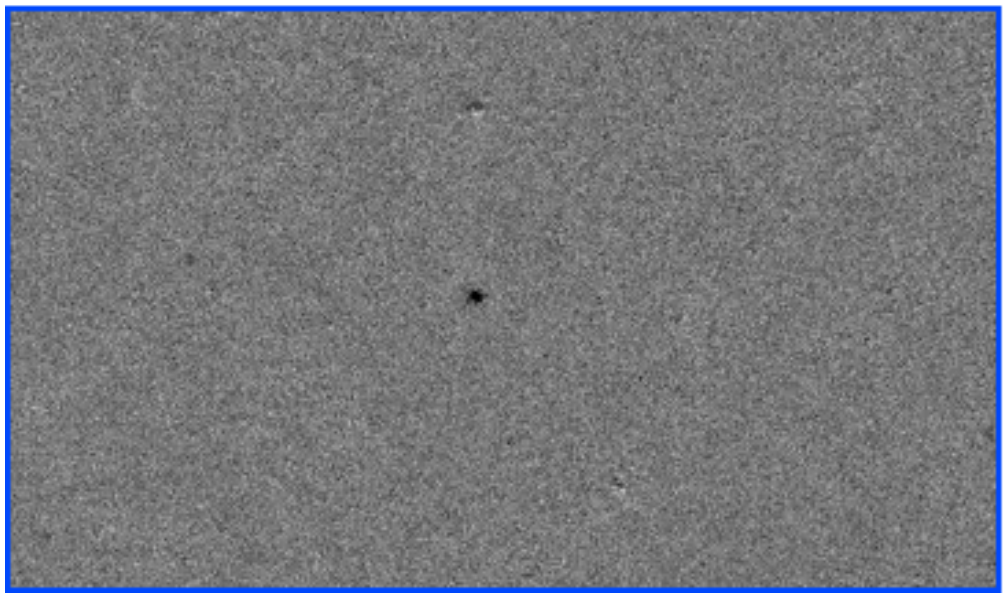
Also used g-data (from commissining)

Challenges: Pixel lensing

Fluxes from multiple stars are overlapped at each position



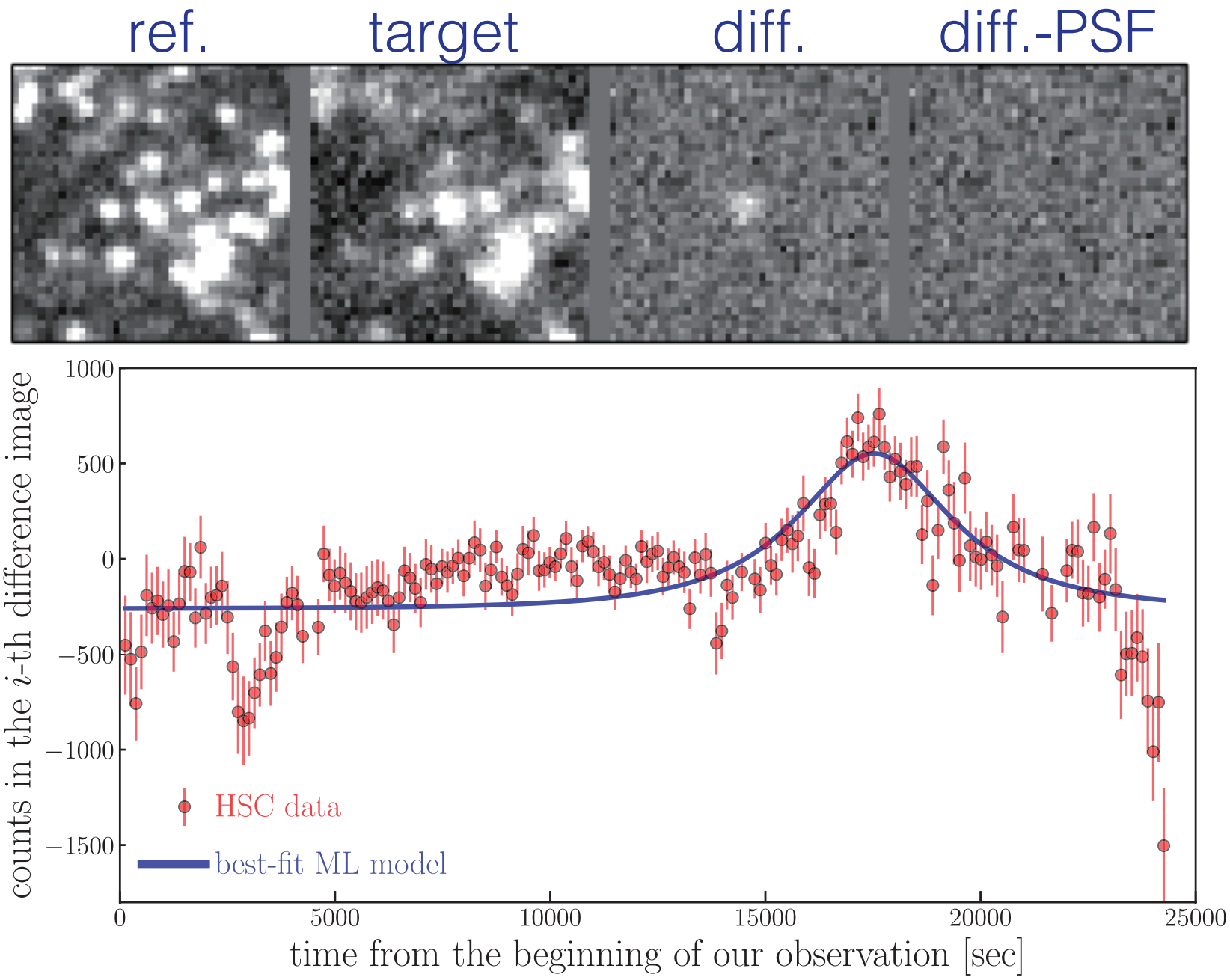




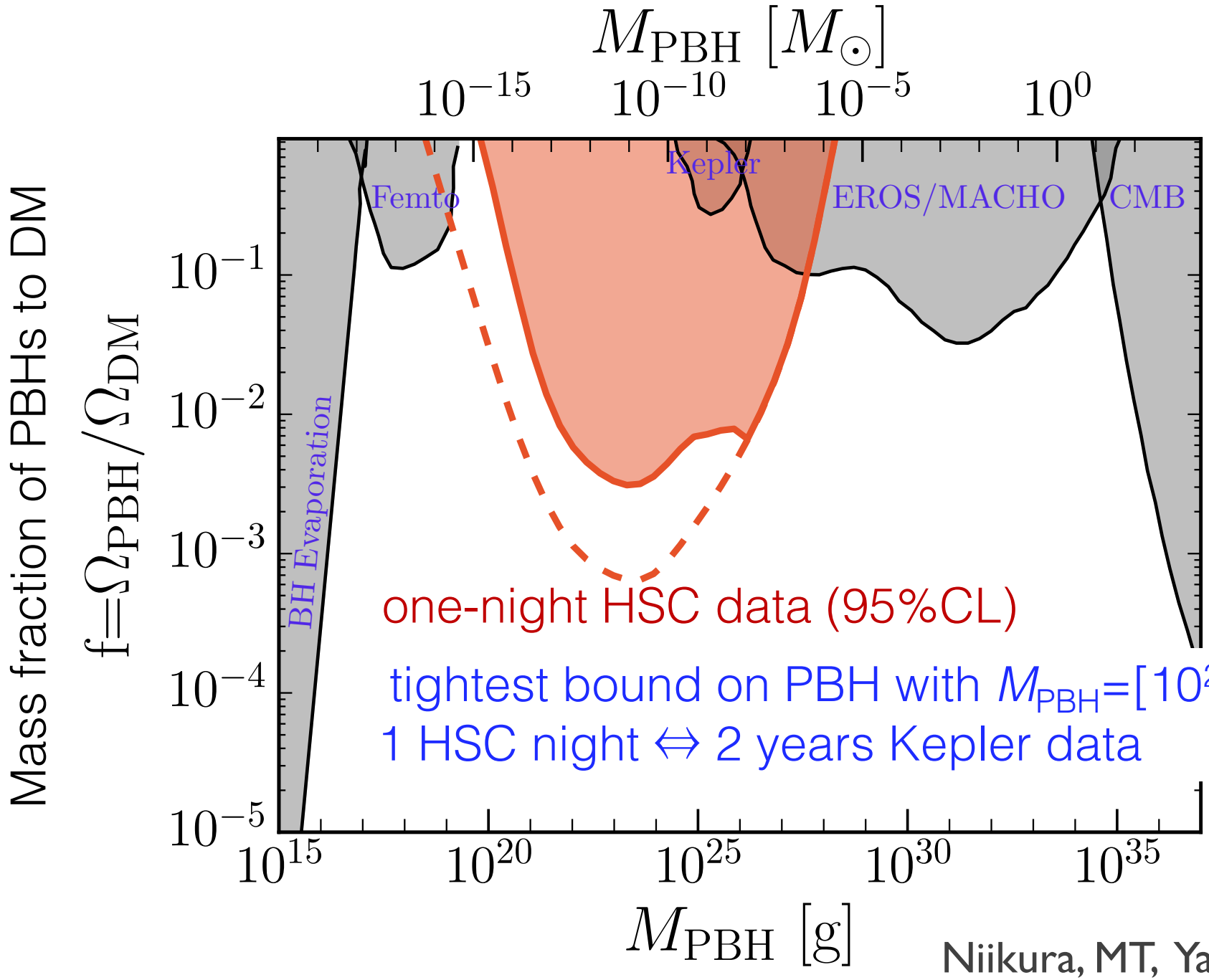
Upper left: reference image (0.5'')
Upper right: target image (0.8'')
Lower: difference image

Accurate PSF and astrometry measurements needed.
HSC pipeline (hscPipe) works!

One real candidate of microlensing …?



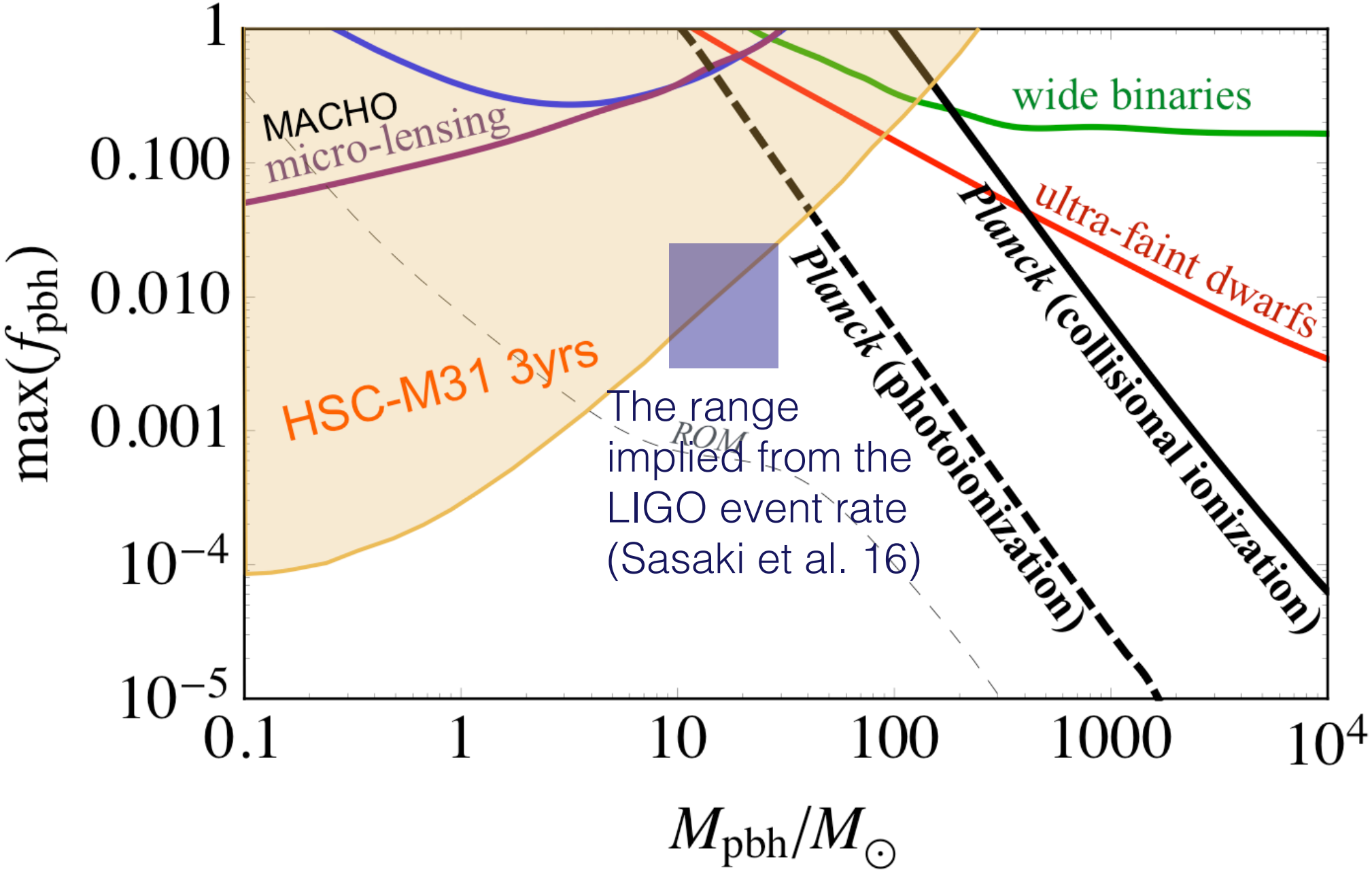
Results: New bound on PBH abundance



Niikura, MT, Yasuda + 17

Prospect for further HSC observation

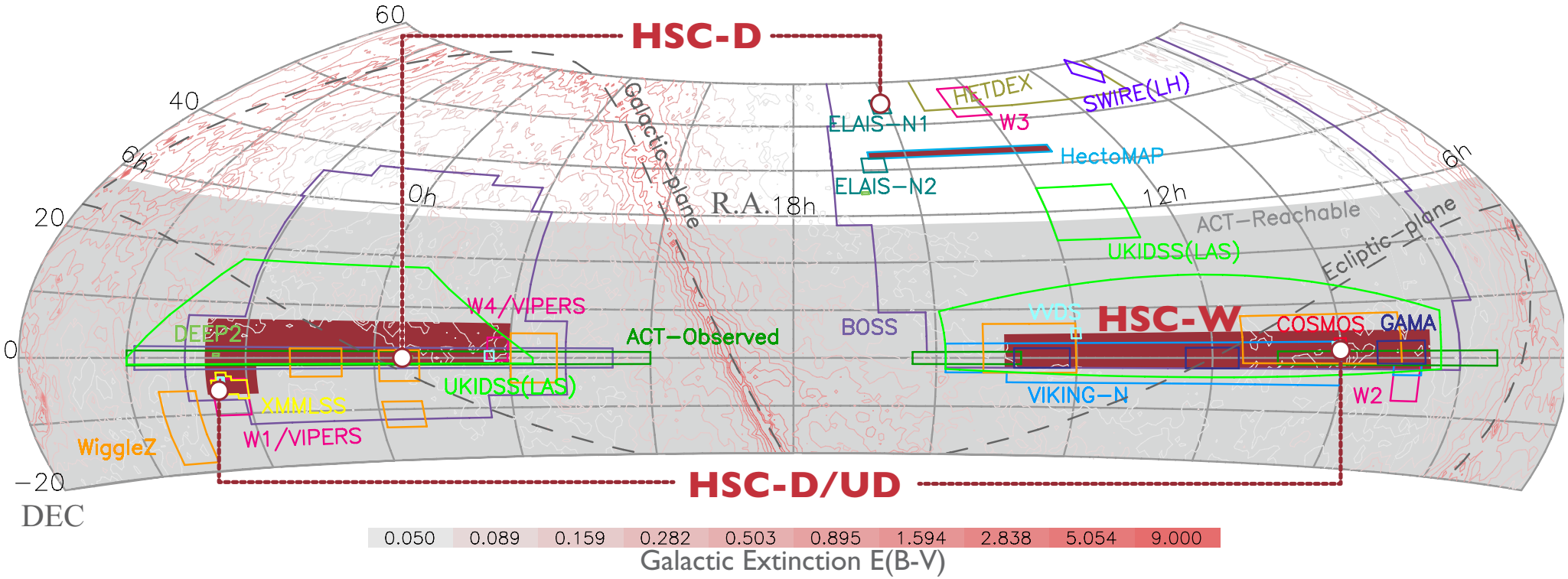
only one or a few Subaru nights in total, sparsely sampled over 3yrs



Subaru-**300**-nights HSC project (2006 -)

International collaboration (Japan, Taiwan, Princeton U.)

HSC Survey Fields



- **Subaru 300 nights** granted (2014 – 19)
- HSC Survey Fields selected based on
  - Overlap with SDSS regions and other interesting, external datasets (ACT CMB, NIR, spectroscopic surveys, …); Low dust extinction; Spread in RA
- The main scientific objectives are
  - Wide: Cosmology, Deep: galaxy evolution, UD: cosmic reionization

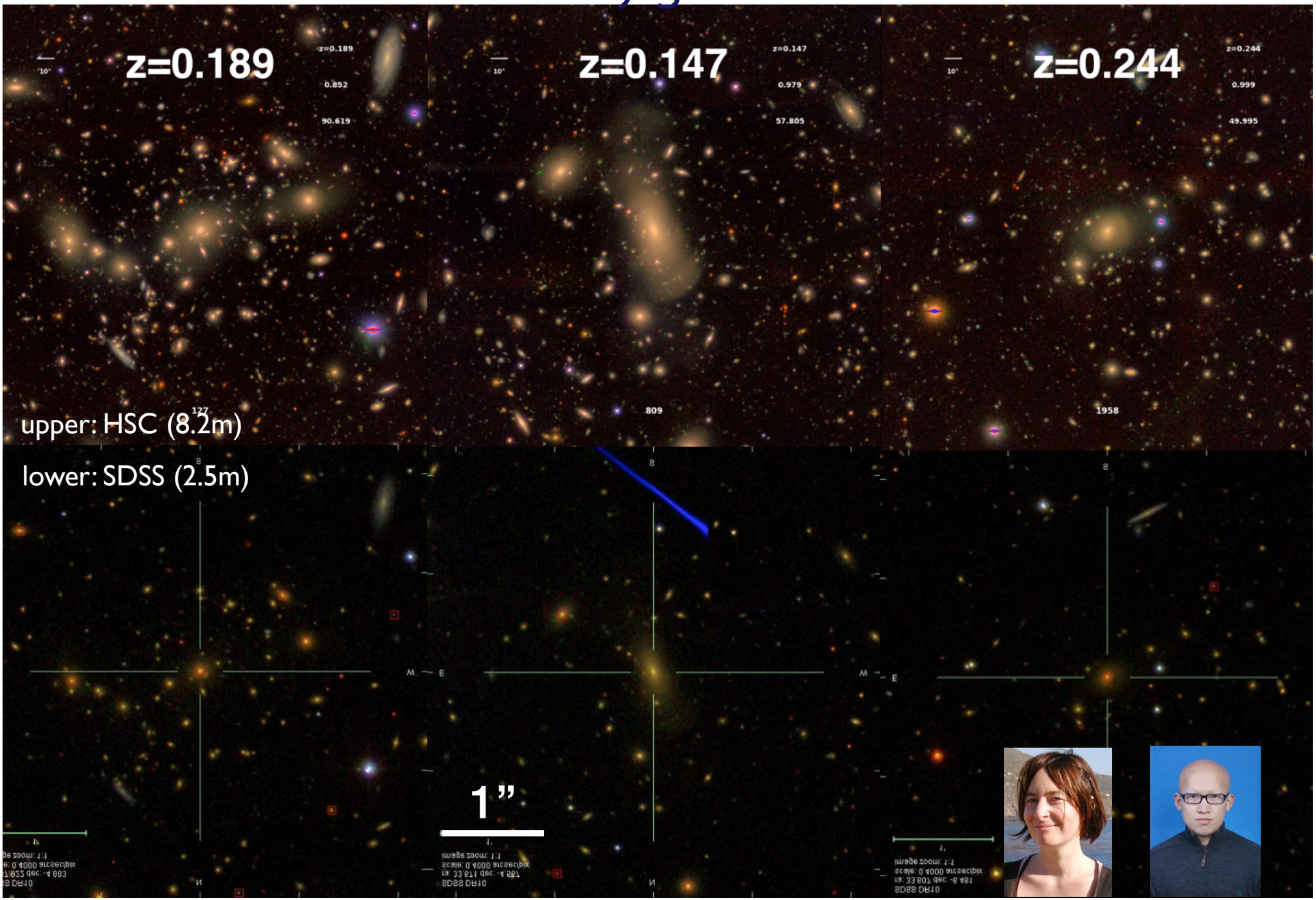
First Data Release (DR1) of HSC SSP
28 Feb, 2017

~60 Subaru nights, ~100 sq. deg., ~10^8 objects ≃10yrs SDSS

First Public Data Release by the Hyper Suprime-Cam Subaru Strategic Program

February 28, 2017 | Topics

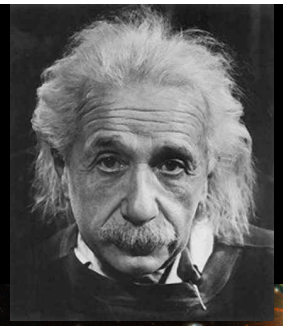
Nearby galaxies



All data reduced by the HSC pipeline

A. Leauthaud S. Huang

Gravitational lensing = GR prediction

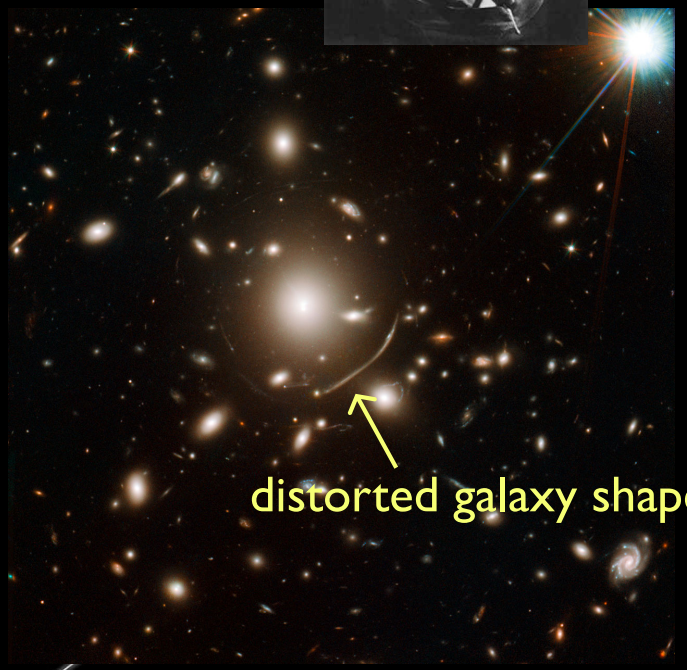


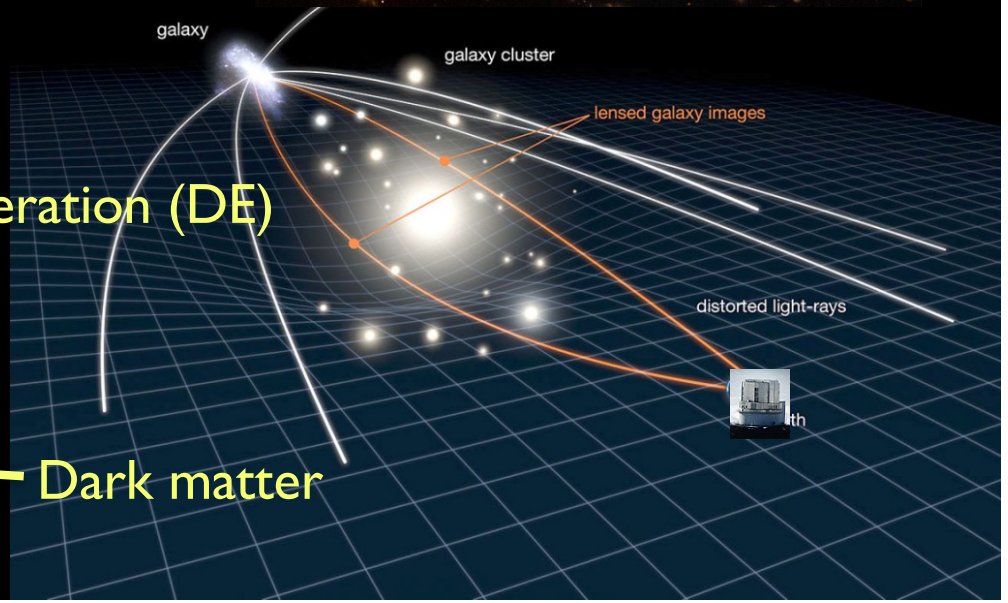
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\Rightarrow \text{ light path: } \boldsymbol{x} = \boldsymbol{x}[z; g_{\mu\nu}]$$

Light-ray path, emitted from a distant galaxy, is bent by the foreground matter distribution

It causes a distortion in galaxy image



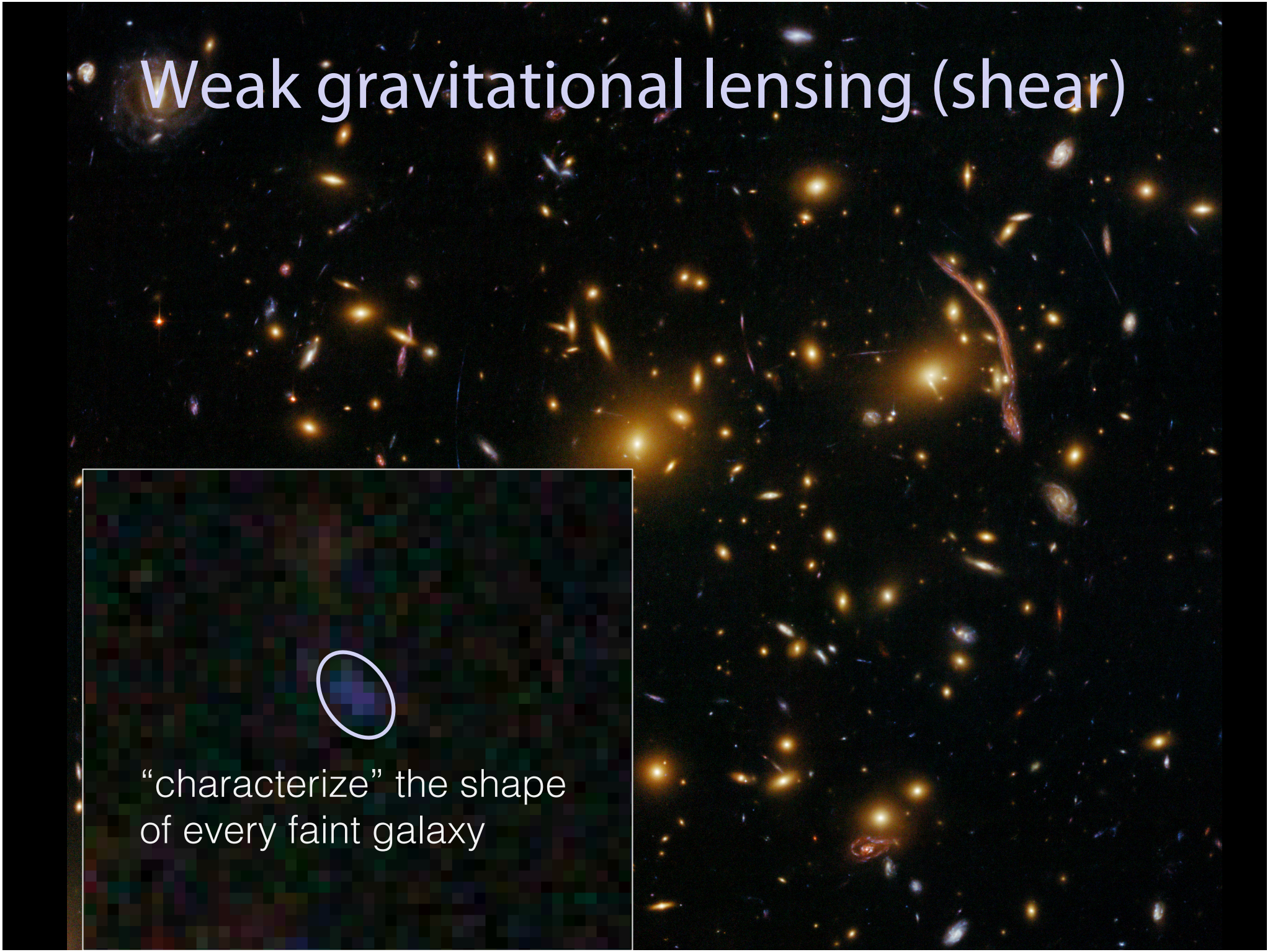


Lensing strength =

(geometry of the universe) ← Cosmic acceleration (DE)

× (total matter of lens(es)) ← Dark matter

Weak gravitational lensing (shear)

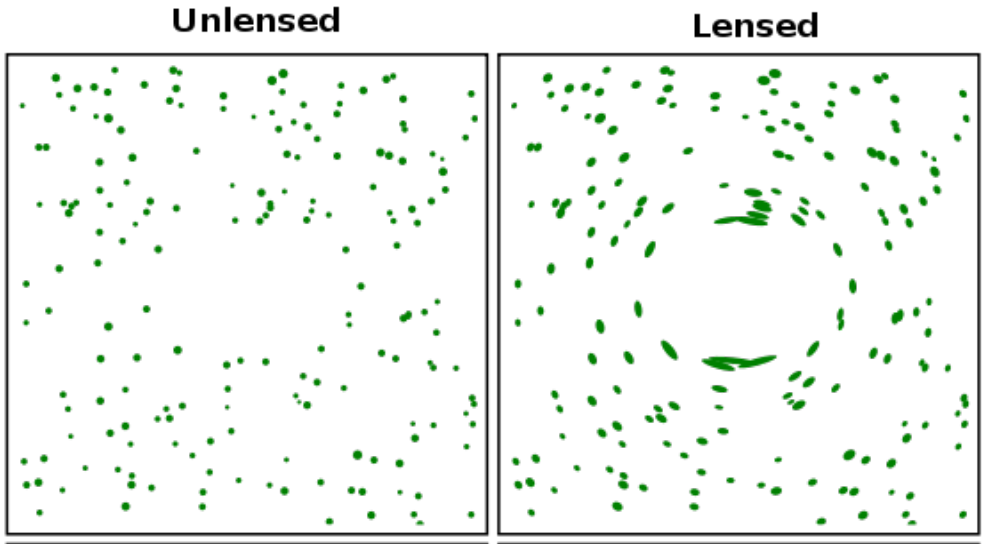


Weak lensing shear (cont'd)

- Tiny signal on individual galaxy (typically **only 1%** in its ellipticity)
- Measure "coherent" shear signals (need a large number of galaxies)
- **The great thing**, however, is that, once measured accurately, we can recover the **physical quantities (total matter, mostly DM, distirbution)** without any ambiguity, because of **the linear relation**
- This opens up an opportunity; reconstructing DM distribution **everywhere**

observable (ellipticity) output: DM distribution

$$\gamma_{ij} \sim \int_0^{z_s} \mathrm{d}z_l \; W(z_s, z_l) \nabla_{\perp i} \nabla_{\perp j} \Phi[\mathbf{x}(t)] \rightarrow \Phi^{\mathrm{2D}} \sim \nabla^{-1} \nabla^{-1} \gamma_{ij} \rightarrow \Sigma_m^{\mathrm{2D}}(\boldsymbol{\theta})$$



Galaxy shape catalog now fixed (after 3 years work)!

About 1/10 data of the full 5-year data

R. Mandelbaum
(CMU)

H. Miyatake
(JPL/Caltech
⇒Nagoya/IPMU)

Publ. Astron. Soc. of Japan accepted

Publ. Astron. Soc. Japan (2014) 00(0), 1–41
doi: 10.1093/pasj/xxx000

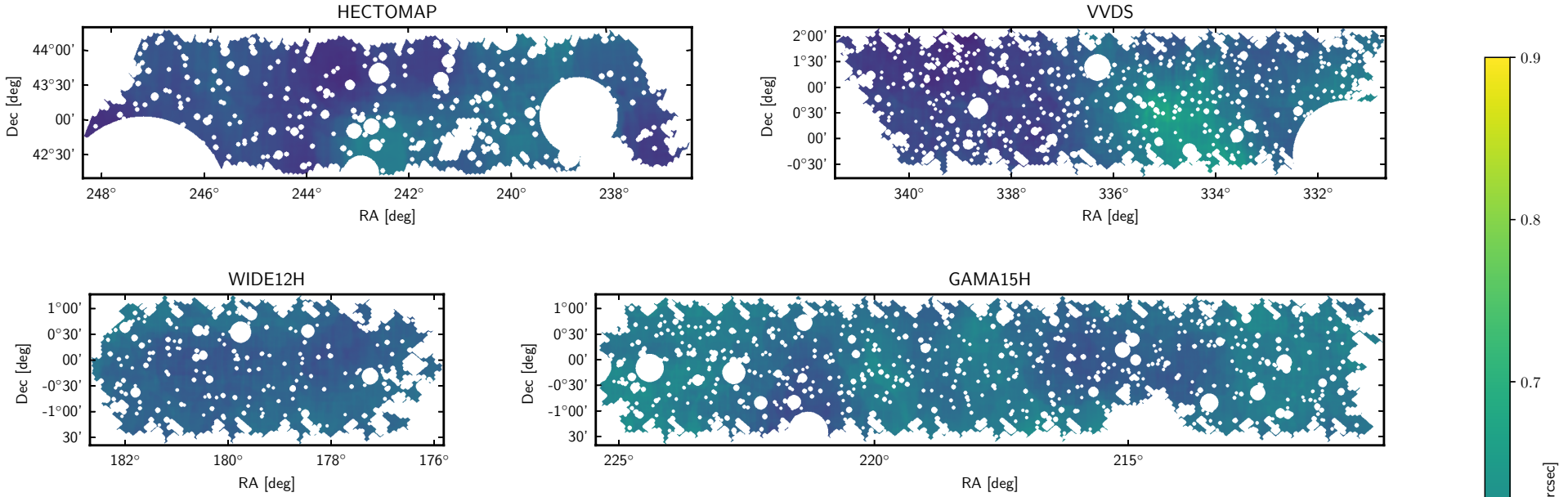
galaxy shape

The first-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey

Rachel Mandelbaum[1], Hironao Miyatake[2,3], Takashi Hamana[4], Masamune Oguri[5,6,3], Melanie Simet[7,2], Robert Armstrong[8], James Bosch[8], Ryoma Murata[3,6], François Lanusse[1], Alexie Leauthaud[9], Jean Coupon[10], Surhud More[3], Masahiro Takada[3], Satoshi Miyazaki[4], Joshua S. Speagle[11], Masato Shirasaki[4], Cristóbal Sifón[8], Song Huang[3,9], Atsushi J. Nishizawa[12], Elinor Medezinski[8], Yuki Okura[13,14], Nobuhiro Okabe[15,16], Nicole Czakon[17], Ryuichi Takahashi[18], Will Coulton[19], Chiaki Hikage[3], Yutaka Komiyama[4,20], Robert H. Lupton[8], Michael A. Strauss[8], Masayuki

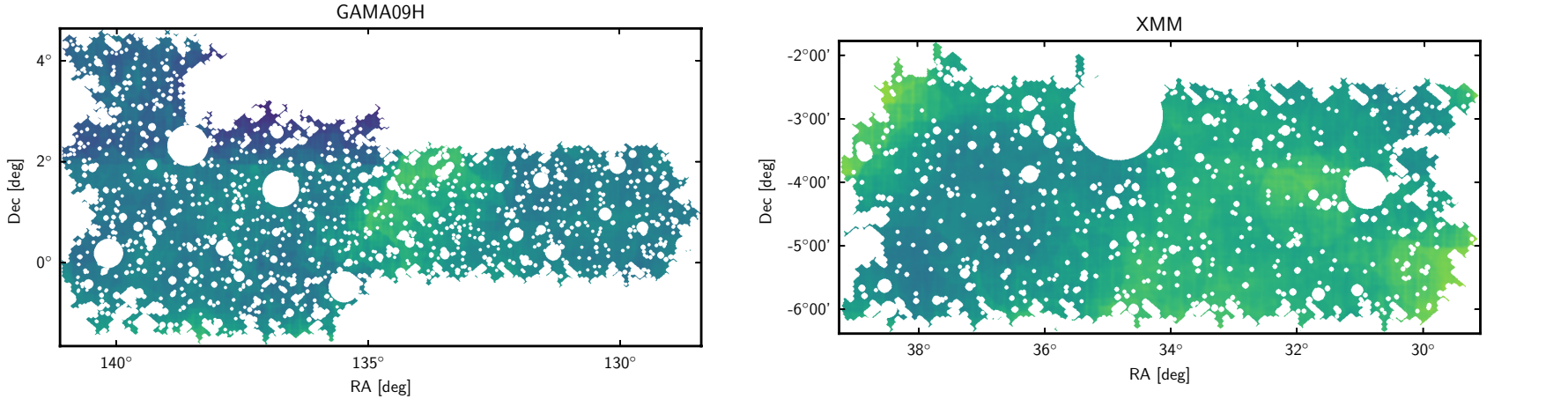
Subaru HSC = superb image quality

6 fields (~150 sq. deg. in total)



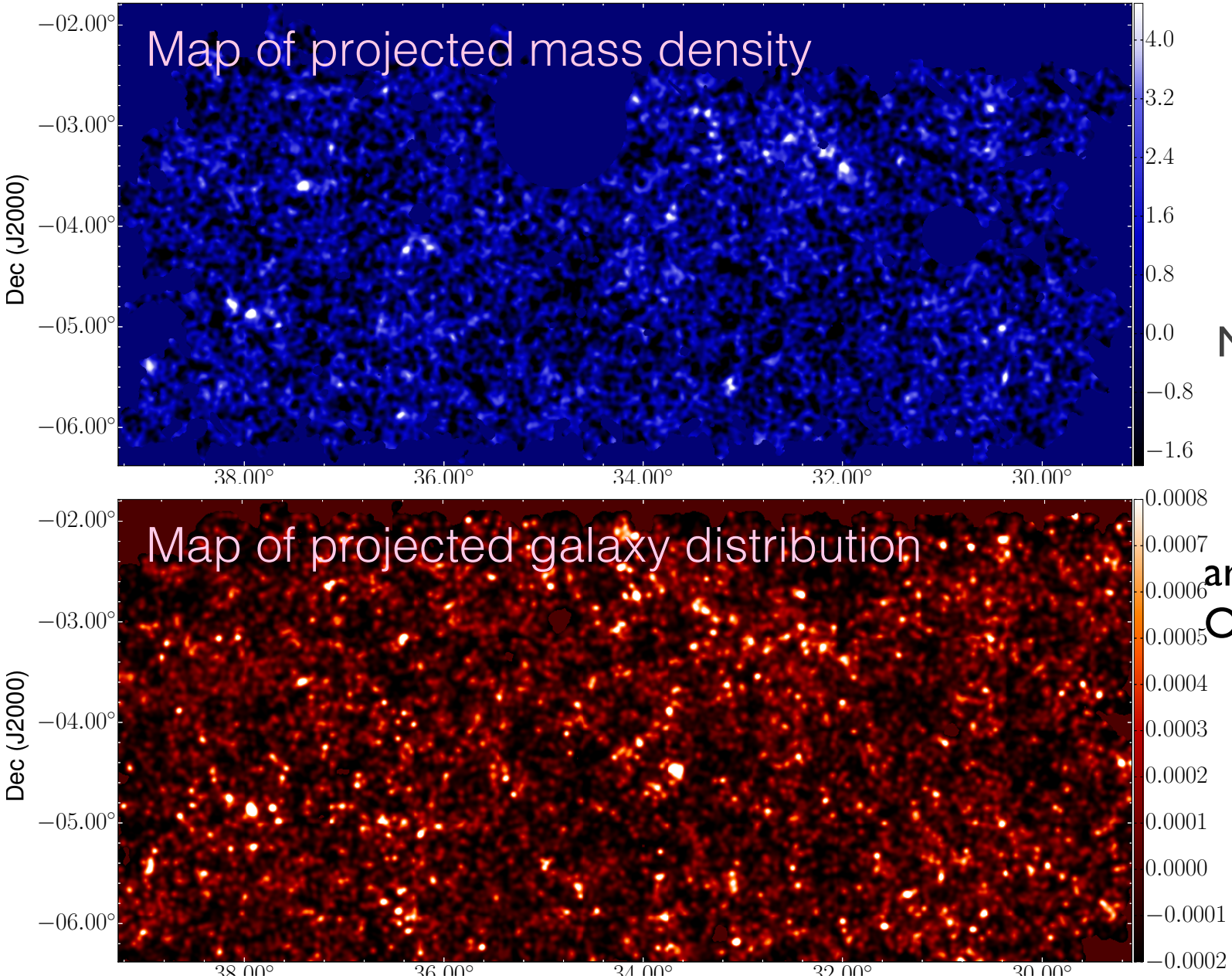
Subaru HSC typically **0.6" seeing** FWHM (spatial resolution)

⇔ DES: ~0.9"



WL mass (dark matter) maps

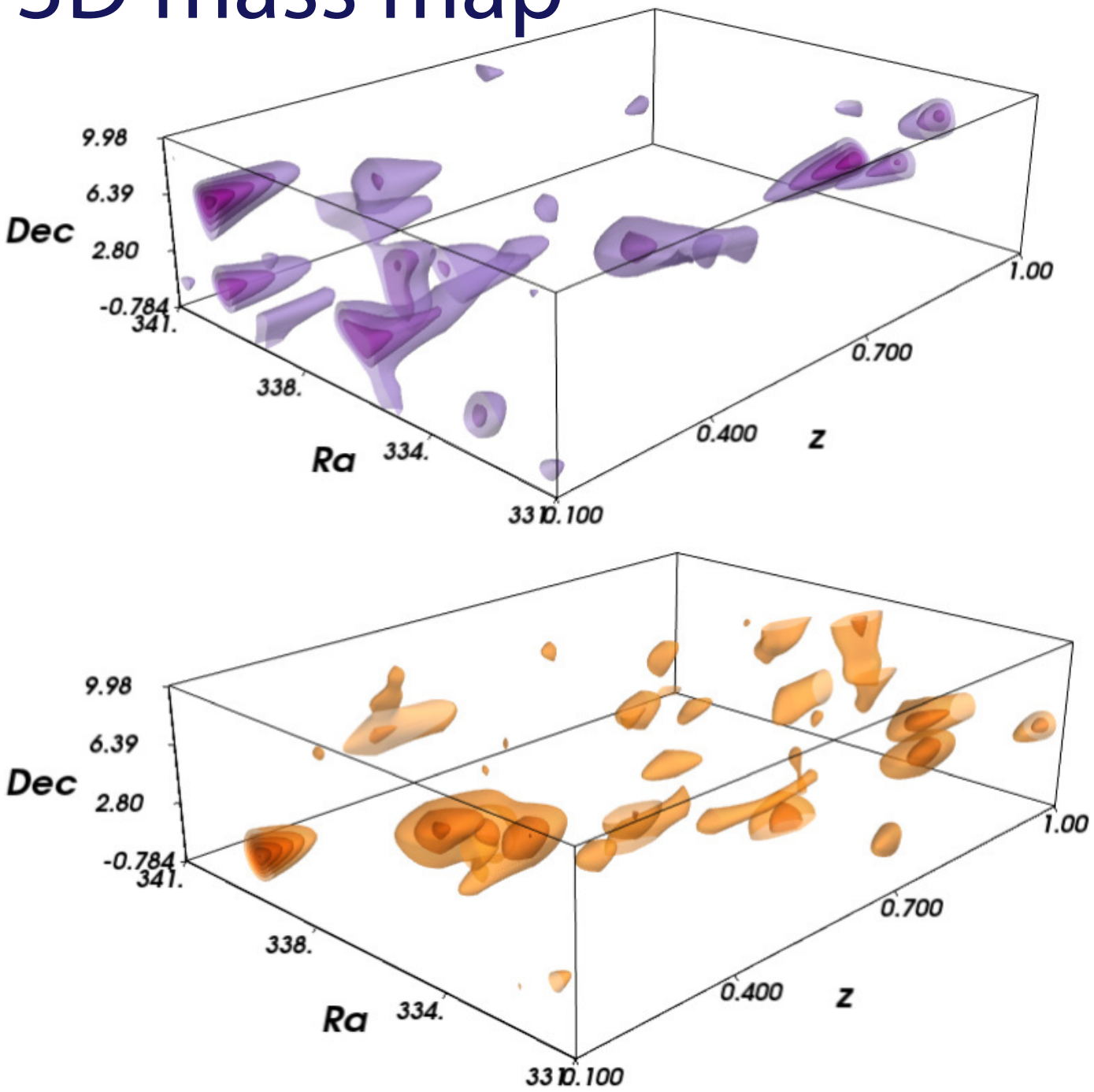
$$\gamma_{ij} \sim \int_0^{z_s} \mathrm{d}z_l \; W(z_s, z_l) \nabla_{\perp i} \nabla_{\perp j} \Phi[\mathbf{x}(t)] \rightarrow \Phi^{\mathrm{2D}} \sim \nabla^{-1} \nabla^{-1} \gamma_{ij} \rightarrow \Sigma_m^{\mathrm{2D}}(\boldsymbol{\theta})$$



Masamune Oguri
(Tokyo/IPMU)

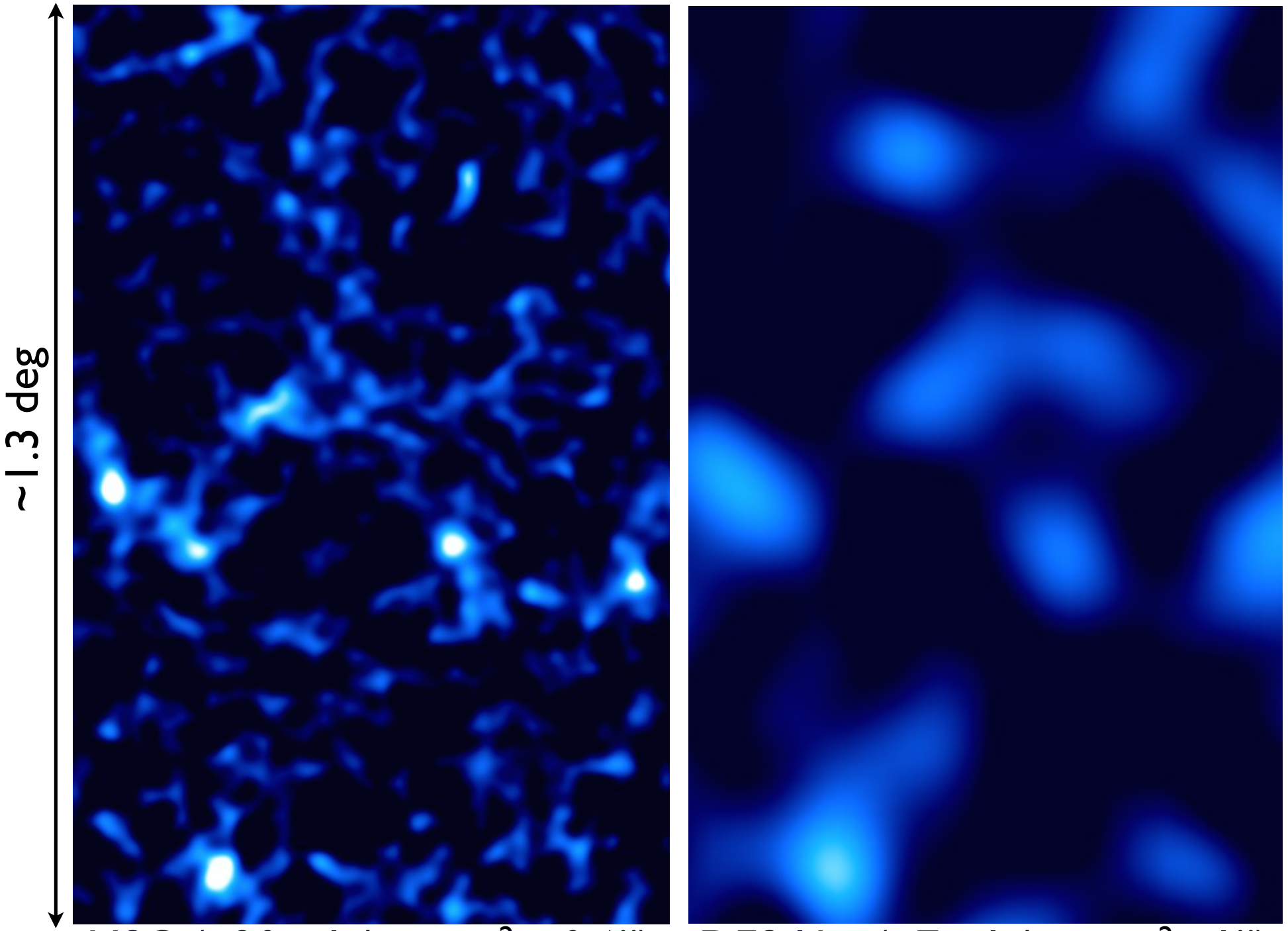
arXiv:1705.06792
Oguri et al.

3D mass map



Combining the galaxy shapes and photometric redshift of each galaxy (approximate distance measure), we can recover the 3D distribution of matter

Mass and galaxy maps show a nice correspondence


~1.3 deg
HSC (~20 gals/arcmin^2, ~0.6")
DES-like (~7 gals/arcmin^2,~1")

Summary

- Subaru **Hyper Suprime-Cam** = most powerful imaging camera for **wide-field** cosmology/astronomy
- **Tightest** constraints on primordial black holes (PBHs) in $M_{PBH}=[10^{-13},10^{-6}]$Msun, from the microlensing search of M31 star
  - Plan to extend the search to ~10Msun PBHs, possible candidate of LIGO events (only a few Subaru nights, but over several years)
- Soon deliver **cosmological constraint** from Subaru-300-nights large program of HSC
  - Address whether **sigma8 tension** between Planck and LSS still remains – new physics? (***coming soon!***)
- (Prime Focus Spectrograph project is well underway)