arXiv:1701.02151 Niikura et al.

Hiroko Niikura (U.Tokyo/IPMU)

Subaru HSC constraints on primordial black holes and SuMIRe project

Masahiro Takada (Kavli IPMU)

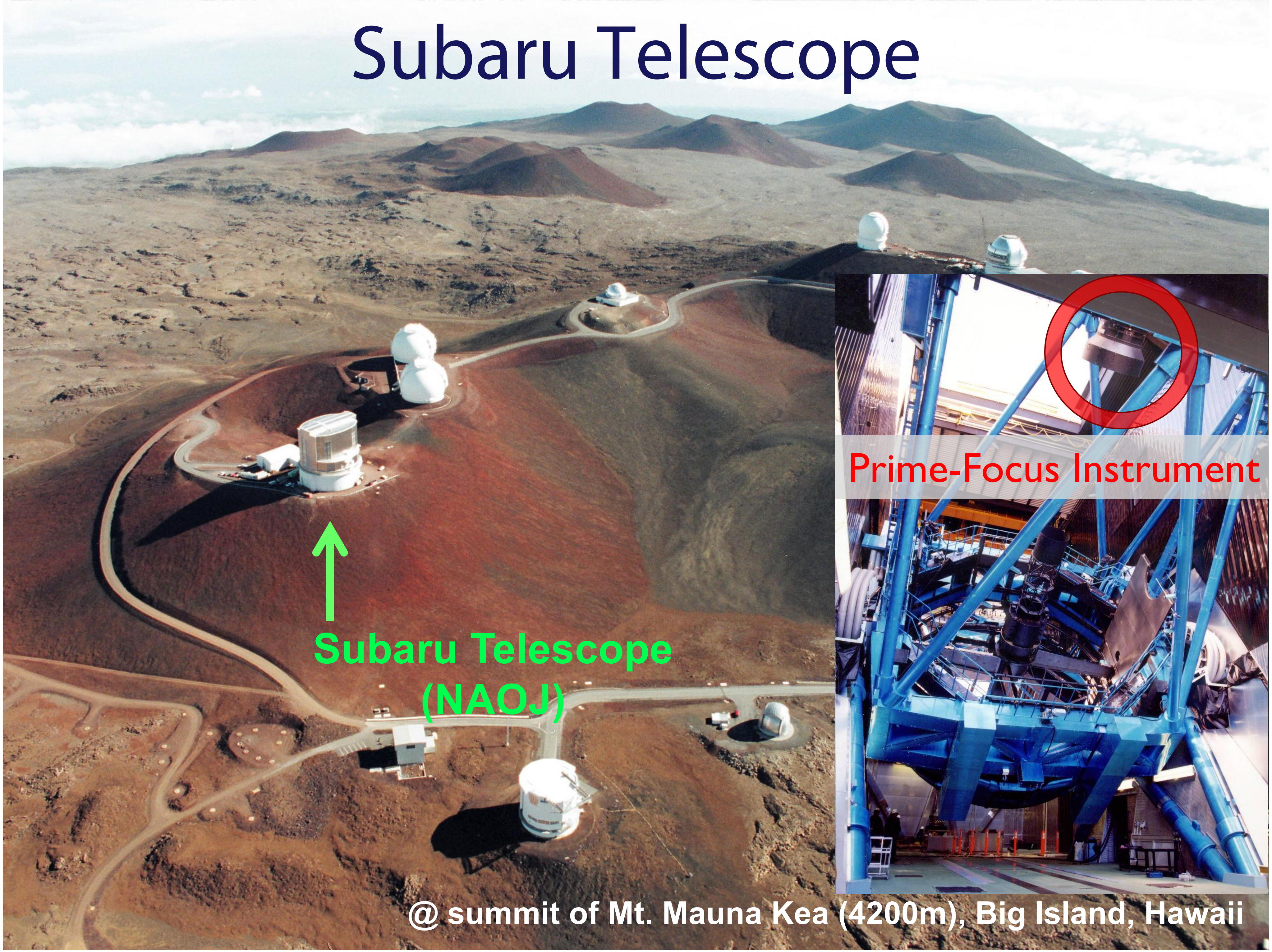
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

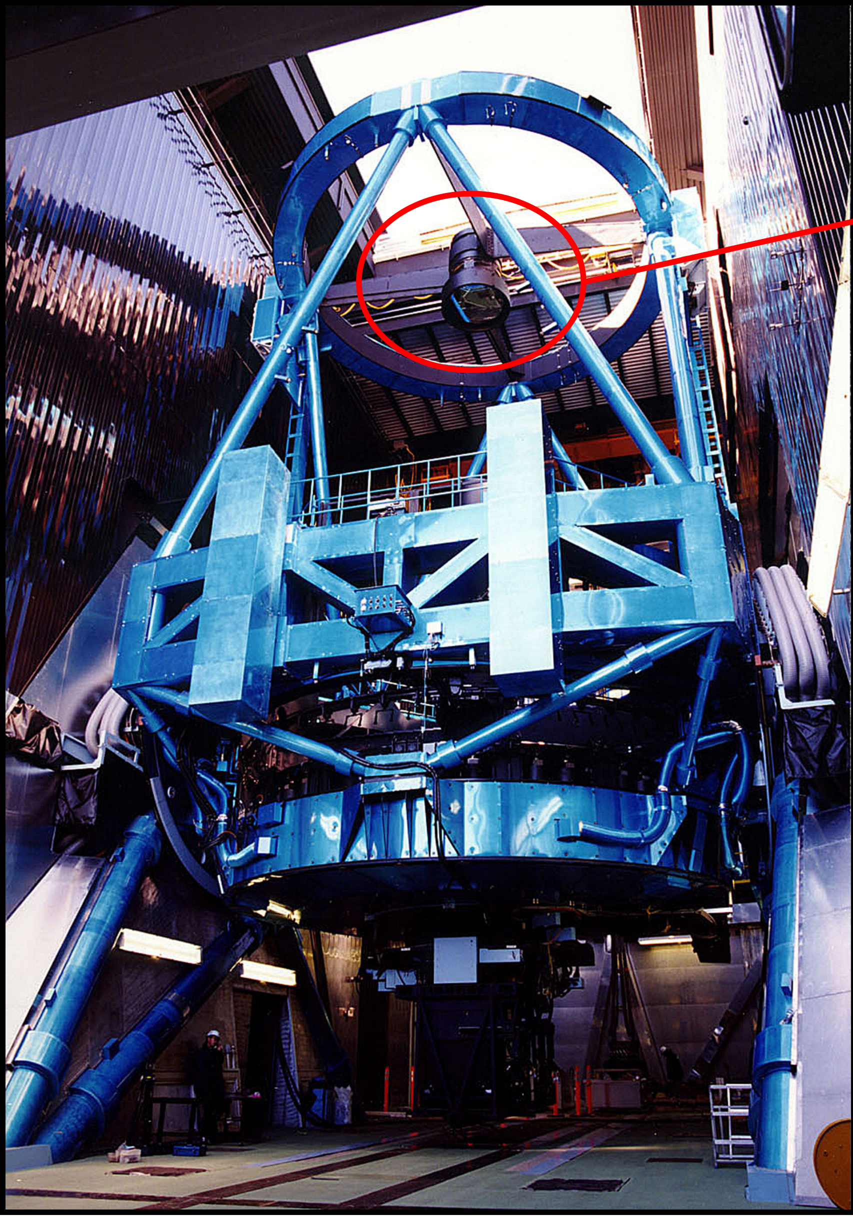
wpi

@ YKIS2018., Feb 2018

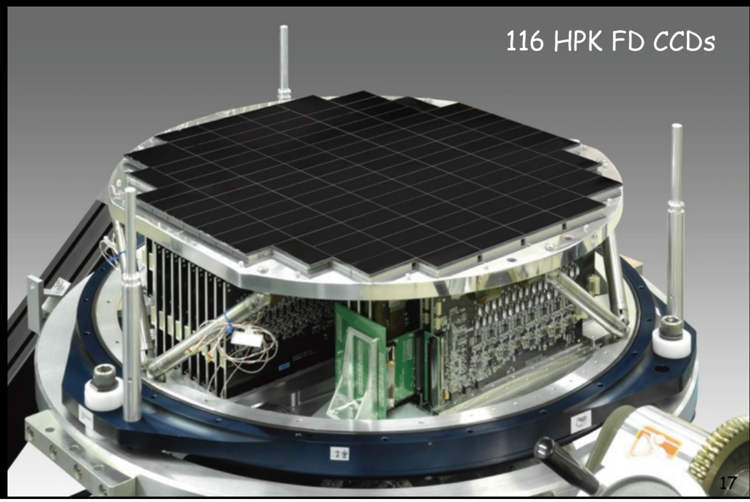
Subaru Telescope



Hyper Suprime-Cam (HSC)



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




HSC

wi

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)

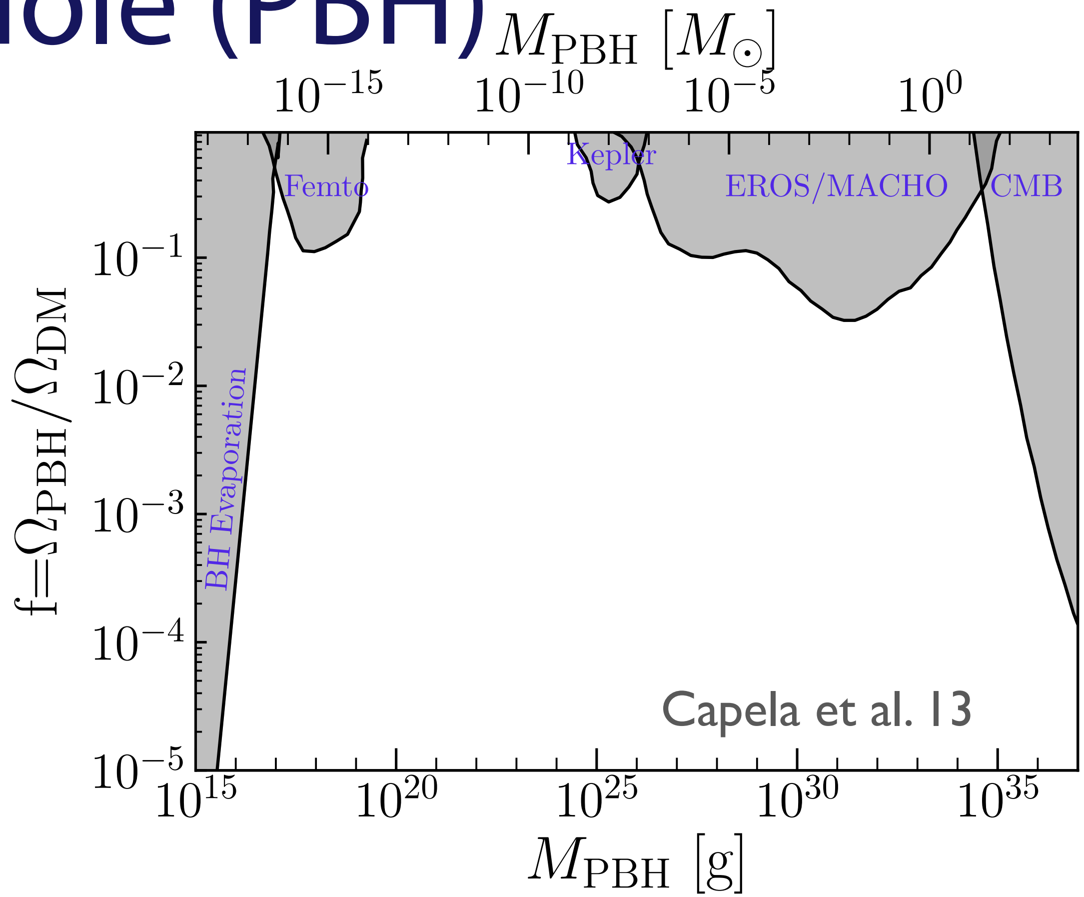
Installing Hyper Suprime-Cam on the Subaru Telescope

Candidates of dark matter

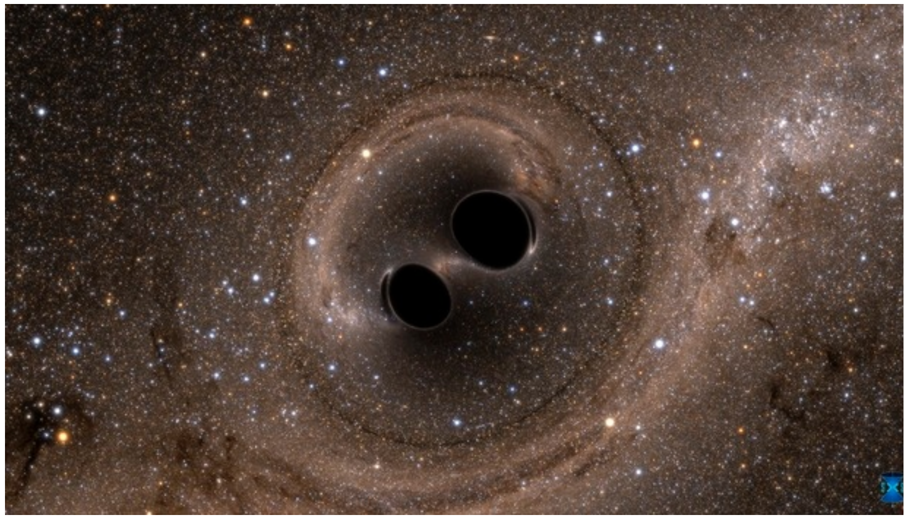
- Weakly Interacting Massive Particles (WIMP), but has yet to be found by LHC, Fermi, other direct experiments, …
- Neutrinos ⇒ *No!*
- MAssive Compact Halo Objects (MACHO) ⇒ *No!*
- Primordial Black Hole (PBH) ⇒ this talk

Primordial Black Hole (PBH)

- Dark matter needed
- Can be formed in the early universe (Zel'dovich & Novikov67; Hawking1971); not from any astrophysical processes)
- One of viable candidates of CDM
- Progenitor of LIGO GW binary BHs? (Sasaki, Suyama, Tanaka & Yokoyama, PRL 2016; Bird te al. 16)



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

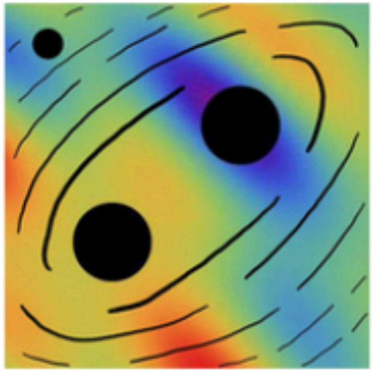


Editors' Suggestion

Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914

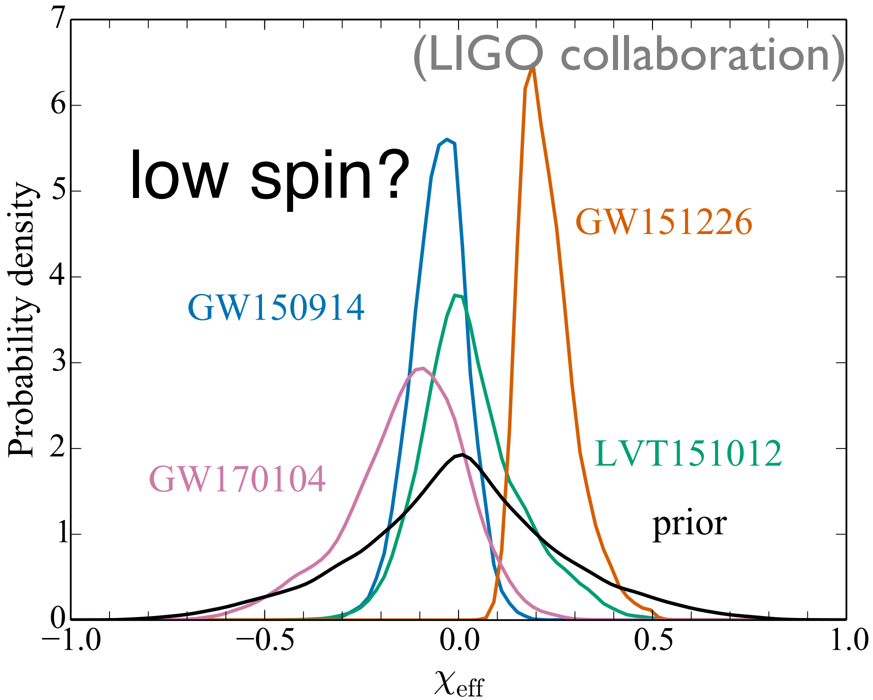
Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama

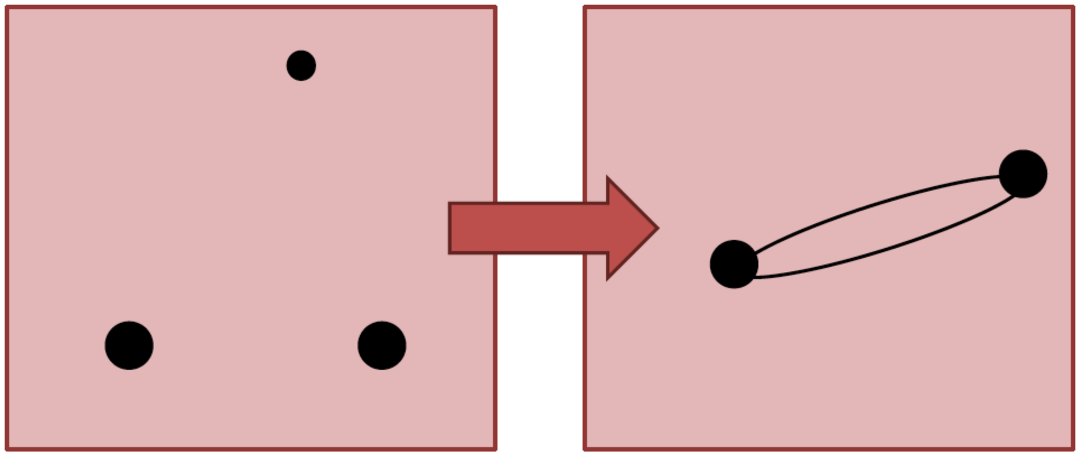
Phys. Rev. Lett. **117**, 061101 (2016) – Published 2 August 2016



A theoretical analysis examines the possibility that the gravitational wave signal (GW150914) detected by LIGO was due to the coalescence of primordial black holes created by the extremely dense matter present in the early Universe.

Show Abstract +

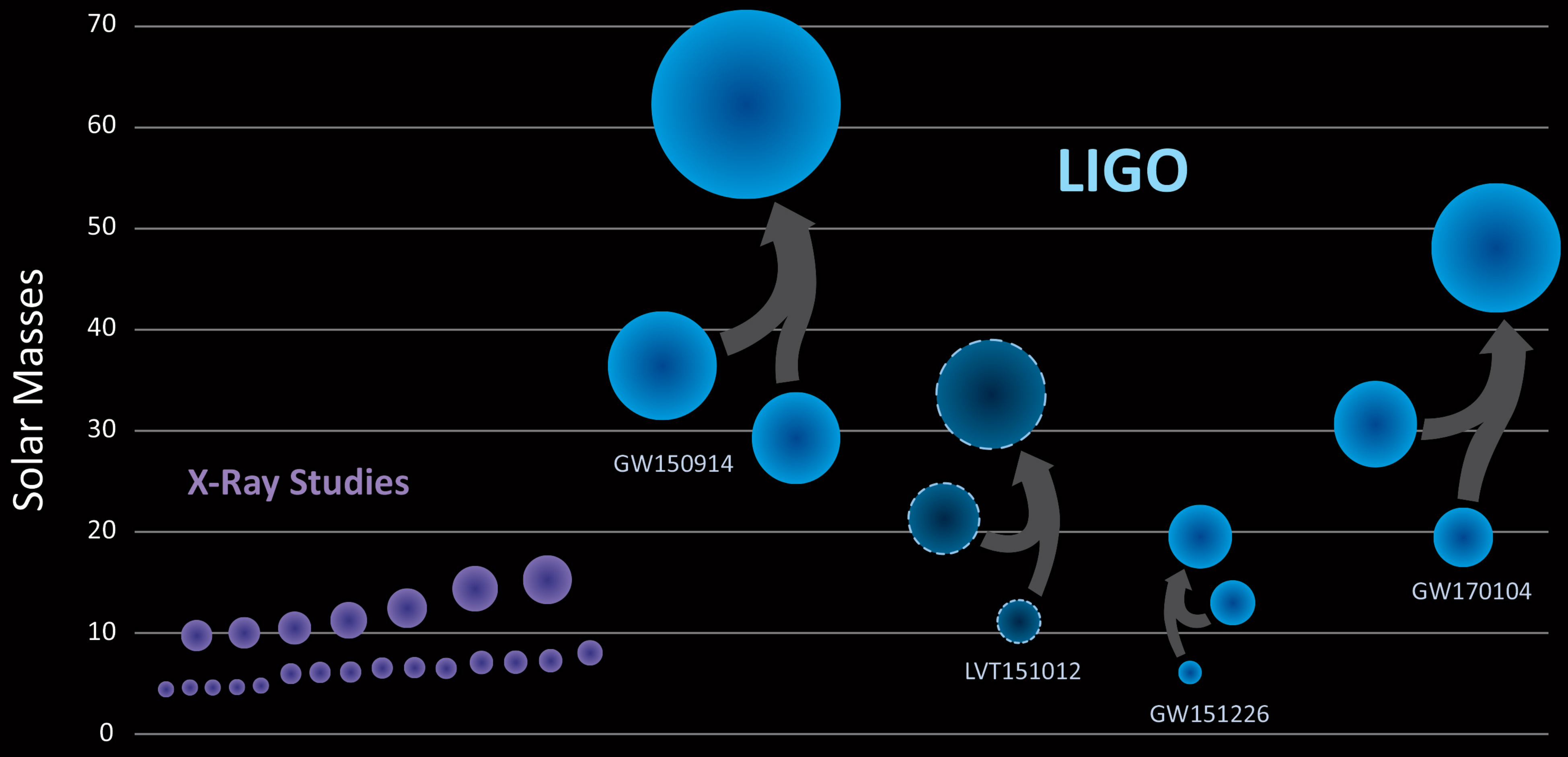




$$f_{\rm PBH/DM} \sim 10^{-2} - 10^{-3}$$

needed to explain the LIGO event rate

Black Holes of Known Mass



The origin of these BHs?

PBH formation

- PBH can be formed by the gravitational collapse of the Hubble patch in the radiation dominated era, if a large orverdensity of δ~O(0.1) is injected in the patch (Zel'dovich & Novikov 67; Hawking 71)

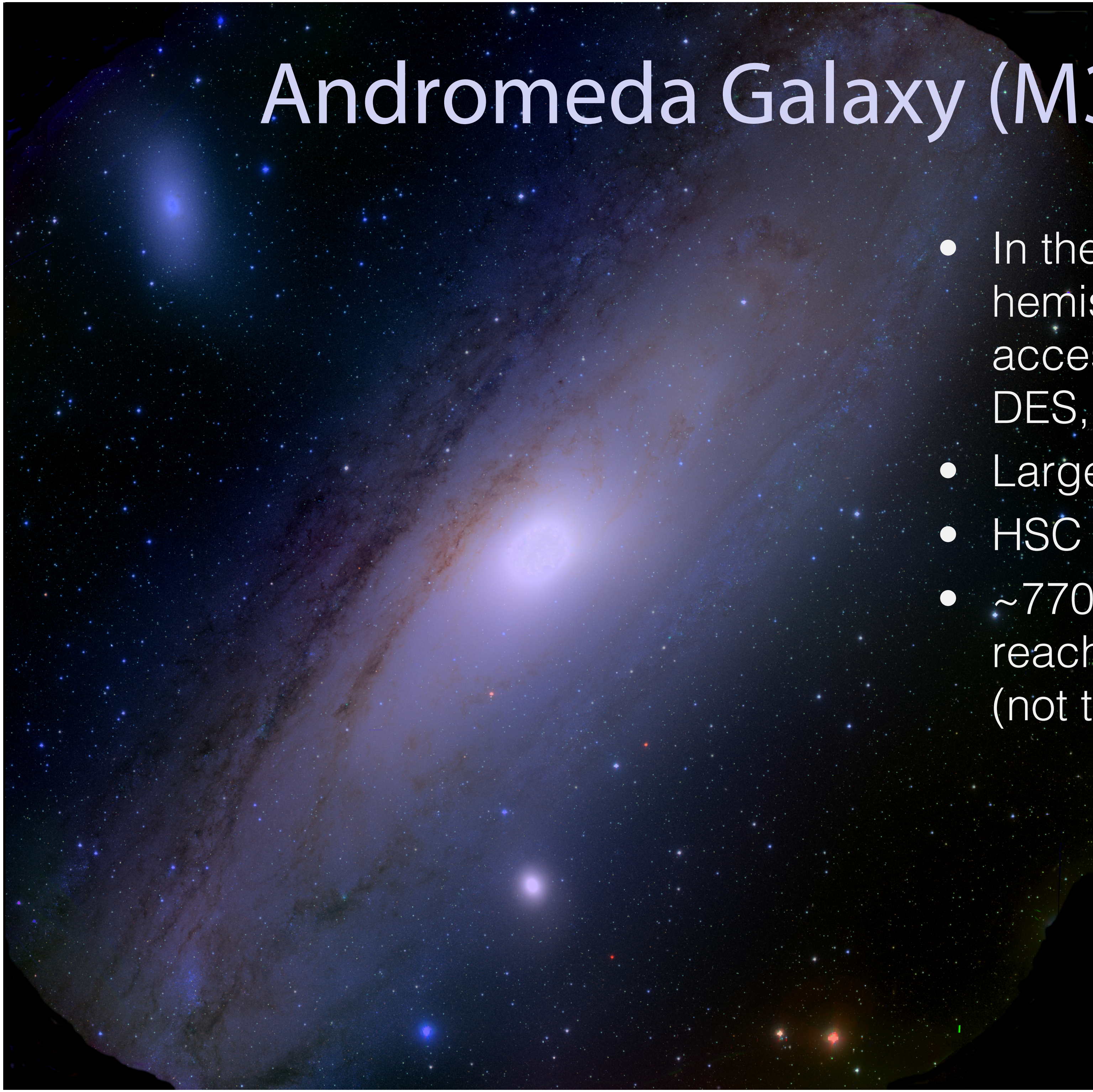
$$\left(\frac{\dot{R}(t)}{R(t)}\right)^2 = \frac{8\pi G}{3}\bar{\rho}_r(1+\delta_r) - \frac{k}{R^2}$$

- PBHs can contribute DM, by a fraction given as

$$\frac{\Omega_{\rm PBH}(M_{\rm PBH})}{\Omega_{\rm DM}} \sim \left(\frac{\beta(M_{\rm PBH})}{6\times 10^{-14}}\right)\left(\frac{100}{g}\right)^{1/4}\left(\frac{0.12}{\Omega_{\rm DM}h^2}\right)\left(\frac{M_{\rm PBH}}{10^{-10}M_\odot}\right)^{-1/2}$$

$$\beta(M_{\rm PBH}(k)) = \int_{O(1)}^{\infty} {\rm d}\delta\, \frac{1}{\sqrt{2\pi}\sigma(k)} e^{-\frac{\delta^2}{2\sigma(k)^2}}$$

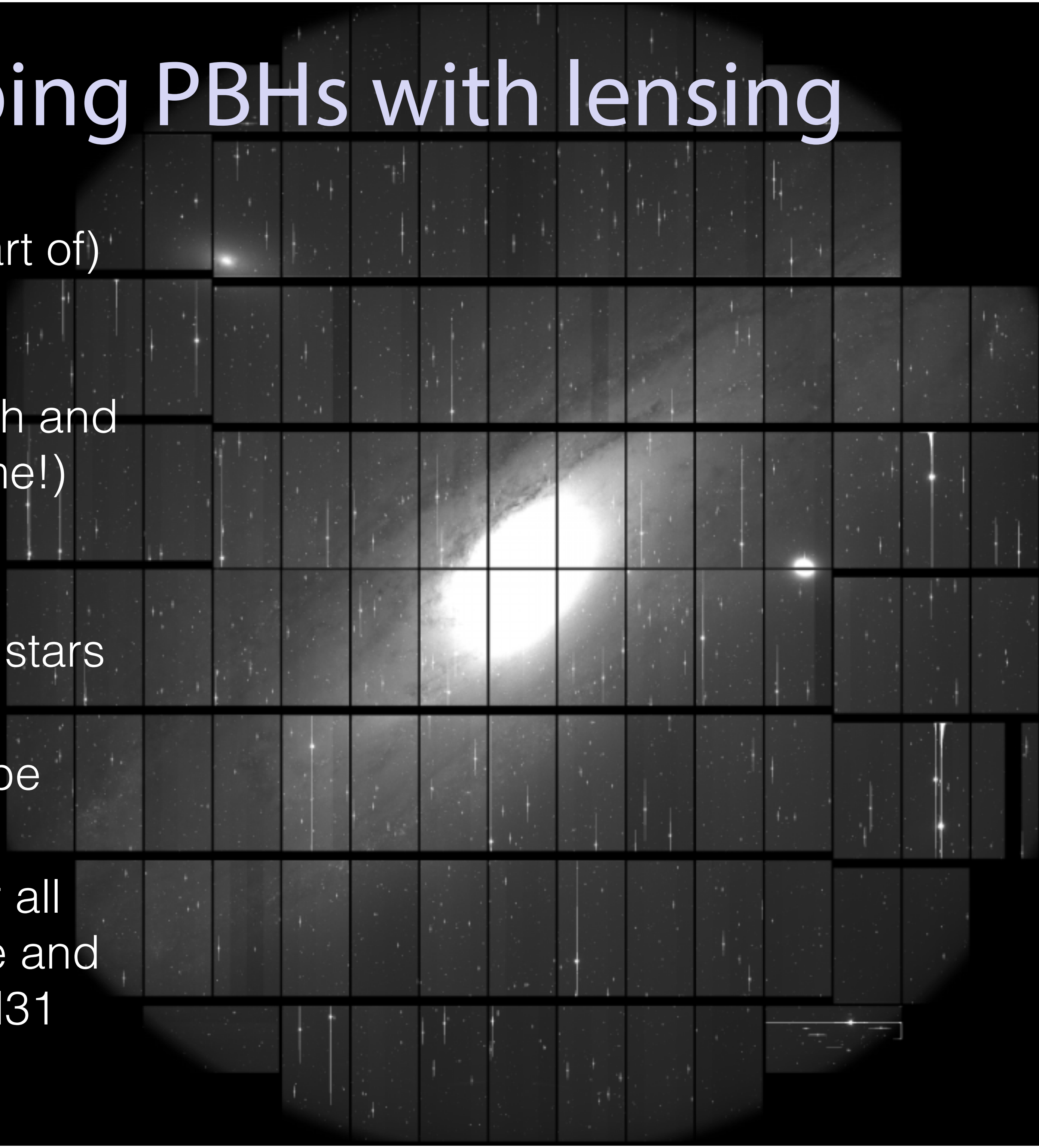
Andromeda Galaxy (M31)



- 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)!

probing PBHs with lensing

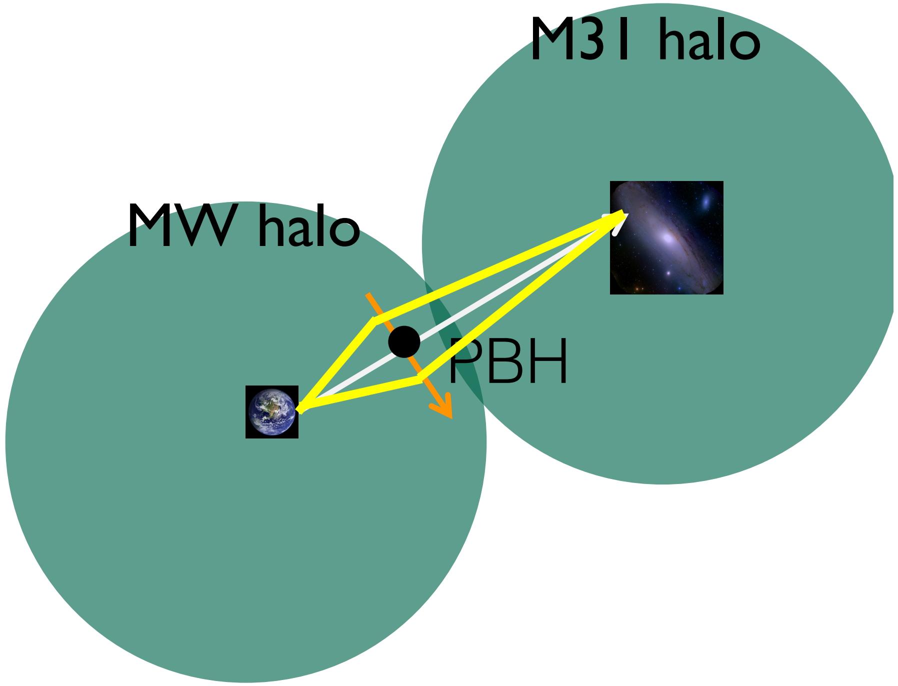
- If PBHs are (a part of) dark matter, they should exist in between the Earth and M31 (huge volume!)
- PBHs cause microlensing magnification on stars in M31
- Lensing can probe invisible
- HSC can monitor all stars in the bulge and disk regions of M31



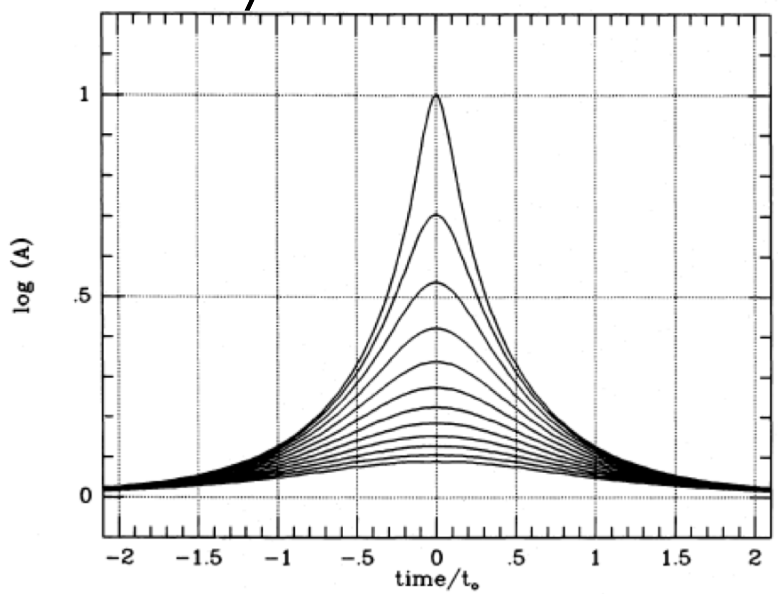
PBH microlensing on M31 star

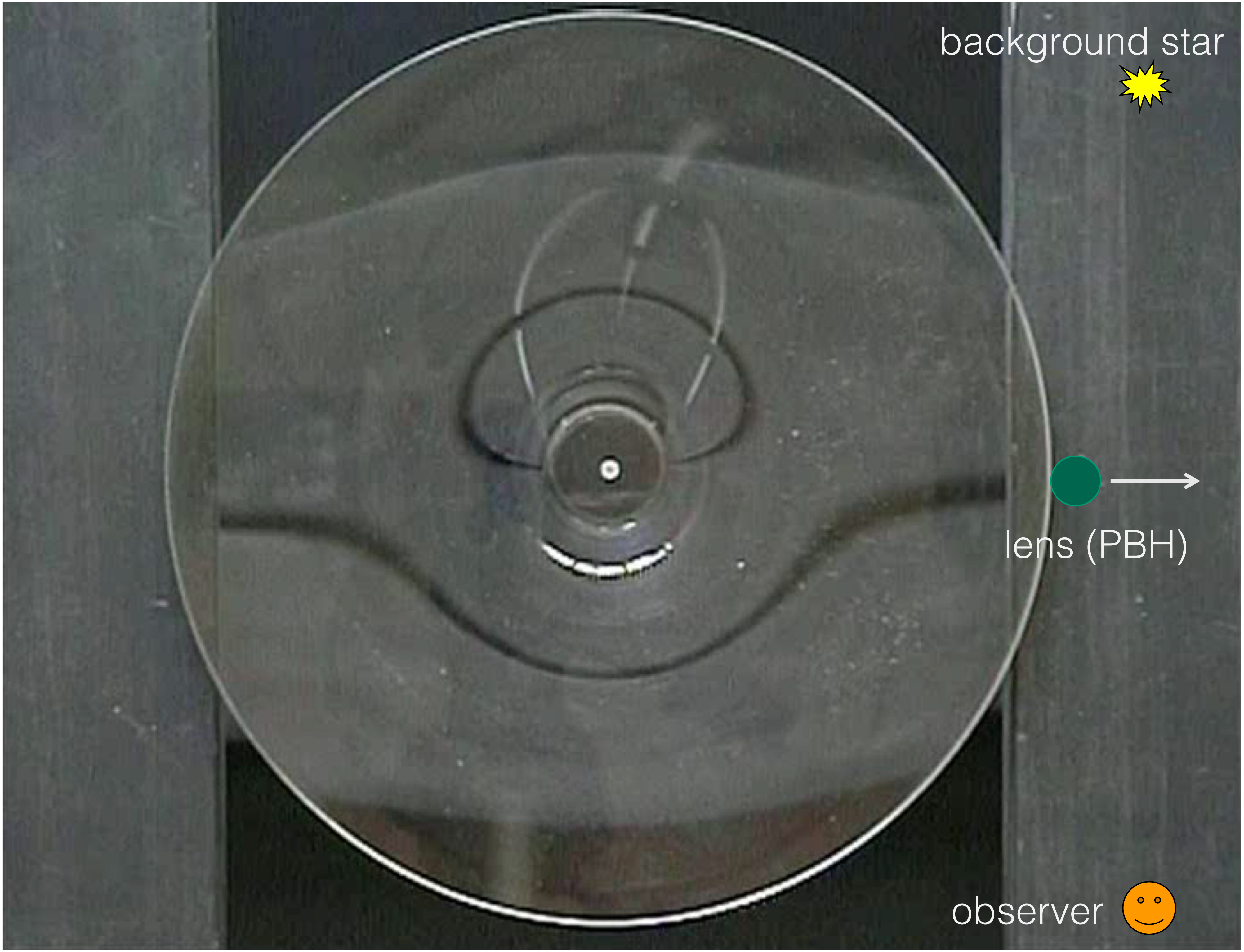
- Lensed image can't be resolved with optical resolution (~10^{-8} arcsec) ⇒ only light curve is a signal
- Huge volume
- MW/M31 halo ~ 10^{12}Msun (we assumed NFW models)
- PBH has a peculiar velocity of ~200km/s
- Need to monitor brightness of the same star as a function of "time" (time domain astronomy)

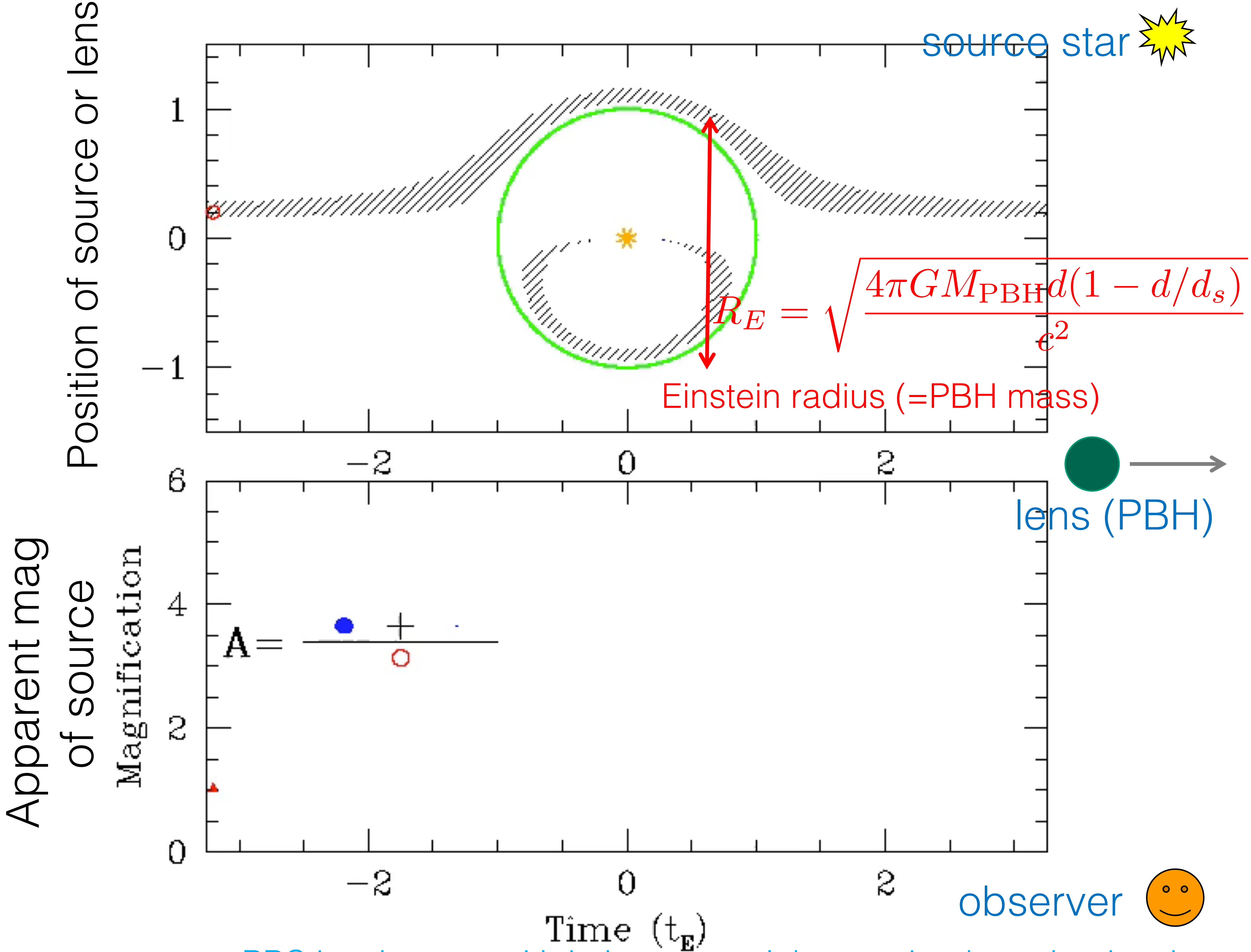
$$R_E = \sqrt{\frac{4\pi G M_{\rm PBH} d(1-d/d_s)}{c^2}}$$



Paczynski 86



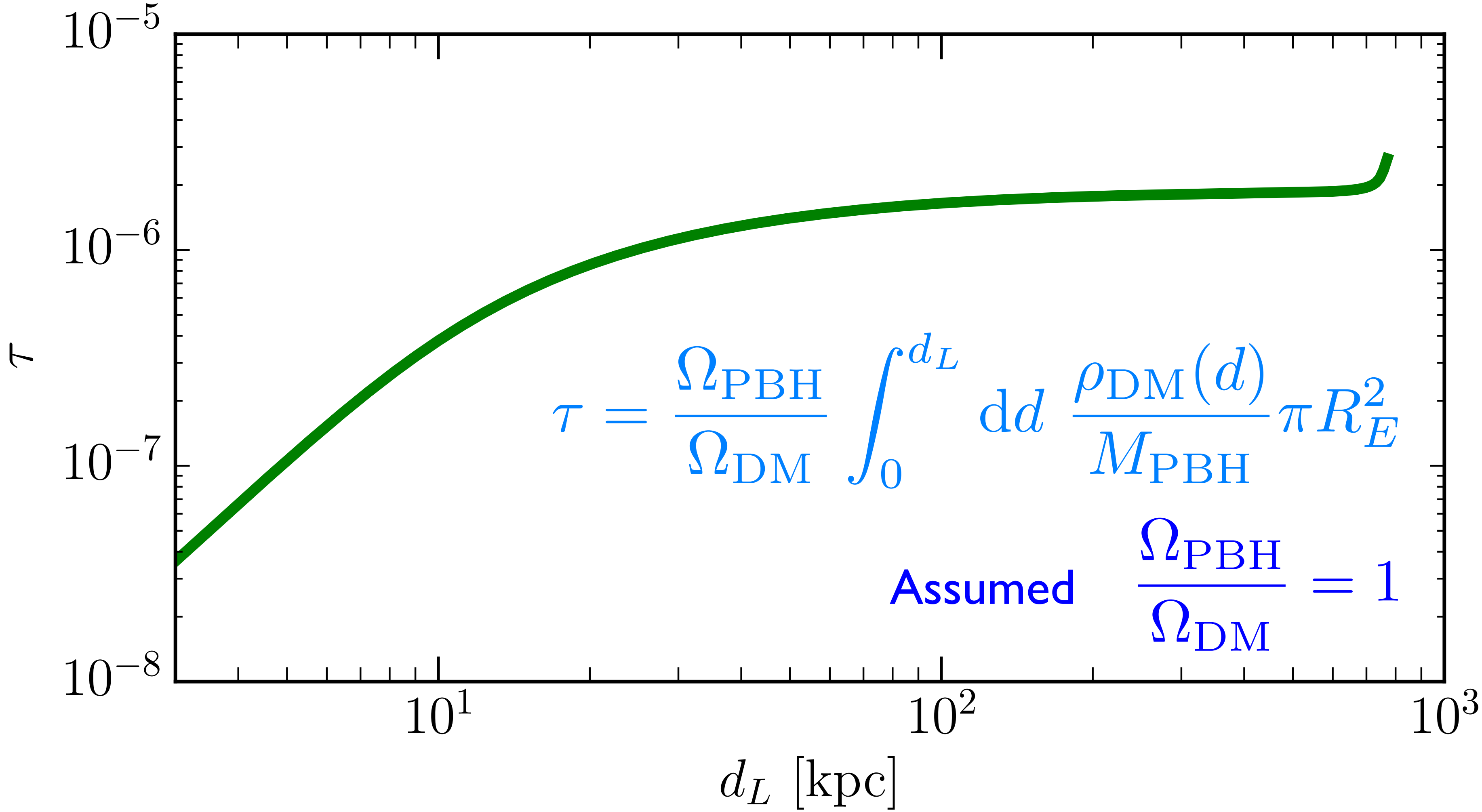

background star
lens (PBH)
observer



PBS lensing ⇒ multiple image can't be resolved ⇒ microlensing

PBH microlensing on M31 star

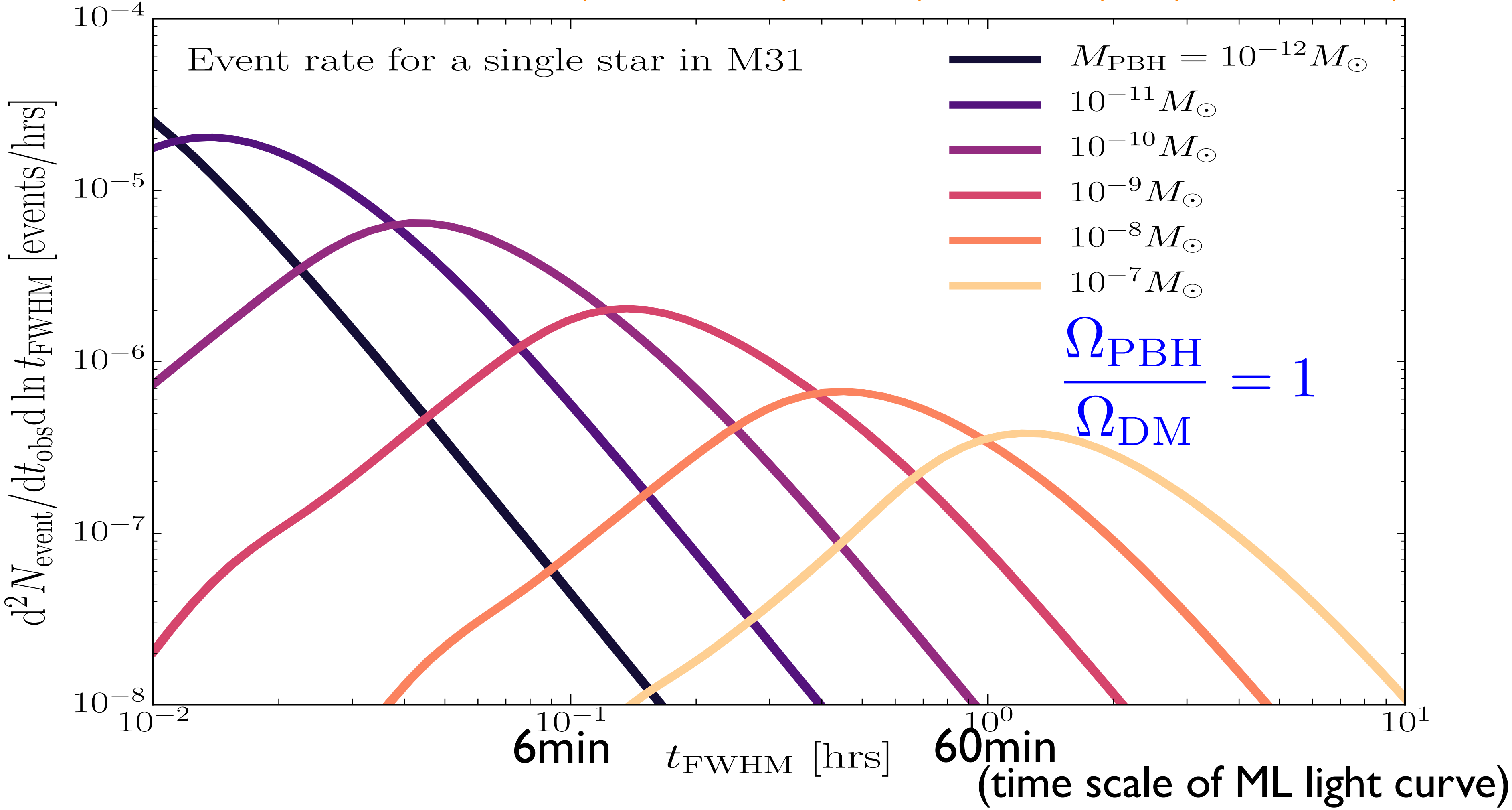
Cumulative optical depth of PBH microlensing for a **single** star in M31



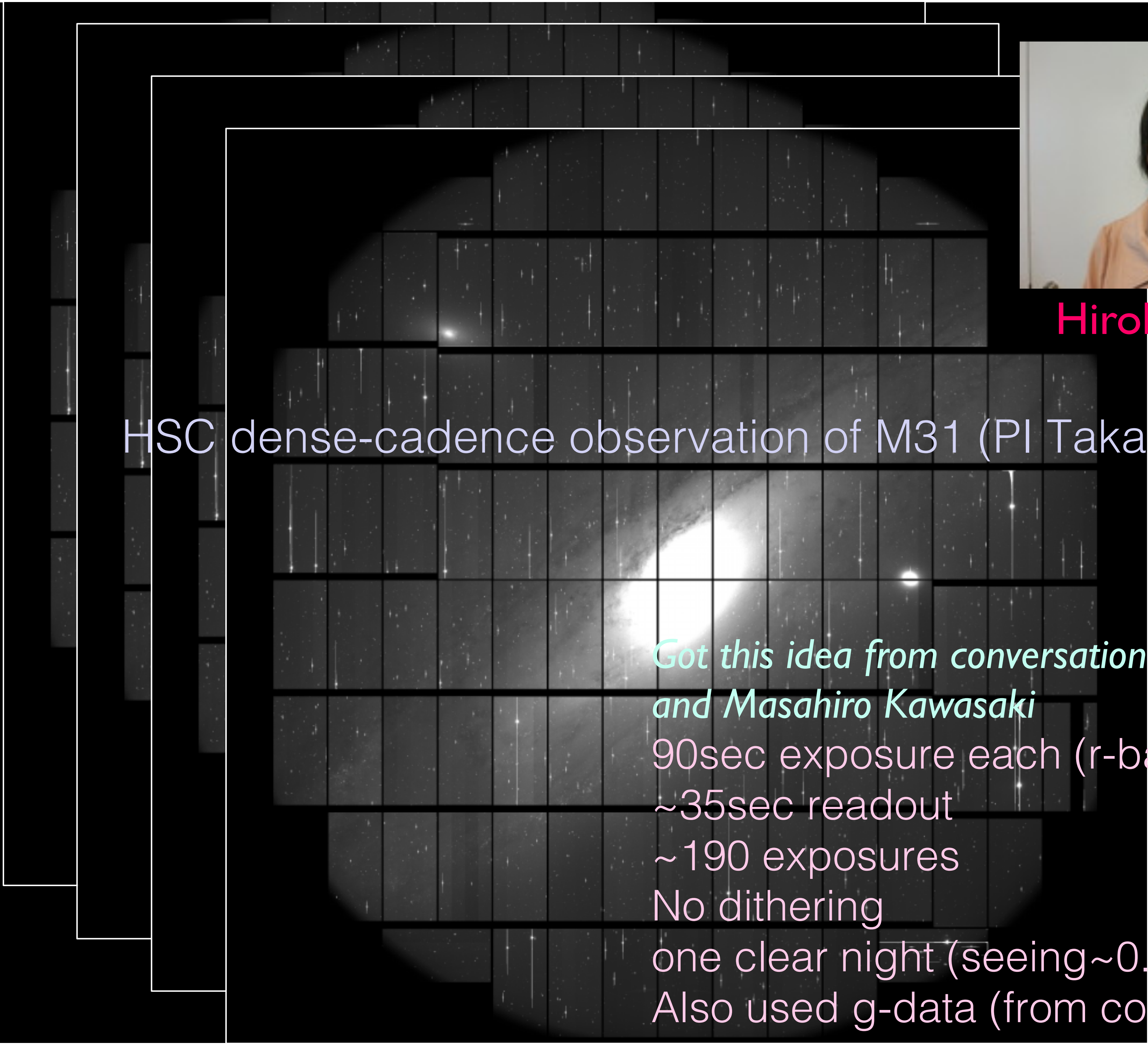
If we observe **~10^6 stars** at one time, **one star at leas**
should be micro-lensed if PBHs are DM

PBH microlensing event rate

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



Event rate per **unit obs. time** and per **a single star** in M31 for **a given timescale of light curve**



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

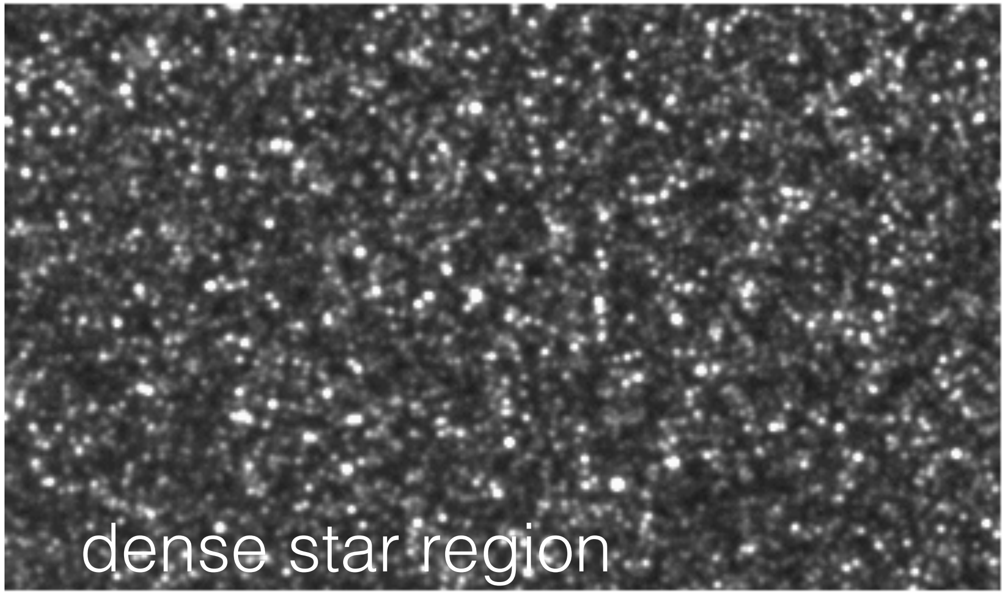
No dithering

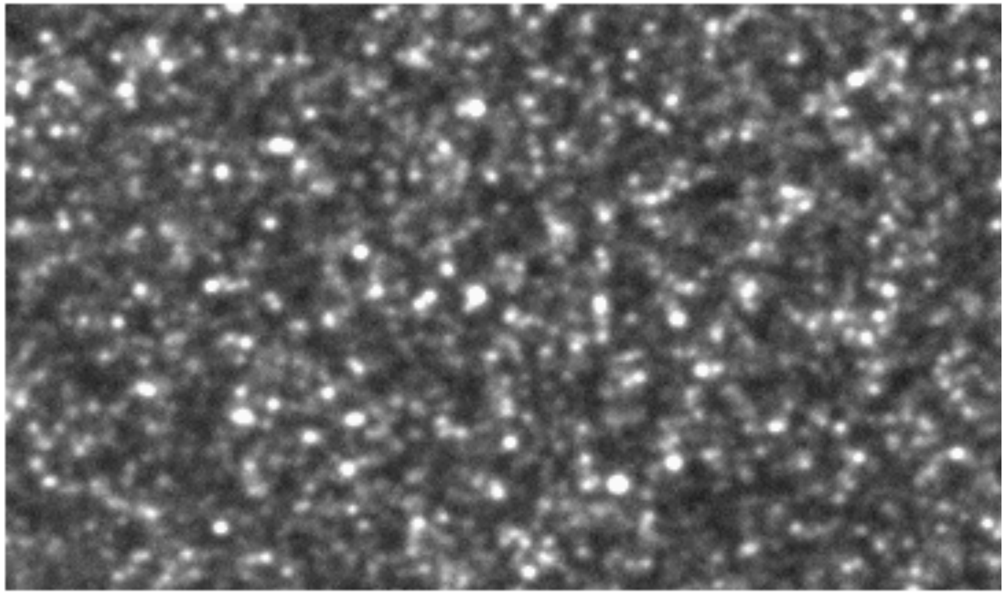
one clear night (seeing~0.5-0.6”)

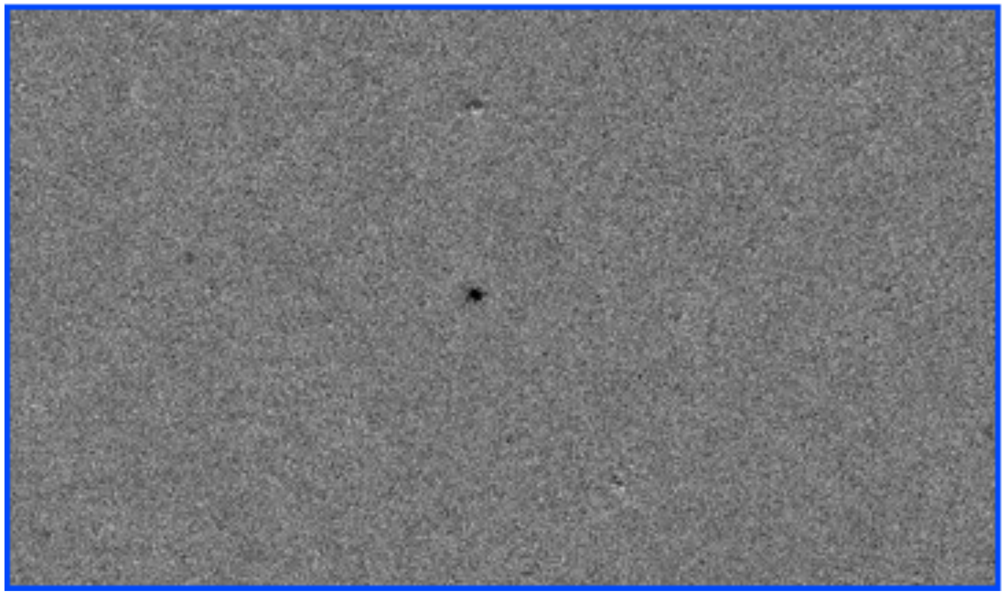
Also used g-data (from commissining)

Challenges: Pixel lensing

Fluxes from multiple stars are overlapped at each position





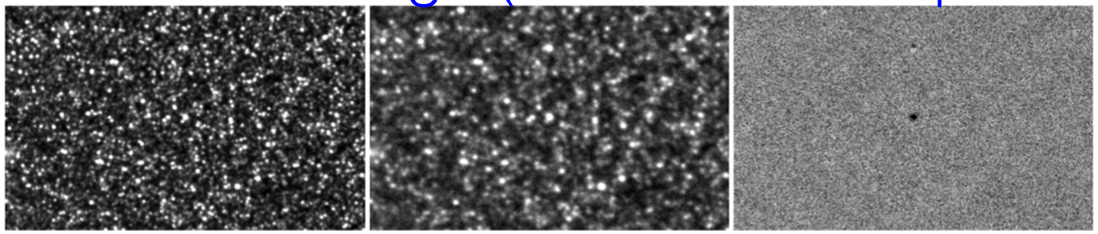


Upper left: reference image (0.5'')
Upper right: target image (0.8'')
Lower: difference image

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

Procedures: search for ML events

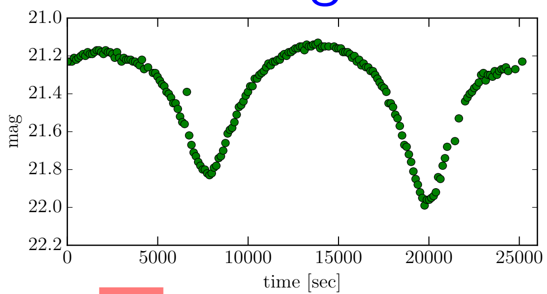
difference image (coadds of 3 exposures)

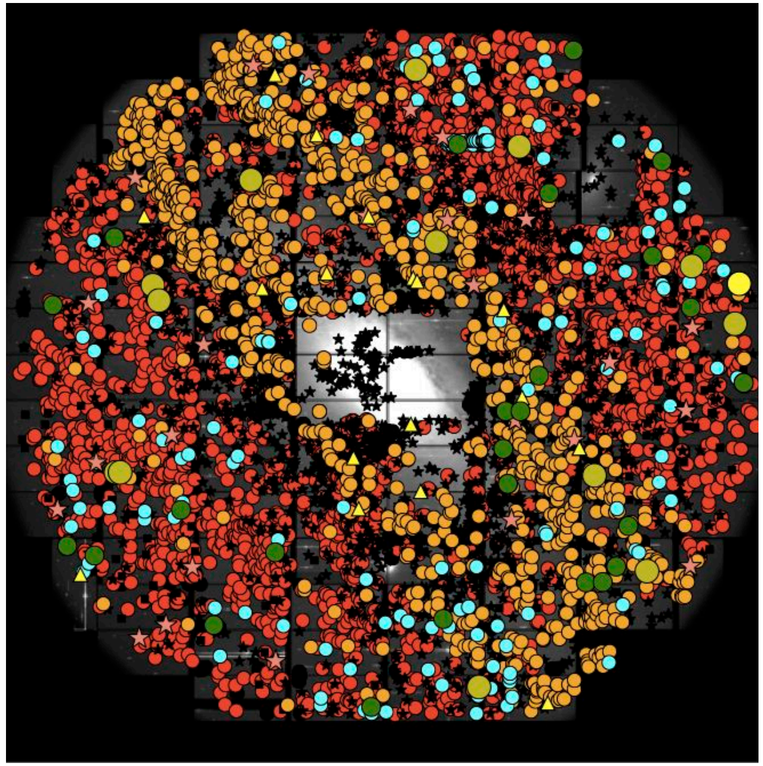


identify candidates in each diff. image

⇒15,571

measure light curve (188 data points)

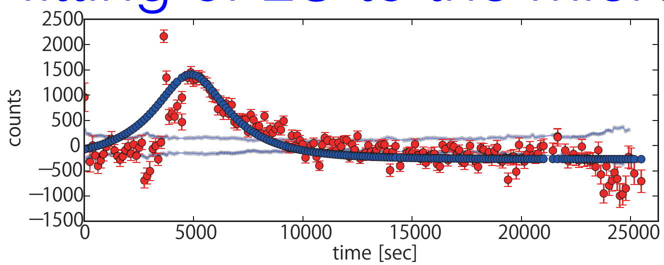




candidates with bump-like light curve

⇒ 11,703

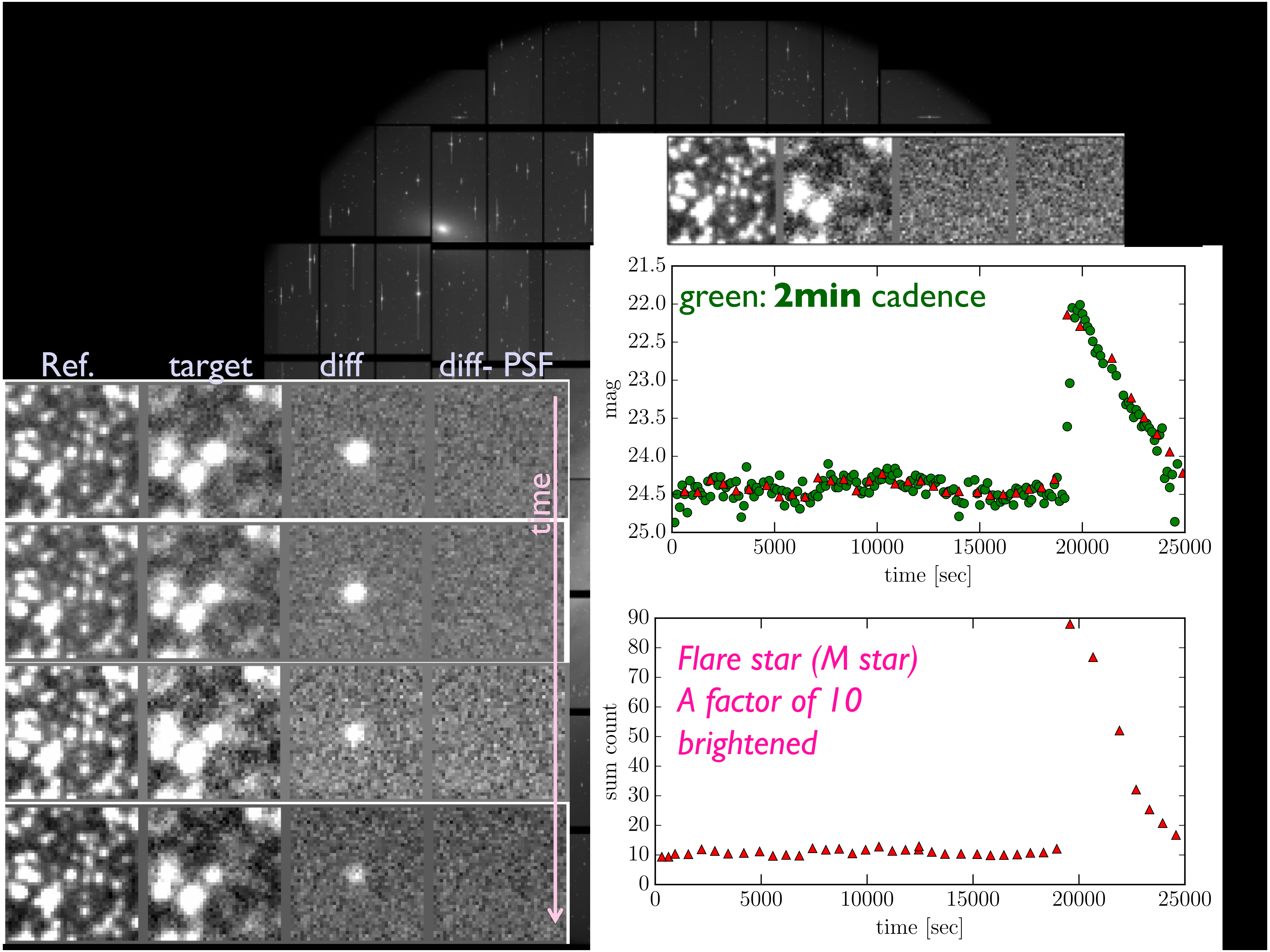
fitting of LC to the microlensing model

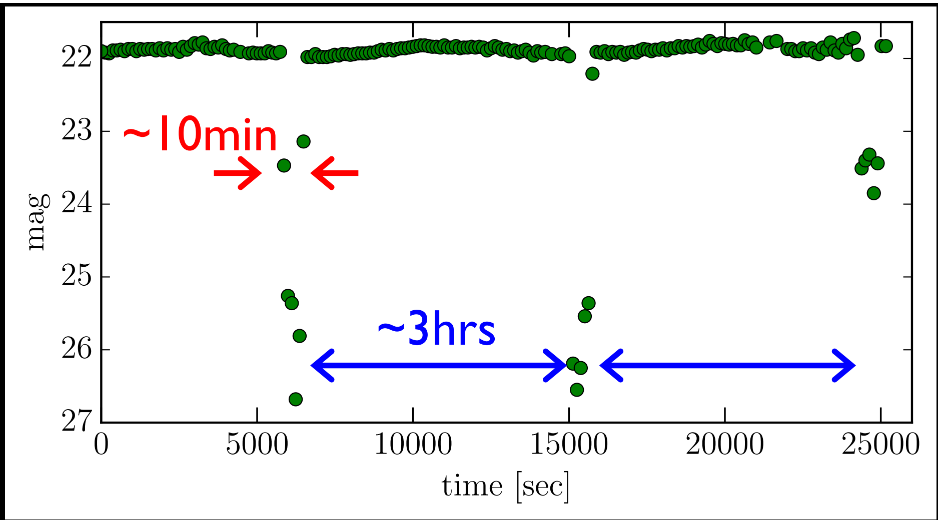


selection criteria

⇒ 66

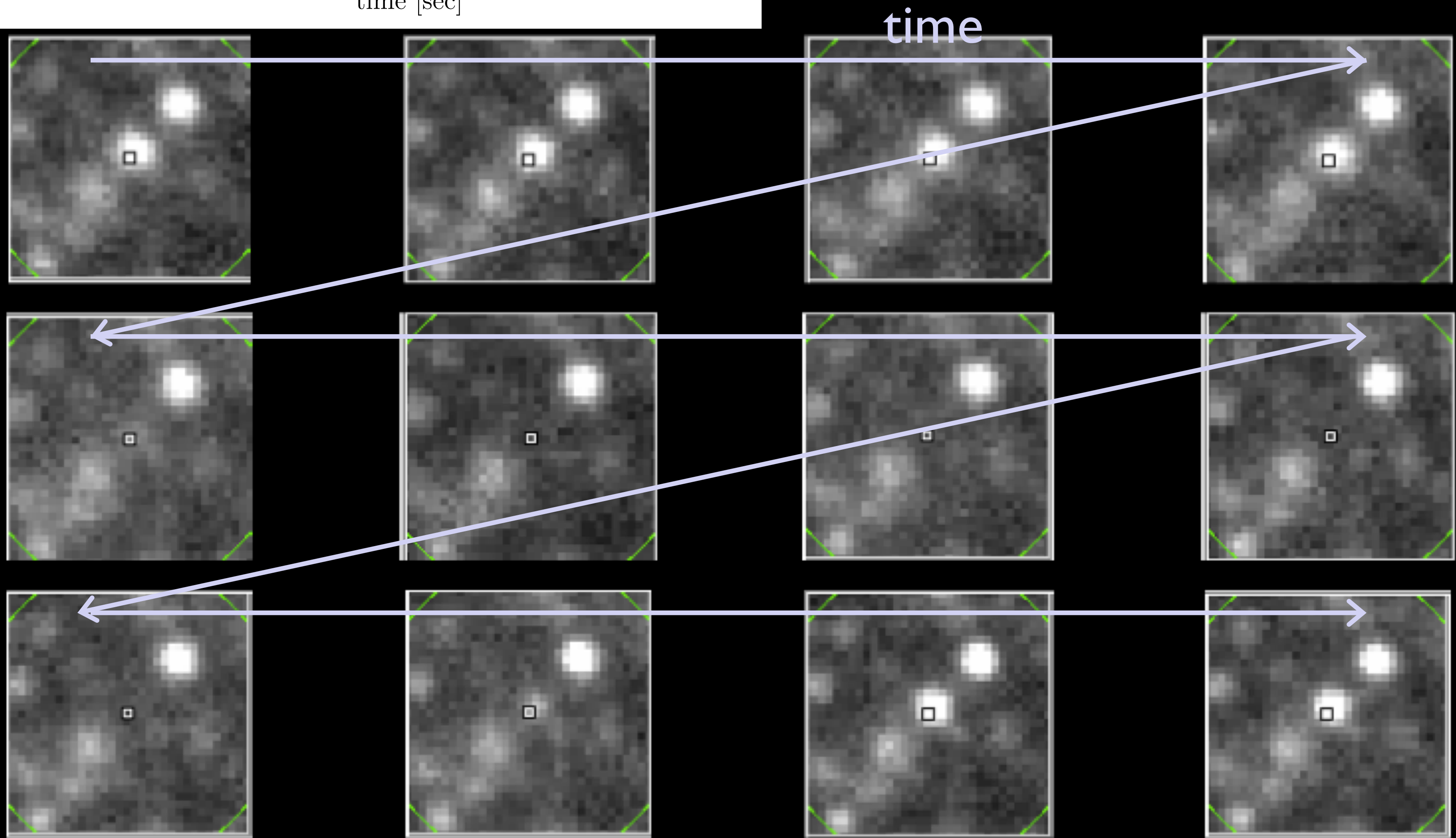
visual inspection of individual candidates…


Ref.
target
diff
diff- PSF
time
green: **2min** cadence
mag
time [sec]
sum count
Flare star (M star)
A factor of 10
brightened
time [sec]



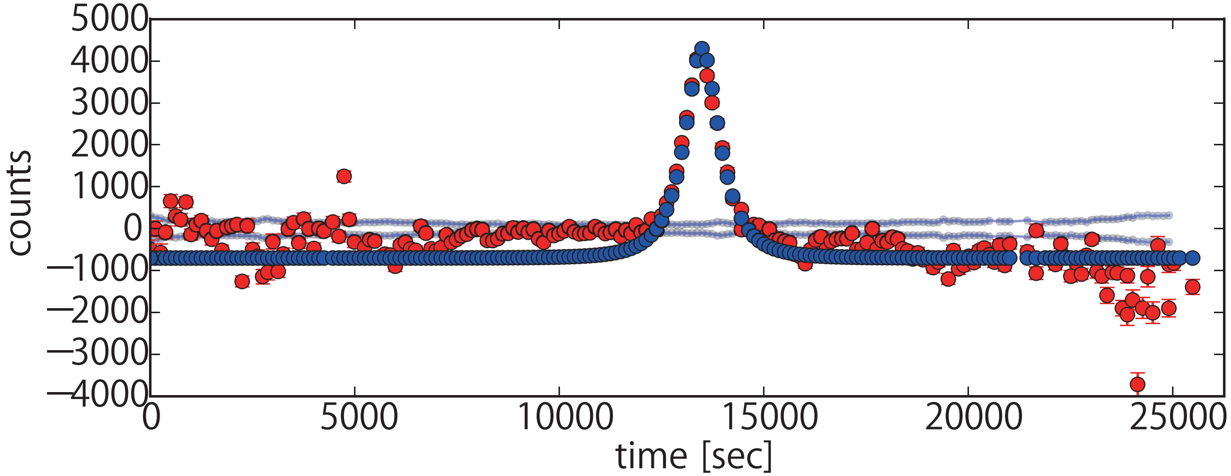
An entire star disappears for ~10min, with a 3hrs interval

WD – brown dwarf binary

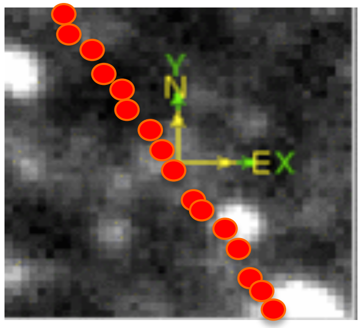


Visual inspection stage…

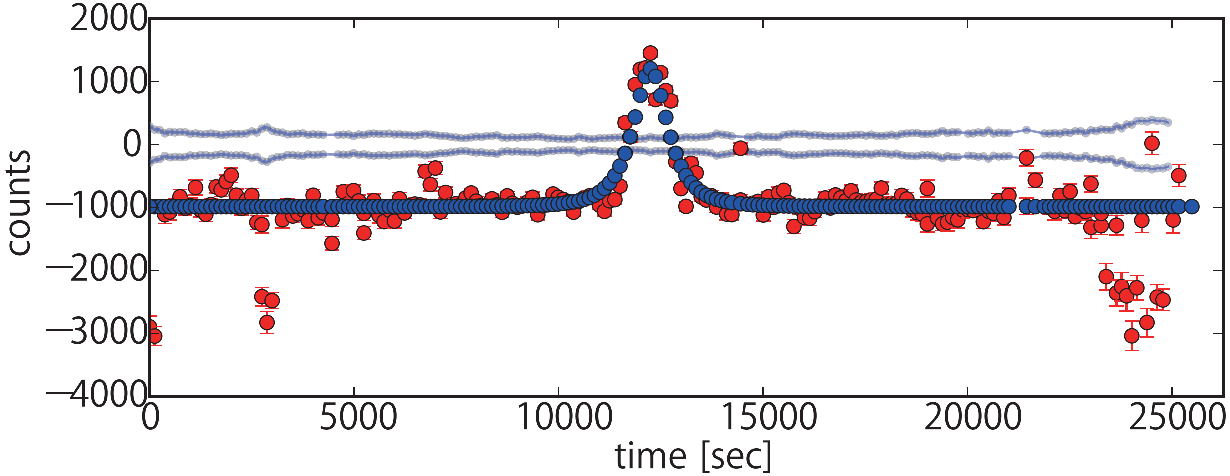
Visual inspection of 66 candidates to identify junks…

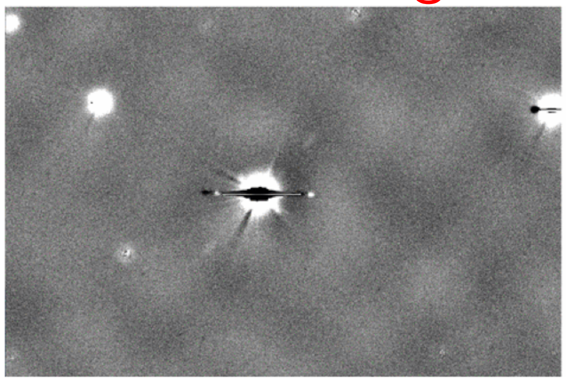


asteroid



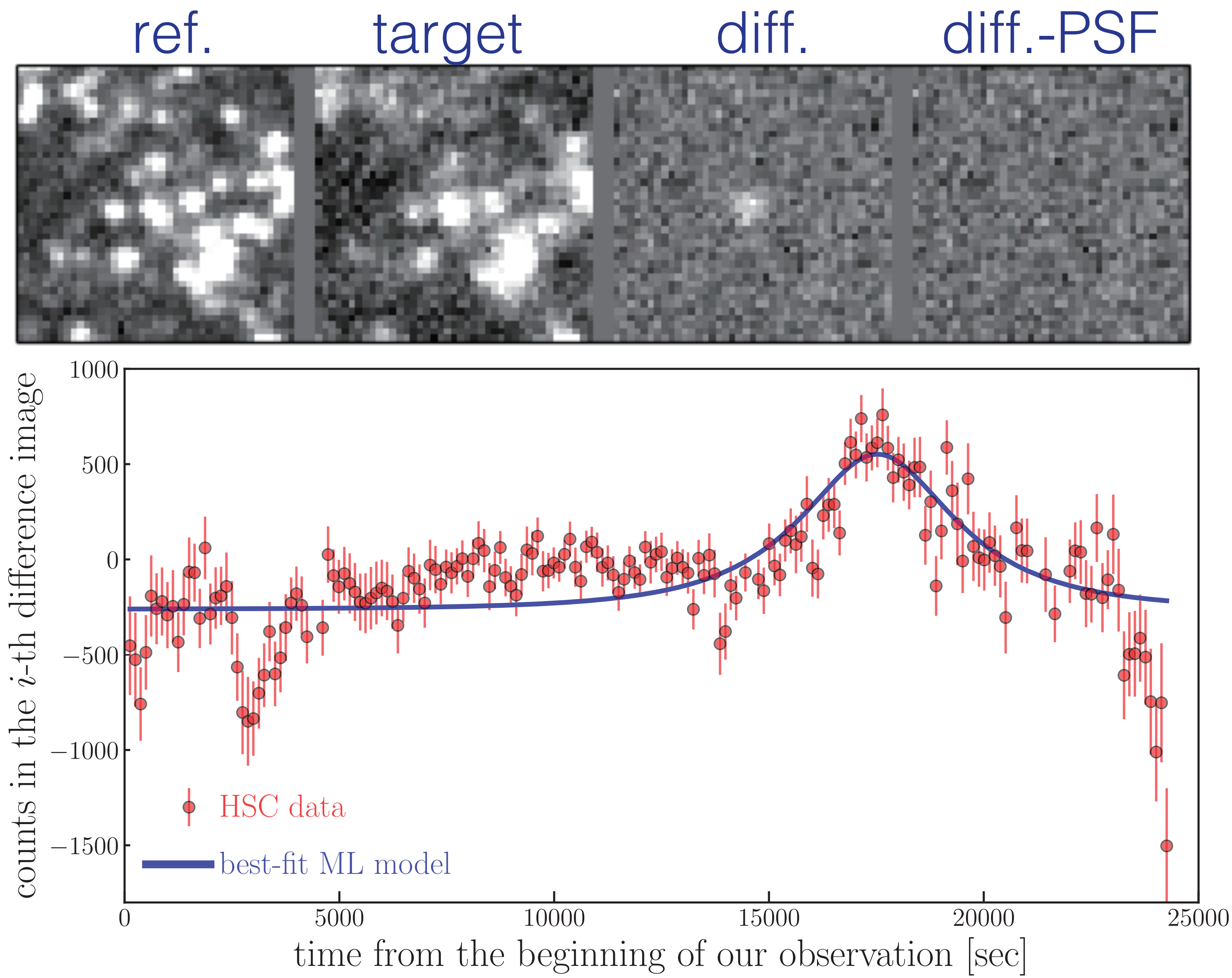
spike around a bright star





66 ⇒ 65 junks

One real candidate of microlensing …?



To constrain the PBH abundance

- Expectation number of PBH microlensing events

$$N_{\rm exp} = \Delta t_{\rm obs} \int {\rm d}m_r \, \frac{{\rm d}N_{\rm s}}{{\rm d}m_r} \int {\rm d}t_{\rm FWHM} \, \frac{{\rm d}\Gamma}{{\rm d}t_{\rm FWHM}} \epsilon(t_{\rm FWHM}, m_r)$$

duration of observation time (about 7 hours)

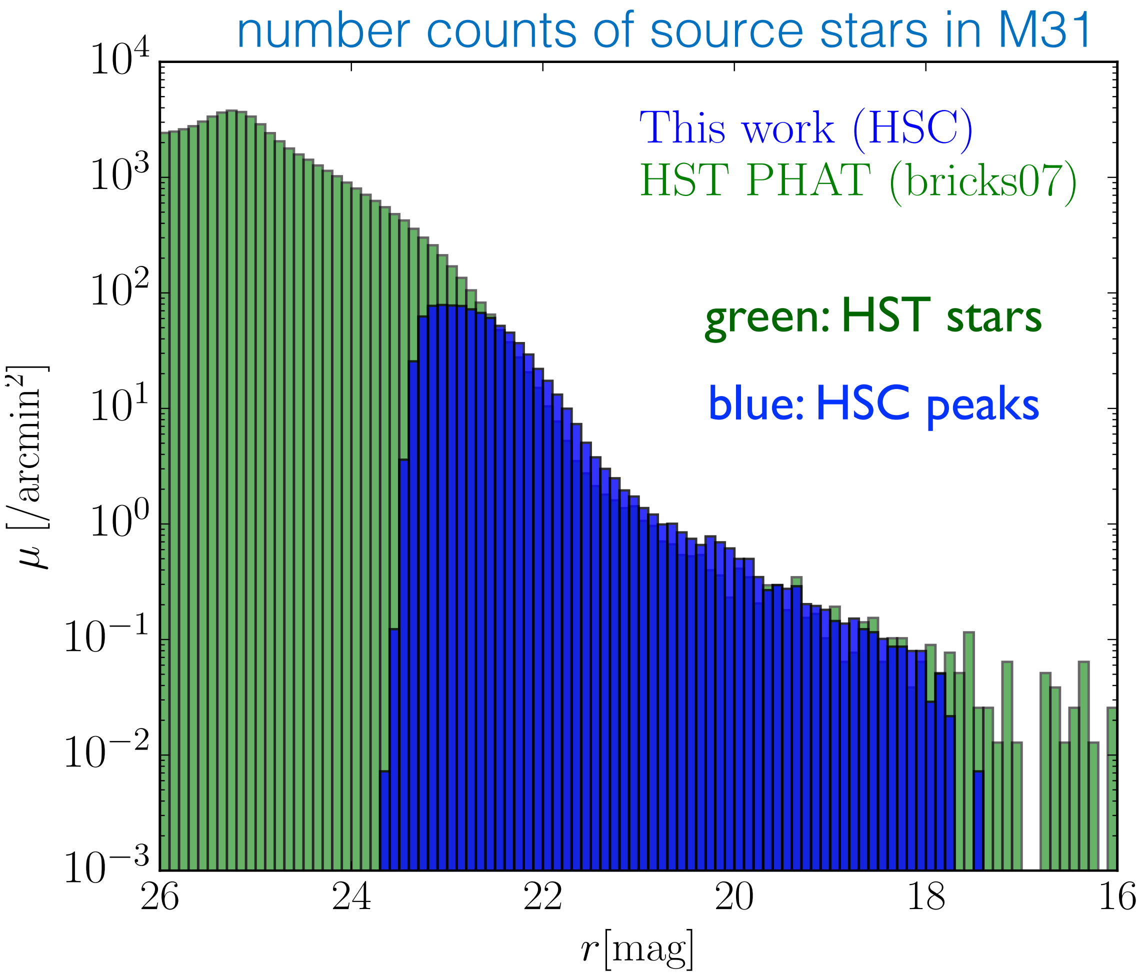
number of source stars in the magnitude range [m, m+dm] (see later)

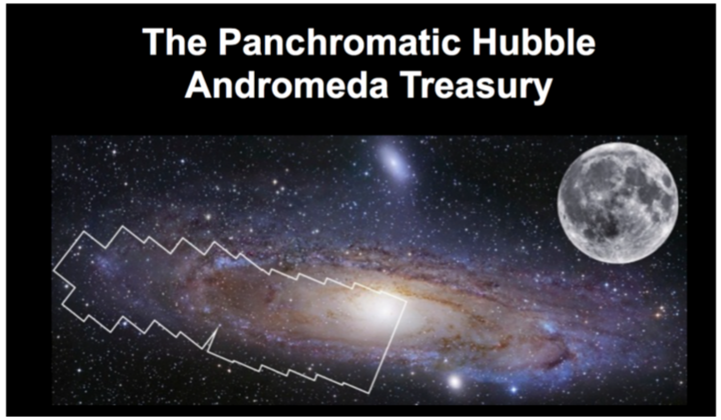
Event rate of PBH microlensing (computed assuming NFW profiles of the MW and M31 halos)

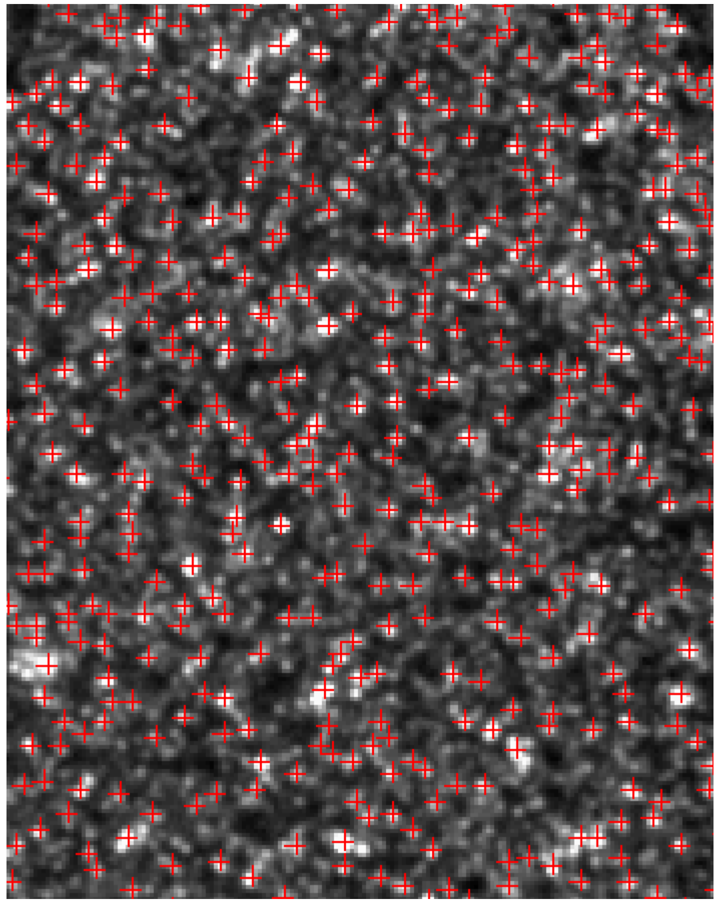
Detection efficiency for microlensing event of timescale t_FWHM for a star of magnitude, m_r (see later)

Number of source stars

HSC can't resolve individual stars due to blending





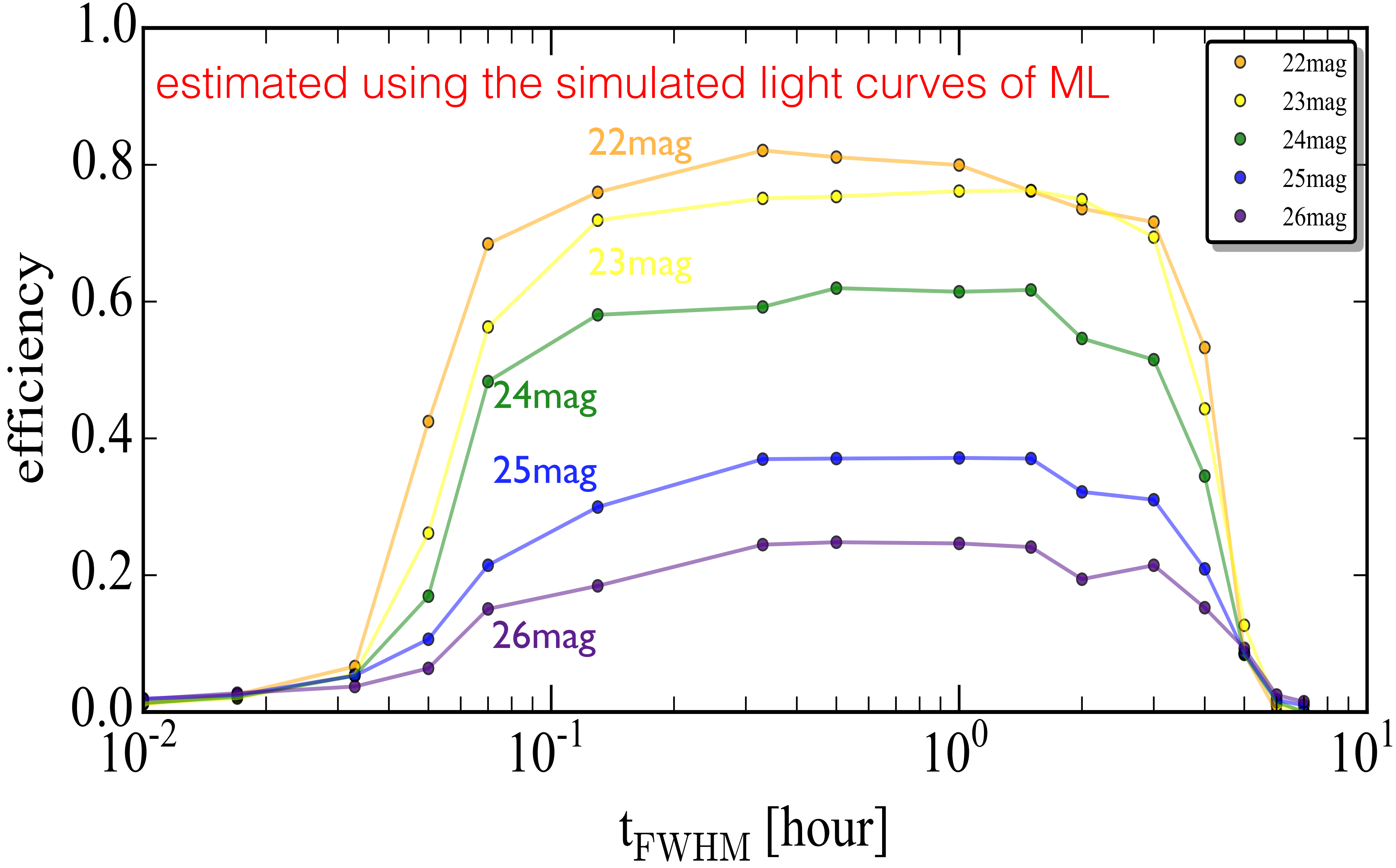


6.4×10^6 HSC peaks (conservative)

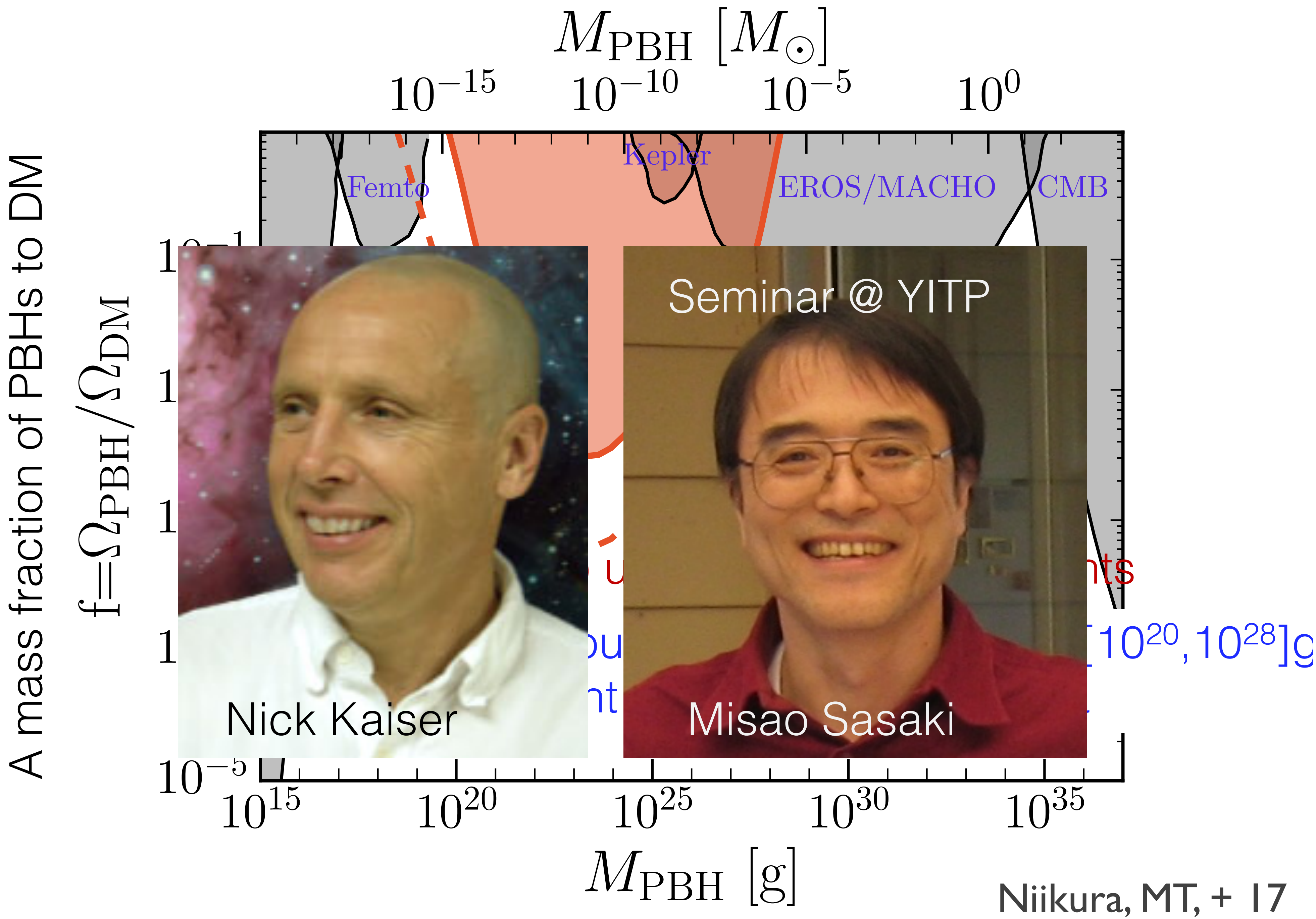
8.7×10^7 stars if extrapolated from the HSC star counts for the M31 disk regions

Detection efficiency

$$N_{\rm exp} = \Delta t_{\rm obs} \int dm_r \, \frac{dN_s}{dm_r} \int dt_{\rm FWHM} \frac{d\Gamma}{dt_{\rm FWHM}} \epsilon(t_{\rm FWHM}, m_r)$$



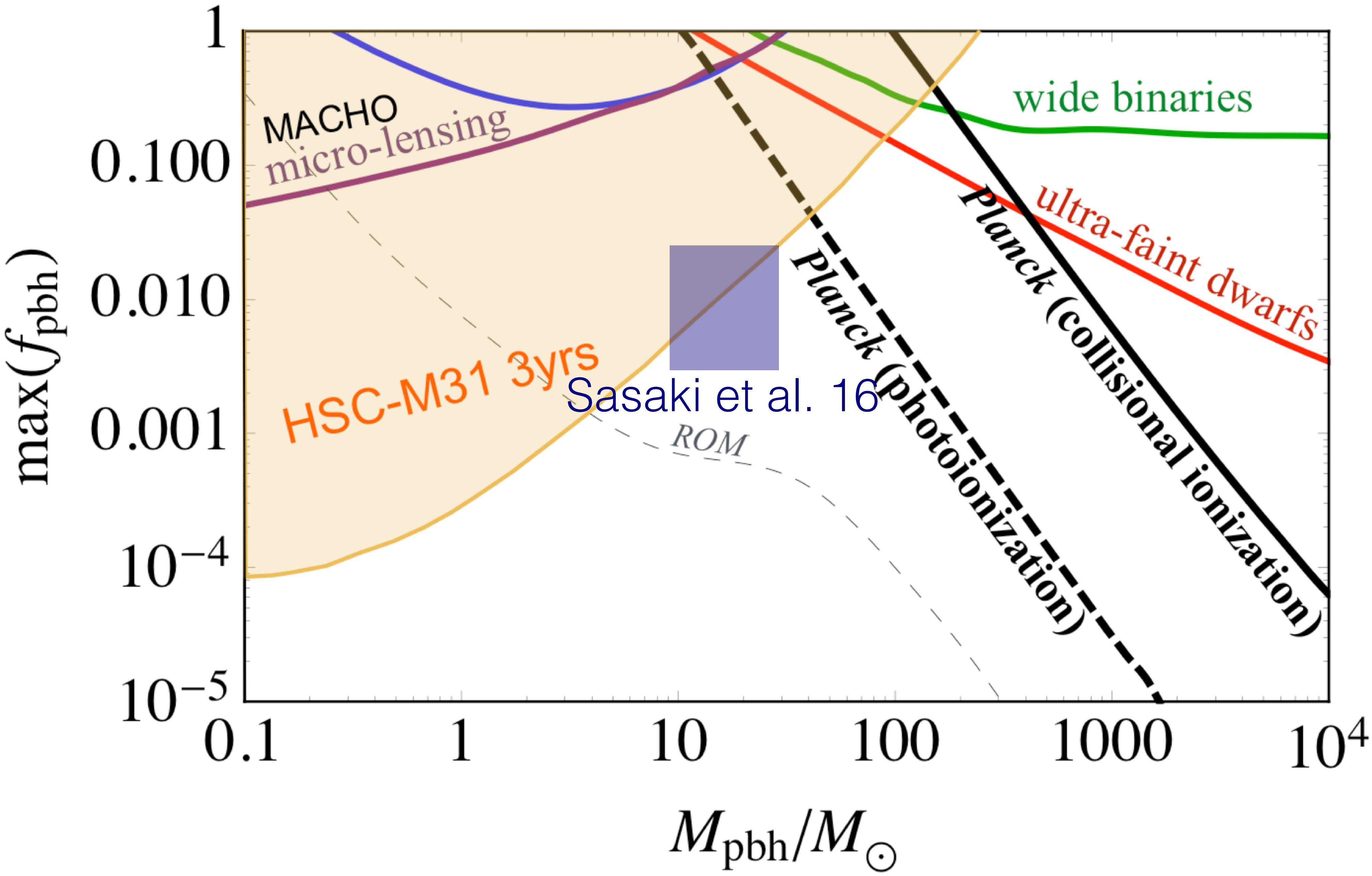
Results: New bound on PBH abundance



Niikura, MT, + 17

Prospect for further HSC observation

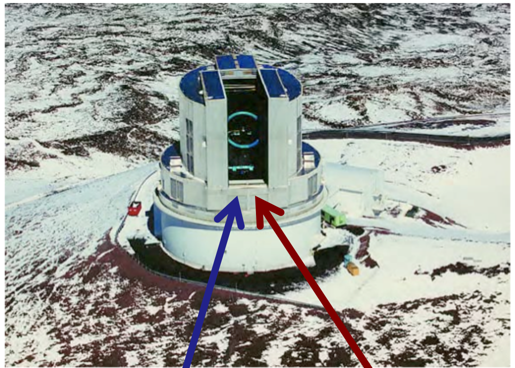
only one or a few Subaru nights in total, sparsely sampled over 3yrs



SuMIRe = Subaru Measurement of Images and Redshifts

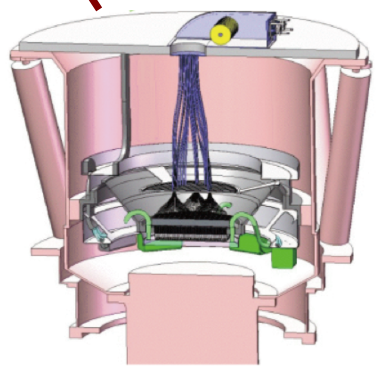
H. Murayama (Kavli IPMU Director)

- IPMU director Hitoshi Murayama funded (~$32M) by the Cabinet in Mar 2009, as one of the stimulus package programs
- Build *wide-field* camera (Hyper Suprime-Cam; ~$55M) and *wide-field* multi-object spectrograph (Prime Focus Spectrograph; ~$80M) for the Subaru Telescope (8.2m)
- Explore the fate of our Universe: dark matter, dark energy
- Keep the Subaru Telescope a world-leading telescope in the TMT era
- Precise images of 1B galaxies
- Measure distances of ~4M galaxies
- **Do SDSS-like survey at z>1**

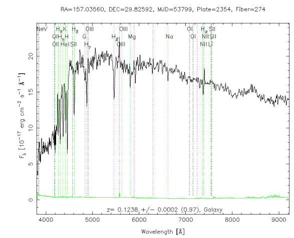


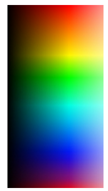
Subaru (NAOJ)

HSC



PFS

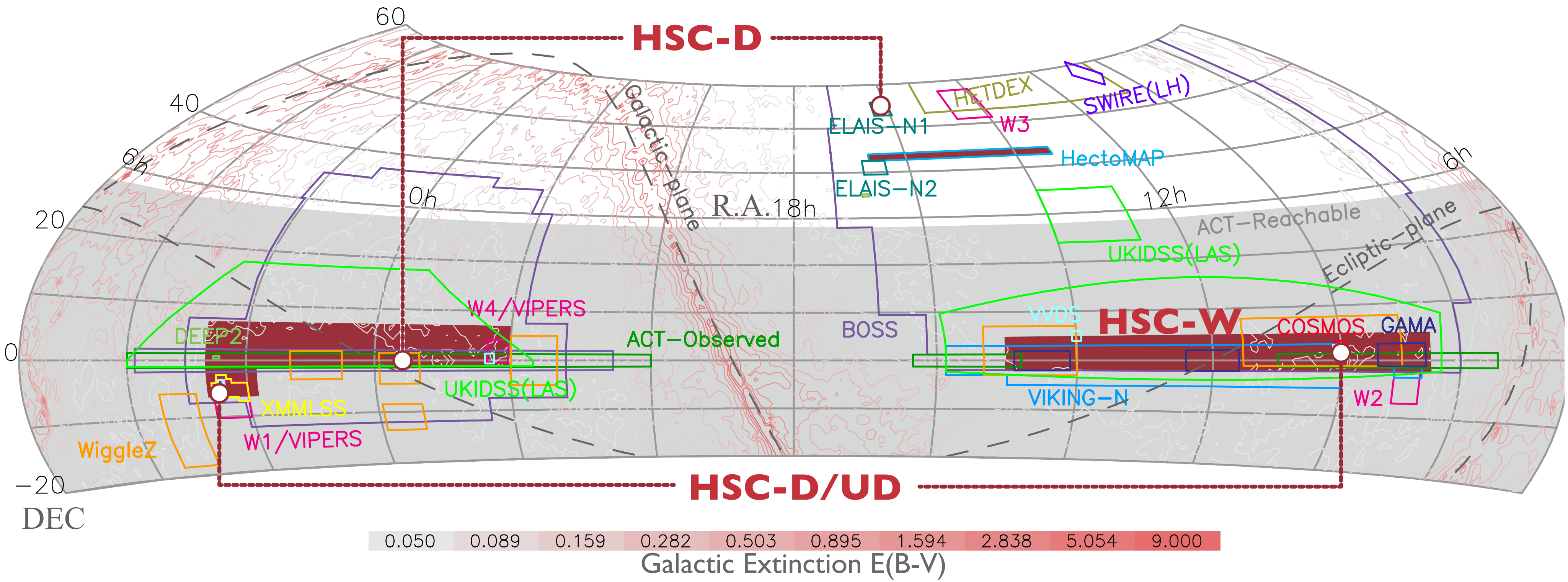




Subaru-**300**-nights HSC project (2006 -)

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

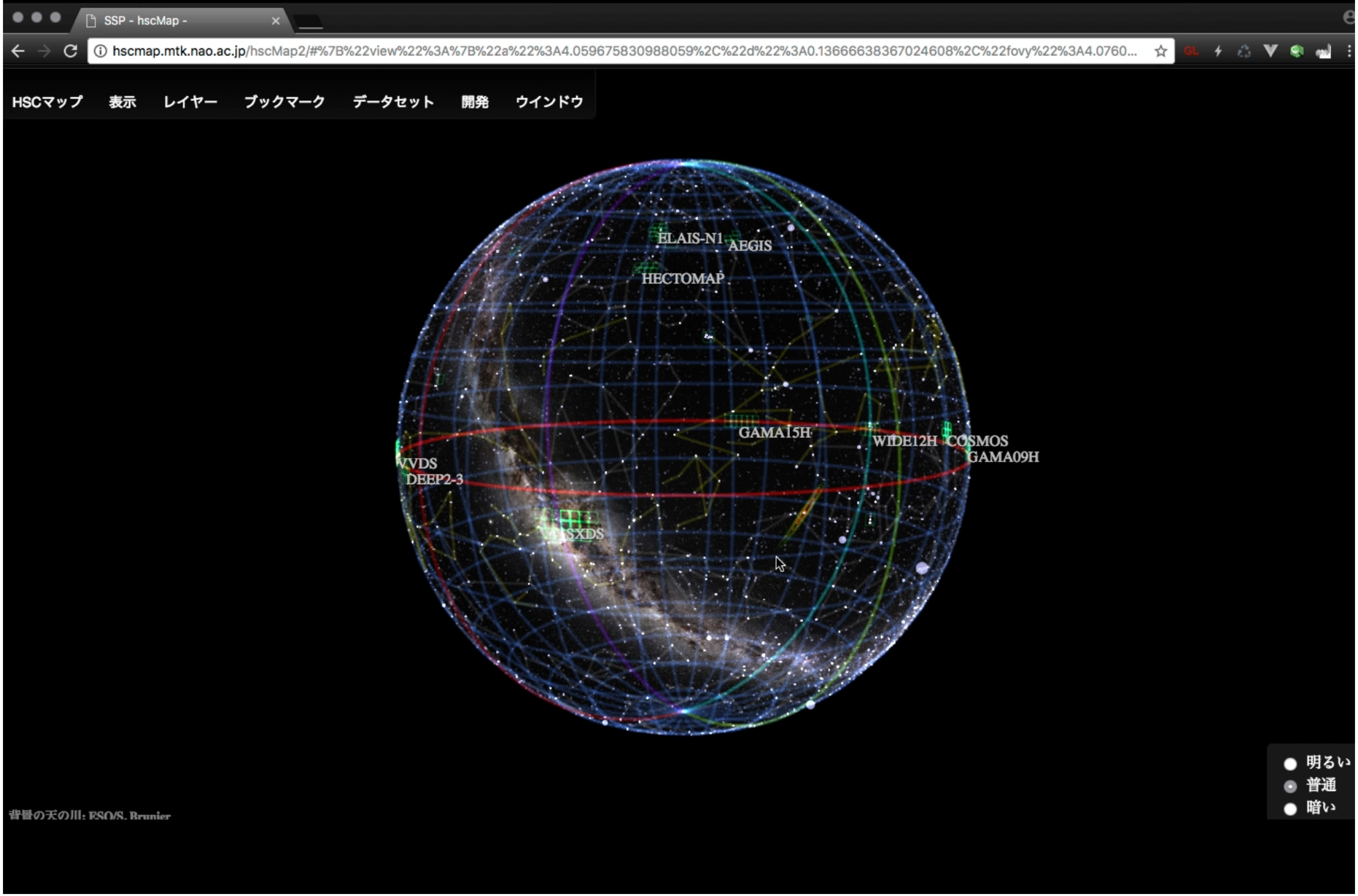
First Data Release (DR1) of HSC SSP
28 Feb, 2017

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

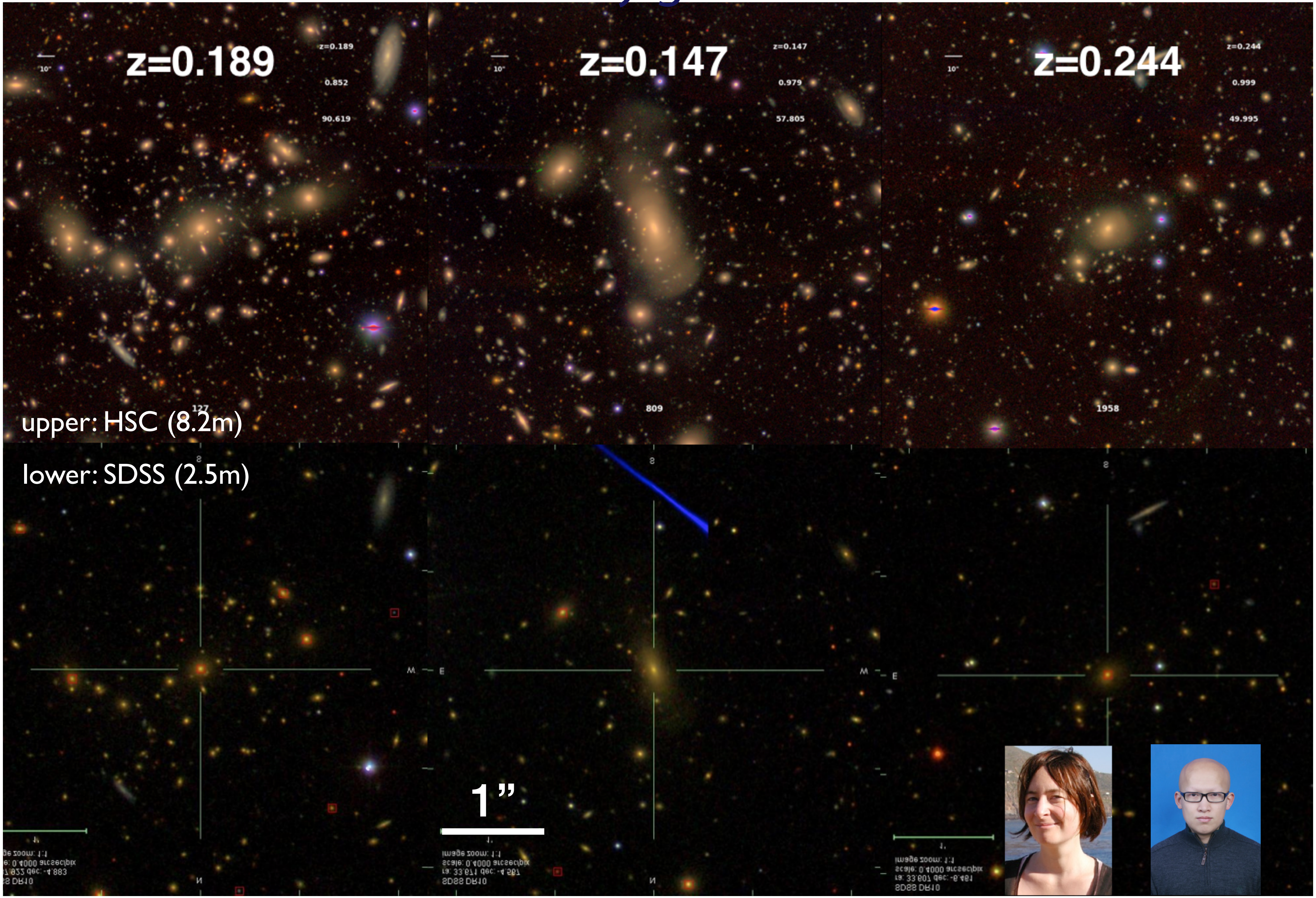
First Public Data Release by the Hyper Suprime-Cam Subaru Strategic Program

February 28, 2017 | Topics

hscMap: user interface



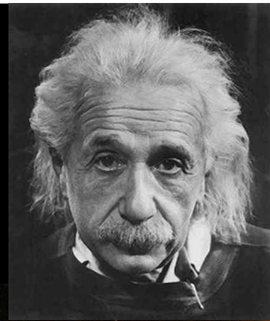
Nearby galaxies



All data reduced by the HSC pipeline

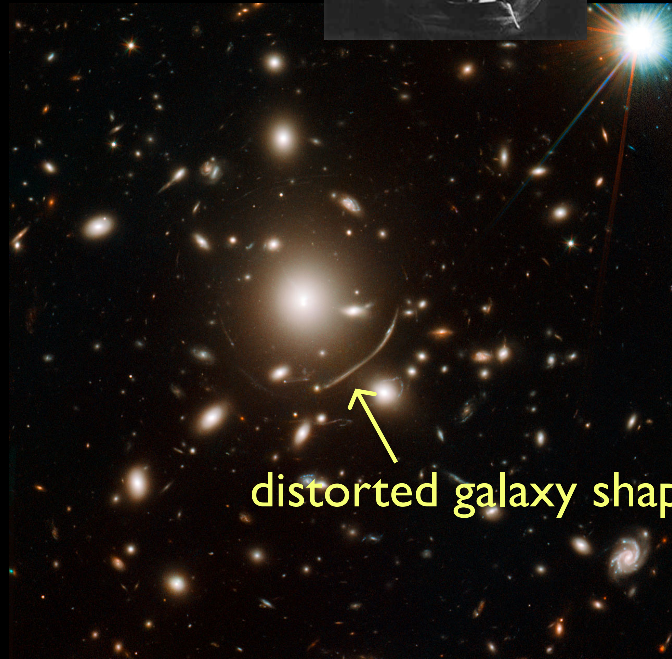
A. Leauthaud S. Huang

Gravitational lensing = GR prediction



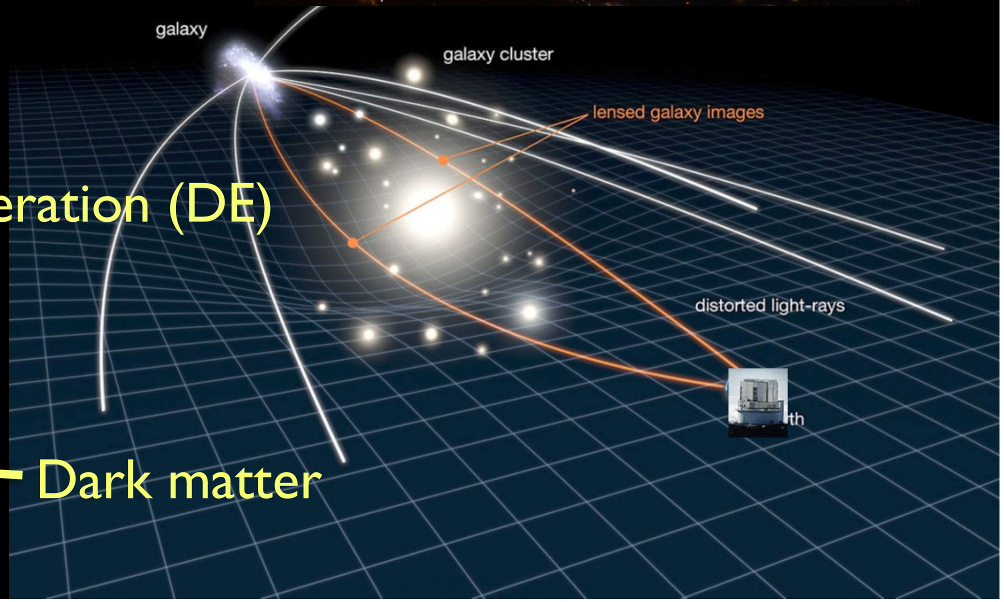
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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



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

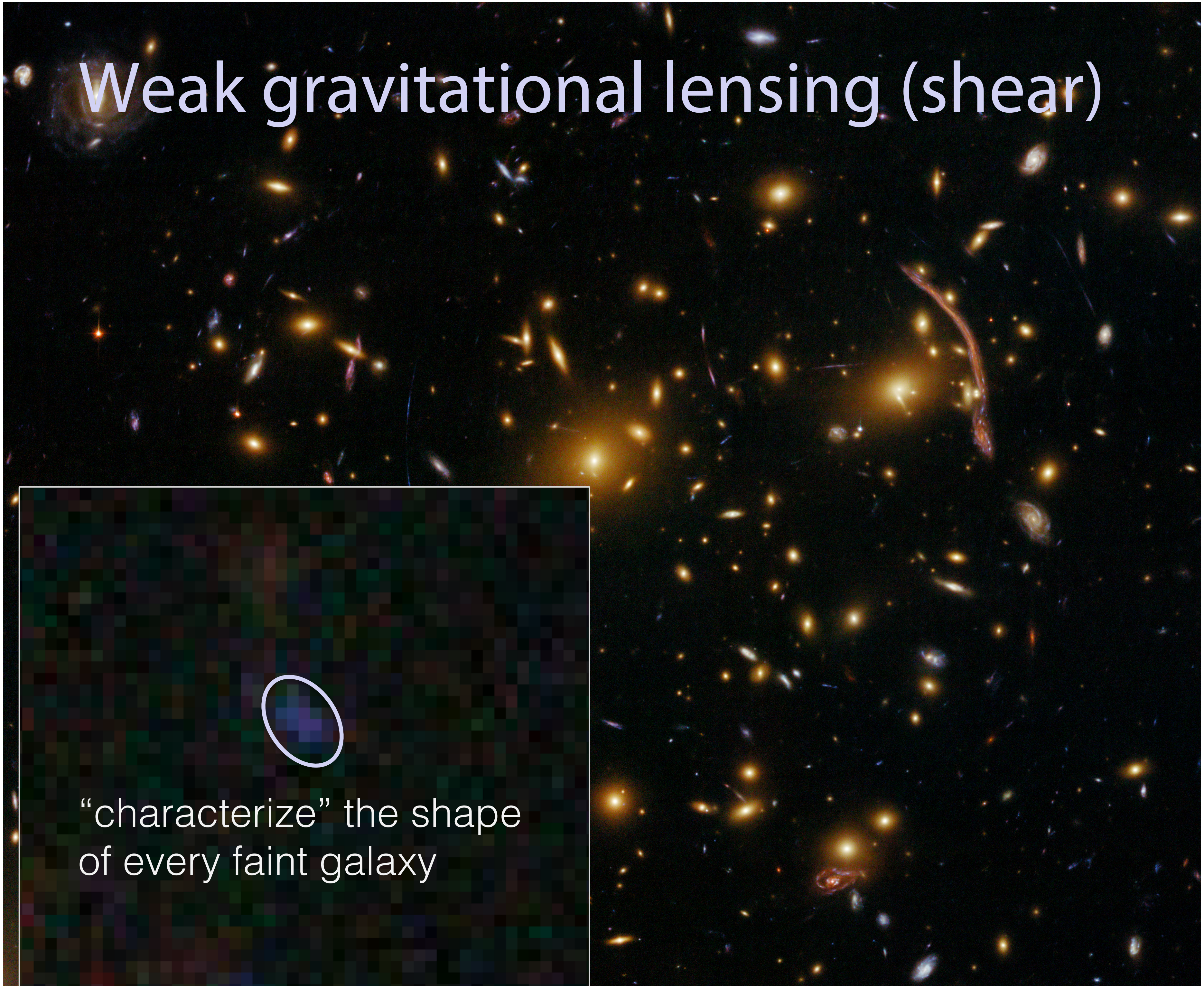
It causes a distortion in galaxy image



Cosmic acceleration (DE)

Lensing strength = (geometry of the universe) × (total matter of lens(es))

Dark matter


Weak gravitational lensing (shear)
“characterize” the shape
of every faint galaxy

For me, galaxies = numbers

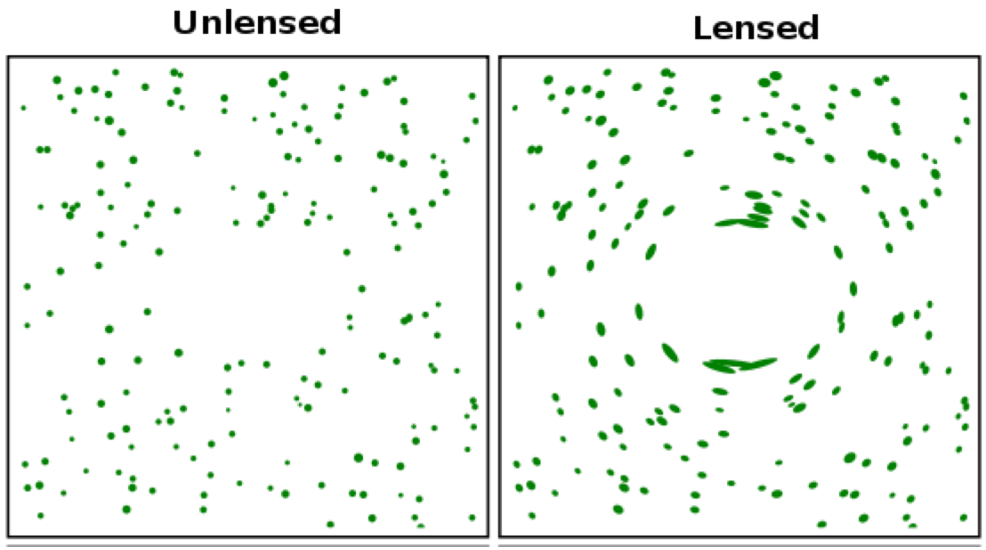
	object_id	parent_id	ira	idec	iflux_kron	iflux_kron_err	iflux_kr...	imag_kron	imag_kron_err	imag_c
1	73979570428054640	0	213.7985	51.84384	8.504140E-29	4.593317E-31		21.5759	0.005864	21.6
2	73979570428054766	0	213.80921	51.84618	1.596781E-29	6.690010E-31		23.3919	0.045489	23.4
3	73979570428054794	0	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	0.021113	22.5
4	73979570428054844	0	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	0.034431	23.2
5	73979570428055234	0	[illegible]	51.85532	1.222690E-29	4.107814E-31		23.6817	0.036477	23.6
6	73979570428055285	0	213.89554	51.85558	1.244757E-29	3.819837E-31		23.6623	0.033318	23.5
7	73979570428055331	0	213.80149	51.85738	7.723727E-31	2.396201E-30		26.6804	3.36838	24.2
8	73979570428055455	0	213.8055	51.85954	7.489265E-30	6.370268E-31		24.2139	0.092351	24.1
9	73979570428055529	0	213.79617	51.86112	1.142162E-29	6.177813E-31		23.7557	0.058726	24.0
10	73979570428055561	0	213.79818	51.86168	5.524251E-30	3.560247E-31		24.5443	0.069973	24.4
11	73979570428055570	0	213.88059	51.8612	7.356544E-30	3.634025E-31		24.2333	0.053634	24.1
12	73979570428055601	0	213.79551	51.86271	5.253717E-29	5.235109E-31		22.0988	0.010819	22.1
13	73979570428055610	0	213.82333	51.86247	1.097313E-29	3.973071E-31		23.7992	0.039312	23.7
14	73979570428055710	0	213.82804	51.86456	2.656856E-29	5.525464E-31		22.8391	0.02258	22.8
15	73979570428055791	0	213.79094	51.86662	1.471843E-29	9.626954E-31		23.4803	0.071015	23.9
16	73979570428055860	0	213.88954	51.86709	1.084344E-29	7.116006E-31		23.8121	0.071251	24.0
17	73979570428055936	0	213.82123	51.86912	1.042733E-29	5.450464E-31		23.8546	0.056752	23.8
18	73979570428055959	0	213.79837	51.86971	9.101518E-30	5.423166E-31		24.0022	0.064694	24.0
19	73979570428055966	0	213.88424	51.86908	1.167941E-29	6.259547E-31		23.7314	0.05819	23.8
20	73979570428056010	0	213.79016	51.87074	6.363427E-30	4.339140E-31		24.3908	0.074035	24.3
21	73979570428056113	0	213.83133	51.87251	1.160774E-29	4.764544E-31		23.7381	0.044565	23.7
22	73979570428056185	0	213.78598	51.87434	1.052555E-28	8.382704E-31		21.3444	0.008647	21.4
23	73979570428056199	0	213.88646	51.87352	9.360481E-30	4.508771E-31		23.9718	0.052298	23.9
24	73979570428056219	0	213.89283	51.87387	1.408683E-29	6.372821E-31		23.528	0.049118	23.6
25	73979570428056231	0	213.7967	51.87504	1.658527E-30	2.424954E-30		25.8507	1.58747	24.3
26	73979570428056251	0	213.79243	51.87547	9.509173E-30	5.551205E-31		23.9546	0.063382	23.9
27	73979570428056257	0	213.88499	51.8749	-1.862690E-31	1.933658E-30				24.4
28	73979570428056342	0	213.79918	51.87717	1.313530E-29	4.186944E-31		23.6039	0.034608	23.6
29	73979570428056377	0	213.88431	51.8772	1.413942E-29	6.095634E-31		23.5239	0.046807	23.6
30	73979570428056383	0	213.79355	51.87816	2.612706E-29	5.893613E-31		22.8573	0.024491	22.7
31	73979570428056387	0	213.82763	51.87793	5.986320E-30	4.392153E-31		24.4571	0.07966	24.5
32	73979570428056520	0	213.79641	51.88102	1.180581E-29	6.598727E-31		23.7198	0.060686	23.9
33	73979570428056563	0	213.80574	51.8818	1.907350E-28	8.868550E-31		20.6989	0.005048	20.6
34	73979570428056601	0	213.82372	51.88231	1.067101E-28	1.064829E-30		21.3295	0.010834	21.4
35	73979570428056775	0	213.88284	51.88498	1.303106E-29	3.655387E-31		23.6126	0.030456	23.5
36	73979570428056779	0	213.82172	51.88564	1.089255E-29	5.317668E-31		23.8072	0.053005	23.8
37	73979570428056788	0	213.84372	51.88556	8.398296E-30	5.162690E-31		24.0895	0.066744	24.0
38	73979570428056816	0	213.88021	51.88585	6.754212E-30	6.072494E-31		24.3261	0.097615	24.3
39	73979570428056827	0	213.87206	51.8861	1.061777E-29	7.500699E-31		23.8349	0.0767	24.0
40	73979570428056833	0	213.79234	51.88735	5.436434E-29	6.371324E-31		22.0617	0.012724	22.1
41	73979570428056846	0	213.80921	51.88721	1.067762E-28	6.436782E-31		21.3288	0.006545	21.2
42	73979570428056850	0	213.83987	51.88708	4.627139E-29	9.125668E-31		22.2367	0.021413	22.4
43	73979570428056858	0	213.85303	51.88695	1.590651E-29	5.116353E-31		23.3961	0.034923	23.3
44	73979570428056864	0	213.84775	51.88714	9.348670E-30	1.051104E-30		23.9731	0.122073	24.4
45	73979570428057024	0	213.79882	51.89079	6.393567E-30	6.979971E-31		24.3856	0.118532	24.4
46	73979570428057101	0	213.80487	51.89223	1.388592E-29	5.331566E-31		23.5436	0.041687	23.5

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

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



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

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

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doi: 10.1093/pasj/xxx000

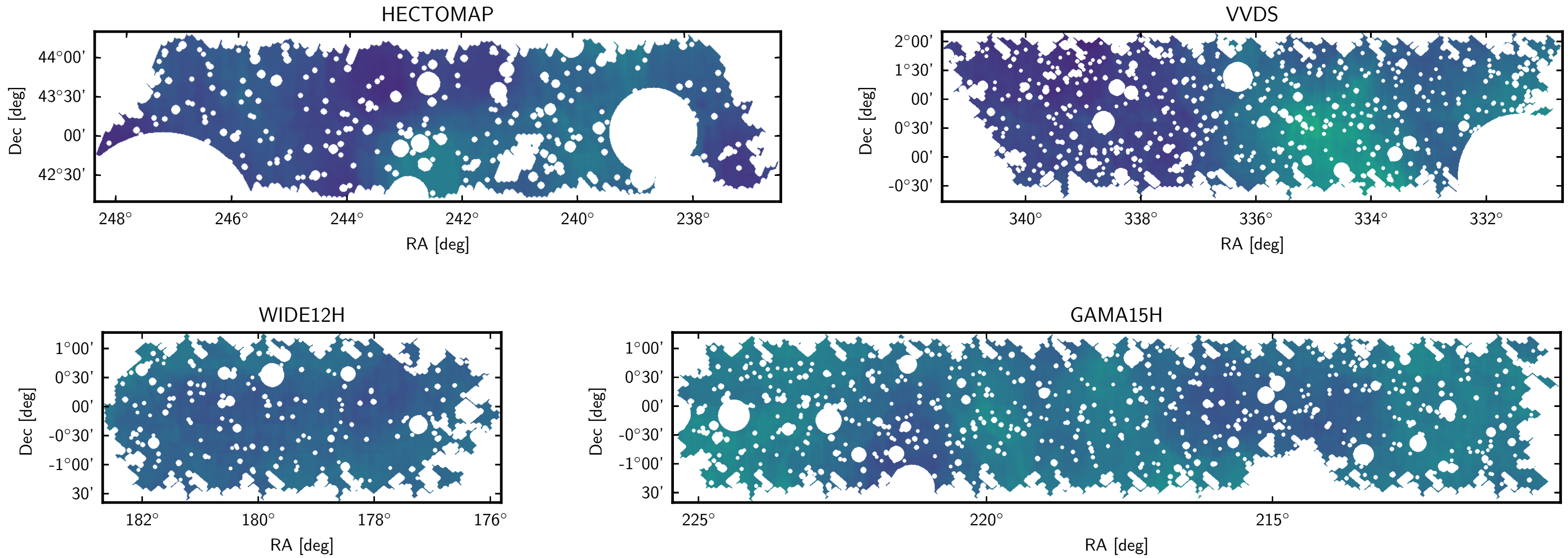
galaxy shape

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

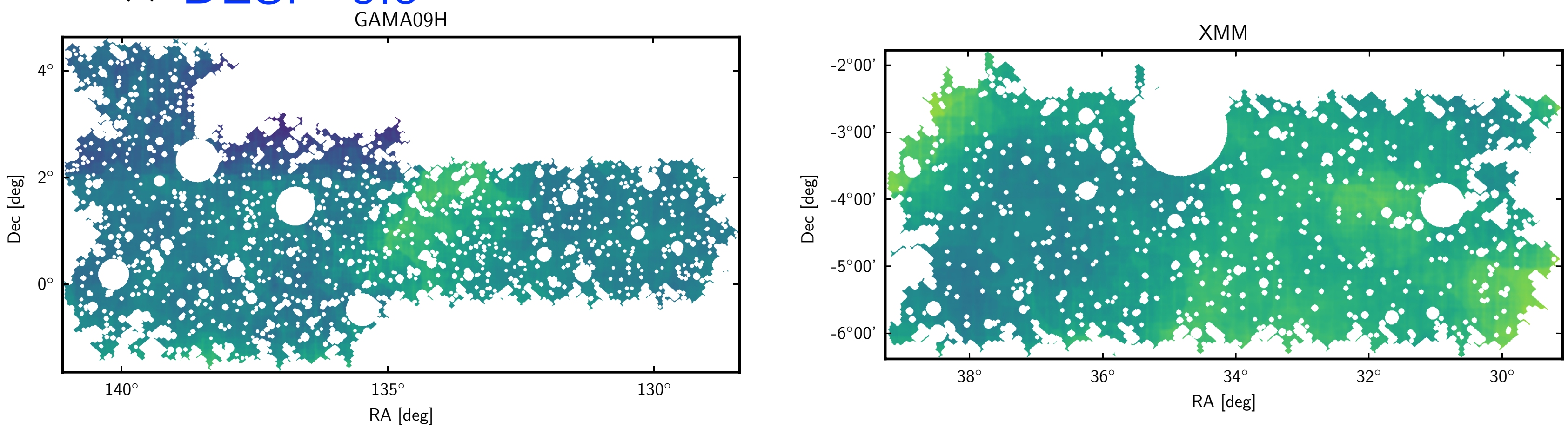
Subaru HSC = superb image quality

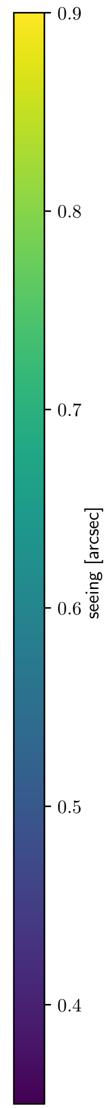
6 fields (~150 sq. deg. in total)



Subaru HSC typically 0.6" seeing FWHM (spatial resolution)

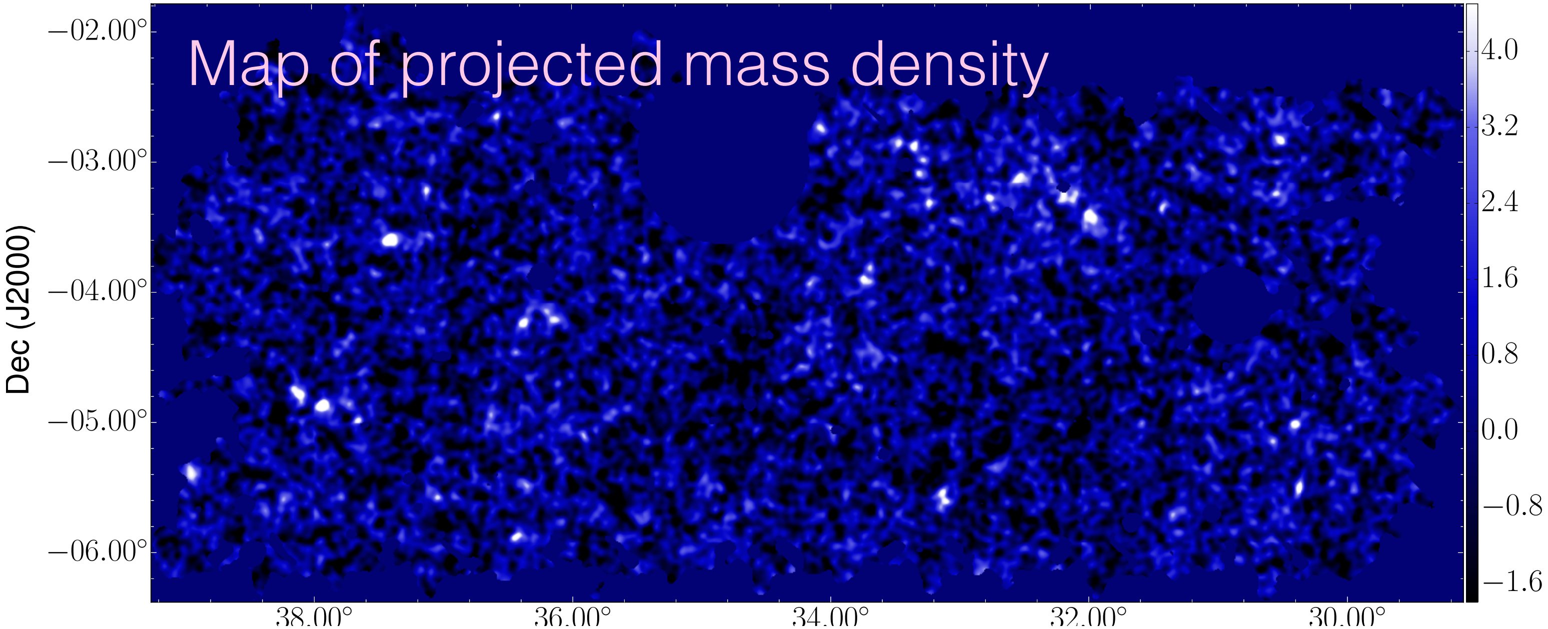
⇔ DES: ~0.9"



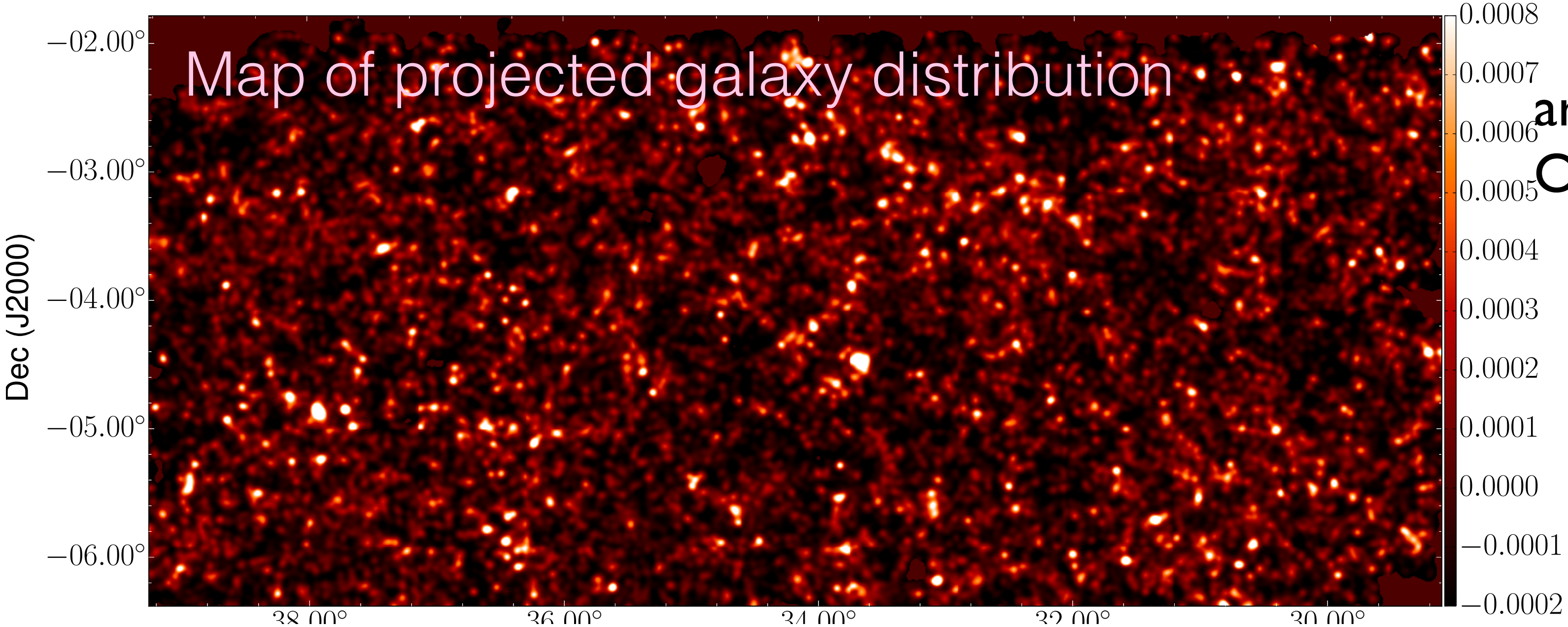


WL mass (dark matter) maps

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

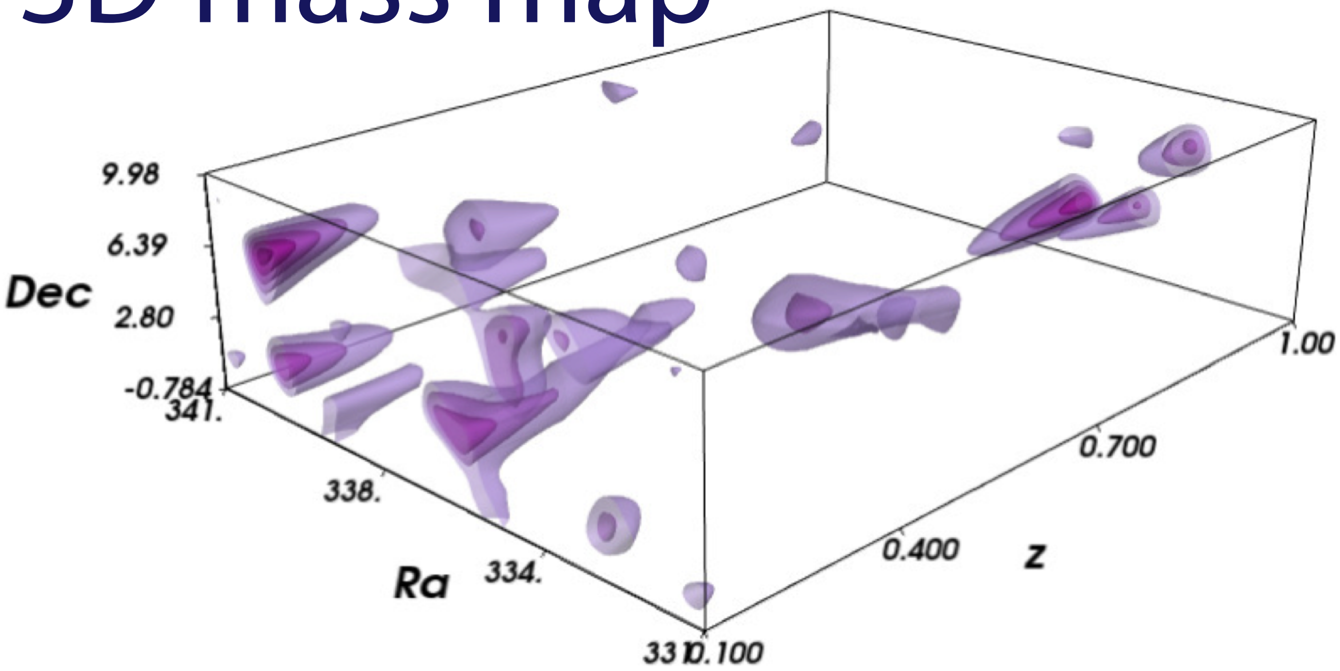


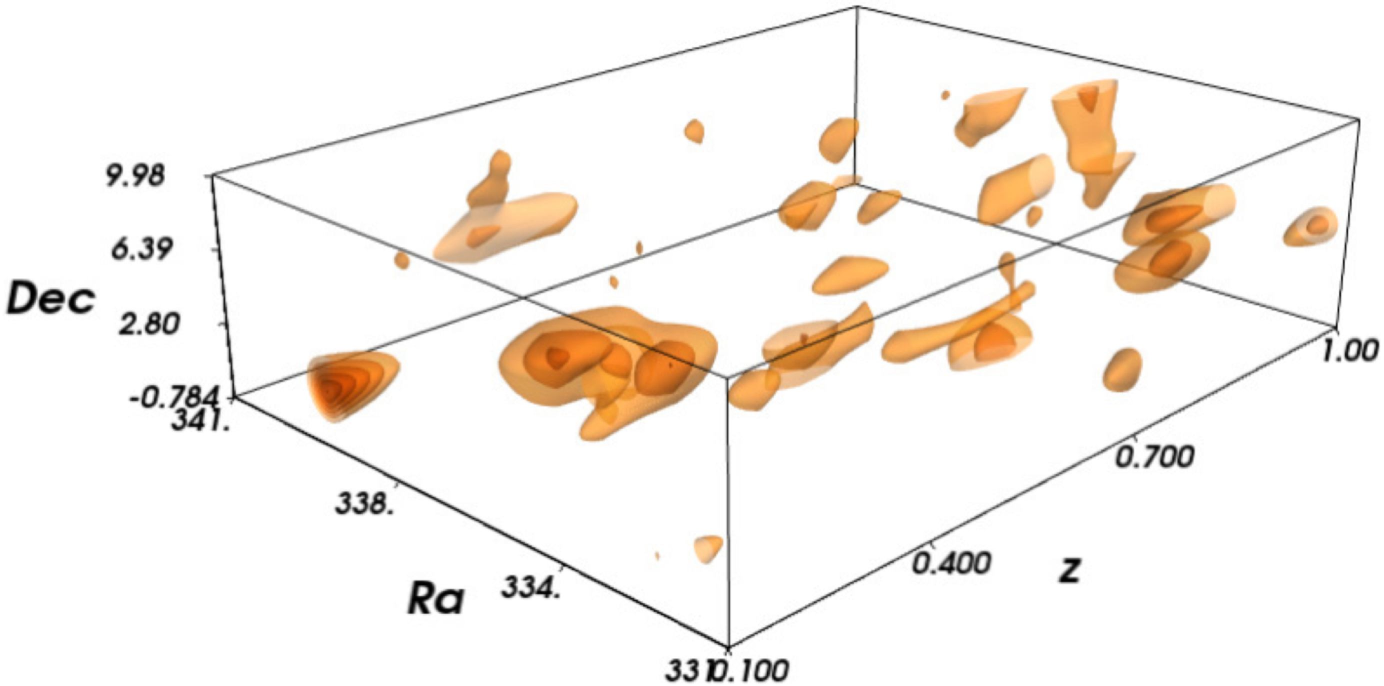
Masamune Oguri
(Tokyo/IPMU)



arXiv:1705.06792
Oguri et al.

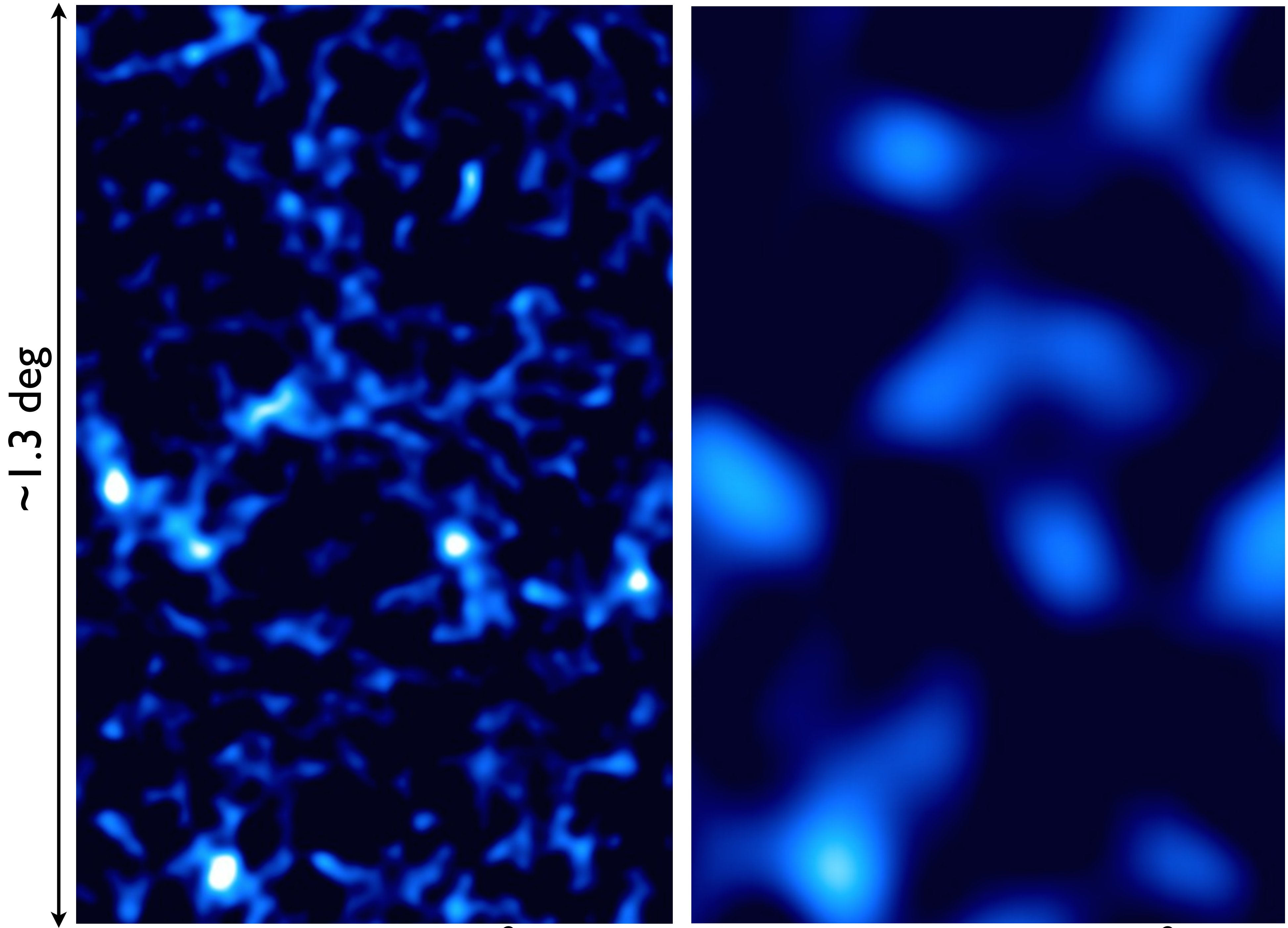
3D mass map





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

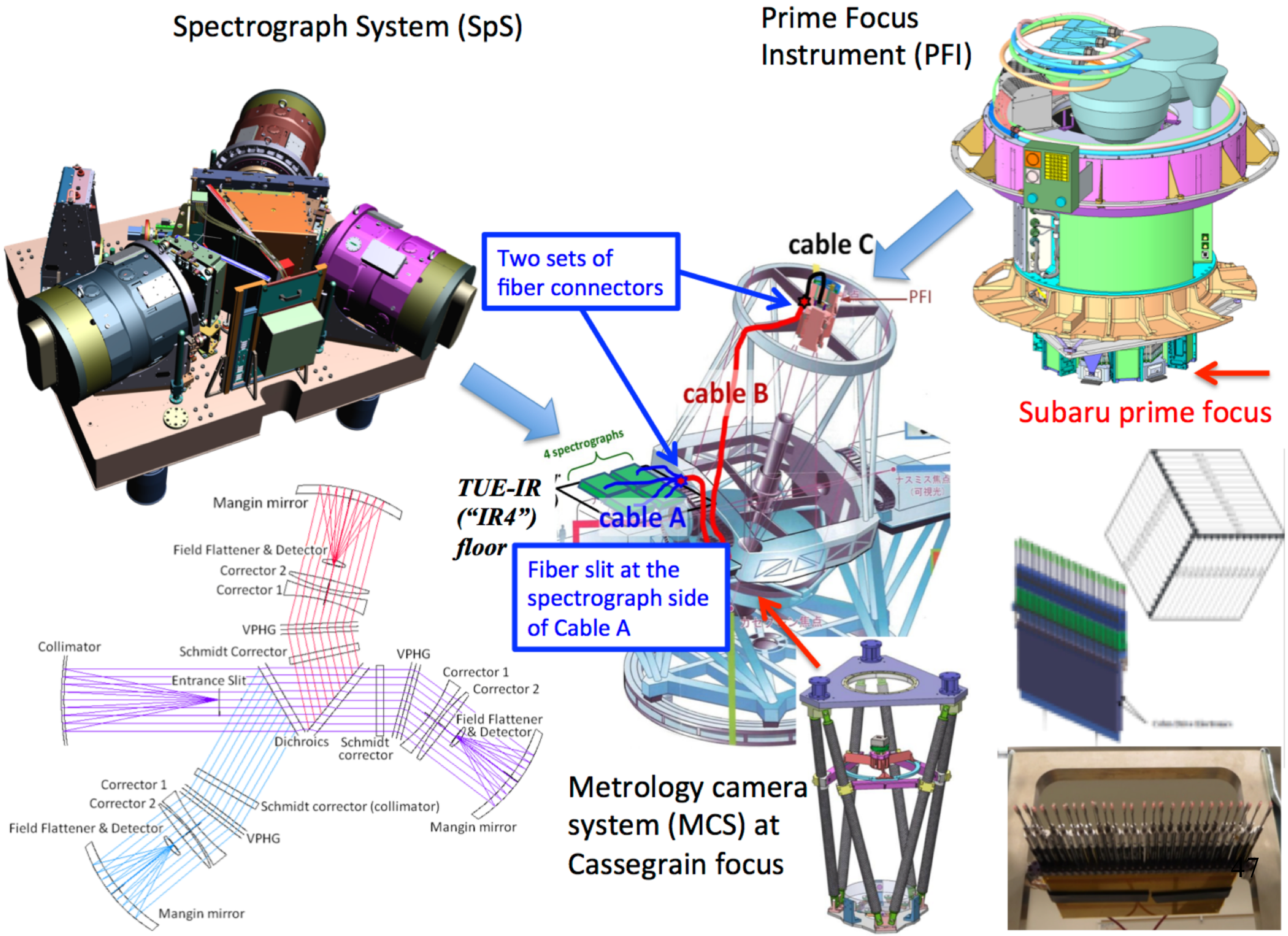
Mass and galaxy maps show a nice correspondence



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

Subaru Prime Focus Spectrograph

Tamura et al. SPIE (2016)



Summary

- Subaru HSC/PFS project is VERY EXCITING
- HSC: a wide-field imaging camera (on-going!)
  - Obtained the tightest upper bound on the bundance of PBHs of lunar mass scales
    - A longer-term monitor of M31 (SNe, red giants, …)
  - Very powerful, indeed best, instrument for weak lensing measurements
    - Dark matter, dark energy, neutrino mass …
- PFS: a wide-field, multi-object spectrograph
  - Mapping out the three-dimensional distribution of galaxies
  - Cosmology, Galaxy Evolution, Galactic Archaeology