

Searching for Strong Lenses to Probe Dark Matter Substructures



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Collaboration

* Observation:

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* <u>Simulation</u>:

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Motivation



Cosmology probe dark energy through time delays of lenses

→ Galaxy evolution

study galaxy structure/substructures and probe dark matter

Black holes

co-evolution of supermassive black holes and spheroids

 Currently there are only a handful of 4-image lensed quasars
 → expect to have ~600 lensed quasars (~80 quads) in HSC survey (Oguri & Marshall 2010)









Strong Lens Hunter



重力和影像探奥號 Chung-li He In-hsiang Tan Ao Hao CHTTAH

Chan et al. 2015 (arXiv:1411.5398)













Procedure Overview

- Separate Lens and Images
- Estimate Lens center and Image positions
- Classify potential **quads (4-image)** and **doubles (2-image)**
- Fit SIE/SIS model to quads/doubles

	q	uad (4-imag	ge)	do	dud		
	bright	faint	ultra-faint	bright	faint	ultra-faint	(non-lens)
large sep. $(r_{ein} > 1.1'')$							
small sep. $(r_{ein} < 1.1'')$							

TPR & FPR

• Given a lens (mock):

- TP = true positive = correct identification
- FN = false negative = incorrect rejection

TPR = true positive rate

 $=\frac{\# \text{ of correct identification}}{\# \text{ of all lenses}} = \frac{\text{TP}}{\text{TP} + \text{FN}}$

• Given a non-lens (dud):

• TN = true negative = correct rejection

• FP = false positive = incorrect identification

FPR = false positive rate

of incorrect identification _ FP

of all non-lenses TN + FP







Results

- * CHITAH finds much purer sample of quads than doubles.
- * For bright large-sep. ($r_{ein} > 1.1''$) quads: TPR ~ 90% and FPR ~ 3%.
- For faint large-sep. quads:TPR ~ 80% and FPR ~ 5%
- * A sharp drop of TPR as $r_{\rm ein} \leq 0.5''$
 - \Rightarrow the PSF seeing of the mock lenses



Relative to the Gaussian PSF, the extended wings of Moffat PSF decrease the TPRs by a few percent.

Chan et al. 2015 (arXiv:1411.5398)

COSMOS 5921+0638





COSMOS 5921+0638



HST ACS F814W



Subaru Suprime-Cam *B* band Chan et al. 2015 (arXiv:1411.5398)





Typical Apparent Diameter of the Moon (0.5 degrees)



Suprime-Cam First Light Release January 1999

Suprime-Cam Image Release September 2001 Hyper Suprime-Cam Image Release July 2013



Wide	1400 deg ²	grizy	r~26
Deep	27 deg ²	grizy+3NB	r~27
Ultra-Deep	3.5 deg ²	grizy+3NB	r~28



Lens Candidates in HSC

Galaxy-scale Lens

- matches (64) between GAMA blended spectra catalog (Holwerda et al. 2015) and HSC early data release S14A0_b
- * preselection (10) via redshifts and morphology (CHITAH, Chan et al. 2015)
- confirmation via lens modeling (GLEE, Suyu & Halkola 2010)





Quasar Lens (preliminary)

- Atsunori and Yuriko produce a quasar catalog via photometric quasar selection method (Richards et al. 2009).
- ✤ CHITAH classifies objects in HSC S14A_0b imaging data using the quasar catalog.
- We visually grade the lens candidates.



Database

Lens Candidates

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1.88	e i						-	-	-20.5	54	1.031	0.956	-	2.8	2.0	1.5	1.5	-	2.5	1.0	-	SHS: spiral arm or lensed galaxy? JHHC: 2014A&A562A23G
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Flux Anomalies





lens	$R_{ m cusp}$
B1422+231	0.187
B0712+472	0.254
B2045+265	0.501

lens	$R_{ m fold}$
MG0414+0534	0.087
B0128+437	0.263
B1555+375	0.235
B1608+656	0.327
B1933+503	0.656

Xu et al. 2015

Myers et al. 2003 and Browne et al. 2003

Flux anomalies

✤ Dust?

It does not affect radio lenses.

Substructure?

CDM substructures only affect < 5% of flux relation.

(Xu et al. 2015)

From gravitational imaging, substructure mass fraction is though consistent with CDM simulation, but a bit higher? (Vegetti et al. 2014)

New dark matter model?



ψDM: wave dark matter

- * ψ DM consists of extremely light bosons (~10⁻²² eV)
- The corresponding de Broglie wavelength becomes astronomical scale.
- The wave mechanics can be described by Schrödinger's equation, coupled to gravity by means of Poisson's equation.
- * Simulation is very expensive. $\rightarrow GAMER$ (Schive et al. 2009)

High-z mass fluctuation



Potential solution to the missing satellites problem

Schive et al. 2015





Future prospect

Search for new lenses in surveys with CHITAH:
 HSC data, CFHTLS data, DES data and KiDS/VIKING data

GPU version

- Lensed galaxy search improvement
- New lens candidates followup
- Flux anomalies via more \u00f8DM halos
- * *vDM* confirmation through both simulation and observation