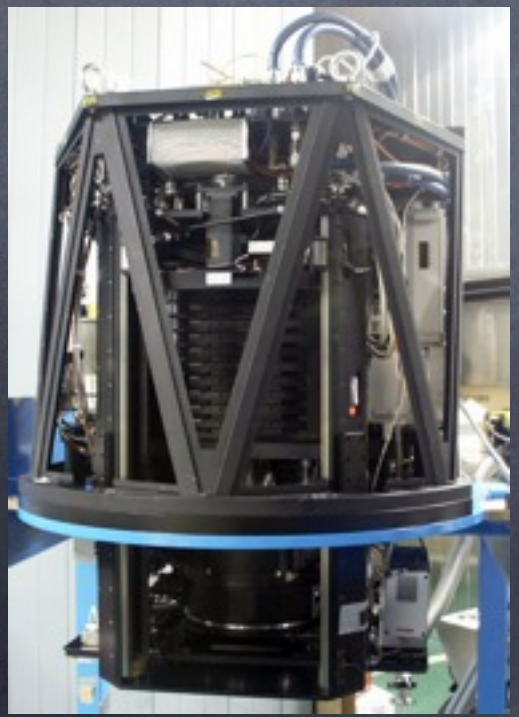
Subaru/Suprime-Camの
サーベイデータを利用した
時間変動天体の研究

諸隈 智貴
(国立天文台 --> 東京大学)

Contents

0. 時間変動天体を研究するには...
1. すばる観測所プロジェクトSDF/SXDSデータを用いた時間変動天体の研究
2. アーカイブデータを用いた時間変動天体の研究
3. 今後...
4. まとめ



Suprime-Cam

時間変動天体を研究するには...

「注目する天体の変動タイムスケールに合った」

「時間間隔(と積分時間)で」

「複数回」

「同じ望遠鏡+装置で」

「根気強く」　　観測することが必要

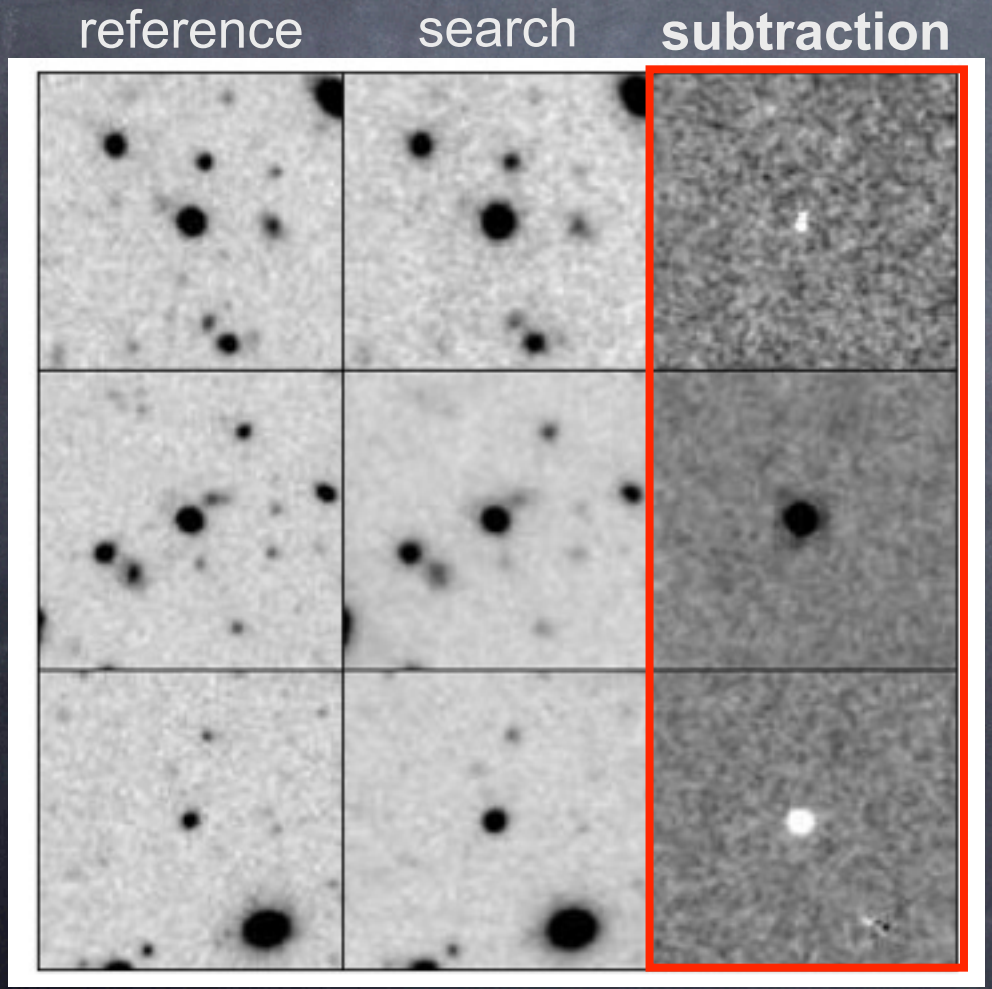
「(普通の天文学者よりも)晴れ男/女」

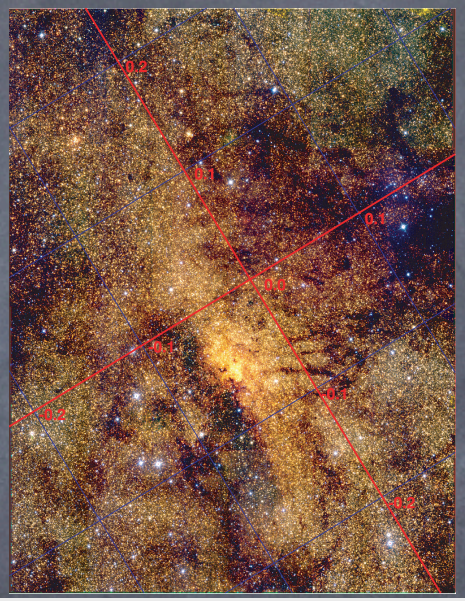
「(普通の天文学者よりも)観測が好き」　　であることも必要(?)

「(ToOや非常に中途半端なデータサンプリングになった
ときは)皆様のご協力・ご理解」　　が必要

Flux Variability Detection

+ PSF photometry: 変光星@bulge, globular clusterなど...混んだ領域が多い。
+ image subtraction: 変光星(Alard&Lupton 1998), 超新星/AGN (TM+2008)
+ profile fitting: nearby AGN (e.g., Bentz+2006, Sakata+2010...)





Matsunaga+2009

シンプルなphotometryでは広がった天体中のpoint sourceの時間変動をとらえるのが難しい。<-- seeing/PSFが時間変動する(地上望遠鏡の宿命)

Image subtraction method
(Alard & Lupton 1998, Alard 2000)

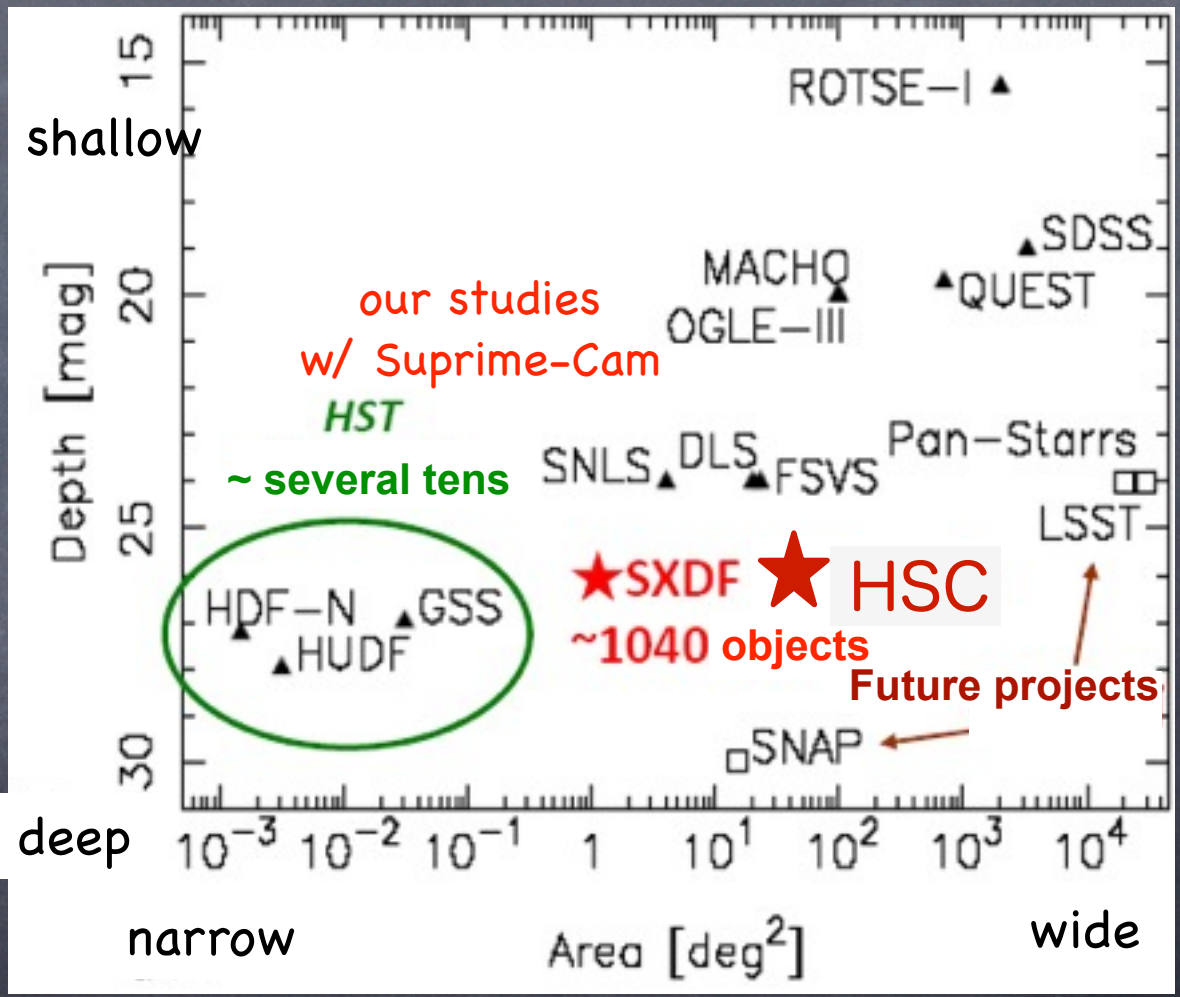
時間変動天体を研究するには...

- 中小口径望遠鏡を専有して

(MACHO, OGLE, QUEST, SDSS, MAGNUM, LOSS, PTF, ...)

- **大口径望遠鏡のdeep surveyデータ(HDF, UDS, SDF, SXDS, ...)を使って変光を調べる研究**

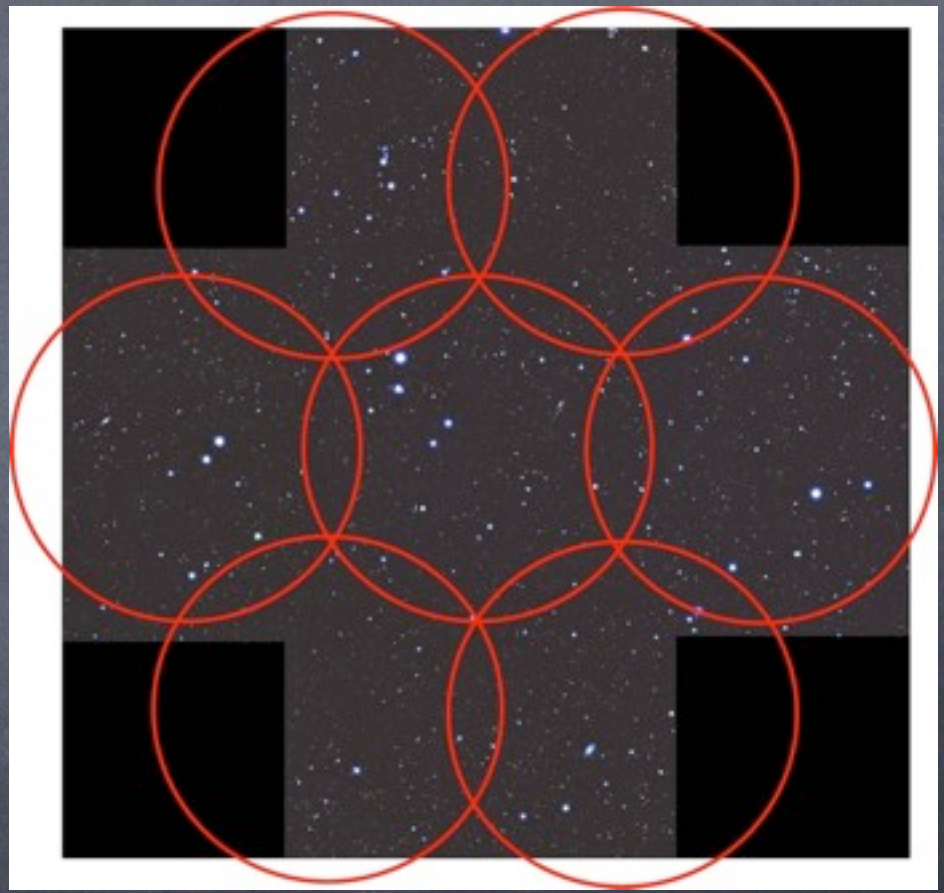
- HST Treasury Survey
  Cepheid distance of nearby galaxies



すばる観測所プロジェクト
SDF/SXDSデータを用いた
時間変動天体の研究

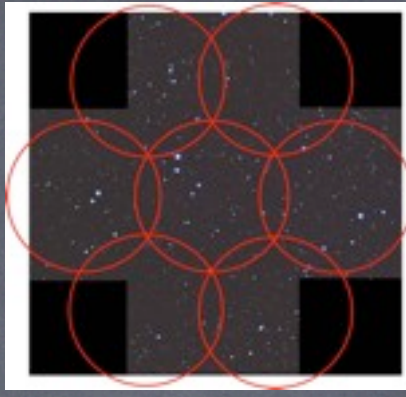
すばる観測所プロジェクト
SDF/SXDS

Subaru Deep Field
(SDF)



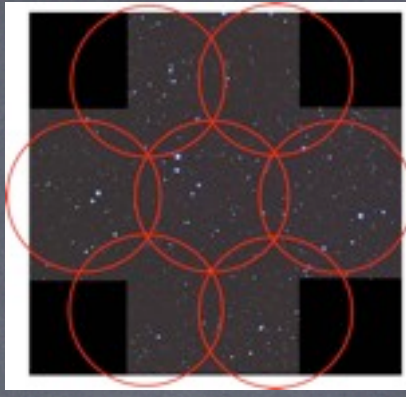
Subaru/XMM-Newton Deep Survey
(SXDS)

すばる観測所プロジェクト
SDF/SXDS



project	SDF	SXDS
FoV	0.25 deg2 (1 FoV)	1.2 deg2 (5 FoVs)
PI		
Suprime-Cam観測	2002/04 ~	2002/09 ~
多波長データ (may be incomplete) プロジェクトベースでないデータも含む	GALEX, KPNO/MOSAIC, HST/NICMOS&WFC3, KPNO/NEWFIRM, UKIRT/WFCAM, Spitzer/IRAC&MIPS, ASTE/AzTEC,	XMM, GALEX, CFHT/MegaCam, CTIO, HST/WFC3, UKIRT/WFCAM, Spitzer/IRAC&MIPS, Herschel, JCMT/SCUBA, ASTE/AzTEC, VLA
特徴	とにかく深く	X線、ある程度広く深く

Supernova Surveys @ SDF & SXDS



- 土居(東京大学)、安田(国立天文台)、Perlmutter(LBNL), Hook (Oxford), Lidman (ESO), Pain (LPNHE), ... (Supernova Cosmology Project)
- Suprime-Cam + HST/ACS&WFPC2&NICMOS + 8m&HST/ACS分光
- 2002年秋: 土居さんintensive観測+SXDSプロジェクト観測

Schedule for September 2002

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Sep 01	Sep 02	Sep 03	Sep 04	Sep 05	Sep 06 ●	Sep 07
S02A-109 Nakamura SCam		S02A-146 Wolfe SCam	UH-39A Chambers SCam		S02A-127 Kodama SCam	S02A-122 Hayashino SCam
Sep 08	Sep 09	Sep 10	Sep 11	Sep 12	Sep 13 ◐	Sep 14
S02A-122 Hayashino SCam	UH-45A Hu SCam		Telescope Eng	S02A-030 Greiner FOCAS	S02A-148 Zheng FOCAS	Eng FOCAS / Obs FOCAS
Sep 15	Sep 16	Sep 17	Sep 18	Sep 19	Sep 20	Sep 21 ○
Eng FOCAS / Obs FOCAS	Telescope Eng / S02A-046 Sugitani IRCS	Telescope Eng / S02A-046 Sugitani IRCS	Telescope Eng / S02A-046 Sugitani IRCS	S02A-015 Murayama IRCS		GTO IRCS/AO
Sep 22	Sep 23	Sep 24	Sep 25	Sep 26	Sep 27	Sep 28 ◑
GTO IRCS/AO	Telescope Eng / Obs HDS	Telescope Eng / Obs HDS	Telescope Eng		S02A-080 Yamada SCam	
Sep 29	Sep 30					
Obs SXDS SCam						

Schedule for October 2002

Sun	Mon	Tue	Wed	Thu	Fri	Sat
		Oct 01	Oct 02	Oct 03	Oct 04	Oct 05 ●
		Obs SXDS SCam	UH-40A Meech SCam / UH-46A Wang SCam	UH-40A Meech SCam / UH-46A Wang SCam	S02B-046 Fuse SCam / S02B-121 Kinoshita SCam	S02B-046 Fuse SCam / S02B-121 Kinoshita SCam
Oct 06	Oct 07	Oct 08	Oct 09	Oct 10	Oct 11	Oct 12
S02B-121 Kinoshita SCam	Obs SXDS SCam		S02B-086 Iwata SCam		Eng CIAO	Obs CIAO / Tel Eng
Oct 13 ◐	Oct 14	Oct 15	Oct 16	Oct 17	Oct 18	Oct 19
Obs CIAO / Tel Eng	Obs CIAO / Tel Eng	S02B-089 Sugitani CIAO		S02B-110 Fukugita CISCO		Obs IRCS
Oct 20 ○	Oct 21	Oct 22	Oct 23	Oct 24	Oct 25	Oct 26
S02A-085 Itoh IRCS / Eng IRCS	GTO AO/IRCS		S02A-002 Imanishi IRCS	S02B-016 Suto HDS	S02B-177 Aoki HDS	S02B-016 Suto HDS
Oct 27	Oct 28 ◑	Oct 29	Oct 30	Oct 31		
S02B-177 Aoki HDS	Obs SXDS SCam		S02B-163 Kodaira SCam			

Schedule for November 2002

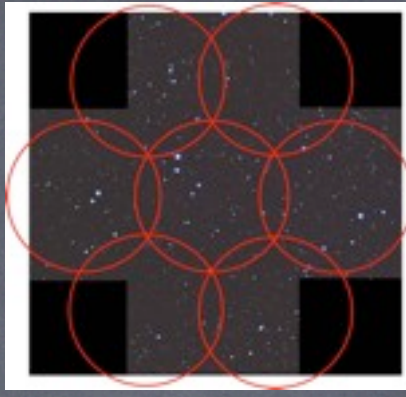
Sun	Mon	Tue	Wed	Thu	Fri	Sat
					Nov 01	Nov 02
					Obs SXDS SCam	
Nov 03	Nov 04 ●	Nov 05	Nov 06	Nov 07	Nov 08	Nov 09
S02B-105 SCam	S02B-104 Doi FOCAS		S02B-163 Kodaira SCam	UH-32A Chambers SCam		Obs SXDS SCam
Nov 10	Nov 11 ◐	Nov 12	Nov 13	Nov 14	Nov 15	Nov 16
Obs SXDS SCam	S02B-104 Doi FOCAS		S02B-004 Imanishi FOCAS	S02B-104 Doi CISCO		
Nov 17	Nov 18	Nov 19 ○	Nov 20	Nov 21	Nov 22	Nov 23
S02B-104 Doi CISCO			Obs Project CIAO		S02B-042 Hayashi CIAO	
Nov 24	Nov 25	Nov 26 ◑	Nov 27	Nov 28	Nov 29	Nov 30
S02B-042 Hayashi CIAO	S02B-193 Takami IRCS	S02B-030 Pyo IRCS/AO	Obs SXDS SCam	Tel Eng	Obs SXDS SCam	

Schedule for December 2002

Sun	Mon	Tue	Wed	Thu	Fri	Sat
Dec 01	Dec 02	Dec 03	Dec 04 ●	Dec 05	Dec 06	Dec 07
Obs SXDS SCam	UH-31A Kaiser SCam	S02B-121 Kinoshita SCam	UH-32A Chambers SCam		Obs SXDS SCam	
Dec 08	Dec 09	Dec 10	Dec 11 ◐	Dec 12	Dec 13	Dec 14
UH-49A Chun IRCS/AO / UH-21A Rayner IRCS	GTO AO IRCS/AO	UH-49A Chun IRCS/AO / UH-21A Rayner IRCS	UH-21A Rayner IRCS	Eng AO IRCS/AO	Tel Eng / Eng COMICS	Eng COMICS / GTO COMICS
Dec 15	Dec 16	Dec 17	Dec 18 ○	Dec 19	Dec 20	Dec 21
GTO COMICS	S02B-063 Saito COMICS	S02B-001 Sadakane HDS	S02B-077 Uchida HDS		TBD	UH-33B Hodapp IRCS
Dec 22	Dec 23	Dec 24	Dec 25	Dec 26 ◑	Dec 27	Dec 28
GTO AO IRCS/AO			S02B-147 Yamashita IRCS		Tel Eng	
Dec 29	Dec 30	Dec 31				
Tel Eng	UH-16A Sanders CISCO / UH-37B Aussel CISCO	Obs CIAO/AO				

SXDS Supernova Survey @ 2002 9-12月

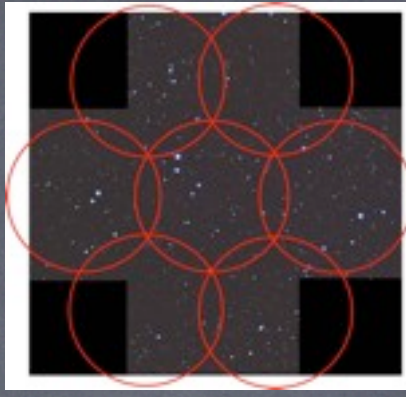
Variability Surveys @ SDF & SXDS



観測所プロジェクトとしてのデータ取得終了後もnormal proposalで追加観測

- ● Supernova Rate (Poznanski+2007)
- ● Variable Object Survey (TM+2008a)
- ● Variability-Selected AGN (TM+2008b)
- ● Delay Time Distribution of SNe Ia in early-type galaxies (Totani, TM+2008)
- ○ z~7 LAE: IOK-1 (Iye+2008)
- ● High Proper Motion Stars 1 (Richmond, TM+2009)
- ● High Proper Motion Stars 2 (Richmond, TM+2010)
- ● Supernova Spectra w/ FOCAS (TM+2010)
- ● Delay Time Distribution of SNe Ia (Okumura, Totani+2010, in prep.)
- ● Supernova Rate (Ihara 2010 PhD thesis, Ihara+2010, in prep.)
- ● SN Ia Cosmology (Suzuki+2010, in prep.)
- ○ z~7 LBGs (Ouchi+2010)

Variability Survey @ SXDS



- Variable Object Survey (TM+2008a)
- Variability-Selected AGN (TM+2008b)
- Delay Time Distribution of SNe Ia in early-type galaxies (Totani, TM+2008)
- Supernova Spectra w/ FOCAS (TM+2010)
- Delay Time Distribution of SNe Ia (Okumura, Totani, TM+2010, in prep.)
- Supernova Rate (Ihara 2010 PhD thesis, Ihara+2010, in prep.)
- SN Ia Cosmology (Suzuki+2010, in prep.)

THE SUBARU/*XMM-NEWTON* DEEP SURVEY (SXDS). V.
OPTICALLY FAINT VARIABLE OBJECT SURVEY[1]

Tomoki Morokuma,[2,3] Mamoru Doi,[3] Naoki Yasuda,[4] Masayuki Akiyama,[5] Kazuhiro Sekiguchi,[2,5] Hisanori Furusawa,[5] Yoshihiro Ueda,[6] Tomonori Totani,[6] Takeshi Oda,[6,7] Tohru Nagao,[2,7] Nobunari Kashikawa,[2] Takashi Murayama,[8] Masami Ouchi,[9,10] Mike G. Watson,[11] Michael W. Richmond,[12] Christopher Lidman,[13] Saul Perlmutter,[14] Anthony L. Spadafora,[14] Greg Aldering,[14] Lifan Wang,[14,15] Isobel M. Hook,[16] and Rob A. Knop[17]

Received 2007 September 28; accepted 2007 November 30

ABSTRACT

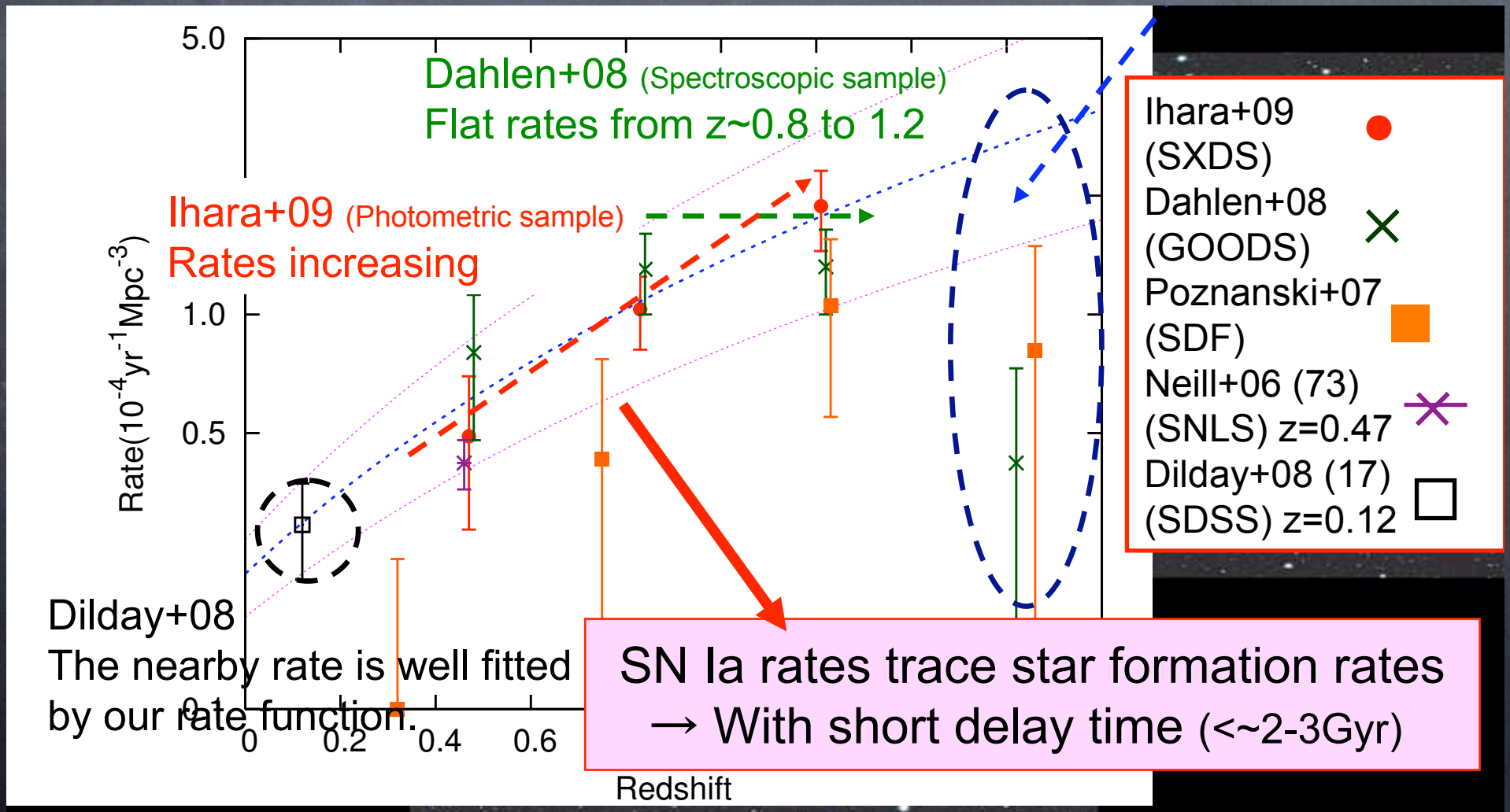
We present our survey for optically faint variable objects using multiepoch (8–10 epochs over 2–4 years) i'-band imaging data obtained with Subaru Suprime-Cam over 0.918 deg^2 in the Subaru/*XMM-Newton* Deep Field (SXDF). We found 1040 optically variable objects by image subtraction for all the combinations of images at different epochs. This is the first statistical sample of variable objects at depths achieved with 8–10 m class telescopes or the *Hubble Space Telescope*. The detection limit for variable components is $i'_{\rm var} \sim 25.5$ mag. These variable objects were classified into variable stars, supernovae (SNe), and active galactic nuclei (AGNs), based on the optical morphologies, magnitudes, colors, and optical–mid-infrared colors of the host objects, spatial offsets of variable components from the host objects, and light curves. Detection completeness was examined by simulating light curves for periodic and irregular variability. We detected optical variability for 36% ± 2% (51% ± 3% for a bright sample with $i' < 24.4$ mag) of X-ray sources in the field. Number densities of variable objects as functions of time intervals Δt and variable component magnitudes $i'_{\rm var}$ are obtained. Number densities of variable stars, SNe, and AGNs are 120, 489, and 579 objects deg^{-2}, respectively. Bimodal distributions of variable stars in the color-magnitude diagrams indicate that the variable star sample consists of bright ($V \sim 22$ mag) blue variable stars of the halo population and faint ($V \sim 23.5$ mag) red variable stars of the disk population. There are a few candidates of RR Lyrae providing a possible number density of $\sim 10^{-2}$ kpc^{-3} at a distance of >150 kpc from the Galactic center.

Subject headings: galaxies: active — stars: variables: other — supernovae: general — surveys

- 2-4 yrs baseline
- 8-10 epochs
- 1040 variable objects over 0.918 deg2
- i<25.5mag
- ~100 variable stars, ~400 supernovae, ~500 AGN

Supernova rates (SXDS)

Ihara 2010 (PhD thesis), Ihara+2010 in prep.
50 SNe Ia by photometric typing from TM+2008's sample



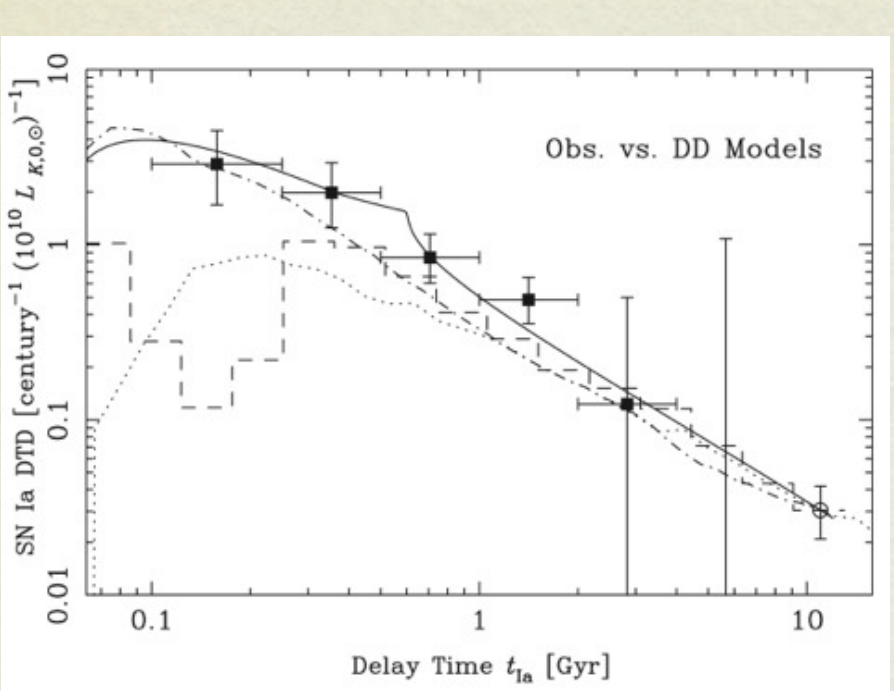
Delay Time Distribution of Type Ia Supernova in early-type galaxies (0.2<z<1.4)

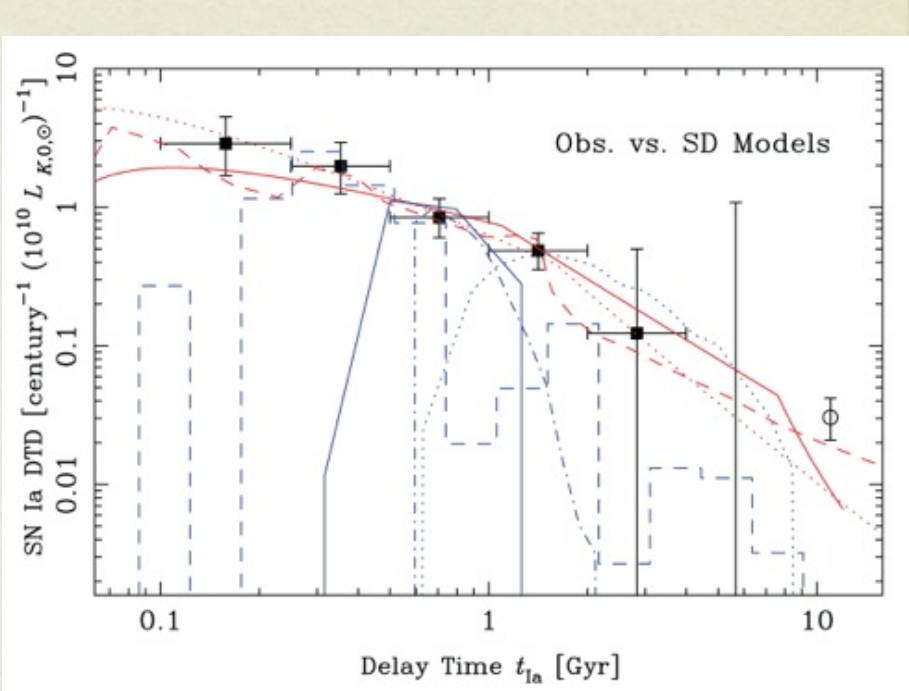
65 SNe Ia from TM+2008a's sample (Totani, TM+2008)

SN Ia progenitor: white dwarf(s) in binary system

single-degenerate (SD) vs double-degenerate (DD)

SN Ia rateはt^-1に比例 (e.g., t^-0.5@Pritchet+2008, t^-1@Maoz+2010)





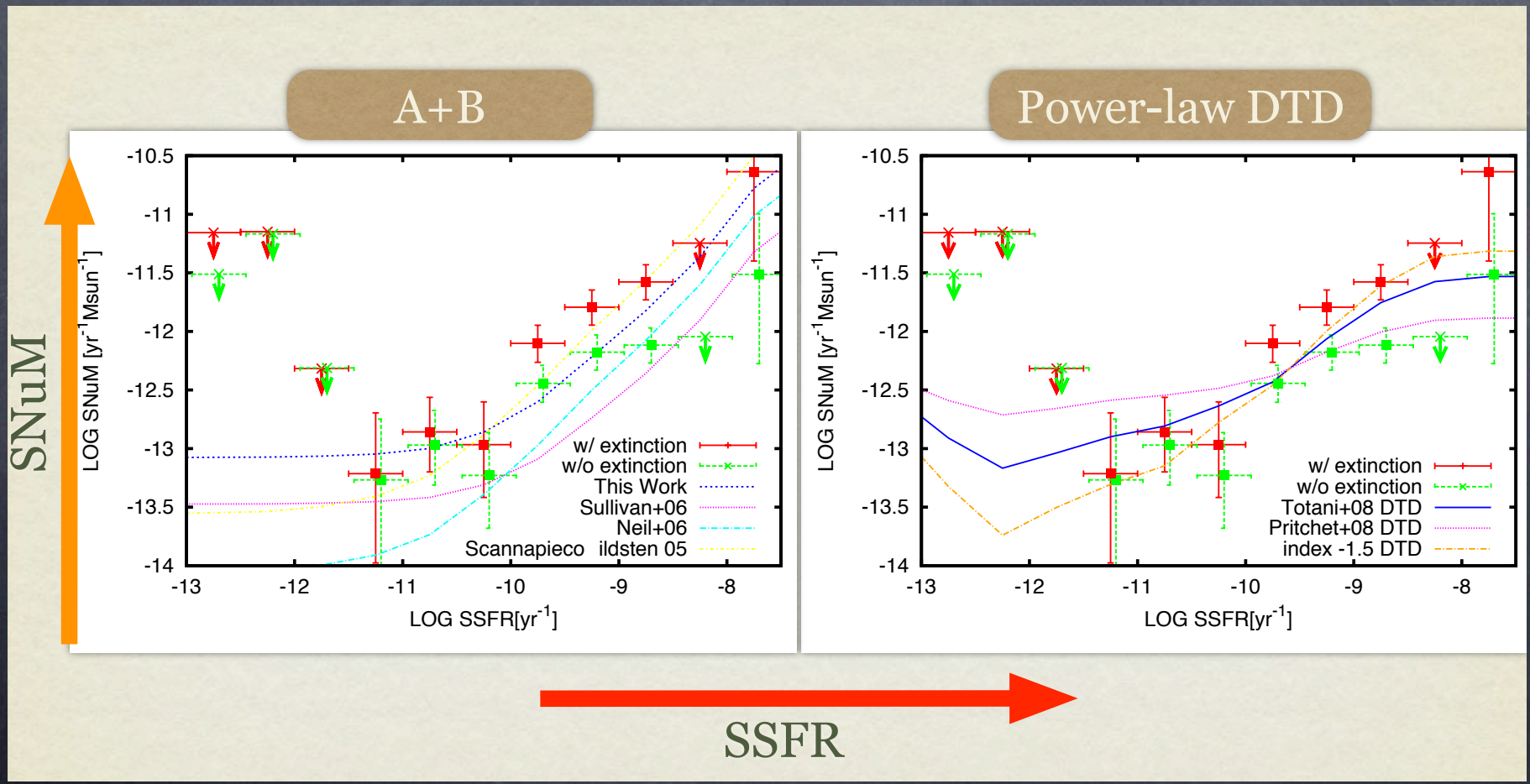
consistent with generic DTD features of DD models

Type Ia Supernova rate dependence on host galaxy properties

50 SNe Ia from Ihara+2010's sample (Okumura+2010, in prep.)

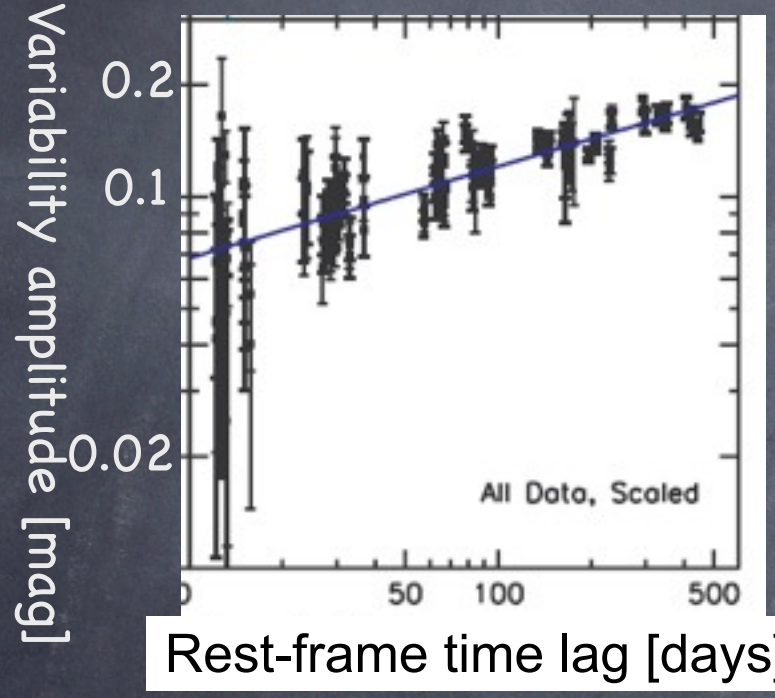
SN Ia rate = (stellar massに比例する成分) + (SFRに比例する成分)

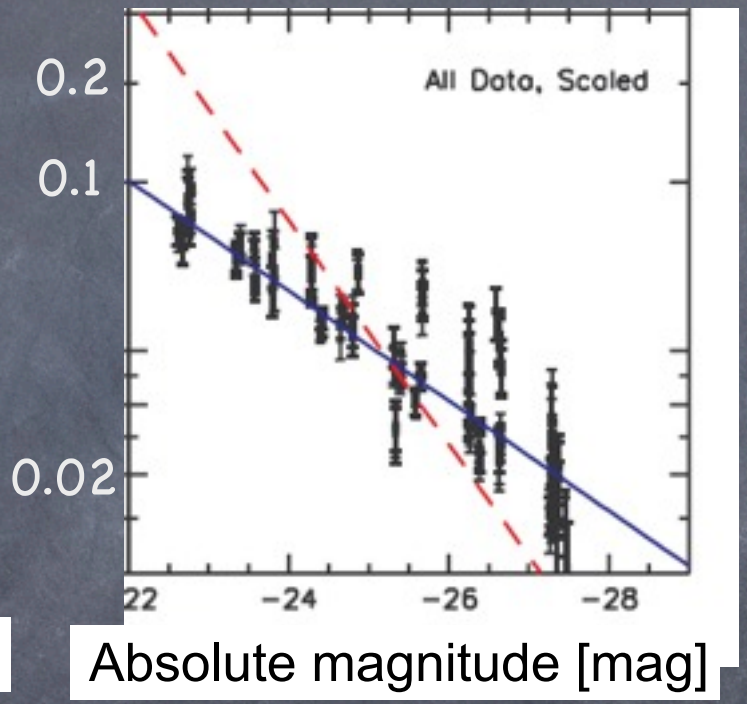
delay time distributionはt^-1の方がよさそう。



Optical Variability of AGN

- すべての(1型)AGNは可視域で(他の波長帯でも)変光 (Hawkins 1993, Hook+1994, Giveon+1999, many SDSS studies ...).
- 暗いAGNほど大きなamplitudeで変光



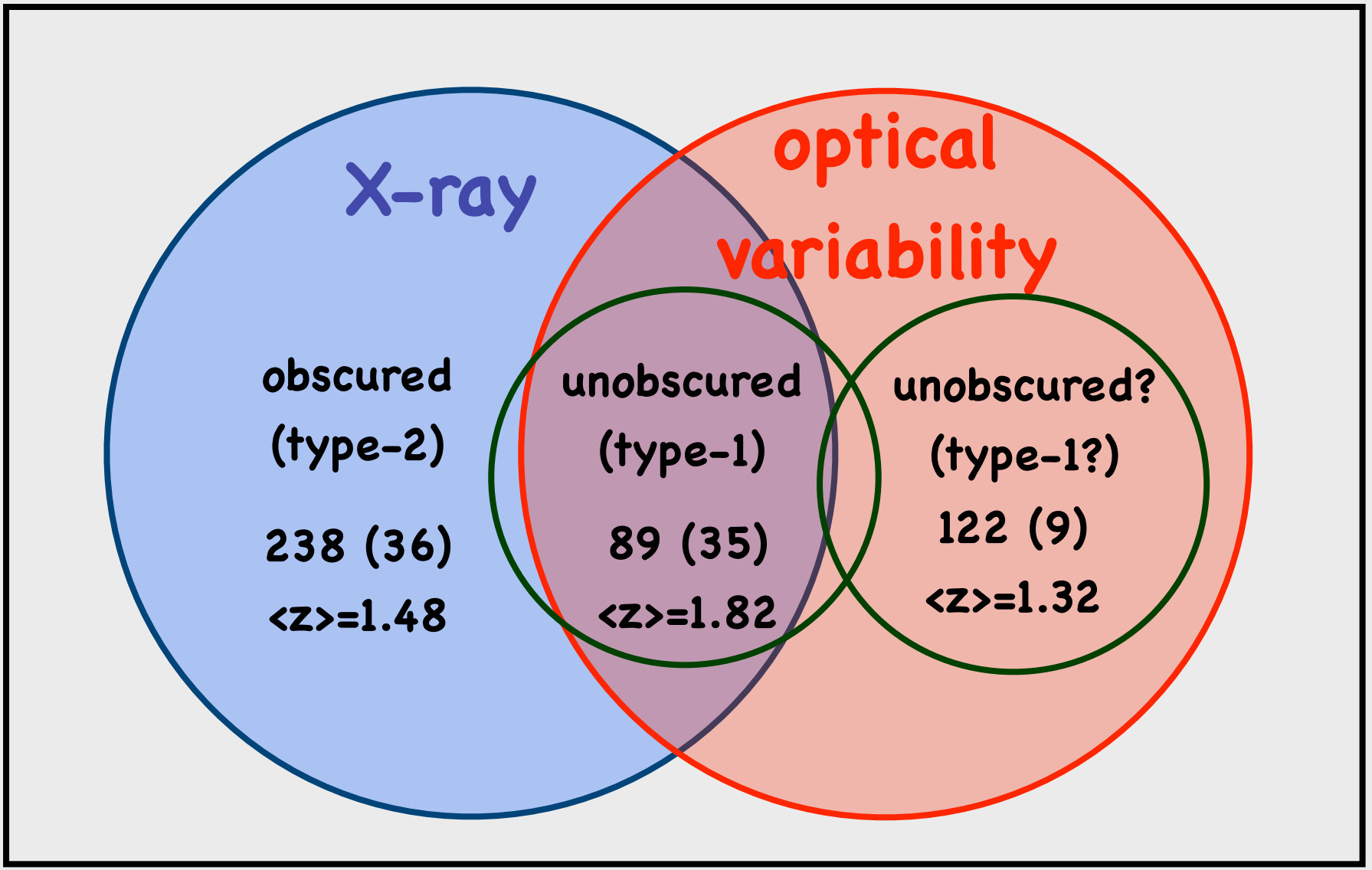


Vanden Berk+2004

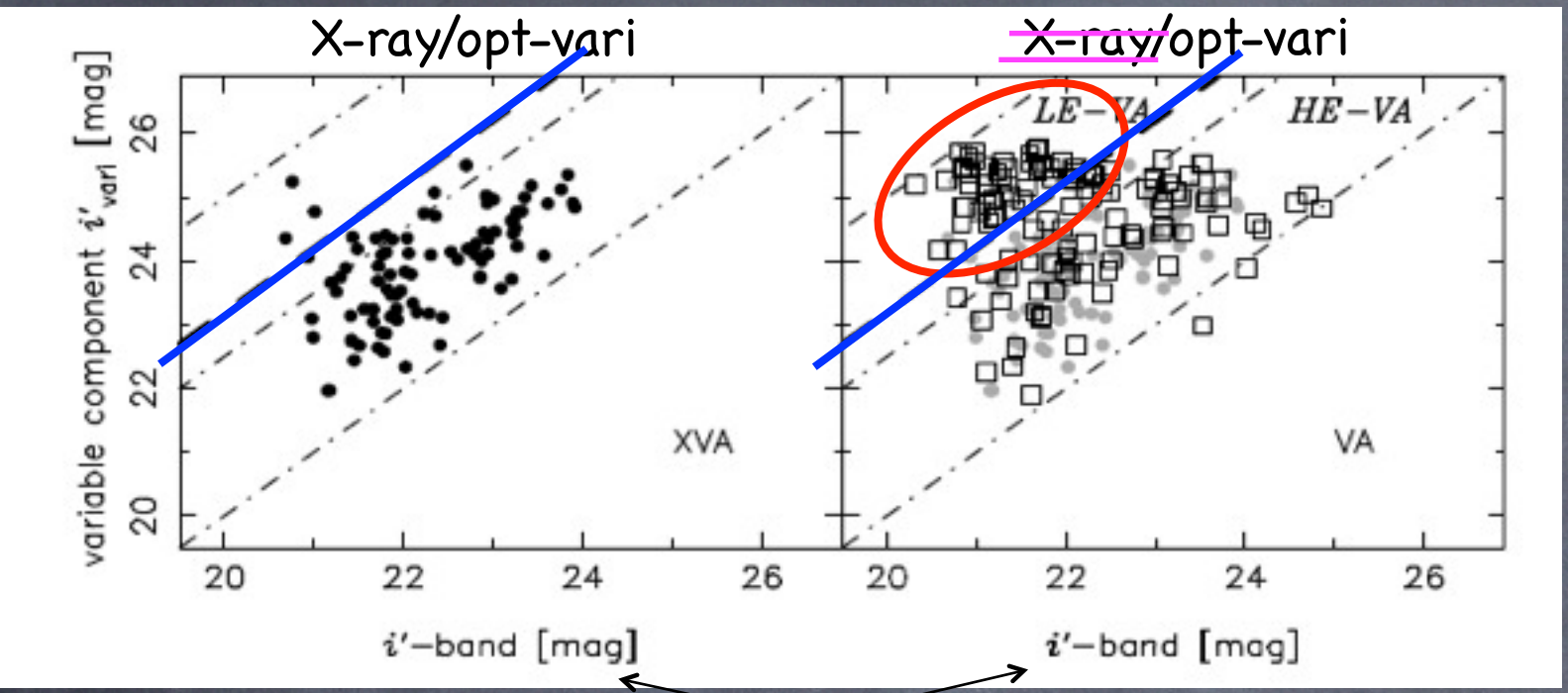
Optical variability can be a good tracer for low-luminosity AGN.

- Subaru (Suprime-Cam): Totani+2005, TM+2008a,b
- HST (WFPC2, ACS): Sarajedini+2000,2003,2006, Cohen+2006
  - (low-luminosity) type-1 AGN (up to z~5)
  - ~580 AGN / deg^2
  - significant fractions (~50%) of AGN w/o X-ray detections

AGN samples


X-ray
optical variability
obscured
(type-2)
238 (36)
<z>=1.48
unobscured
(type-1)
89 (35)
<z>=1.82
unobscured?
(type-1?)
122 (9)
<z>=1.32

properties of variability-selected AGN



total flux (incl. host)

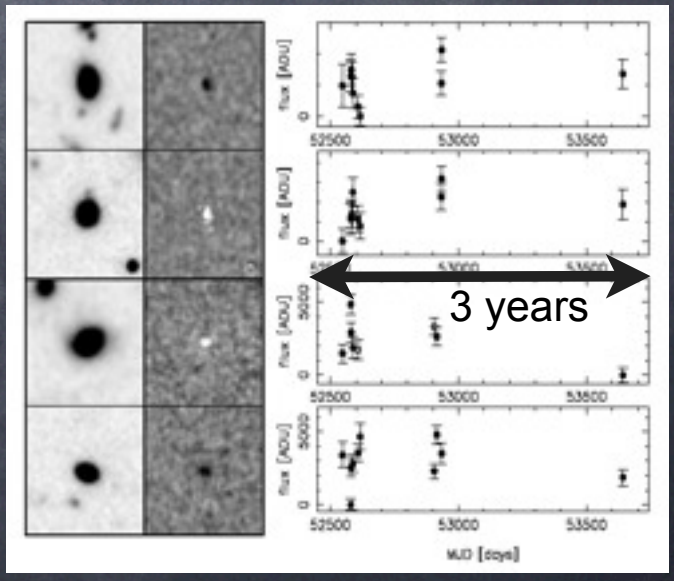
differential flux between max and min

low differential flux ~ low AGN flux

- X-ray undetected optical-variability-selected AGN
- not optical color selection

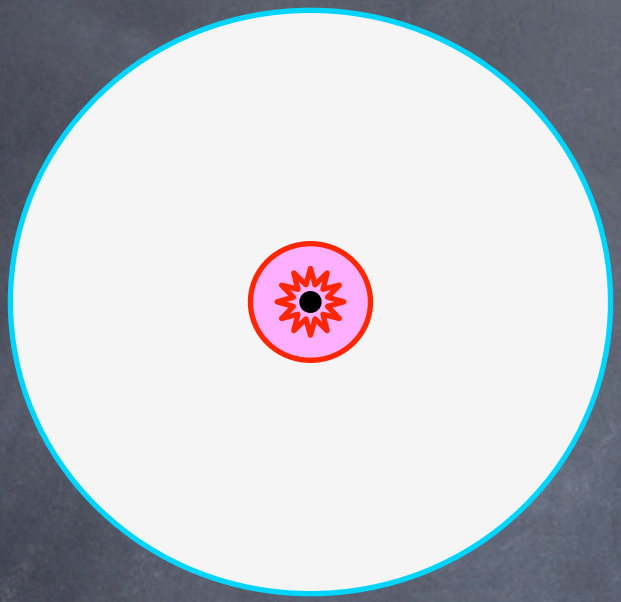
- faint AGN in bright elliptical galaxies at z_{photo}~0.5 (e.g.Totani +2005)
- flare-up? radiatively inefficient accretion flow (RIAF)?
- radio-mode feedback? nearby LINER analogous?
- ~10^8Mo SMBHs. ending phase of mass accretion?
- 5-10% of bright galaxies show variability

→ several tens percent in total?
(unknown detection efficiency...)



アーカイブデータを用いた時間変動天体の研究

Supernova Shock Breakout

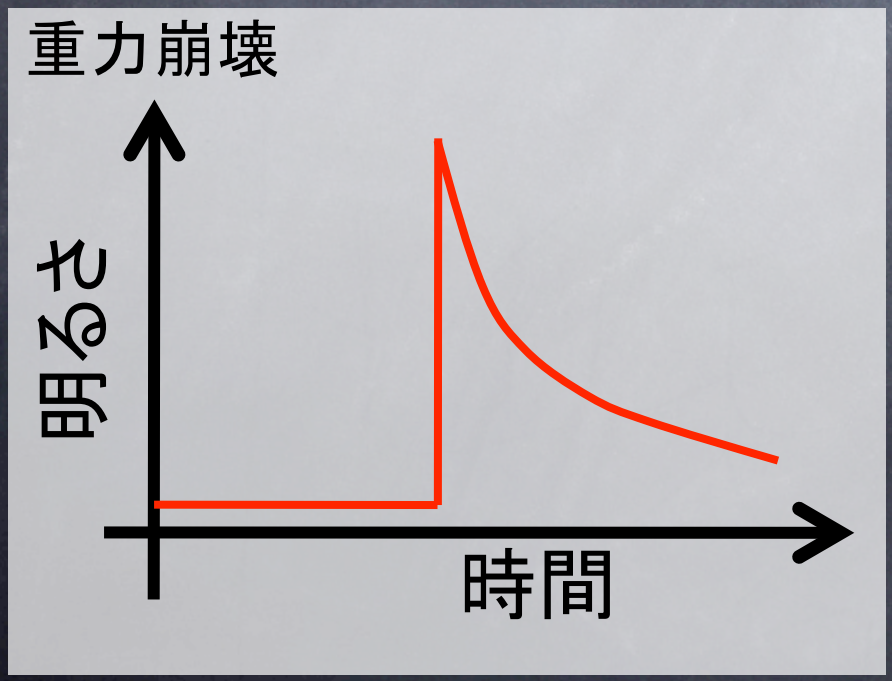


Massive Star (>10$M_\odot$)

e^--capture SNe (8-10$M_\odot$)

重力崩壊
重力エネルギー解放
衝撃波形成

衝撃波が星を伝わり、
星表面に到達すると
たまっていたエネルギーが放出。

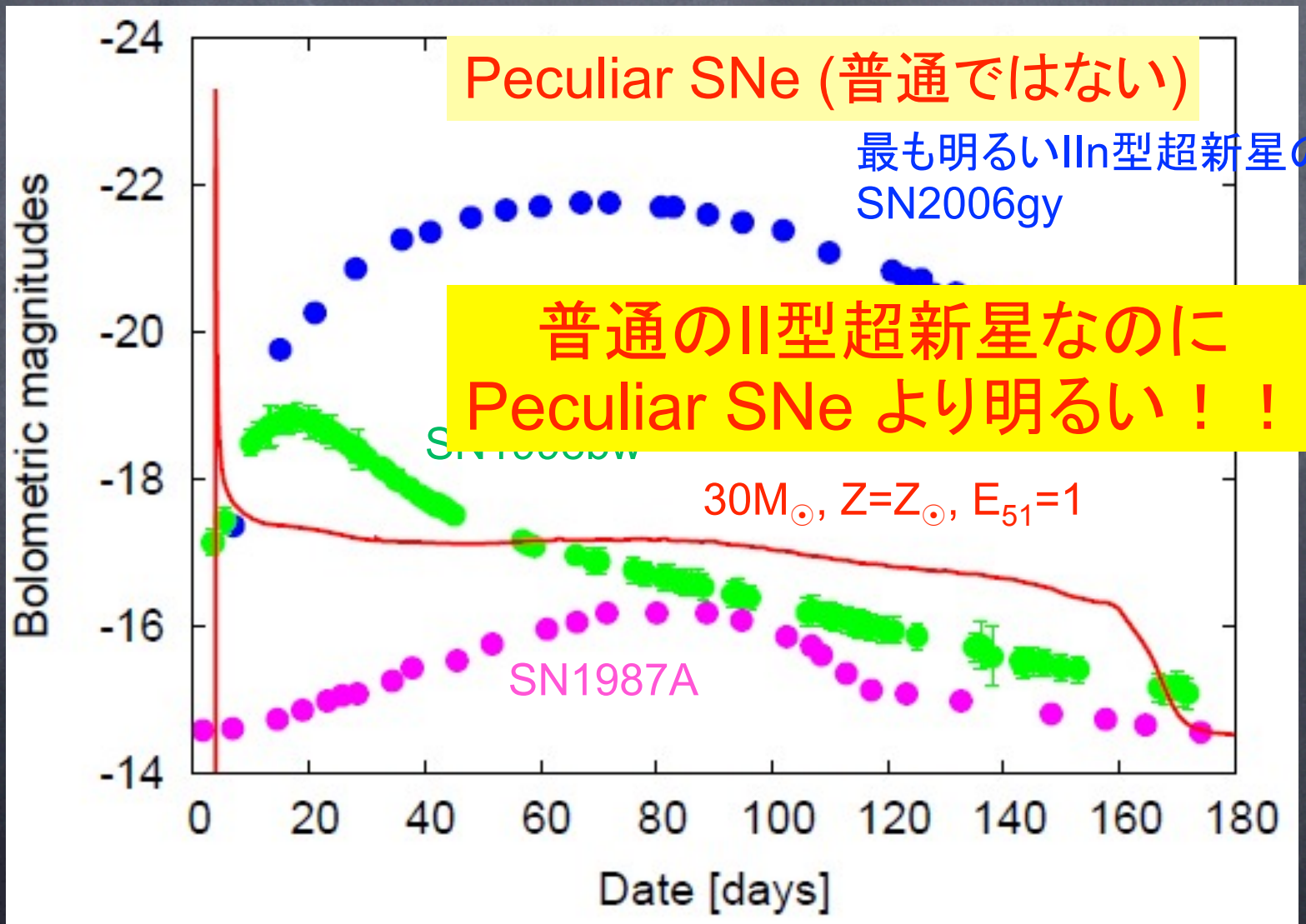


スペクトルはほぼ黒体輻射
温度は大体
$T \sim R^{-3/4}E^{1/4}$

Supernova Shock Breakout

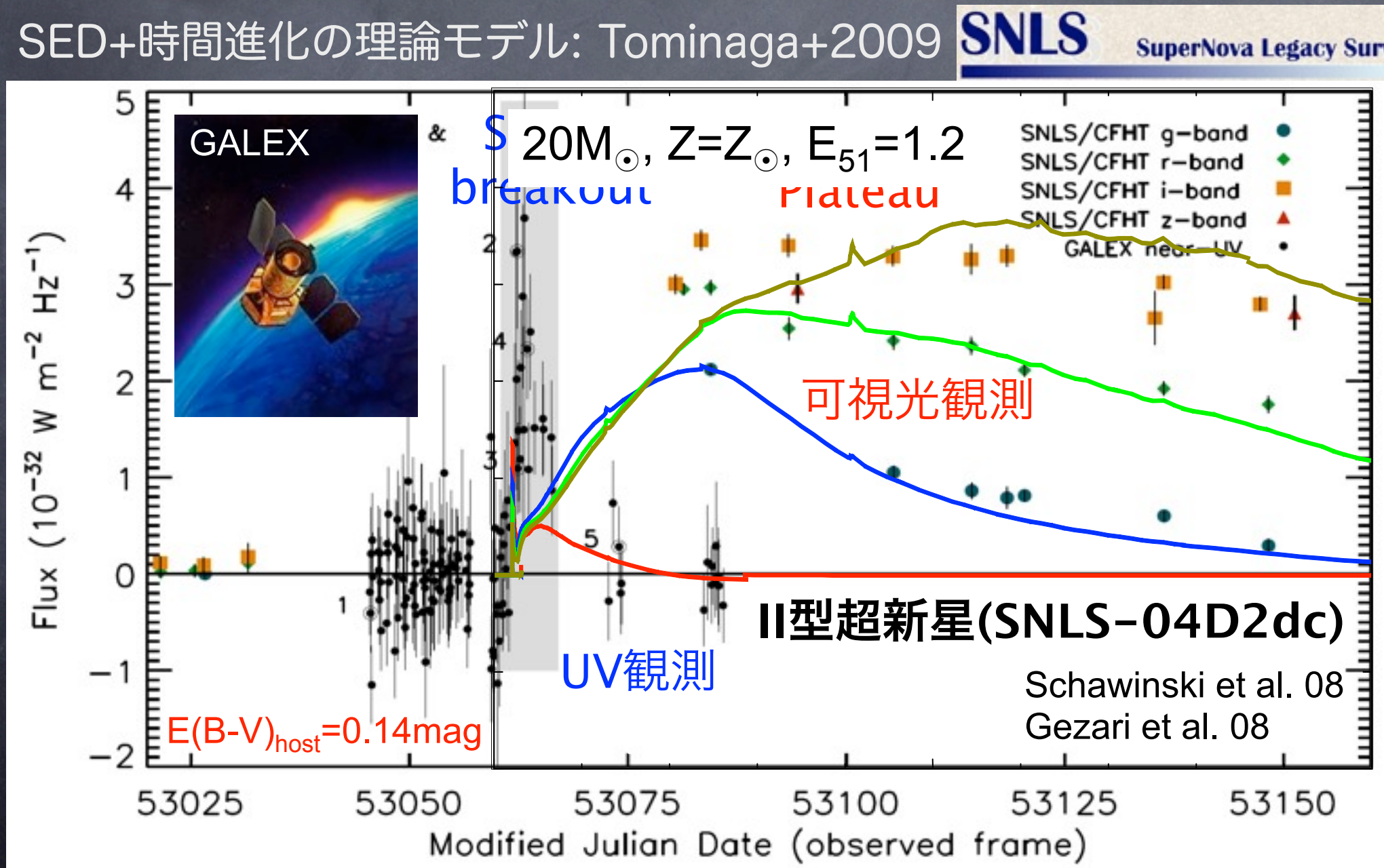
SN 2006gy (z=0.02: Smith+08; Kawabata+09)

- M_R~-22 (M(^{56}Ni)~15M_{sun} or CSM相互作用)



Supernova Shock Breakout

SED+時間進化の理論モデル: Tominaga+2009

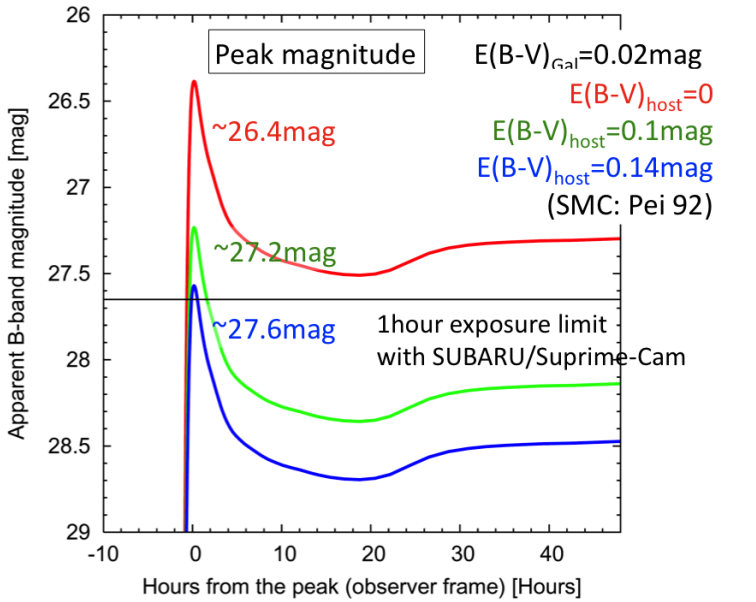


Supernova Shock Breakout Survey w/ Suprime-Cam Archival Data (and HSC)

必要なデータ
- Suprime-Cam
- ある程度深く行ける青いバンド@可視: B, g, V, r, Rc, ...
- 2日連続で観測
- 1晩の中で適当に散らばっている or 3,4時間連続で観測
- 今のところこういうデータはない。
- が、近いデータはなくはない。

観測 (Schawinski+08; Gezari+08,10; Soderberg+08) 理論モデル (NT+09)

同一の超新星@z=1のB-band光度曲線

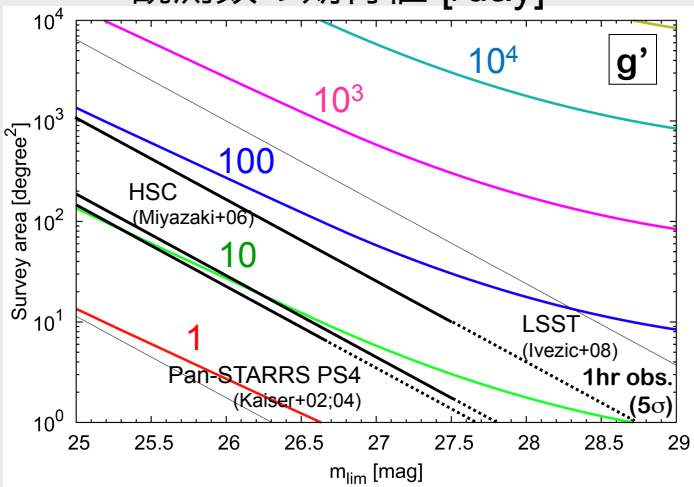


世界初の可視検出

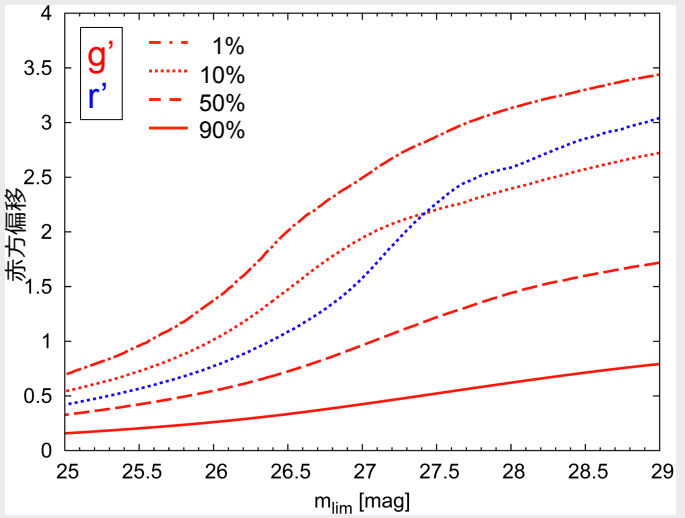
~1 per day per FoV

SDF, SSA22, ...
アーカイブ+α

観測数の期待値 [/day]



観測される超新星の赤方偏移



$m_{g',lim}$=28mag (すばる望遠鏡1時間積分S/N=3)
→ ~6 SNe/deg^2/day: z>0.6 (90%) z>1.5 (50%)

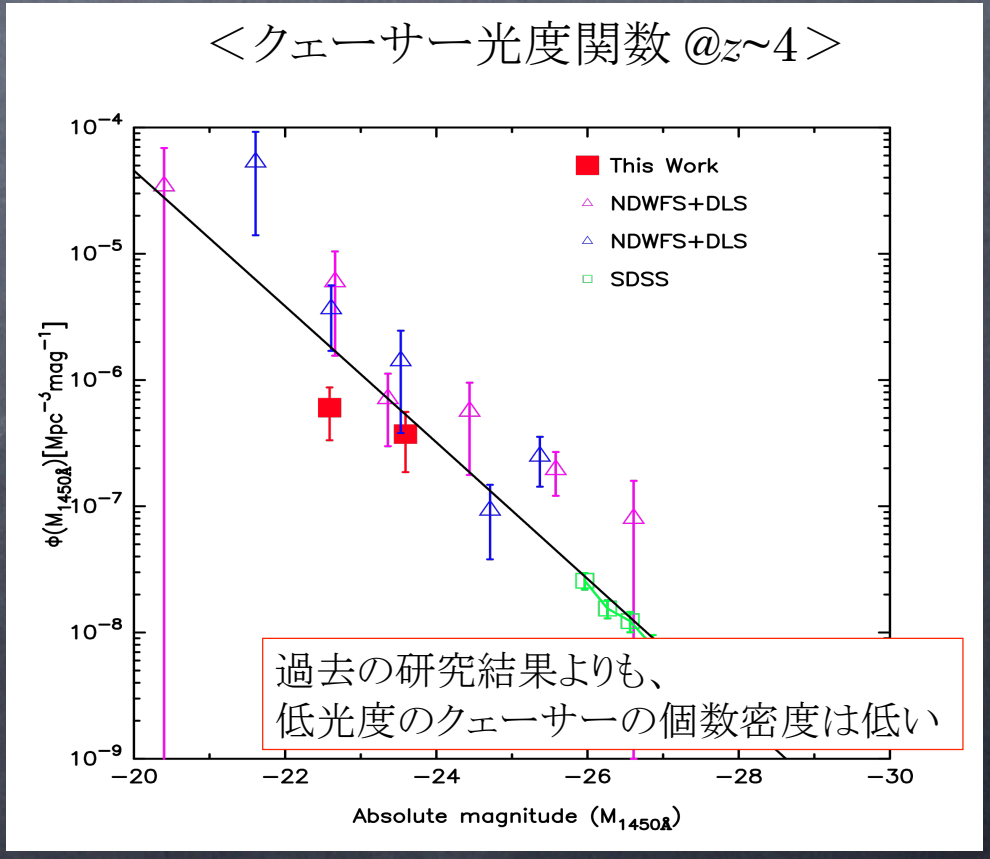
Faint Quasar Surveys at z~4

- SDSS, 2dF等で大規模quasarサンプル構築 (Richards+2009, ...)
- 普通はcolor selectionで選ぶ (暗いquasarと明るいLBGが区別できない)
- ただし、high-z (>3)だと明るいものばかり
- SMBH進化を語るにはfaint-endが重要

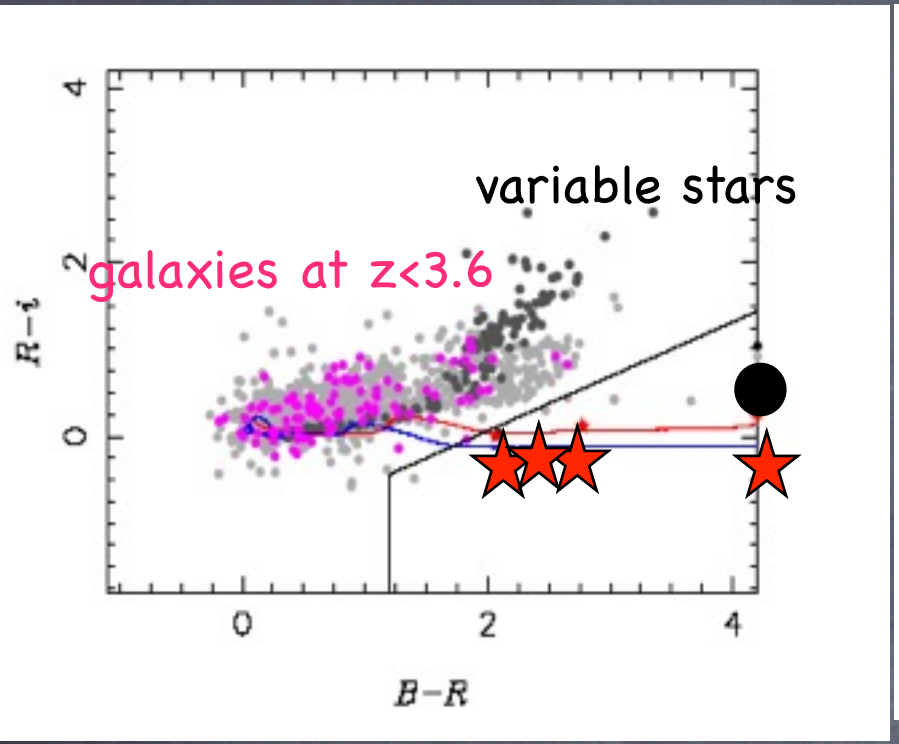
--> 4-10m級+広視野カメラの出番

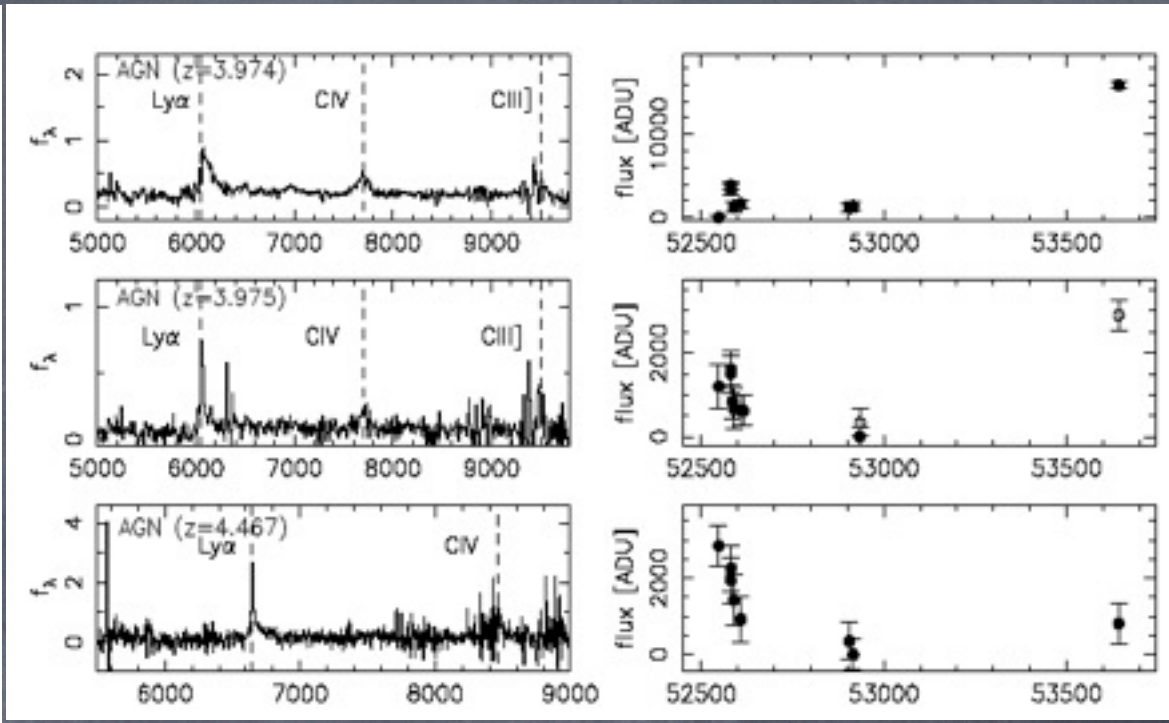
Ikeda+2010, in prep.
- 8 quasars @ z~4
- COSMOS field
- Suprime-Cam gri selection

LBGと区別するために時間変動
(1型AGNには普遍の性質)を利用しよう
(TM+2010, in prep.)



High-Redshift Low-Luminosity Quasars





暗いquasarを探そうとすると、"Dropout"法は明るいLBGも選んでしまう

--> 時間変動でquasarだけを選ぼう

- 8-10 times over 3 years
- B-dropout & optical variablity@SXDS (~1deg2): 5 candidates

- i=22-25mag
- X-ray detection: 2 objects
- 4 objects spectroscopically identified. all are z~4.
- M1450 ~ -23mag

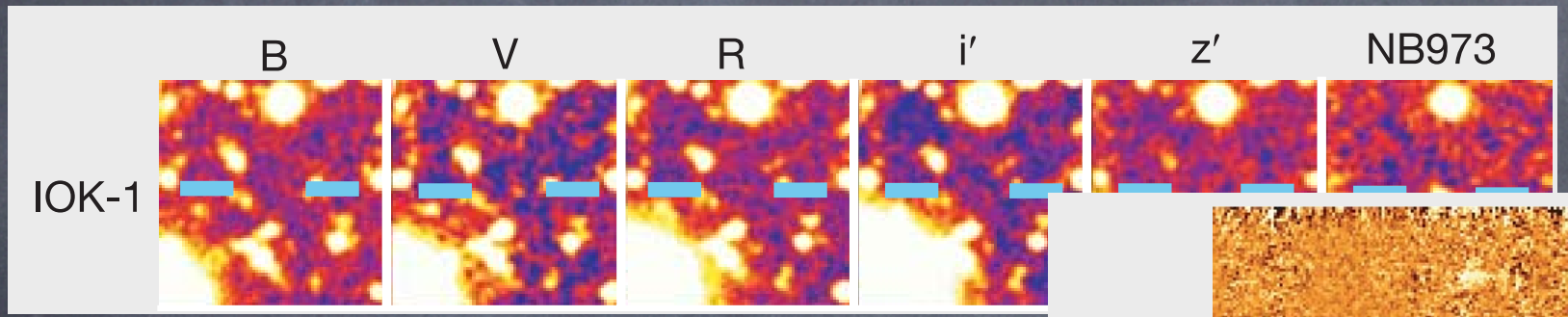
SDF, GOODS-N, COSMOS, CDF-S, Lockman-Hole, SSA22, ...
アーカイブ+α

Real LAE? Just A Variable Object?

◯z~7 LAE: IOK-1 (Iye+2006, Nature)

選択基準: z-NB973>1.0

z: 2002-2004年, NB973: 2005年

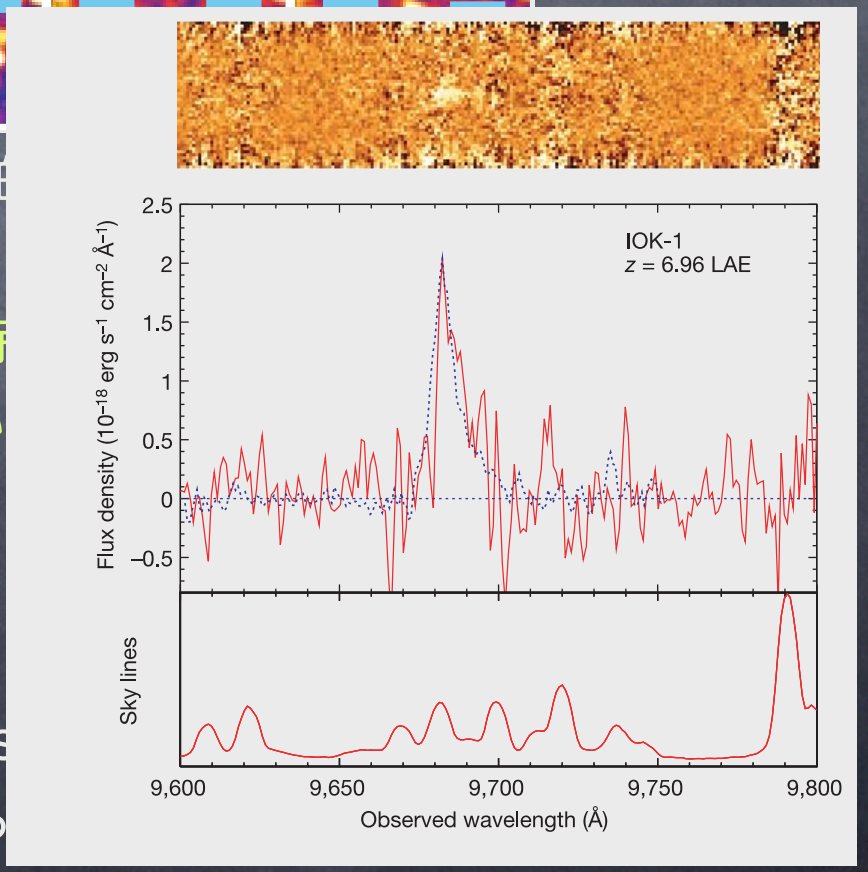


Nvari: [時間変動天体数の期待値], Ntarget: [目

(Nvari > Ntarget) or (Nvari ~ Ntarget)

見つけた天体が、”real”かどうかは確信は持

全部、時間変動によるartifactかもしれない



In order to be more confident...

- 分光観測による確認
- 同じ時期にとったデータを使ってカラー/exces
- むかしのデータを見て、過去の時間変動を見る

今後は……

Hyper Suprime-Cam (HSC): 戦略枠観測 = "legacy survey"

3 layers: wide/deep/ultradeep

- supernova (Ia, IIn, shock breakout)
- AGN
- GRB (orphan) afterglow
- solar system
- high proper motion stars
- variable stars
- ……

collaboration meeting, WG(HSC-transient)で議論

2011年 first light --> 2012年 戦略枠観測スタート?

今後は.....

- Subaru/Hyper Suprime-Cam (HSC)
  - supernova Ia
  - supernova shock breakout
  - low-luminosity AGN
- WISH: NIR wide-field imager
  - dust-free supernova Ia
- Kiso/Kiso Wide Field Camera (KWFC)
  - supernova Ia/CC
  - supernova shock breakout

wide-field imagerは見つけるのは得意

follow-upも同じくらい重要

(使いやすい)pre-imageがあると非常にうれしい

Summary

- Subaru/Suprime-Camによるすばる観測所プロジェクト SDF, SXDSのデータを時間分割
- 主に、supernova、AGNに関する時間変動天体研究
- アーカイブデータを使ってsupernova shock breakout, high-z quasarを見つけようという試み
- 今後は(follow-upも含めた)もっとwell-organizedな観測を。Subaru/HSC, WISH, Kiso/KWFCでのサーベイ。pre-image=アーカイブの利用も重要。