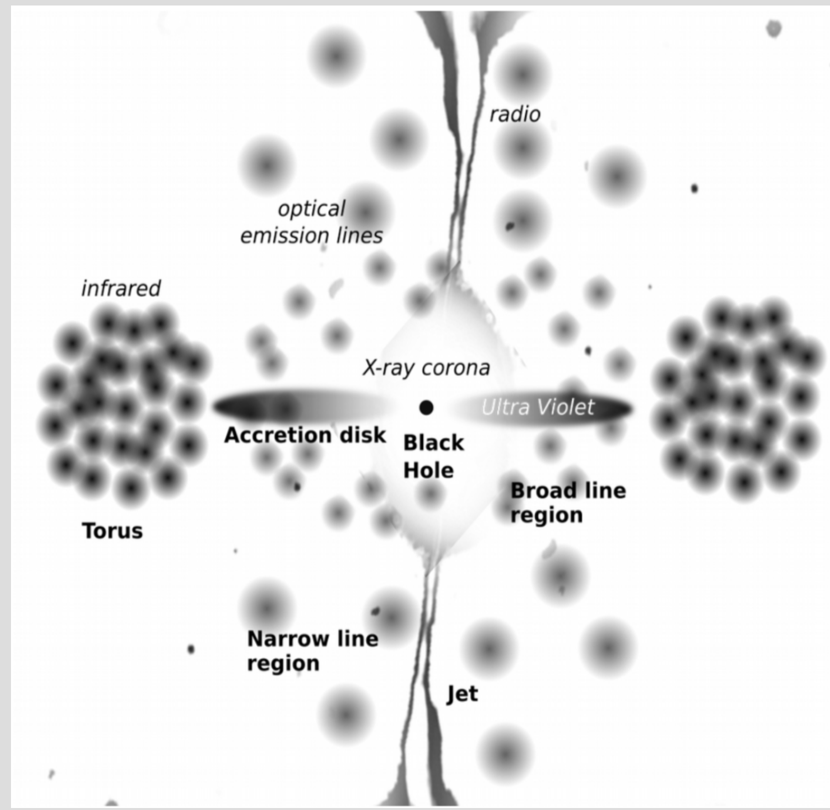
Supermassive Black Hole Studies with the LSST

Niel Brandt - For the LSST AGN Science Collaboration

G. Lombardi



S. Fotopoulou

Talk Outline

Brief review of the LSST surveys (AGN perspective).

AGN selection with LSST and multiwavelength data.

Examples of exciting science investigations:

- Variability studies
- Transient SMBH fueling events
- AGN investigations at high redshift

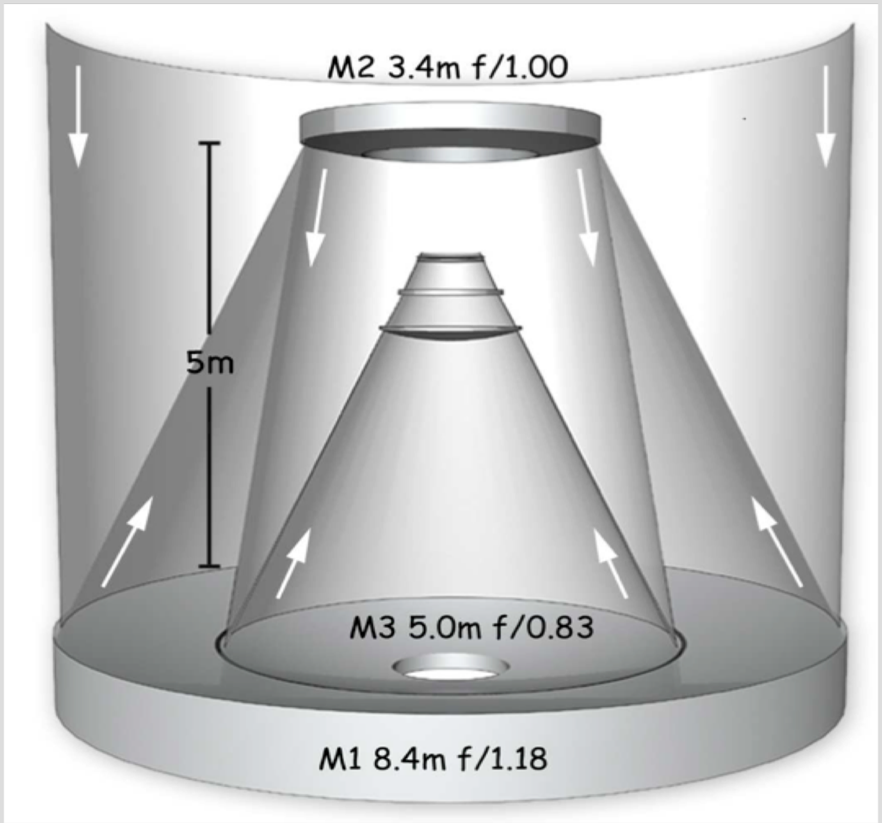
The LSST AGN Science Collaboration.

Brief Review
of the
LSST Surveys

(from an AGN perspective)

Very Brief Summary

A public optical/NIR survey of ~ half the sky in the *ugrizy* bands to *r* ~ 27.5 based on ~ 820 visits over a 10-year period.



8.4 m, 6.7 m effective - 10 deg^2 - 3.2 Gpix camera

Wide

The observable southern sky. Each exposure covers 50 full Moons.

Deep

10-100 times deeper than other very wide-field surveys.

Fast

Rapidly scans the sky with 15 sec exposures, providing a color movie of objects that change or move. Whole observable sky scanned every ~ 4 nights.

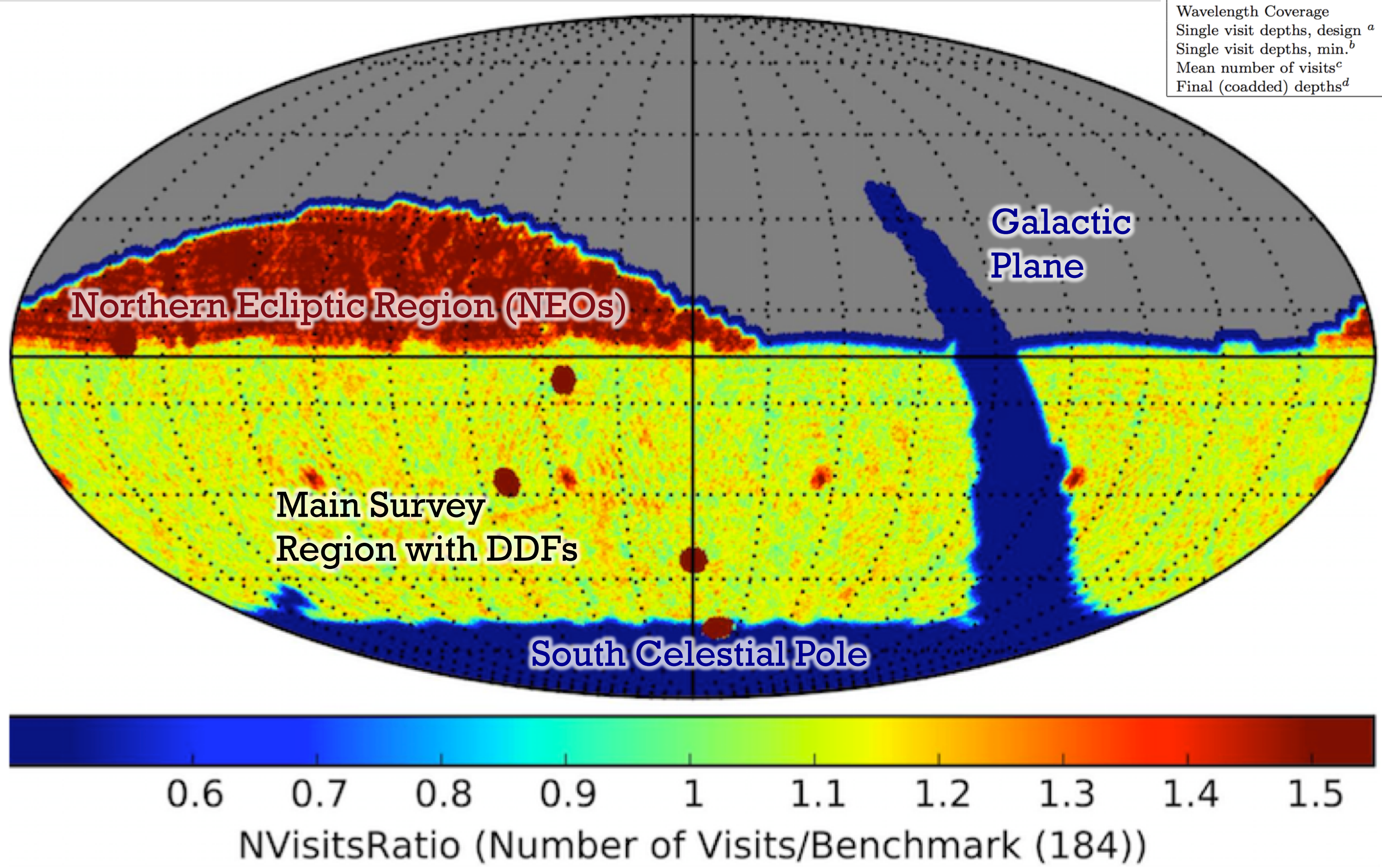
See Ivezic et al. (2019) for many more details - arXiv:0805.2366.

Main Survey - Brief Details

Example Operations Simulation of r-Band Visits
(Details Subject to Change)

The LSST Baseline Design and Survey Parameters

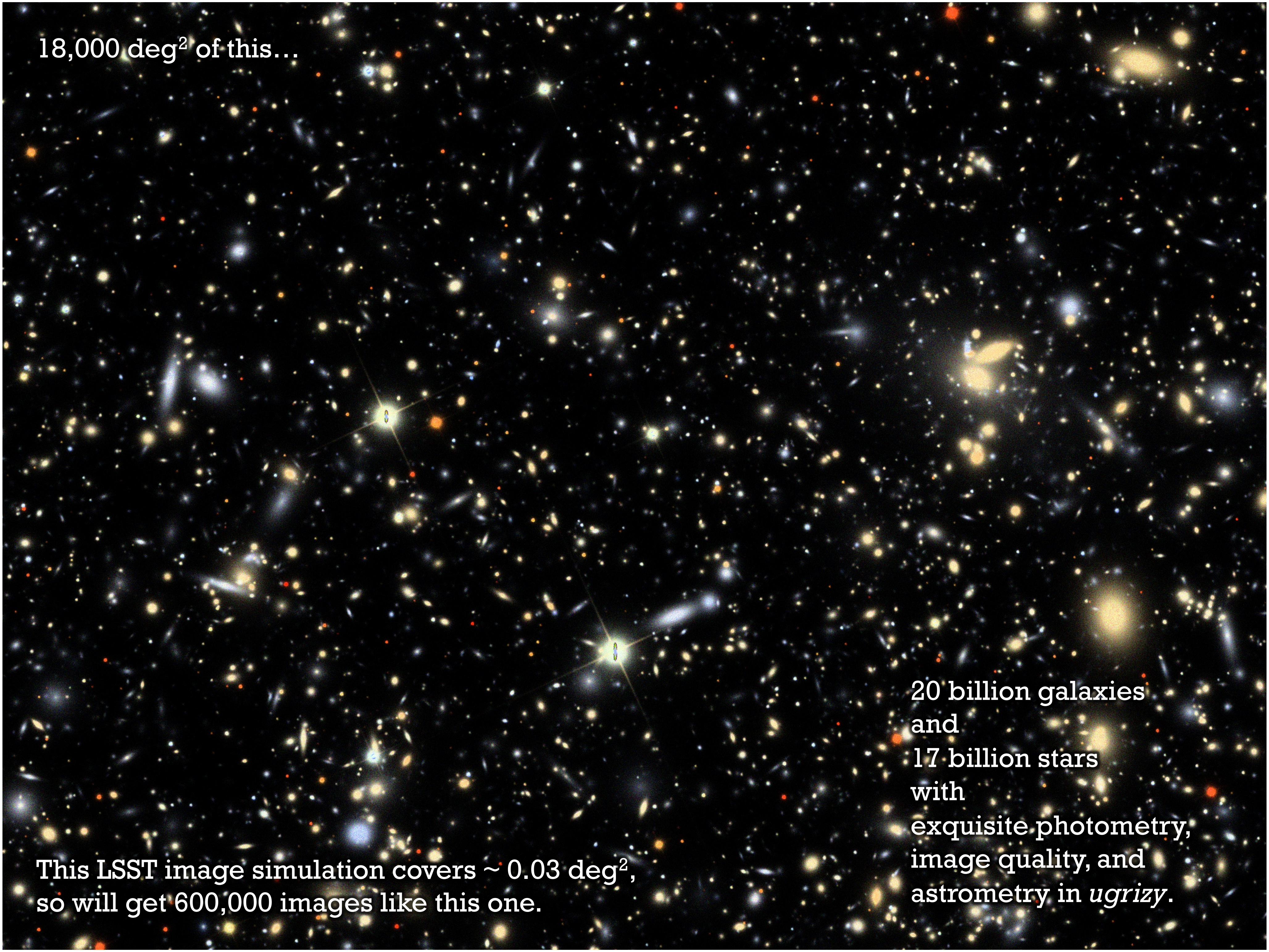
Quantity	Baseline Design Specification
Optical Config.	3-mirror modified Paul-Baker
Mount Config.	Alt-azimuth
Final f-ratio, aperture	f/1.234, 8.4 m
Field of view, étendue	9.6 deg^2, 319 m^{2}deg^2
Plate Scale	50.9 μm/arcsec (0.2" pix)
Pixel count	3.2 Gigapix
Wavelength Coverage	320 – 1050 nm, *ugrizy*
Single visit depths, design [a]	23.9, 25.0, 24.7, 24.0, 23.3, 22.1
Single visit depths, min.[b]	23.4, 24.6, 24.3, 23.6, 22.9, 21.7
Mean number of visits[c]	56, 80, 184, 184, 160, 160
Final (coadded) depths[d]	26.1, 27.4, 27.5, 26.8, 26.1, 24.9



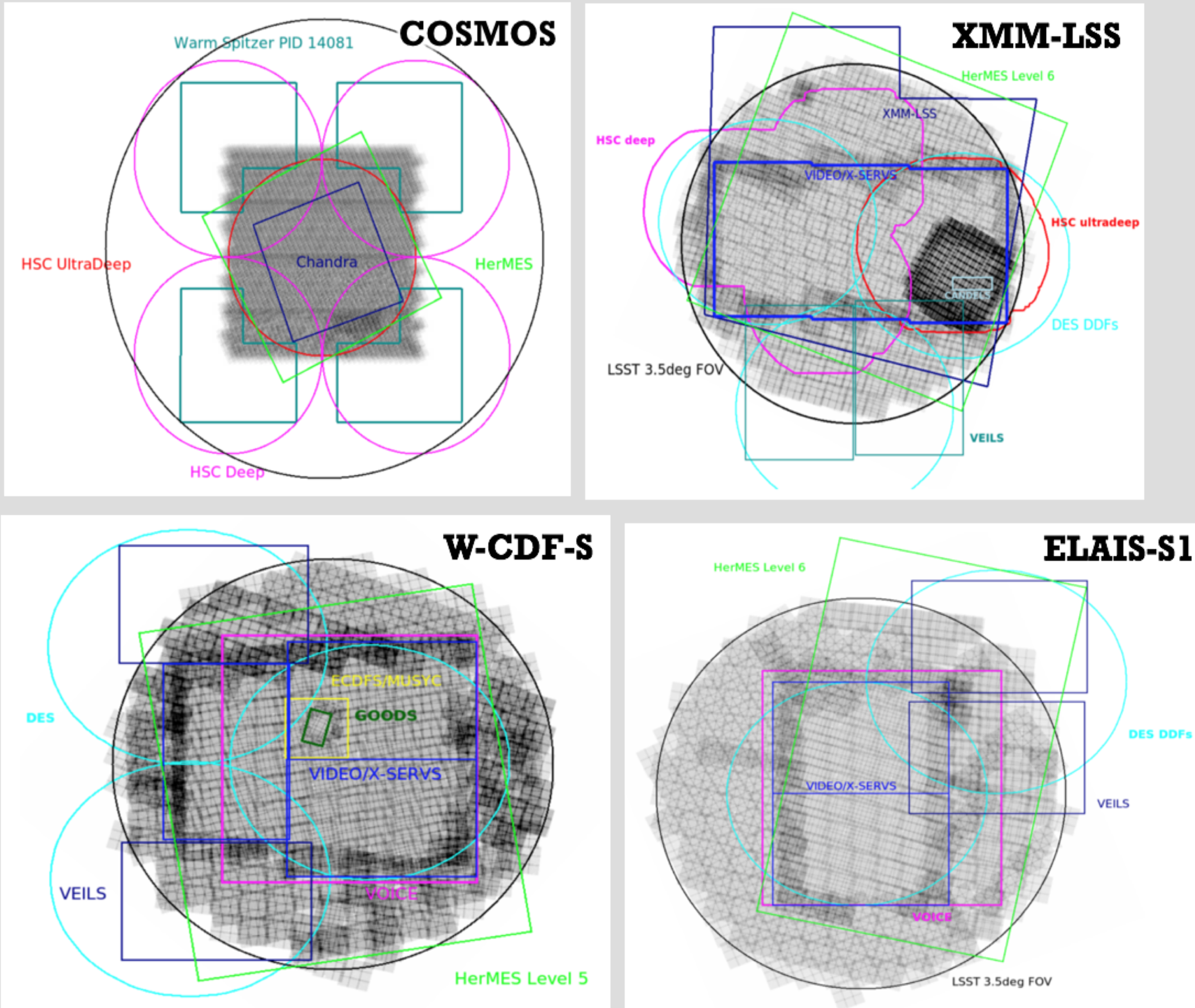
Main survey optimized for homogeneity of depth and number of visits.

~ 18000 deg^2

Uses ~ 90% of the LSST time.


18,000 deg^2 of this…
This LSST image simulation covers ~ 0.03 deg^2,
so will get 600,000 images like this one.
20 billion galaxies
and
17 billion stars
with
exquisite photometry,
image quality, and
astrometry in *ugrizy*.

Four Chosen LSST Deep Drilling Fields



Each chosen LSST DDF is 10 deg^2 (black circles).

Have superb and rapidly growing multiwavelength data - critically important for AGN science!

Brandt et al. (2018)
arXiv:1811.06542

Survey Strategy Optimization Process

Goal: Determine how to observe main survey and spend 10-20% of time on "mini-surveys".

Mini-surveys could include more DDFs, TOOs, Galactic Plane, N. Ecliptic Region, Magellanic Clouds, Solar System, etc.

Community White Paper Response

WFD/All Sky	20 (10 cadence)
Deep Drilling Fields	4
Mini-Surveys	26
ToO	3

- ~~July 2018: Call issued~~
- ~~Nov 2018: White papers received~~
- April 2019: LSST Science Advisory Council review with list of recommendations for next-step Operations Simulations runs *Publicly available as of May 1st and worth reading!*
- Early 2020: Project delivers simulations to the "Survey Cadence Optimization Committee" (SCOC)
- Early 2021: SCOC delivers recommendations to LSST Operations Director
- Mid 2021: Project delivers baseline simulation of initial survey strategy
- Late 2022: LSST Operations start

L. Jones et al.

LSST AGN White Papers

Active Galaxy Science in the LSST Deep-Drilling Fields: Footprints, Cadence Requirements, and Total-Depth Requirements

W.N. Brandt (Penn State), Q. Ni (Penn State), G. Yang (Penn State), S.F. Anderson (Univ Washington), R.J. Assef (Univ Diego Portales), A.J. Barth (UC Irvine), F.E. Bauer (Católica), A. Bongiorno (Oss Ast Roma), C.-T. Chen (MSFC), D. De Cicco (Católica), S. Gezari (Univ Maryland), C.J. Grier (Penn State), P.B. Hall (York Univ), S.F. Hoenig (Univ Southampton), M. Lacy (NRAO), J. Li (Univ Illinois), B. Luo (Nanjing Univ), M. Paolillo (Univ Naples Fed II), B.M. Peterson (Ohio State), L.Č. Popović (Ast Obs Belgrade), G.T. Richards (Drexel Univ), O. Shemmer (Univ N Texas), Y. Shen (Univ Illinois), M. Sun (USTC), J.D. Timlin (Penn State), J.R. Trump (Univ Connecticut), F. Vito (Católica), Z. Yu (Ohio State)

November 2018

arXiv:1811.06542

Footprints

Cadence requirements

Total-depth requirements

Desired Visits and Expected Depths

Quantity of Interest	u	g	r	i	z	y
Visits Every 2 Nights	4	1	1	3	5	4
Depth Every 2 Nights	24.6	25.0	24.7	24.6	24.2	22.9
Total Visits in 10 yr	3600	900	900	2700	4500	3600
Total Depth in 10 yr	28.3	28.7	28.4	28.3	27.9	26.5

(Each "visit" is 30 seconds)

Testing of LSST AGN Selection Using Rolling Cadences

Gordon Richards (Drexel), Weixiang Yu (Drexel), W.N. Brandt (Penn State), Qingling Ni (Penn State), Christina Peters (Toronto), Guang Yang (Penn State), Franz E. Bauer (PUC/SSI)

November 2018

Abstract

The Supernova community has expressed an interest in so-called "rolling cadences", in order to achieve better sampling of SNe light curves. Here we explore how such rolling cadences would affect both the identification of AGNs and the science that can be derived from their resulting light curves. We present a metric that quantifies how well parameters of a particular variability model would be recovered for a given opSim cadence. We conclude that extreme rolling cadences (with few or no observations during some seasons) would be detrimental to AGN science. Less extreme rolling cadences require further investigation as the answer depends critically on both the science and the desired cadence.

Explores effects of main-survey cadence on AGN selection and characterization.

AGN Selection

(with LSST and Multiwavelength Data)

LSST AGN Selection

Multicolor selection in *ugrizy* from z = 0-7.5

- Ultraviolet excess below $z \sim 2.5$
- Lyman-α forest at high redshifts
- Works best when $L_{\rm AGN} > L_{\rm Host}$

Variability

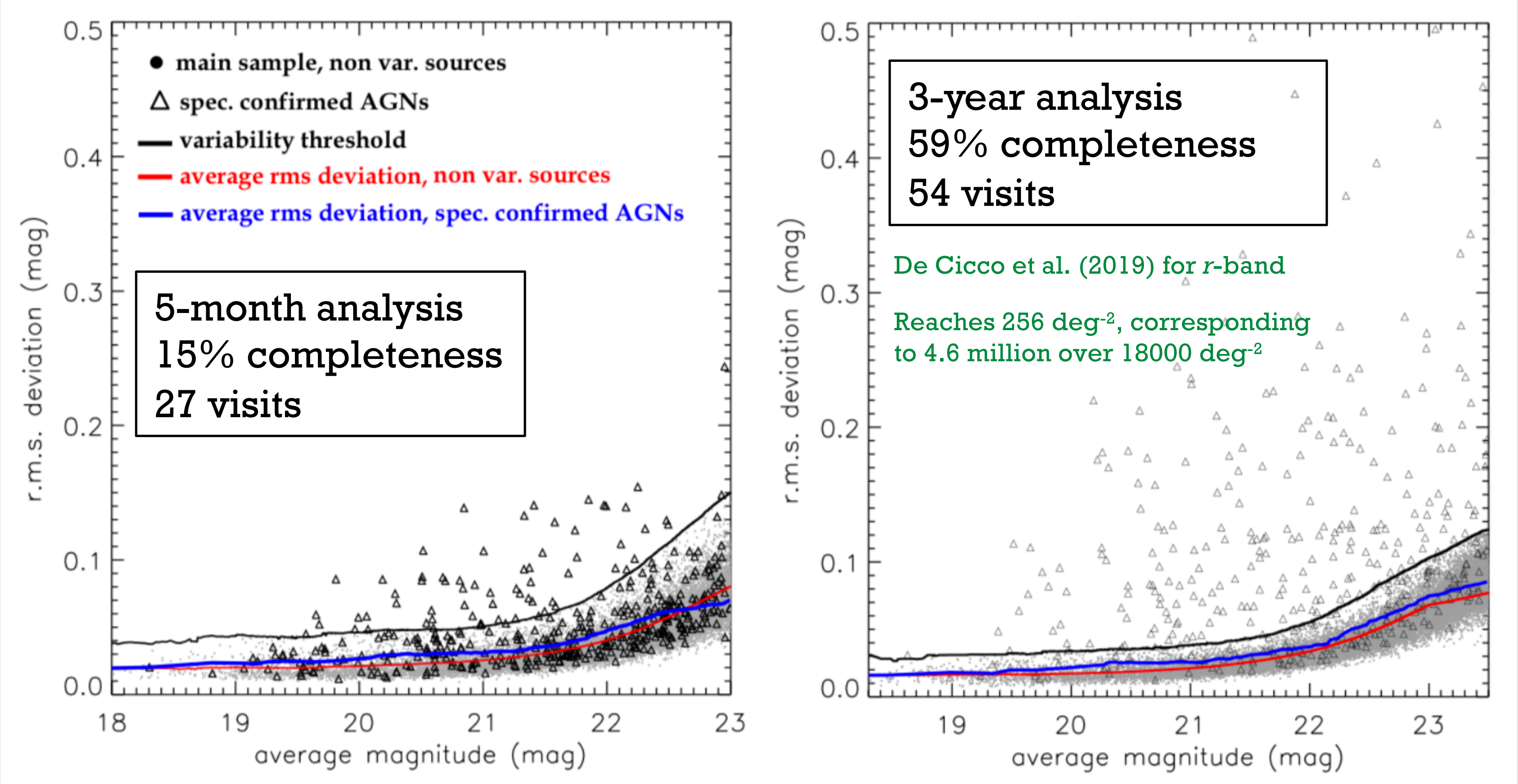
- 55-185 samplings per band over 10 yr
- Highly effective complement to color selection
- Need effectiveness assessments for $L_{\rm AGN} \sim L_{\rm host}$

Astrometry - Lack of proper motion and differential chromatic refraction

- Will reach ~ 1 mas yr^{-1} at $r \sim 24$
- Minimizes confusion with stars

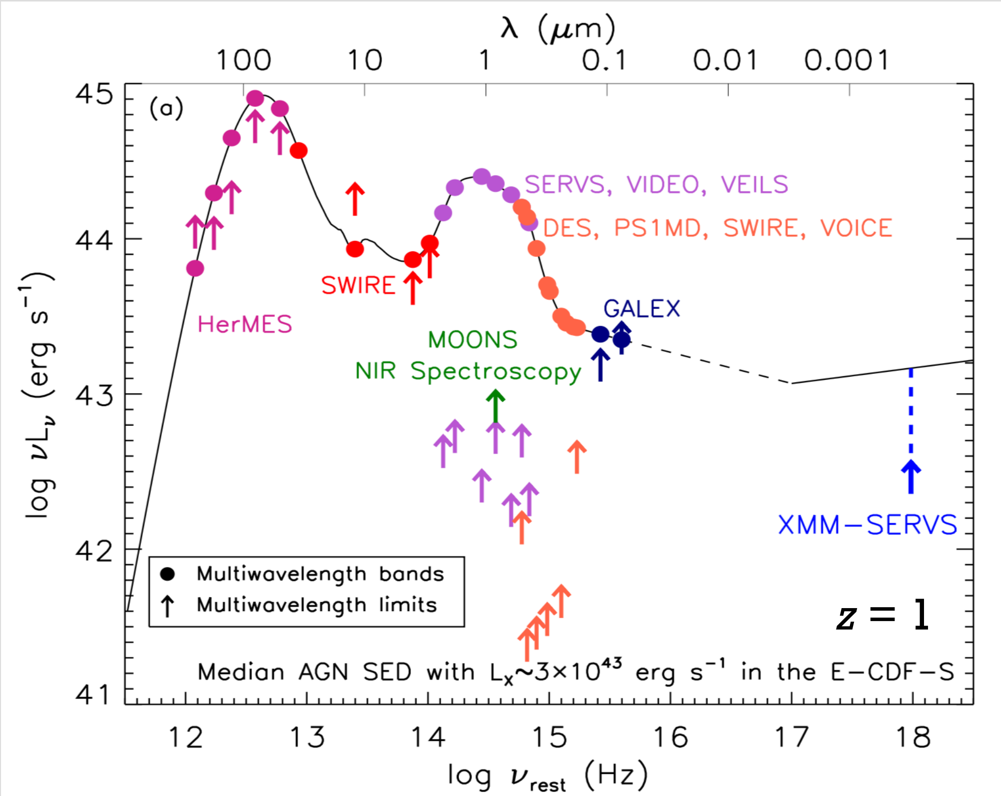
Optical Variability Selection of X-ray AGNs in COSMOS

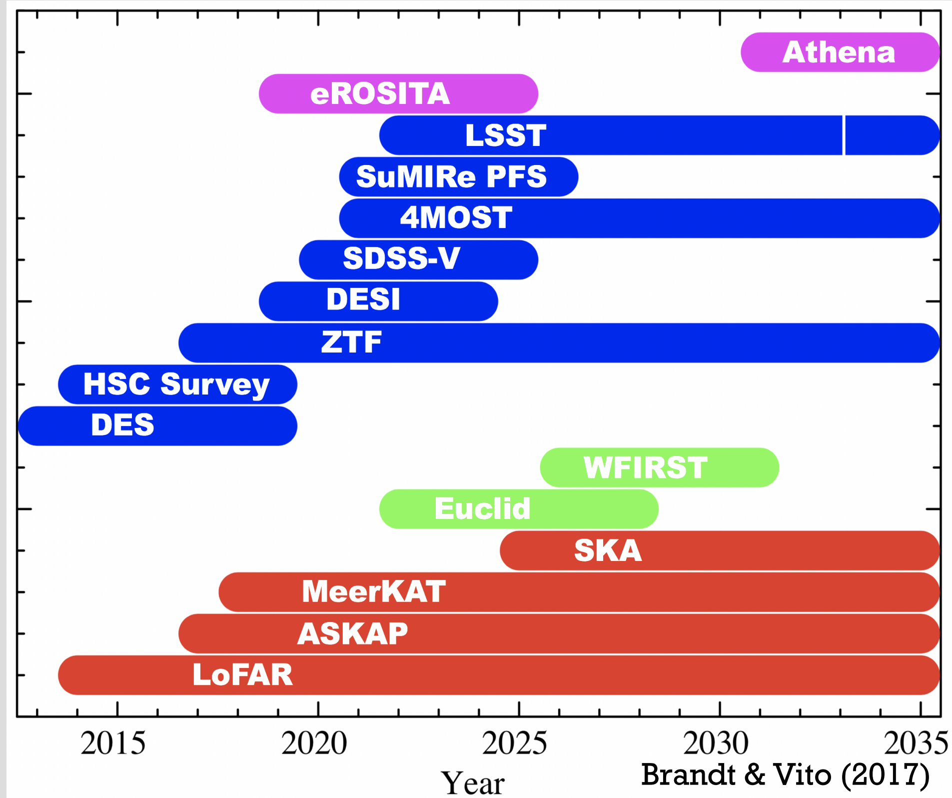
Long Baselines and Many Epochs Greatly Aid AGN Selection

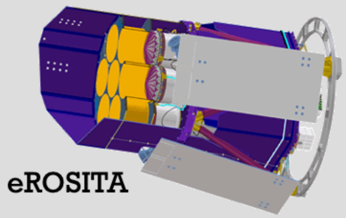


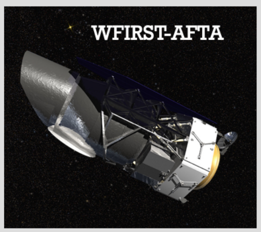
LSST will do even better with longer baseline, more epochs, deeper epochs, and more bands.

Power of LSST and Multiwavelength Data



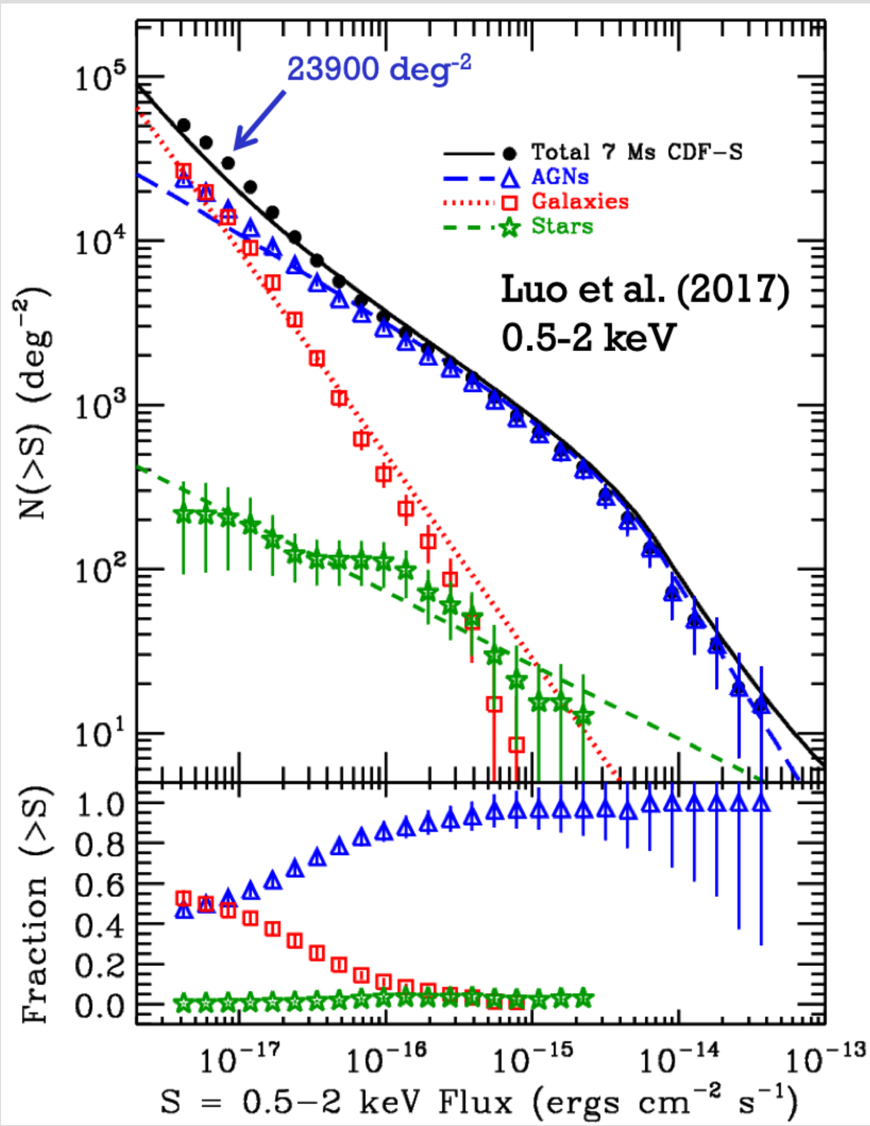






Plausible AGN Yields

Chandra Deep Field-South Number Counts



LSST will *detect* ~ 300+ million AGNs in 18000 deg^2 main-survey area.

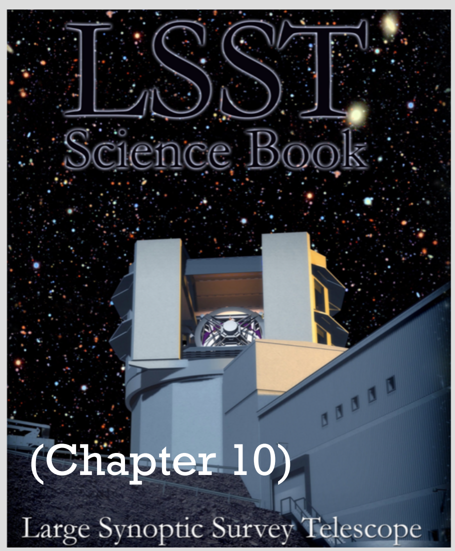
Obscuration and host-galaxy dilution will hinder AGN *selection*.

Confidently can select <u>20 million</u> (7%).

Hope to select <u>50+ million</u>, especially using multiwavelength data.

Example AGN Science Investigations

For more information:



AGN Science Collaboration

agn.science.lsst.org

Nightly LSST SMBH Science

Monitoring of ~ 75 million AGNs (5+ million selected).

Discovery of ~ 50 large AGN flares
(e.g., blazars and accretion-disk instabilities).

Discovery of ~ 3 stellar tidal disruption events.

Discovery of ~ 0.1 strong quasar microlensing events.

Binary SMBH inspirals and mergers?

Also ~ 2500 SNe and ~ 5 “orphan” GRB afterglows.

Massive AGN Variability Studies

Millions of well-sampled, accurate, multicolor AGN light curves, spanning minutes-to-years (billions of photometric measurements).

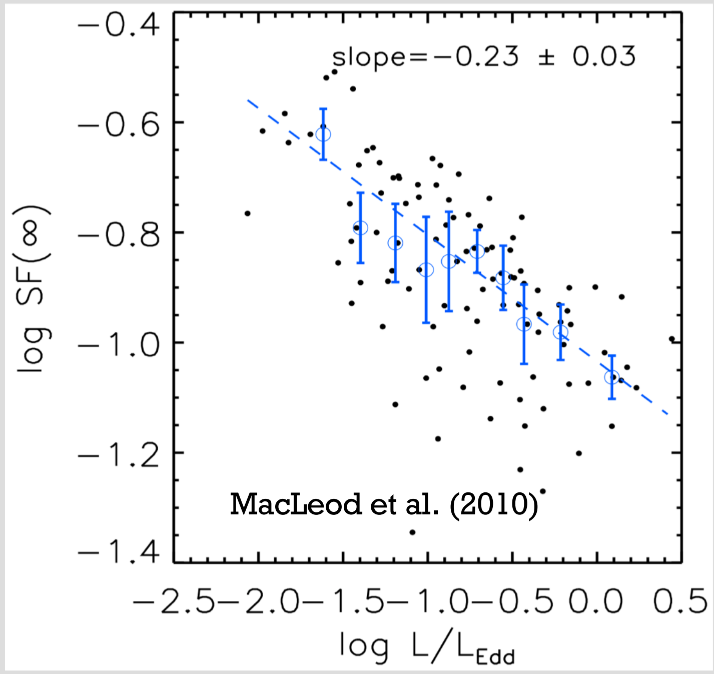
Even better sampling and depth for ~ 10^5+ AGNs in the DDFs.

Can combine with DES, HSC, Pan-STARRS, SDSS for longer baselines.

Can powerfully study general luminosity and spectral variability as a function of L, z, λ, Δt, color, radio properties, line properties, $M_{\rm BH}$, $L/L_{\rm Edd}$ (some require one-epoch spectra).

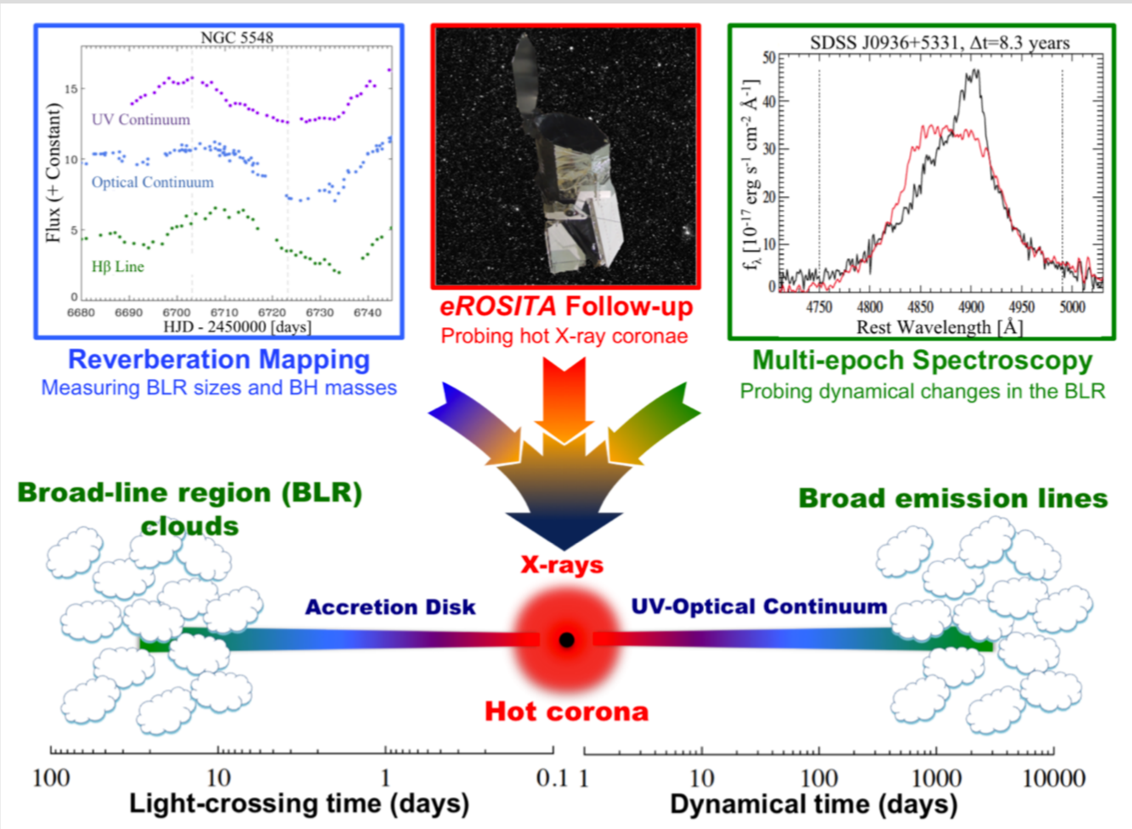
Rare but important events - large disk instabilities, strong jet flares, swan-song events, QPOs.

Eddington-Ratio Dependence of Long-Timescale RMS Variability



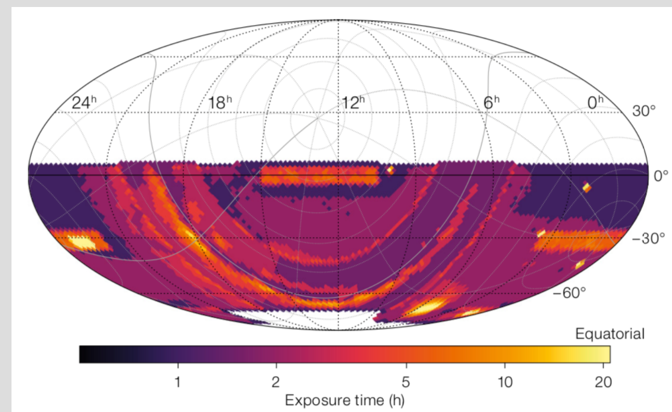
LSST + Time-Domain Spectroscopy

SDSS-V Black Hole Mapper will Reverberation Map AGNs in Three LSST DDFs: 2020-2025



4MOST TiDES Component in LSST DDFs: 2022-2027

Location	Area (square degrees)	Average t_{exp} (hours)
Bulge and Inner Galaxy	500	4–6
Magellanic Clouds	200–300	2–10
WAVES-Wide	1300	3–4
WAVES-Deep	50	7
LSST Deep Drilling Fields	4 × 4.2	4 × 60 (or more)
South Ecliptic Pole area	300	4



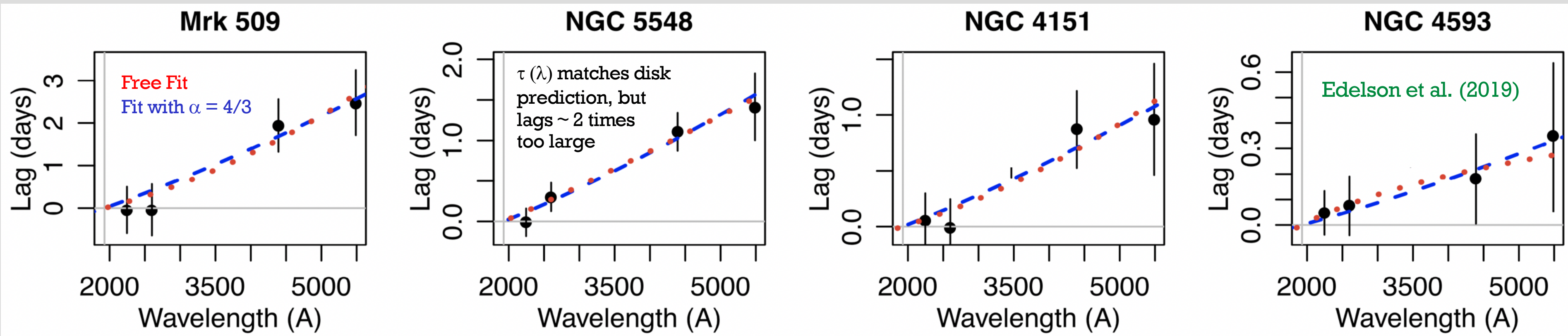
Guiglion et al. (2019)

LSST will provide ~ 900 epochs of outstanding photometry for reverberation mapping.

Also BAL variability, reddening variability, changing-look quasars, general emission-line variability, etc.

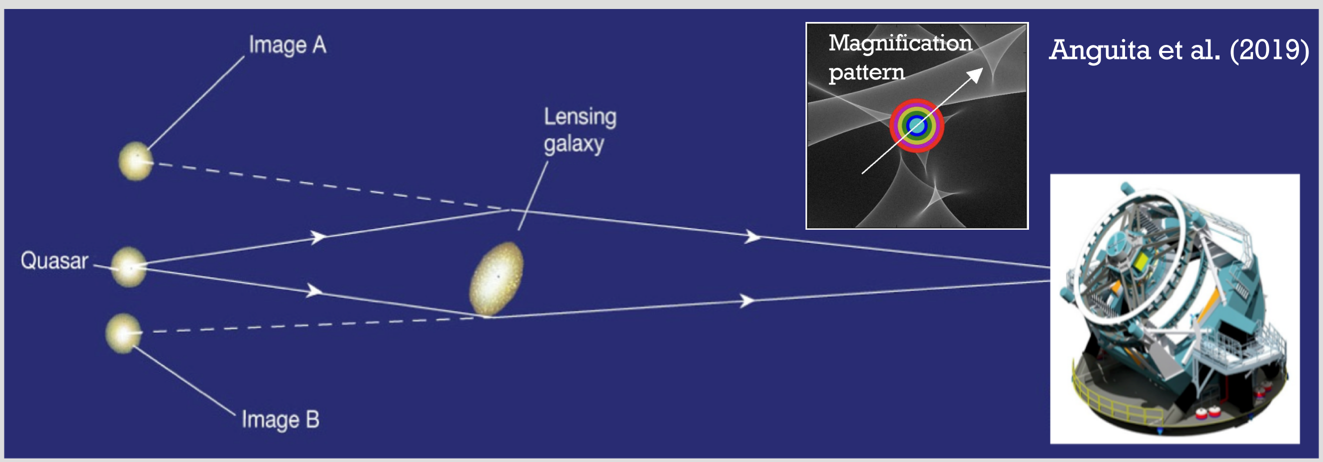
Accretion-Disk Structure with LSST

Accretion-Disk Continuum Reverberation Lags from Swift

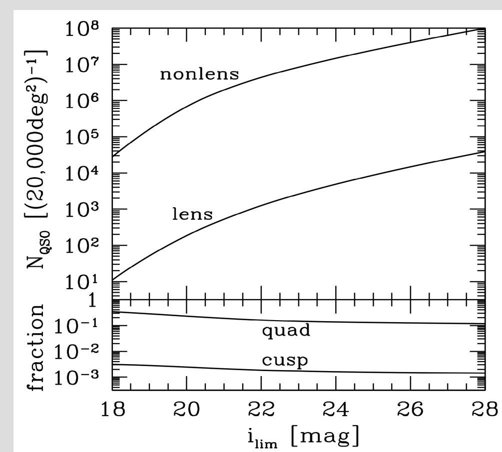


LSST will perform quality accretion-disk RM for ~ 3000 AGNs in the DDFs.

Microlensing of Accretion Disks



Oguri & Marshall (2010)



LSST will monitor ~ 3000 AGNs lensed into multiple images for microlensing - nas resolution.

Small-Separation Binary SMBH

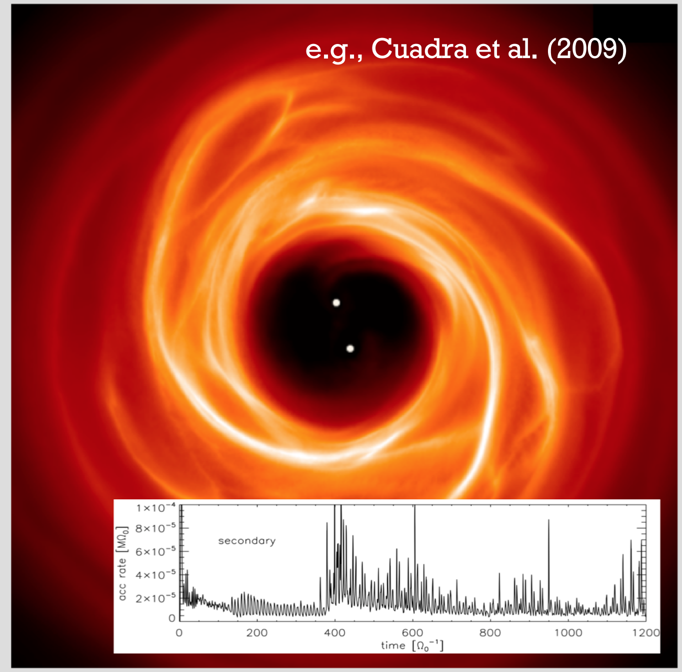
For SMBHs to move from pc to 10^{-3} pc separations, likely need gas accretion to remove binary angular momentum.

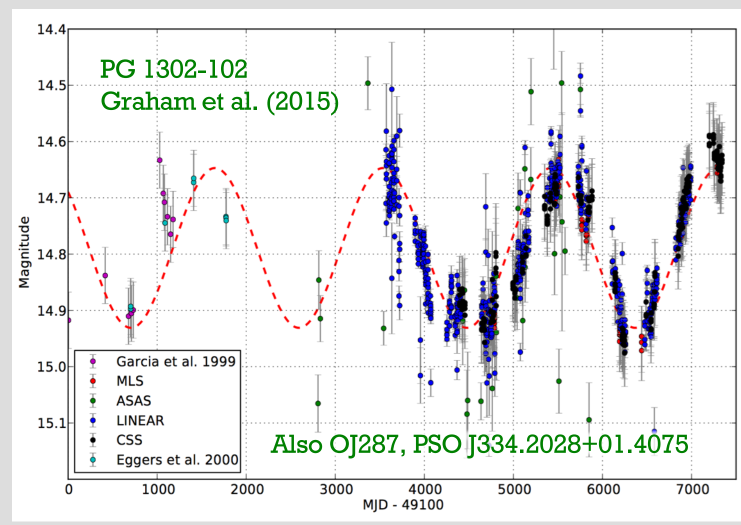
Accretion rate onto both SMBHs may vary on timescales of the binary period.

Month-to-year timescales at ~ 10^{-2} pc, well-suited to LSST monitoring and hard to find in other ways.

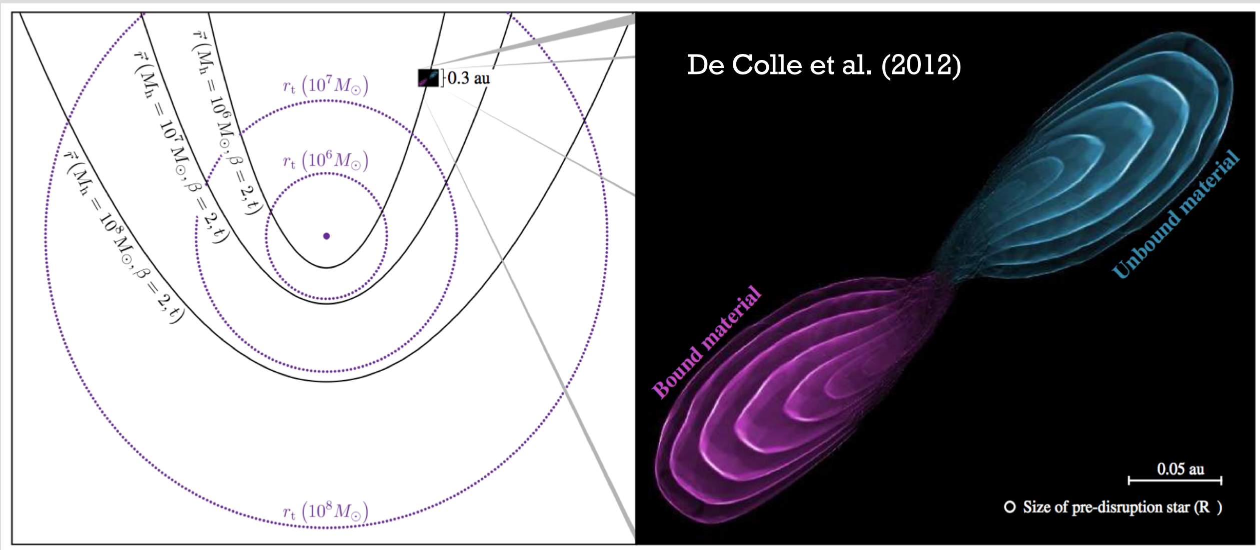
Massive LSST variability survey can find or usefully constrain the uncertain frequency of 10^{-2} pc binary SMBHs.

Already some candidates being found, but interpretation debated. Need rigorous statistical-sample studies from LSST et al.



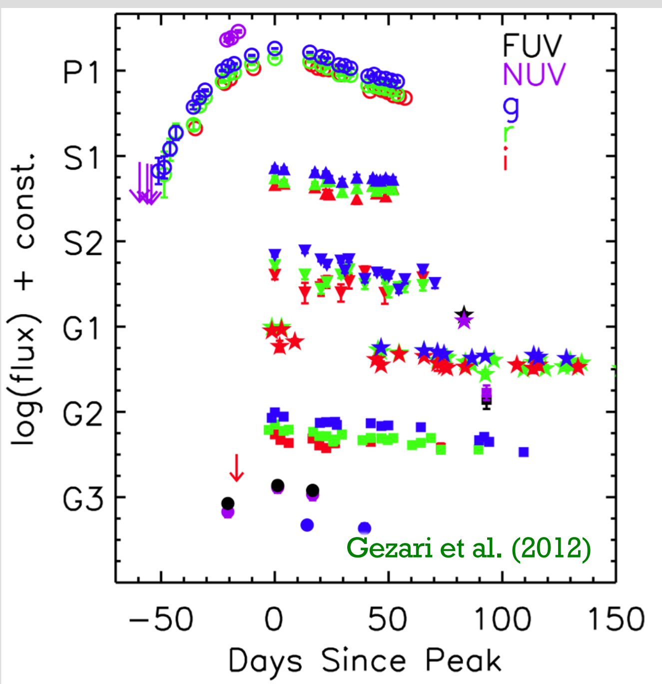


Transient Fueling of Dormant SMBHs



A dormant SMBH can flare to AGN luminosities for months-years via tidal disruption and partial accretion of stars, planets, or gas clouds.

Now being found in wide-field optical/UV and X-ray surveys.



Expect to *detect* ~ 1000+ per year with LSST, but will need to enforce selection cuts to avoid SNe confusion.

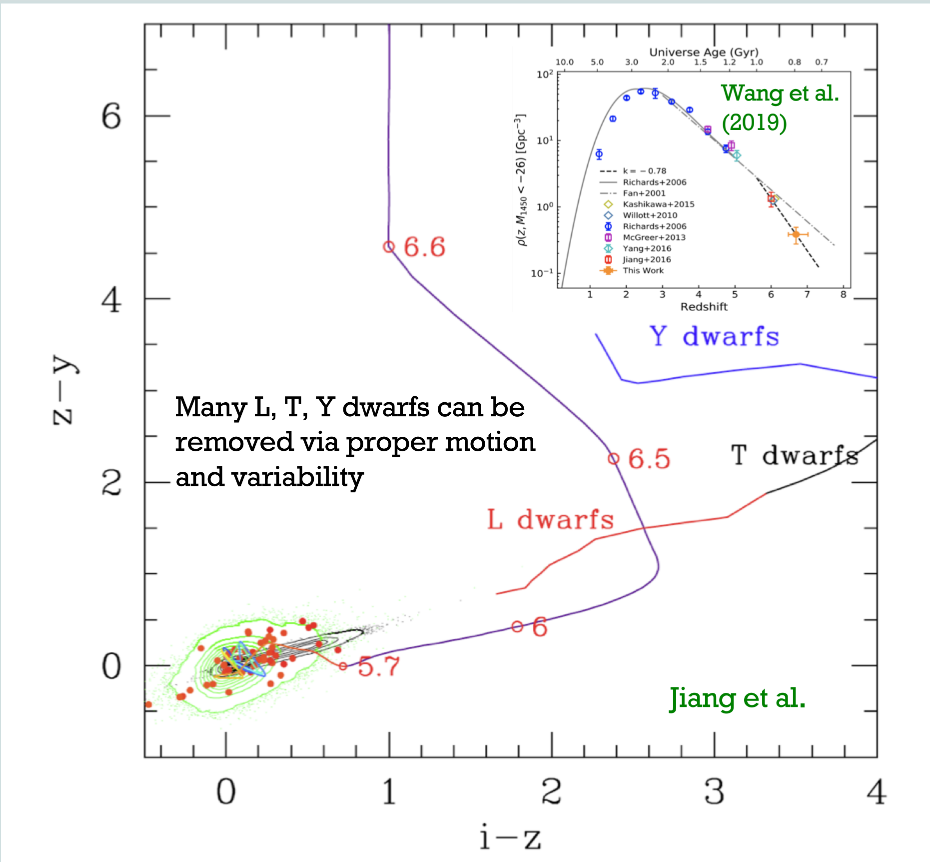
Measure rates as function of galaxy type and redshift.

Understand diversity of these events (L_{Bol}, kT, jet power)

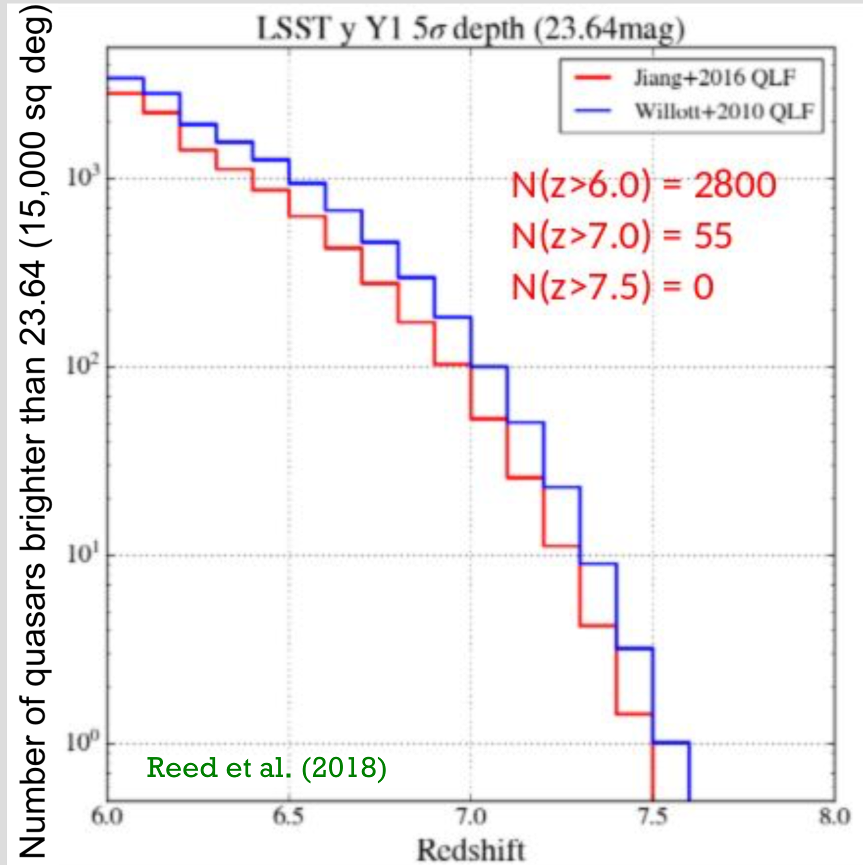
Find remarkable events - e.g., white-dwarf disruptions by IMBH, giant-planet disruptions, gas-cloud captures.

LSST High-Redshift AGN Selection

Colors of High-Redshift Quasars



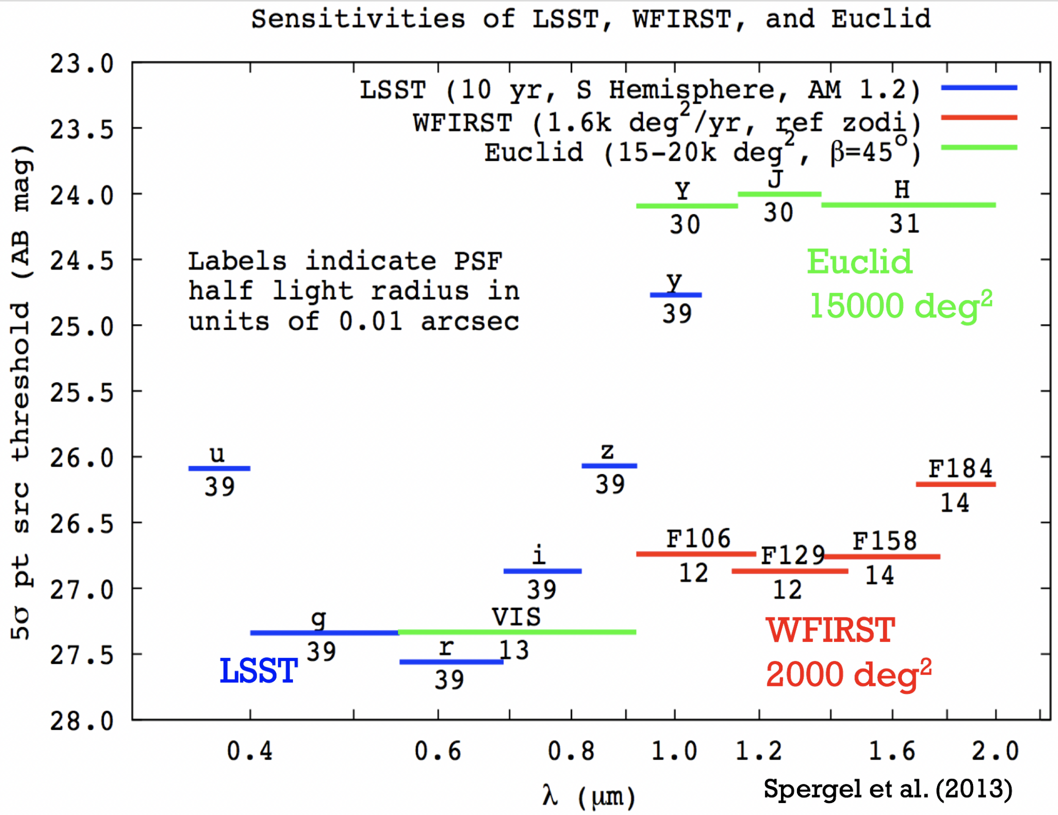
Expected Numbers of z > 6 Quasars



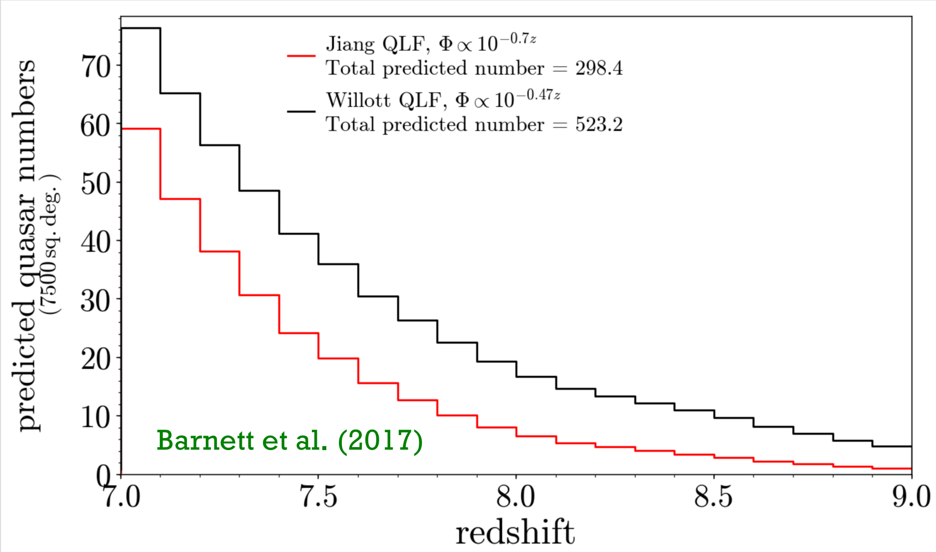
LSST alone will provide significant numbers of AGNs to $z \sim 7.5$ down to moderate luminosities ($L_{\rm Opt} \sim 10^{44}$ erg s^{-1}).

High-Redshift Quasars from LSST, Euclid, and WFIRST

These missions together will allow quasar discovery at $z \sim 7.5 - 9$



LSST + Euclid Selection - *zYJH*



LSST + WFIRST will discover fainter $z \sim 7.5 - 9$ quasars.

These will be great multiwavelength targets to investigate SED evolution.

LSST + X-ray Investigations of High-Redshift, Obscured AGNs

Combine Chandra and XMM-Newton source catalogs, especially for deeper observations, with LSST, Euclid, and WFIRST – also eROSITA.

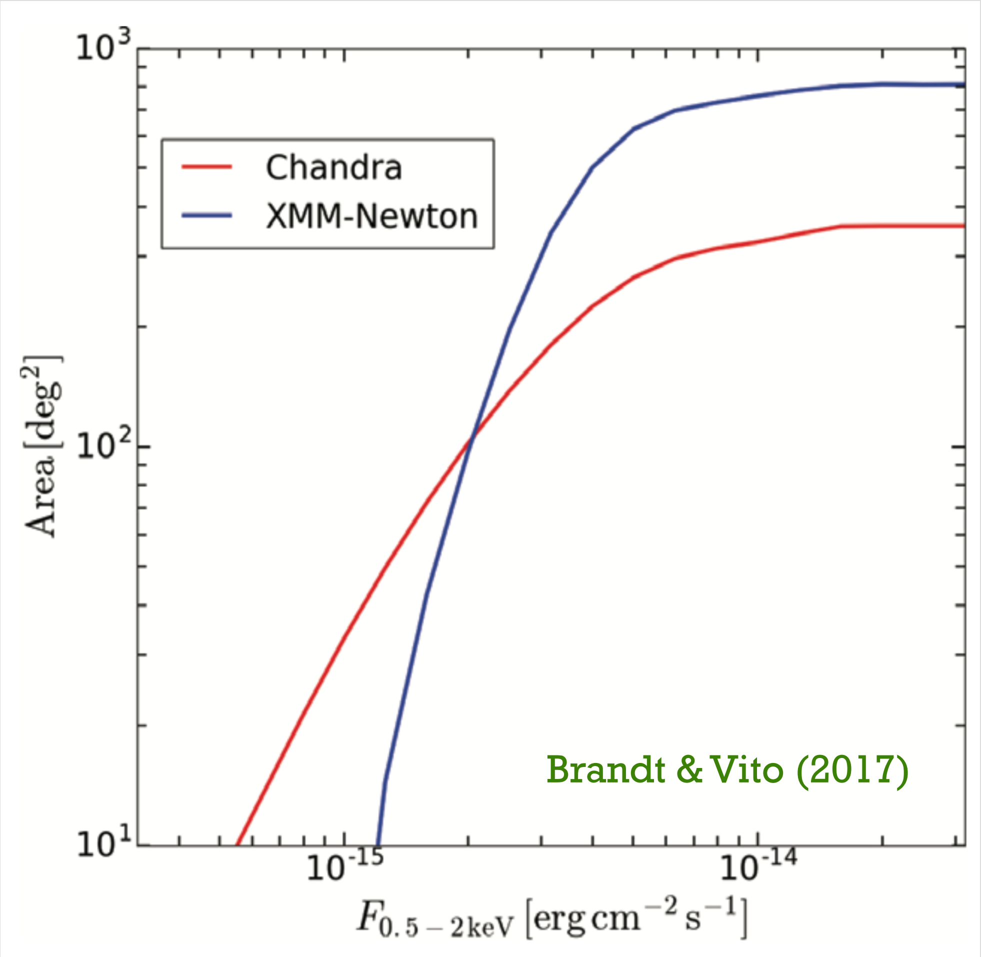
Can aim for an effective $z \sim 4$ - 8 AGN survey, *including obscured AGNs*, over ~ 1100 deg^2.

Identify X-ray sources with optical / NIR colors indicating high redshifts.

Only new cost is follow-up spectroscopy, which could use DESI, SDSS-V, 4MOST, and PFS.

Measure XLF bright end and f_{obsc} with
500-1100 sources at $z = 4$ - 6 and
10-100 sources at $z = 6$ - 8.

Solid Angle vs. Depth for a 25 yr Chandra + XMM-Newton Survey



The LSST AGN Science Collaboration

agn.science.lsst.org

lsst-agn@lists.lsst.org

The AGN Science Collaboration (SC)

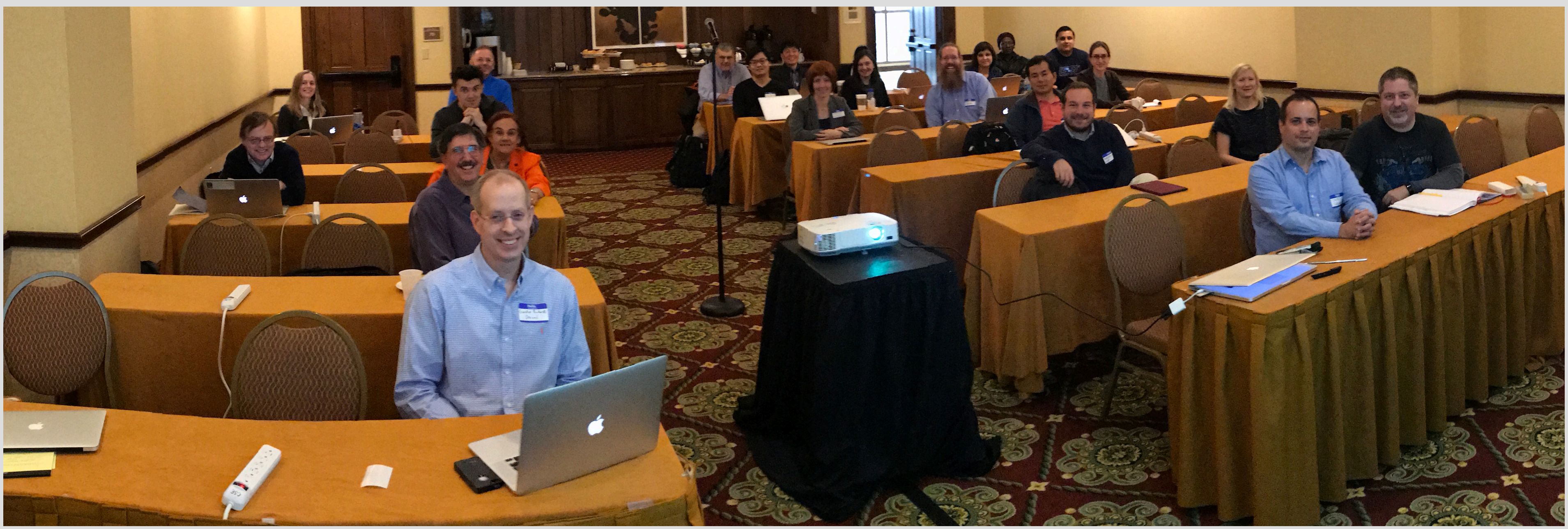
Currently has 57 members:

Country	Number of Members
USA	37
Chile	7
United Kingdom	6
Italy	3
Poland	2
Germany	1
Serbia	1
Australia	1
Canada	1

New members have been welcome from the LSST consortium.

There are some recent challenges owing to the revised LSST funding model and data policy - details still being determined.

2017 January - Grapevine, Texas




WE
CATER
FOR


COPPELL
FARMERS MARKET

UK AGNs and Galaxies Folks

2017 September - Cambridge, UK

Some Chilean AGN Folks

2017 December - Santiago, Chile

Overall Organization and Roadmap

Presently working as a loose confederation, but *hope* to become a hard-core collaboration as LSST construction proceeds. Re-organization underway.

A <u>huge</u> amount of work is needed including on basic AGN selection, analysis of LSST simulations, detailed science planning, and pooling of observational resources.

LSST
AGN Science Collaboration
Roadmap

Prepared by the LSST AGN Science Collaboration,
with support from the LSST Corporation

Version 1.0
January 24, 2018

Contents

AGN Science Collaboration

agn.science.lsst.org

Two Successful Approaches to Date

The lack of USA LSST science funding has posed challenges for LSST AGN science preparation - "creativity" needed!

One basic approach has been to <u>bootstrap</u> our way along:

Deep Fields and Stripe 82 - Pan-STARRS - DES - HSC – LSST

Another approach has been gathering <u>multiwavelength data</u>; e.g., with Spitzer and XMM-Newton.

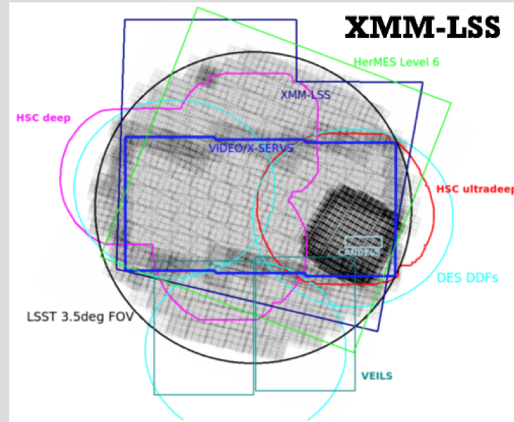
Spitzer DEEPDRILL Survey of LSST DDFs

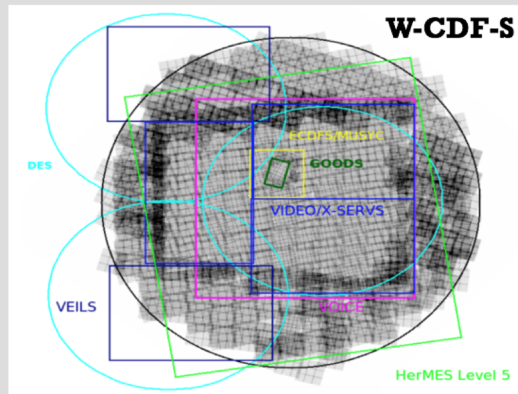
Spitzer Space Telescope General Observer Proposal #11086.

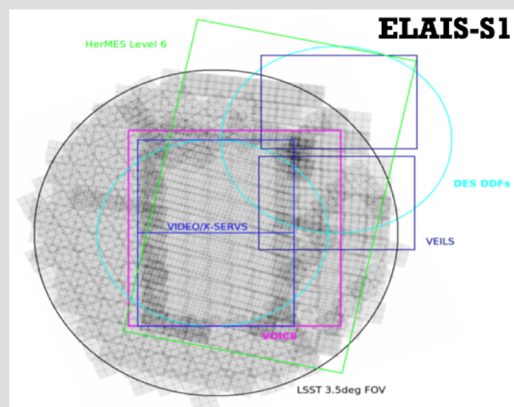
A warm Spitzer survey of the LSST/DES "Deep drilling" fields

Principal Investigator: Mark Lacy
Institution: National Radio Astronomy Observatory (NRAO)
Electronic mail: mlacy@nrao.edu
Technical Contact: Mark Lacy, National Radio Astronomy Observatory (NRAO)
Co–Investigators: Duncan Farrah, Virginia Tech
Niel Brandt, Penn State
Masao Sako, U Penn
Gordon Richards, Drexel
Ray Norris, CSIRO/Macquarie University
Susan Ridgway, NOAO
Jose Afonso, Lisbon
Robert Brunner, Illinois
Dave Clements, Imperial College
et al.

Abstract:
We propose a warm Spitzer survey to microJy depth of the four predefined Deep Drilling Fields (DDFs) for the Large Synoptic Survey Telescope (LSST) (three of which are also deep drilling fields for the Dark Energy Survey (DES)). Imaging these fields with warm Spitzer is a key component of the overall success of these projects, that address the "Physics of the Universe" theme of the Astro2010 decadal survey. With deep, accurate, near–infrared photometry from Spitzer in the DDFs, we will generate photometric redshift distributions to apply to the surveys as a whole. The DDFs are also the areas where the supernova searches of DES and LSST are concentrated, and deep Spitzer data is essential to obtain photometric redshifts, stellar masses and constraints on ages and metallicities for the >10000 supernova host galaxies these surveys will find. This "DEEPDRILL" survey will also address the "Cosmic Dawn" goal of Astro2010 through being deep enough to find all the >10^11 solar mass galaxies within the survey area out to z~6. DEEPDRILL will complete the final 24.4 square degrees of imaging in the DDFs, which, when added to the 14 square degrees already imaged to this depth, will map a volume of 1–Gpc^3 at z>2. It will find ~100 > 10^11 solar mass galaxies at z~5 and ~40 protoclusters at z>2, providing targets for JWST that can be found in no other way. The Spitzer data, in conjunction with the multiwavelength surveys in these fields, ranging from X–ray through far–infrared and cm–radio, will comprise a unique legacy dataset for studies of galaxy evolution.

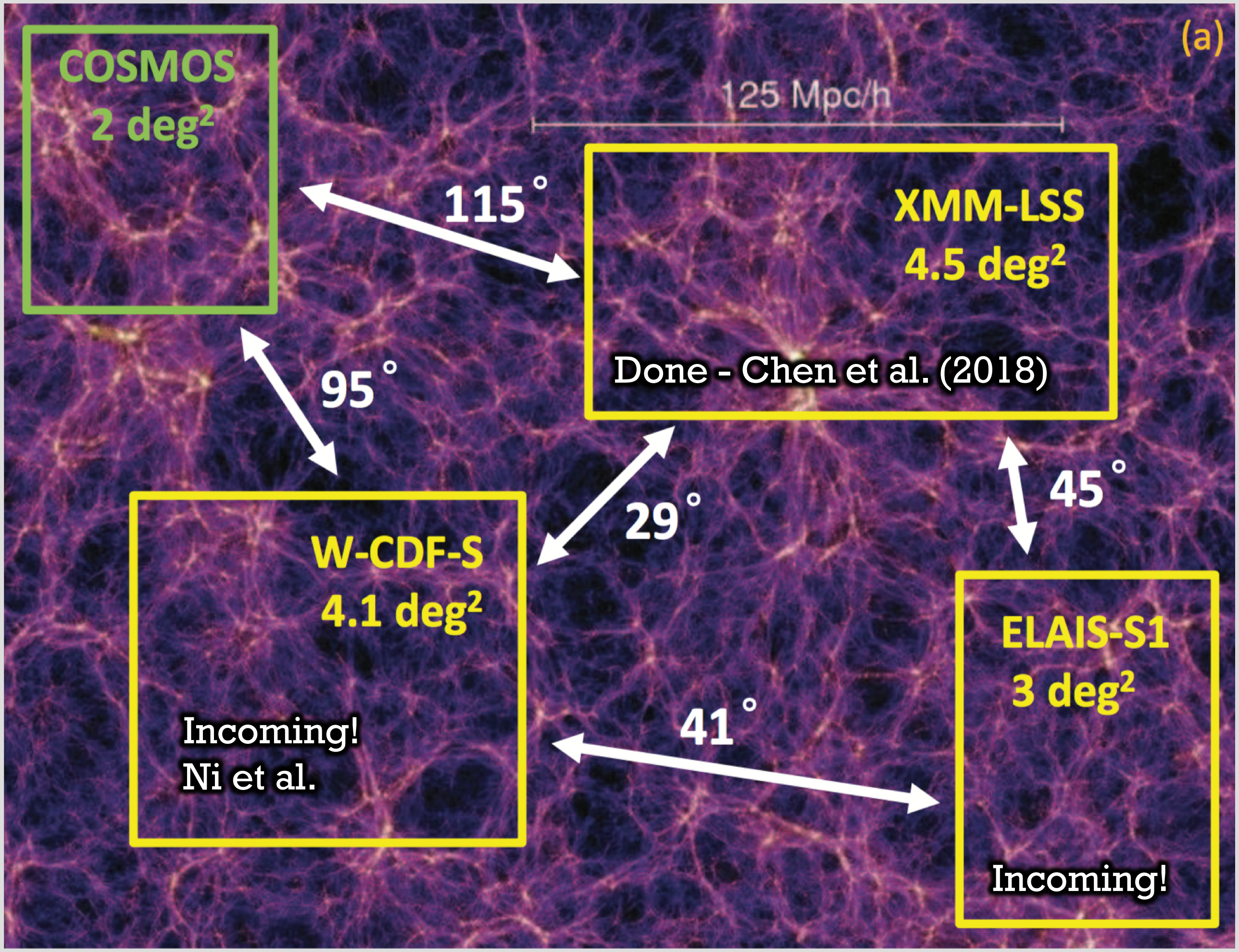






Spitzer coverage is gray shading.

XMM-SERVS: XMM-Newton Coverage of LSST DDFs



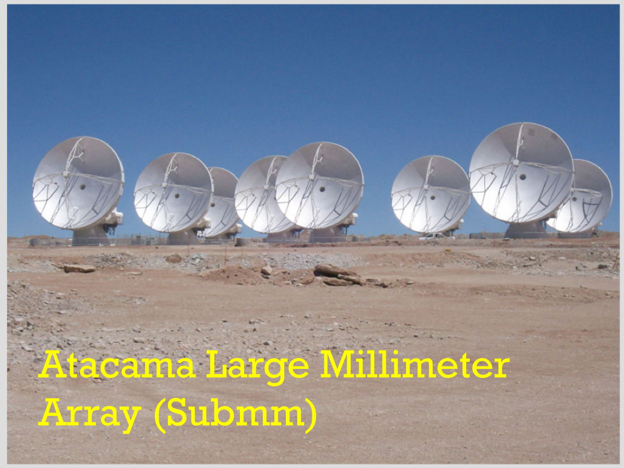
5 Ms Multi-Year Heritage Program

At 50 ks XMM-Newton depth, expect 12,000 AGNs and 760 X-ray groups/clusters.

SMBH growth across the full range of cosmic environments and SMBH/galaxy connections.

Incredible legacy value as LSST/DES Deep-Drilling Fields, MOONS/PFS fields, ALMA fields.

More Multiwavelength & Spectroscopic Data Coming for LSST DDFs!



LMT

TolTEC

ASU Cardiff INAOE Michigan NIST Northwestern UMass Wisconsin

SuMIRe

Prime Focus Spectrograph

4MOST

WAVES

wide area vista extragalactic survey


The End

Extra Slides

Plausible AGN Yields

Variability Selected Quasar Predictions from Palanque-Delabrouille et al. (2013)

Table 8. Predicted number of quasars over $15.5 < g < 25$ and $0 < z < 6$ for a survey covering 10 000 deg^2, based on our best-fit luminosity function.

g/z	0.5	1.5	2.5	3.5	4.5	5.5	Total
15.75	76	15	0	0	0	0	92
16.25	174	55	11	0	0	0	239
16.75	402	172	61	0	0	0	635
17.25	939	535	180	6	0	0	1661
17.75	2163	1630	508	21	1	0	4323
18.25	4740	4720	1409	57	2	0	10 928
18.75	9456	12 380	3784	156	5	0	25 781
19.25	16 612	27 796	9409	422	14	0	54 255
19.75	25 537	51 561	20 579	1128	39	1	98 846
20.25	35 185	80 209	38 096	2923	107	4	156 523
20.75	45 008	110 341	59 939	7085	289	10	222 671
21.25	54 980	141 918	82 650	15 386	779	27	295 740
21.75	64 988	176 959	103 733	28 916	2036	74	376 706
22.25	74 189	217 815	122 861	46 636	5064	201	466 766
22.75	80 370	266 716	141 310	65 652	11 408	545	566 001
23.25	79 024	325 945	160 621	82 972	22 419	1436	672 417
23.75	61 347	398 006	182 048	97 320	37 756	3632	780 110
24.25	15 976	480 676	206 510	109 295	55 090	8401	875 949
24.75	0	492 283	234 874	120 118	71 481	17 111	935 866
Total	571 169	2 789 734	1 368 583	578 092	206 489	31 444	5 545 510

Notes. Bins are centered on the indicated magnitude and redshift values. The ranges in each bin are $\Delta g = 0.5$ and $\Delta z = 1$.

where we call "quasar" an object with a luminosity $M_i[z = 2] < -20.5$ and either displaying at least one emission line with FWHM greater than 500 km s^{-1} or, if not, having interesting/complex absorption features.

AGN Inputs into LSST Cadence

Science-Driven Optimization of the LSST Observing Strategy

Prepared by the LSST Science Collaborations, with support from the LSST Project.

Version 1.0

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8 Active Galactic Nuclei

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Summary

To zeroth order, AGN science with LSST will benefit from the longest temporal baseline (to aid both selection and variability studies), the most uniform cadence in terms of even sampling for each band, and uniform sky coverage while maximizing the area, but excluding the Galactic plane. It is also expected that any reasonable perturbation to the nominal LSST observing strategy will not have a major effect on AGN science. While denser sampling at shorter wavelengths will aid investigations of the size and structure of the AGN central engine via intrinsic continuum variability and microlensing, care must be taken not to compromise the coadded Y-band depth which is crucial for detecting the distant-most quasars. Assuming two visits per night, two different bands are preferred. Science cases related to intrinsic continuum and broad-emission line variability will benefit from the denser sampling offered in the DDFs. These fields will provide powerful "truth tables" that are crucial for AGN selection algorithms, enable construction of high-quality power spectral density functions, and enable measurements of continuum-continuum and line-continuum time lags. The benefits and tradeoffs with respect to the main survey involve high-quality light curves but for only a small fraction ($\sim 1\%$) of all sources, preferentially those at lower luminosities. Certain science cases will benefit greatly from even denser sampling, i.e., $\sim 1-1000\ \mathrm{d}^{-1}$, of a smaller area, perhaps during the commissioning phase, as long as the temporal baseline will extend over the ten years of the project. Another justification to this strategy is the fact that very few AGNs, or transient AGNs, have been monitored at these frequencies on such a long baseline, leaving room for discovery.

8.1 Introduction

The purpose of this chapter is to identify AGN science cases that may be affected by the LSST observing strategy and to specify the metrics that can be used to quantify any potential effects. Since the total number of metrics that can be quantified is quite large, and the potential effects are not likely to be significant in most cases, the goal of this chapter is to identify potential "show stoppers" that may undermine key AGN research areas. For example, certain perturbations may reduce significantly the number of "interesting" AGNs, such as $z > 6$ quasars, lensed quasars, or transient AGNs. Another example is photometric reverberation mapping which is one of LSST's

W-CDF-S HSC Images & Catalog

Deep Hyper Suprime-Cam Images and a Forced Photometry Catalog in W-CDF-S

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ABSTRACT

The Wide Chandra Deep Field-South (W-CDF-S) field is one of the SERVS fields with extensive multiwavelength datasets, which can provide insights into the nature and properties of objects in this field. However, the public optical data from DES (*grizy* to $m_{\rm AB} \approx 21.4 - 24.3$) are not sufficiently deep to match well the NIR data from VIDEO ($ZYJHK_s$ to $m_{\rm AB} \approx 23.5 - 25.7$), which limits the investigation of fainter objects at higher redshifts. Here, we present an optical catalog of $\approx$ 2,000,000 objects in W-CDF-S utilizing archival Hyper Suprime-Cam observations in the g,r,i,z bands covering ≈ 5.7 deg^2. The estimated depth is ≈ 25.9 for g-band, 25.6 for r-band, 25.8 for i-band, and 25.2 for z-band, which is deep enough to complement the NIR data, and will benefit AGN/galaxy studies in W-CDF-S in the future.