Student intro training

Python for data processing of AGN variability within LSST

Virtual Event on
March 26, 2022

ZOOM ETIQUETTE

zoom

BE ON TIME
Set your alarm!
Log on a few minutes early.

LIMIT DISTRACTIONS
Find a quiet place.
Check your surroundings.

BE PREPARED
Charge your computer, use headphones, turn on camera.

PRESENTATION
Wear appropriate clothes, sit up straight, camera at eye level.

MUTE YOURSELF
Mute yourself when you are not speaking.

PARTICIPATE!
Don't multitask, stay focused, take notes, contribute!

CHAT RESPONSIBLY
Use chat to ask questions.
Watch out for gossip! It may be recorded!

SPEAK CLEARLY
Speak into your mic, slow down, take breaks to check in with others.

SHOW RESPECT
Practice good netiquette.
Listen, be respectful, be considerate.

Adapted in Canva by @RLCooney. Inspired by others. 2020

Thank you all for joining!

80 registered participants!

from 18 different institutions from Ethiopia, Serbia, Bosnia & Herzegovina

+ lecturers

from USA, Germany, Chile, Serbia

We are grateful to:

LSST Corporation

for the support of our project

Ethiopian Space Science and Technology Institute

for helping in organization

Program

I session, 9:00 Belgrade (11:00 Addis Ababa)

- General introduction: LSST and AGN variability - **60min (10min Q&A)**
  by *Dragana Ilic, Andjelka Kovacevic, Paula Sánchez Sáez*

  5min break
- Tutorial 1: intro to Jupyter notebooks - *Viktor Radovic* - **30min (5min Q&A)**
- Tutorial 2: presentation of PhotoRM notebook - *Isidora Jankov* - **30min (5min Q&A)**

II session, 13:15 Belgrade (15:15 Addis Ababa)

- Presentation of Astro DataLab - *Robert Nikutta* - **30min**
- Tutorial 3: time domain notebook from Astro DataLab - *Robert Nikutta* - **45min**

  5min break
- Presentation of TVS science collaboration - *Rachel Street* - **15min**
- Presentation of AGN science collaboration - *Matthew Temple* - **15min**
- Presentation of Ethiopian Space Science and Technology Institute - *Seblu Humne* **- 15min**

Q&A session

Next 1h is about….

Introduction of :

- **2021 LSST Enabling Science Call** ⟶ DLE Team
- Vera C. Rubin Observatory -**Legacy Survey of Space and Time (LSST)**
- Active Galactic Nuclei (AGN)
- AGN variability
- How to measure the dimension of a region surrounding SuperMassive Black Hole (reverberation mapping = RM)
- General Cross Correlation function (CCF) as a math tool for RM when signals are not mixed
- **Photo-reverberation mapping (PhotoRM) - when signals are mixed**

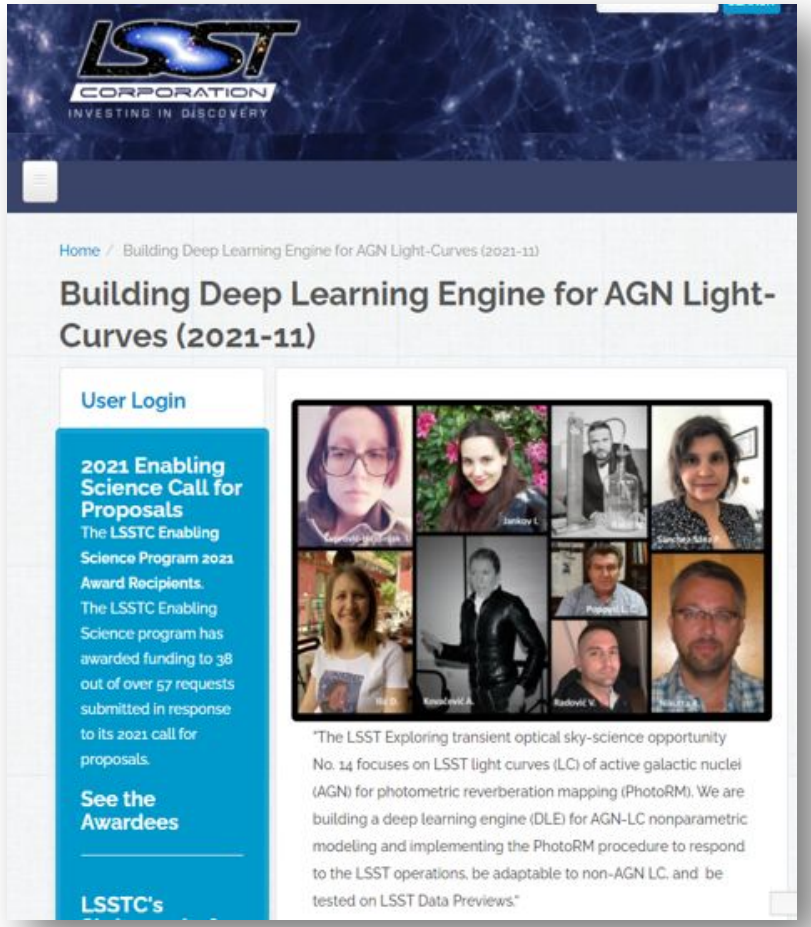
Who we are?

2021 Enabling Science Call project

”Building Deep Learning Engine (DLE) for AGN light-curves”

Visit us @ https://github.com/LSST-sersag/dle

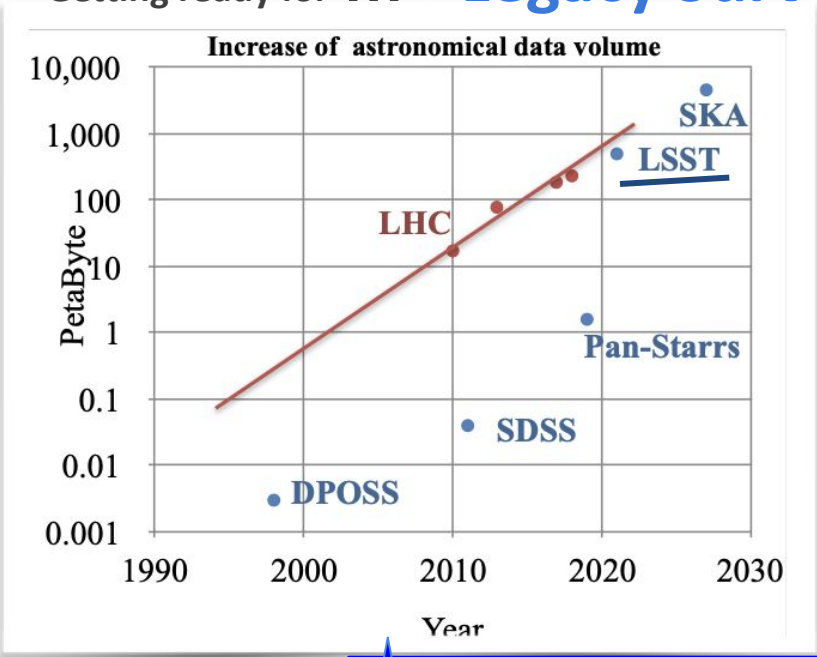
@https://www.lsstcorporation.org/node/265



- **PIs:** Andjelka Kovacevic (andjelka@math.rs), Dragana Ilic (dilic@math.rs), University of Belgrade
- **Co-Is:** Luka C. Popovic (Astronomical Observatory Belgrade, lpopovic@aob.rs), Paula Sánchez Sáez (Pontificia Universidad Católica de Chile, pasanchezsaez@gmail.com), Robert Nikutta (NOIRLab, robert.nikutta@noirlab.edu)
- **Postdocs:** Viktor Radović (rviktor@math.rs, University of Belgrade), Djordje Savić (djasvic@aob.rs, Astronomical Observatory Belgrade)
- **PhD students:** Iva Čvorović Hajdinjak (iva_cvorovic@gmail.com, University of Belgrade), Isidora Jankov (isidora_jankov@math.rs, University of Belgrade), Nemanja Rakić (rakinemanja@gmail.com, University of Belgrade)
- **Short-term internship students:** Nikola Andrić Mitrović (andricmitrovicnikola@yahoo.com, University of Belgrade)

Getting ready for ...

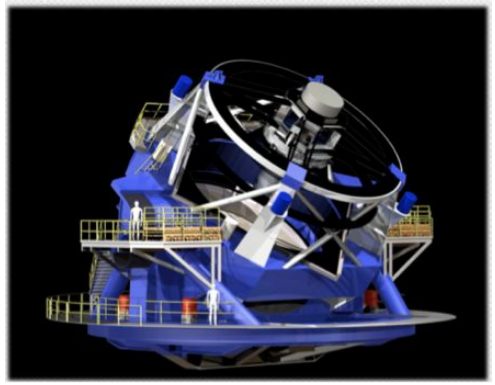
Legacy Survey of Space and Time



The telescope will produce the deepest, widest, image of the Universe:

- 8.4-m mirror, the width of a singles tennis court
- 3200 megapixel camera
- Each image the size of 40 full moons
- 37 billion stars and galaxies
- 10 year survey of the sky
- Up to 10 million alerts,
- 20 Terabytes of data .. every night!

$$LSST = \int \text{Observatory} + \text{Telescope} + \text{Camera} + \text{Data Management System} = \text{Fully Reduced Data}$$



LSST (images+catalogs) ⟫ **Scientific discoveries**

```
$ head -n 3 output/galaxy_catalog.dat
galtileid, objectId, raJ2000, decJ2000, redshift, u_ab, g_ab, r_ab, i_ab, z_ab,
222500350435, 222500350435, 199.56648010, -9.28911042, 0.87100780, 24.72078514,
222501392641, 222501392641, 199.57937323, -9.29996667, 0.70250392, 26.08153725,
```

telescope → **images** → **catalogues**

4 SCIENTIFIC-AVENUES OF LSST (IVEZIĆ+19, ApJ)

SPATIAL+TIME DIMENSION

- Dark energy and dark matter
  Weak lensing, WL
  Large-scale structure, LSS
  Time delays in lensed quasar and supernova (SN)
  Constraining the nature of dark energy

LOCAL SPATIAL DIMENSION

- Census of the Solar System, NEOs, MBAs, Comets, KBOs, Oort Cloud

TIME DIMENSION -variability+periodicity

- Transient optical skySupernova, GRBs, AGN
  Source characterization
  Instantaneous discovery

GALACTIC SPATIAL DIMENSION

- Mapping the Milky Way
  Galactic structure

VERA C. RUBIN OBSERVATORY

DATA MINING RESEARCH WITH LSST

Definitions of data mining:

1. *An information extraction activity whose goal is to discover previously hidden facts (patterns, relationships, links, correlations, trends) contained in large databases.*
2. *The transformation of knowledge from a data format representation into a rule format representation.*
3. *Knowledge Discovery in Databases (KDD).*

Data ➔ Information ➔ Knowledge ➔ Understanding / Wisdom!

Astronomers are trained as data miners because we:

- **Characterize the known (clustering)**
- **Assign the new (classification)**
- **Discover the unknown (outlier detection)**

The enormous LSST data archive and object database enables a diverse multidisciplinary research program:

- Astronomy & astrophysics
- Machine learning (data mining)
- Exploratory data analysis
- XLDB (extremely large databases)
- Scientific visualization
- Computational science & distributed computing
- Inquiry-based science education – using data in the classroom

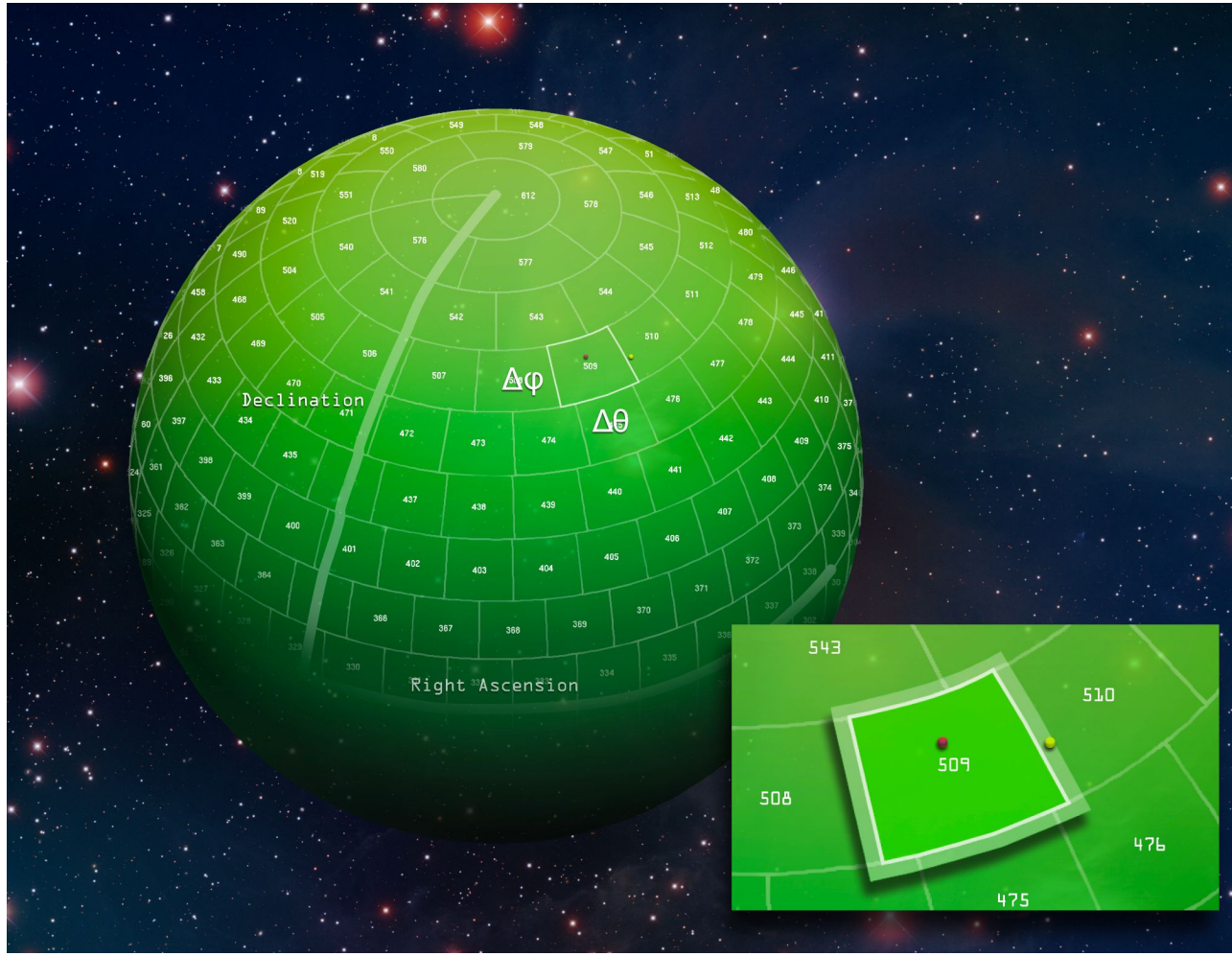
From presentation by Borne, Strauss and Tyson

LSST is…Big Data in practice

-

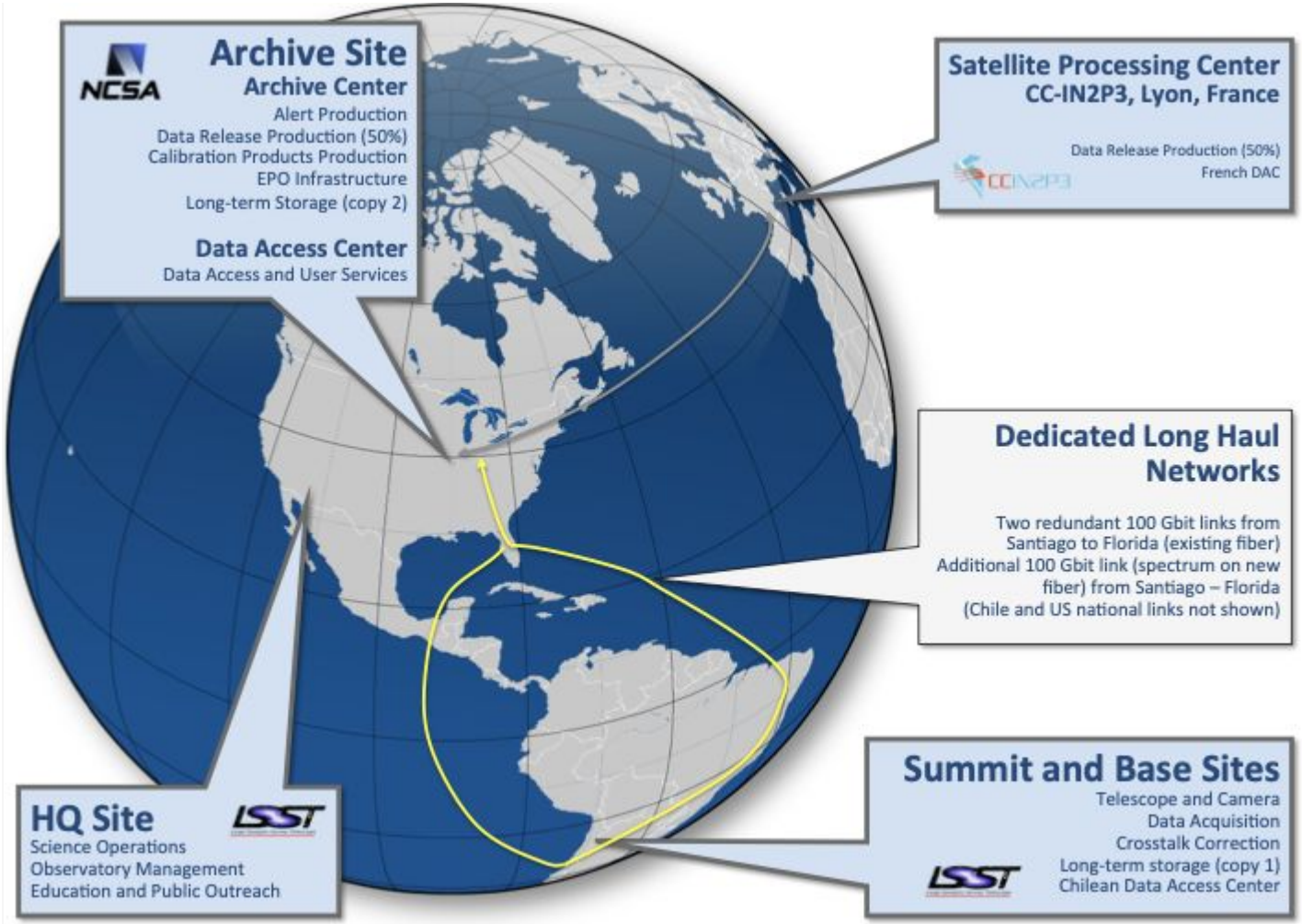
LSST Database Contents:

- A source catalog with 7 trillion rows
- An object catalog with 37 billion rows, each with 200+ attributes
- A moving object catalog with 6 million rows
- An alerts database, with alerts issued worldwide within 60 seconds, and
- Calibration, configuration, processing, and provenance metadata.

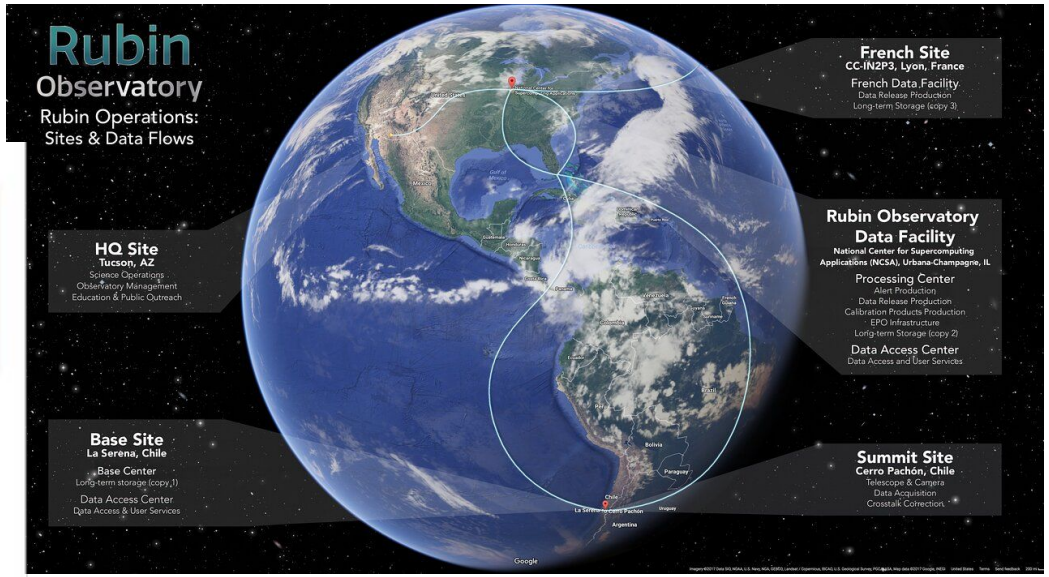


Innovative "data mining sphere" developed by Rubin Observatory database team

LSST OPERATIONS SITES AND DATA FLOW

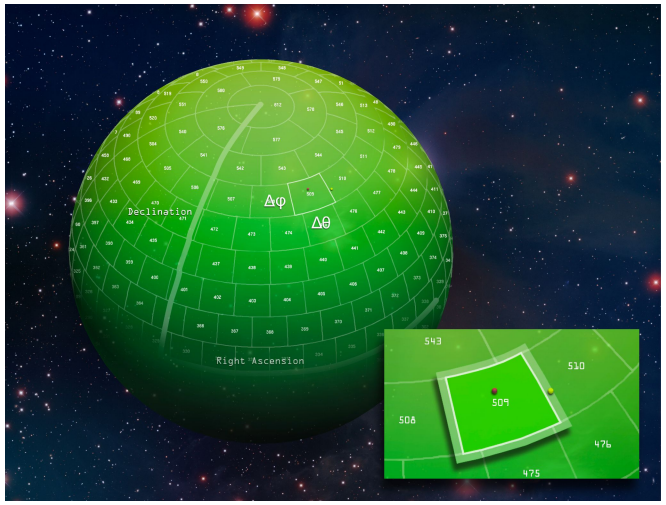


Jurić+15



Credit: Rubin Observatory/NSF/AURA

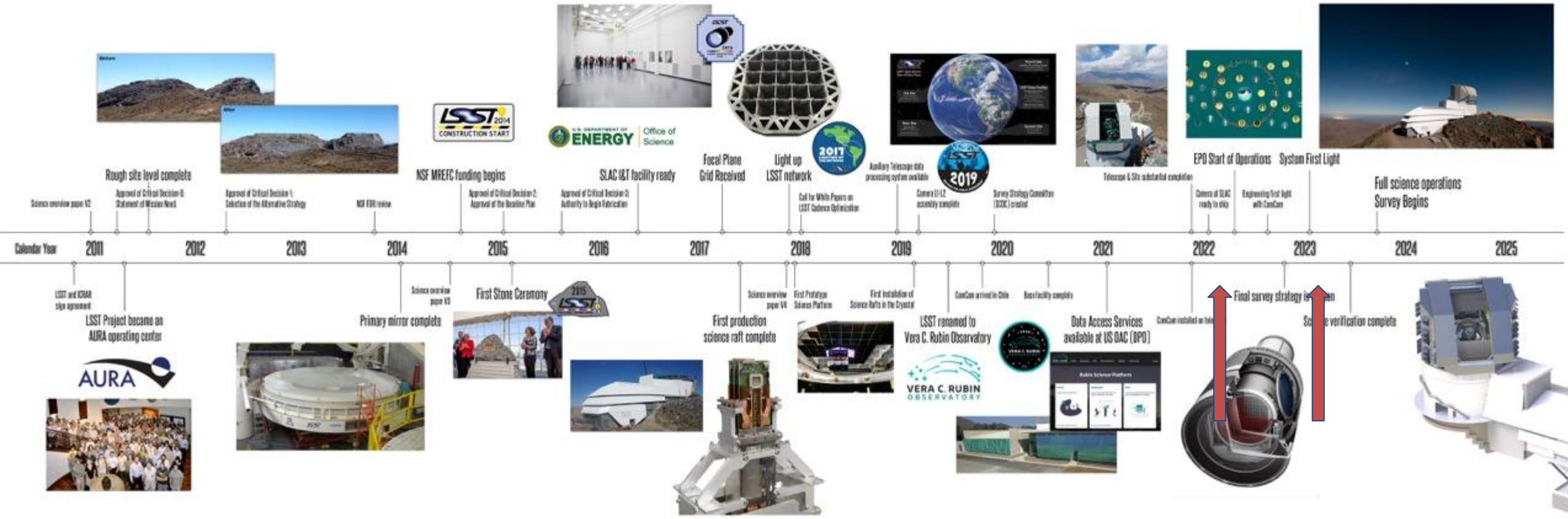
LSST needs the next generation (YOU) of big data astronomers (THINK BIG :))



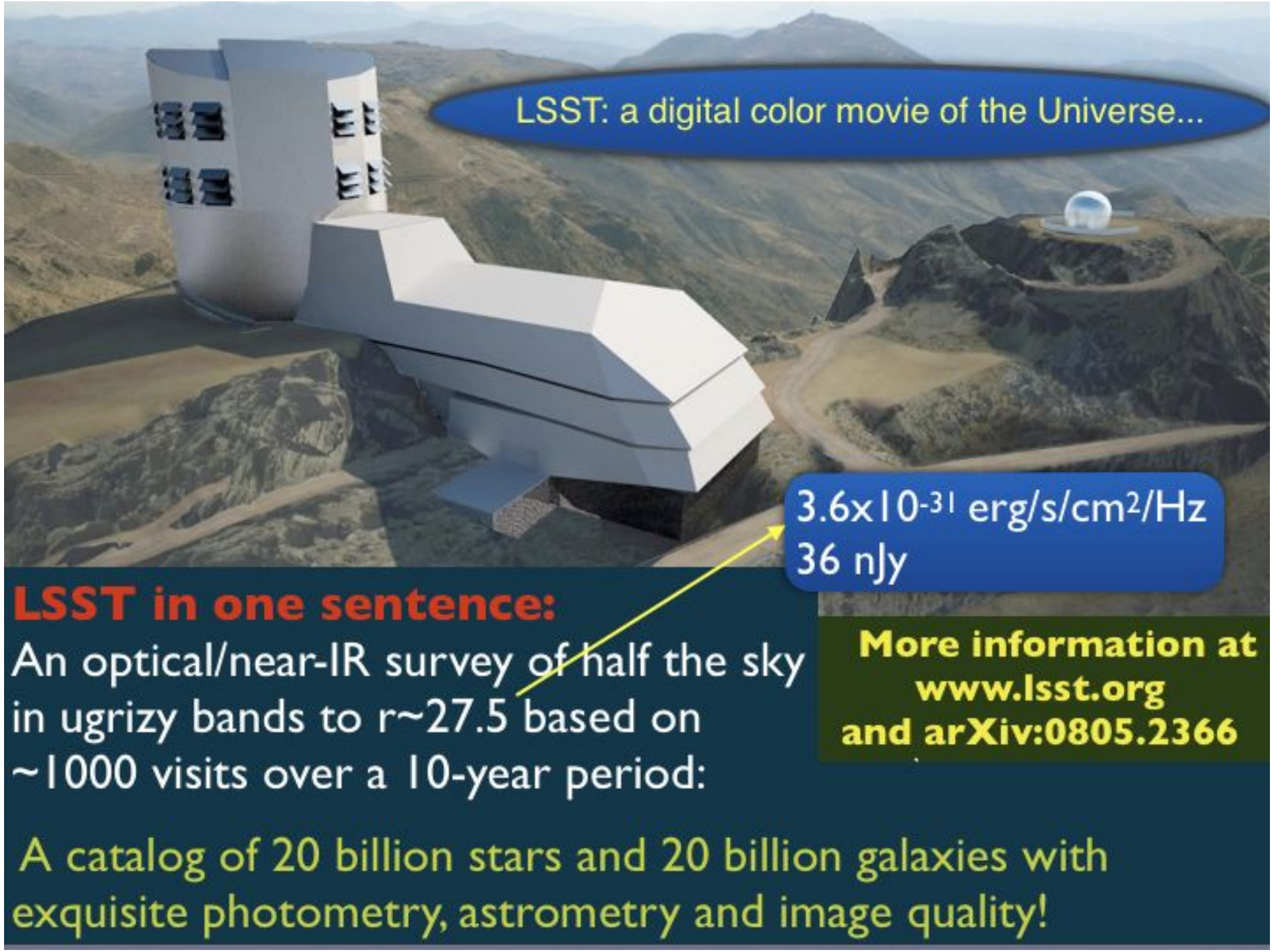
Kirk Borne: **Traditional data analysis is more about fitting a physical model to observed data.** When I was growing up, we didn't have sample sizes like this. We were trying to understand a particular phenomenon with our small sample sets. **Now, it's more unsupervised.** Instead of asking 'tell me about my model,' you ask 'tell me what you know.' **Data become the model, which means that more is different."**

Mario Juric, Associate Professor of Astronomy at the University of Washington, and the LSST Data Management System Science Team Coordinator. "**Students need to understand early on what it's like to do large-scale experiments, to design equipment and software, and to collaborate with very large teams. Astronomy today is entering the age of big data just like particle physics did 20 or 30 years ago.**

LSST is on the way! First light in 2023!



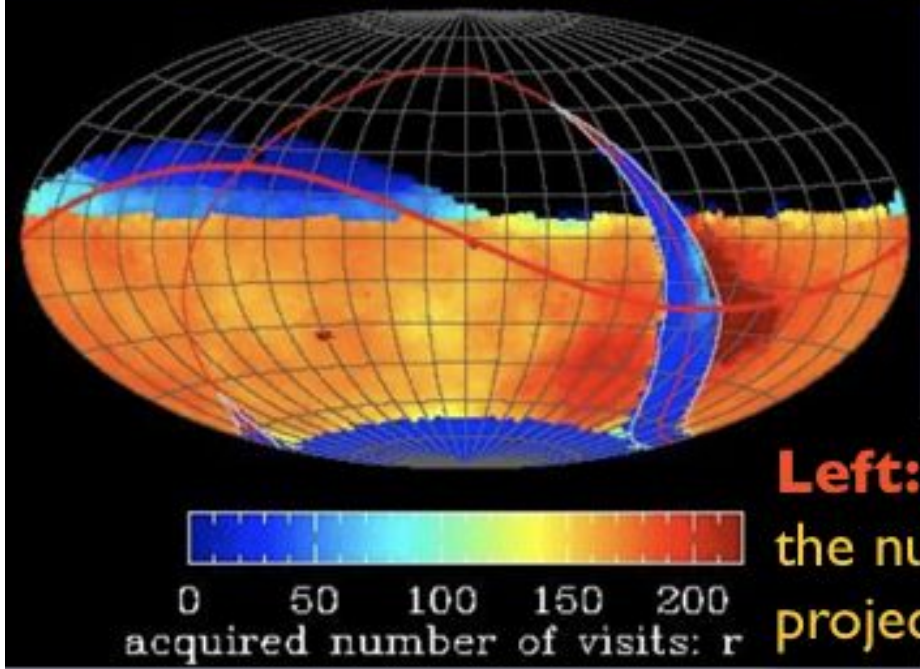
https://www.lsst.org/about/timeline



From Zeljko Ivezic slides
Rubin Observatory Director

Basic idea behind LSST: **a uniform sky survey**

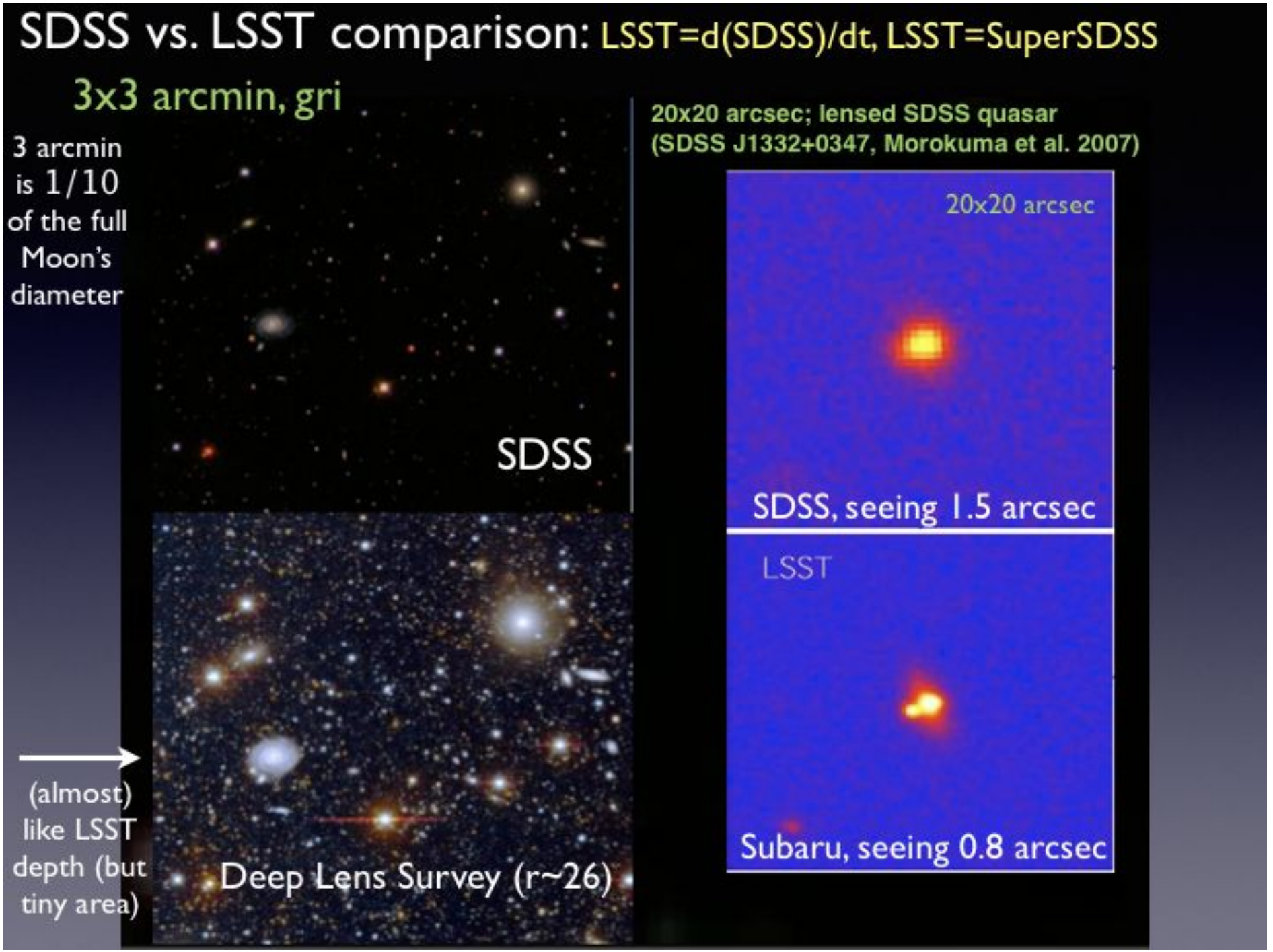
- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night
- after 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky
- ~100 PB of data: about a billion 16 Mpix images, enabling **measurements for 40 billion objects!**



LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

From Zeljko Ivezic slides
Rubin Observatory Director



SDSS =
Sloan Digital Sky Survey

2.5m optical telescope

From Zeljko Ivezic slides
Rubin Observatory Director

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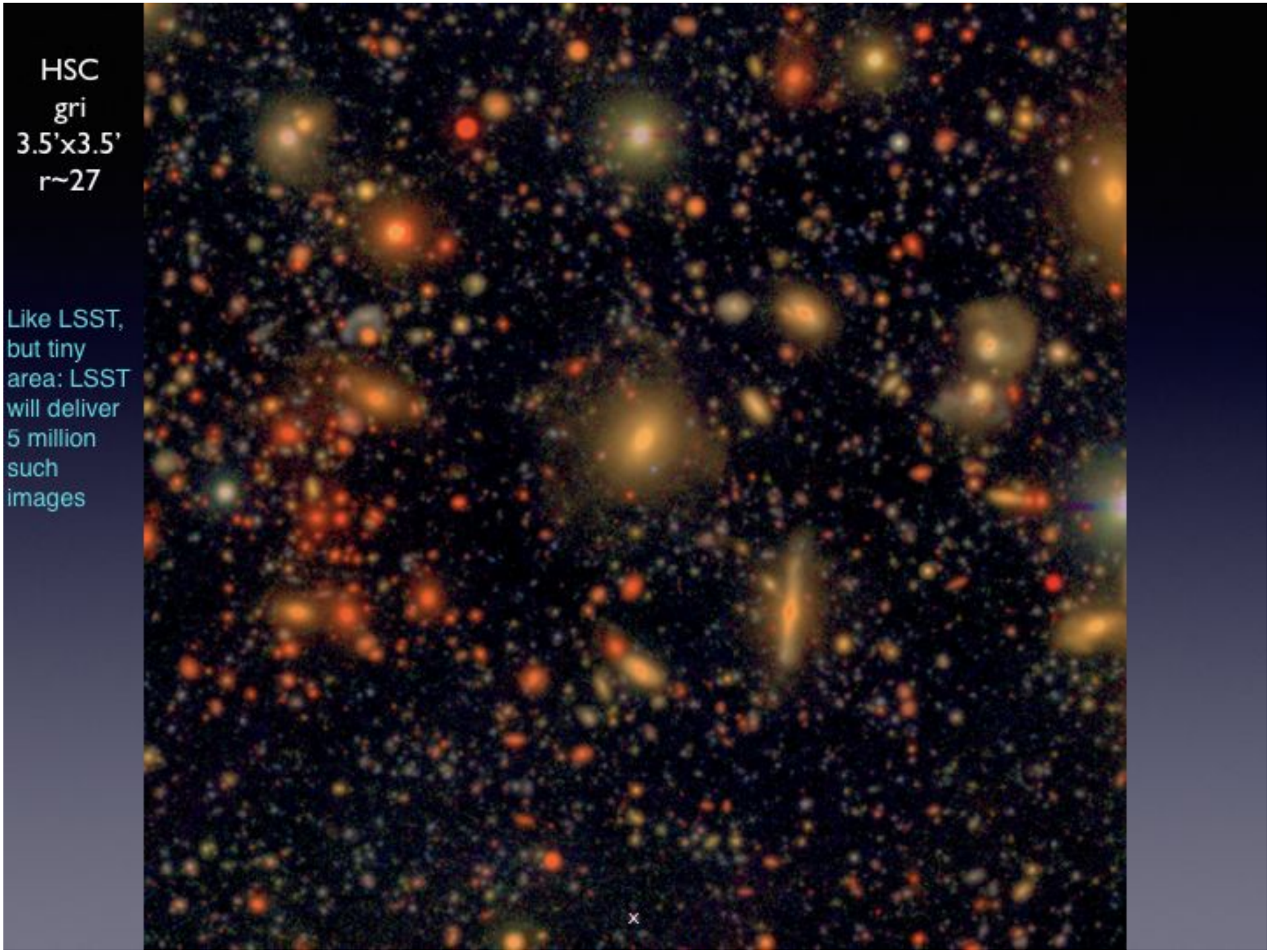
Rubin Observatory Director



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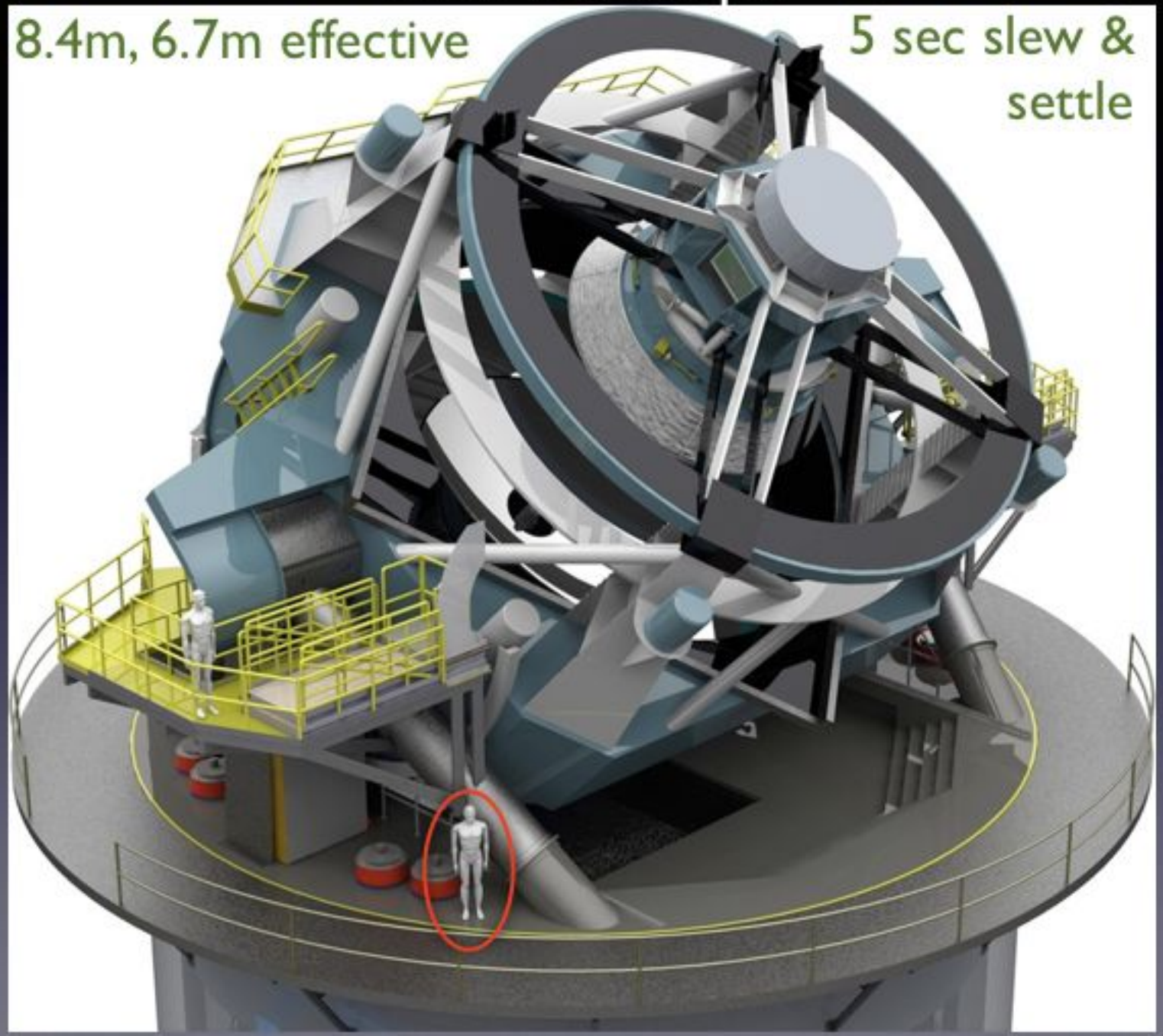
Rubin Observatory Director

LSST Telescope



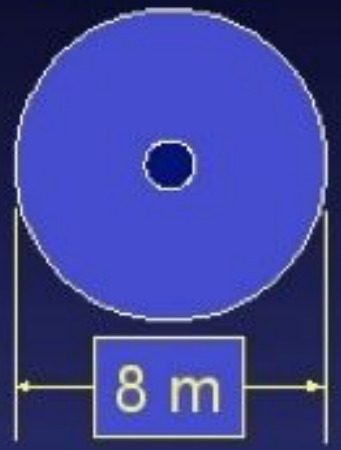
From Zeljko Ivezic slides
Rubin Observatory Director

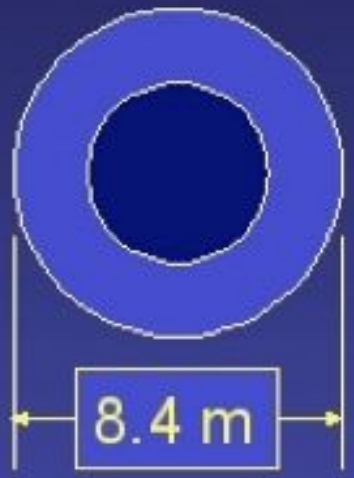
The field-of-view comparison: Gemini vs. LSST

Gemini South Telescope

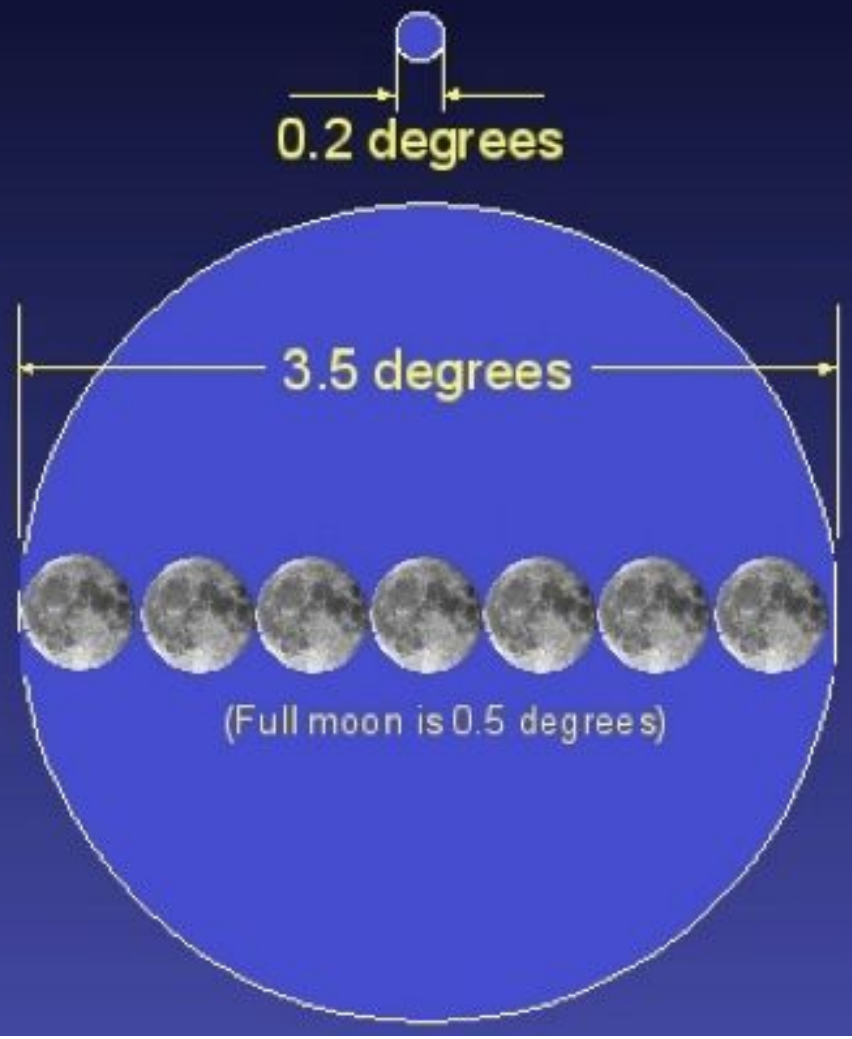
LSST

Primary Mirror Diameter



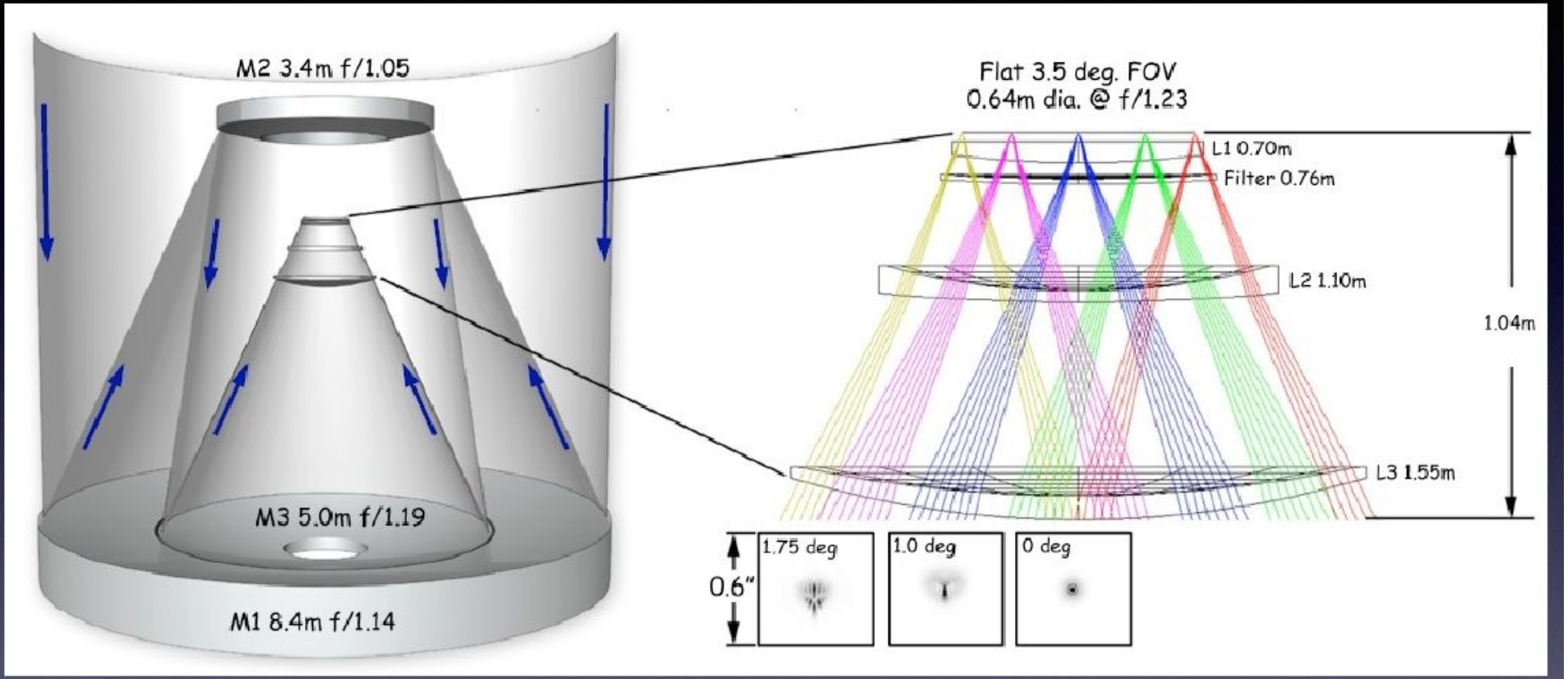


Field of View



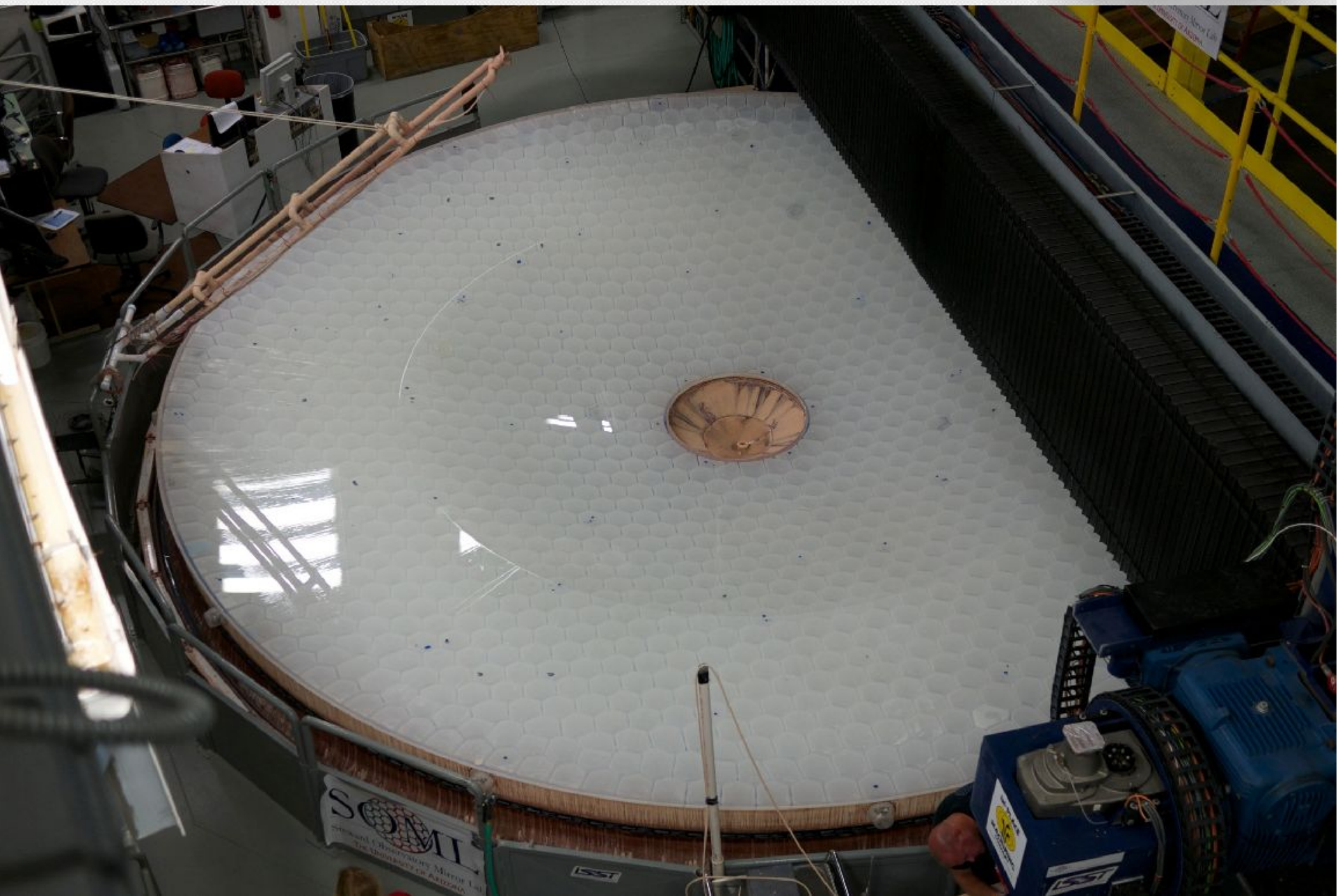
From Zeljko Ivezic slides
Rubin Observatory Director

Optical Design for LSST



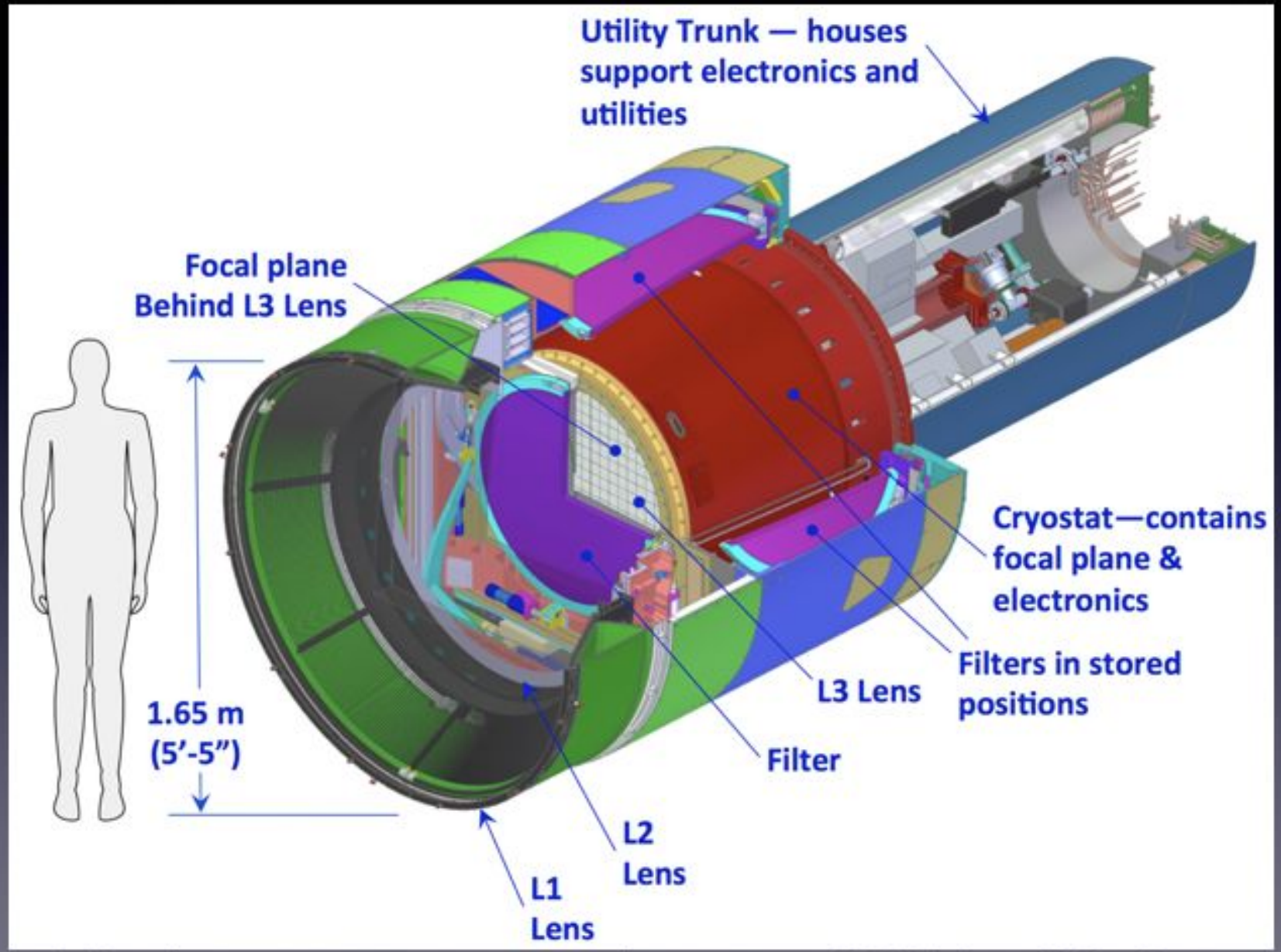
Three-mirror design (Paul-Baker system)
enables large field of view with excellent image quality:
delivered image quality is dominated by atmospheric seeing

From Zeljko Ivezic slides
Rubin Observatory Director



From Zeljko Ivezic slides
Rubin Observatory Director

LSST camera



The largest astronomical camera: 2800 kg, 3.2 Gpix

From Zeljko Ivezic slides
Rubin Observatory Director

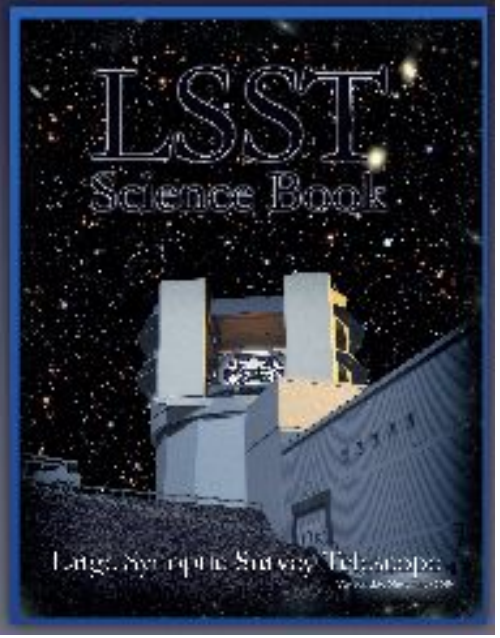
LSST Science Themes

- Dark matter, dark energy, cosmology (spatial distribution of galaxies, gravitational lensing, supernovae, quasars)
- Time domain (cosmic explosions, variable stars)
- The Solar System structure (asteroids)
- The Milky Way structure (stars)

LSST Science Book: arXiv:0912.0201

Summarizes LSST hardware, software, and observing plans, science enabled by LSST, and educational and outreach opportunities

245 authors, 15 chapters, 600 pages



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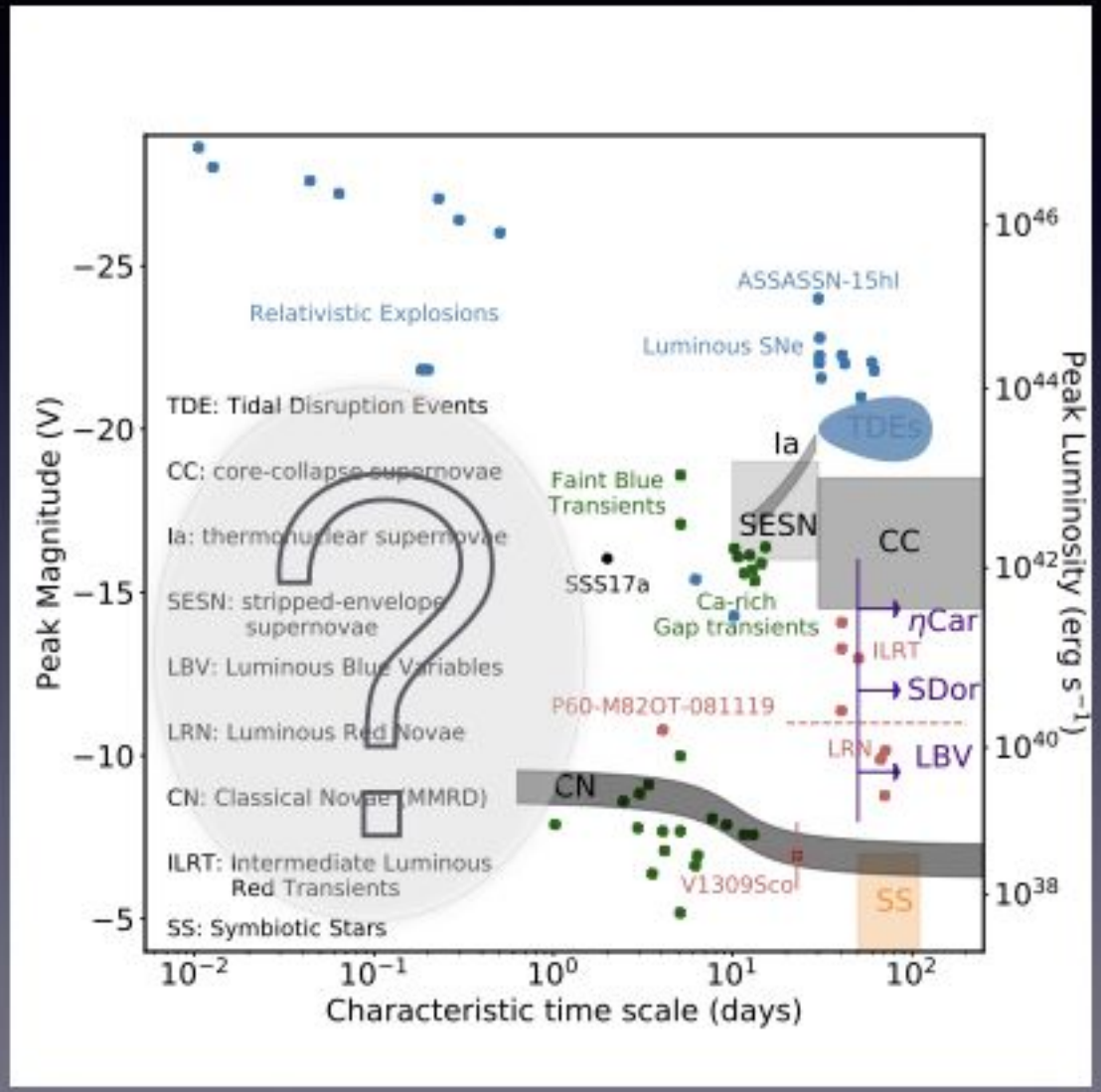
Time Domain: objects changing in time

positions: asteroids and stellar proper motions

brightness: cosmic explosions and variable stars



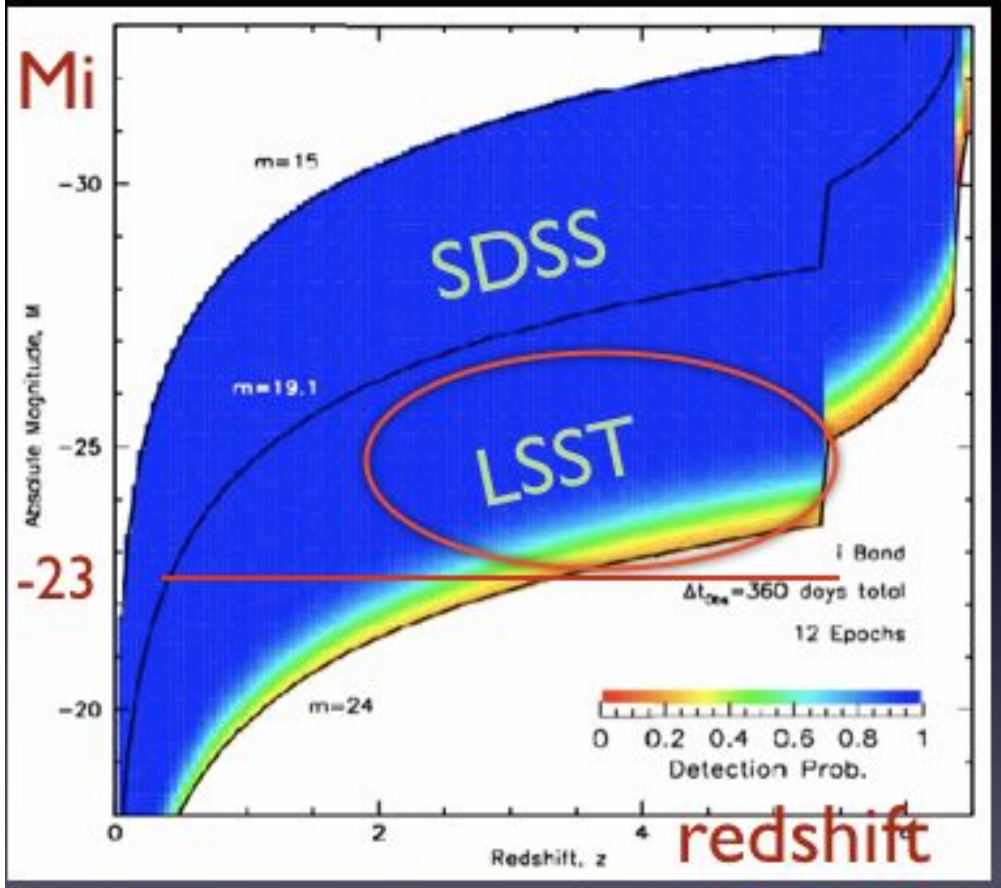
LSST will extend time-volume space a hundred times over current surveys (new classes of object?)

known unknowns

unknown unknowns

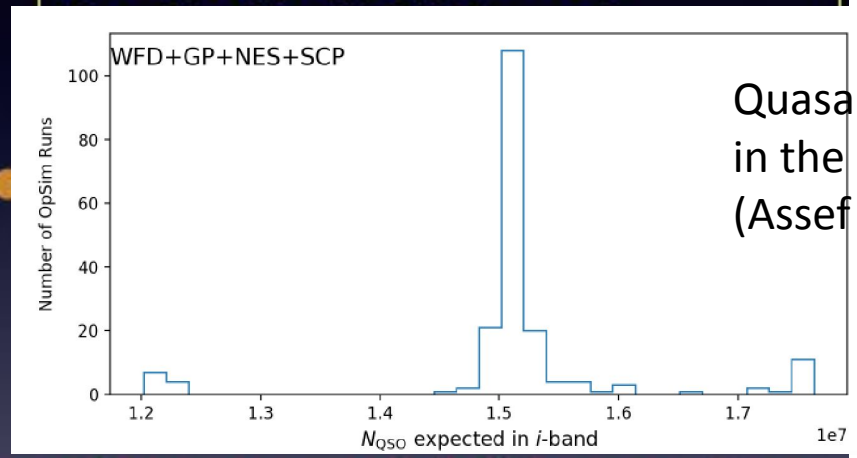
From Zeljko Ivezic slides
Rubin Observatory Director

Extragalactic astronomy: quasars



Top: absolute magnitude vs. redshift diagram for quasars

- About 10 million quasars will be discovered using variability, colors, and the lack of proper motions



Quasar Counts in 10-years in the main + mini surveys (Assef et al. 2021)

- Quasar variability studies will be based on millions of light curves with 1000 observations over 10 yrs

Today: ~31 quasars with 6<z<7.5

Reionization studies!

LSST will detect ~10,000 quasars with 6<z<7.5!

From Zeljko Ivezic slides
Rubin Observatory Director

Summary

- Rapid tour of LSST
  - multi-color time-resolved **faint** sky map
  - 20 billion stars and 20 billion galaxies

There is **a lot of work to be done** to turn LSST Data Release data products into papers!

- Data analysis challenges ahead of us
  - large data sets
  - complex analysis
  - aiming for small systematics

Time-domain data enables and motivates new methods:

- better sample of periodic variables by combining bands
- seeing invisible by combining data and theory
- sample selection competitive with spectroscopy

From Zeljko Ivezic slides
Rubin Observatory Director

LSST: how to get involved

- https://www.lsst.org/participate
- Attend Project&Community Workshop (PCW)
- Join different science collaboration, e.g. AGN, TVS

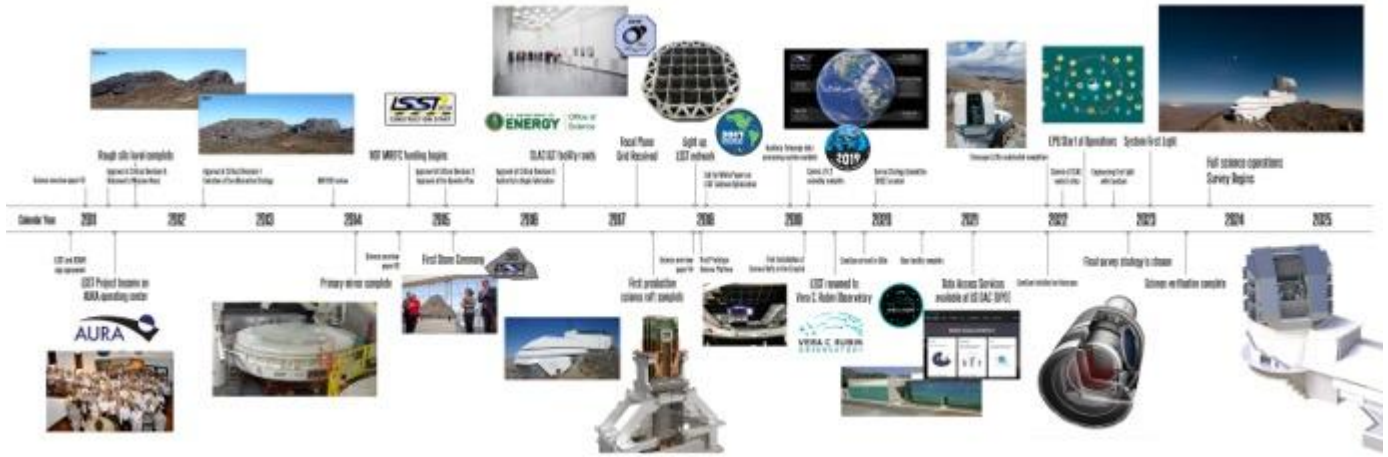
- Follow activities of LSST Corporation
  - e.g. Enabling science call for proposals
- Participate in Data Challenges
  - E.g. AGN Data Challenge in summer 2021
    https://github.com/RichardsGroup/AGN_DataChallenge

LSST Science Collaborations

- Dark Energy Science Collaboration
- Transients and Variable Stars Science Collaboration
- Strong Lensing Science Collaboration
- Active Galactic Nuclei Science Collaboration
- Galaxies Science Collaboration
- Stars, Milky Way, and Local Volume Science Collaboration
- Solar System Science Collaboration
- Informatics and Statistics Science Collaboration

Summary

- **LSST, will be the largest 10-year long movie of the sky!**
  Operation starts April 2023



- 500 petabyte set of images and data products
- Time domain astronomy is coming

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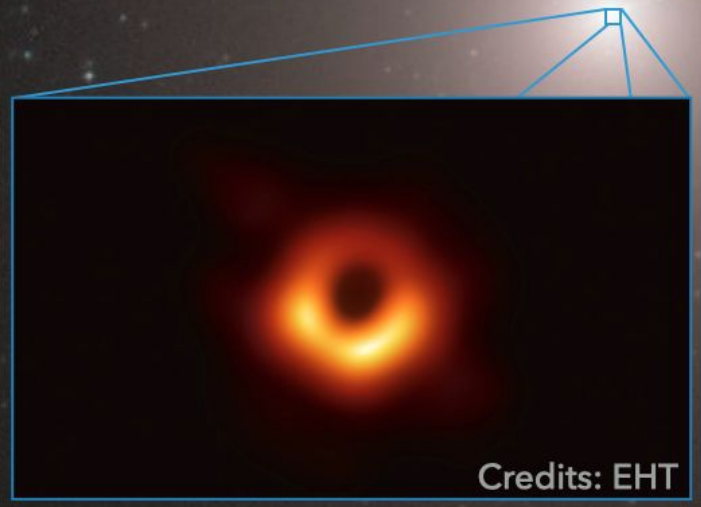
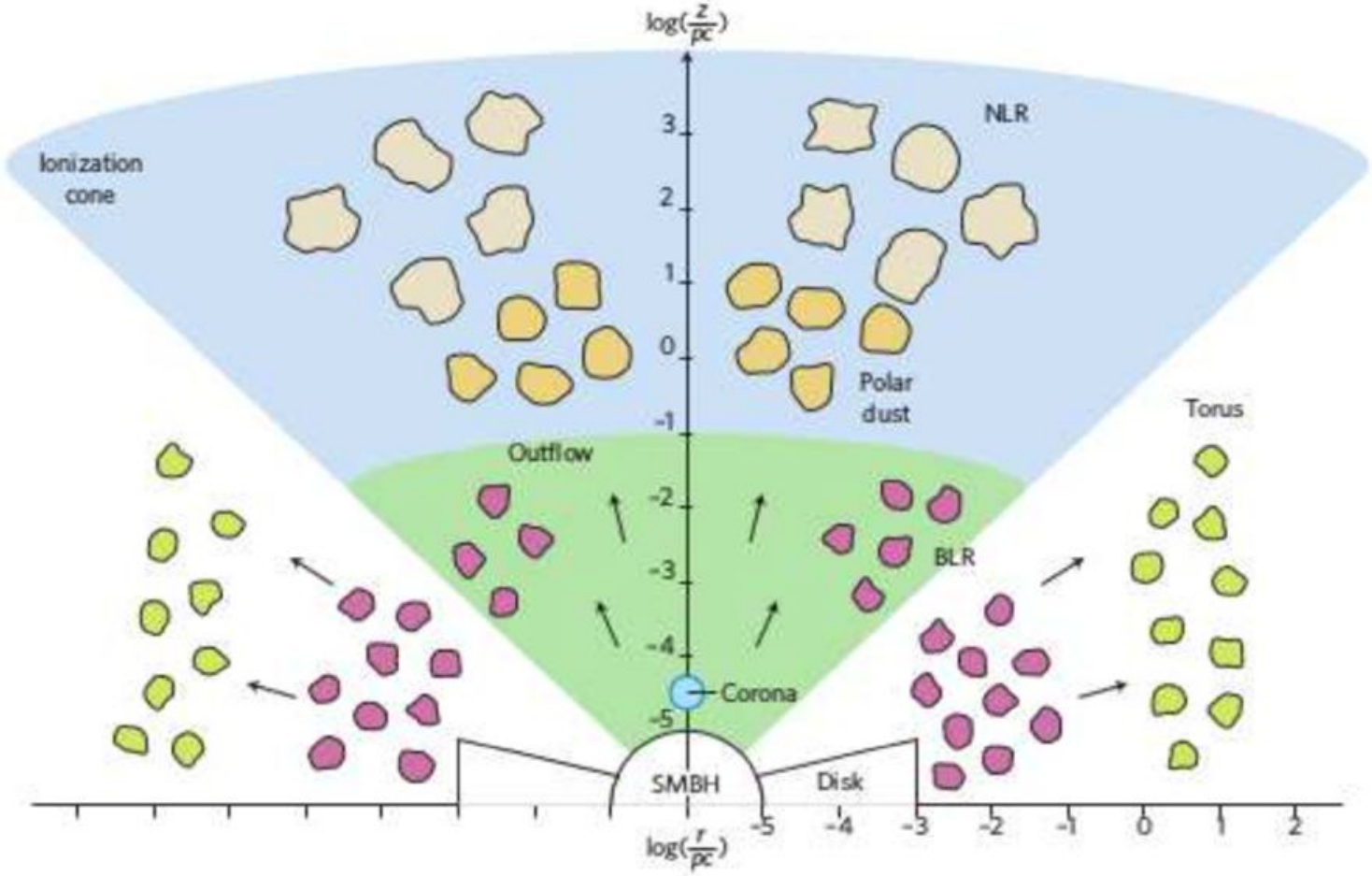
Active Galactic Nuclei (AGN)

AGNs are powered by the release of gravitational energy related with the accretion of material onto a supermassive black hole (SMBH), with masses larger than $10^6\ M_\odot$



M87, Credits: ESO

Active Galactic Nuclei (AGN)

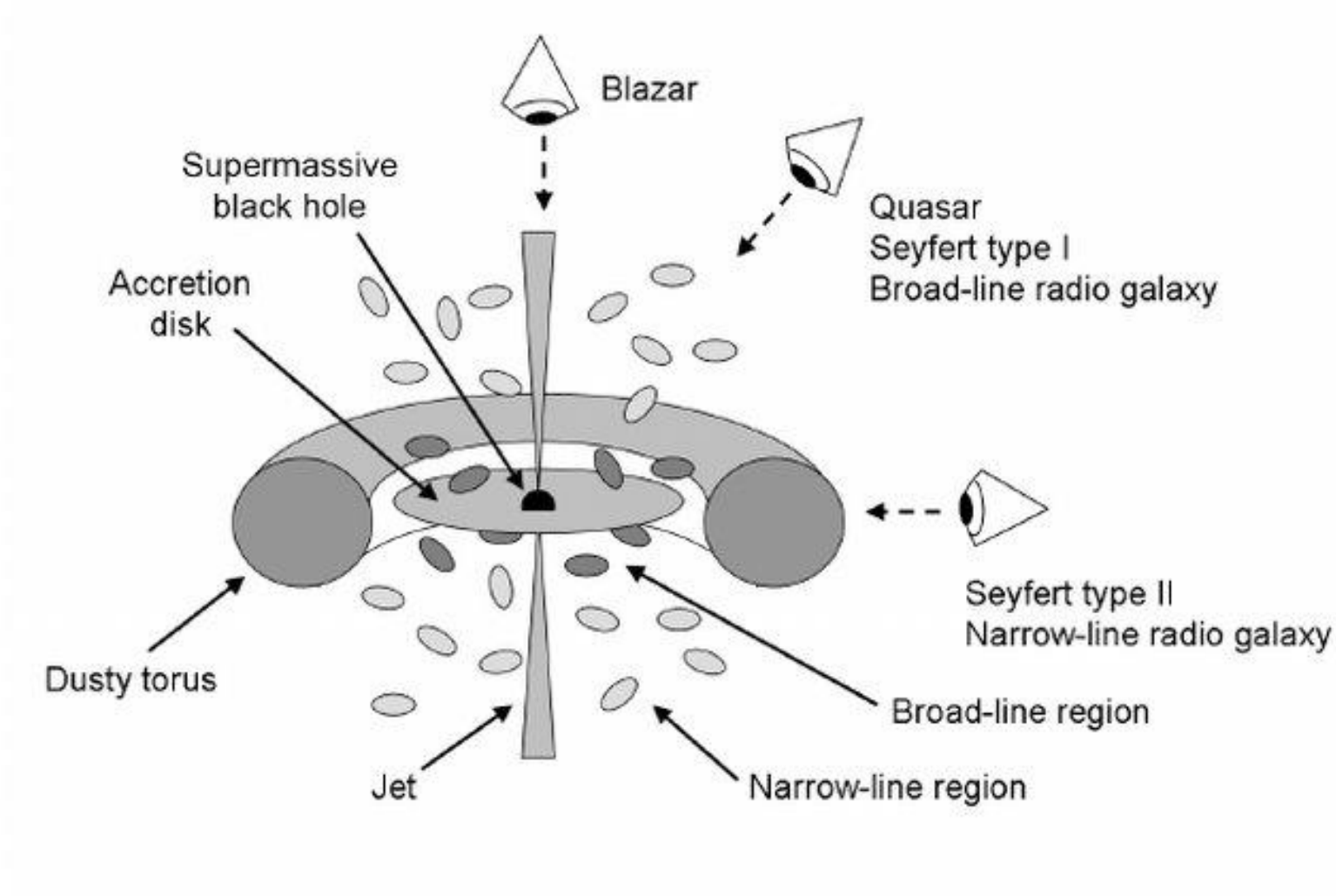


Ramos Almeida & Ricci (2017)

- Black Hole Mass $10^6 \lesssim M_{\rm BH} \lesssim 10^9\,(M_\odot)$
- Luminosity $10^{12} \lesssim L_{\rm AGN} \lesssim 10^{15}\,(L_\odot)$
- Spin $-1 \lesssim a_* \lesssim 1$
- Accretion rate $0.01 \lesssim \dot{M} \lesssim 10\,(M_\odot/{\rm yr})$
- Eddington ratio $0.01 \lesssim \frac{L}{L_{\rm Edd}} \lesssim 1$

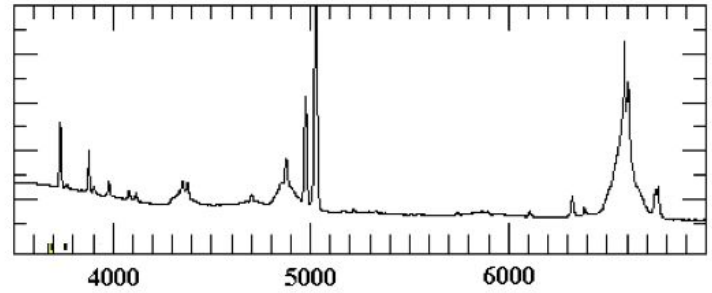
$$\frac{L}{L_{\rm Edd}} \propto \frac{L_{\rm AGN}}{M_{\rm BH}}$$

AGN types

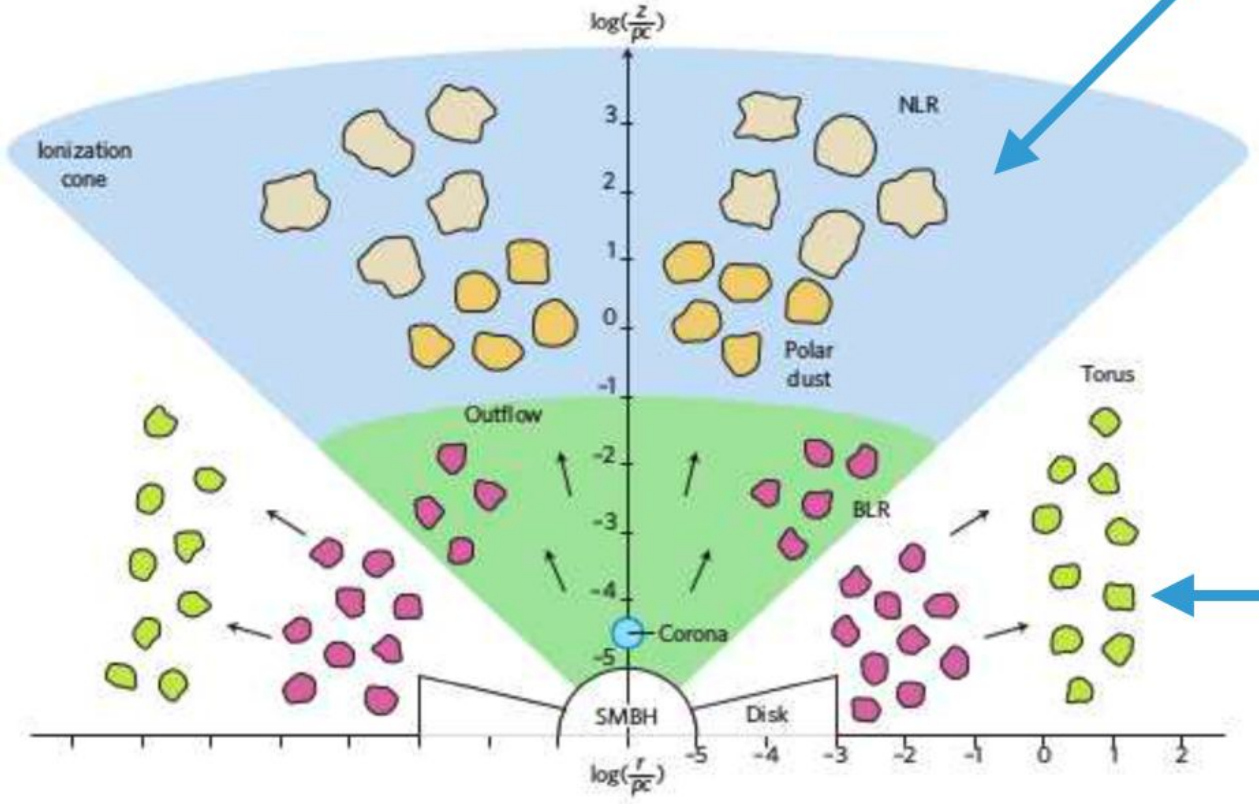


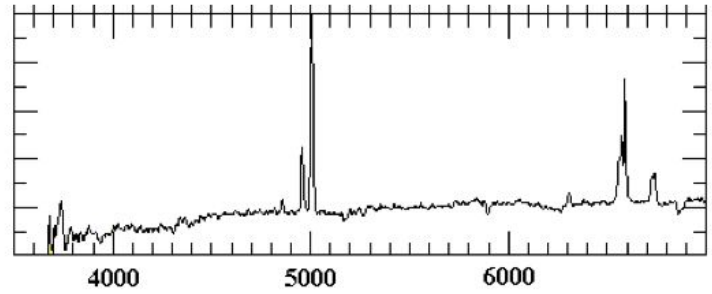
credits: Zackrisson 2005

AGN Types



Type 1 or unobscured



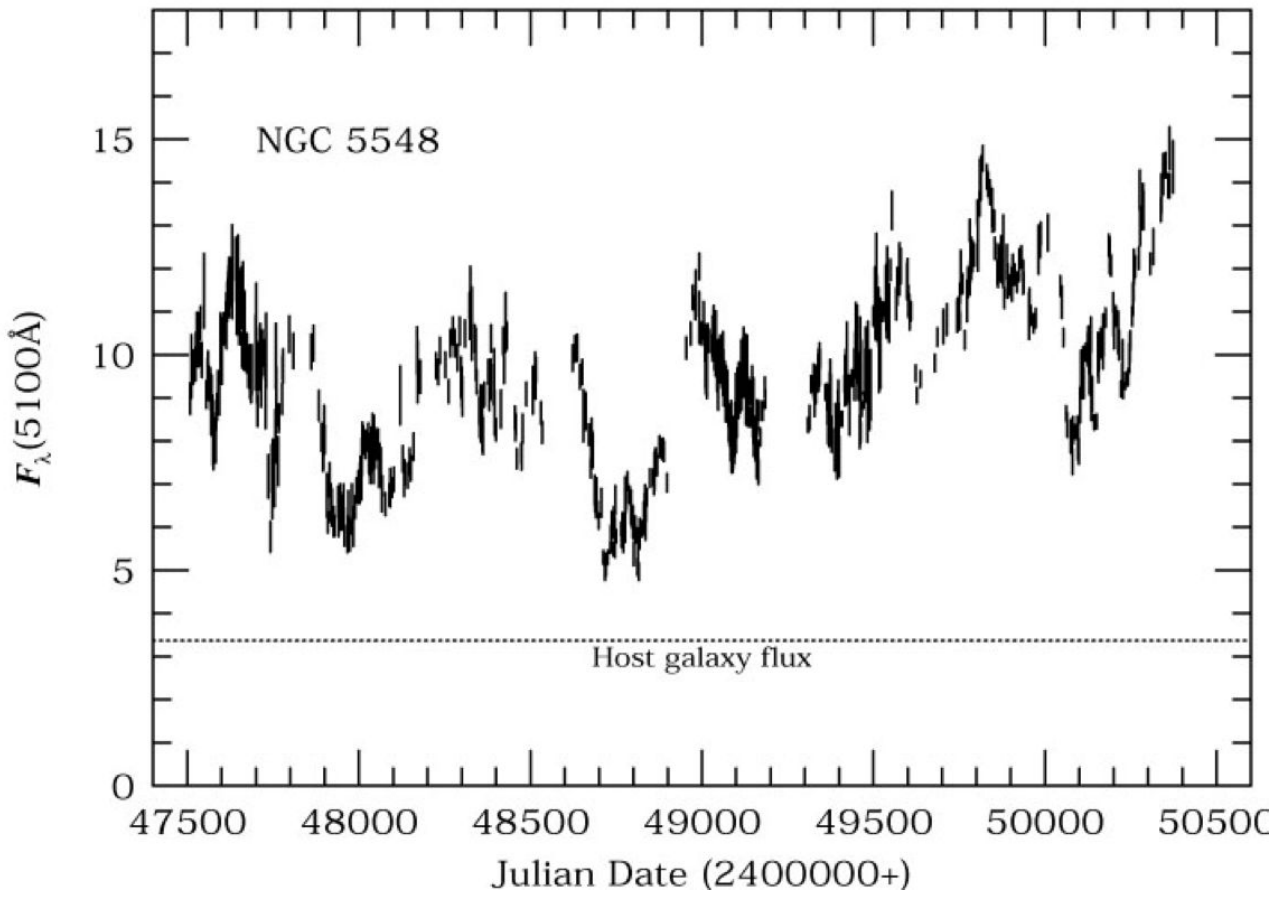


Type 2 or obscured

Ramos Almeida & Ricci (2017)

AGN Variability: what do we know?

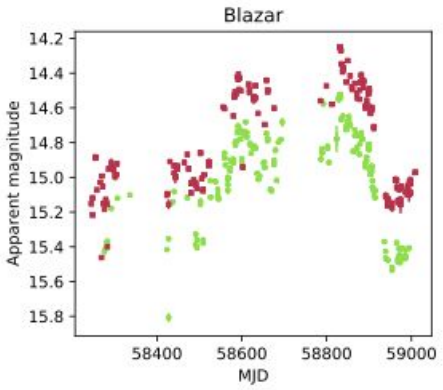
- AGN are variable!



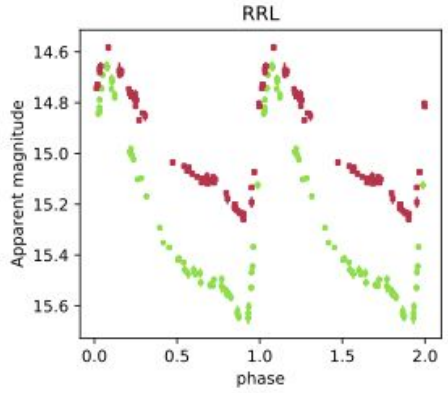
AGN Variability: what do we know?

AGN variability seems to be well described as a stochastic process: behavior that is not predictable forever as in the periodic case, but unlike temporally localized events (transient), variability is always there.

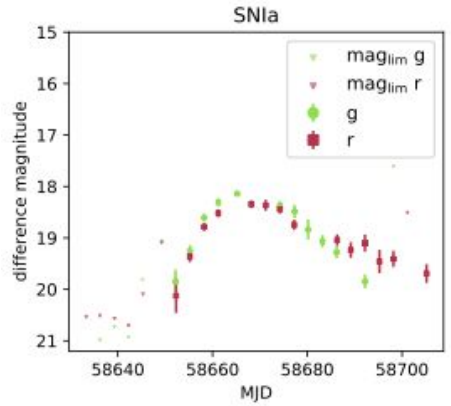
Stochastic



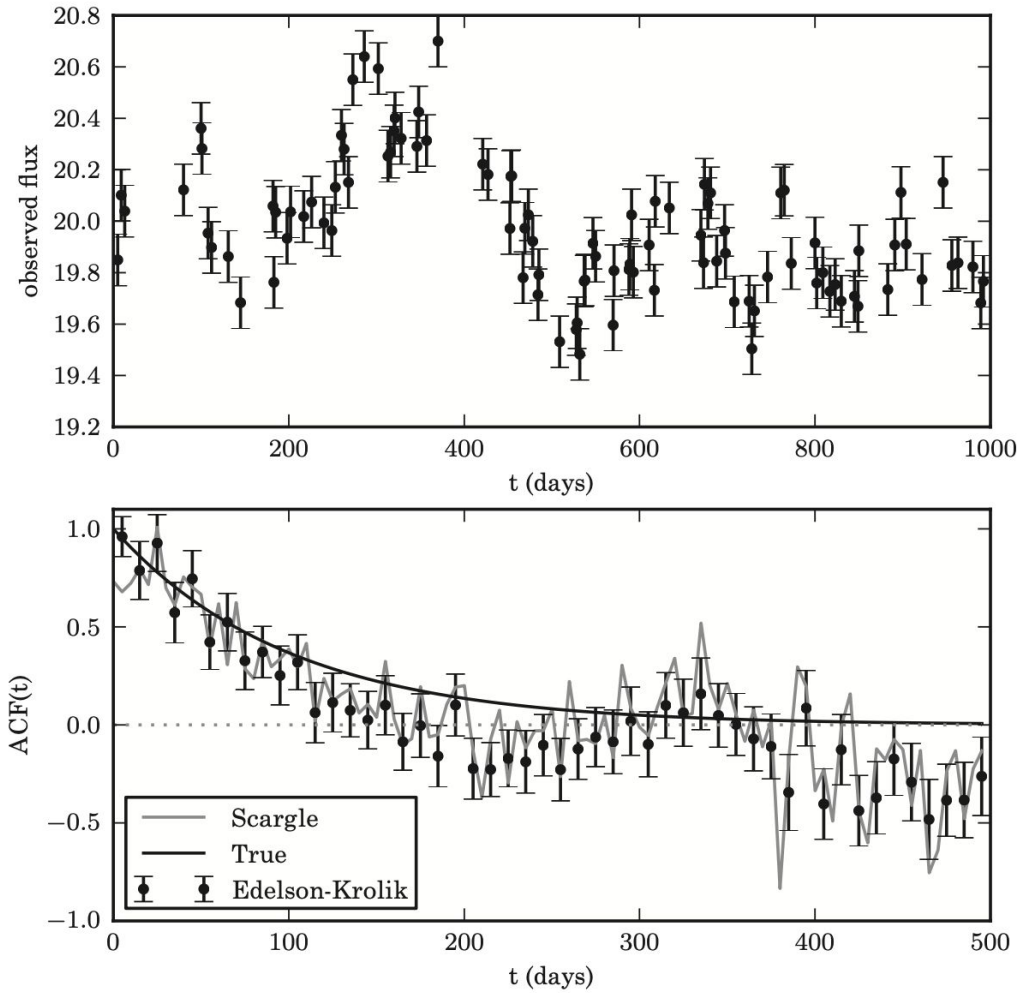
Periodic



Transient

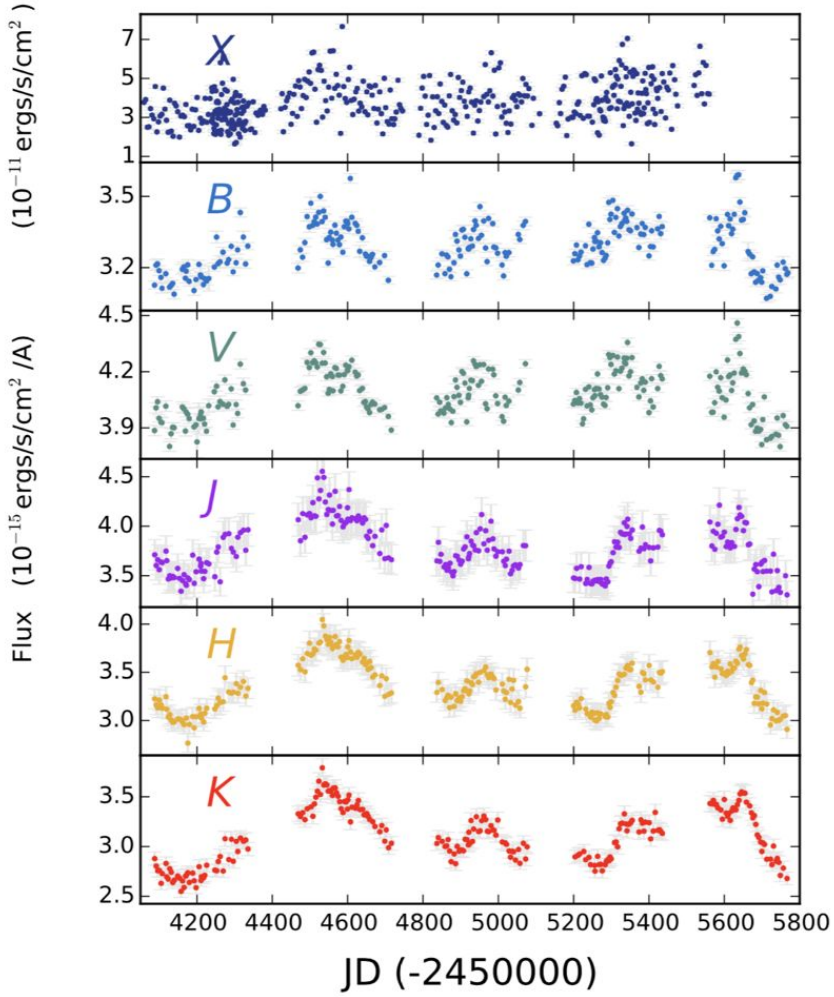


credits: Sánchez-Sáez et al. 2021a.



AGN Variability: what do we know?

- The characteristic time-scales of the variability range from hours to years, with the shortest time-scales being associated with shorter emission wavelengths.
- There is a connection between the variations seen at different wavelengths.



MCG-6-30-15 from Lira et al. 2015

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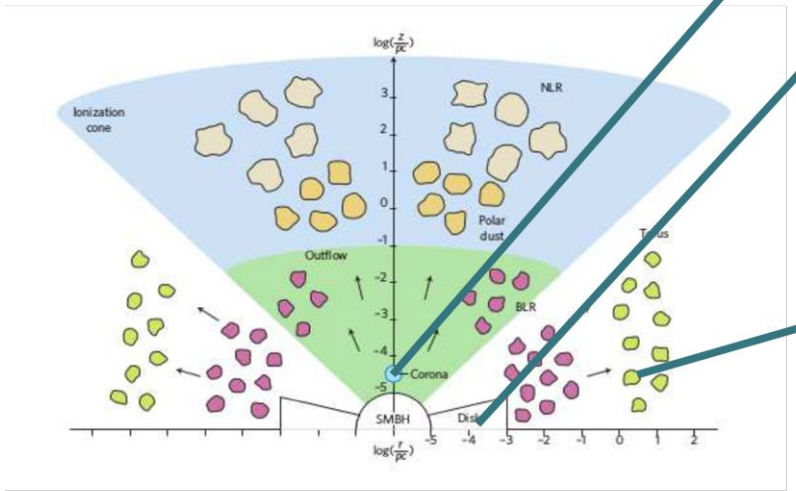
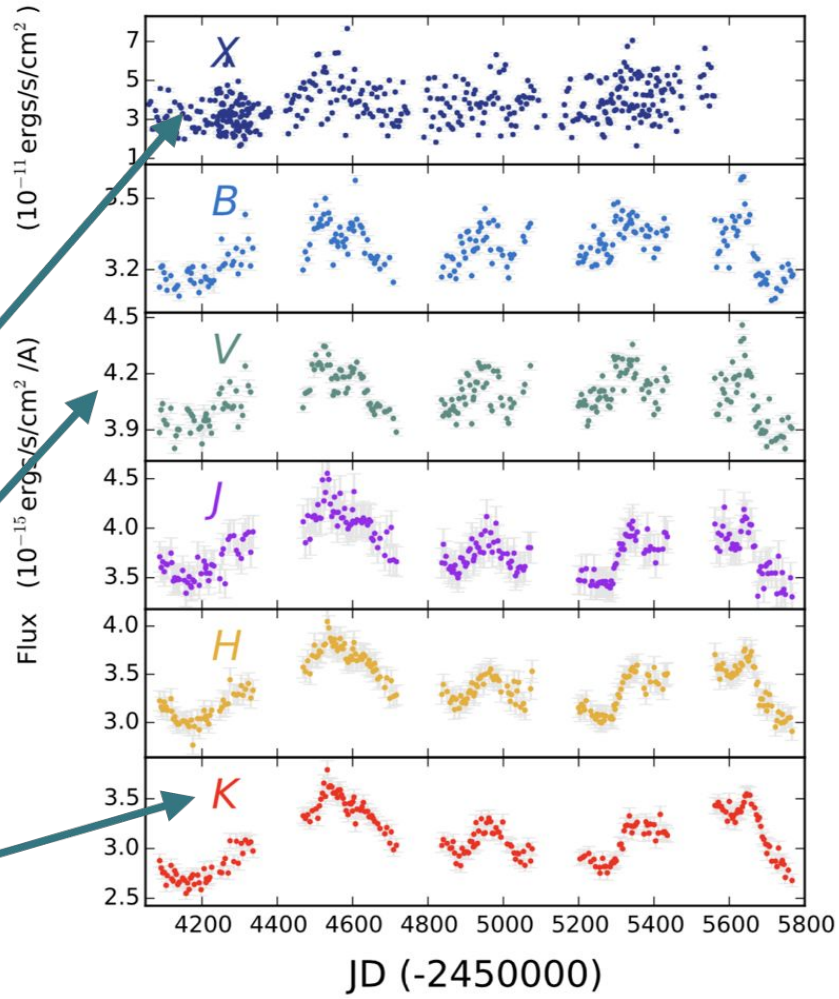


Ramos Almeida & Ricci (2017)



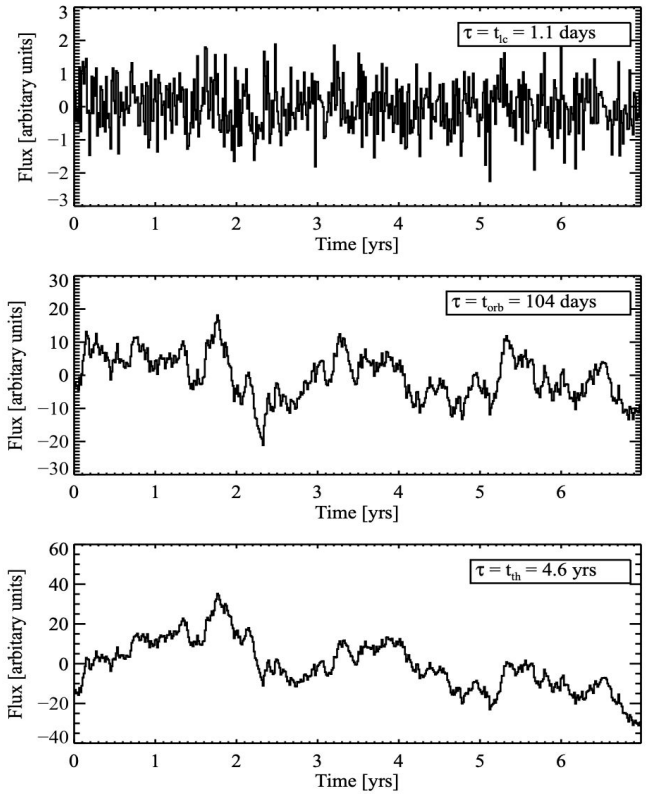
MCG-6-30-15 from Lira et al. 2015

AGN Variability: what do we know?

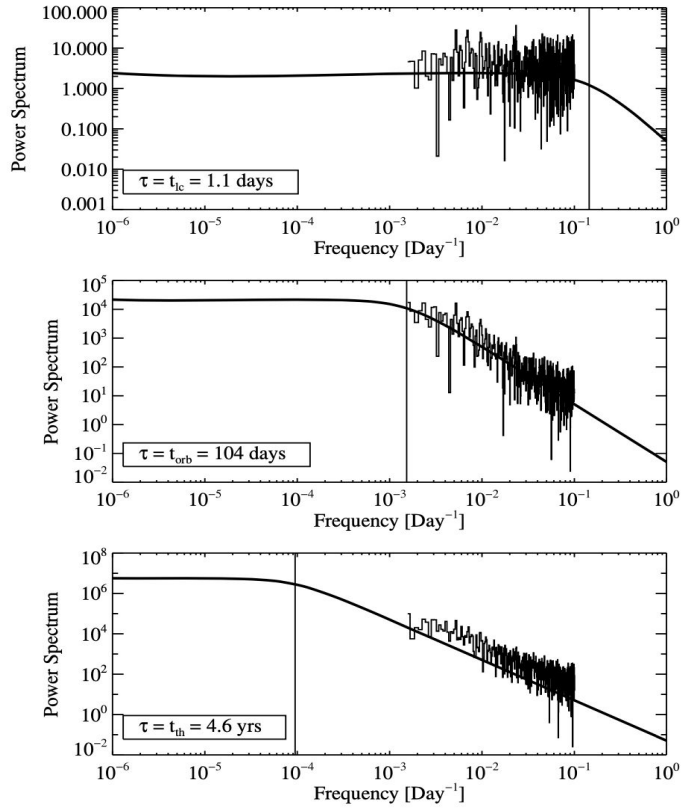
Kelly et al. (2009) proposed that a Damped Random Walk (DRW) process can be a good descriptor for AGN light curves.

$$dX(t) = -\frac{1}{\tau}X(t)dt + \sigma_{DRW}\sqrt{dt}\,\epsilon(t) + b\,dt$$

$$\mathrm{PSD}(f) = \frac{2\sigma_{DRW}^2\tau^2}{1+(2\pi\tau f)^2}$$



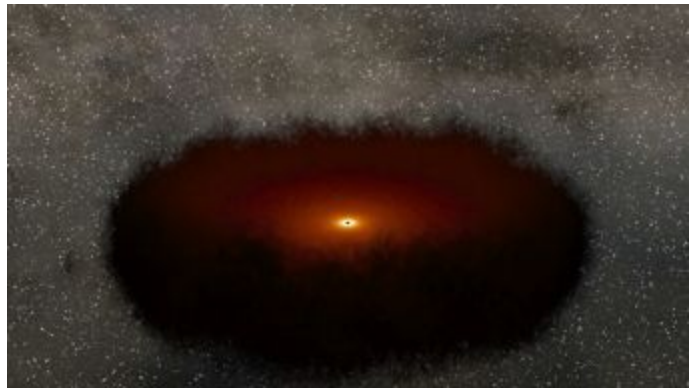
Fourier transformation

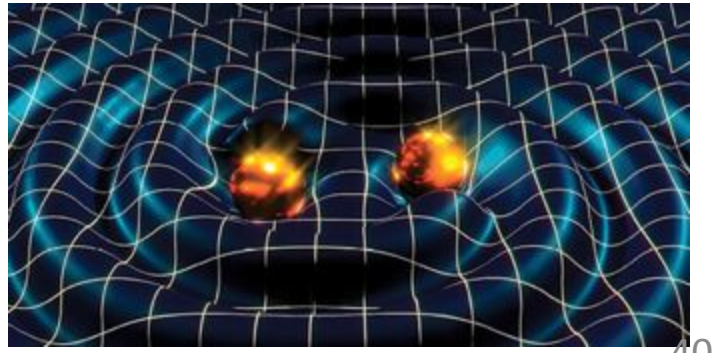


AGN variability hot topics

1. map accretion disk and BLR through **reverberation mapping**:
   - map the BLR and measure SMBH mass (see review Popović 20)
   - among priorities of LSST AGN Science Collaboration (e.g. Brandt+18)
2. detect oscillation in AGN light curves, **searching for periodicities**
   - detection of close binary SMBHs, possible GW sources
   (for a review see Popović 12, and recent works Kovačević+ 19, 20)
3. long-term trends in AGN optical variability
   - extreme cases of variability, e.g. changing-look AGN (MacLeod+16)

NASA/JPL-Calt





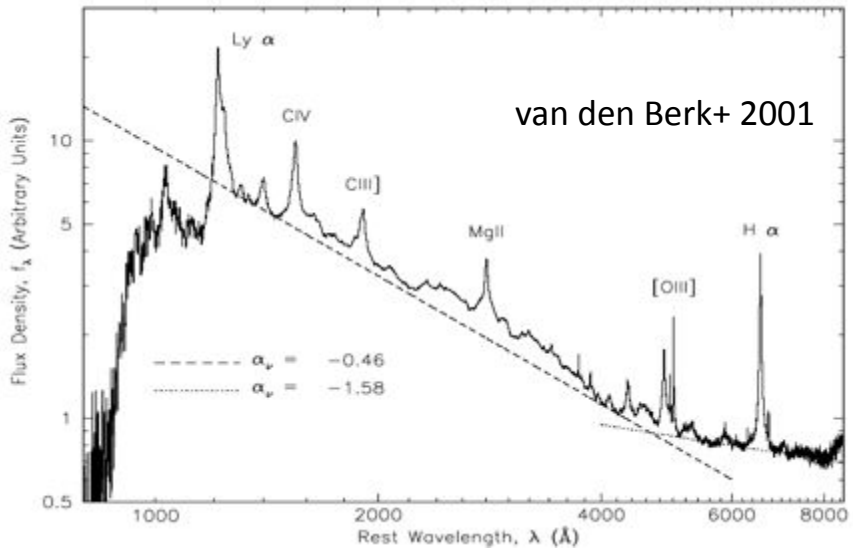
AGN contain line-emitting gas

- many AGN spectra have broad emission lines
  - *Broad Line Region - BLR*

- how do we know there is a BLR? **WE DON'T!**

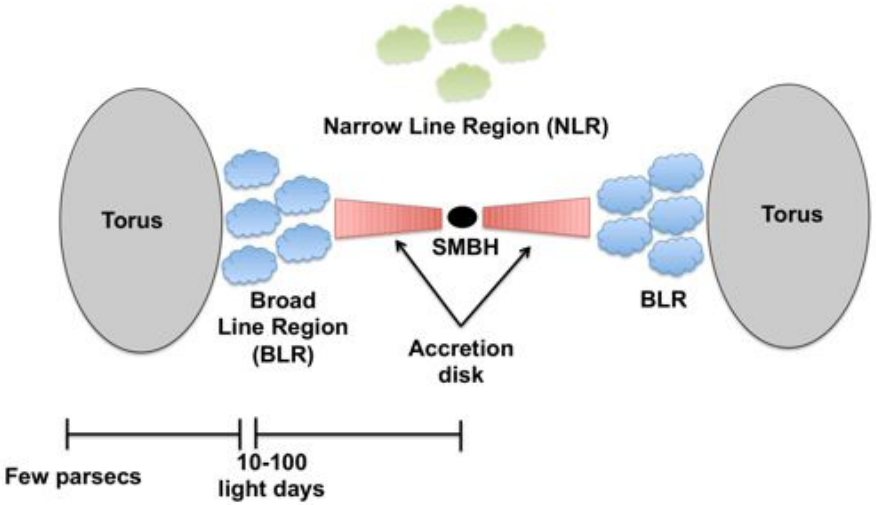
 imaging: VLT- GRAVITY (10 μas, Sturm+ 18,20,21), future ELTs

  spectroscopy very important!
  how can we use photometry?



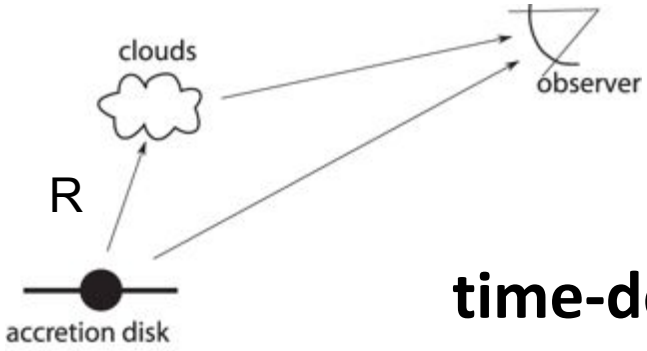
- yet, BLR physics and geometry not fully known

 1. e.g. what is gas temperature and density? (Ilic+2012)
 2. is it virialized to the supermassive black hole? (Popovic+2019)
 3. do we have outflows, inflows? (e.g. Wang+2017)
 4. what is the inclination? (e.g. Afanasiev+2018)



Reverberation Mapping (RM)

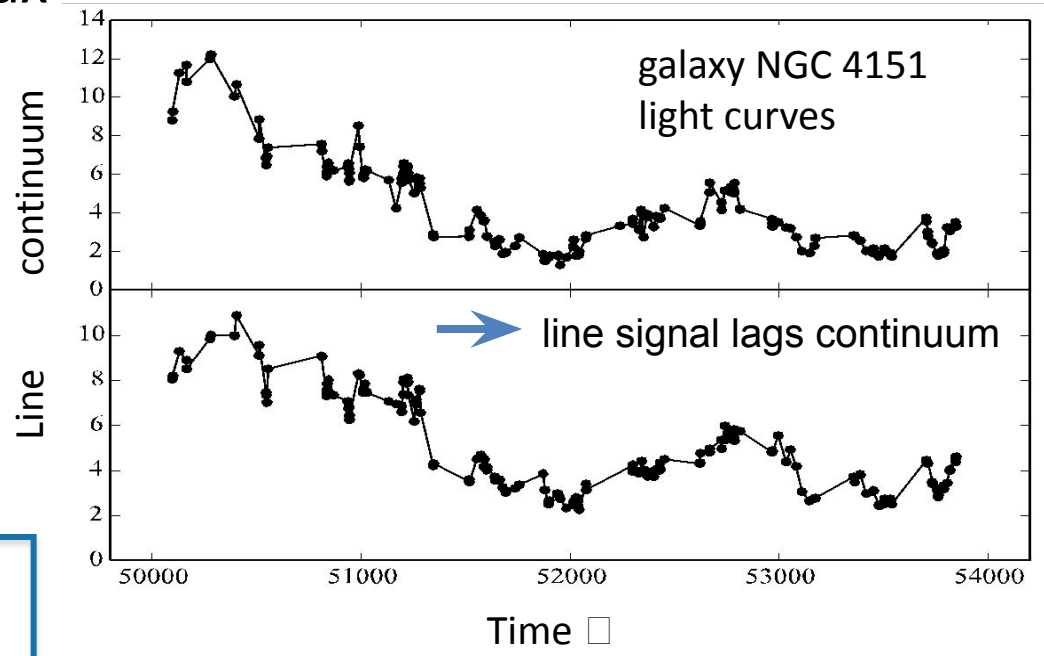
- there is a **time-delay** between continuum and line flux



Lyutyi & Cherepashchuk, 1972;
Blandford & McKee, 1982;
Gaskell & Sparke, 1986;

time-delay τ = size R_{BLR}

Shapovalova+ 2008



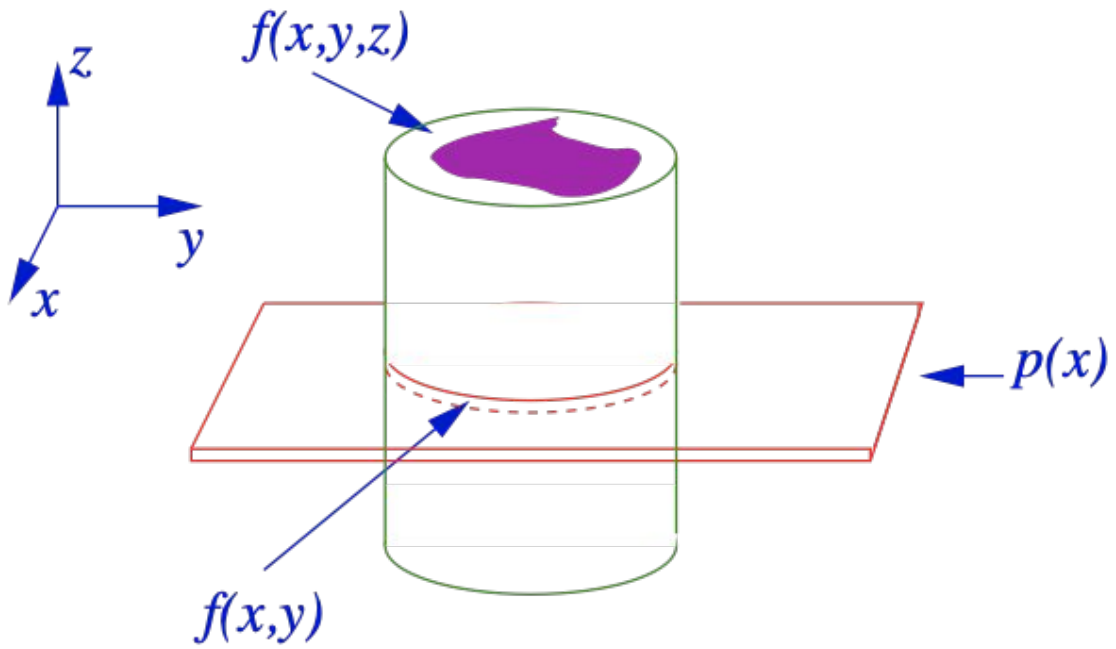
with the BLR size and the BLR gas velocity (easily obtained from the line width) → black hole mass

$$M_{BH} = f \frac{R_{BLR} FWHM^2}{G}$$

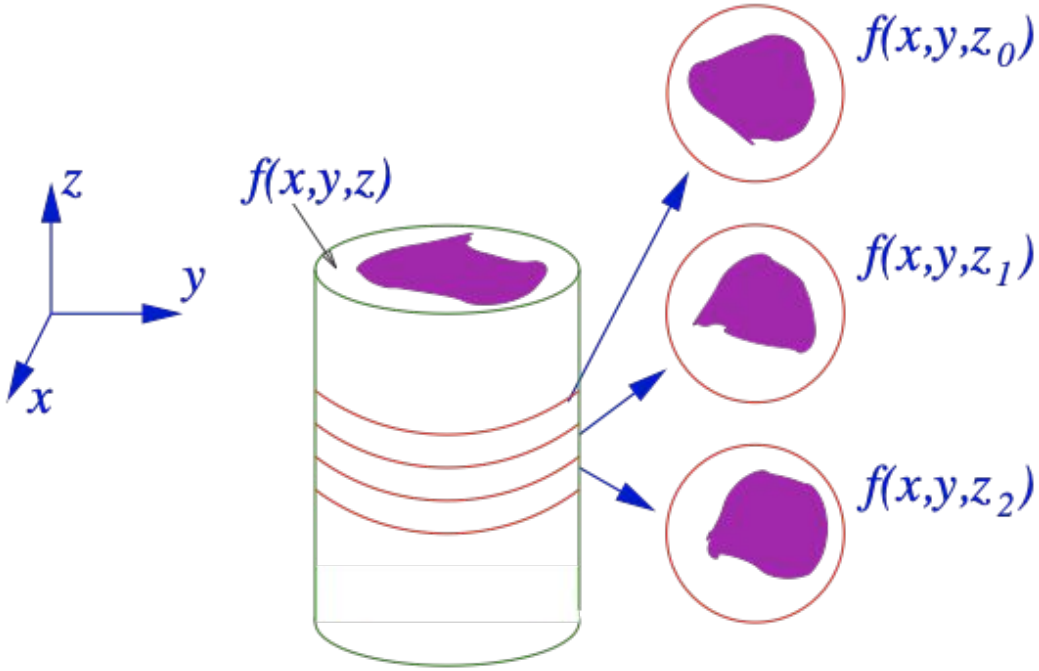
Dibai method

https://ned.ipac.caltech.edu/level5/Sept09/Gaskell/Gaskell5.html

TOMOGRAPHIC IMAGING



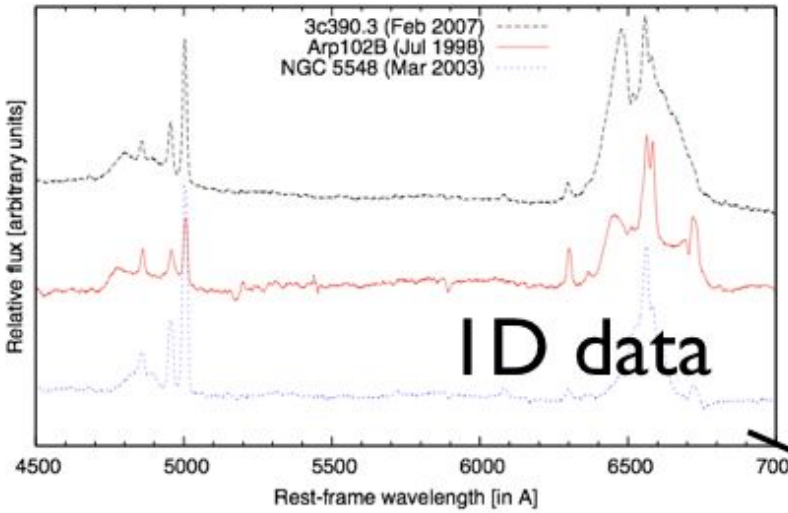
Basic layout of a tomographic system to image a slice through a three-dimensional object.



Imaging of a three-dimensional object by taking a series of slices.

Images Credit: School of Physics DIA(U01358) and TOIP(P00809)

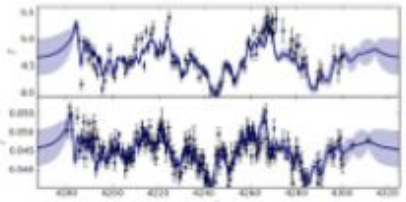
Astronomical tomography



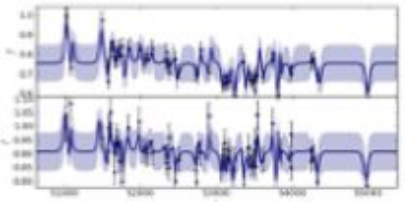
1D data

Figure 1: Examples of spectra of objects from our monitoring campaign: 3C 390.3, Arp 102B, and NGC 5548. The dates of observations are given in brackets.

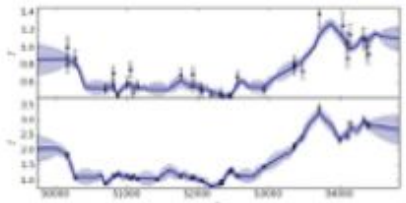
1D data



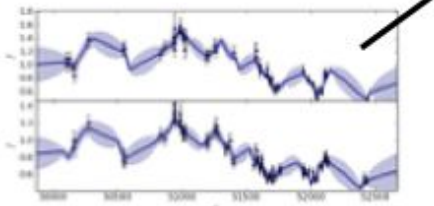
(a) NGC 4051, top: cont., bottom: Hβ line



(b) Arp 102B, top: cont., bottom: Hα line

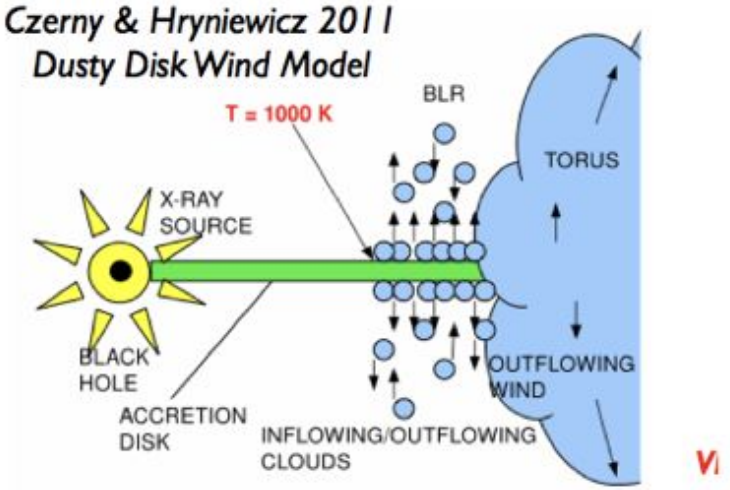


(c) 3C 390.3, top: cont., bottom: Hα line

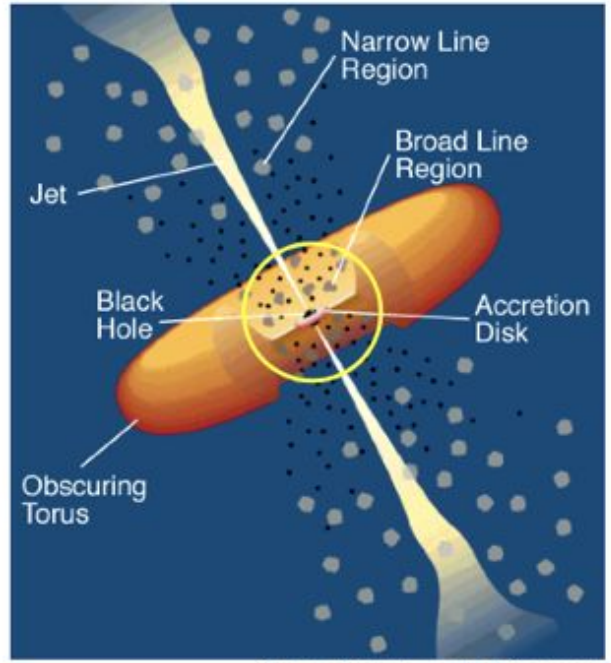


(d) NGC 5548, top: cont., bottom: Hβ line

3D model

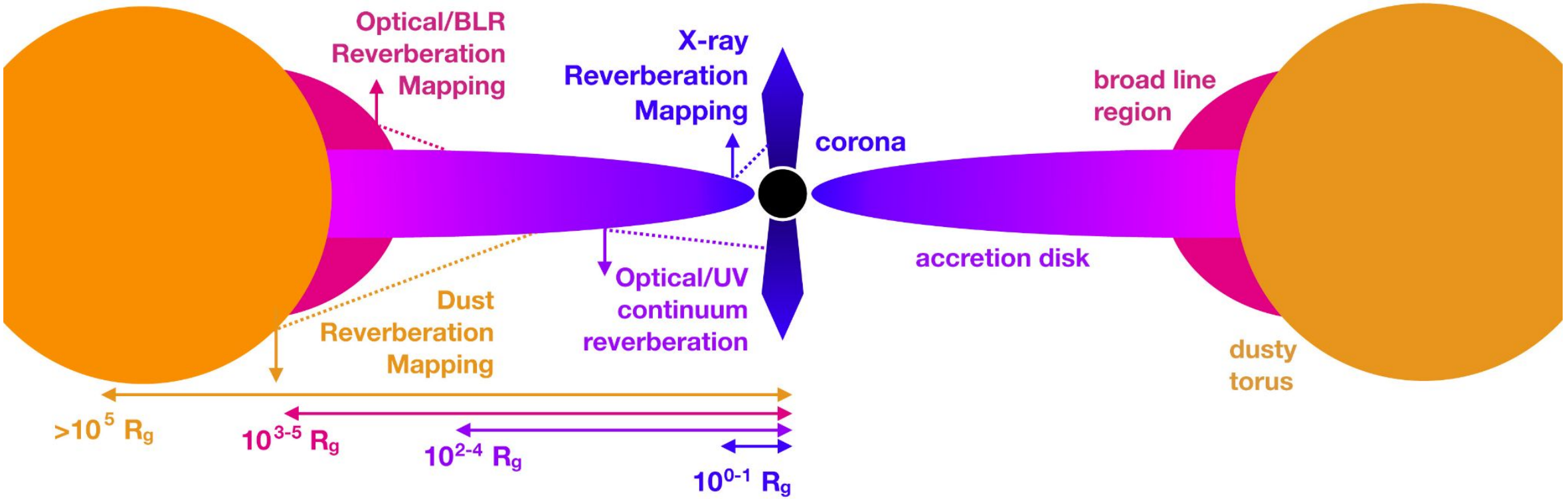


BH hrs | Disk days | BLR weeks | Torus months



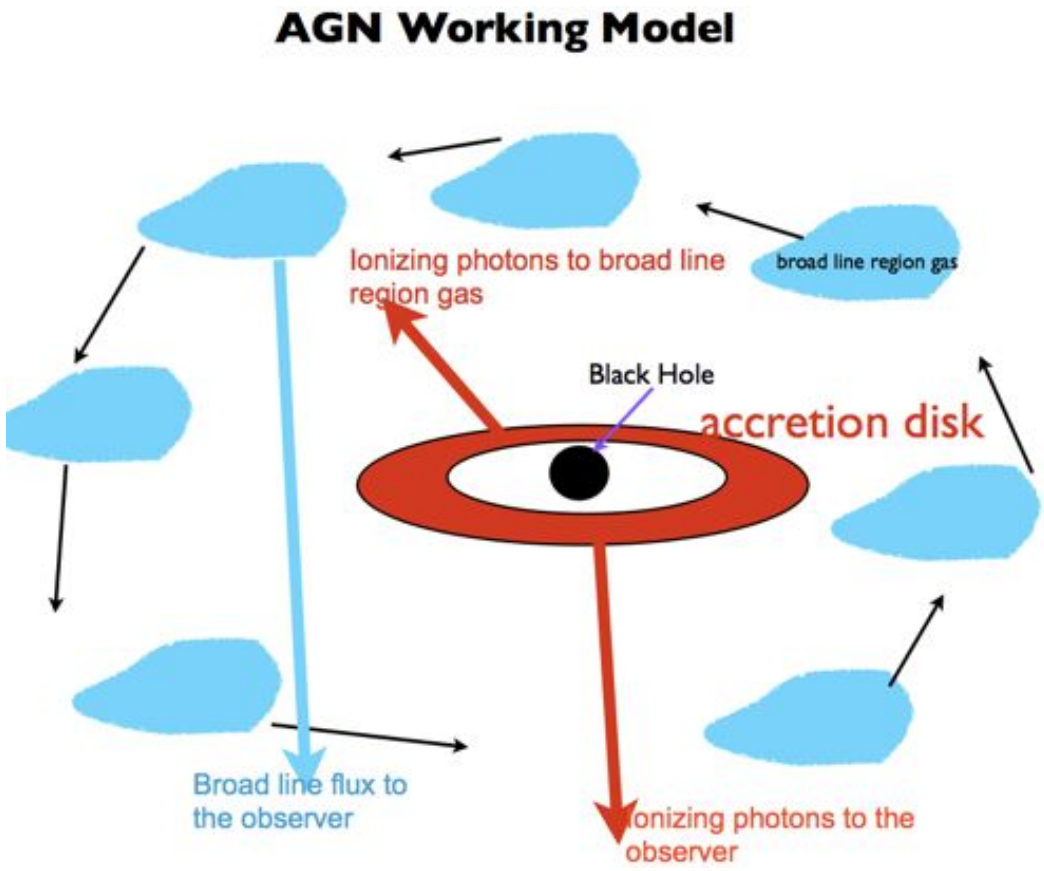
Credit: C.M. Urry and P. Padovani

4 types of reverberation mapping



Cackett+21: The schematic highlights the main components and the four types of reverberation: X-ray reverberation, optical/UV continuum reverberation broad line region reverberation, and dust reverberation (with general radial scales from the black hole indicated by labels.

Optical/UV AGN reverberation mapping



Simplified assumptions of reverberation mapping:

- (a) the irradiating flux (red color in Figure left) originates from a single central source,
- (b) that the light travel time is the most important timescale
- (c) the relationship between the observed reprocessed (blue color in Figure left) and ionizing fluxes (red color in Figure left) is linear.

$$F_i(t) = \bar{F}_i + \Delta F_i(t)$$ **irridating flux**

$$F_r(t) = \bar{F}_r + \Delta F_r(t),$$ **output reprocessed flux**

$$\Delta F_r(t) = \int_0^{\tau_{max}} \Psi(\tau)\Delta F_i(t-\tau)d\tau$$

TRANSFER FUNCTION

ARP 102 B

observed:
1987–2010

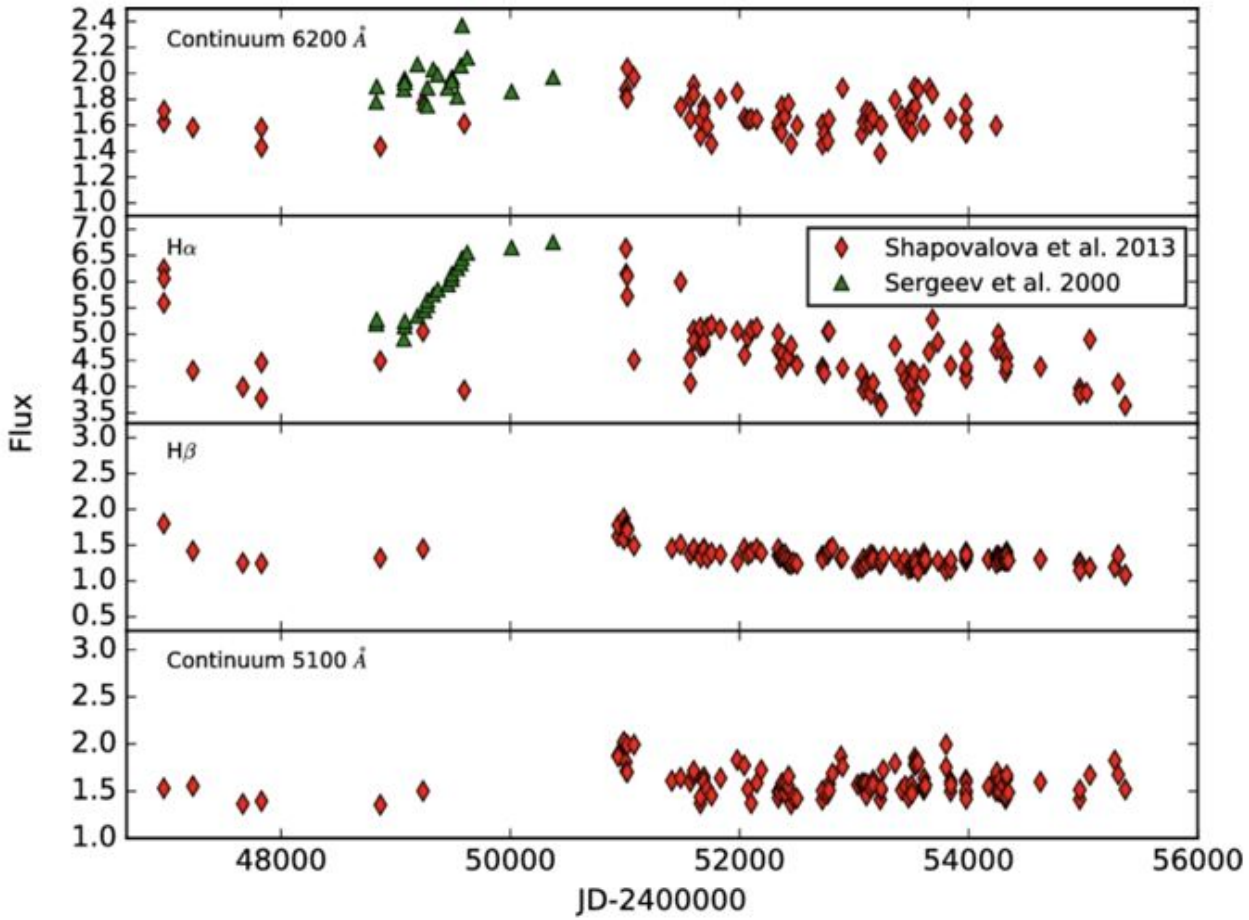
sampling:

78.1days

77 days

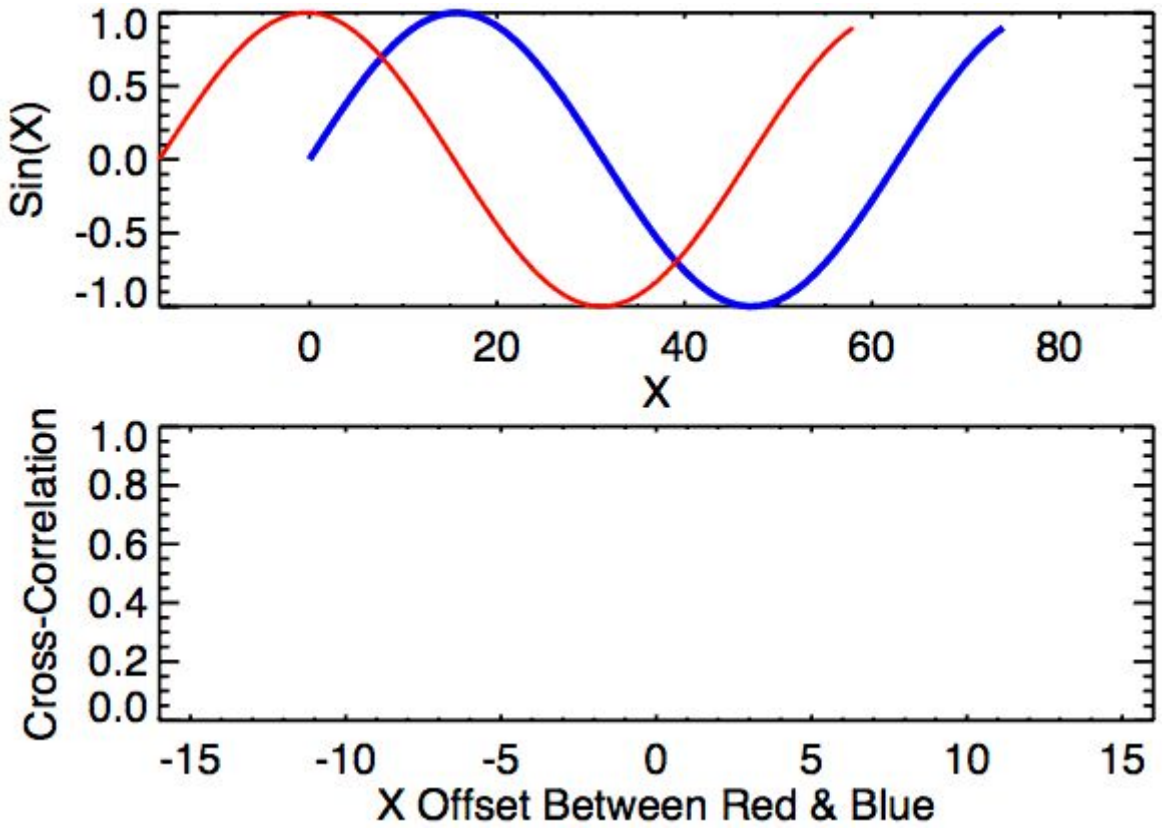
73 days

60 days



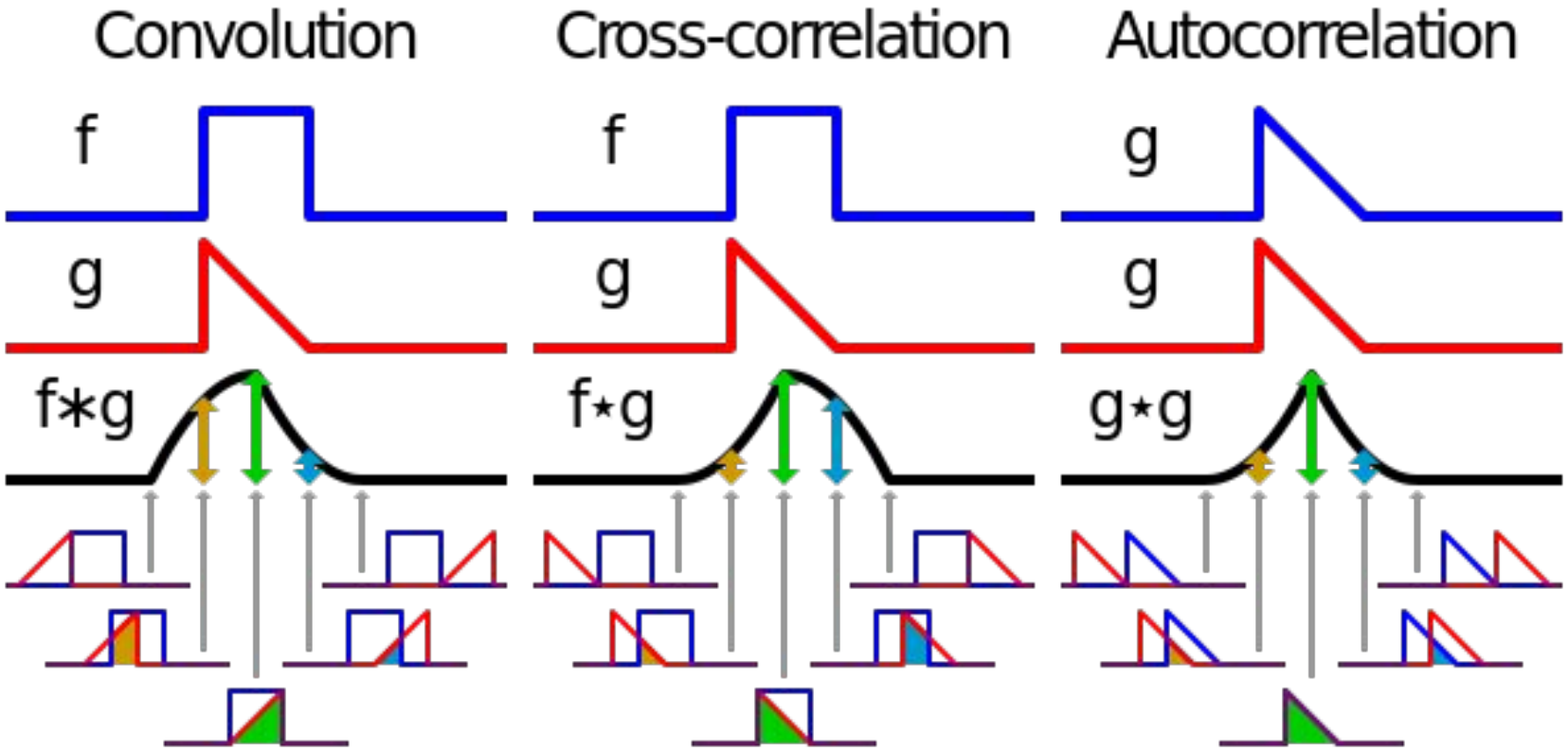
VISUAL EXPLANATION OF CROSS-CORRELATION

Cross-correlation is a measure of similarity between two signals. It works by sliding one signal across another and finding the optimal match. This is also known as a sliding dot product or sliding inner-product and is closely related to convolution.



A cross-correlation "slides" one signal along another to determine maximal overlap. Animated gif from WSU's RoboSub project.

COMPARISON OF OPERATIONS ON SIGNALS



https://primo.ai/index.php?title=Convolution_vs._Cross-Correlation_(Autocorrelation)

The Standard Definitions of the ACF and CCF

The standard definition of the cross–correlation function of two time series x_i and y_i sampled at discrete times t_i $(i = 1, ..., N)$ with equal sampling $(\Delta t = t_{i+1} - t_i)$ is:

$$CCF(\tau_k) \equiv \frac{\frac{1}{N}\sum_{i=1}^{N-k}(x_i - \bar{x})(y_{i+k} - \bar{y})}{\left[\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2\right]^{1/2}\left[\frac{1}{N}\sum_{i=1}^{N}(y_i - \bar{y})^2\right]^{1/2}} \quad (1)$$

where the lag τ_k is the size of the time shift: $\tau_k = k\Delta t$, $k = 0, ..., N-1$ and $\bar{x}$, $\bar{y}$ are the means of x_i and y_i (see e.g. Jenkins & Watt (1969), Chatfield (1996)). The ACF is similarly defined, with x_i itself in place of y_i. [NB: for negative lags, simply interchange x and y.]

It will be helpful to express the CCF more succinctly, and we will use the continuous definition

to do so:

$$CCF(\tau) = \int x(t)y(t+\tau)dt \quad (2)$$

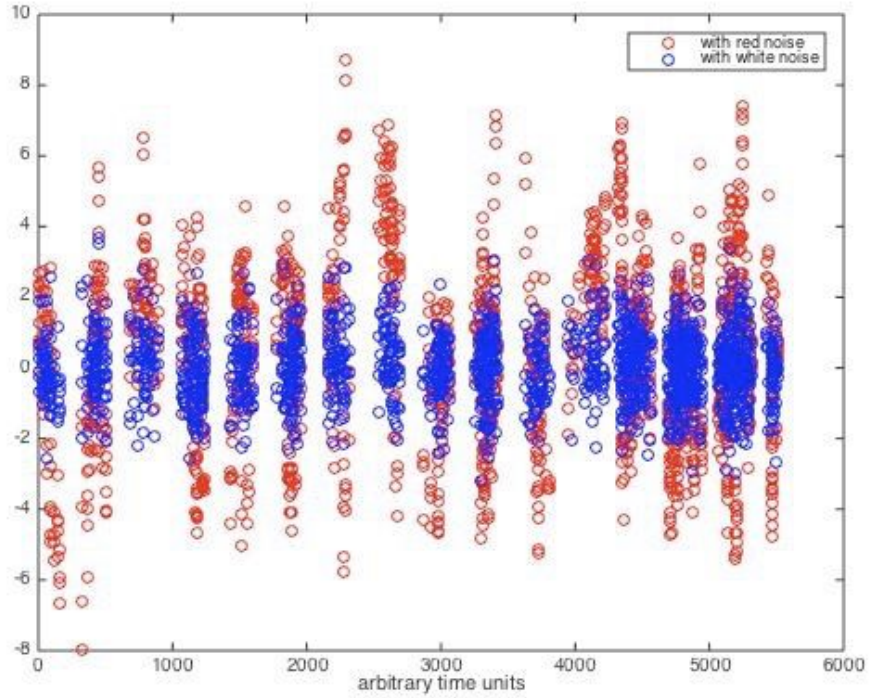
$$ACF(\tau) = \int x(t)x(t+\tau)dt \quad (3)$$

It should be explicitly stated that we use equations (2) & (3) only as shorthand representations of equation (1), as the discrete and continuous CCF are not the same. Also note that in this nomenclature $\bar{x}$ and $\bar{y}$ are by definition zero and the light curves have been normalized to unity variance.

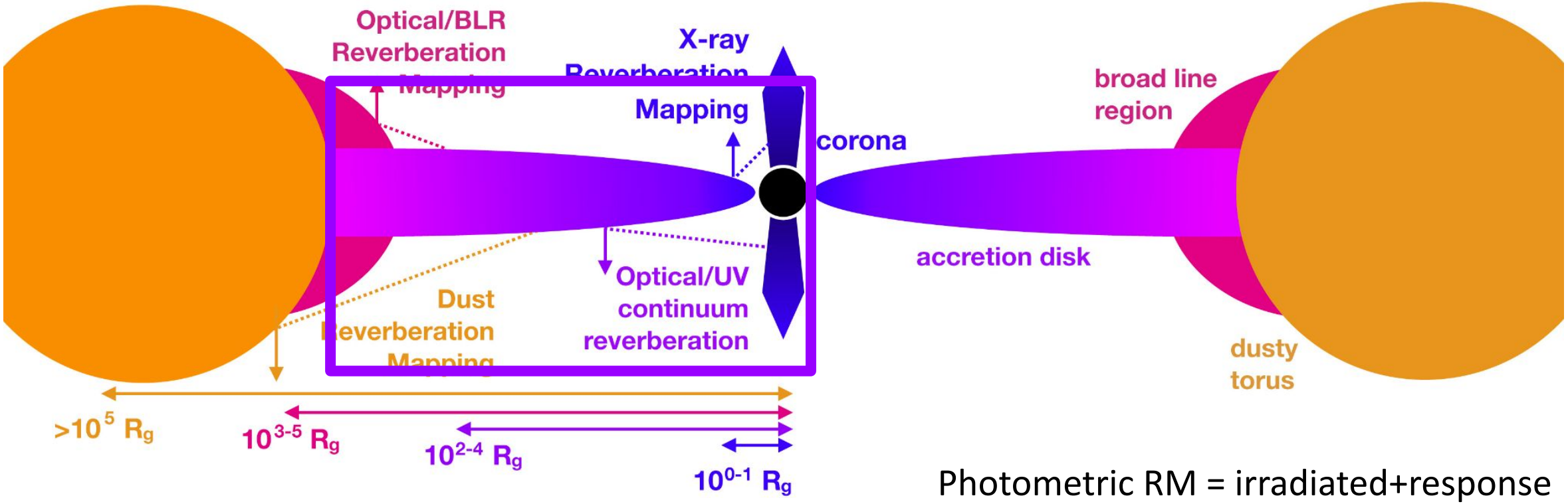
Red noise

our data are emersed in red noise

- At optical wavelengths, De Vries et al. (2005) found evidence for the variability of quasar emission following red-noise laws on timescales as long as approximately 40 years.
- problem: how to recover spectrum of very "red" processes?(e.g. Mushotzky et al. 2011)



4 types of reverberation mapping

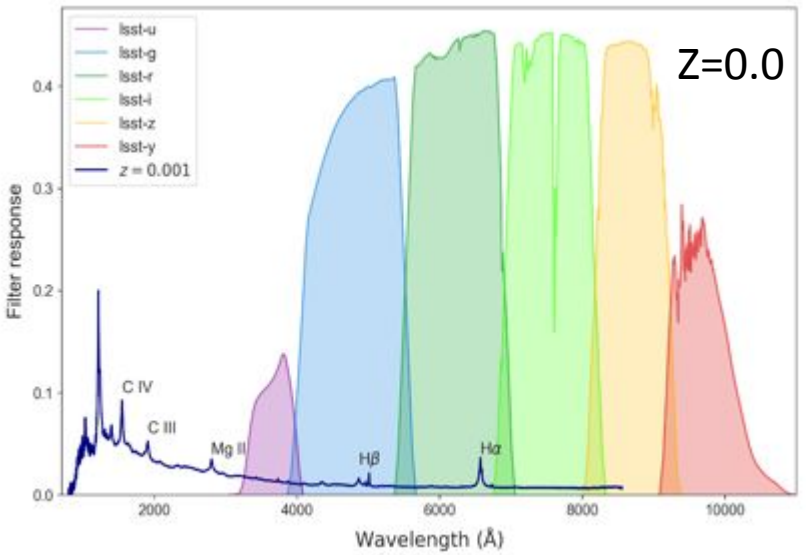


Photometric RM = irradiated+response flux

Cackett+21: The schematic highlights the main components and the four types of reverberation: X-ray reverberation, optical/UV continuum reverberation broad line region reverberation, and dust reverberation (with general radial scales from the black hole indicated by labels.

Photometric RM = PhotoRM

- employs a broad band to measure AGN continuum variations and a suitable narrow band to trace the echo of an emission line in the BLR (Haas et al. 2011)
- PhotoRM:
  - efficiently measuring hundreds of BLR sizes and host-subtracted AGN
  - suitable for upcoming large surveys like the LSST

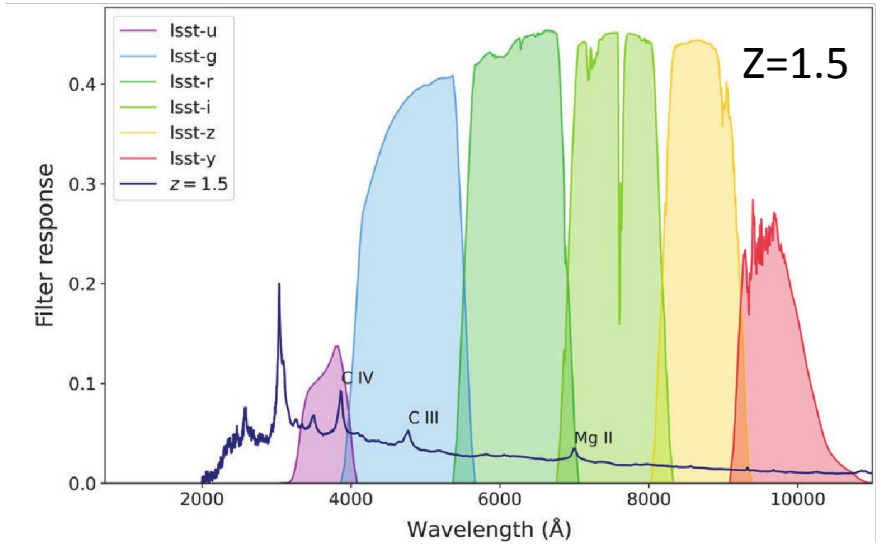


Jankov et al. 2022

- line emission hidden in the broadband light curve
- time lag from cross (CCF) and auto-correlation functions (ACF)

$$\mathrm{CCF}(\tau) \approx \mathrm{CCF}_{\mathrm{XY}}(\tau) - \mathrm{ACF}_{\mathrm{X}}(\tau)$$

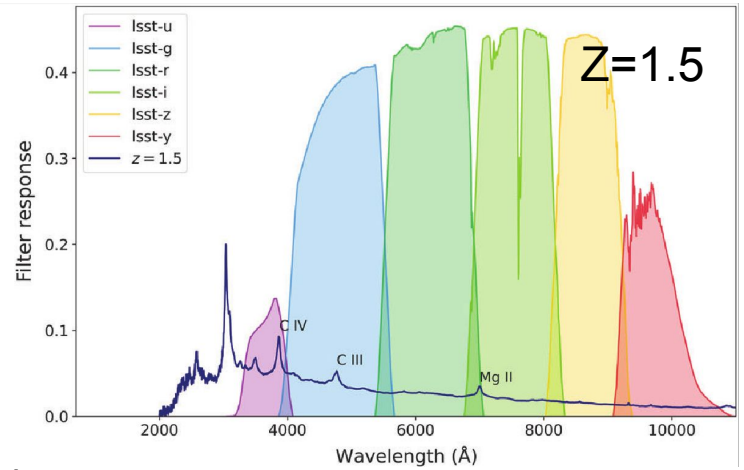
(Chelouche & Daniel 2012, Edri et al. 2012)



Photometric reverberation mapping

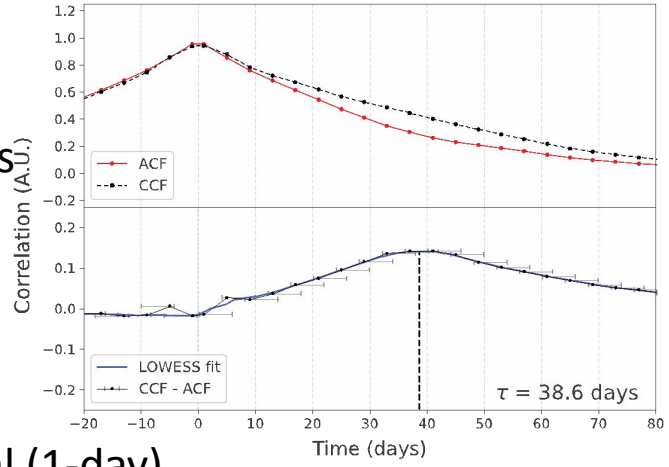
- the line emission hidden in the broadband light curve
- formalizm developed by Chelouche & Daniel (2012)
- time lag from cross (CCF) and auto-correlation functions (ACF)

$$\mathrm{CCF}(\tau) \approx \mathrm{CCF}_{\mathrm{XY}}(\tau) - \mathrm{ACF}_{\mathrm{X}}(\tau)$$

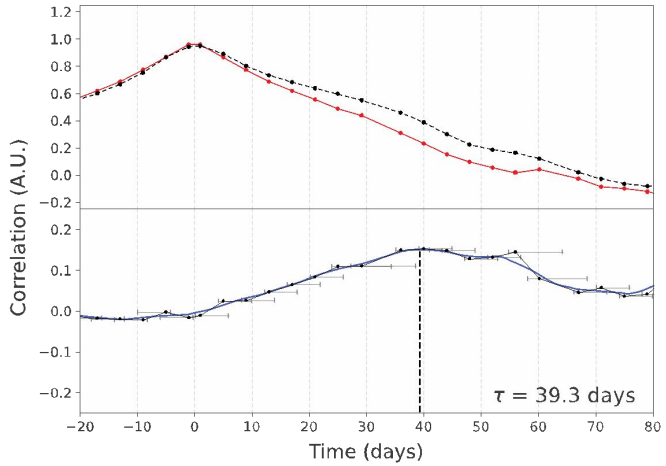


- Used artificial light curves based on DRW (Kovačević et al. 2021) with different cadences

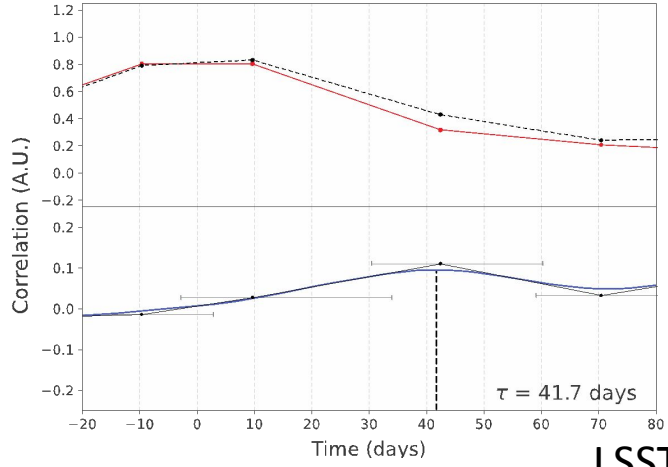
True lag
36.9 days



ideal (1-day)



with gaps

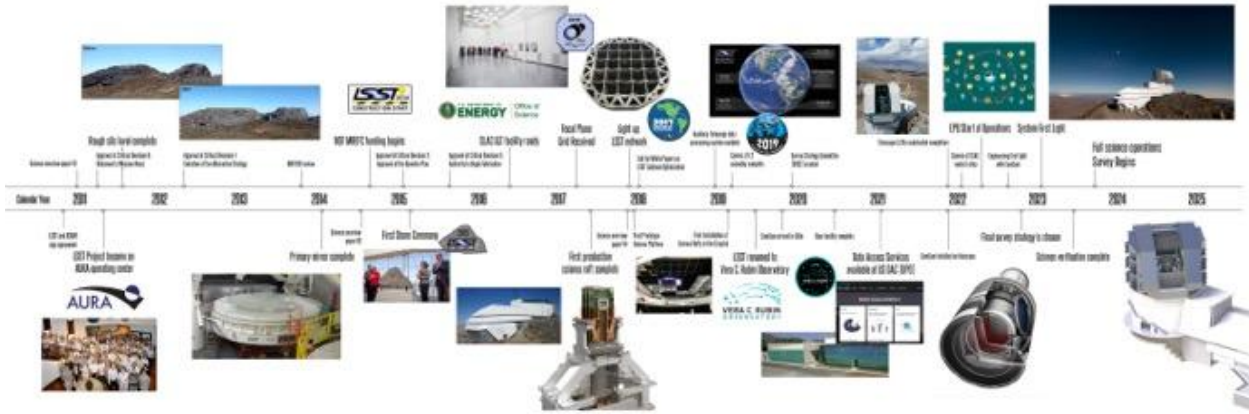


LSST-like

see for details Jankov et al. 2022

Summary

- LSST, will be the largest 10-year long movie of the sky!
  Operation starts April 2023



- Opens the new parameter space for AGN research
  - Photo Reverberation Mapping (PhotoRM)
  - Search for period signals and possible supermassive BH binaries

- https://github.com/LSST-sersag/dle/tree/main/activities/workshop

Erasmus Mundus Master

- Erasmus Mundus Joint Master Degree (EMJMD) program in Astrophysics and Space Science
- **Master in Astrophysics and Space Science (MASS)**
- 2 year master studies, 120
- Partner Universities:
  - University of Rome Tor Vergata, Rome Italy
  - University of Belgrade, Belgrade, Serbia
  - University of Bremen, Bremen, Germany
  - University of Côte d'Azur, Nice, France

- Just approved for 6 years: 2021-2027
- **Important**: there are dedicated scholarships for the students from some underrepresented regions

EACEA
European Commission
Education, Audiovisual and Culture Executive Agency

MASS
MASTER IN ASTROPHYSICS AND SPACE SCIENCE