Istraživanja aktivnih galaksija u pripremi za LSST projekat opservatorije Vera C. Rubin

Dragana Ilić i SER-SAG tim:
Luka Č. Popović, Dragana Ilić, Andjelka Kovačević, Maša Lakićević, Đorđe Savić, Saša Simić, Viktor Radović, Isidora Jankov, Iva Čvorović-Hajdinjak, Jelena Kovačević-Dojčinović, Slađana Marčeta-Mandić, Oliver Vince, Mladen Nikolić, Nemanja Rakić, Marko Stalevski

[1]Katedra za astronomiju, Univerzitet u Beogradu – Matematički fakultet
[2]Astronomska Opservatorija Beograd

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АСТРОНОМИЈА
И АСТРОФИЗИКА

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SER-SAG (Serbian AGN Group)

SER-SAG Tim: Luka Č. Popović, Dragana Ilić, Andjelka Kovačević, Maša Lakićević, Đorđe Savić, Saša Simić, Viktor Radović, Isidora Jankov, Iva Čvorović-Hajdinjak, Jelena Kovačević-Dojčinović, Slađana Marčeta-Mandić, Oliver Vince, Mladen Nikolić, Nemanja Rakić, Marko Stalevski

Trenutna istraživanja i planovi naše grupe

- analiza profila emisionih linija sa ciljem određivanja BLR osobina
- praćenje kratkoročnih i dugoročnih promena u liniji i kontinumu sa ciljem merenja dimenzija BLR, kao i detekciji periodičnih promena (dvojne crne rupe)

- učešće u Large Synoptic Survey Telescope – LSST (*in-kind contribution)*

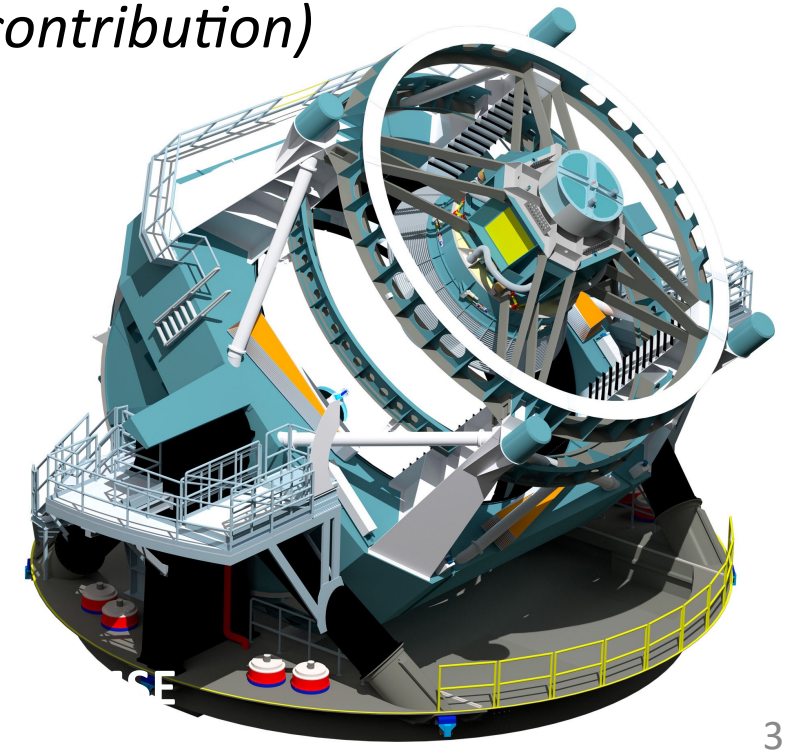
  → *ispitivanje oscilacija krivih sjaja*

  → *ispitivanje varijabilnosti i kašnjenja*

  → *dodatna spektroskopska posmatranja iz naše kampanje*

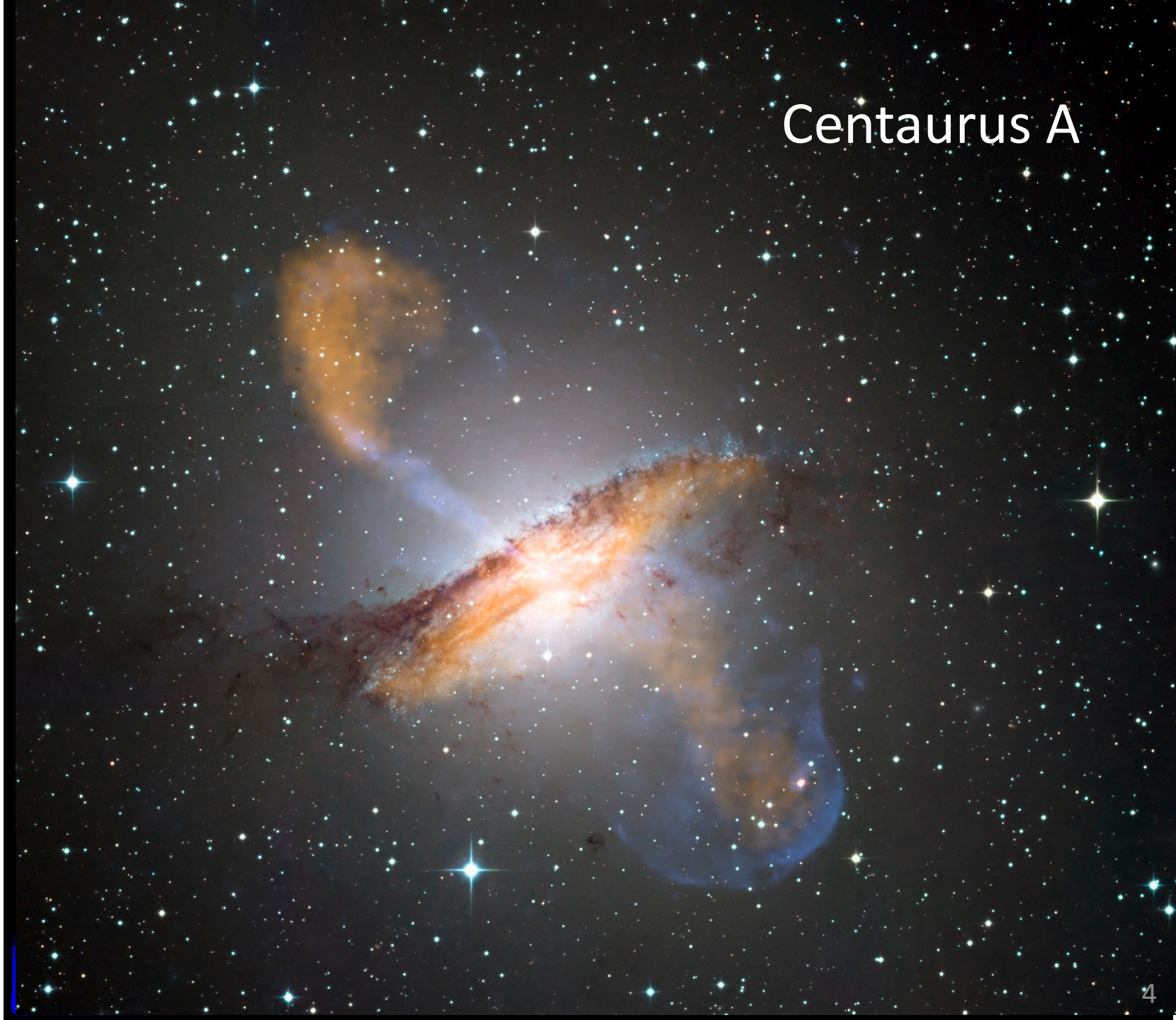
Sa Seminara
Feb 2020.

Vera C. Rubin Observatory



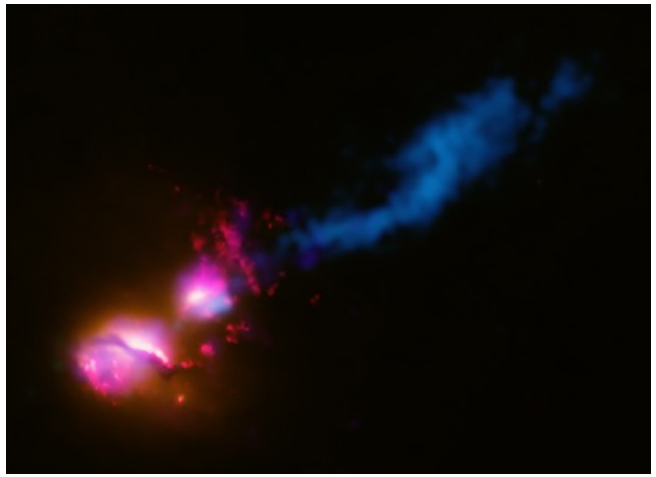
Aktivna Galaktička Jezgra (AGJ)=kvazari

*važno: centar i dalje teško može direktno da se posmatra!



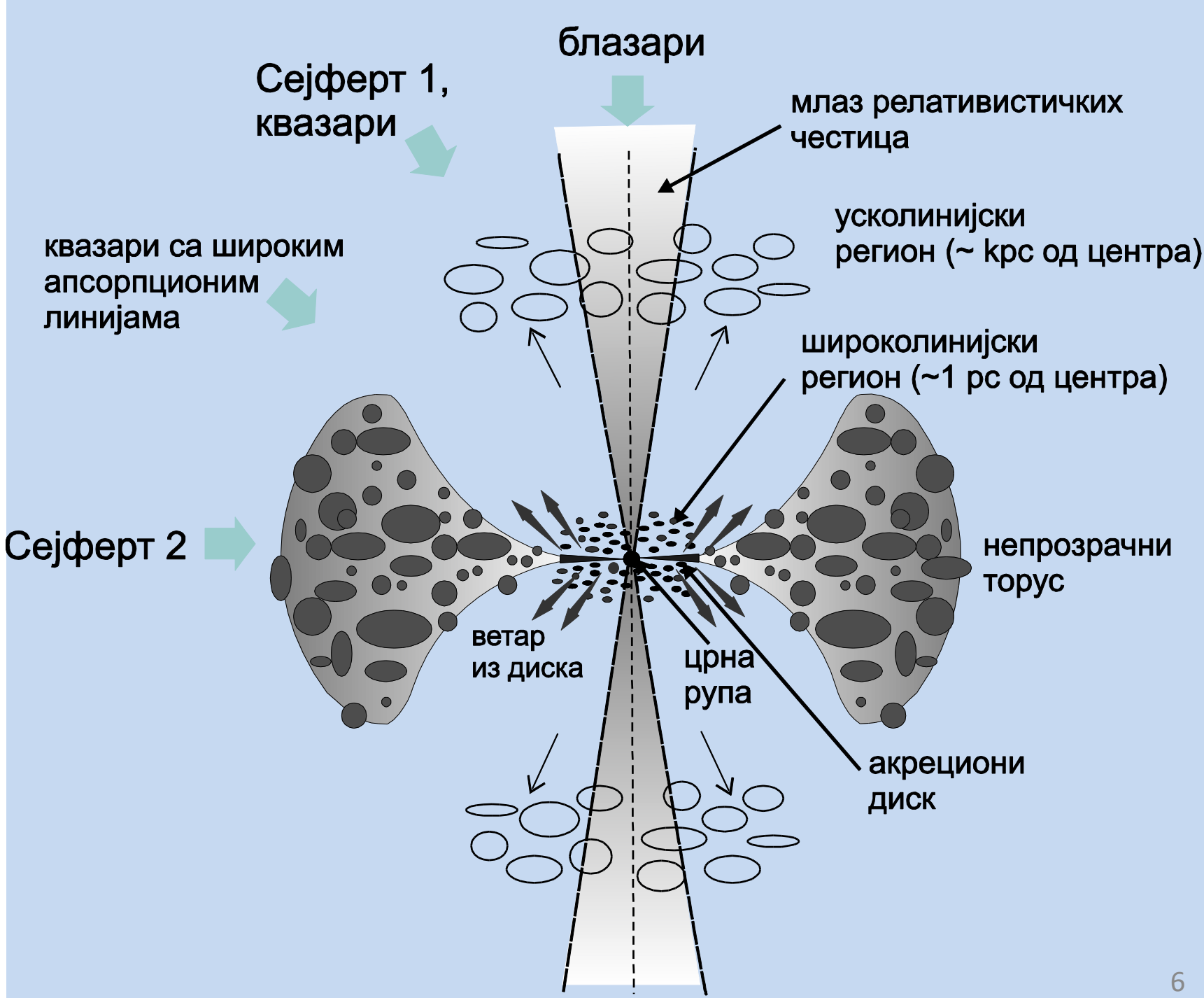
AKTIVNA GALAKTIČKA JEZGRA (AGJ)

- posmatrane karakteristike AGJ :
  - kompaktna veličina
  - ogroman sjaj: do 10^{15} puta luminoznost Sunca
  - zrače na svim talasnim dužinama
  - intenzivne široke i uske emisione linije
  - promenjivost fluksa (~1 dan!)
  - najjači radio-izvori
  - polarizovano zračenje



Jedinstveni model AGJ

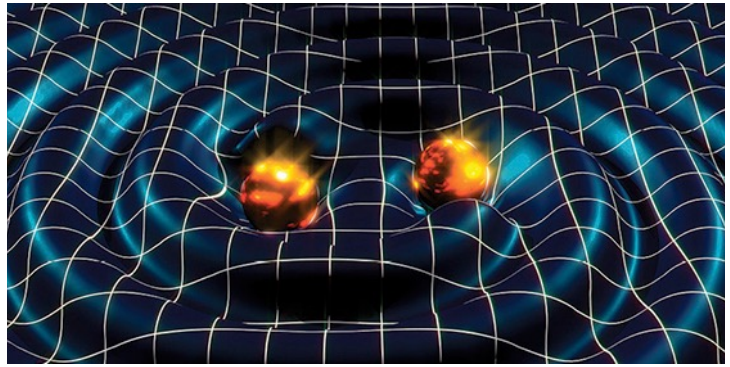
- supermasivna crna rupa
  - od milion do 10 milijardi Msun
- akrecioni disk
- emisioni regioni koji emituju široke i uske emisione linije
- “torus” prašine
- mlazevi relativističkih elektrona



Značaj AGJ/kvazara

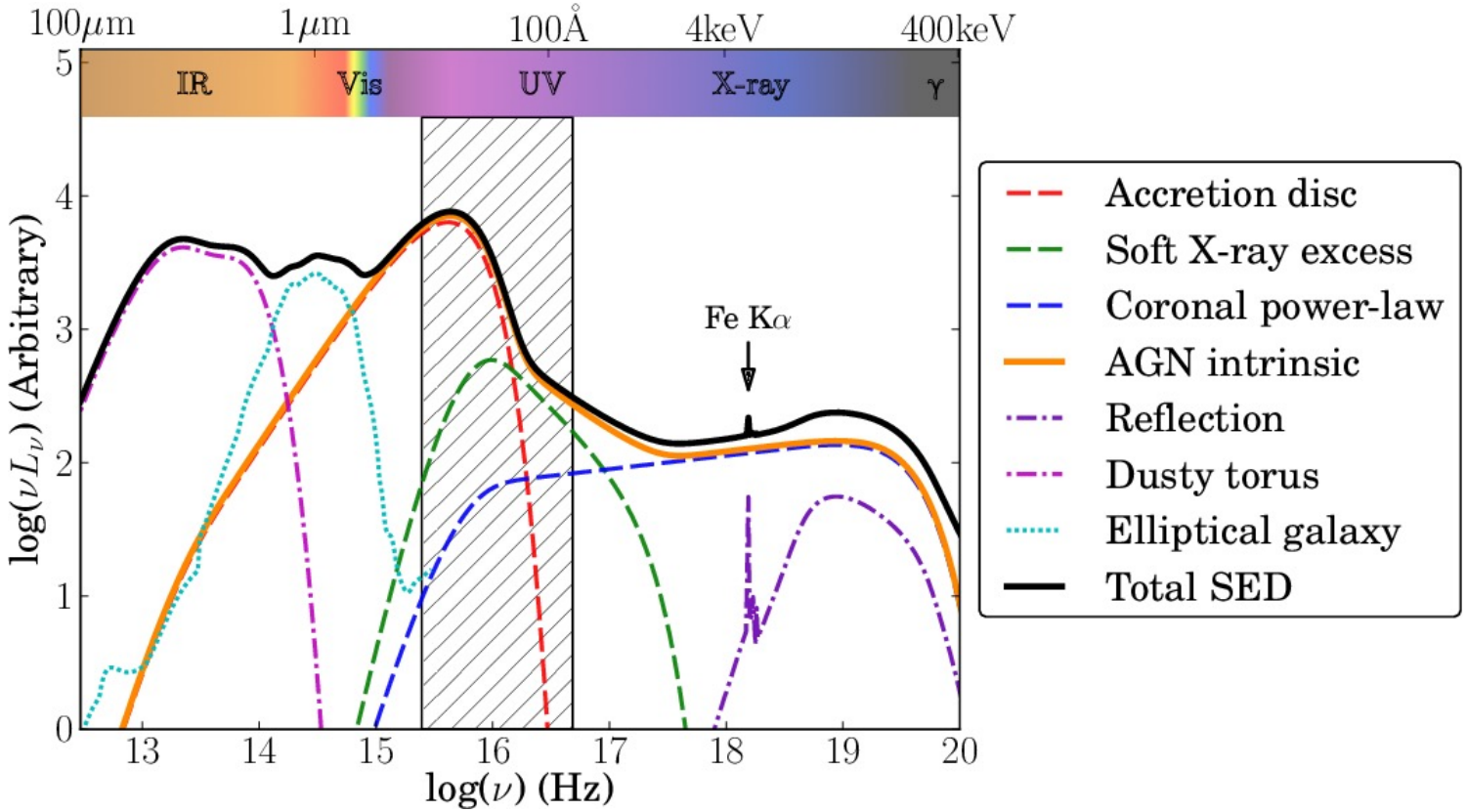
- Formiranje i evolucija galaksija
  - aktivnost u galaksijama – verovatno prisutna u svakoj galaksiji u nekoj fazi evolucije
  - sve (velike)galaksije imaju u svom jezgru supermasivnu crnu rupu
    - kako nastaju? kako rastu? uticaj na okolnu galaksiju?
- "multimessenger" astronomija: gravitacioni talasi
  - potraga za dvojnim supermasivnim crnim rupama
    - teško ih je naći na malim skalama (e.g. Popović+12, Komossa+03, Ge+12, Benitez+18)
    - važnost spektroskopije (Bon+12,16, Liu+16) i analize periodičnosti u fotometrijskim krivama sjaja (Graham+09,17, Kovačević+2019)
- osnovni cilj astronomije → nove metode za merenje rastojanja koristeći kvazare
  - npr. koristeći UV i optičke široke emisione linije (e.g. Watson+11, Marziani+20)

M87, EHT Collaboration, 2019



Šta možemo da posmatramo?

- spektar na svim talasnim dužinama
- sve tehnike
  - fotometrija
  - spektroskopija
  - polarimetrija

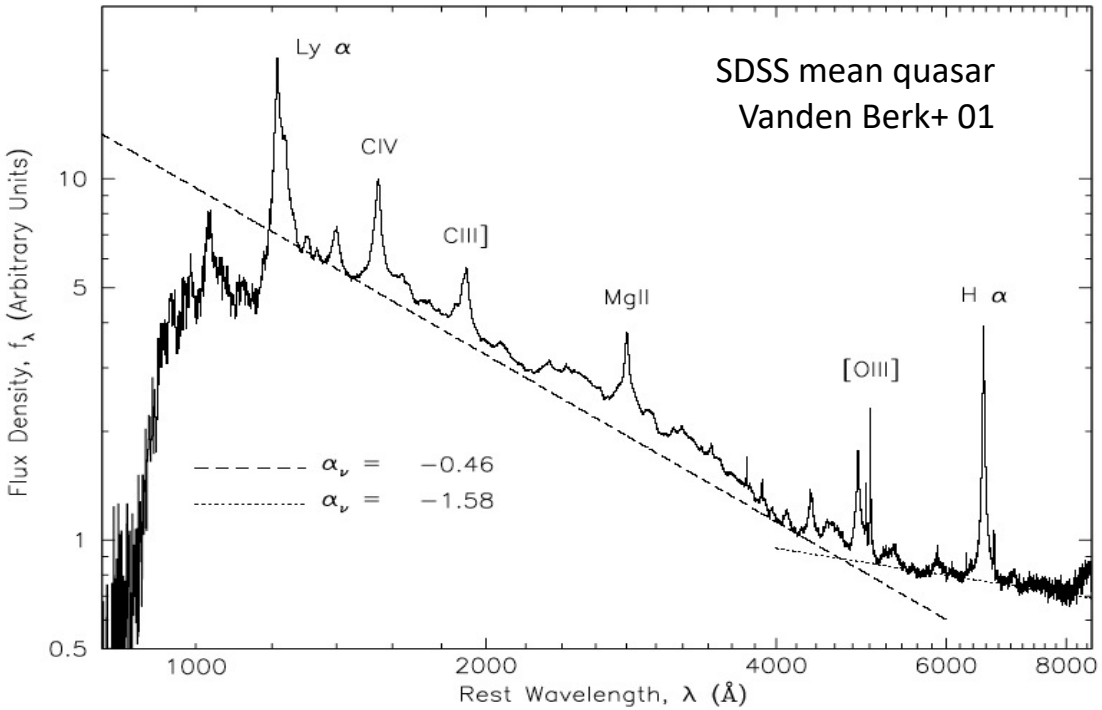


Collinson et al. 2016

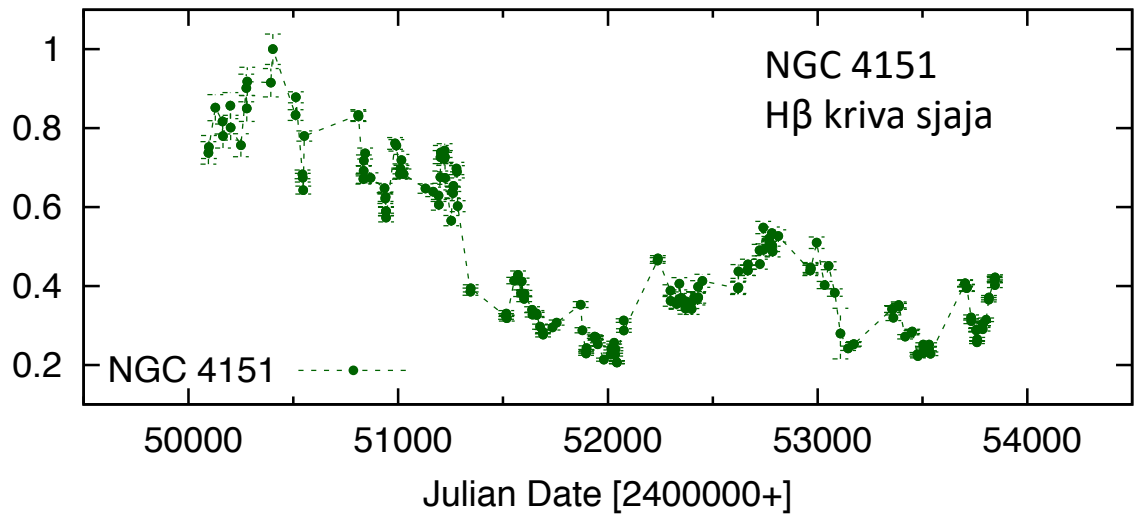
Optička spektroskopija AGJ

Široke emisione linije (širina i preko 10,000 km/s)
- Različiti stepeni jonizacije
- Kompleksni profili
- Moćan alat za dijagnostiku fizičkih i kinematičkih uslova

Sve se menja!
- fluks kontinuuma i u linijama
- profili linija
- ponekad ekstremna promenjivost



Shapovalova+ 2008



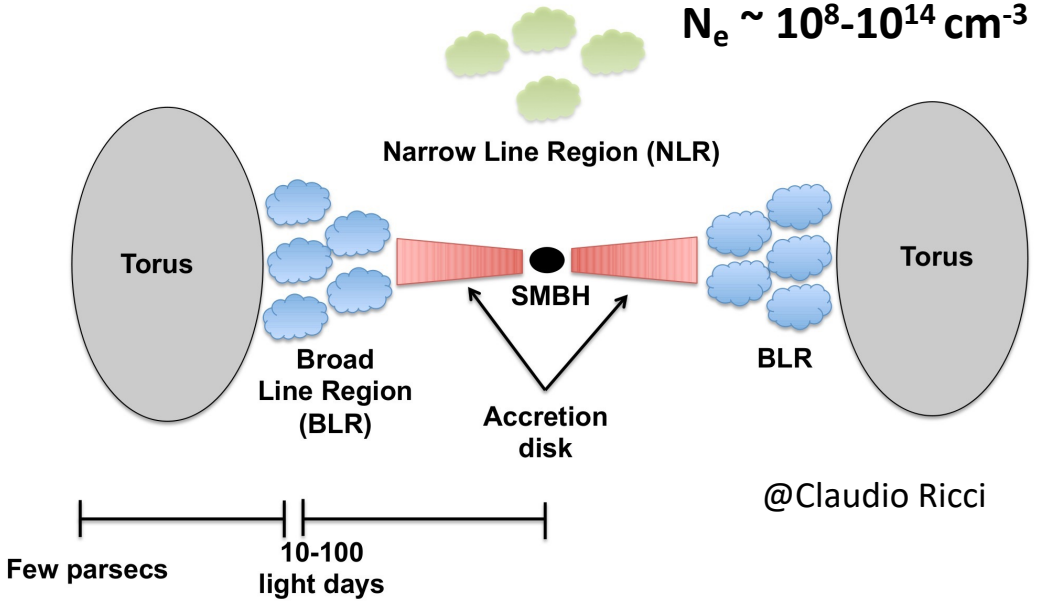
Emisioni gas u AGJ

- **tip 1 AGJ** – sa širokim emisionim linijama
  → širokolinijska oblast (***Broad Line Region - BLR***)

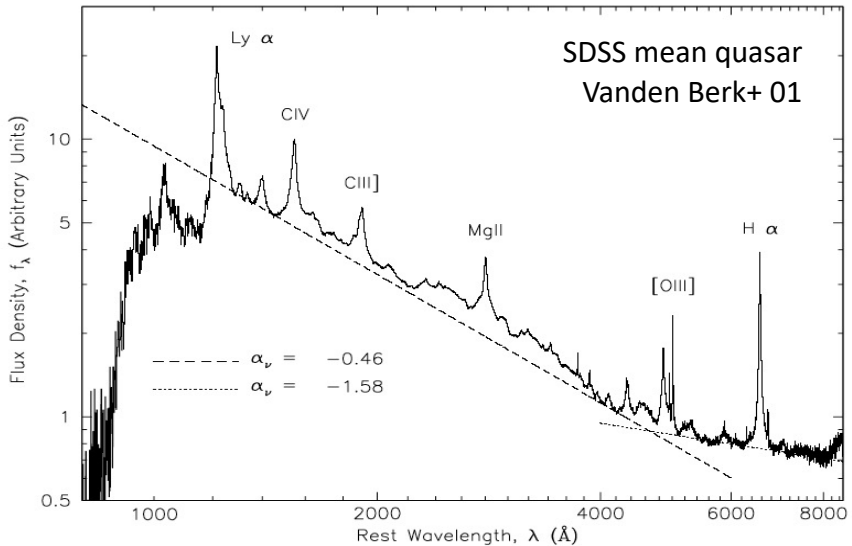
- kako znamo da postoji BLR? NE ZNAMO!
  → imaging: VLT- GRAVITY - 10 μas
  (GRAVITY Collaboration 18, 20, 21), budući ELTs
  → **spektroskopija i dalje jako važna**

- BLR fizika i geometrija i dalje nisu u potpunosti istražene
  → koja je temperatura gasa i gustine? (Ilić+12)
  → da li je BLR gravitaciono vezana za crnu rupu? (Popović+2019)
  → kakva su kretanja gasa, rotacija ili izbacivanje? (e.g. Wang+17)
  → koji je nagib ovog regiona prema posmatraču? (e.g. Afanasiev+18)

BLR gas: $T_e \sim 10^4$ K
$N_e \sim 10^8$-10^{14} cm^{-3}

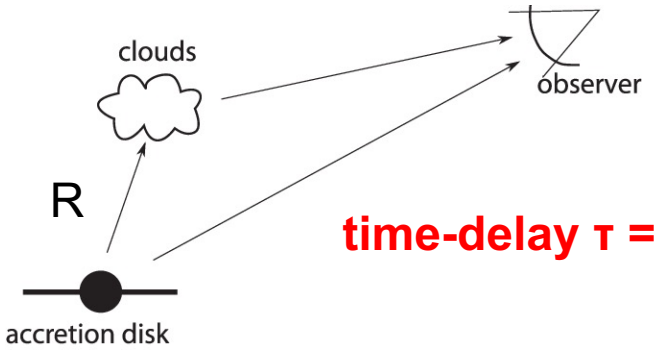


@Claudio Ricci



Reverberation Mapping (RM)

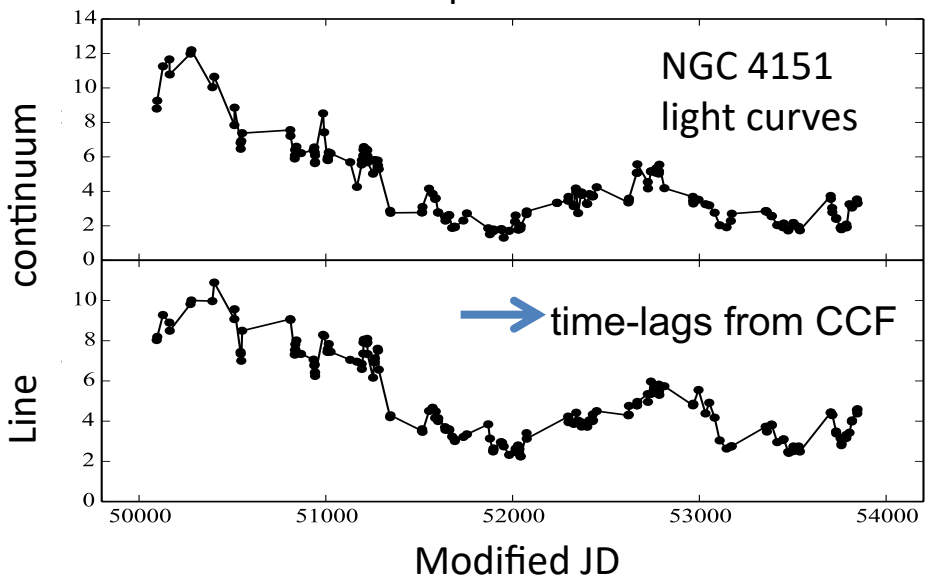
- there is a **time-delay** btwn. continuum and line flux



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

time-delay τ = size R

Shapovalova+ 2008

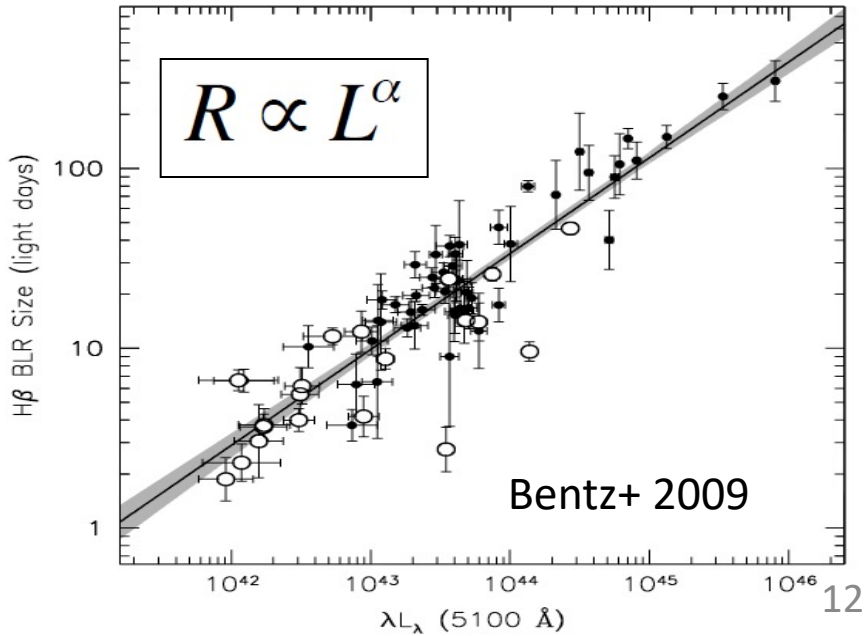


- only for ~100s AGN: direct measure of $\mathbf{R_{BLR}}$
- **once we have the radius** → can get **SMBH mass** from **single epoch** observation (e.g. Dibai 1977, Kaspi+ 2000, Peterson+ 2004, Bentz+2009)

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

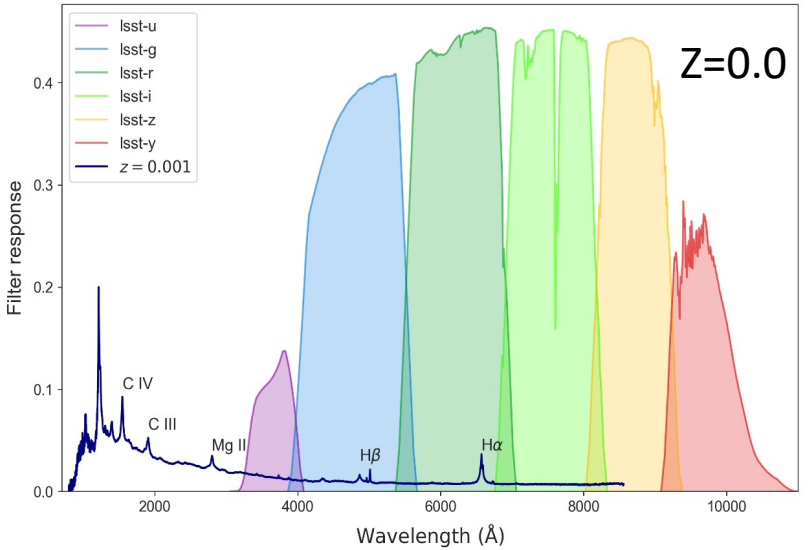
Dibai method

- empirical Radius-Luminosity (R-L) relation



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

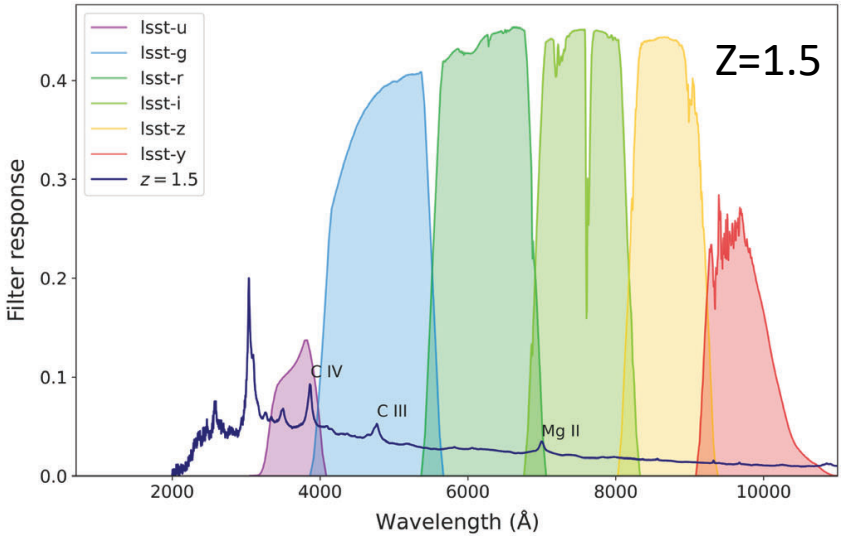


Jankov et al. 2022

- 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)



AGN variability hot topics

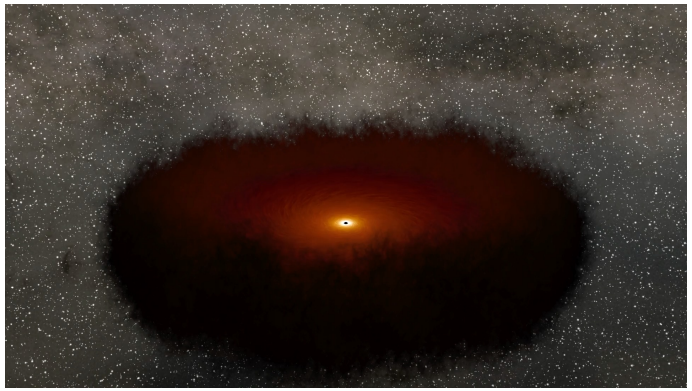
AGN structure **can be resolved in time-domain**

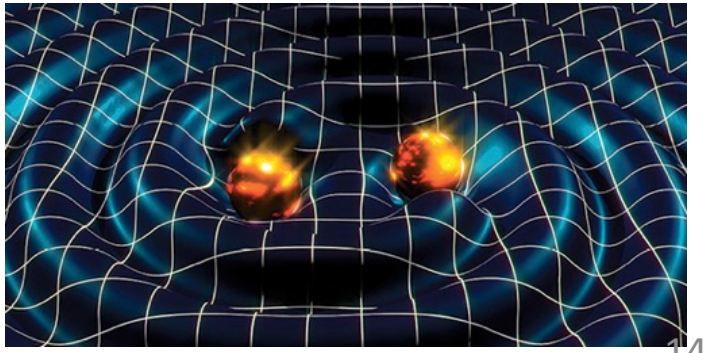
1. map accretion disk and BLR through **reverberation mapping**:
   → map the BLR and measure SMBH mass (see review Popović 20)
   → among priorities of LSST AGN Science Collaboration (e.g. Brandt+18)

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-Caltech





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Getting ready for

Legacy Survey of Space and Time

- Vera C. Rubin Observatory aims to conduct the 10-year **Legacy Survey of Space and Time (LSST)**
- 500 petabyte set of images and data products
- Time domain astronomy is coming
- Planned start in 2023, 8m telescope, Chile
- **Big data, movie of the sky**

VERA C. RUBIN
OBSERVATORY

July 2021

3.6×10^{-31} erg/s/cm^2/Hz
36 nJy

LSST in one sentence:

An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 based on ~1000 visits over a 10-year period:

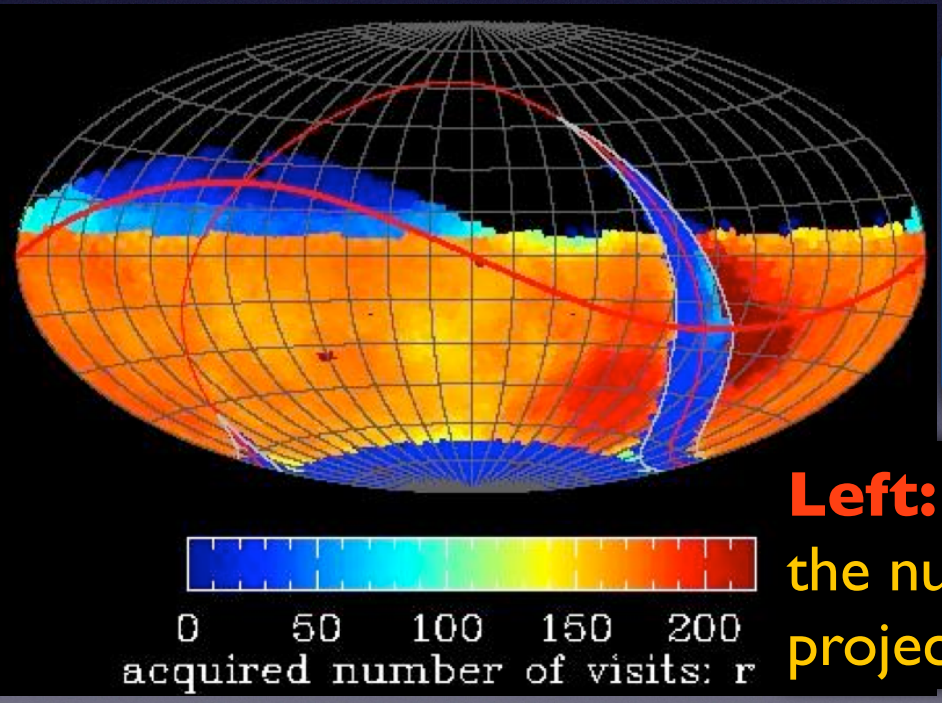
More information at www.lsst.org and arXiv:0805.2366

A catalog of 20 billion stars and 20 billion galaxies with exquisite photometry, astrometry and image quality!

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.

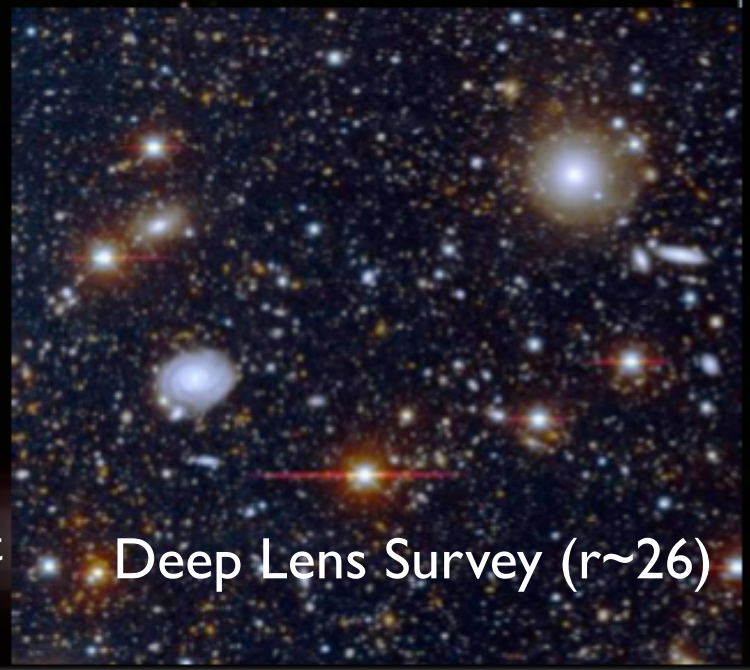
Left: a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

From Zeljko Ivezic slides
Rubin Observatory Director

SDSS vs. LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

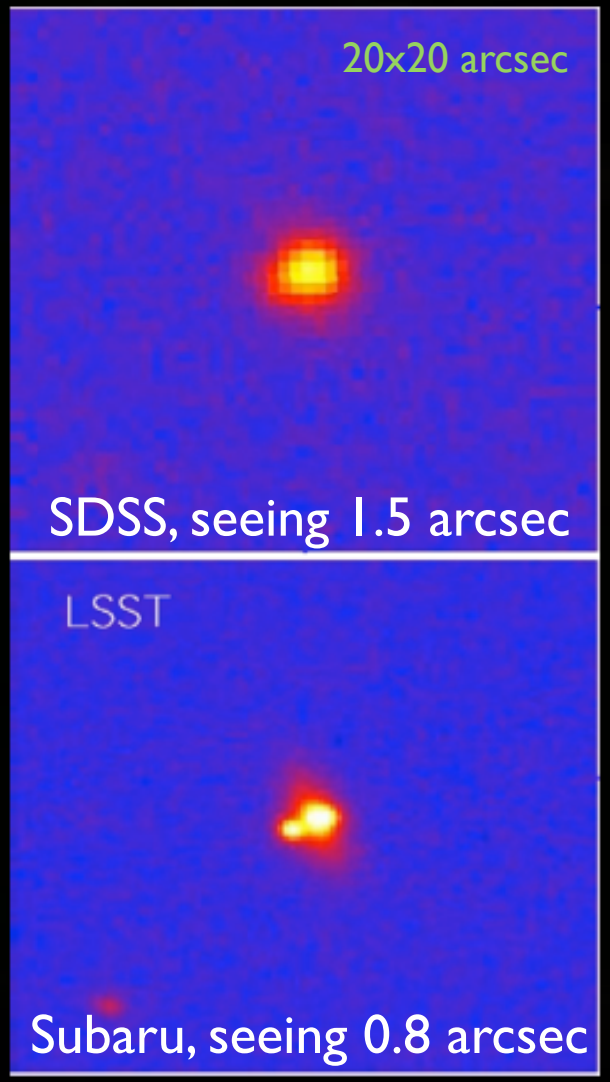
3x3 arcmin, gri

3 arcmin is 1/10 of the full Moon's diameter



(almost) like LSST depth (but tiny area)

20x20 arcsec; lensed SDSS quasar (SDSS J1332+0347, Morokuma et al. 2007)



From Zeljko Ivezic slides
Rubin Observatory Director

SDSS
gri
3.5'x3.5'
r~22.5

From Zeljko Ivezic slides
Rubin Observatory Director

HSC
gri
3.5'x3.5'
r~27

Like LSST, but tiny area: LSST will deliver 5 million such images

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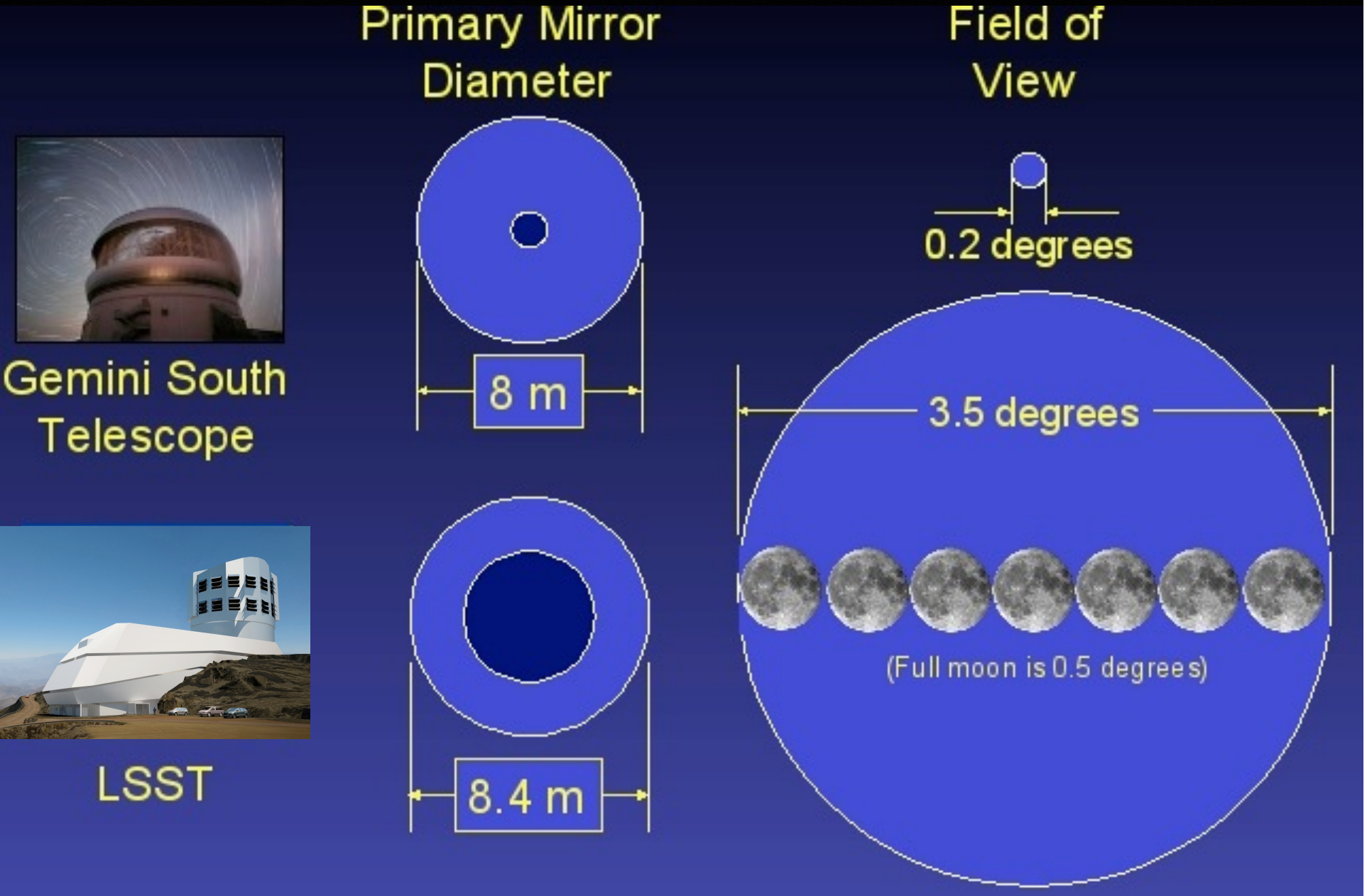
The field-of-view comparison: Gemini vs. LSST



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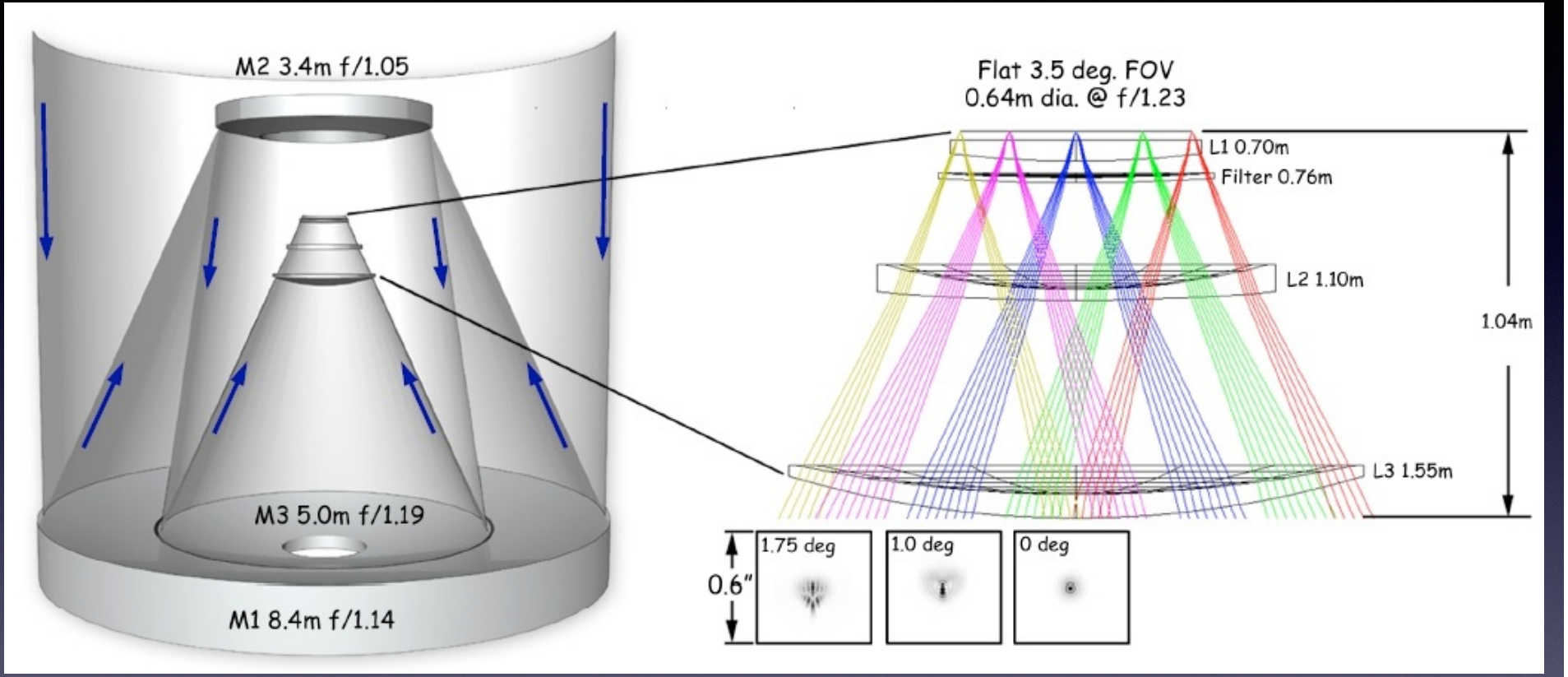
Optical Design for LSST



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

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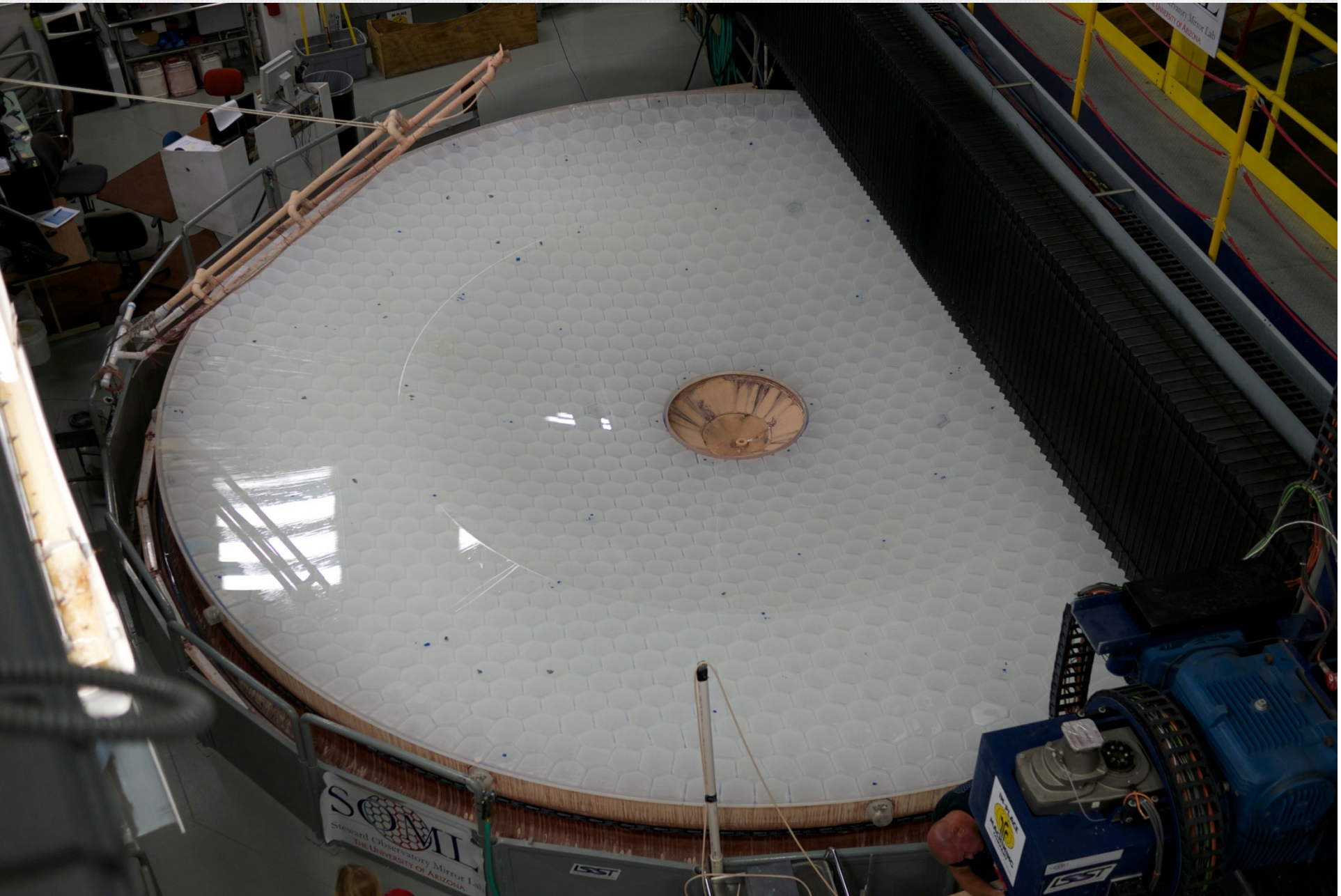

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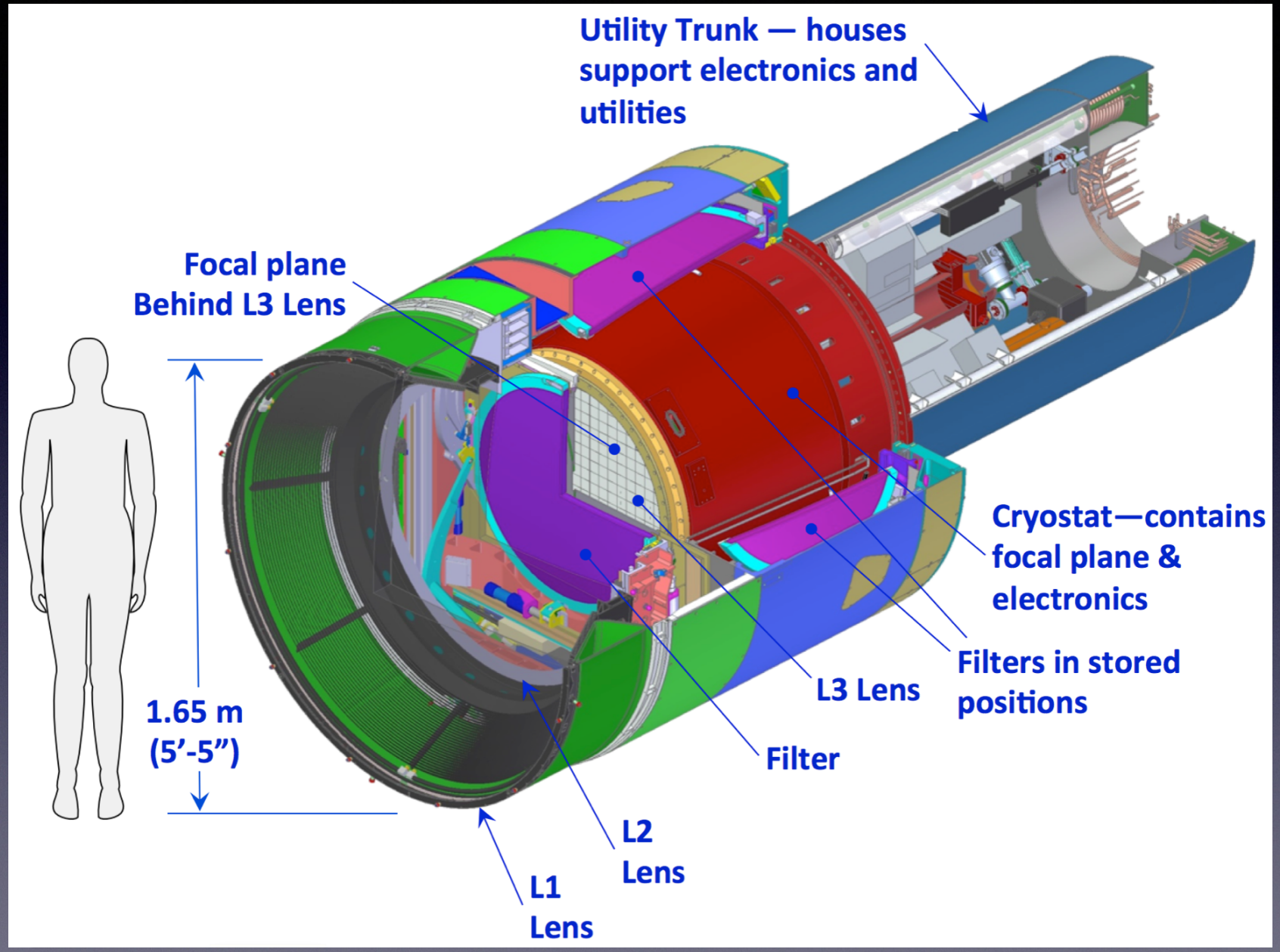
LSST camera



The largest astronomical camera: 2800 kg, 3.2 Gpix

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Rubin Observatory Director

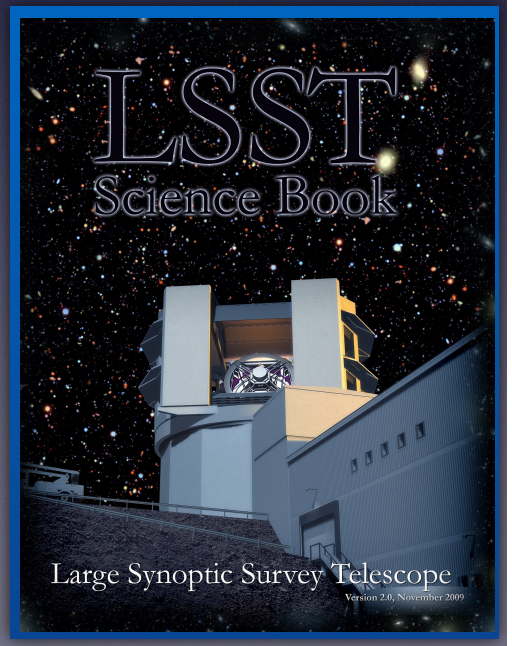
LSST Science Themes

- 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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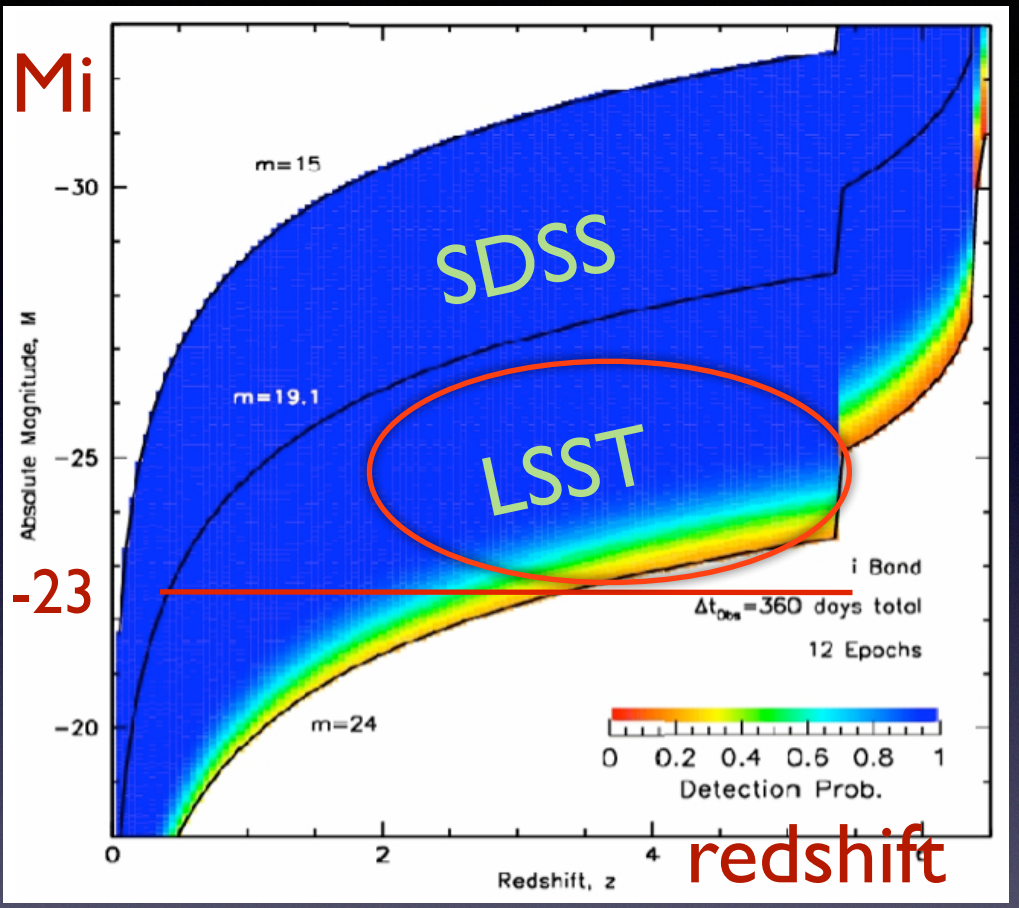
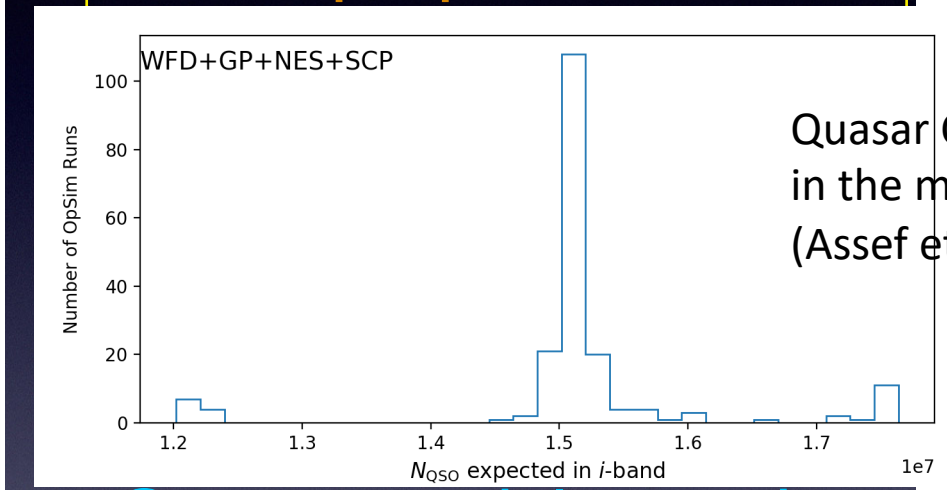
Extragalactic astronomy: quasars



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

Reionization studies!

Today: ~31 quasars with 6<z<7.5

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!

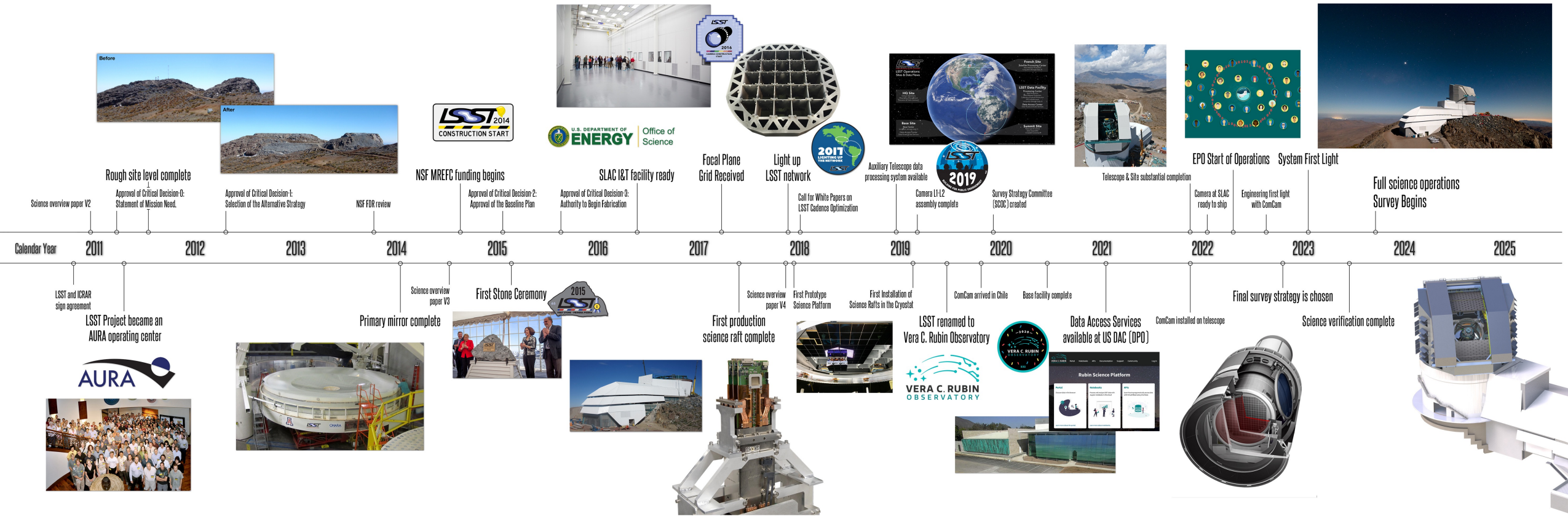
- Data analysis challenges ahead of us
  - large data sets
  - complex analysis
  - aiming for small systematics

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 is on the way! First light in 2023!



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

LSST: how to get involved

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

- 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

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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

Serbian Participation in LSST

- We got involved fairly-early - interest in 2009/2010
- Signed MOA's for 4 PI in 2013 (France + Serbia first to join)
  - standard contribution (20k$/year – increase from 2017) + in-kind
  - PI: Darko Jevremović: DESC and Transients and Varaible stars
    PI: Luka Popović: Active galactic nuclei
    + Junior associates
- Background: stellar atmospheres, stellar flares, use of HPC in astronomy + VO and astroinformatics; AGN and gravitational lenses
- Development of AlertSim (as in-kind)

LSST Project and Community Workshop
Tucson, AZ August 14-19, 2016

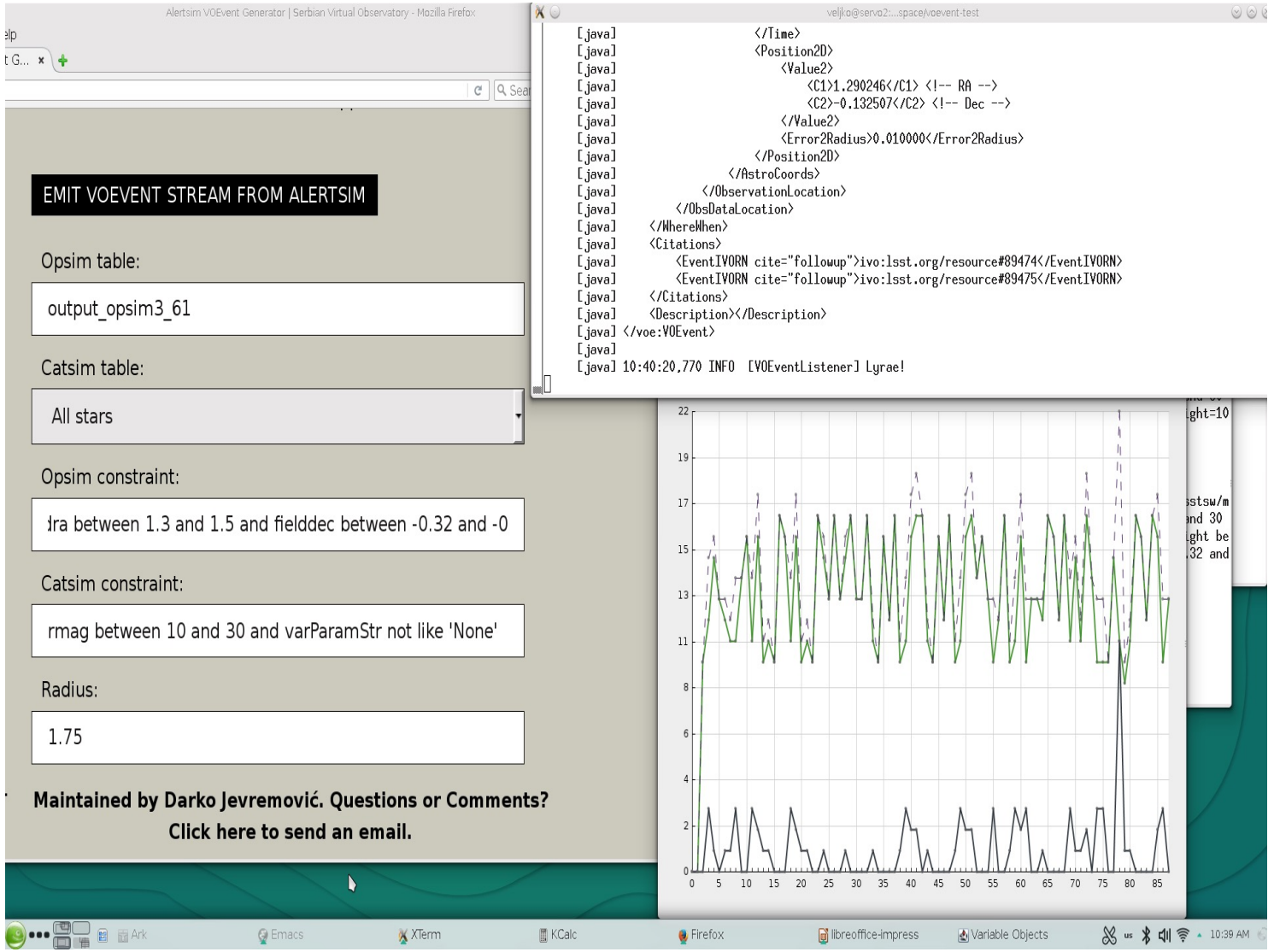
AlertSim Demo

From Nov 2016 AlertSim is included in the LSST Simulation codebase

Basic idea is to provide brokers (Antares etc.) heads up playground

Mainly for stellar science

Contacts: darko@aob.rs



International in-kind

- New Call for proposal, September 2020
  - In-kind Proposal Handbook at http://ls.st/RDO-031
- *Full proposal to make specific in-kind contributions of labor, computing resources, equipment, telescope time or synergistic datasets, to the Rubin Observatory or the Rubin Observatory LSST science program, in return for the same LSST data rights and access as enjoyed by US and Chilean scientists.*

- Review, feedback, update, approval, approvals: July 2021
  - In-kind Program Manual at http://ls.st/RDO-041

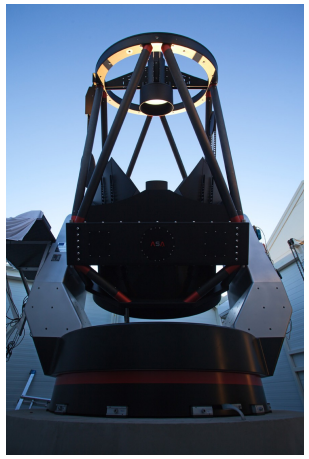
SER-SAG in-kind LSST contribution

- Serbian AGN Team in LSST → **SER-SAG**
  - members of AGN and TVS Science Collaboration

There was a call for in-kind proposals in september 2020

- Institutions: Astronomical Observatory, Department of Astronomy
- Proposal Lead: Luka Č. Popović
  Project Manager: Dragana Ilić
  Contribution Leads: Anđelka Kovačević, Maša Lakićević

Vidojevica 1.4m



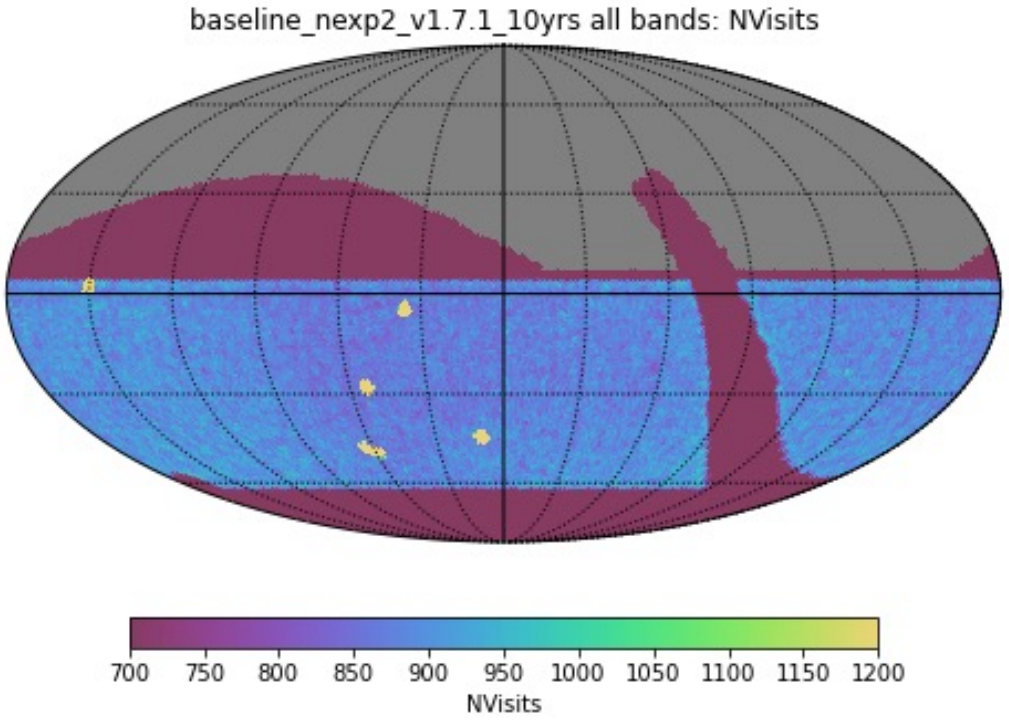
two in-kind efforts:

1. **Directable software development** for analysis of variability of celestial sources (Lead: A. Kovačević)
2. **Optical follow-up of bright LSST transients** with AS Vidojevica, join via AEON (Lead: M. Lakićević)

Rubin Observatory

LSST operation strategies

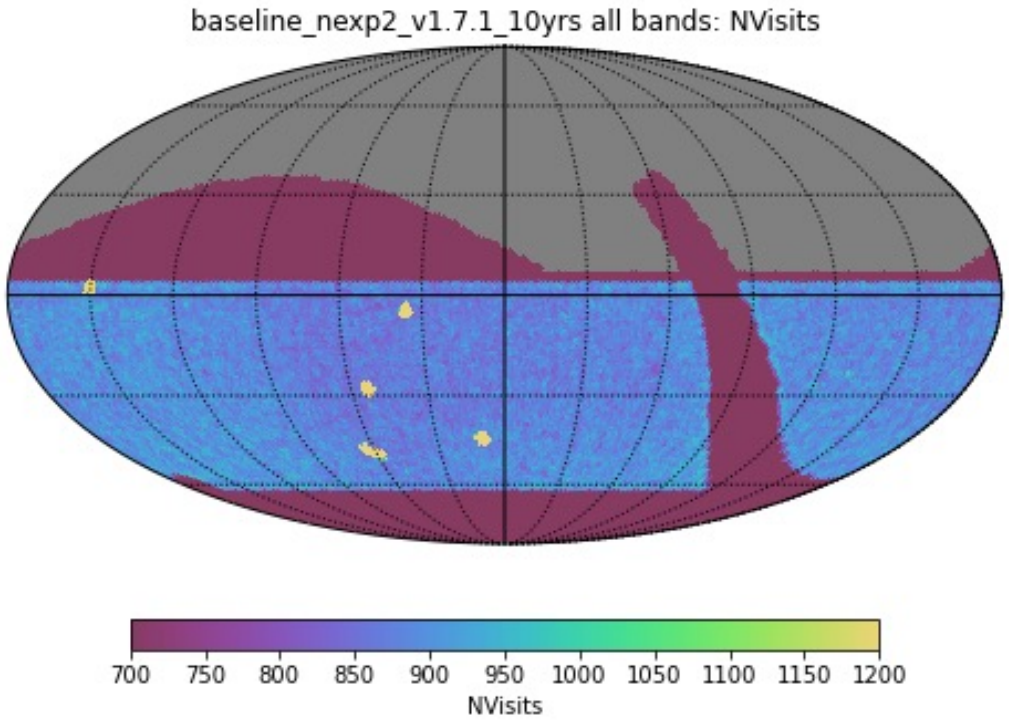
- Main survey – Wide Fast Deep (WFD)
  - currently in decision: cadence optimization
- Mini surveys – e.g. Deep Drilling Fields (overlap with other missions, e.g. Euclid)
- Micro Surveys



LSST call for cadence notes

- community is asked to comment the LSST Operation Simulation (OpSim, Jones et al.)

- Important to test different proposed cadence (e.g. rolling cadences) for all proposed science cases
  - E.g. For our case to test if with the proposed cadence we could extrat accurate time-lag or periodicity from light curves



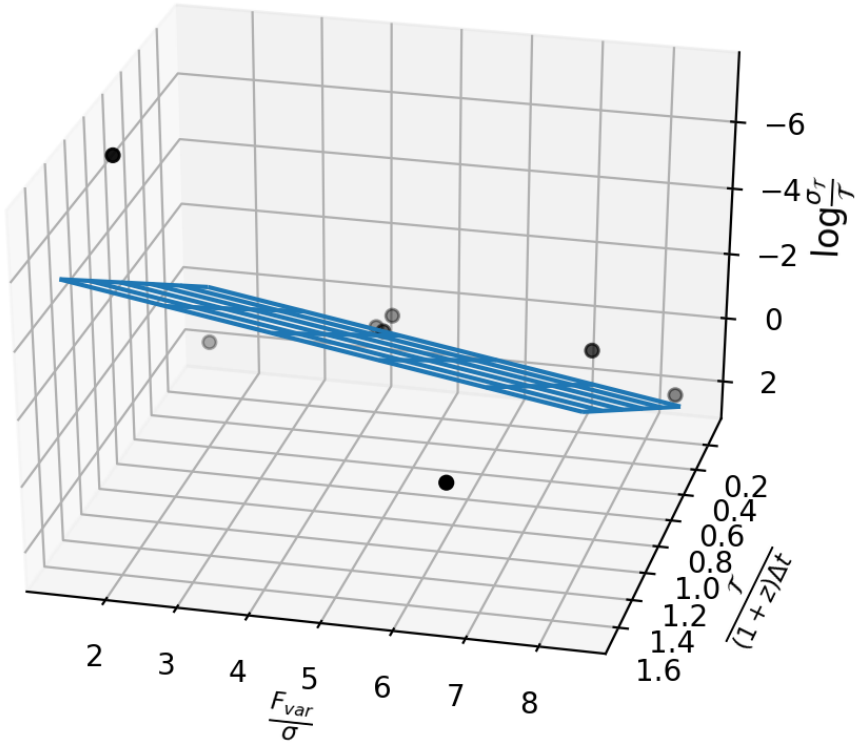
In-kind software contribution

- Directable Software in-kind contribution
  - Contribution Lead: Anđelka Kovačević
  - Members: Viktor Radović, Mladen Nikolić
- **Tasks and activities**
  - developed metric for AGN RM time lag measurement
  - pipeline for periodicity detection (under-construction)
  - Project “Deep Learning Engines”

https://github.com/LSST-sersag/maf_metrics

2D Cadence metrics for time-lags and periodicity detection in AGN light curves

- probe the accuracy of time-lag/periodicity estimates
- AGN structure function metrics
- based on real AGN light curves & simulated data (e.g. LSST OpSim)



Kovacevic, Ilic, Popovic, MNRAS, 2021

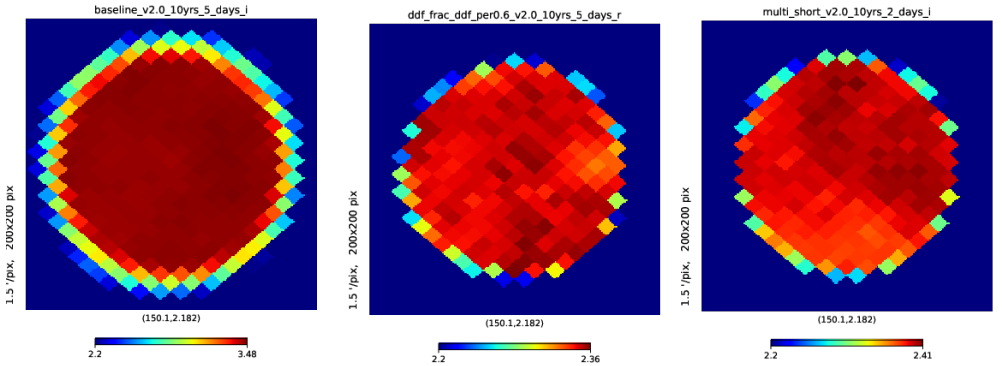
In-kind software contribution

- A. Kovacevic, R. Viktor: developed metric to assess LSST obs. strategies for AGN continuum-continuum time lags estimates
- relies on Nyquist sampling criterion → atlas of LSST sky regions good for continuum time-lags
  - the best strategies in DDFs with the best sampling ($\lesssim$ 5 days)
  - even with inferior sampling quality, time lags could be determined with accuracy of $\sim$ 10%.
- LSST continuum RM can apply deep learning techniques to improve the time-lag measurement

(Kovacevic et al., 2022, ready for submission to ApJS special issue dedicated to LSST operation strategies)

$$\frac{\tau_{\rm obs}}{(1+z)\Delta t^c} > 2.2$$

Kovacevic et al., 2022, in prep.

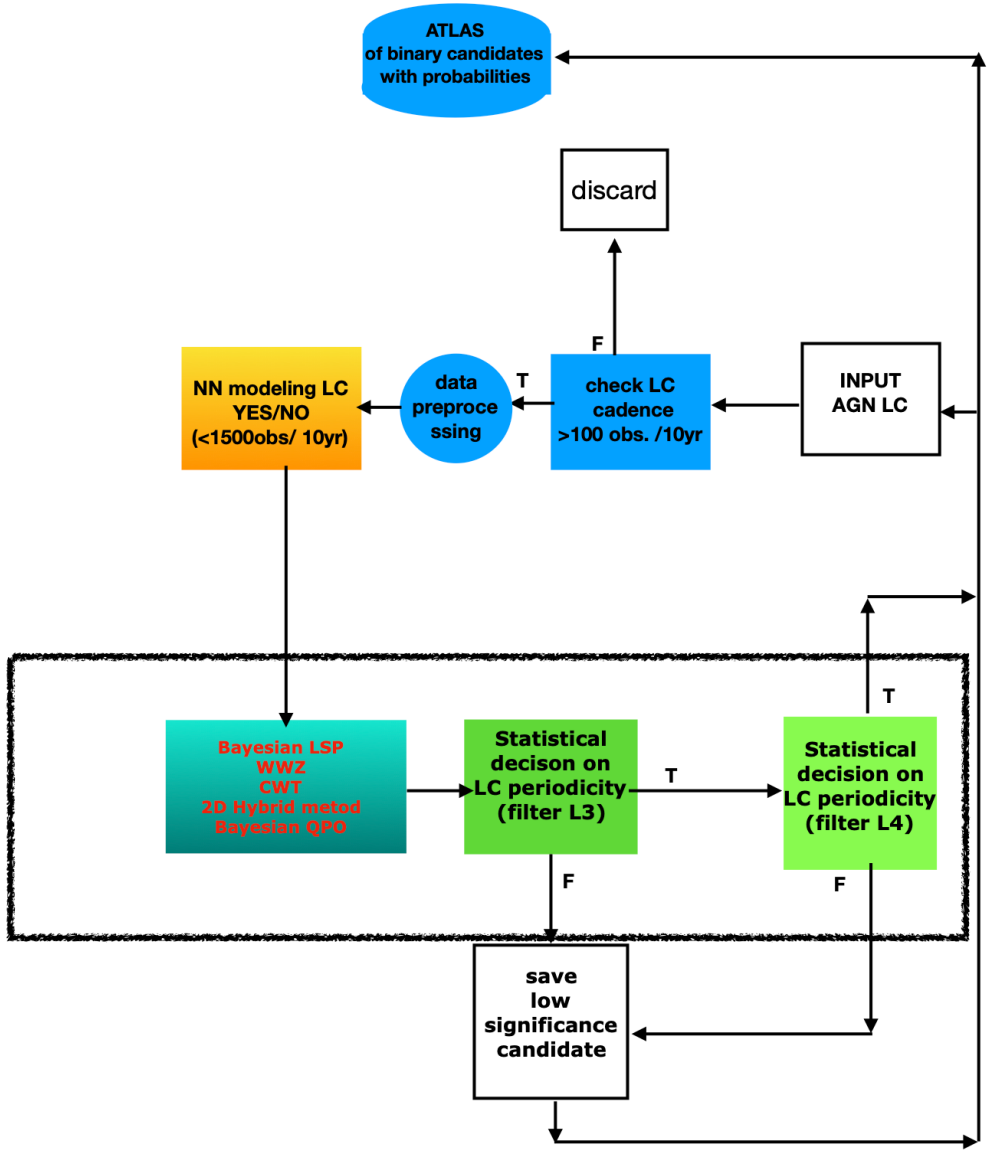


incorporated in LSST Metrics Analysis Framework (MAF)

In-kind software contribution

- Development of the periodicty-search pipeline for TVS and AGN SC
- jointly w/Rachel Street (co-chair of TVS SC)

- nonparametric and parametric light curve modelling
  - different time-domain period-detection algorithms
  - machine learning of light curves
  - estimates of significance of potential periods



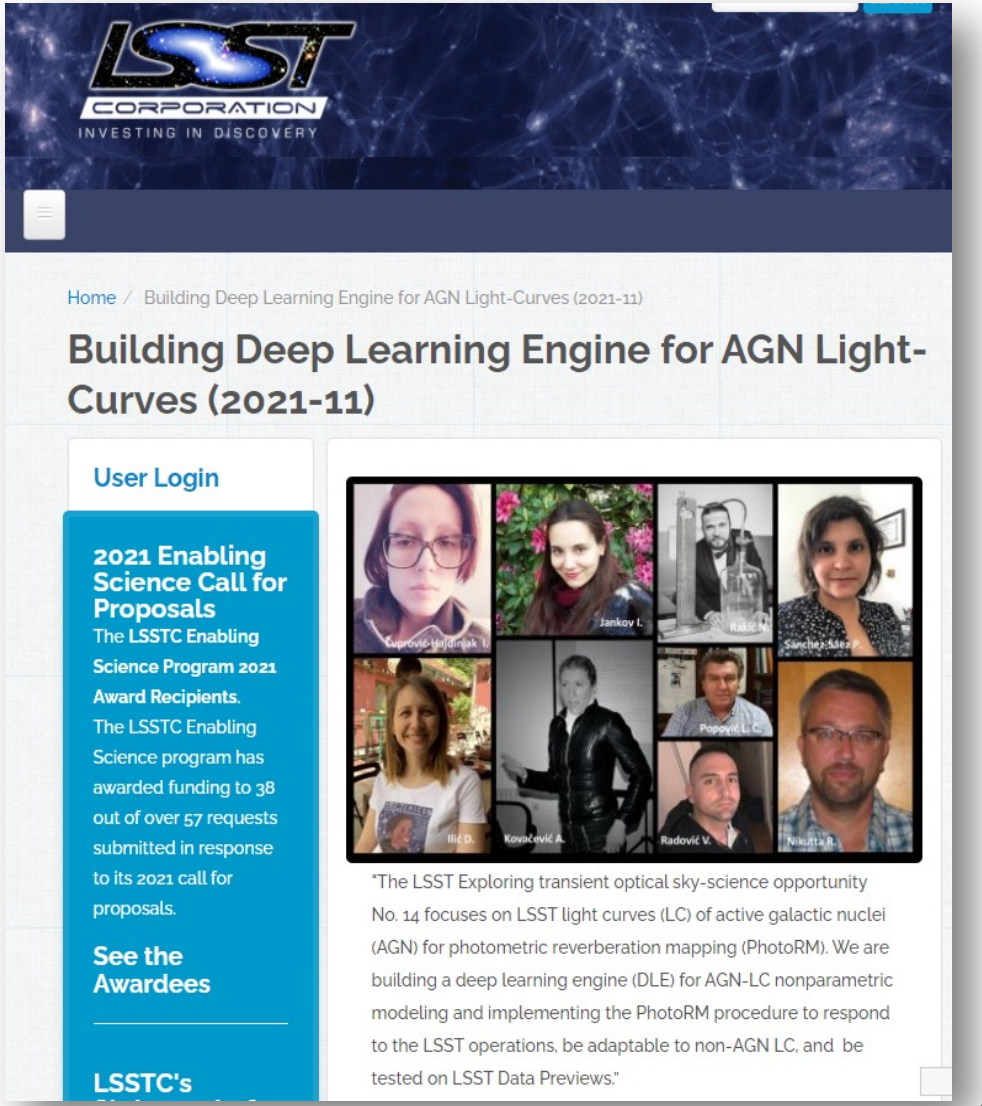
DLEs: Deep Learning Engines

- Developing deep learning engines (DLEs) for non-parametric modeling and extracting of information from AGN light-curves

- PIs: Andjelka Kovacevic, Dragana Ilic
- Co-Is: Luka C. Popovic, Paula Sánchez Sáez, Robert Nikutta

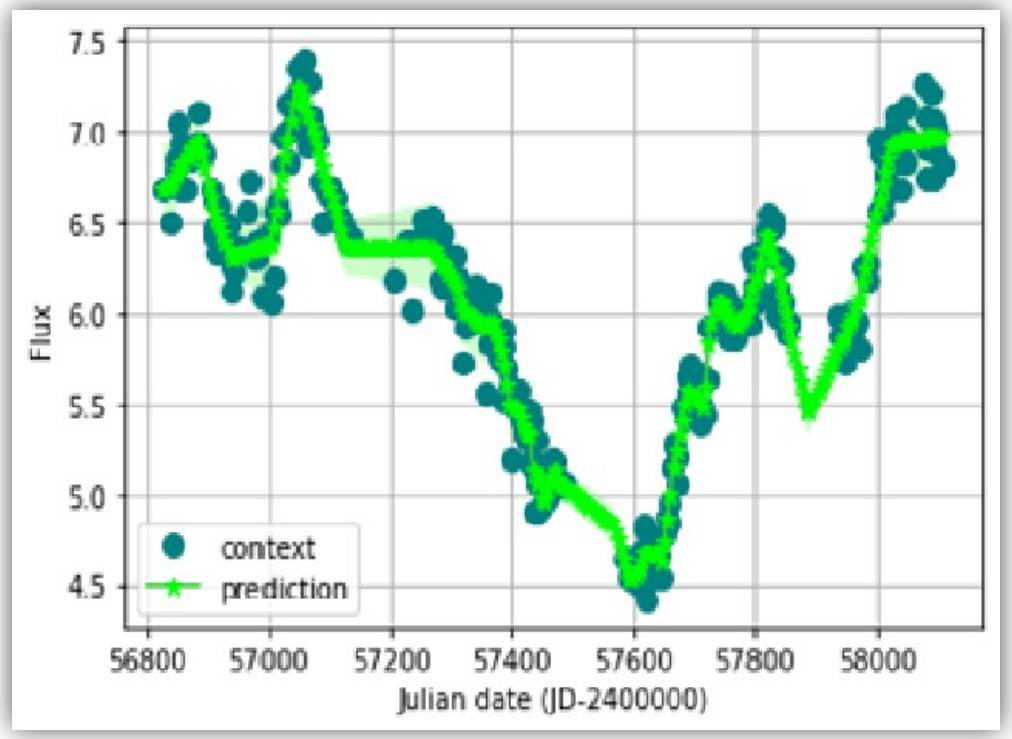
- **support for student research for 10 months in 2021-2022**

https://github.com/LSST-sersag/dle



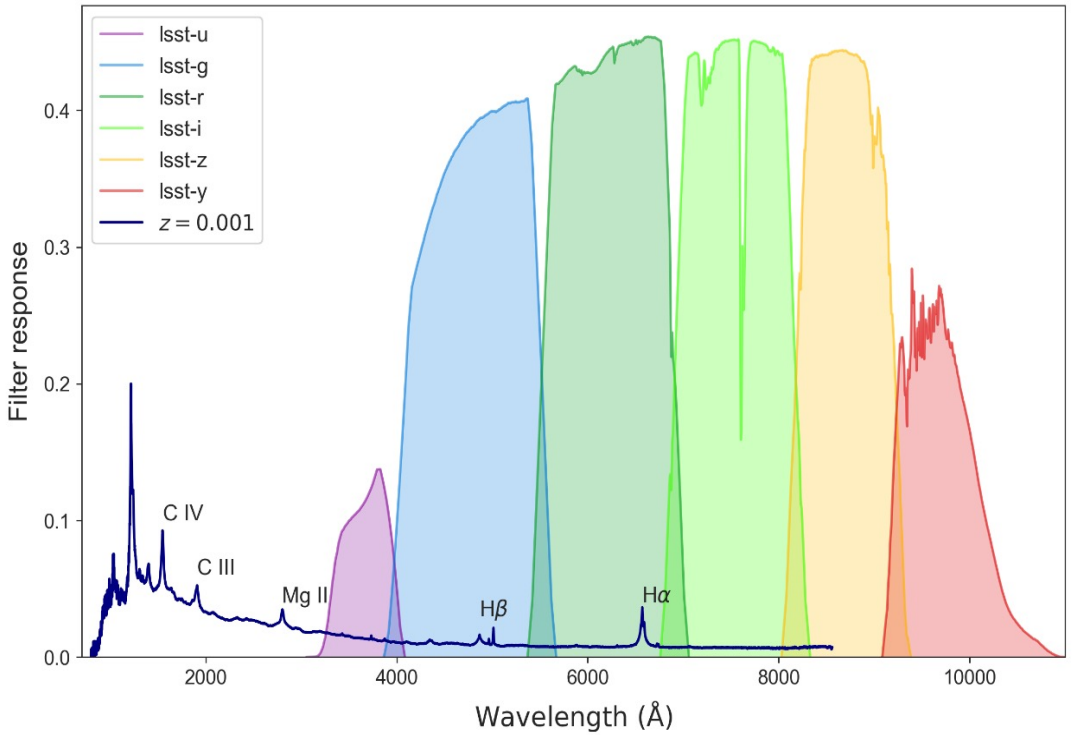
Two main projects

DLE subtask 1 (DLE1): Light Curve nonparametric modeling (Conditional Neural Process)



Learned LC will enable us to improve time-lag determination as a goal of PhotoRM.

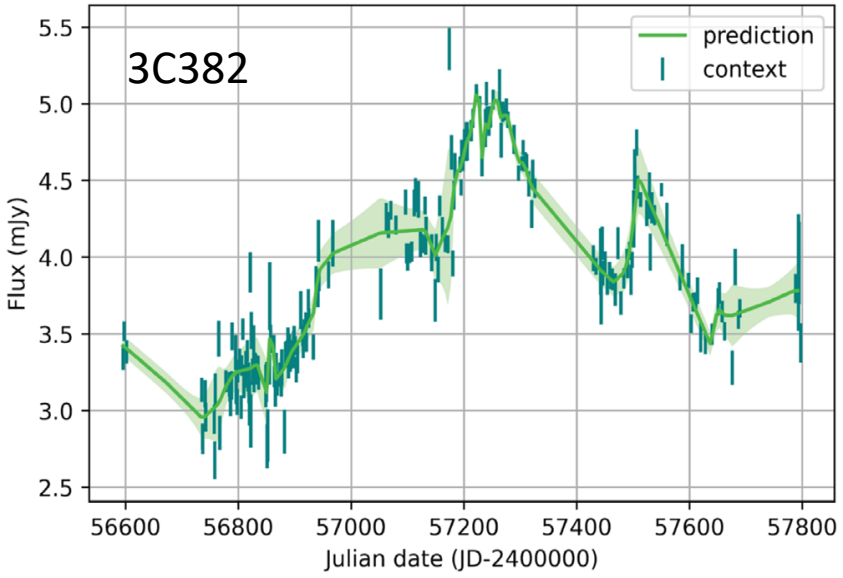
DLE subtask 2 (DLE2): photometric reverberation mapping (PhotoRM)

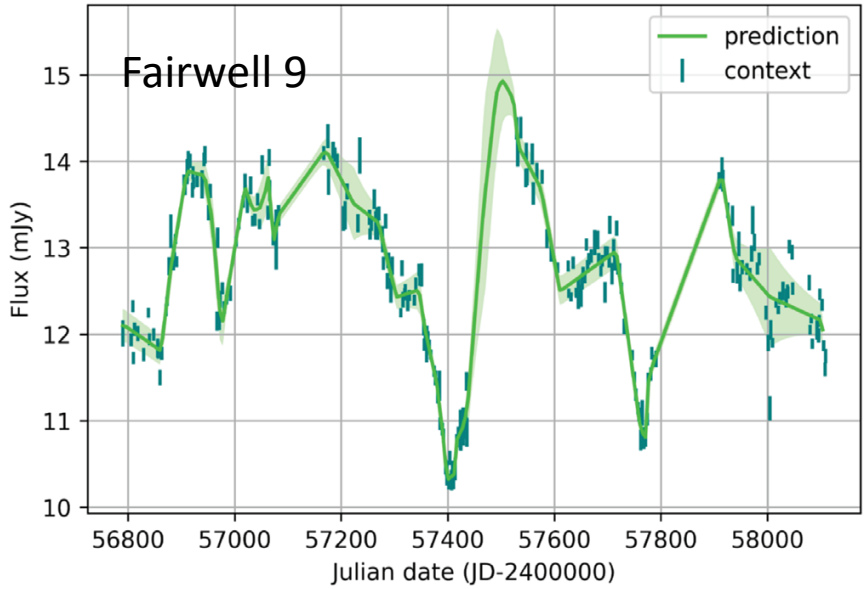


New tools for PhotoRM based on the formalism by Chelouche & Daniel (2012)

Non-parametric modeling of AGN light curves

- used Conditional Neural Process (Garnelo et al. 2018) for nonparametric modeling of AGN light curves
- tested on a sample of ~150 AGNs light curves from ASAS-SN (Holoien et al. 2017) with different structures (strong gradients, gaps, etc.) – **difficult to model**





see for details Čvorović-Hajdinjak et al. 2022

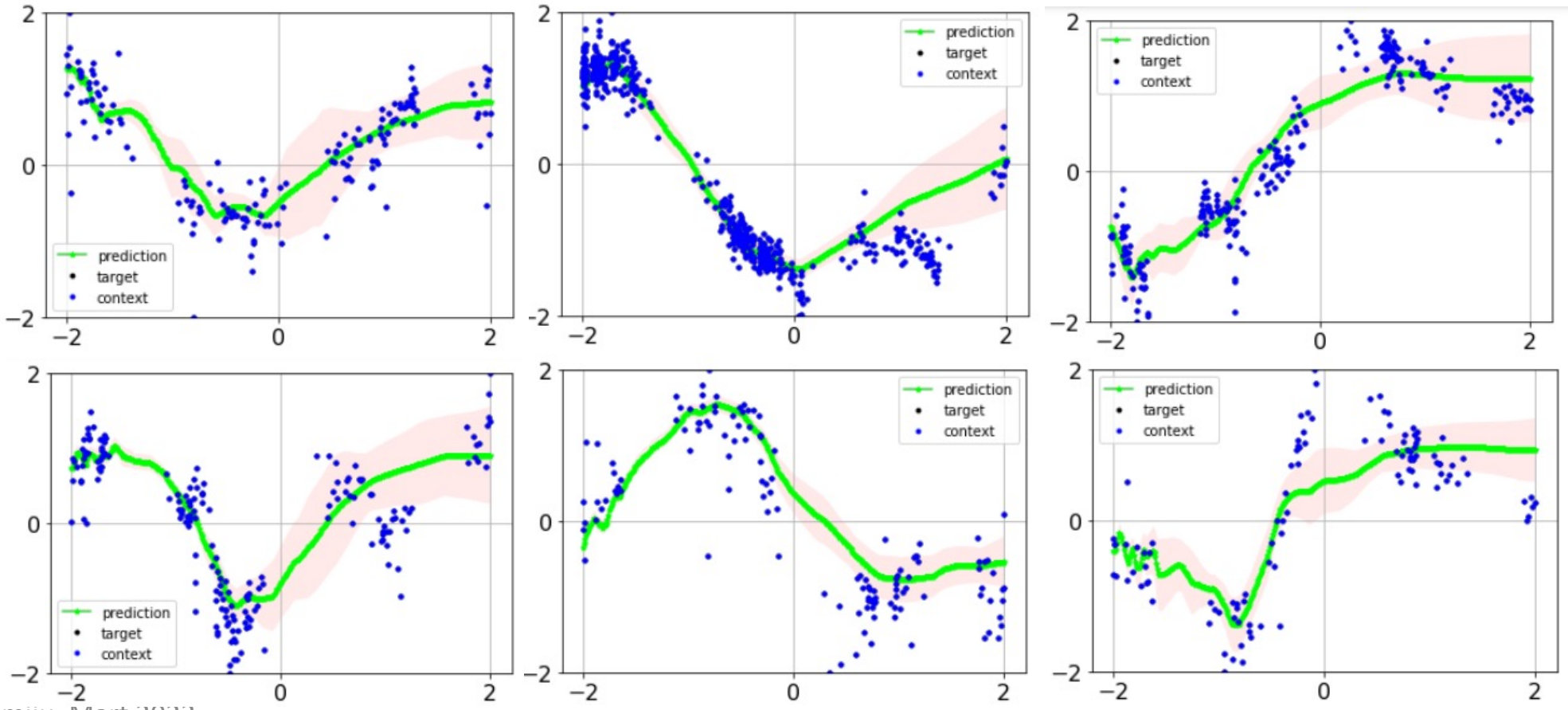
upgrade for large number of LCs

- Conditional Neural Processes trained on ~39,000 light curves for ~30h on 2,560 CUDA cores
- ZTF quasar light curves from Sánchez-Sáez, P., et al. (2021)

by Andrić Mitrović et al. 2022

Train

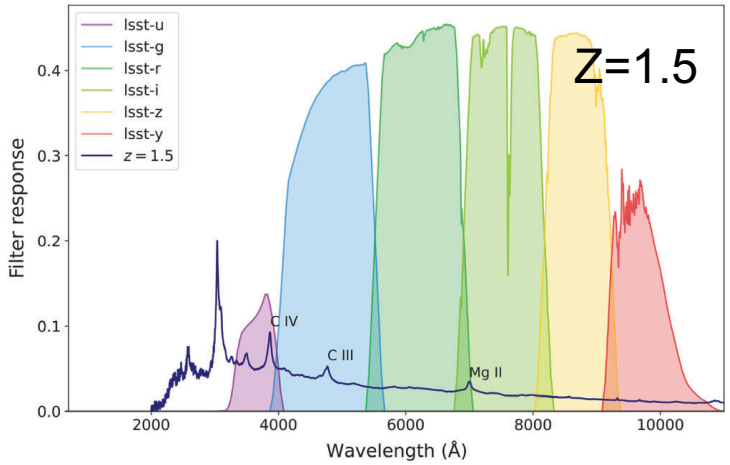
Test



Photometric reverberation mapping

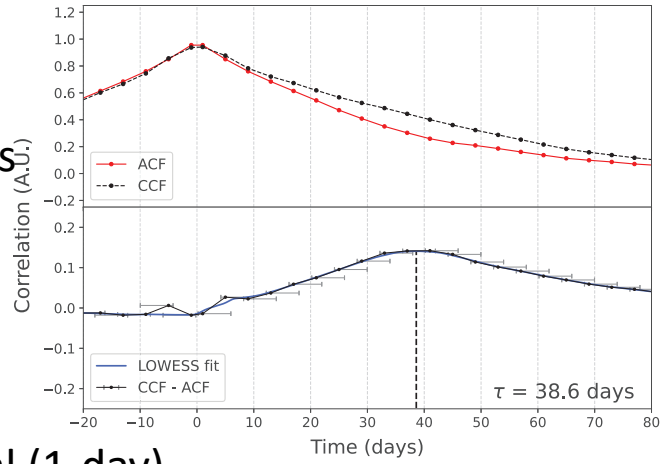
- the line emission hidden in the broadband light curve
- formalizm developed by Chelouche & Daniel (2012)
- time lag from cross (CCF) and auto-correlation functions (ACF)

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

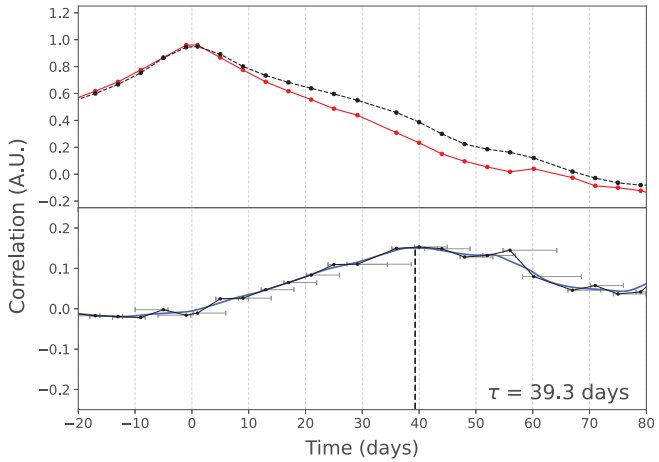


- Used artificial light curves based on DRW (Kovačević et al. 2021) with different cadences

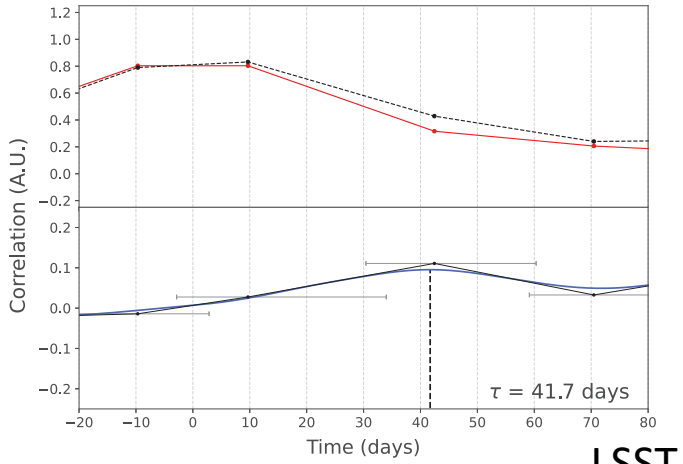
True lag
36.9 days



ideal (1-day)



with gaps

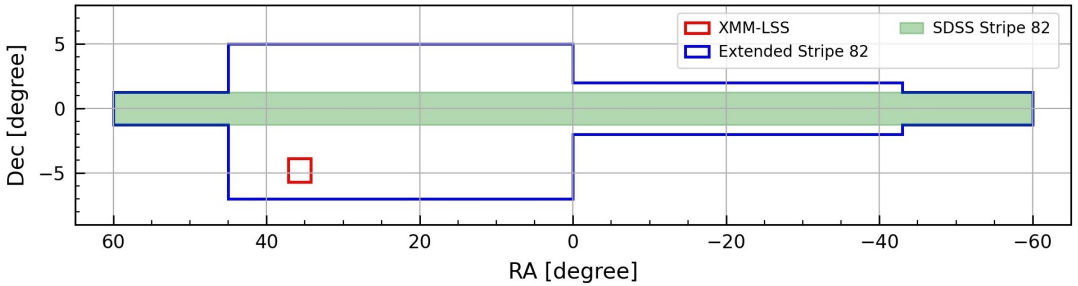


LSST-like

see for details Jankov et al. 2022

AGN Data Challenge 2021

- Aims: developing the data driven machine learning methods for studying AGN with the LSST
- dataset mimic the future LSST data release catalogs as much as possible (column names and follow that listed in the LSST Data Products documents (LSE-163)
- Dataset info:
  - ~440,000 objects
  - drawn from two main survey fields,
    an extended Stripe 82 area and the XMM-LSS regio
  - stars, quasars/AGNs and galaxies
  - tabular data (flux, astrometry, etc.), images and light curves

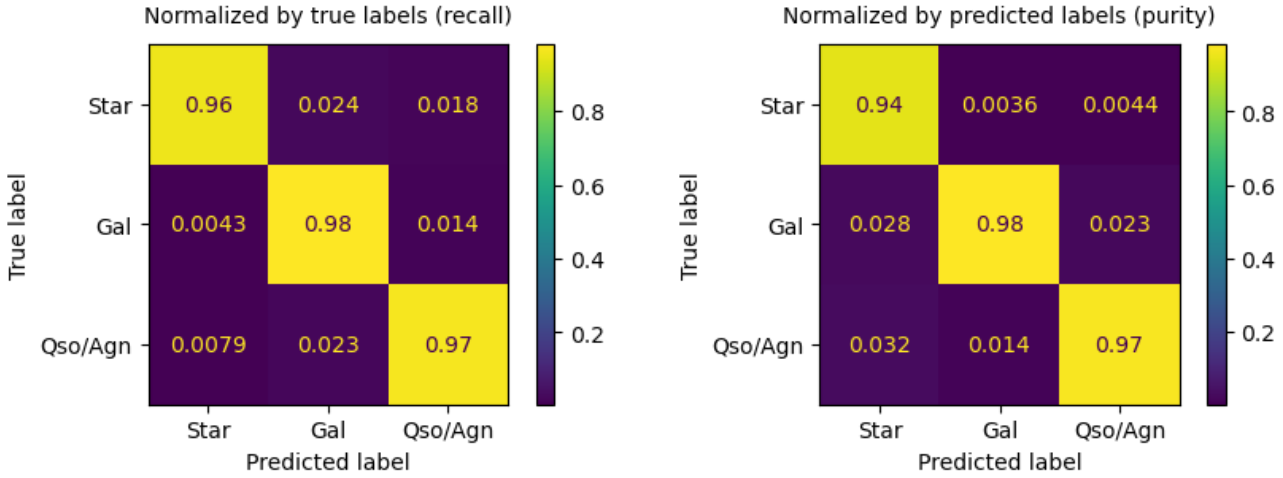


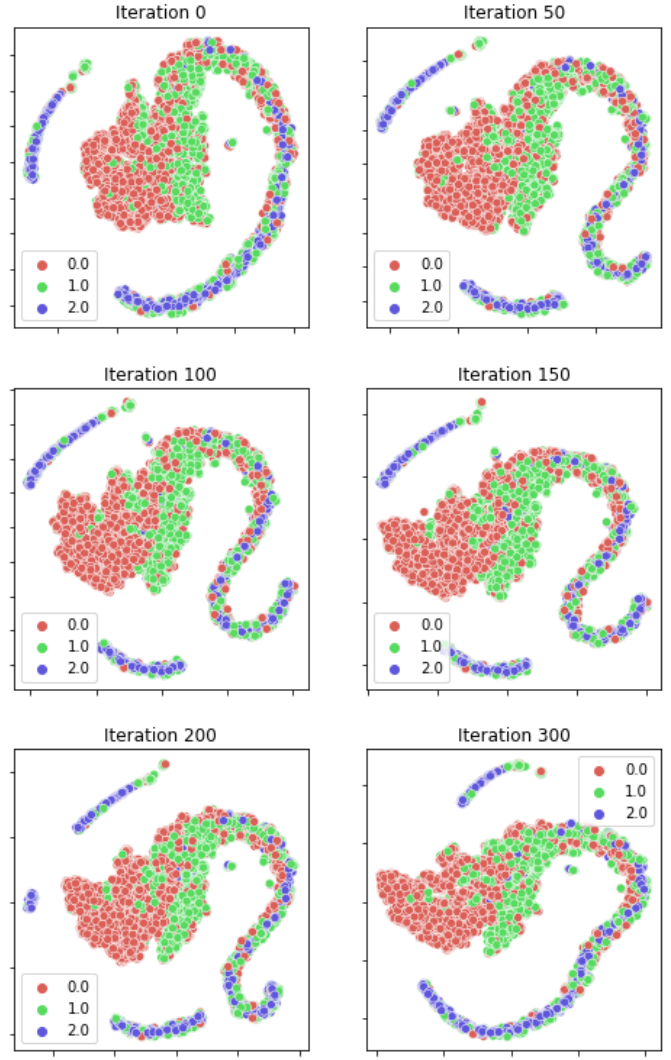
- all contributions treated the main problem of AGN selection
- methods: simple statistics, supervised SVM, RF and XGB, deep convolutional artificial neural networks
- very high baseline classifying accuracy (>98%) - when adequate light curve features added in model

https://github.com/RichardsGroup/AGN_DataChallenge

AGN Data Challenge 2021

- Our contribution: Djordje Savic et al.
  - Classifier: Artificial Neural Network
    - also tested: random forest, support vector machine, XGBoost
  - Reached >98% accuracy
  - Blind sample tests 94-96%
  - Total number test objects: ~15,000





0=star
1=gal
2=agn

t-Distributed Stochastic Neighbor Embedding (t-SNE)

TVS Kickstarter Grant

Community awards managed by LCO

With support from HEISING-SIMONS FOUNDATION

- 2021: Preparing for Astrophysics with LSST for 3 Rubin Science Collaborations:
  Transients and Variable Stars (TVS)
  Stars, Milky Way and Local Volume (SMWLV)
  Solar System Science Collaboration (SSSC)

- PI: S. Simic (Uni.Kragujevac) “Regional Storage Support for LSST Related Science”
  - partnerships: i) Faculty of Sciences, University of Kragujevac; ii) Astronomical Observatory Belgrade; iii) Faculty of Mathematics, University of Belgrade; iv) Department of Physics, University of Rijeka; v) Ruđer Bošković Institute, Zagreb, and vi) Hvar Observatory of the University of Zagreb’s Faculty of Geodesy

MATΦ
University of Belgrade
Faculty of Mathematics

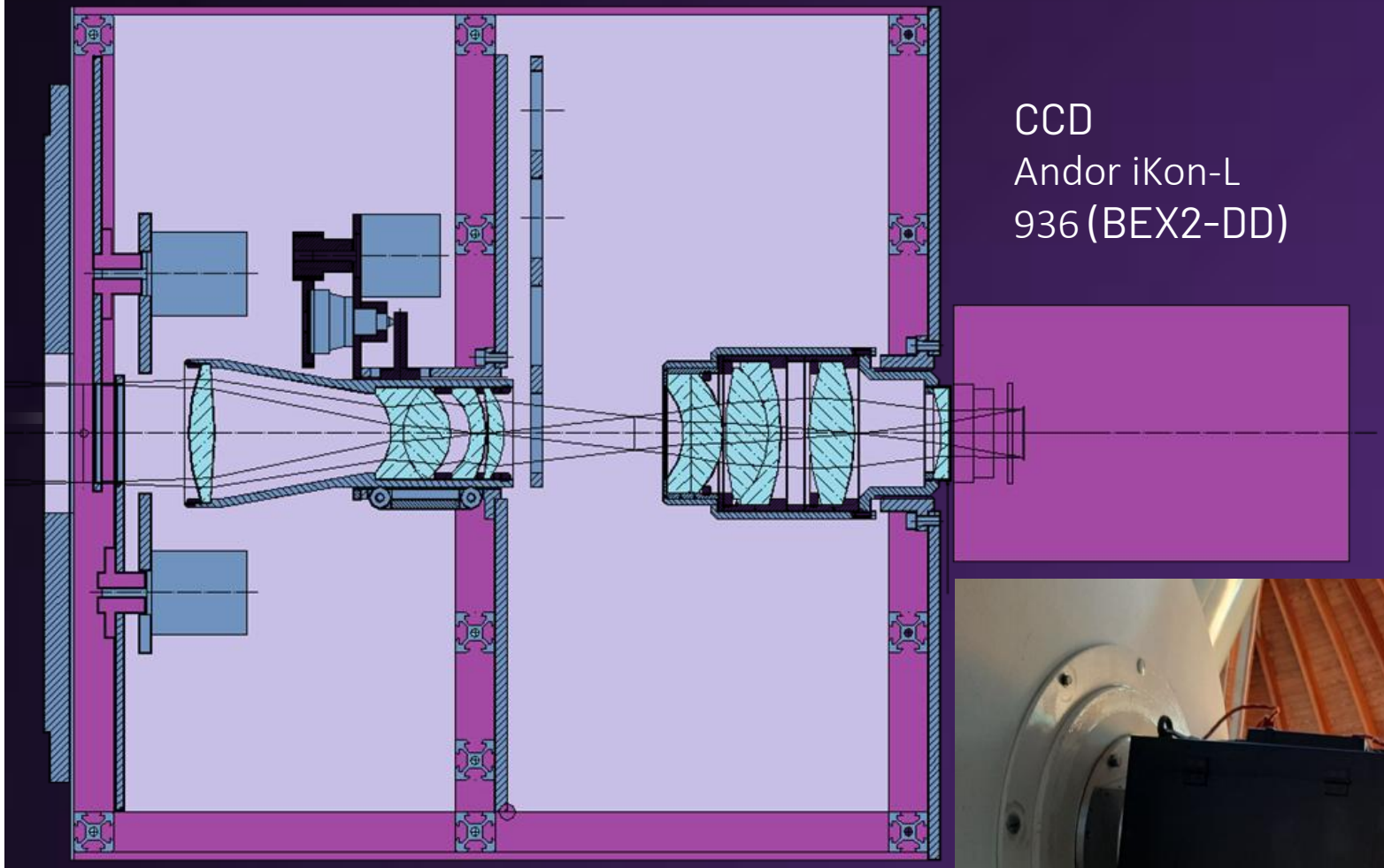
In-kind telescope time (Lead: M.Lakicevic)

- Astronomical Station Vidojevica, Serbia
  - Average seeing ~1.5”
- 1.4m telescope
  - possibility of fast response (telescope moving speed is 4-6 degree/sec)
- Photometer:
  - Andor iKon-L, pixel scale 0.244 arcsec/pixel, Field of view 8.3x8.3 arcmin
  - Filters: BVRI broad bands (+L very broad filter) + Halpha, SII, red continuum narrow bands
- 6-year long experience in the Gaia-FUN-TO
- In process of joining AEON
- Members: J. Kovacevic-Dojcinovic, S.Marceta-Mandic, O.Vince

possible upgrade to spectropgraph?

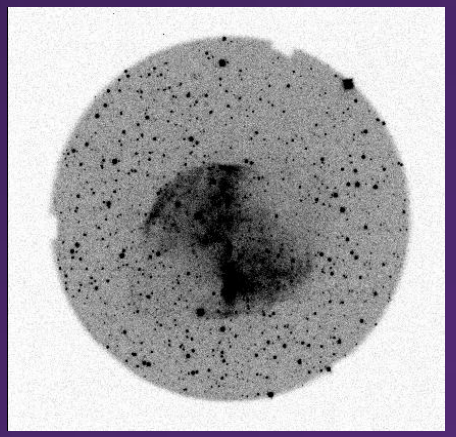
Slides from Roman Uklein

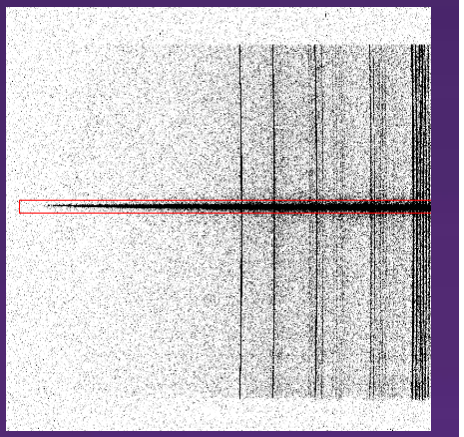
MAGIC : Monitoring of Active Galaxies by Investigation of their Cores

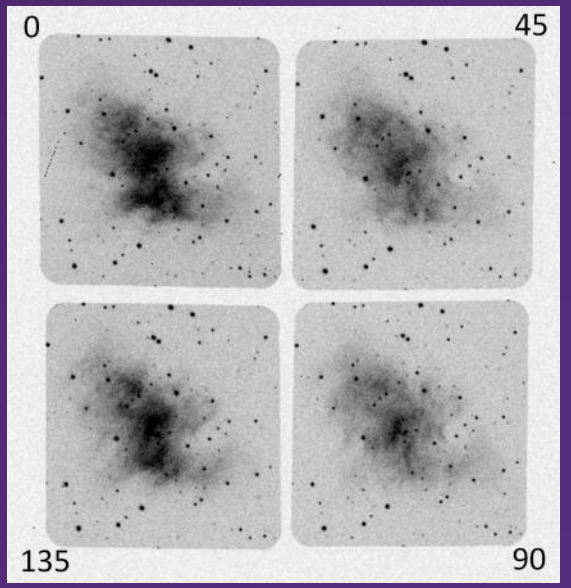


CCD
Andor iKon-L
936 (BEX2-DD)

3 observational modes:



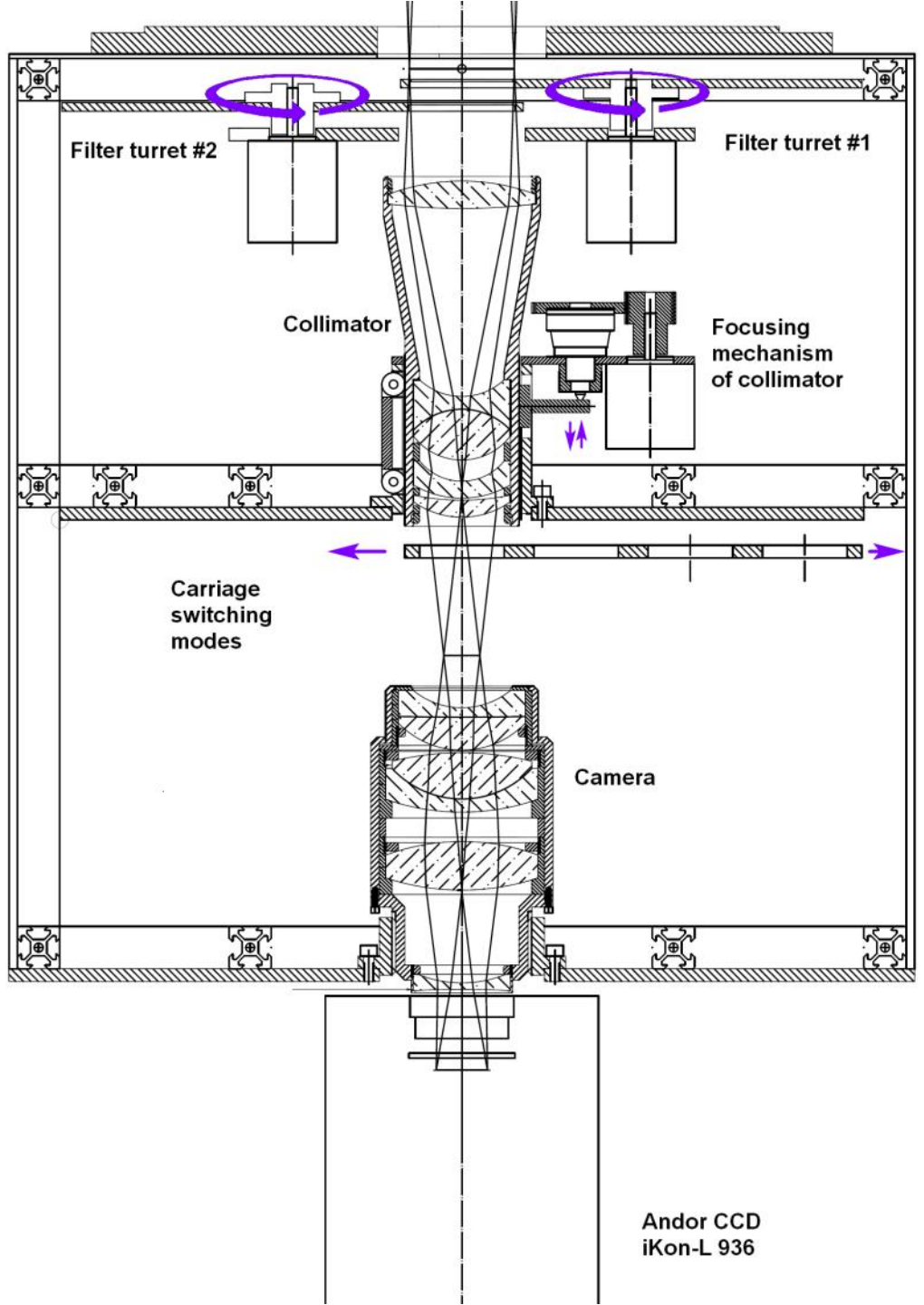


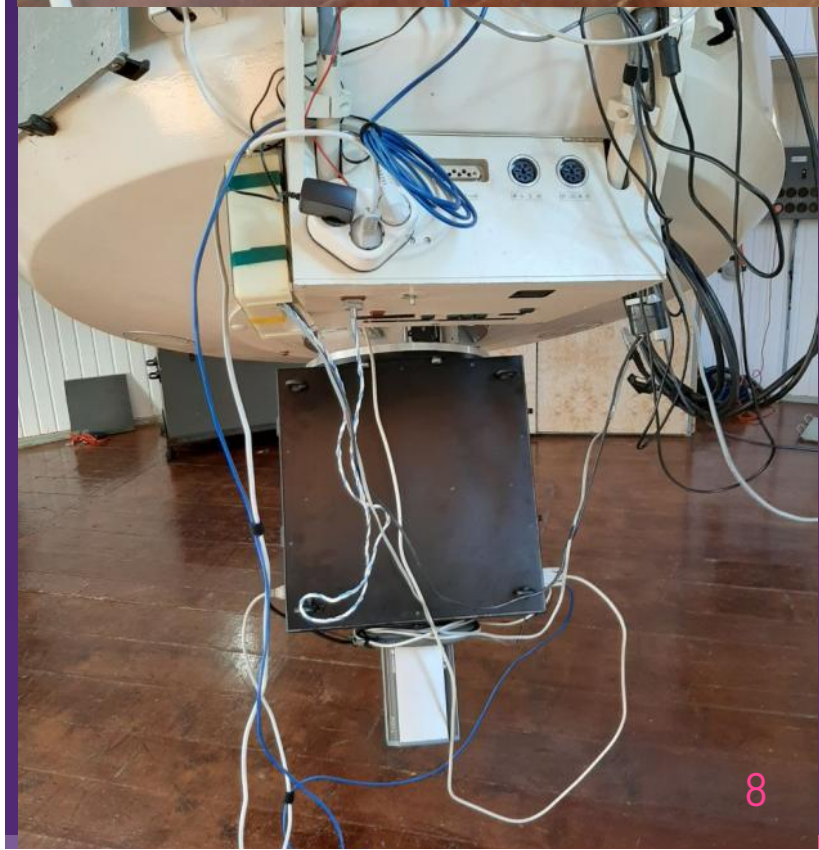


Slides from Roman Uklein

MAGIC :

Weight of the device (without CCD and turntable) - 23 kg, dimensions 410x420x270mm. The turntable is 14 kg, CCD is 7 kg.

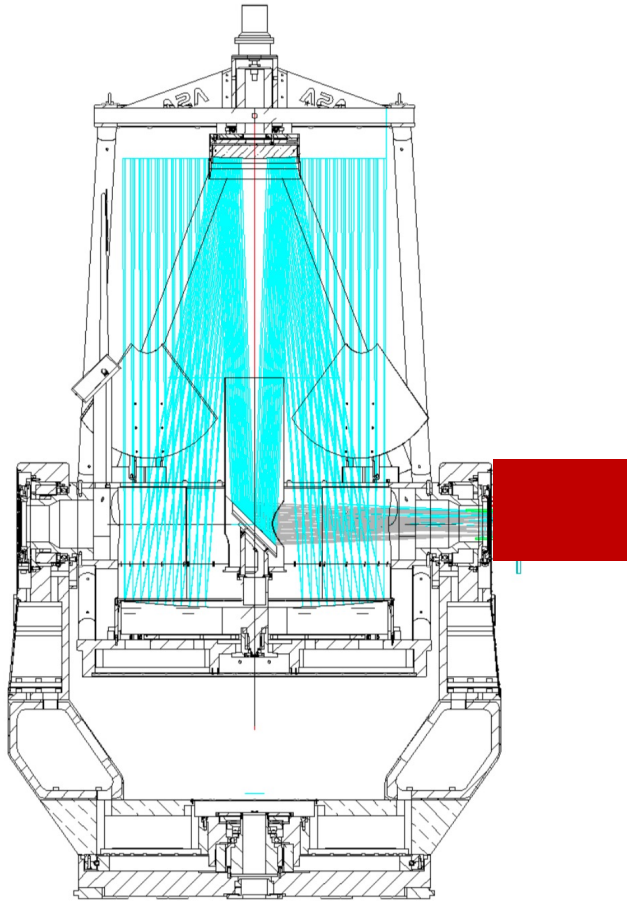




Upgrade for 1.4m Milankovic

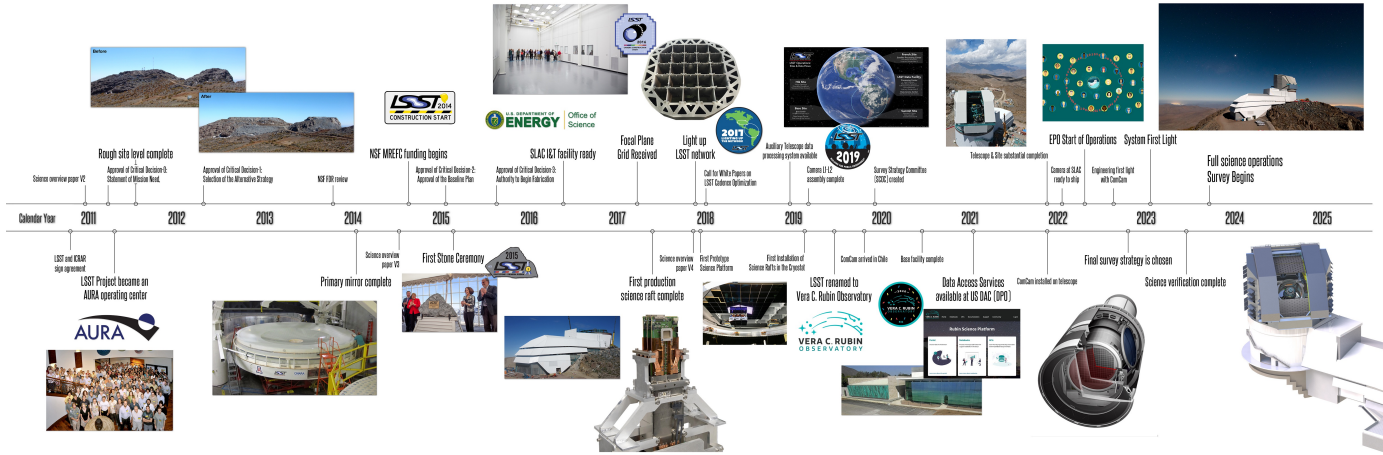
- **to the universal (multi-mode) focal reducer of high efficiency**
- Optical scheme of 1.4m Milankovic telescope, with the UPDATED multi-mode instrument (red box) installed on its left port

- 3 main observing modes:
  - Photometer (large field of view, better transparency of the instrument, 2 filter wheels with 18 positions (14 positions are available for filters)
  - Long-slit spectrograph (high-efficiency long-slit, grism)
  - Polarimeter (Wollaston prism)



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

  → Search for period signals and possible supermassive BH binaries

→ SER-SAG: ongoing efforts in developing tools and techniques for future large and time-domain surveys

VERA C. RUBIN OBSERVATORY

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

EACEA
European Commission
Education, Audiovisual and Culture Executive Agency

MASS
MASTER IN ASTROPHYSICS AND SPACE SCIENCE