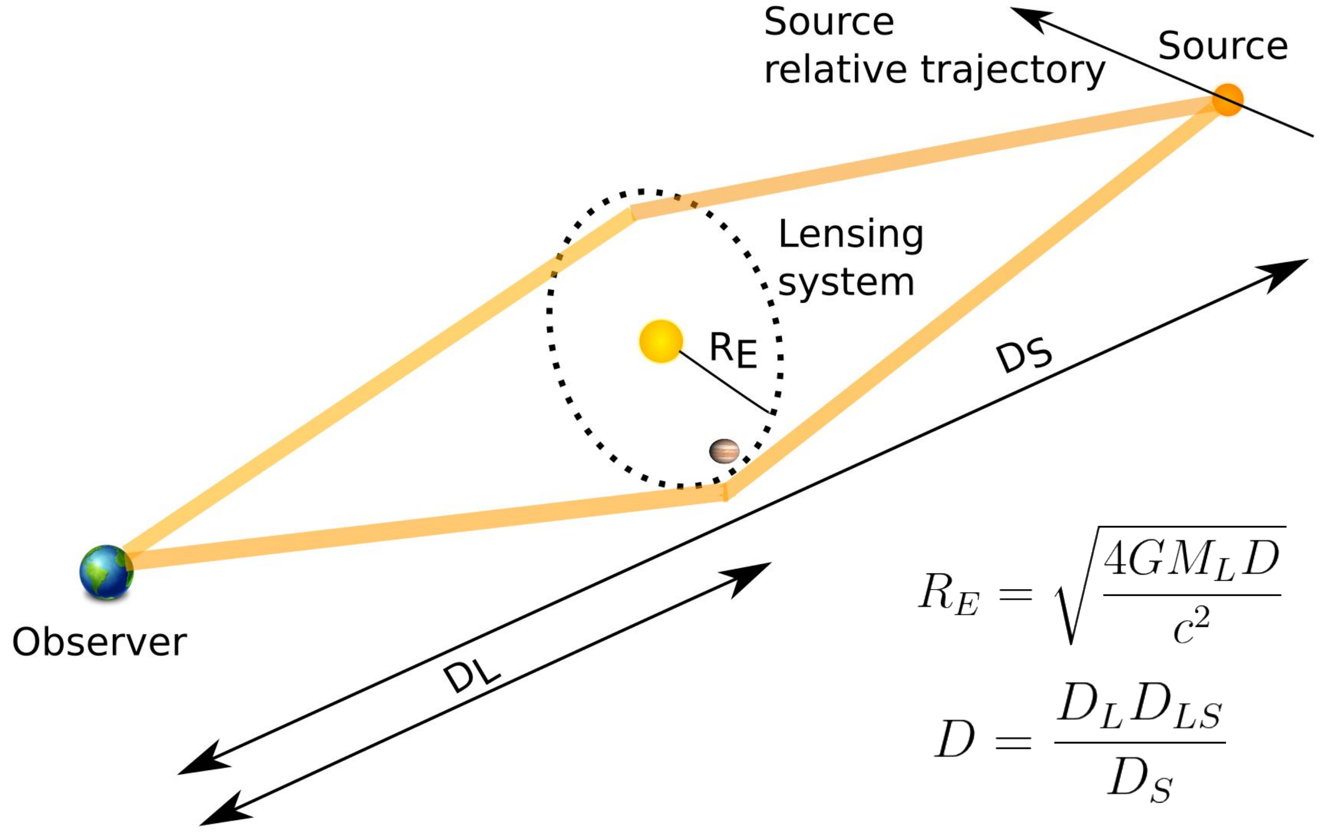
Microlensing with LSST

Rachel Street, Las Cumbres Observatory
OMEGA Key Project Team
TVS Microlensing Subgroup

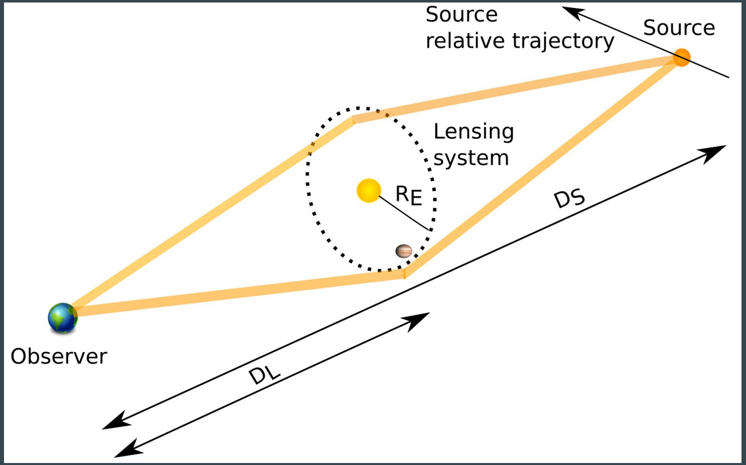
Microlensing

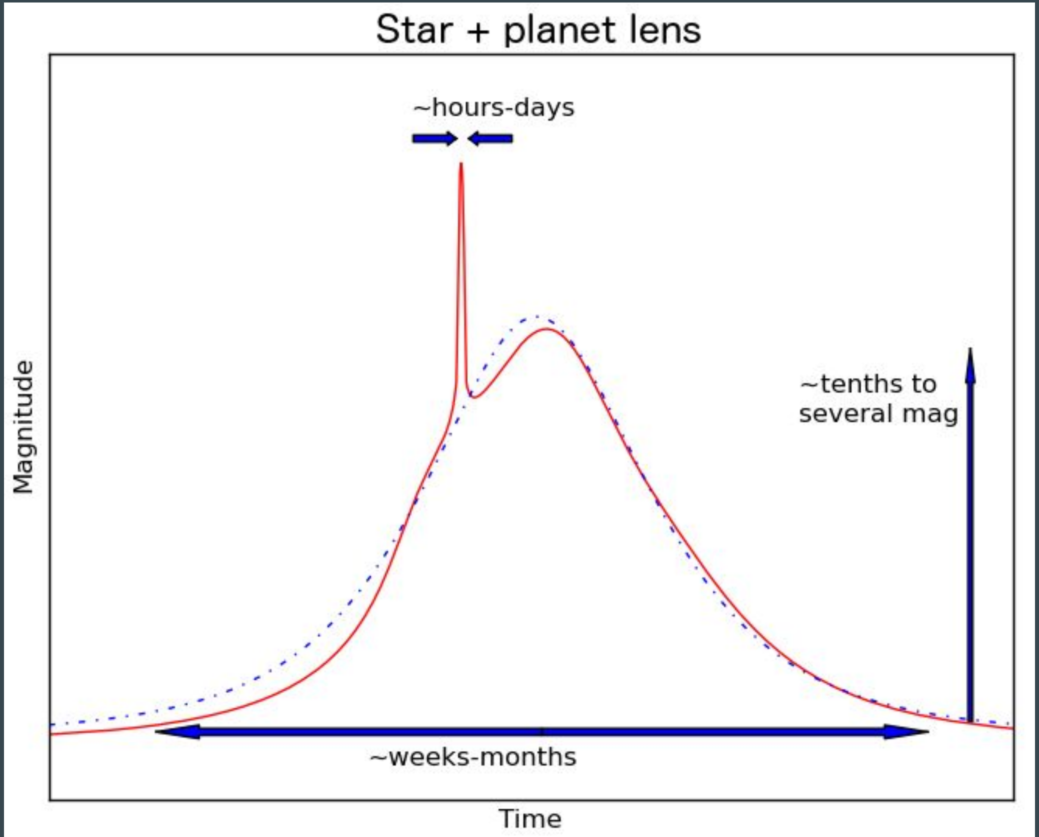


$$R_E = \sqrt{\frac{4GM_L D}{c^2}}$$

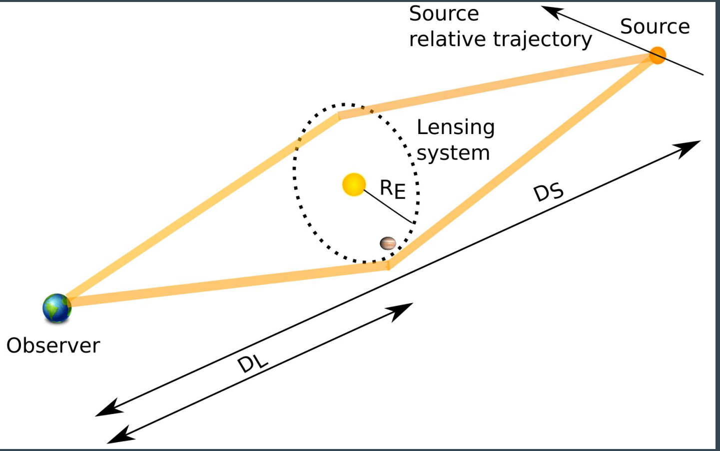
$$D = \frac{D_L D_{LS}}{D_S}$$

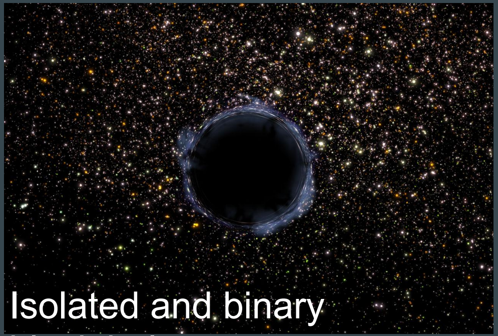
Microlensing





Microlensing





Isolated and binary black holes

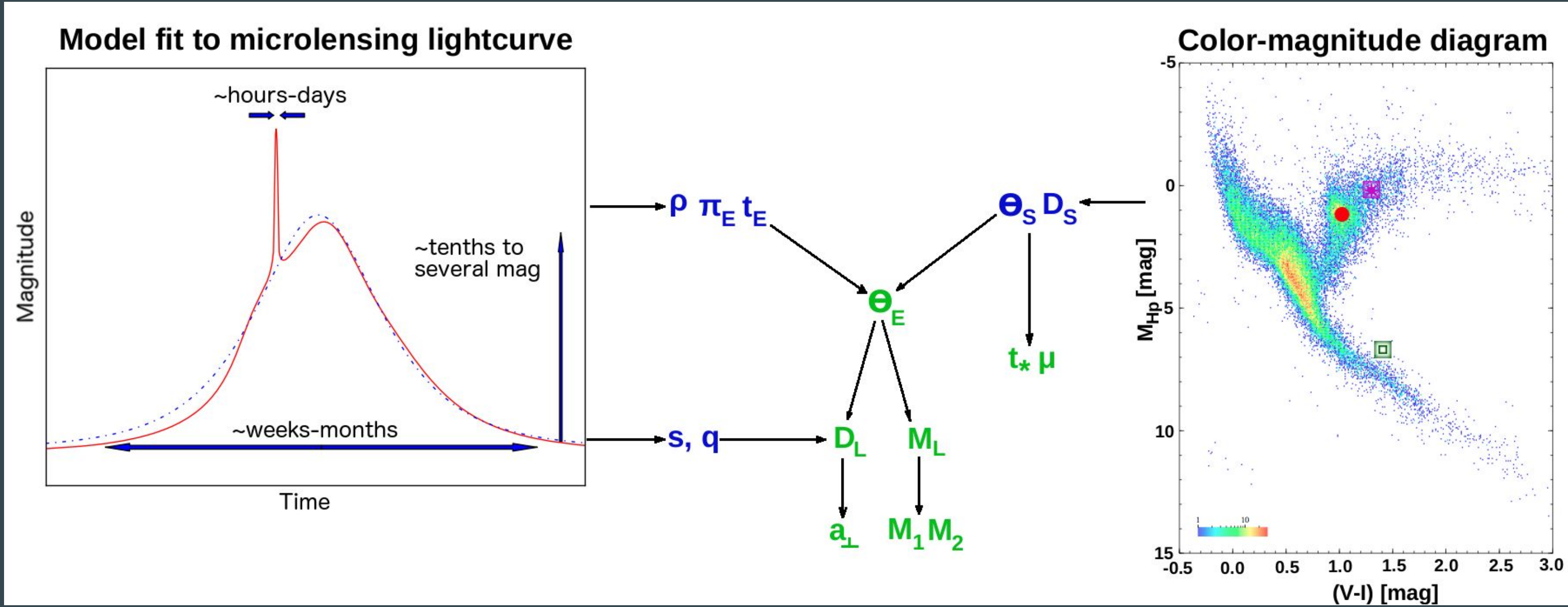
Stellar binaries, triples, exoplanets, brown dwarfs

White dwarf and neutron stars, companions

Free-floating planets

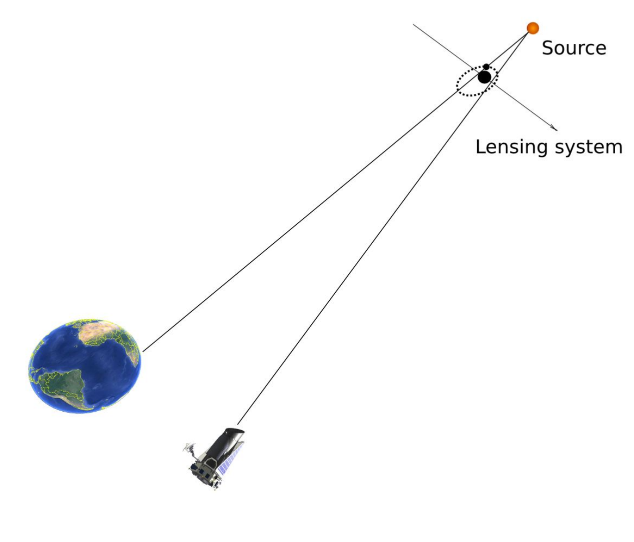
Image credits: NASA, JPL-Caltech, T. Pyle, NASA Goddard

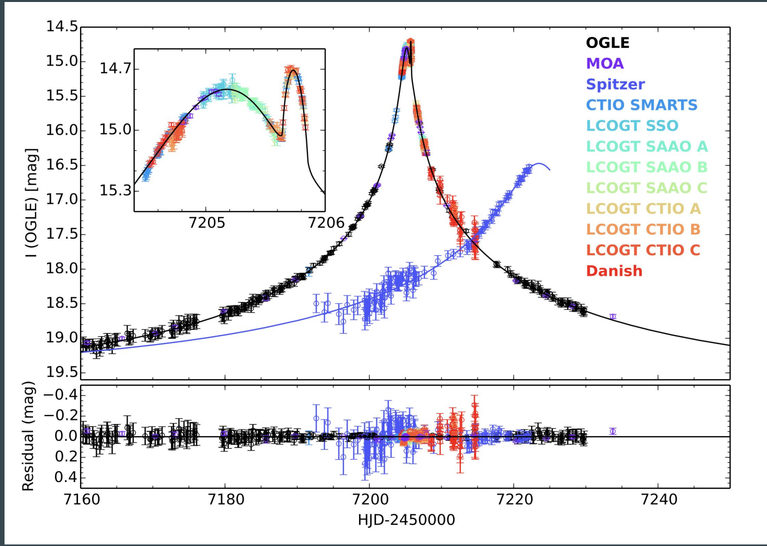
What can microlensing tell us?



Distance (D_L), masses (M_L) of lensing bodies, projected orbital separation, $a_\perp$

Determining parallax





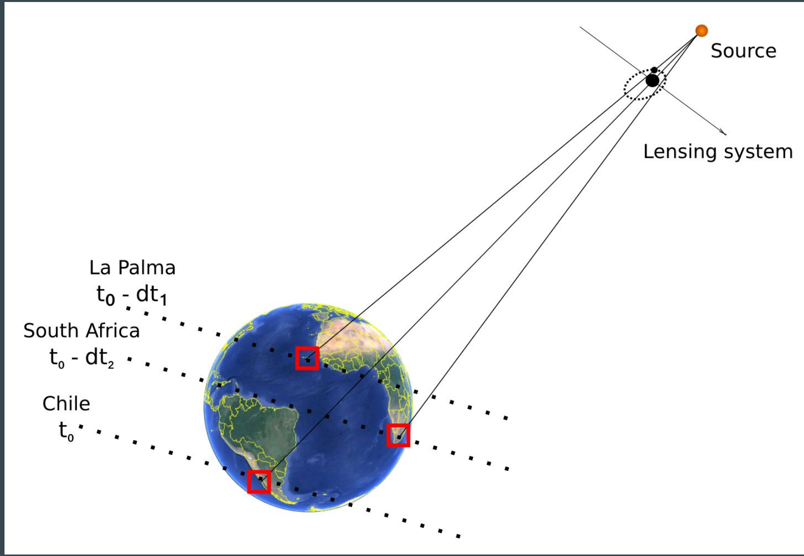
Space-based parallax

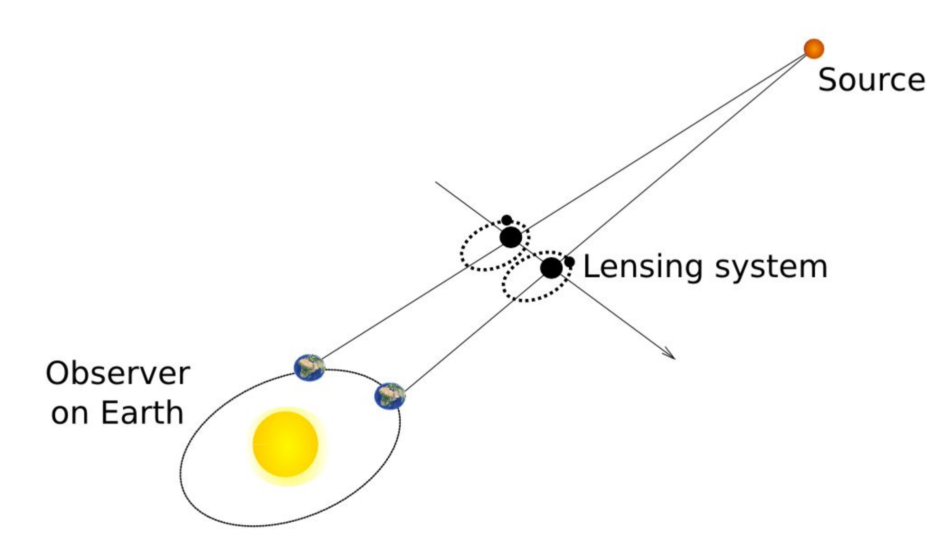
E.g. Spitzer microlensing program [Yee, Gould]

E.g. OGLE-2015-BLG-0966 Street et al. 2016, ApJ, 819, 93

See also: Shvartzvald, Y.+2017, ApJL, 840, L3, Shvartzvald, Y.+2019, AJ, 157, 106, Ryu, Y-H+, 2018, AJ, 155, 40,
Calchi Novati, S.+, 2018, 155, 261, Wei, Z.+ 2016, ApJ, 825, 60,
Chung, S-J+, 2017, ApJ, 838, 154, Dong, S.+ 2005, ApJ, 664, 862,
And other publications

Determining parallax





Terrestrial parallax

OGLE-2007-BLG-224
Gould, A. +, 2009, ApJL, 698, L147

“Annual” parallax

Most common for events >30d

Observational Requirements

- Long baseline time series photometry
  - Millions of stars
  - Cadence < 3day, ideally <1 day
  - Alerts events at early phases and for anomalies
  - Variable cadence in response to lightcurve features
- Multi-filter time series photometry
- Limiting mag i~22mag
- Spatial resolution <1 arcsec

Observing cadence required, shading proportional to increasing cadence

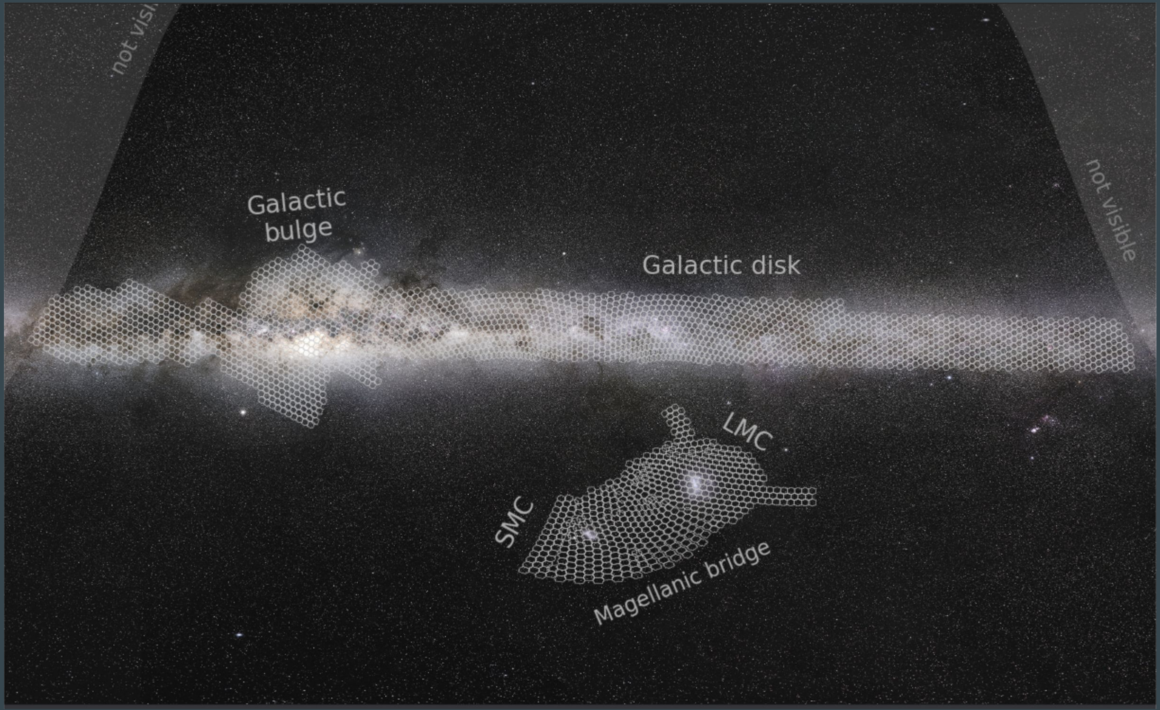
Microlensing discovery space

Discovery of exoplanets:

- High cadence (<1 day)
- Limited region (Bulge)

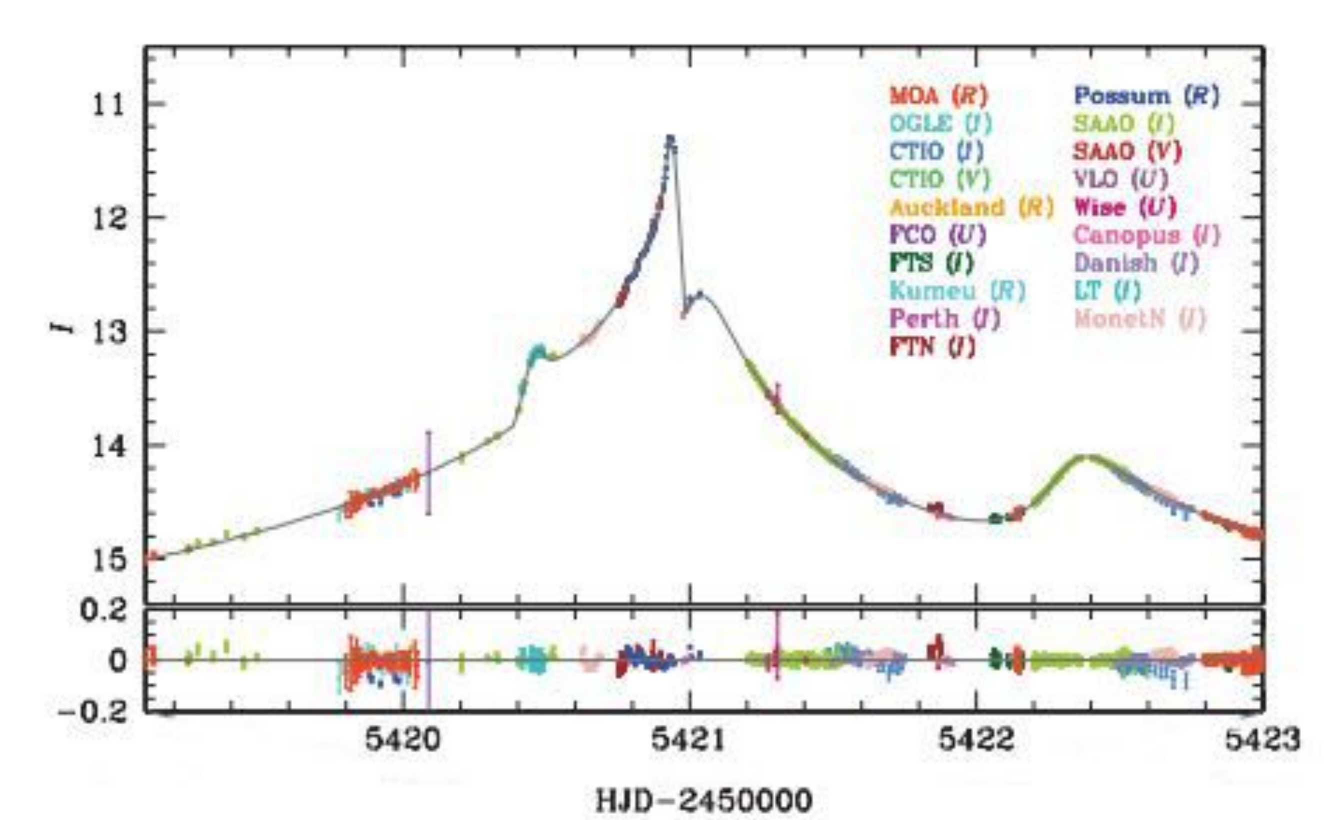
Discovery of black holes:

- Lower cadence (<3 day)
- Wide region
- Deep limiting magnitude



Credit: OGLE Team. Footprint of the OGLE-IV survey

Microlensing survey+follow-up



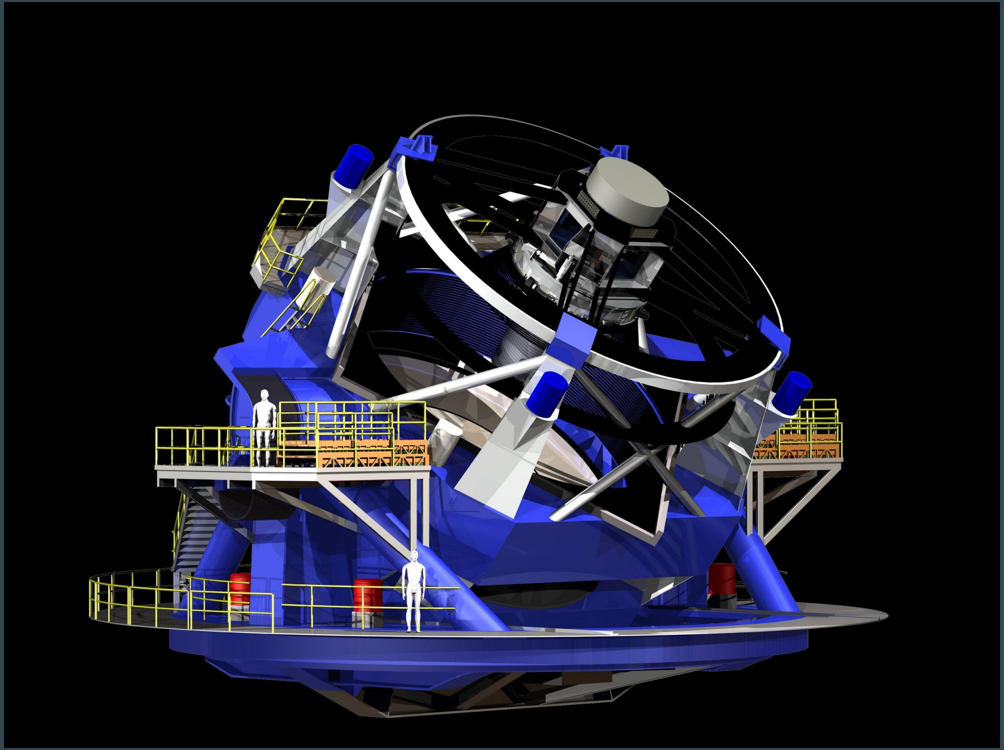
MOA-2010-BLG-477
Bachelet +2012, MNRAS, ApJ, 754, 73

Surveys:
OGLE, MOA, KMTNet, UKIRT

Follow-up:
MicroFUN, PLANET, RoboNet, MiNDSTEp

Citizen science collaborators

The Potential of the Rubin Observatory's LSST

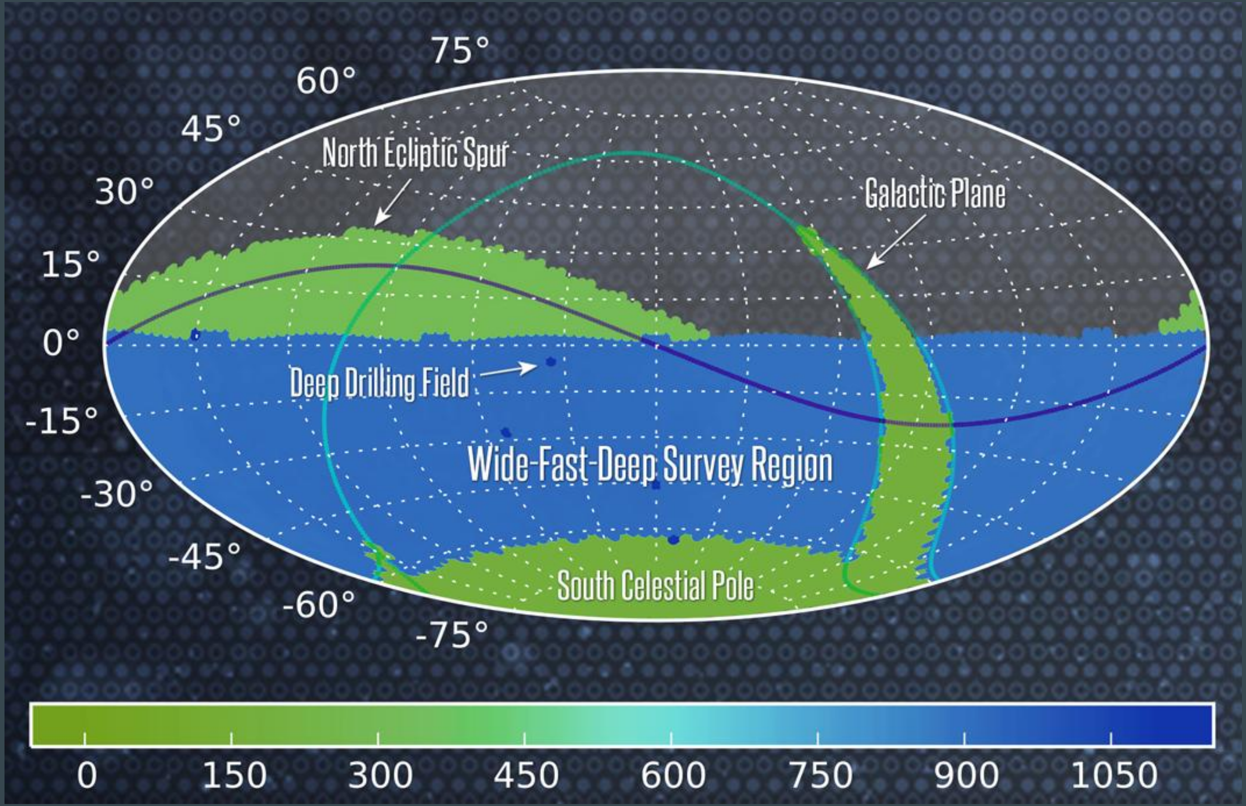


Effective aperture: 6.4m
Field of view: 9.6 sq. deg.
Spatial resolution: 0.2 arcsec/pixel
Limiting mag: i~24 mag
Filterset: u, g, r, i, z, y

Legacy Survey of Space & Time:
10-yr baseline, ~3-day cadence

New discoveries altered within ~60s

Expanding the Wide-Fast-Deep Survey



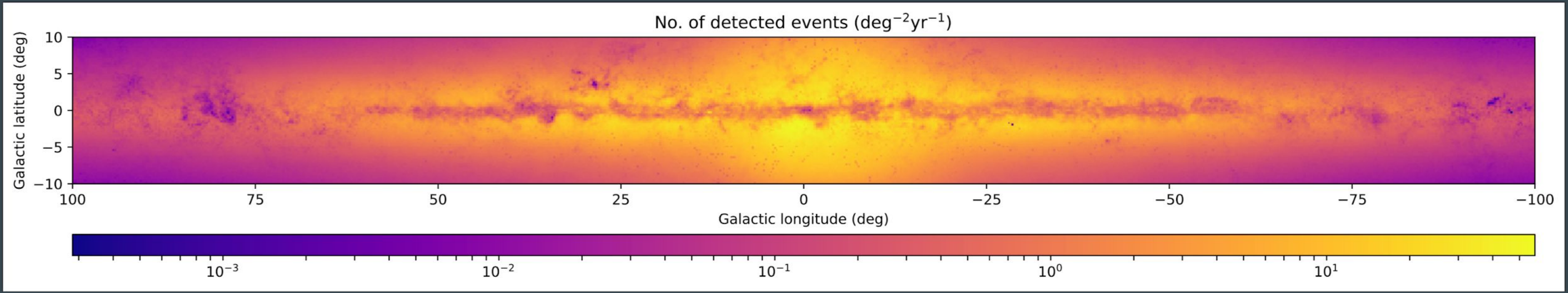
Original 2016 baseline cadence for the Wide-Fast-Deep survey

2018 Call for survey strategy proposals

Two proposals led by microlensing subgroup of the Transients and Variable Stars Science Collaboration

Expanding the Wide-Fast-Deep Survey

Simulations by Martin Donachie



Even with this sparse coverage, LSST will discover thousands of microlensing events across the Galaxy
See Sadajian & Poleski, 2019, ApJ, 871, 17

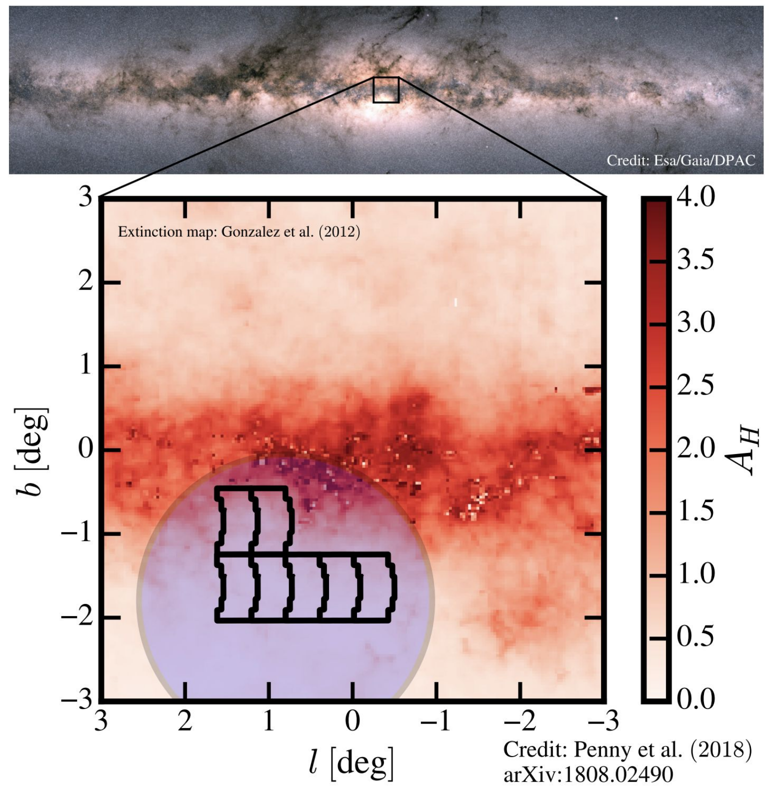
May even detect self-lensing in the Magellanic Clouds

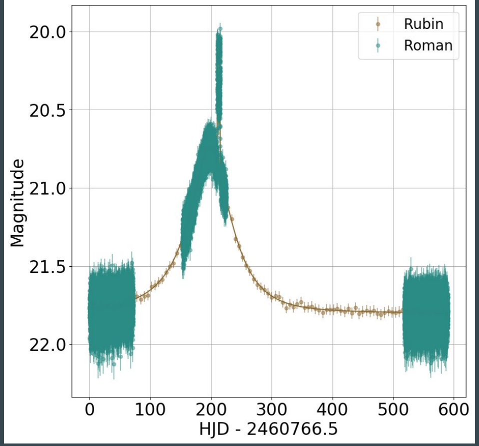
Street et al. 2018, arXiv:1812.03137 proposed to enhance this yield with a pair-wise strategy to extend the WFD to include the Galactic Plane using a limited filterset g, r, i

Credit to TVS Microlensing subgroup and co-authors in the LSST SCs

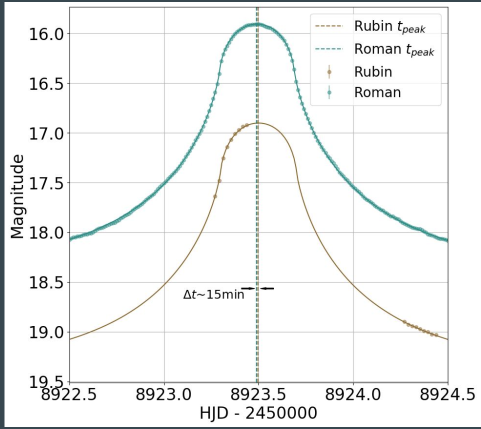
Roman-Rubin Deep Drilling Field

Street + 2018, arxiv/1812.04445





LSST will ensure complete coverage of Roman discoveries



DDF observations could provide parallax constraints even for free-floating planets in the Roman survey

Preparing for Microlensing with LSST

- ✓ Long baseline, deep, high spatial resolution survey
- ✓ Rapid alerting of variable sources

Rubin Observatory

- ☐ Early classification of microlensing events
- ☐ Prioritization of events
- ☐ Reactive follow-up observations

Community

Handling the LSST data rate

Identifying events early from LSST alerts is only the first step to characterization

~10 million alerts / night, will drop after variables classified after first full year but transient rate will still be overwhelming for humans to assess

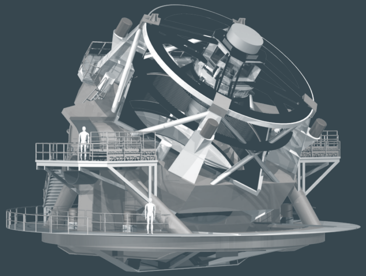
Software tools will be indispensable

The Follow-up Ecosystem

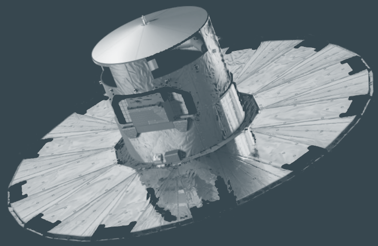
A chain of interacting software systems designed to classify and disseminate discoveries, select candidates of interest and conduct follow-up observations

The Follow-up Ecosystem

Detection



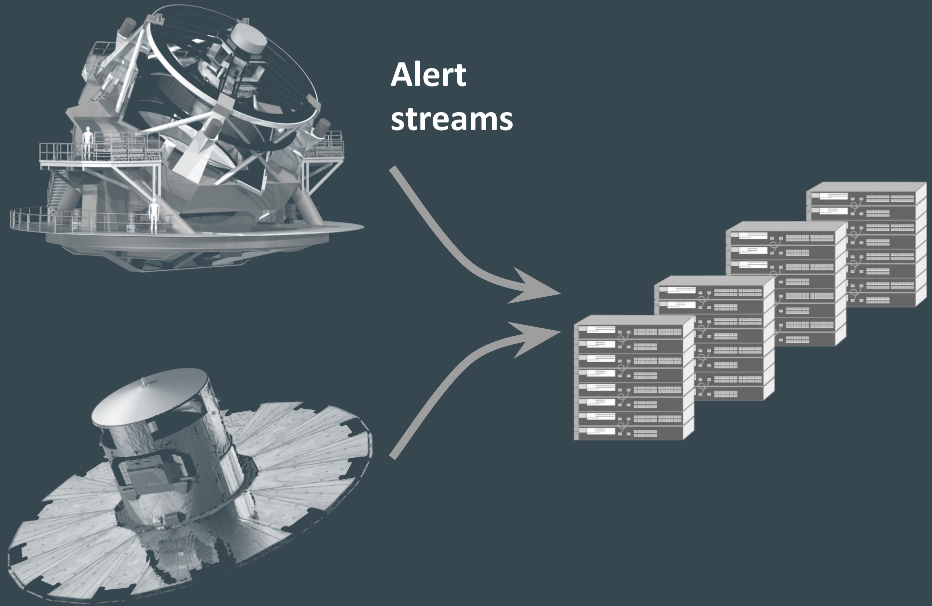
Alert streams



Surveys:
LSST, ZTF, Gaia, LIGO/Virgo

The Follow-up Ecosystem

Detection | **Classification**



Surveys:
LSST, ZTF, Gaia, LIGO/Virgo++

Brokers:
ALeRCE, ANTARES,
Lasair, Fink ++

The Follow-up Ecosystem

Detection | **Classification** | **Selection**

Surveys:
LSST, ZTF, Gaia, LIGO/Virgo++

Brokers:
ALeRCE, ANTARES, Lasair, Fink ++

TOM systems:
Astronomy teams

The Follow-up Ecosystem

Detection

Surveys:
LSST, ZTF, Gaia, LIGO/Virgo++

Classification

Brokers:
ALeRCE, ANTARES,
Lasair, Fink ++

Selection

TOM systems:
Astronomy teams

Follow-up

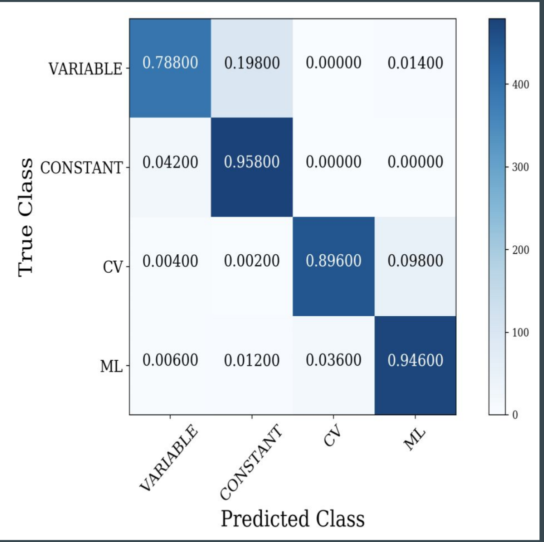
Observatories worldwide

Brokers

- Ongoing selection process for brokers to receive full LSST alert stream
- Rapid development and evolution
  - Main-stream brokers, specialized brokers, downstream brokers...
- Extensive work on classification, machine learning
- Several more advanced brokers offer target filtering/selection capabilities
- Ongoing work to integrate existing microlensing detection software

Classification of microlensing events

- Most effective with >1 yr photometric baseline in multiple filters to eliminate variables
- Challenging due to low cadence
- Classification still complicated by Cataclysmic Variables (CVs)
- Post-event detection is relatively easy - in progress is hard
- Full post-event classification complicated by wide range of binary and triple lightcurves



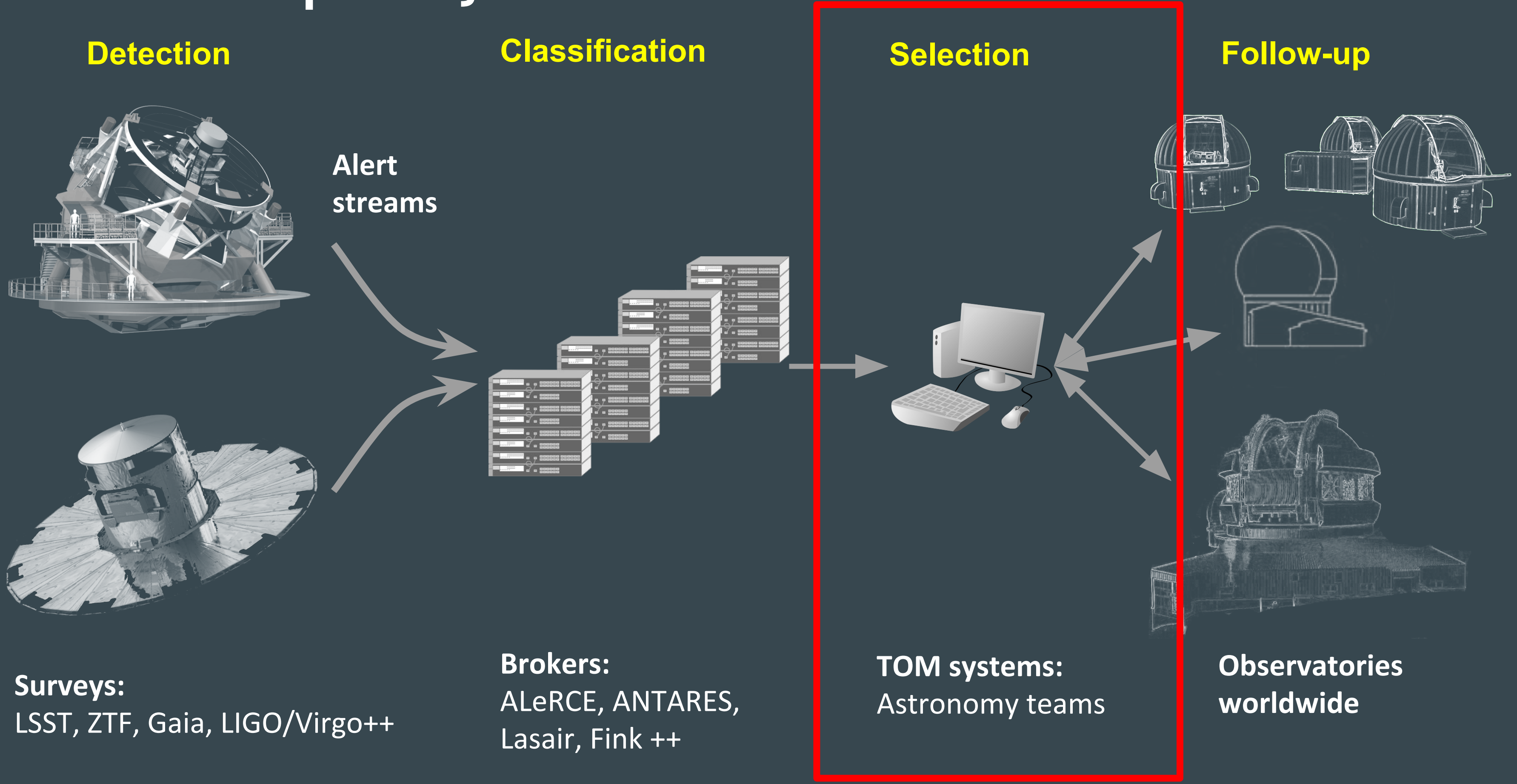
Random forest classifier results from Godines+2019

Range of algorithmic and machine learning approaches applied and under investigation

See work by:

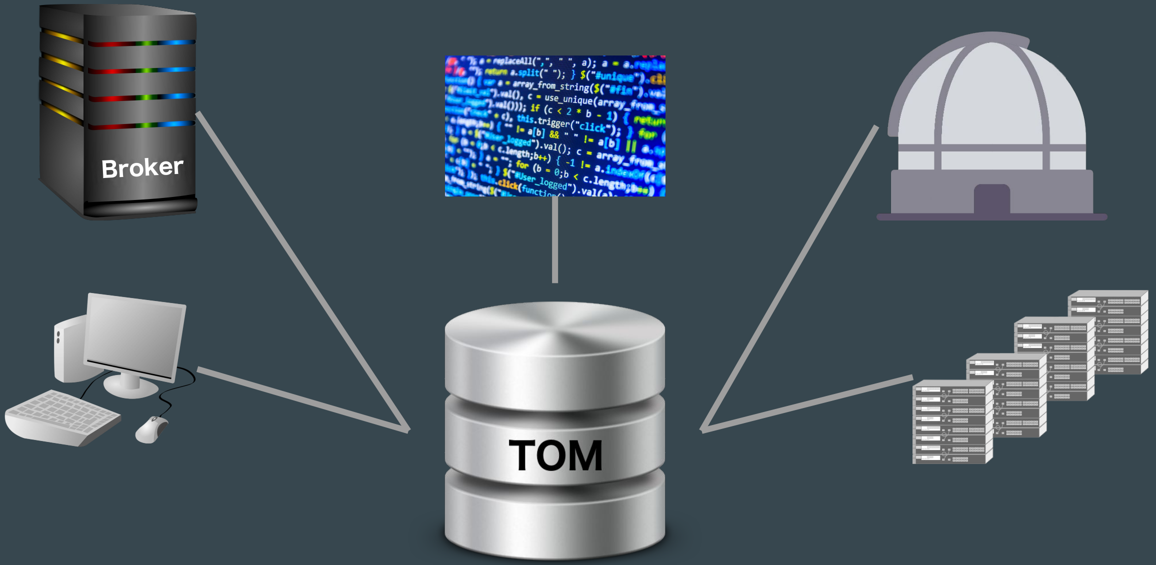
Khakpash, S. et al., 2020, submitted,
Kim, D.-J., et al. 2018, AJ, 155, 76,
Wyrzykowski, Ł., et al. 2015, ApjSS, 216, 12,
Godines, D., et al., 2019, A & C, 28, 100298
Wyrzykowski, Ł., et al. 2016, MNRAS, 458, 3012
Price-Whealan, A., et al., 2014, AJ, 781, 35

The Follow-up Ecosystem



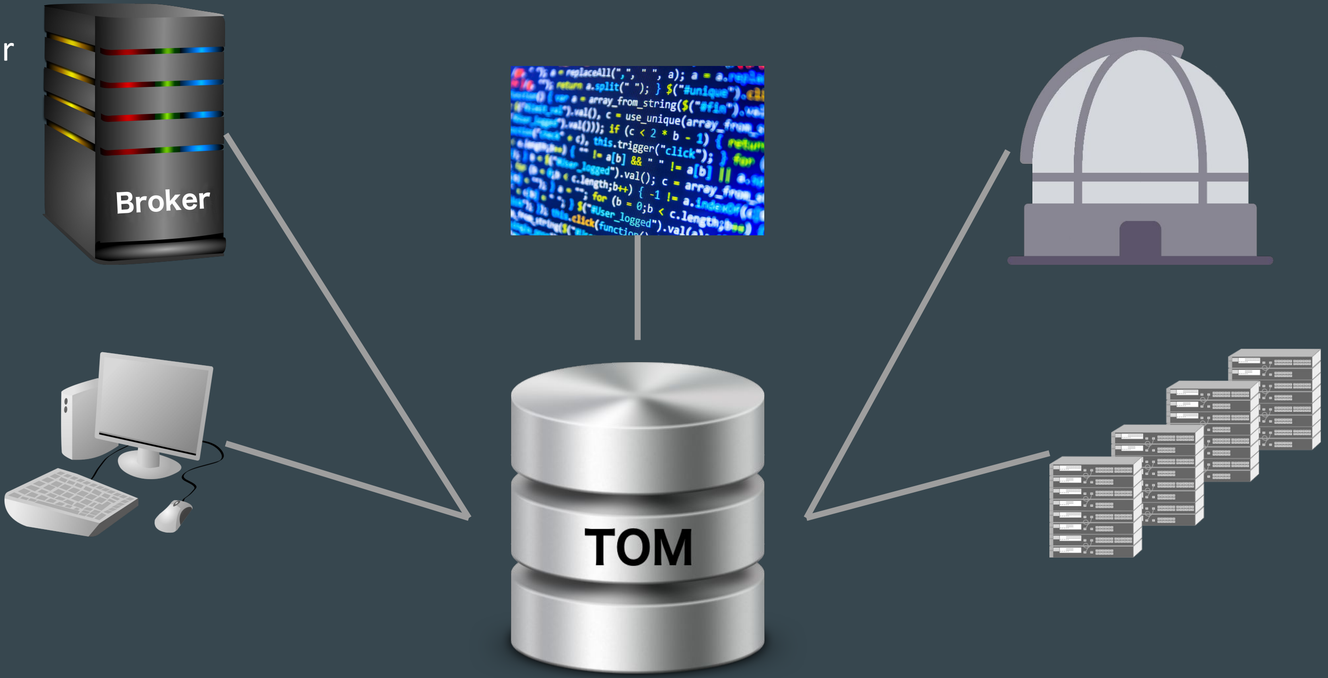
Target and Observation Managers

Database-driven software to conduct all aspects of an observing program, keeping track of targets, observations and data products



Target and Observation Managers

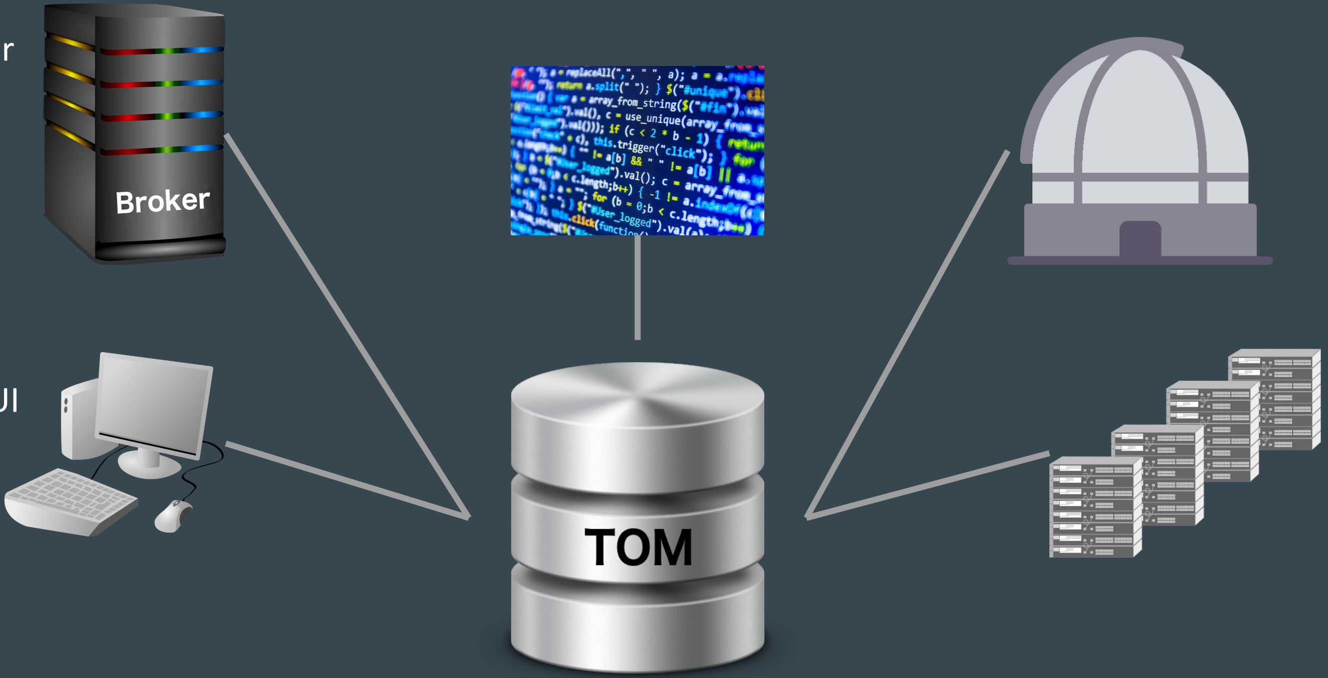
Interfaces with broker services for new targets



Target and Observation Managers

Interfaces with broker services for new targets

Browser-based UI
Standard and customized displays

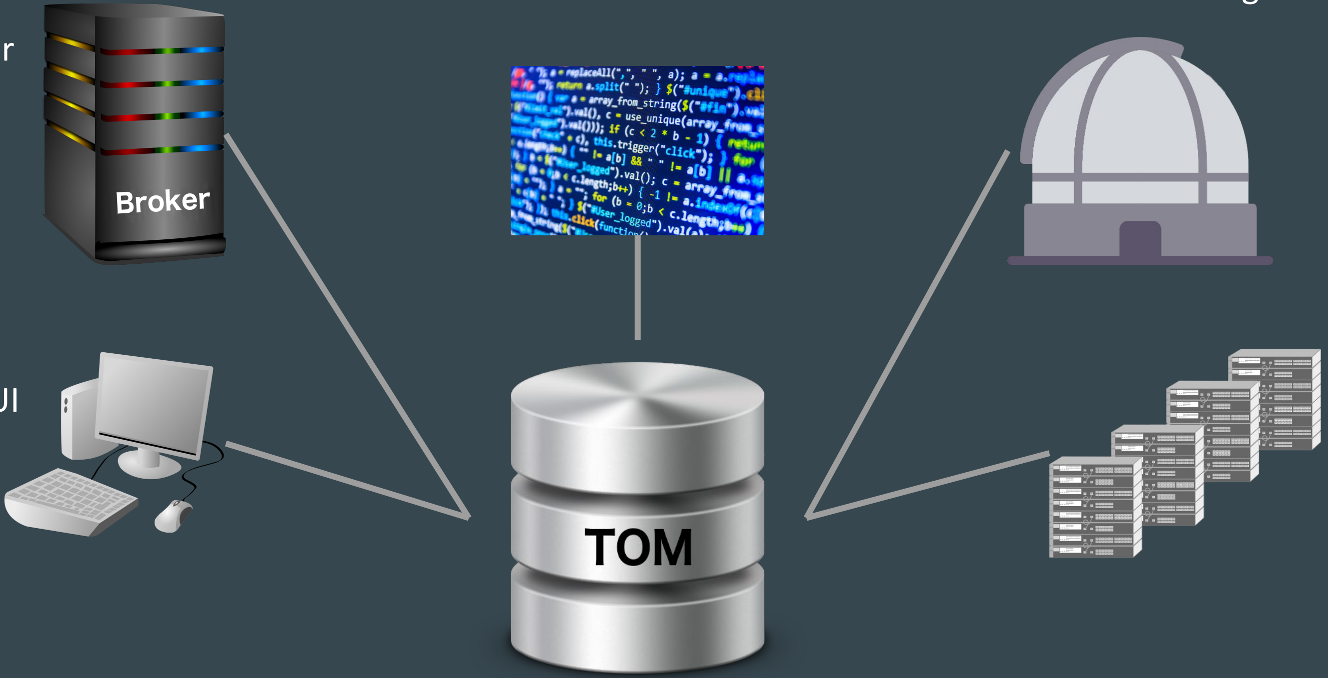


Target and Observation Managers

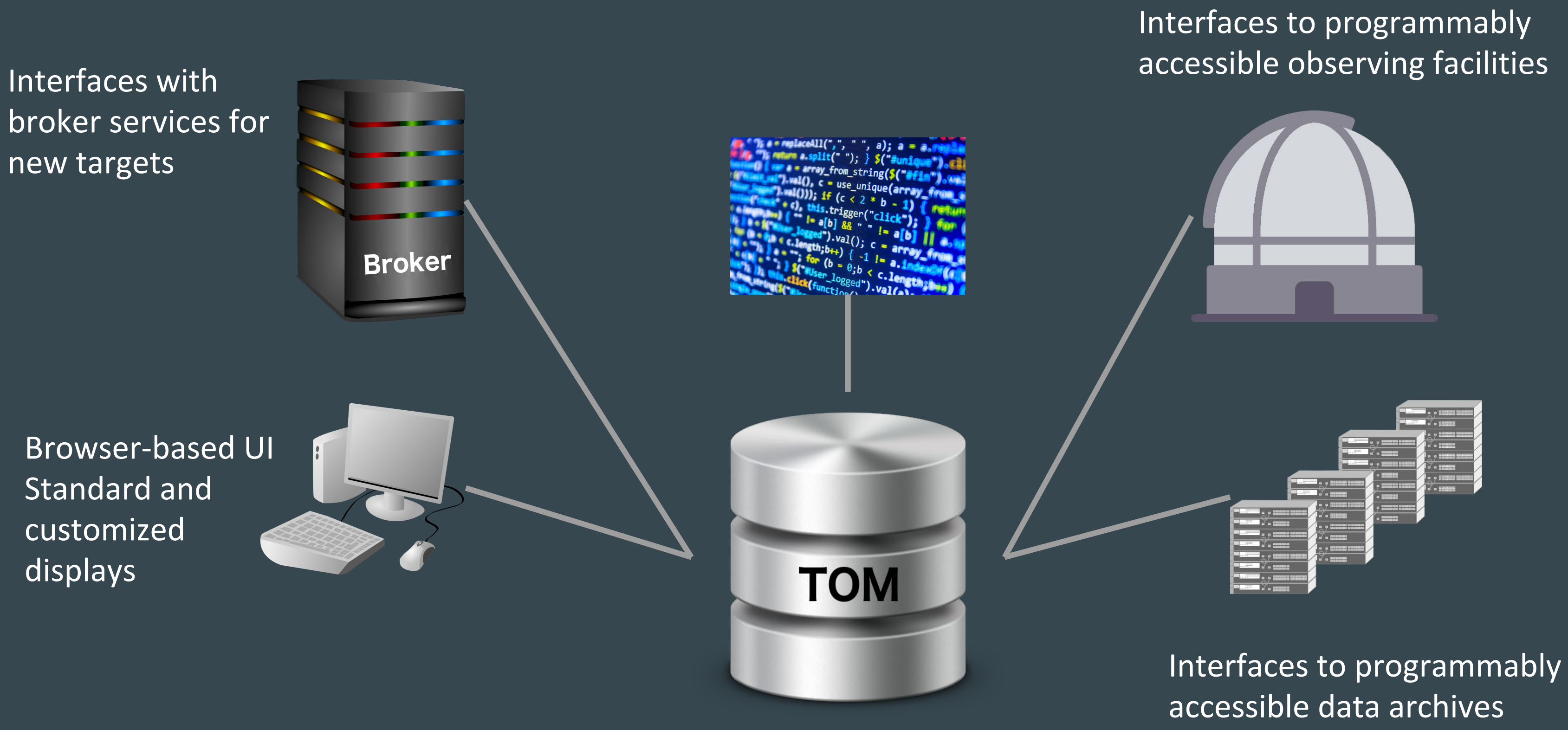
Interfaces with broker services for new targets

Browser-based UI
Standard and customized displays

Interfaces to programmably accessible observing facilities



Target and Observation Managers

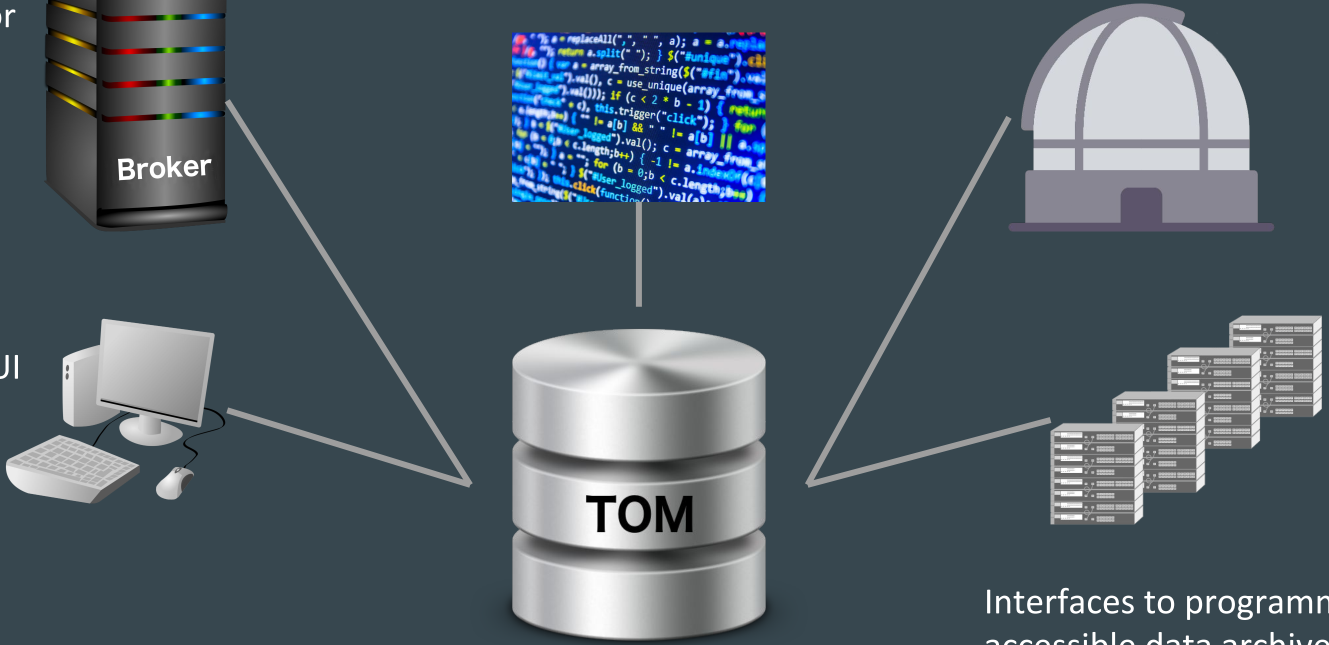


Target and Observation Managers

Interfaces with broker services for new targets

Interfaces with user-written code

Interfaces to programmably accessible observing facilities



Browser-based UI
Standard and customized displays

Interfaces to programmably accessible data archives

Building a TOM

TOM Toolkit: https://lco.global/tomtoolkit/

Open-source, professionally supported package designed to make it easy to build TOM systems

Professional developers available to provide support via Slack:

- https://tom-toolkit-invite.lco.global/

Active user community - several microlensing TOM systems in use for supernovae, microlensing, solar system targets and others

Pathfinder Program: OMEGA

Key Project at Las Cumbres Observatory
PI: Etienne Bachelet, LCO
Team: R. Street, M. Hundertmark, Y. Tsapras, P. Mroz, L. Wyrzykowski, M. Dominik , A. Fukui, C. Briceno, J. Wambsganss, R. Figuera Jaimes, V. Bozza

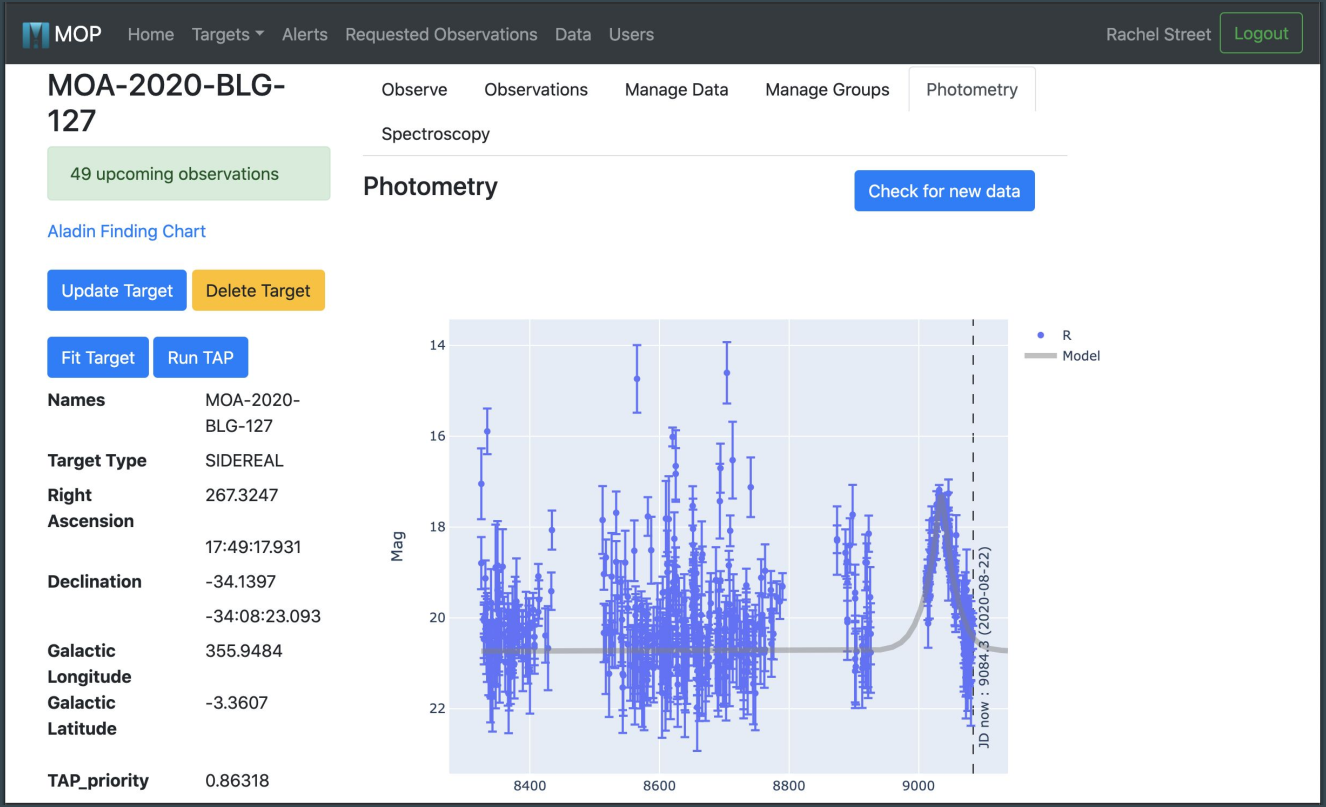
Duration: 2020-2023

Goal is to characterize stellar, planetary and black hole microlensing events, particularly those outside the Galactic Bulge

Responding to alerts from ZTF and Gaia as well as from MOA, KMTNet

Relatively low ZTF, Gaia cadence provides a technology testbed for LSST.

Microlensing Observing Platform https://mop.lco.global



- Developed by Etienne Bachelet
- Real-time modeling with PyLIMA software
- Fully automated target selection, prioritization and observation
- Working on pipeline interface

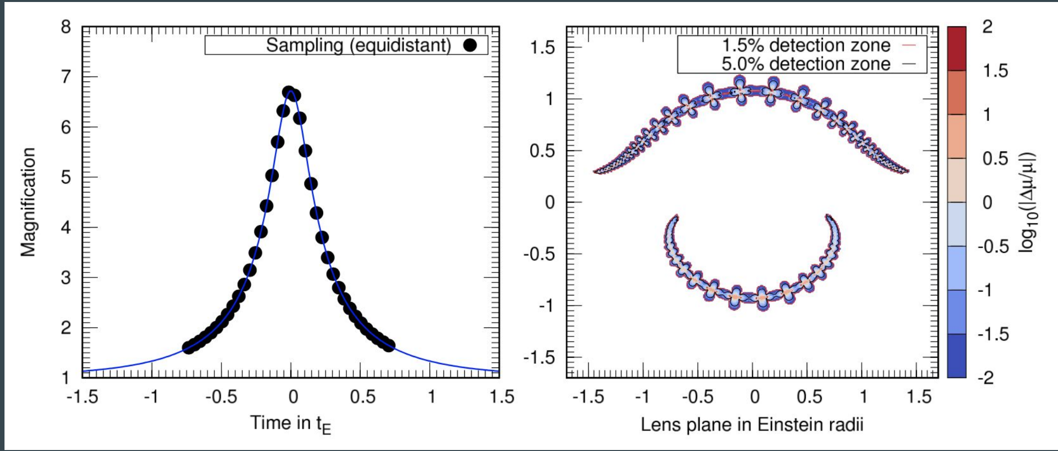
Prioritizing microlensing events

Events can be prioritized by their sensitivity to binary lens companions

Additional constraints for telescope limiting magnitude, maximum exposure time, etc

Algorithm makes real-time recommendations of which target to observe

Well-understood selection biases



Hundertmark+ 2017, A&A, 609, A55

Topic open for research!

Building a network on follow-up telescopes for LSST

LSST targets will significantly fainter than those from current surveys

Expand follow-up program to larger facilities

Transient targets drive requirements:

- Rapid reaction
- Long-term monitoring
- Programmatic observation request
- Programmatic data access

AEON Astrophysical Events Observatories Network

Partnership to build an extended network of observing facilities optimized for time-domain astronomy

- Queue-schedulable
- Observations can be programmatically submitted
- Beneficial for all astrophysics...not just the time-domain

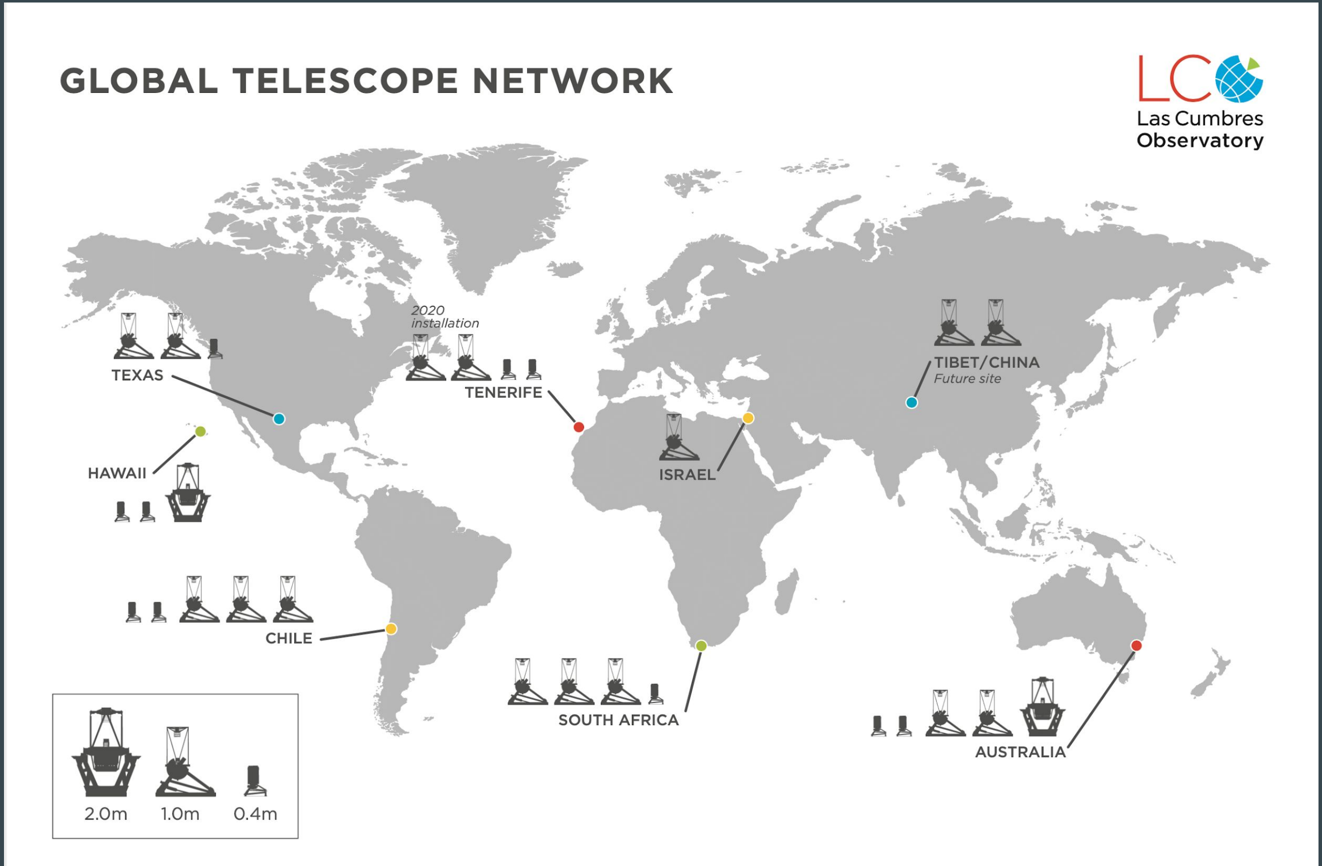
GEMINI OBSERVATORY
Exploring the Universe, Sharing its Wonders

NSF
NSF's National Optical-Infrared Astronomy Research Laboratory

SOAR

LCO

AEON Astrophysical Events Observatories Network



Fully robotic telescope network

Unique network scheduling software designed for time-domain

Programmatically accessible data archive

TOM interface

AEON Astrophysical Events Observatories Network

SOAR 4.1m Telescope

Goodman spectrograph available in AEON-mode since 2019

Programmatically observation submission and scheduling through LCO’s infrastructure when in AEON-mode; block scheduled the rest of the time

Observations carried out by human operators on site in queue-mode

Data programmatically accessible through LCO and NOIRLab archives

AEON Astrophysical Events Observatories Network

Gemini 8m telescopes

- Ongoing re-design of operating system designed with AEON in mind
- Gemini observing module plugin for TOM Toolkit available, built by Bryan Miller, Gemini

Microlensing with LSST

Discovery and characterization of hidden populations: isolated black holes, stellar binaries, exoplanets

Active research in real-time classification of ongoing events

Characterization demands highly responsive real-time follow-up program

Pathfinder OMEGA program now underway, leveraging TOM Toolkit

AEON Network welcomes new members! Resources for *all* LSST programs

Want to learn more about microlensing? Visit our online resource site: http://microlensing-source.org