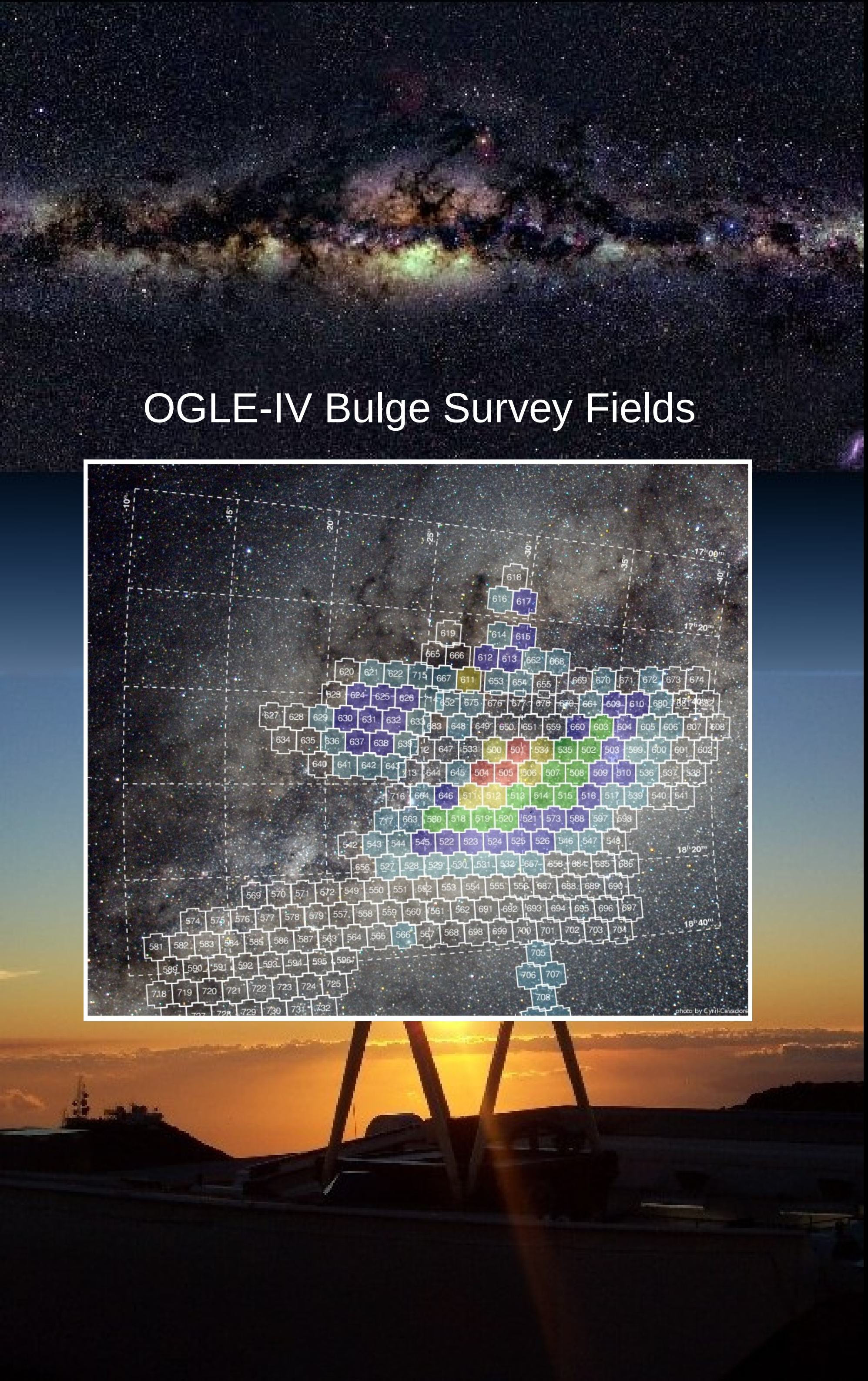
Robotic Microlensing Follow-up

Rachel Street LCOGT.net

- Discovery and follow-up of microlensing events
- Robotic pros and cons
- Robotic approaches
- Robotic Projects



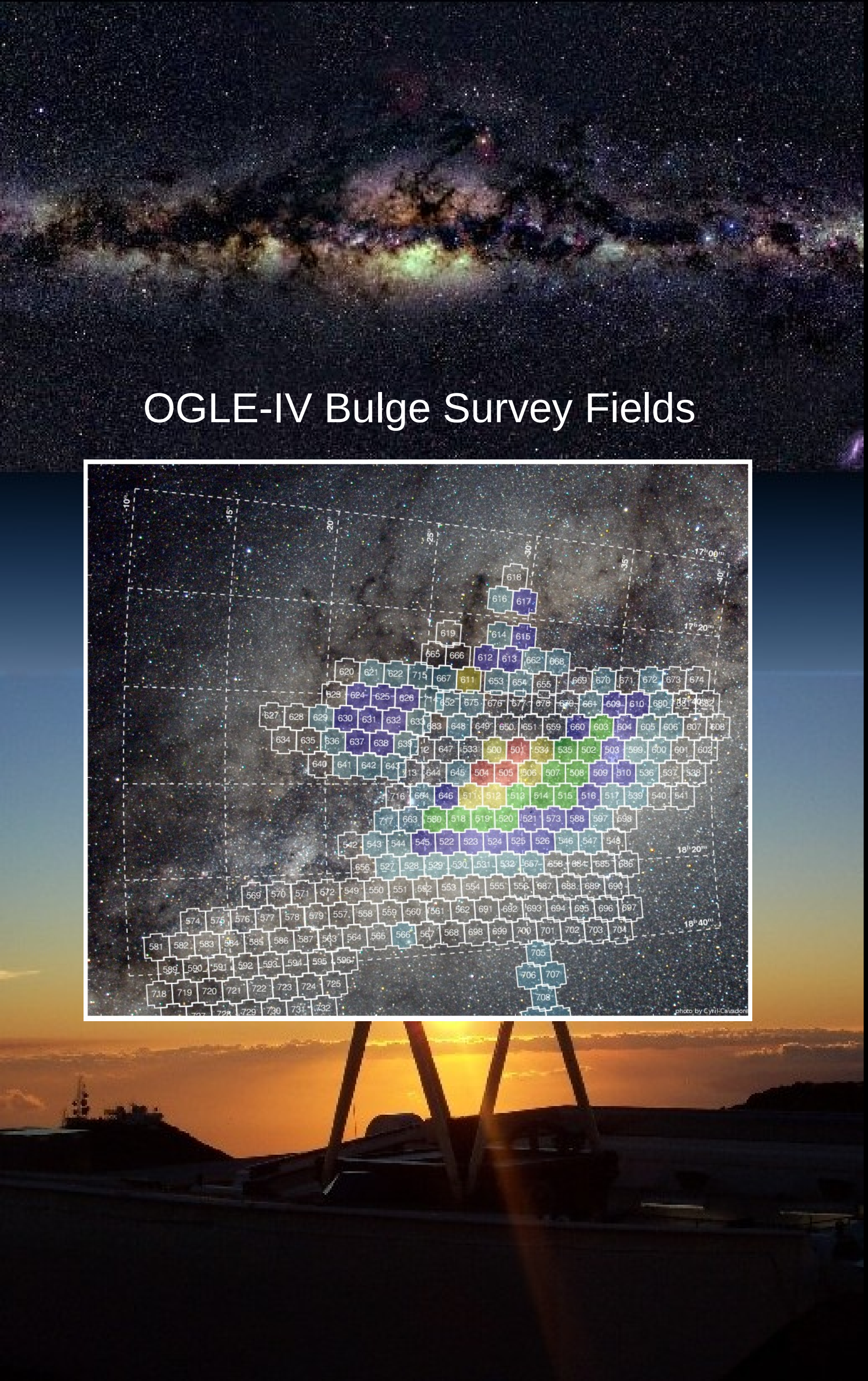
Requirements for Microlensing Planet Detection

Lensing events require precise alignment

- Rare
- Large sample of stars (eg Galactic Bulge)
- Crowded fields, mag range I~12-20mag

→ *Ultra-wide-field instrument*
<1 arcsec pixel scale
~1m telescope

→ *Non-repeating – must get data now!*


OGLE-IV Bulge Survey Fields

Requirements for Microlensing Planet Detection

Lensing events require precise alignment
- Rare
- Large sample of stars (eg Galactic Bulge)
- Crowded fields, mag range I~12-20mag

→ *Ultra-wide-field instrument*
<1 arcsec pixel scale
~1m telescope

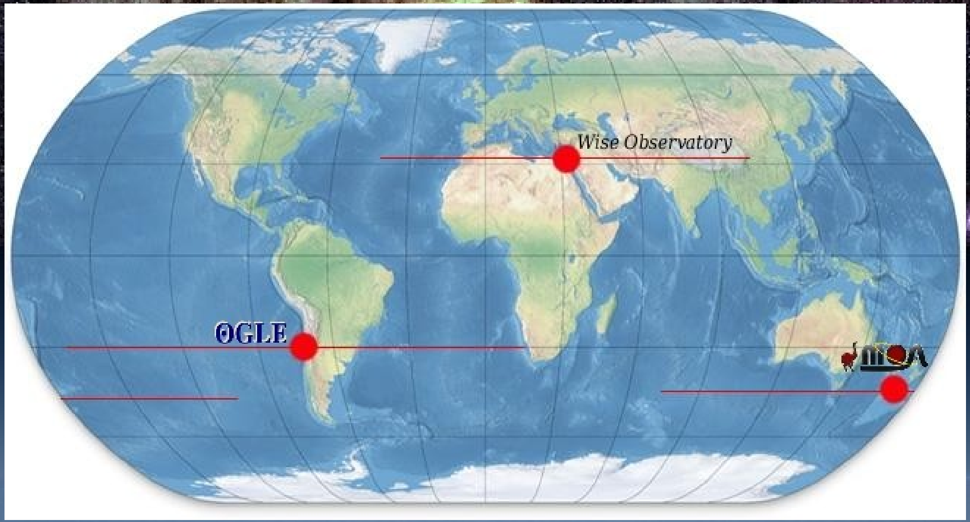
→ *Non-repeating – must get data now!*

- Timescale τ ≥ days - months, some with fast (mins) variations (anomalies)

→ *Dedicated facilities*
→ *Cadence several visits/field/night*

Facilities uncommon, existing surveys single-site

Survey Coverage



Lines represent approximate duration of peak Bulge visibility from site

- Single ground-based observatory can observe for ~6-12 hrs / night
- No single ground-based survey can continuously monitor lensing events (except polar)
- Survey fields overlap in some places ...non-continuous coverage for much of the season
- Weather losses/technical downtime

→ Follow-up network

Global Microlensing Follow-Up Network

- 100s of microlensing events detected in Galactic Bulge each year by MOA, OGLE
- Online alerts of new events and anomalies

But...

- Must select events of interest
- Real time response imperative
- Modeling binary events non-trivial and mostly not automated
- Coordinated response required

Robotic Microlensing Follow-Up

Pros:
- Fast response
- Efficient use of telescope time
- Fast coordination of networked observations
- Cheaper → more telescopes being built/converted to automated operation
- Quicker robotic data handling (used by all teams)

- Algorithmic response easier to determine observational biases

Robotic Microlensing Follow-Up

Pros:

- Fast response
- Efficient use of telescope time
- Fast coordination of networked observations
- Cheaper → more telescopes being built/converted to automated operation
- Quicker robotic data handling (used by all teams)

- Algorithmic response easier to determine observational biases

Cons:

- Rely on algorithm to decide what's interesting
- Modeling binary lensing events non-linear, large parameter space problem
- Robust automation non-trivial

Determining Planet Frequency

▪ Large sample of stars should provide statistically significant sample of planet detections...or non-detections

→ Planet frequency beyond the snowline, down to Earth-mass objects & smaller
→ Test planet formation theories

Determining Planet Frequency

- Large sample of stars should provide statistically significant sample of planet detections...or non-detections

→ Planet frequency beyond the snowline, down to Earth-mass objects & smaller
→ Test planet formation theories

- ***Problem: survey biases***

→ Planet detection/exclusion requires continuous coverage around the peak
→ Follow only a few events continuously
→ Prioritized by human decisions

Determining Planet Frequency

- Large sample of stars should provide statistically significant sample of planet detections...or non-detections

→ Planet frequency beyond the snowline, down to Earth-mass objects & smaller
→ Test planet formation theories

- ***Problem: survey biases***

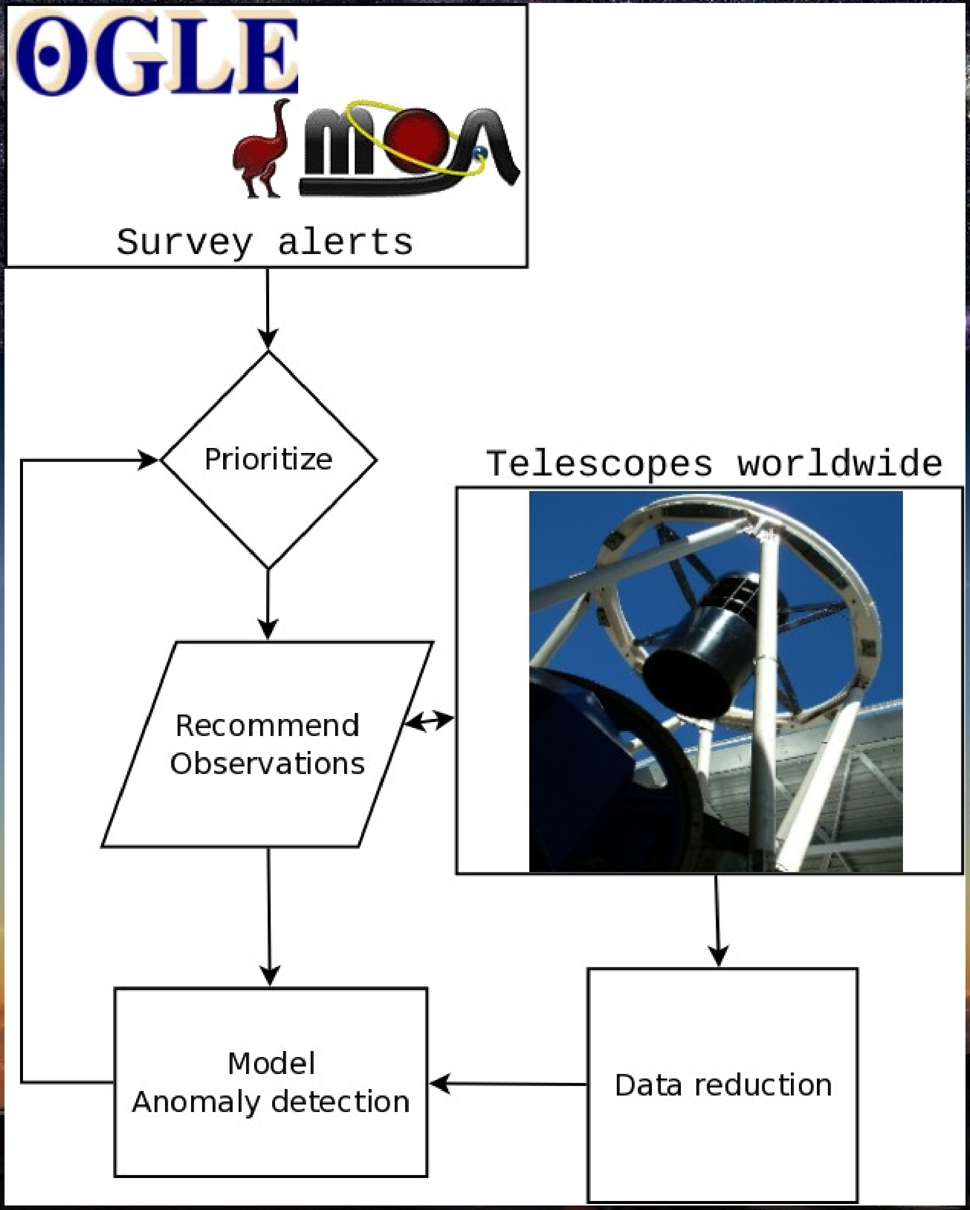
→ Planet detection/exclusion requires continuous coverage around the peak
→ Follow only a few events continuously
→ Prioritized by human decisions

- ***Two solutions:***

→ Follow everything:
  Ground-based survey network, KMTNet
  Space-based WFIRST, Euclid

→ Remove the human decision-making

Microlensing Follow-Up Sequence



Surveys issue online alerts of events in progress

Examine all known events, decide priorities

Recommend current targets per telescope

Telescopes observe targets

Image data reduced quickly

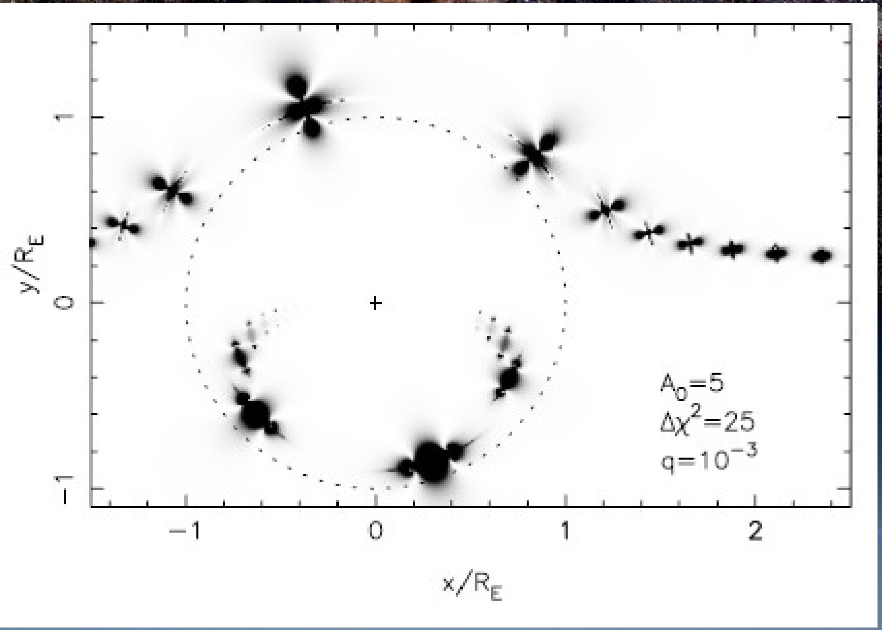
Photometry combined with existing data from all other observers

Event re-modelled, anomalies detected

Observing recommendations updated

Prioritizing Events

Chi-squared Map of Lensing region



Greyscale map:
White low Delta chi^2, black high (detection zones)

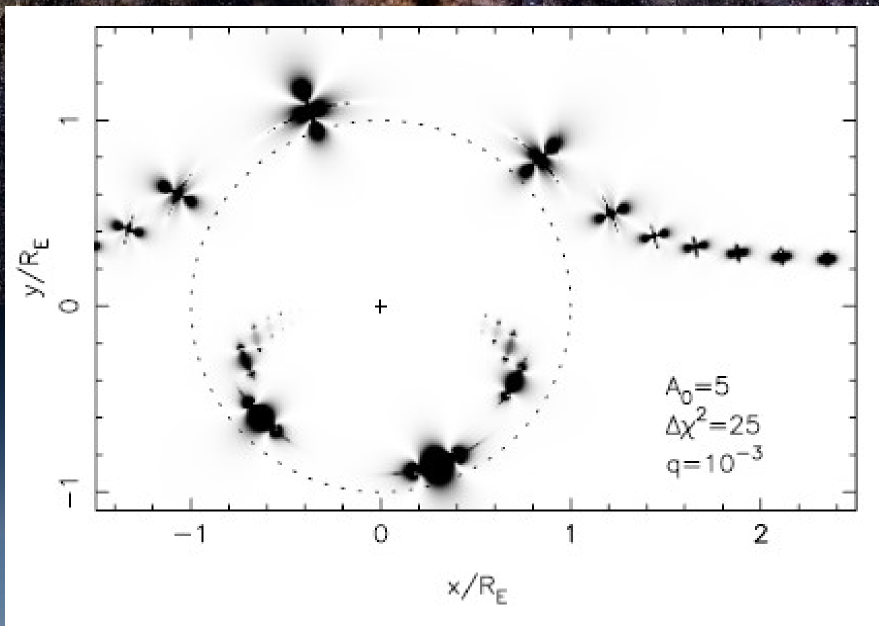
Example case:
q = $1\text{x}10^{-3}$
Amax = 5
Uniformly space datapoints
Delta chi$^2_{thresh}$ > 25

Ref: Horne et al (2009) MNRAS,396, 2087
Dominik et al. (2010) AN, 331, 671

- Estimate gain factor from return .vs. investment
- Return is the planet detection probability, function of current magnification
- Investment = t_{obs}/dt

Prioritizing Events

Chi-squared Map of Lensing region



Greyscale map:
White low Delta chi^2, black high (detection zones)

Example case:
$q = 1\times10^{-3}$
Amax = 5
Uniformly space datapoints
Delta $chi^2_{thresh} > 25$

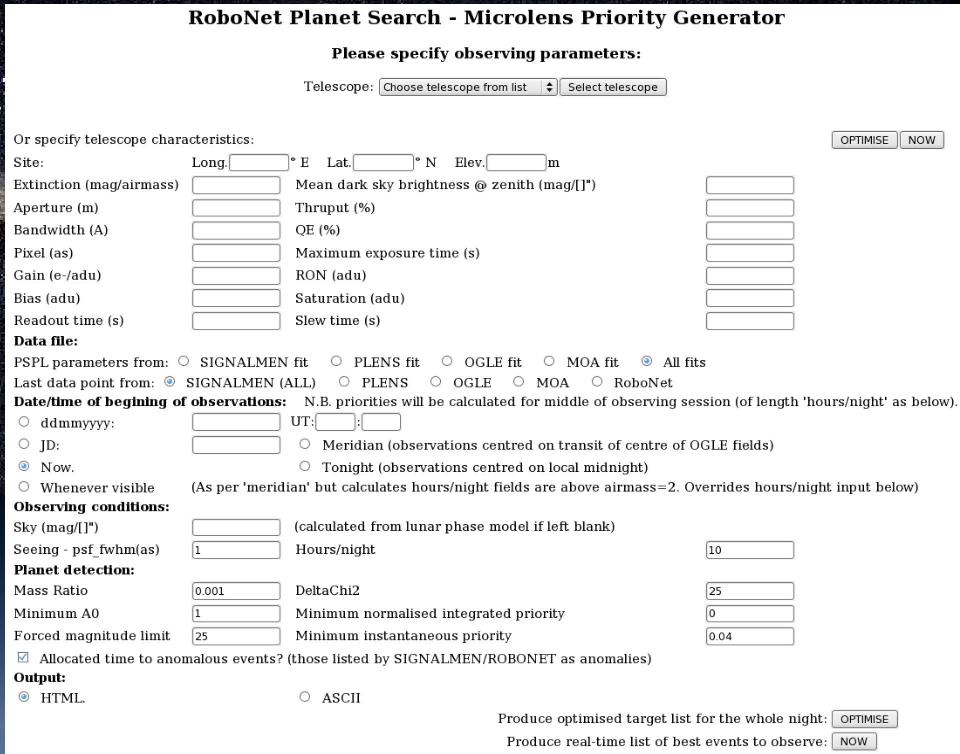
Ref: *Horne et al (2009) MNRAS,396, 2087*
Dominik et al. (2010) AN, 331, 671

- Estimate gain factor from return .vs. investment
- Return is the planet detection probability, a function of current magnification
- Investment = t_{obs}/dt

Sampling interval dt depends on magnification

Required exposure determined from S/N required, telescope aperture, current target brightness, observing conditions

- Targets prioritized dynamically according to gain



RoboNet Planet Search - Microlens Priority Generator

Please specify observing parameters:

Telescope: Choose telescope from list | Select telescope

Or specify telescope characteristics: OPTIMISE | NOW

Site: Long. ° E Lat. ° N Elev. m

Extinction (mag/airmass)		Mean dark sky brightness @ zenith (mag/[]")	
Aperture (m)		Thruput (%)	
Bandwidth (A)		QE (%)	
Pixel (as)		Maximum exposure time (s)	
Gain (e-/adu)		RON (adu)	
Bias (adu)		Saturation (adu)	
Readout time (s)		Slew time (s)	

Data file:

PSPL parameters from: SIGNALMEN fit | PLENS fit | OGLE fit | MOA fit | All fits

Last data point from: SIGNALMEN (ALL) | PLENS | OGLE | MOA | RoboNet

Date/time of begining of observations: N.B. priorities will be calculated for middle of observing session (of length 'hours/night' as below).

ddmmyyyy: UT: :

JD: Meridian (observations centred on transit of centre of OGLE fields)

Now. Tonight (observations centred on local midnight)

Whenever visible (As per 'meridian' but calculates hours/night fields are above airmass=2. Overrides hours/night input below)

Observing conditions:

Sky (mag/[]") (calculated from lunar phase model if left blank)

Seeing - psf_fwhm(as)	1	Hours/night	10

Planet detection:

Mass Ratio	0.001	DeltaChi2	25
Minimum A0	1	Minimum normalised integrated priority	0
Forced magnitude limit	25	Minimum instantaneous priority	0.04

Allocated time to anomalous events? (those listed by SIGNALMEN/ROBONET as anomalies)

Output:

HTML. ASCII

Produce optimised target list for the whole night: OPTIMISE

Produce real-time list of best events to observe: NOW

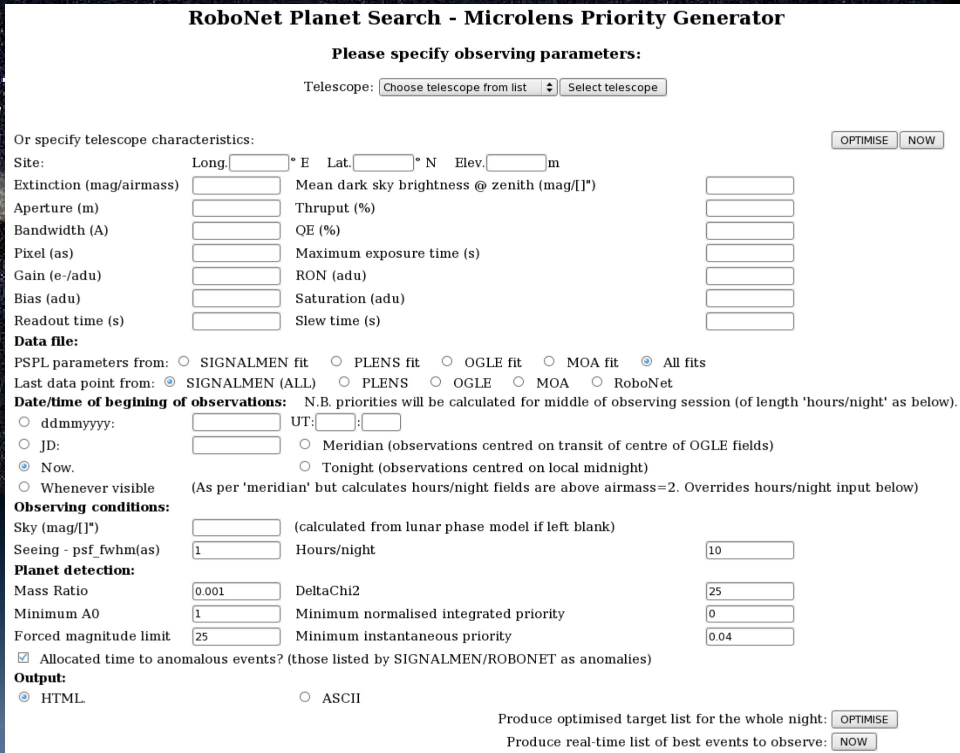
Online Resources

WebPLOP

`robonet.lcogt.net`

- Online event archive and prioritizer
- Available to any observer, configurable for any telescope
- Robotically queried by RoboNet system
- Subscribes to ARTEMiS;
  can receive recommendations from humans

Online Resources



RoboNet Planet Search - Microlens Priority Generator

Please specify observing parameters:

Telescope: Choose telescope from list | Select telescope

Or specify telescope characteristics: OPTIMISE NOW

Site: Long. ° E Lat. ° N Elev. m

Extinction (mag/airmass)		Mean dark sky brightness @ zenith (mag/[]")	
Aperture (m)		Thruput (%)	
Bandwidth (A)		QE (%)	
Pixel (as)		Maximum exposure time (s)	
Gain (e-/adu)		RON (adu)	
Bias (adu)		Saturation (adu)	
Readout time (s)		Slew time (s)	

Data file:

PSPL parameters from: SIGNALMEN fit PLENS fit OGLE fit MOA fit All fits

Last data point from: SIGNALMEN (ALL) PLENS OGLE MOA RoboNet

Date/time of begining of observations: N.B. priorities will be calculated for middle of observing session (of length 'hours/night' as below).

ddmmyyyy: UT: :

JD: Meridian (observations centred on transit of centre of OGLE fields)

Now. Tonight (observations centred on local midnight)

Whenever visible (As per 'meridian' but calculates hours/night fields are above airmass=2. Overrides hours/night input below)

Observing conditions:

Sky (mag/[]") (calculated from lunar phase model if left blank)

Seeing - psf_fwhm(as) 1 Hours/night 10

Planet detection:

Mass Ratio	0.001	DeltaChi2	25
Minimum A0	1	Minimum normalised integrated priority	0
Forced magnitude limit	25	Minimum instantaneous priority	0.04

☑ Allocated time to anomalous events? (those listed by SIGNALMEN/ROBONET as anomalies)

Output:

HTML. ASCII

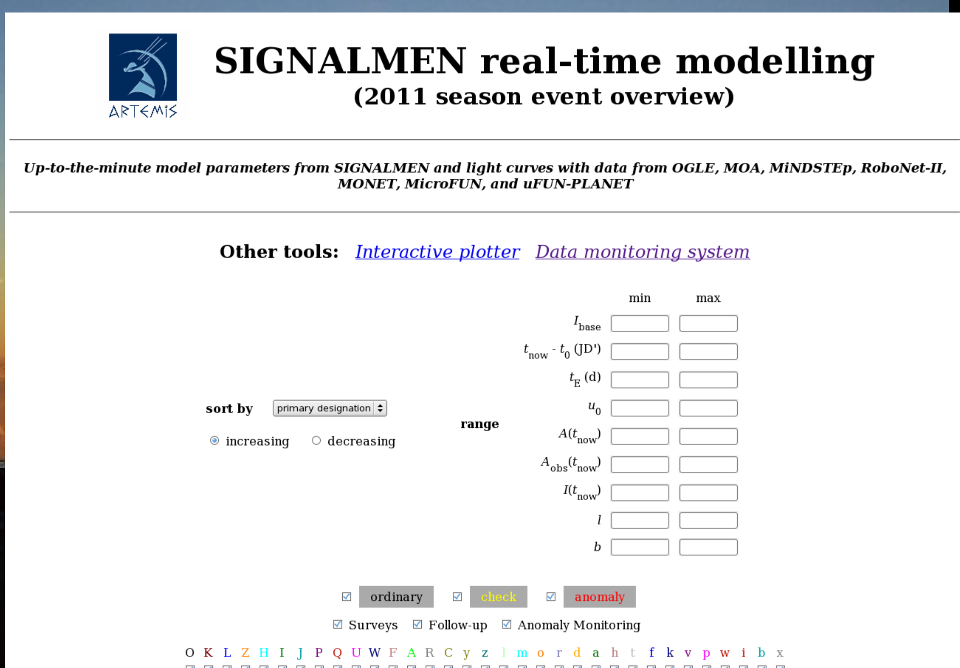
Produce optimised target list for the whole night: OPTIMISE

Produce real-time list of best events to observe: NOW

WebPLOP

robonet.lcogt.net

- Online event archive and prioritizer
- Available to any observer, configurable for any telescope
- Robotically queried by RoboNet system
- Subscribes to ARTEMiS; can receive recommendations from humans



ARTEMiS

SIGNALMEN real-time modelling

(2011 season event overview)

Up-to-the-minute model parameters from SIGNALMEN and light curves with data from OGLE, MOA, MiNDSTEp, RoboNet-II, MONET, MicroFUN, and uFUN-PLANET

Other tools: Interactive plotter Data monitoring system

sort by primary designation

increasing decreasing

range

	min	max
I_{base}		
$t_{now} - t_0$ (JD')		
t_E (d)		
u_0		
$A(t_{now})$		
$A_{obs}(t_{now})$		
$I(t_{now})$		
l		
b		

☑ ordinary ☑ check ☑ anomaly

☑ Surveys ☑ Follow-up ☑ Anomaly Monitoring

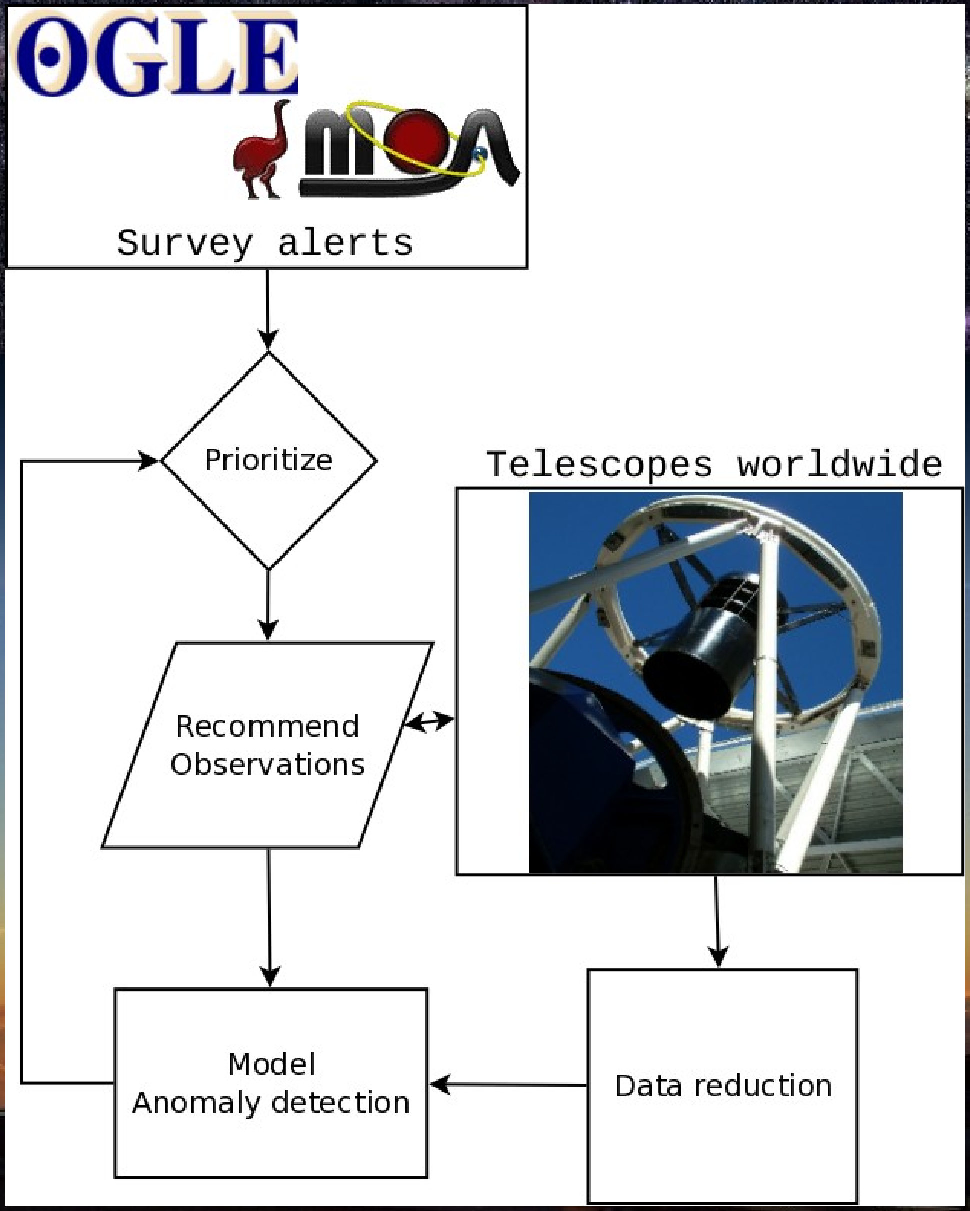
O K L Z H I J P Q U W F A R C y z l m o r d a h t f k v p w i b x

ARTEMiS

www.artemis-uk.org

- SIGNALMEN flags suspected (check) or confirmed (anomaly) ongoing anomalies
- Recommends obs cadence / event
- Event modeling + data visualization facilities

Microlensing Follow-Up Sequence



Surveys issue online alerts of events in progress

Examine all known events, decide priorities

Recommend current targets per telescope

Telescopes observe targets

Image data reduced quickly

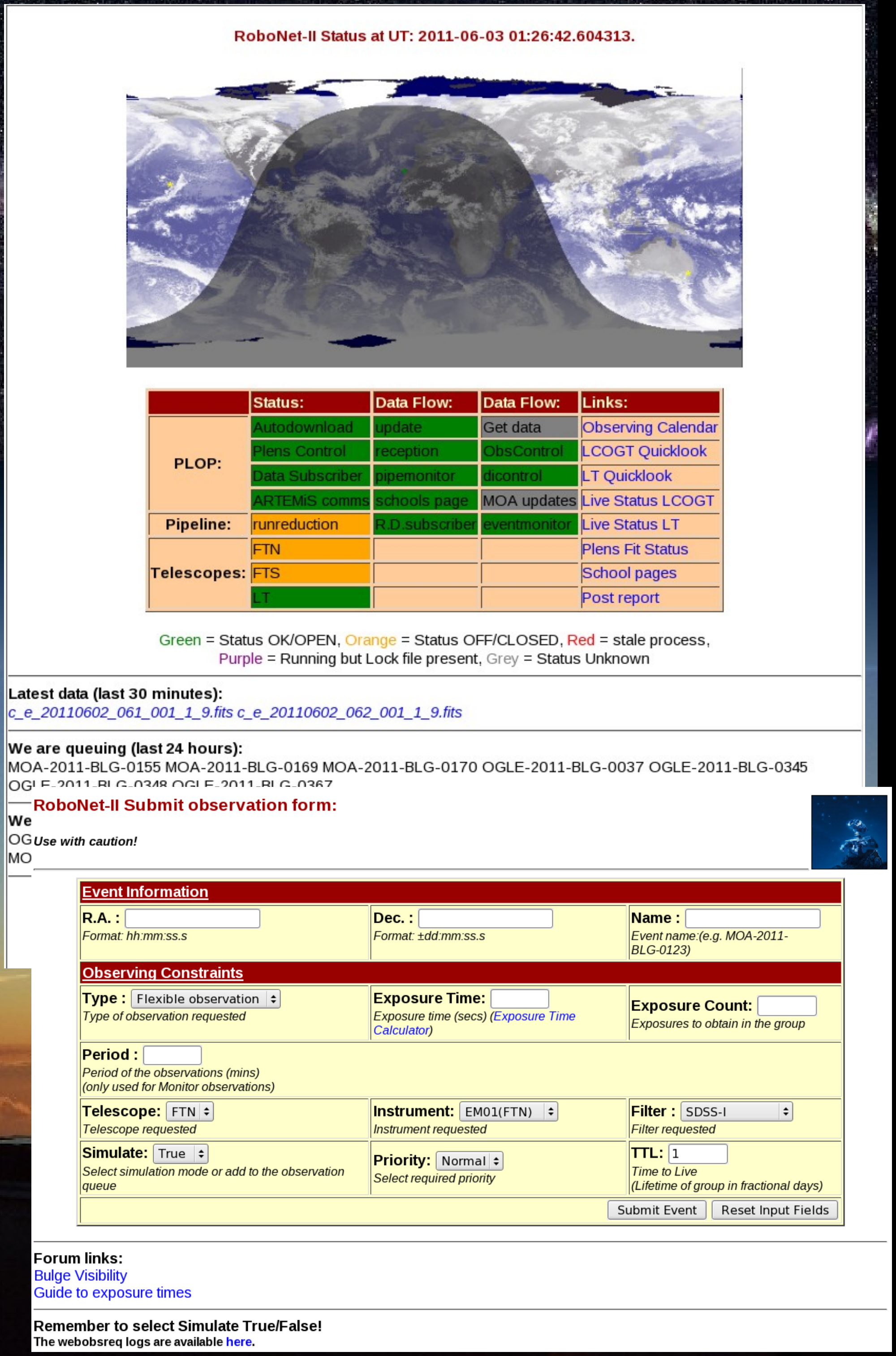
Photometry combined with existing data
from all other observers

Event re-modeled, anomalies detected

Observing recommendations updated

ROBONET-II

ObsControl



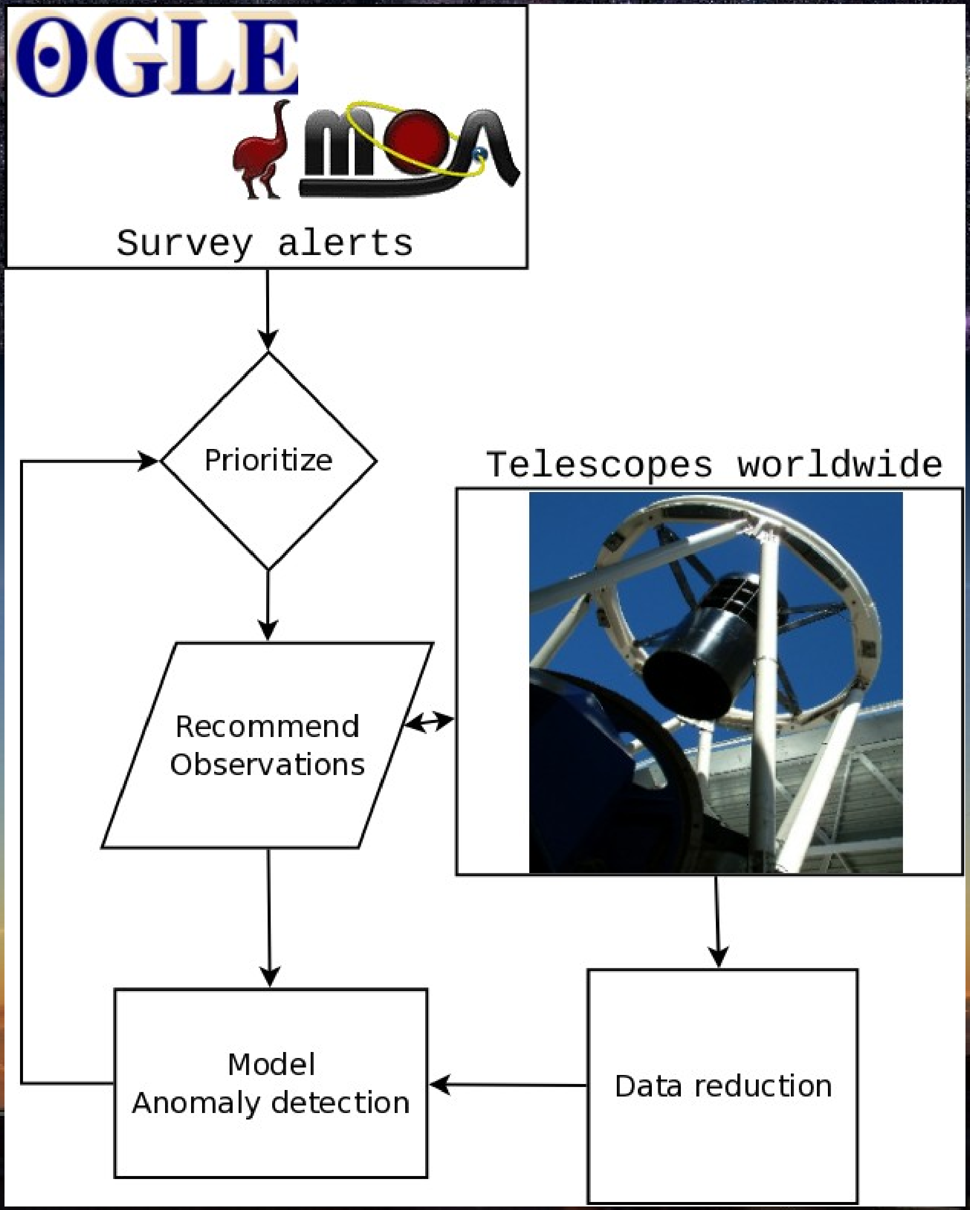
- General-purpose software designed to run observing program with multiple targets and a dynamic target list on any number of telescopes/instruments

- Queries webPLOP for current target priorities (updated ~30min)
Submits observing requests to telescopes
Handles incoming data

- Human interface:
→ Allows humans to request observations also (operators subscribe to wider global follow-up teams and coordinate with them)

→ Allows Target of Opportunity overrides for urgent targets

Microlensing Follow-Up Sequence



Surveys issue online alerts of events in progress

Examine all known events, decide priorities

Recommend current targets per telescope

Telescopes observe targets

Image data reduced quickly

Photometry combined with existing data from all other observers

Event re-modeled, anomalies detected

Observing recommendations updated

Fully robotic DIA pipeline

RoboNet-II Pipeline Status

- Last updated: 2011-06-02 21:46:06 UT Update

For help interpreting this page, please look [here]

Status of pipeline codes running under the crontab:

- pipemonitor.py Operational. Running every 10min OFF
- dicontrol.py Operational. Running every 5min OFF
- eventmonitor.py Operational. Running every 5min OFF

Pipeline Config

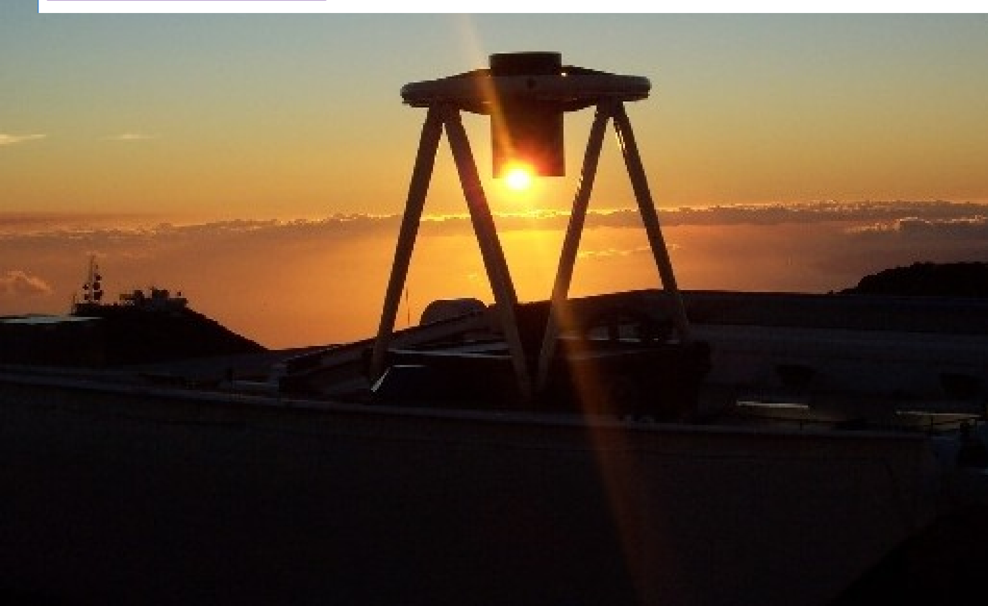
Instructions on how to modify the selection of event data to be processed can be found under the [Pipeline Operations Help]

Currently processing data for ALL events

Ongoing Reduction Processes

Event	Started N hrs ago	Node	ProcID	Red Directory	Process Status	Red Status
MOA-2011-BLG-0142_FTS_SDSS-I	0.00361111111111	2	16965	Locked	Running	OK
MOA-2011-BLG-0169_FTN_SDSS-I	0.000555555555556	3	17232	Locked	Running	OK
OGLE-2011-BLG-0037_LT_SDSS-I	0.00944444444444	0	16673	Locked	Running	OK

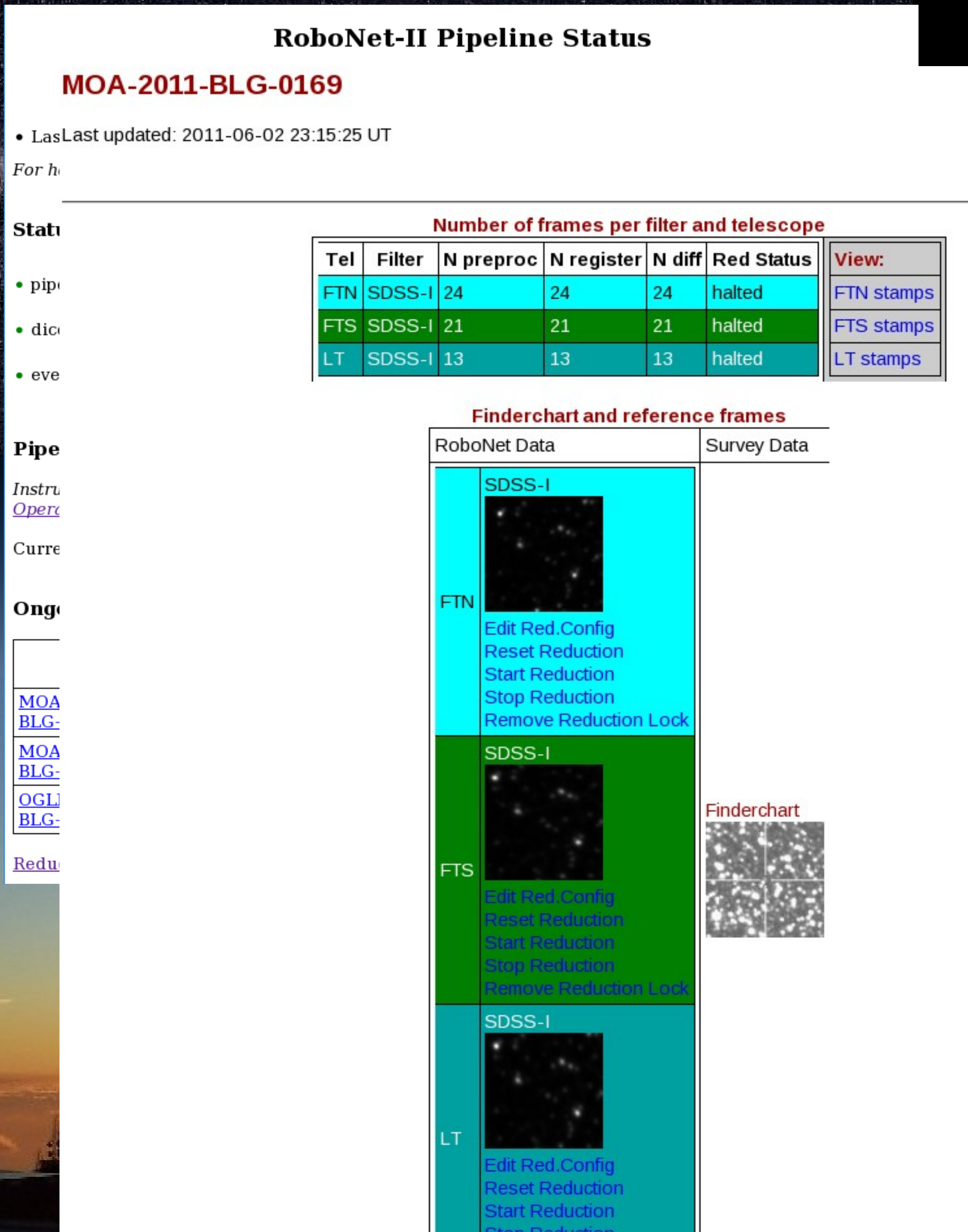
Reduction Status for all events



- Fully automated data-reduction pipeline
- Auto-target identification

ROBONET-II

Fully robotic DIA pipeline



- Fully automated data-reduction pipeline
- Auto-target identification
- Serves updated lightcurves to world community via website/upload.

Fully robotic DIA pipeline

- Fully automated data-reduction pipeline
- Auto-target identification
- Serves updated lightcurves to world community via website/upload.
- Online facilities allow global collaborators to interact with data reductions running on LCOGT Cluster.

RoboNet-II Pipeline Status

MOA-2011-BLG-0169

- LasLast updated: 2011-06-02 23:15:25 UT

For h

Stat

- pip
- dic
- eve

Number of frames per filter and telescope

Tel	Filter	N preproc	N register	N diff	Red Status
FTN	SDSS-I	24	24	24	halted
FTS	SDSS-I	21	21	21	halted
LT	SDSS-I	13	13	13	halted

View:
FTN stamps
FTS stamps
LT stamps

Pipe

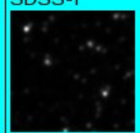
Instru
Opera

Curre

Ong

Finderchart and reference frames

RoboNet Data	Survey Data
FTN SDSS-I	



Edit Red.Config
Reset Reduction

Reset event form

Event : MOA-2011-BLG-0169_FTN_SDSS-I
Reset Code : 1
Reference image :
Target pixel position in fullframe reference (x,y):

Reset event Options:

Code 1: Keeping the same reference image and target location.
Code 2: Re-make the reference frame from the existing choice, auto re-identify target.
Code 3: Keeping the same reference image, auto re-identify target.
Code 4: Re-make the reference image using the frame specified here, auto-identify the target.
Code 5: Re-make the reference image using the frame specified above, with coordinates specified above.
Code 6: full reset - blitz reduction and redo. Forces auto reselection of reference image.

Submit Reset Request | Reset Input Fields

Robotic Observing Programs

<u>RoboNet</u>

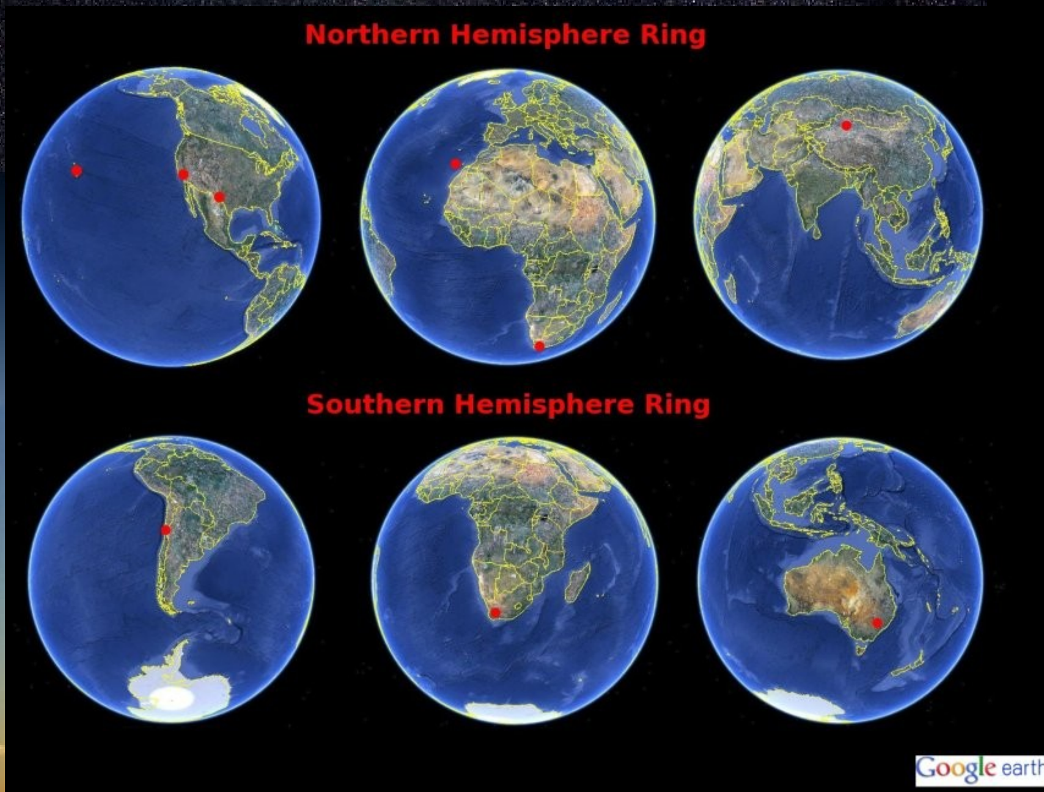
- Fully automated observing system
- Human interactivity optional
- Non-dedicated (queue-scheduled+ToO) time on fully robotic telescopes

<u>MiNDSTEp</u>

- Fully automated observing system
- Time block allocated on quasi-robotic telescopes

<u>SONG</u>

- Building robotic telescopes which will join the MiNDSTEp network



LCOGT.net

SUPA

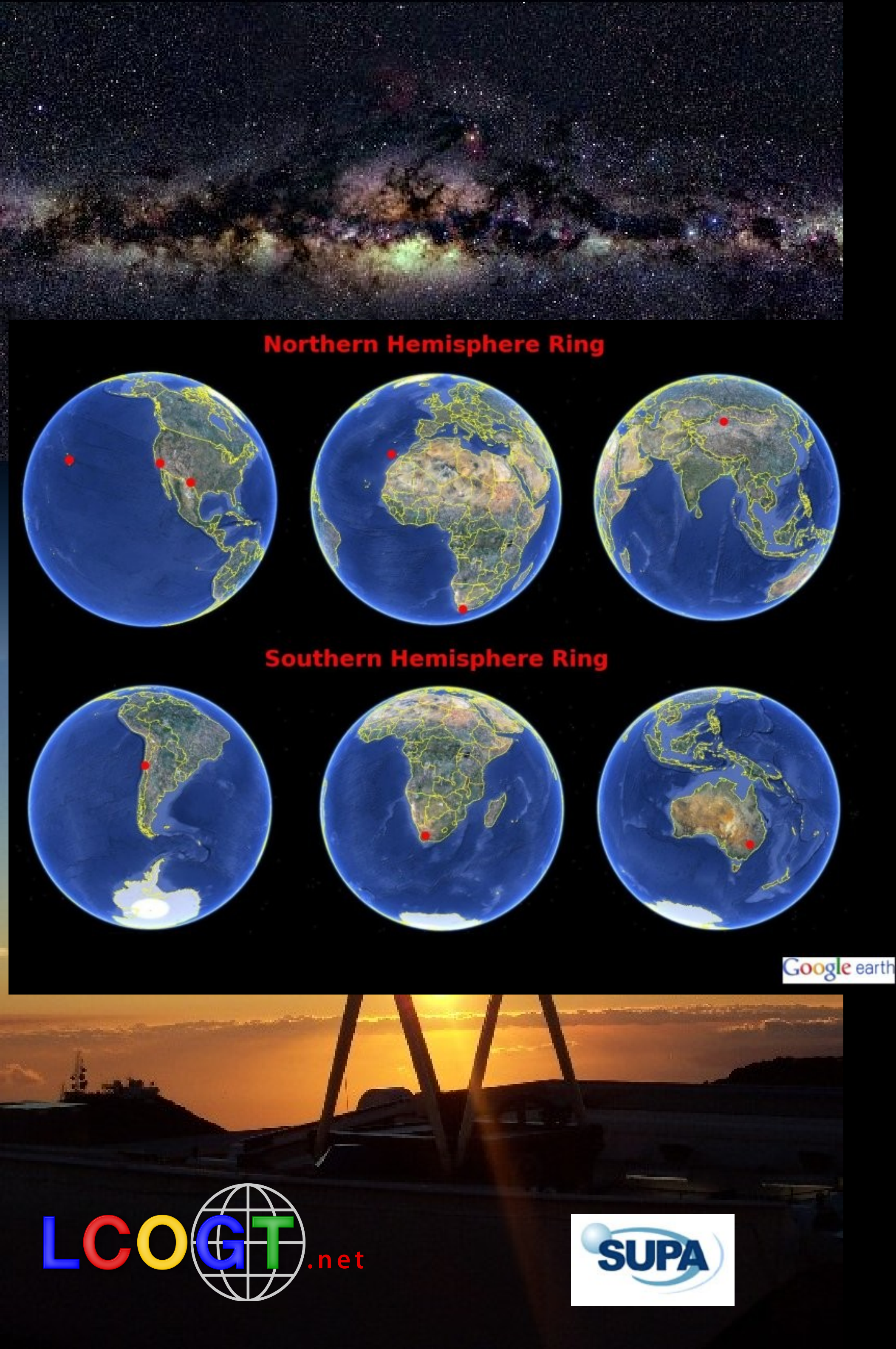
ROBONET-II

robonet.lcogt.net

- Currently:
3 x 2m robotic telescopes
Liverpool Telescopes
LCOGT Faulkes North and South

→ Adaptive queue scheduler
→ Non-dedicated telescopes
→ Fully robotic observation and data reduction
→ webPLOP monitoring strategy +
manual ToO for anomalies

Sagan Workshop 2011



ROBONET-II

robonet.lcogt.net

- Currently:

3 x 2m robotic telescopes
Liverpool Telescopes
LCOGT Faulkes North and South

→ Adaptive queue scheduler
→ Non-dedicated telescopes
→ Fully robotic observation and data reduction
→ webPLOP monitoring strategy +
manual ToO for anomalies

- Future:

→ LCOGT and SUPA/St.Andrews building worldwide multi-aperture telescope network
→ 6 sites worldwide, both hemispheres

→ Two southern 1m to be deployed early 2012

→ Full network by 2014:
2 x 2m
10 x 1m
1 x 0.8m
18 x 0.4m

Sagan Workshop 2011

MONET 1.2m, SAAO

MiNDSTEp

Microlensing Network for the Detection of Small Terrestrial Exoplanets

www.mindstep-science.org

- Quasi-robotic observing network:
  → Danish 1.54m at ESO La Silla (Chile)
  → MONET-S 1.2m at South African Astronomical Observatory

- Future network:
  + MONET-N: 1.2, at McDonald, Texas
  + SONG network (late 2011 onwards)

- Robotic observing following MiNDSTEp strategy

- Block-allocated dedicated time

astro.phys.au.dk/SONG

- Building network of robotic 1m telescopes
- 8 sites, both hemispheres

- Deployment timetable:
  - →Prototype in Canary Islands online Sept 2011
  - →China, Argentine in 2012
  - →Chile and Hawai'i 2013
  - →South Africa/Namibia and Australia 2013/2014

- Science goals

Asteroseismology
Microlensing

- Initially block-allocated time
 (may move to queue-scheduled)
- Will follow MiNDSTEp strategy

Future Directions

- Future worldwide networks of robotic telescopes
  - → Weather/technical redundancy
  - → Better coverage, more consistent datasets
  - → Robotic target selection

- Anomaly modeling and assessment

→ newly automated, largely manual

→ much improved predictive models issued during events guiding observations

- Prioritization of simultaneous anomalies

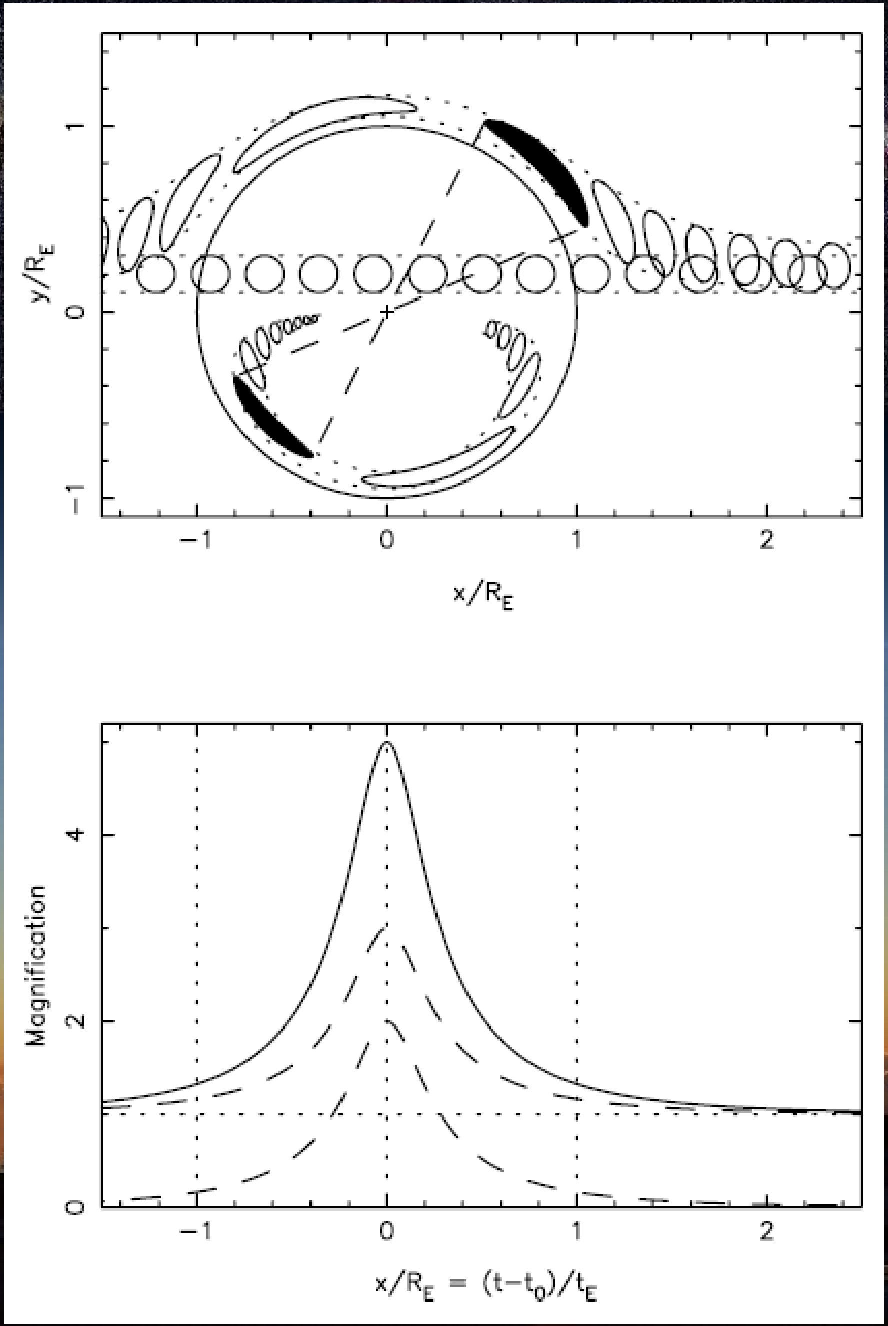
Hard to do while in progress (difficult to distinguish stellar/planetary binaries until quite late on)

→Multiple simultaneous anomalies from upgraded surveys

- Support for space-based mission

Additional Material

Lens-centered geometry



From: Horne et al 2009, MNRAS, 396, 2087

Prioritizing Events

For event combined lightcurve, can fit:
→ PSPL model
→ PSPL + anomaly models for planets at x,y spanning grid around the Einstein ring region

Calculate Delta chi^2 at each x,y

If Delta chi^2(x,y) > threshold, data are sensitive to planets located at (x,y) → map of detection zones

- Detection zones indicate sensitivity to planets (around major and minor image locations at time of observations)

Targets prioritized according to g values