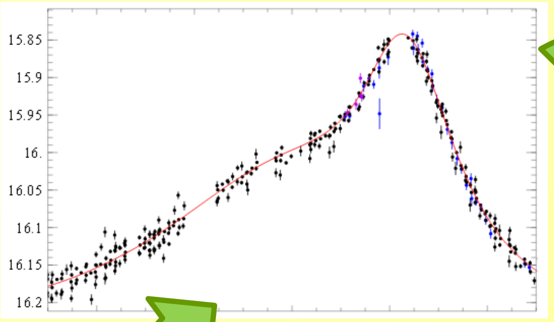
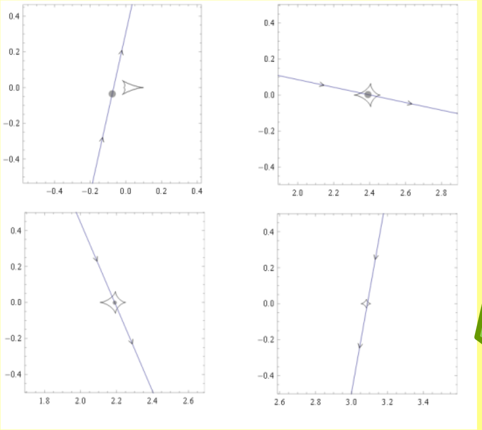
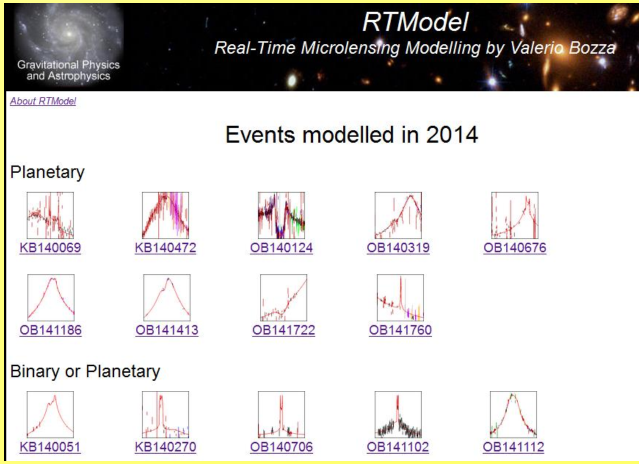
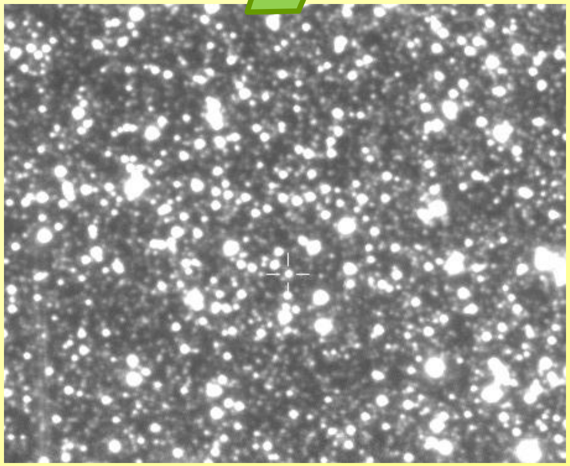
RTModel: automatic fast real-time modelling of microlensing events









Valerio Bozza
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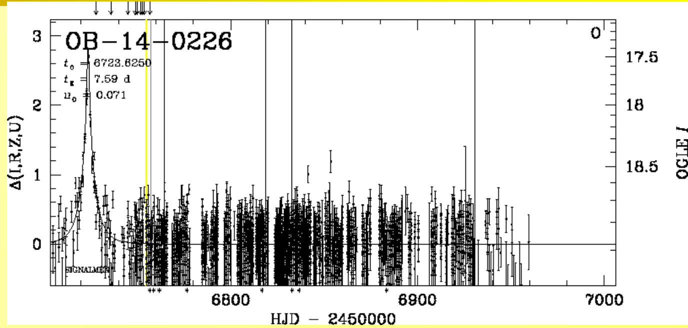
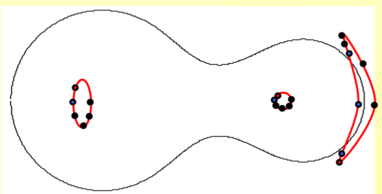
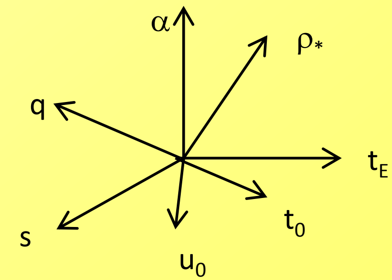
Issues in microlensing modelling



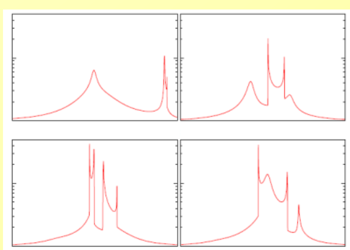
- Microlensing is a **non-repeatable** phenomenon
- Data quantity and quality cannot be improved if insufficient.



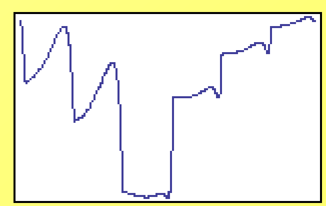
- The **computational time** of a single model point is long.



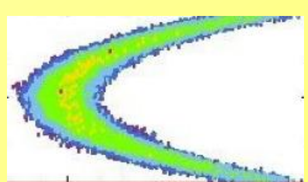
- The **number of** modelling **parameters** is large.



- There is an **extreme variety** of light curve morphologies.



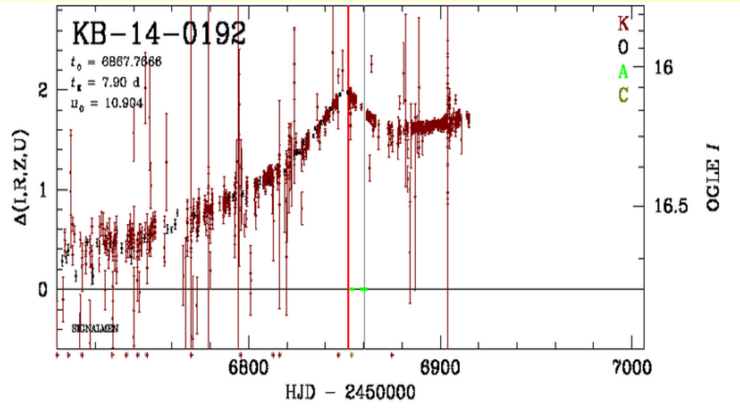
- Chi square is **wildly sensitive** to small variations in the parameters.



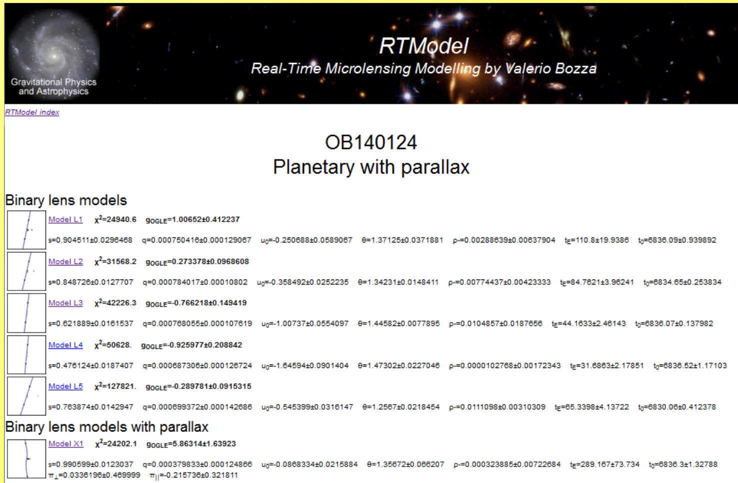
- Many discrete and continuous **degeneracies** exist.

RTModel

- Since 2011 we have been running our computational platform **RTModel** on our good old 8-core workstation.
- More than 600 events have been modelled in 4 years.

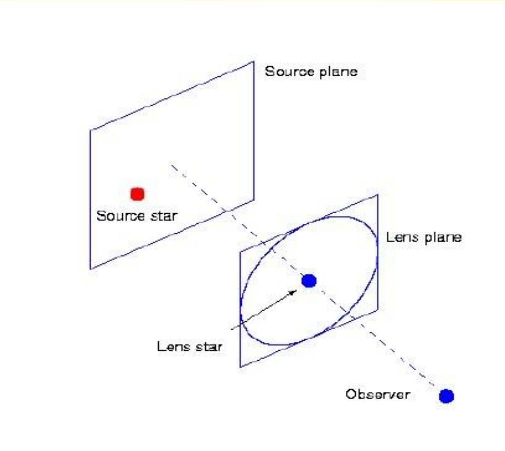


- RTModel automatically responds to anomaly alerts by **ARTEMIS**.
- Data are downloaded and pre-processed.
- Initial conditions are automatically set.
- **Downhill fitting** is performed and higher order effects are considered.
- Models are automatically displayed on a **public webpage**.
- The total time for a single run is kept within **3 hours**.

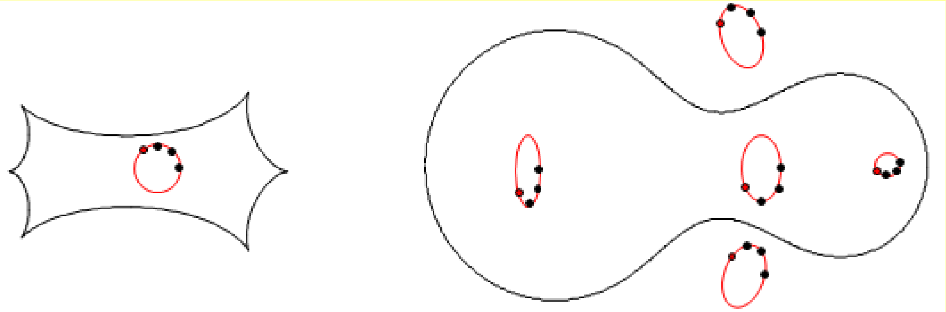


Basic calculation

- First step: for given lens and source positions, we must compute the gravitational lensing magnification.
- **Inverse ray-shooting** amounts to shooting back light rays from the observer to the source plane.

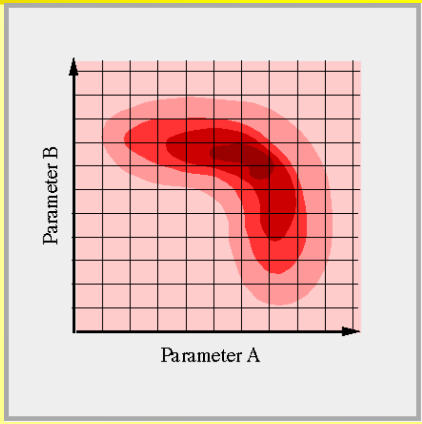


- Light rays are counted if they hit the source disk.
- **Magnification maps** re-usable (save for orbital motion cases). Limb darkening naturally included. Optimizations are possible.

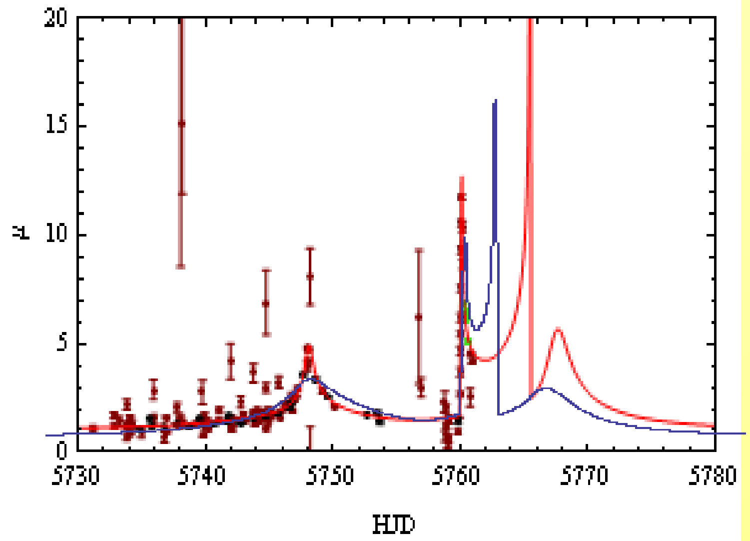


- We use **contour integration**: boundaries of the images are calculated; area is obtained by Green's theorem.
- Elegant and fast. Limb darkening requires multiple contours.
- **Computational time** is somewhat less of ms.
- With thousands of points a single lightcurve may exceed one second.

Initial conditions



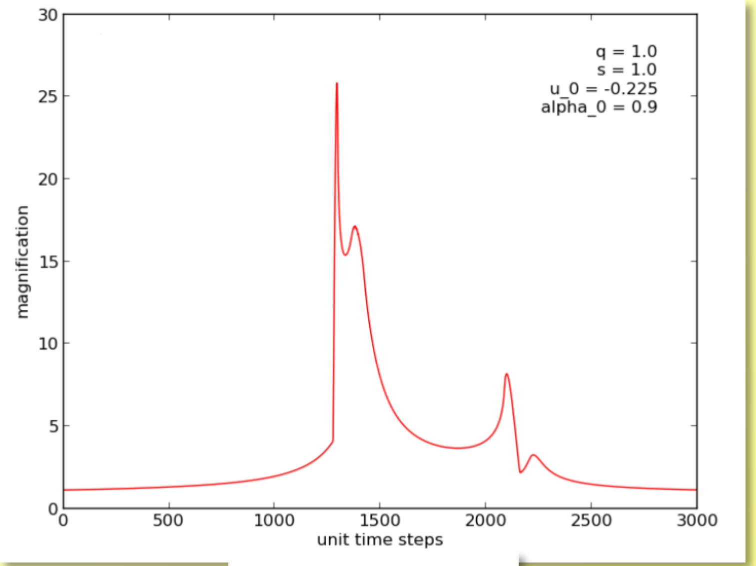
- **Grid search** might cover the interesting regions of the parameter space,
- but is always redundant and needs sufficiently small steps.



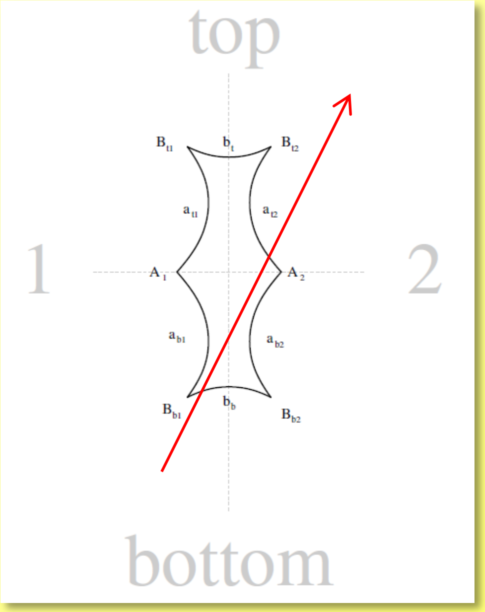
- **Template matching** *(Mao & Di Stefano 1995)* avoids redundancy and promises to be exhaustive.
- More vulnerable to the presence of local minima within a given class.
- Peaks in the datasets are identified and classified by their **prominence**.
- The two most prominent peaks are matched to the peaks in the templates.
- If there is only one peak in the data, the **anomaly alert** time is taken as the second "would-be" peak.

Classification of light curves

- The completeness of the template library is of crucial importance for the effectiveness of this approach.
- We have now published **the first complete catalogue of light curves** in equal-mass binary microlensing
  (Liebig, D'Ago, Bozza and Dominik arXiv:1501.02219).



F-$\bar{\text{F}}$-F $\bar{\text{C}}$

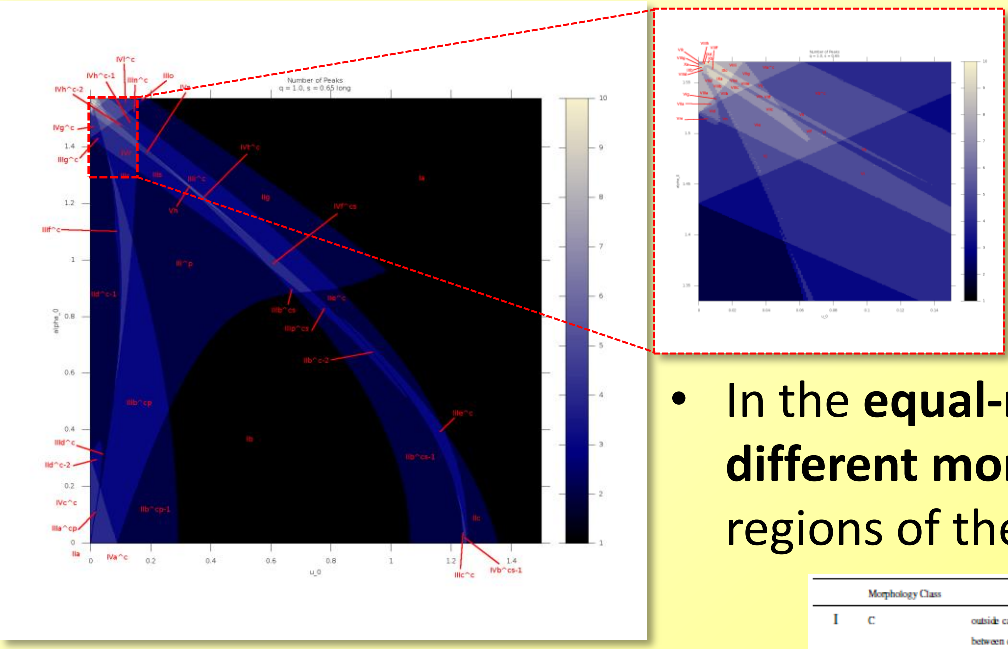


[b_b a_{b1} a_{t2}] A_2

- Every peak in a microlensing light curve can be traced to an interaction of the source with a **caustic**:
- Fold crossing
- Cusp crossing
- Fold approach
- Cusp approach

- Light curve morphologies are classified by their specific sequence of peaks.

The catalogue of light curves



- We have scanned the **parameter space** distinguishing all **regions** corresponding to different morphologies.

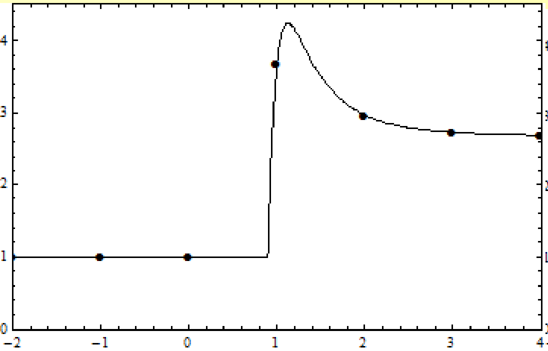
- In the **equal-mass case**, we have identified **73 different morphologies**, arising from 232 different regions of the parameter space.

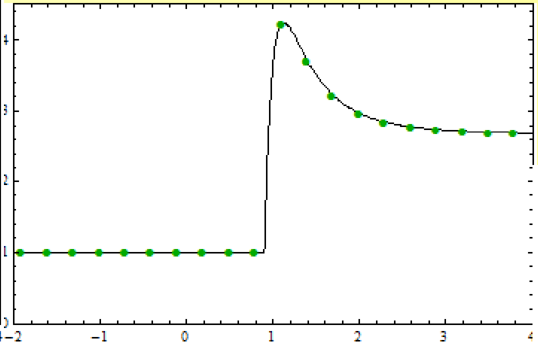
- We can link any observed morphology to the respective regions of the parameter space.
- The classification can be naturally extended to arbitrary mass-ratios.

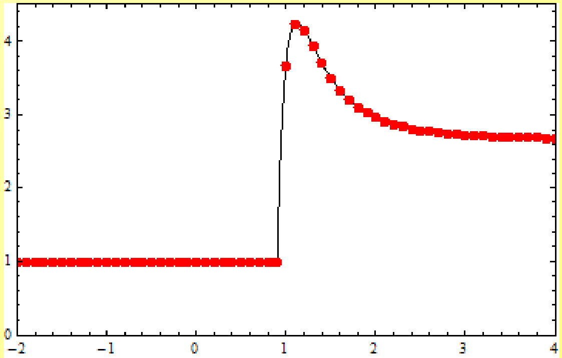
	Morphology Class	Close	Intermediate	Wide
I	C	outside caustics between caustics	outside caustics	outside caustics between caustics
II	F-F	$[a_{tp1}a_{tp2}]$, $[a_{ts1}a_{ts2}]$, $[a_{bp1}a_{tp2}]$, $[a_{ts1}b_t]$, $[a_{bp1}a_{p1}]$	$[a_{i1}a_{i2}]$, $[a_{b1}a_{i2}]$, $[a_{i1}b_i]$, $[a_{b1}b_i]$, $[b_b b_i]$	$[a_{b1}b_{i1}]$, $[b_{b1}b_{i1}]$
	C C	$B_{i1}B_{i2}$, A_1B_{i1}, A_1C_{tp}, A_1C_{ts}, A_1B_{i2}, $C_{ts}B_{i2}$	$B_{i1}B_{i2}$, A_1B_{i1}	$B_{i1}B_{i2}$, A_1B_{i1}, $B_{b1}D_1$, $B_{b1}B_{i2}$
	C-C	$[A_1A_2]$	$[A_1A_2]$	-
	C-F	$[a_{ts1}B_{i2}]$, $[A_1a_{tp2}]$	$[a_{i1}B_{i2}]$, $[A_1a_{i2}]$, $[B_{b1}b_i]$, $[A_1a_{i2}]$	$[B_{b1}b_{i1}]$
III	C F-F	$A_1[a_{tp1}a_{tp2}]$, $A_1[a_{bp1}a_{tp2}]$, $[a_{ts1}b_t]B_{i2}$, $A_1[a_{ts1}b_t]$, $[a_{bp1}a_{tp2}]B_{i2}$, $[a_{bp1}a_{tp1}]B_{i1}$, $[a_{ts1}a_{ts2}]B_{i2}$, $[a_{ts1}a_{tp2}]B_{i2}$, $[a_{bp1}a_{tp2}]C_{tp}$, $[a_{bp1}a_{tp1}]C_{tp}$, $[a_{bp1}a_{tp1}]B_{i2}$	$A_1[a_{i1}a_{i2}]$, $A_1[a_{b1}a_{i2}]$, $[a_{i1}b_i]B_{i2}$, $A_1[a_{i1}b_i]$, $[a_{b1}a_{i2}]B_{i2}$, $[a_{b1}b_i]B_{i2}$, $B_{b1}[a_{b1}b_i]$, $[a_{b1}a_{i1}]B_{i1}$, $[a_{i1}a_{i2}]B_{i2}$, $[a_{b1}b_i]B_{i2}$, $B_{b1}[b_b b_i]$	$[a_{i1}b_{i1}]B_{i2}$, $A_1[a_{i1}b_{i1}]$, $B_{b1}[a_{b1}b_{i1}]$, $[a_{b1}a_{i1}]B_{i1}$, $[a_{b1}b_{i1}]B_{i2}$, $B_{b1}[b_{b1}b_{i1}]$, $A_1[b_{b1}b_{i1}]$, $[a_{b1}b_{b1}]B_{i2}$
	F-F-F	$[a_{ts1}b_t a_{ts2}]$, $[a_{bp1}a_{tp1}a_{tp2}]$	$[a_{i1}b_i a_{i2}]$, $[a_{b1}a_{i1}a_{i2}]$, $[a_{b1}a_{i1}b_i]$, $[b_b a_{b1}b_i]$, $[a_{b1}a_{i2}b_i]$, $[a_{b1}b_i a_{i2}]$	$[a_{b1}a_{i1}b_{i1}]$, $[a_{b1}b_{b1}b_{i1}]$
	C F-C	$[A_1a_{tp2}]A_2$, $C_{bp}[abp1C_{tp}]$	$[A_1a_{i2}]A_2$, $A_1[a_{i1}B_{i2}]$, $[A_1b_i]B_{i2}$	$[A_1b_{i1}]B_{i2}$
	C C C	$B_{b1}A_1B_{i1}$, $A_1C_{ts}B_{i2}$	$B_{b1}A_1B_{i1}$	$B_{b1}A_1B_{i1}$, $B_{b1}D_1B_{i2}$, $A_1B_{i1}B_{i2}$, $B_{b1}A_1B_{i2}$
	C-F-F	-	$[A_1b_i a_{i2}]$	-
	C C-F	$A_1[C_{ts}b_t]$	-	-
IV	C F-F C	$A_1[a_{tp1}a_{tp2}]A_2$, $A_1[a_{bp1}a_{tp2}]A_2$, $A_1[a_{ts1}a_{ts2}]B_{i2}$, $B_{b1}[a_{bp1}a_{tp2}]B_{i2}$, $B_{b1}[a_{bp1}b_{tp1}]B_{i1}$, $C_{bp}[a_{bp1}a_{tp2}]C_{tp}$	$A_1[a_{i1}a_{i2}]A_2$, $A_1[a_{b1}a_{i2}]A_2$, $A_1[a_{i1}b_i]B_{i2}$, $A_1[a_{i1}a_{i2}]B_{i2}$, $B_{b1}[a_{b1}a_{i2}]B_{i2}$, $B_{b1}[a_{b1}a_{i1}]B_{i1}$, $A_1[a_{b1}b_i]B_{i2}$, $B_{b1}[a_{b1}b_i]B_{i2}$	$A_1[a_{i1}b_{i1}]B_{i2}$, $B_{b1}[b_{b1}b_{i1}]B_{i2}$, $B_{b1}[a_{b1}a_{i1}]B_{i1}$, $A_1[a_{b1}b_{i1}]B_{i2}$
	F-F F-F	$[a_{ts1}b_t][b_t a_{ts2}]$, $[a_{bp1}a_{tp1}][a_{tp1}a_{tp2}]$, $[a_{bp1}a_{tp1}][a_{ts1}b_t]$	$[a_{i1}b_i][b_i a_{i2}]$, $[a_{b1}a_{i1}][a_{i1}a_{i2}]$, $[a_{b1}a_{i1}][a_{i1}b_i]$, $[b_b a_{b1}][a_{b1}b_i]$, $[a_{b1}a_{i2}][a_{i2}b_i]$, $[a_{b1}b_i][b_i a_{i2}]$	$[a_{i1}b_{i1}][b_{i2}a_{i2}]$, $[a_{b1}a_{i1}][a_{i1}b_{i1}]$, $[a_{b1}b_{b1}][b_{b1}b_{i1}]$, $[a_{b1}b_{b1}][b_{i2}a_{i2}]$
	C F-F-F	$[a_{bp1}a_{tp1}a_{tp2}]B_{i2}$, $A_1[a_{ts1}a_{ts2}b_t]$	$[a_{b1}a_{i1}a_{i2}]B_{i2}$, $[a_{b1}a_{i1}b_i]B_{i2}$, $B_{b1}[a_{b1}a_{i1}b_i]$, $A_1[a_{i1}b_i a_{i2}]$, $A_1[a_{b1}b_i a_{i2}]$, $B_{b1}[a_{b1}a_{i2}b_i]$	$B_{b1}[a_{b1}a_{i1}b_{i1}]$, $[a_{b1}b_{b1}b_{i1}]B_{i2}$
	F-F-F-F	-	$[b_b a_{b1}a_{i1}b_i]$, $[a_{b1}a_{i1}a_{i2}b_i]$, $[b_b a_{b1}a_{i2}b_i]$	-
	C-F F-F	-	$[a_{b1}a_{i1}][a_{i1}B_{i2}]$, $[A_1b_i][b_i a_{i2}]$	$[A_1b_{i1}][b_{i2}a_{i2}]$
	F-F C C	$[a_{bp1}a_{tp1}]C_{tp}B_{i2}$, $[a_{bp1}a_{tp1}]C_{ts}B_{i2}$, $A_1C_{ts}[a_{ts1}b_t]$, $A_1C_{ts}[a_{ts2}b_t]$, $[a_{bp1}a_{tp1}]C_{ts}B_{i1}$	-	$[a_{b1}b_{b1}]D_1B_{i2}$
	C-C C-C	-	-	$[A_1D_1][D_2A_2]$
	F-F C-F	$[a_{bp1}a_{tp1}][C_{ts}b_t]$	-	-
	C-F C C	-	-	$[A_1b_{i1}]D_1B_{i2}$
	C F-C C	$C_{bp}[a_{bp1}C_{tp}]B_{i2}$	-	-

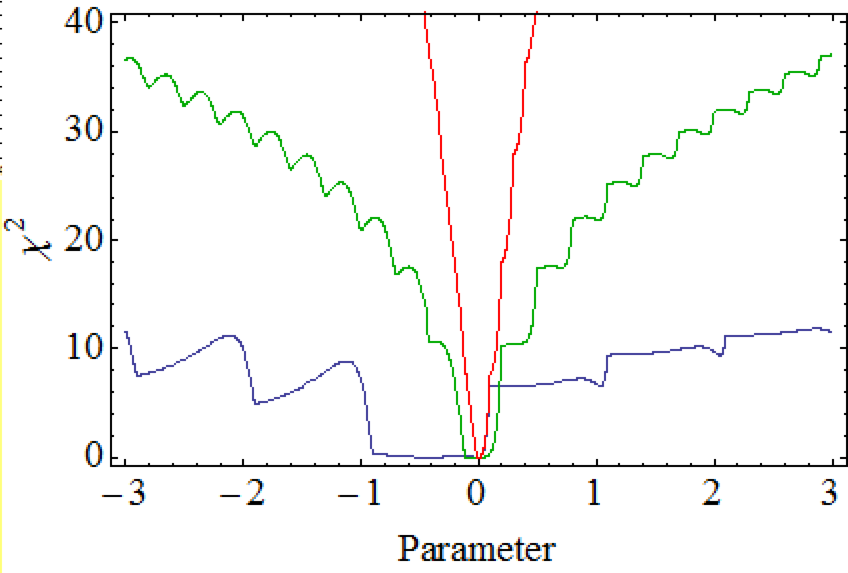
Fitting

- The nightmare of modellers is getting stuck in **a local minimum**.
- Local minima may exist within each region of the parameter space corresponding to a specific morphology class.
- But the presence of **gaps** in the data may copiously generate **see-saw patterns** in the chi square.

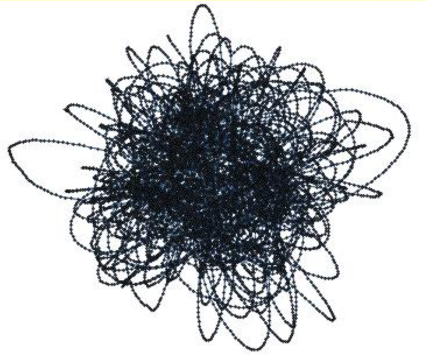






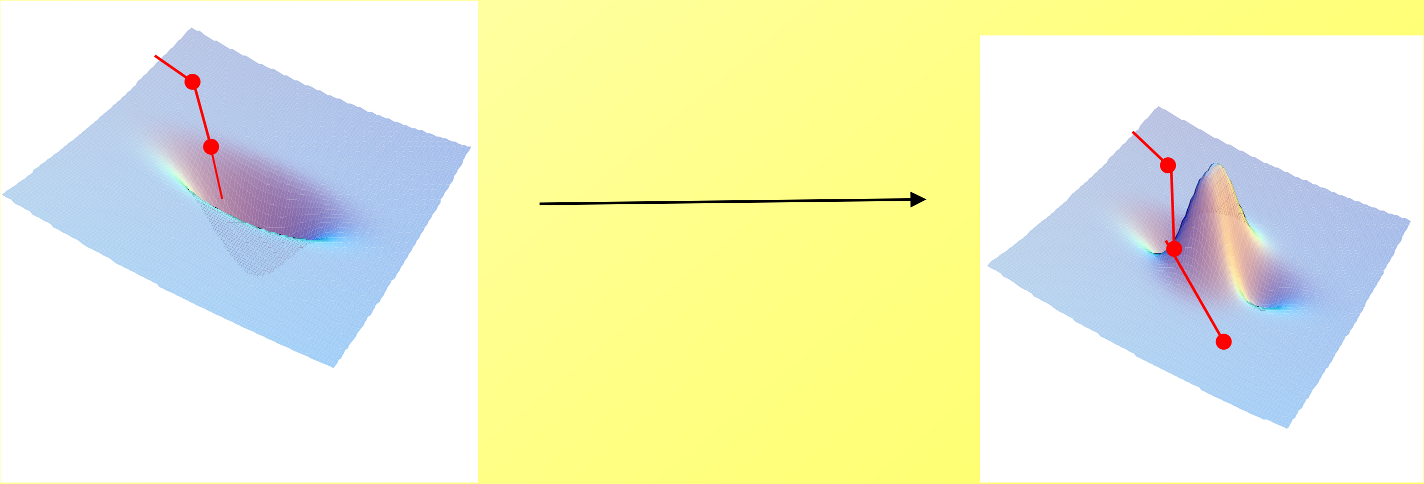


Fitting



- **Markov chains** have a finite probability (depending on the temperature) to jump out of a local minimum.
- However, they require the calculation of a large number of models from any given initial condition.

- We use a **Levenberg-Marquardt** algorithm (interpolating between Newton's and steepest descent).
- In order to jump out of local minima, we fill the minima with **penalty functions** and let the fit roll to the next minimum.

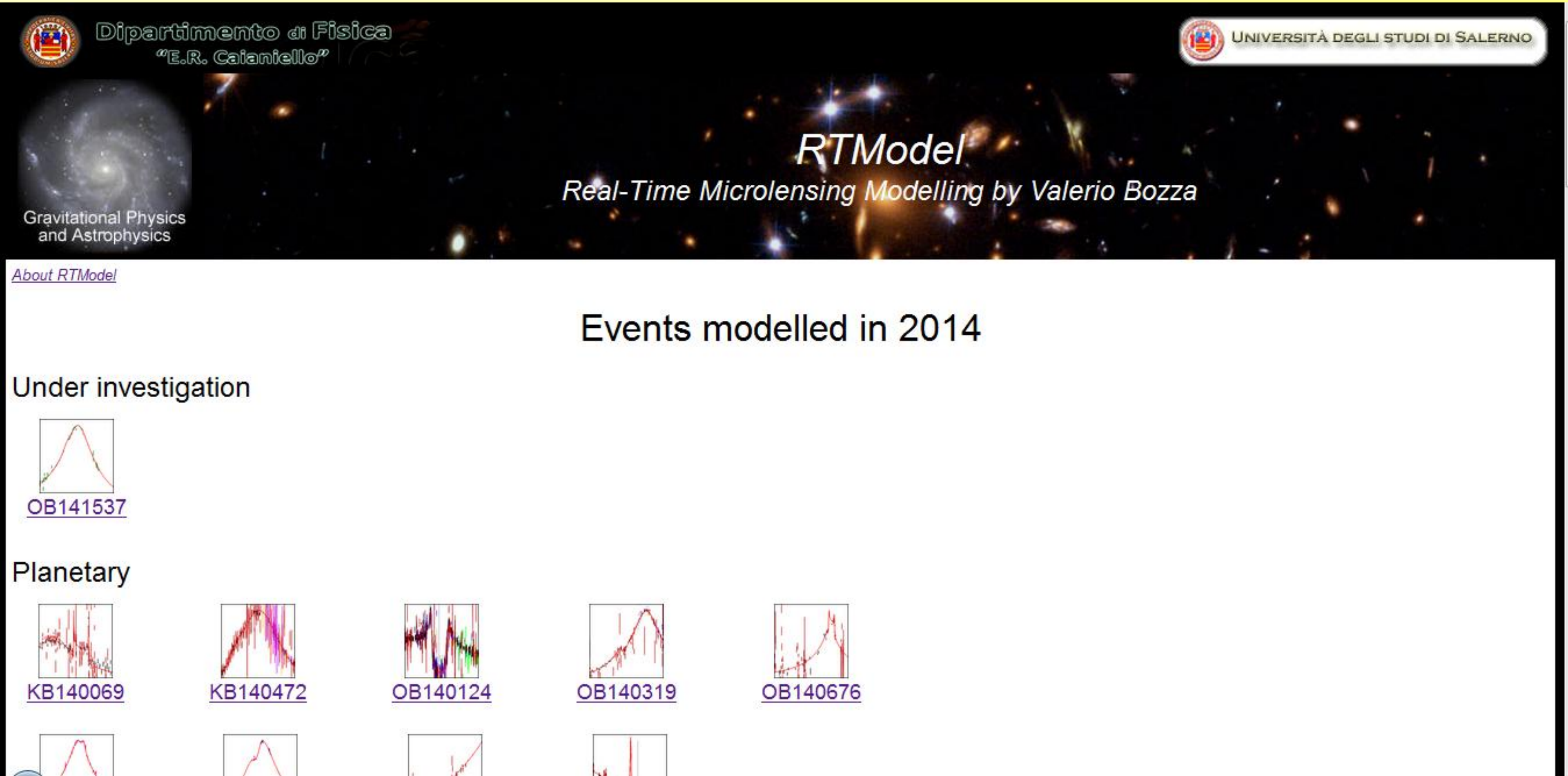


Higher-order effects

- We refine the best static solutions by including **annual parallax** and **orbital motion**.
- For **parallax** we start from $\pi_{\perp} = \pi_{//} = 0$, which is fine for not too large effects.
- For orbital motion we consider **circular orbits** with arbitrary inclination, parameterized by $(ds/dt)_{t0}$, $(d\alpha/dt)_{t0}$ and $(\omega_z)_{t0}$ starting from zero velocities.
- For comparison and completeness, we also calculate the following models:
  - PSPL
  - PSPL with parallax
  - Finite source – single lens
  - Finite source – single lens with parallax
  - Binary source
  - Binary source with parallax
  - Binary source with parallax and orbital motion.

Publication of the results

- A webpage at Salerno University is automatically updated with automatically generated plots
  http://www.fisica.unisa.it/GravitationAstrophysics/RTModel/2014/RTModel.htm

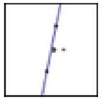


Event webpage

RTModel index

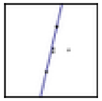
OB140124
Planetary with parallax

Binary lens models



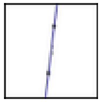
Model L1 χ^2=24940.6 g_{OGLE}=1.00652±0.412237

s=0.904511±0.0296468 q=0.000750416±0.000129067 u_0=-0.250688±0.0589067 θ=1.37125±0.0371881 ρ_*=0.00288639±0.00637904 t_E=110.8±19.9386 t_0=6836.09±0.939892



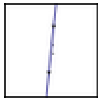
Model L2 χ^2=31568.2 g_{OGLE}=0.273378±0.0968608

s=0.848726±0.0127707 q=0.000784017±0.00010802 u_0=-0.358492±0.0252235 θ=1.34231±0.0148411 ρ_*=0.00774437±0.00423333 t_E=84.7621±3.96241 t_0=6834.65±0.253834



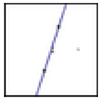
Model L3 χ^2=42226.3 g_{OGLE}=-0.766218±0.149419

s=0.621889±0.0161537 q=0.000768055±0.000107619 u_0=-1.00737±0.0554097 θ=1.44582±0.0077895 ρ_*=0.0104857±0.0187656 t_E=44.1633±2.46143 t_0=6836.07±0.137982



Model L4 χ^2=50628. g_{OGLE}=-0.925977±0.208842

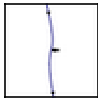
s=0.476124±0.0187407 q=0.000687306±0.000126724 u_0=-1.64594±0.0901404 θ=1.47302±0.0227046 ρ_*=0.0000102768±0.00172343 t_E=31.6863±2.17851 t_0=6836.52±1.17103



Model L5 χ^2=127821. g_{OGLE}=-0.289781±0.0915315

s=0.763874±0.0142947 q=0.000699372±0.000142686 u_0=-0.545399±0.0316147 θ=1.2567±0.0218454 ρ_*=0.0111098±0.00310309 t_E=65.3398±4.13722 t_0=6830.06±0.412378

Binary lens models with parallax



Model X1 χ^2=24202.1 g_{OGLE}=5.86314±1.63923

s=0.990599±0.0123037 q=0.000379833±0.000124866 u_0=-0.0868334±0.0215884 θ=1.35672±0.066207 ρ_*=0.000323885±0.00722684 t_E=289.167±73.734 t_0=6836.3±1.32788
$\pi_\perp$=0.0336196±0.469999 $\pi_{||}$=-0.215736±0.321811

Model pdf file

∗ RTModel by Valerio Bozza – University of Salerno ∗

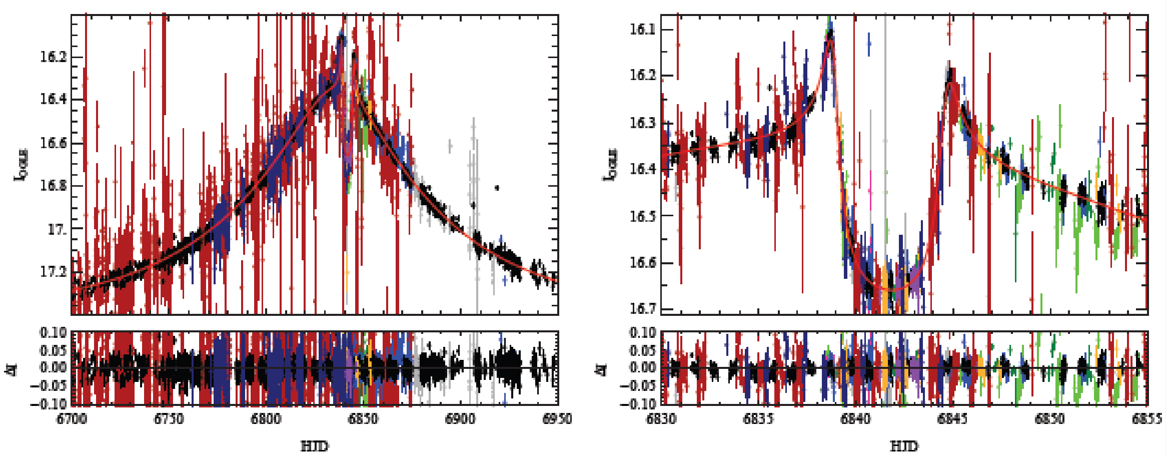
OB140124 – Model: Binary Lens with parallax 1 — 12 January 2015 UT 10:00:39

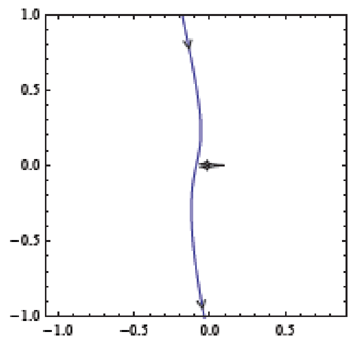
$s=0.990599\pm0.0123037$ $q=0.000379833\pm0.000124866$ $u0=-0.0868334\pm0.0215884$

$\theta=1.35672\pm0.066207$ $\rho_*=0.000323885\pm0.00722684$ $tE=289.167\pm73.734$

$t0=6836.3\pm1.32788$ $\pi1=0.0336196\pm0.469999$ $\pi2=-0.215736\pm0.321811$

$\chi2= 24202.1$





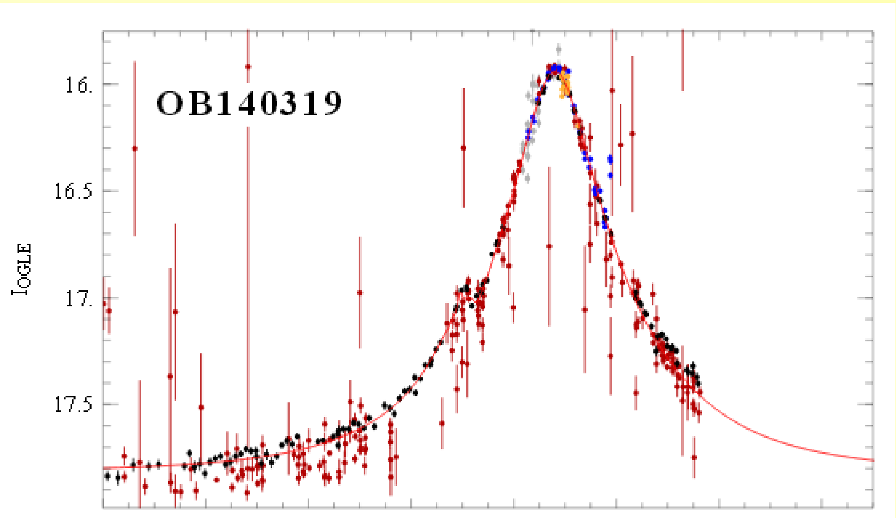
Telescope	BaseLine	FB/FS
SAAO 1.0m	14.6219±0.203904	11.3421±5.69793
CTIO 1.3m	17.8123±0.102974	8.94507±3.18631
CTIO 1.3m	17.4746±0.0791196	7.80274±2.05623
LCOGT CTIO B	19.4413±0.179739	10.4485±4.408
LCOGT CTIO C	Complex	−6.68335±2.67429
FTN 2.0m	20.2446±1.66665	7.81714±14.8599
FTS 2.0m	21.3384±0.218923	6.50503±2.72854
MOA	17.146±0.0633399	5.72746±1.60489
Danish 1.54m	9.81684±0.12607	3.91663±1.21016
Danish 1.54m	8.21532±0.186098	6.57323±2.47557
OGLE	17.3703±0.0632415	5.86314±1.63923

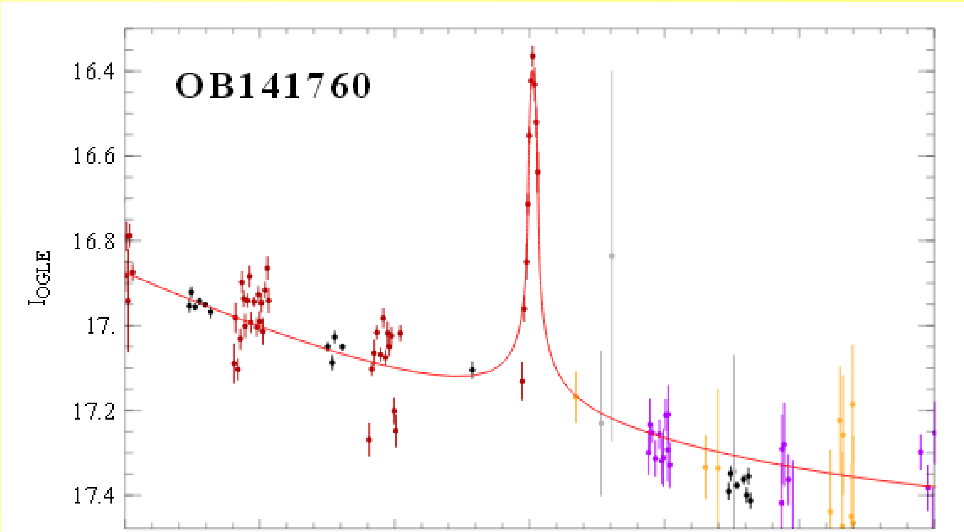
Maximizing results

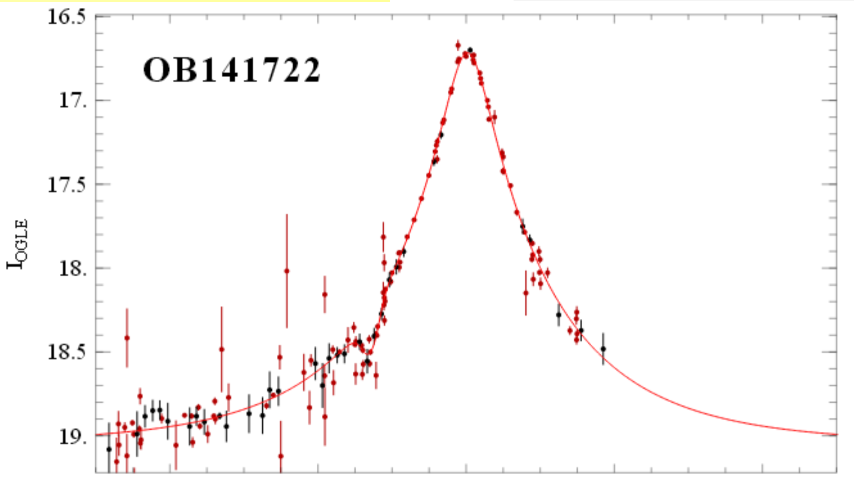
- We are moved by the idea that the **science output** of microlensing could be strongly improved, given the potential in the collected data.
- In order to speed-up the **analysis and publication** of the interesting events, we should make most of the work in a completely **automatic** way.
- Automatic **pipelines** and **early warning systems** are examples working on very large scales.
- **Selecting anomalous events** for intense follow-up observations is a very delicate task (ARTEMIS).
- Unfortunately, yet most planetary microlensing events are only **discovered after the anomaly** is over.

Late-alert planets

- Unfortunately, yet most planetary microlensing events are only **discovered after the anomaly** is over.

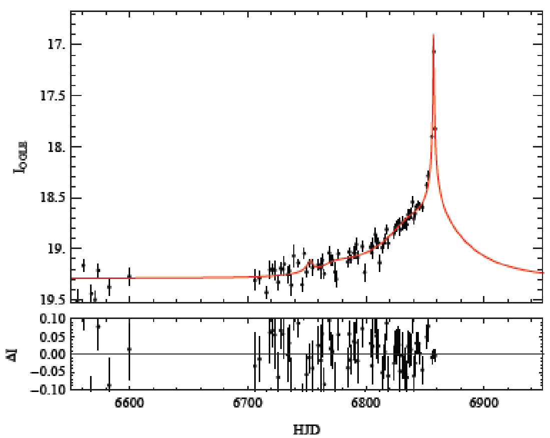


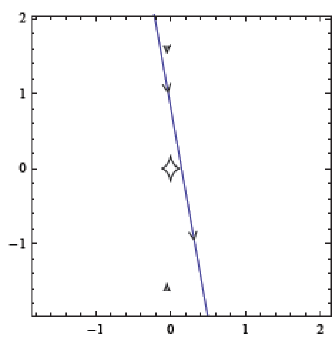




Real-time modelling service

- As soon as an anomaly alert is issued, RTModel is able to automatically model the data and find preliminary models.
- Even if the final model may differ from those preliminary ones, the **nature of the anomaly** can be immediately guessed, ruling out competitors.





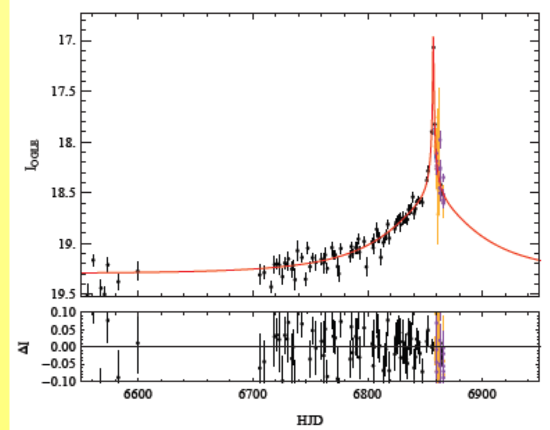
-----Messaggio originale-----
Da: Valerio Bozza [mailto:valboz@sa.infn.it]
Inviato: domenica 20 luglio 2014 21:11
A: 'ulens Analysis'
Oggetto: ob141075

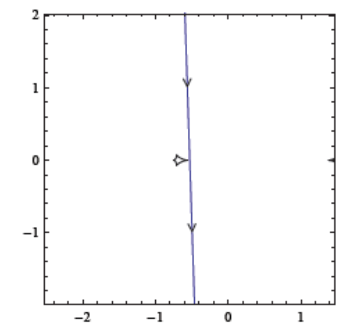
Dear all

following ARTEMIS' alert, here are my first two models. It is a cusp approach or "cut", but, in practice, there are many many possibilities open.

Best wishes

Valerio





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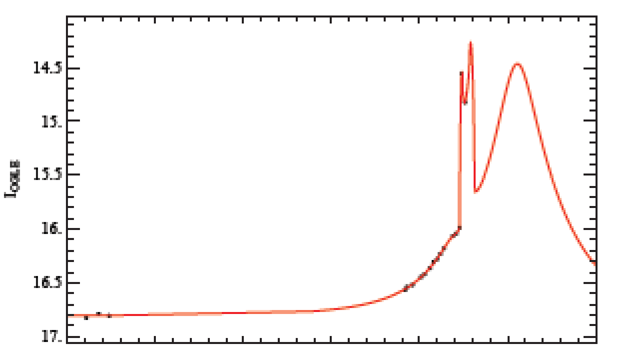
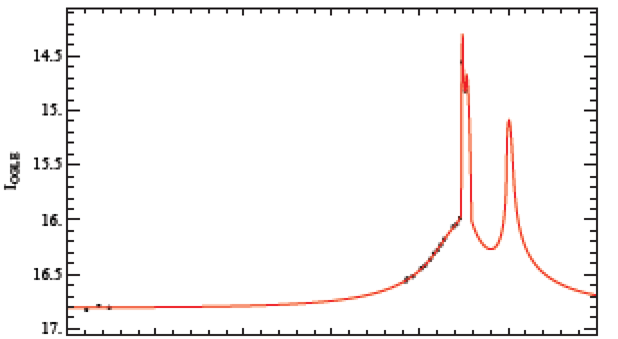


Telescope	BaseLine	FB/FS
OGLE	16.8096±0.492663	−0.575273±0.157278



Telescope	BaseLine	FB/FS
OGLE	16.8099±0.298534	2.97617±2.42739

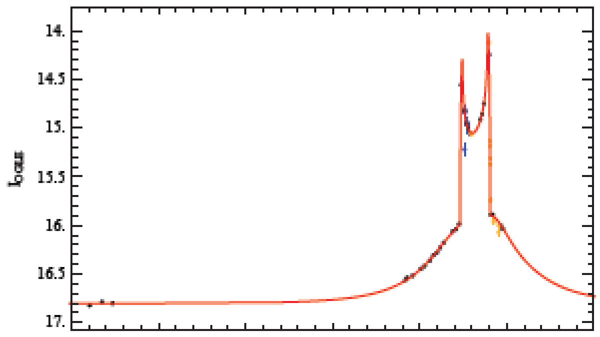
-----Messaggio originale-----
Da: Valerio Bozza
[mailto:valboz@sa.infn.it]
Inviato: martedì 29 aprile 2014 10:10
A: 'ulens-analysis'
Oggetto: ob140431

Dear all

with just two data points by OGLE, the anomaly is still obscure. I can find many planetary and binary models at the same chi square level. Planetary models prefer zero or moderately negative blending, while binary mass ratios
prefer positive blending.

Best wishes

Valerio



Telescope	BaseLine	FB/FS
Danish 1.54m	6.51565±0.0846791	2.05691±0.25551
OGLE	16.8089±0.0962466	−0.0103647±0.0610068
LCOGT SAO A	20.3419±0.157467	−0.0127732±0.126623

Planetary Probability Indicator

- For ongoing microlensing events we can build a planetary probability.
  - → Chi square
  - → Non-negative Blending constraint
  - → Source size
  - → Parallax
  - → Bayesian arguments
- A **quantitative indicator** to support follow-up decisions.

TO DO!

Facing future challenges

- **NASA funded program** to develop highly automated modeling code for the analysis of microlensing events.
  PI: Rachel Street, Co-Is: R. Barry, V. Bozza,
  Collaborators.: M. Dominik, K. Horne, M. Hundertmark, Y. Tsapras.
- Build on experience and capabilities of **RTModel**
- Develop the capacity to model microlensing events from **WFIRST-AFTA**
- **Open Source** Project: code will be publicly available
- Extensive verification: **Data Challenge** to test performance against existing packages

LCOGT.net

- 3yr **post-doctoral position** offered at LCOGT: deadline Feb 1, 2015
- See: lcogt.net/job/post-doc-microlensing jobregister.aas.org/node/50222

Direct Imaging
Riccardo Claudi
INAF - OAP, Italy

Gravitational Microlensing
Andy Gould
Ohio State University, USA

Planetary Transit
A. Collier Cameron
Univ. of St Andrews, UK

Radial Velocity
Artie P. Hatzes
Thuringian State Observatory, Germany

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