Interferometric observations of microlensing events

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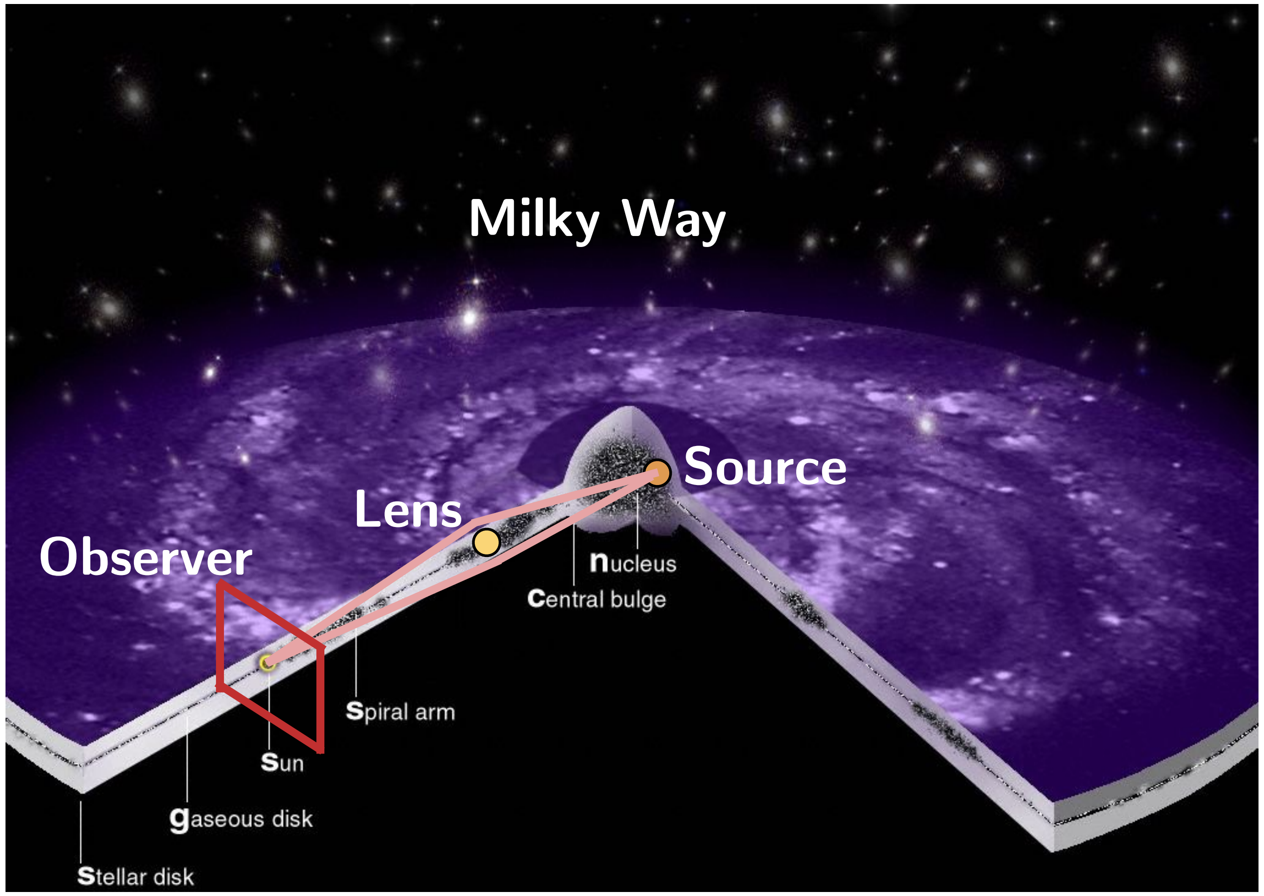
CHARA Meeting 2016, Nice – Tuesday March, 15th

Gravitational microlensing

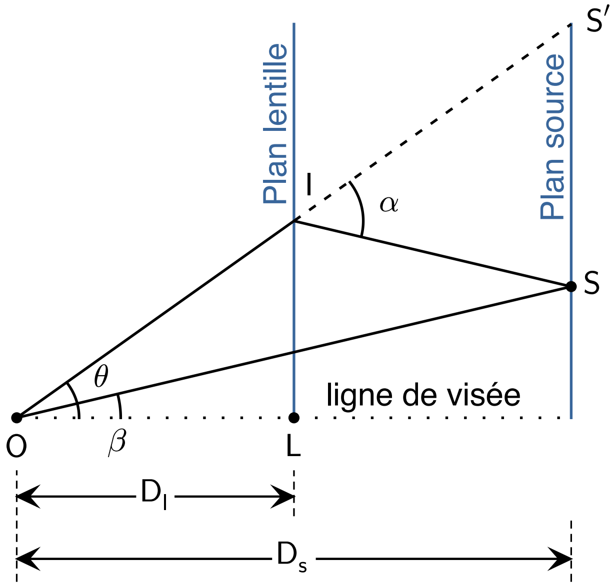
- Deflection of light due to the gravity of a star. microlens



Credit: ESA

- Creation of **multiple images**

$D_S \approx 8\,\mathrm{kpc}$
$D_L \in [0.5\,;8]\,\mathrm{kpc}$
$\theta_E \approx 1\,\mathrm{mas}$



- **Compactness** red dwarf: $\Xi = \frac{GM}{c^2 R} \sim 10^{-5}$

Low probability of alignement

- Single lens: 2 images

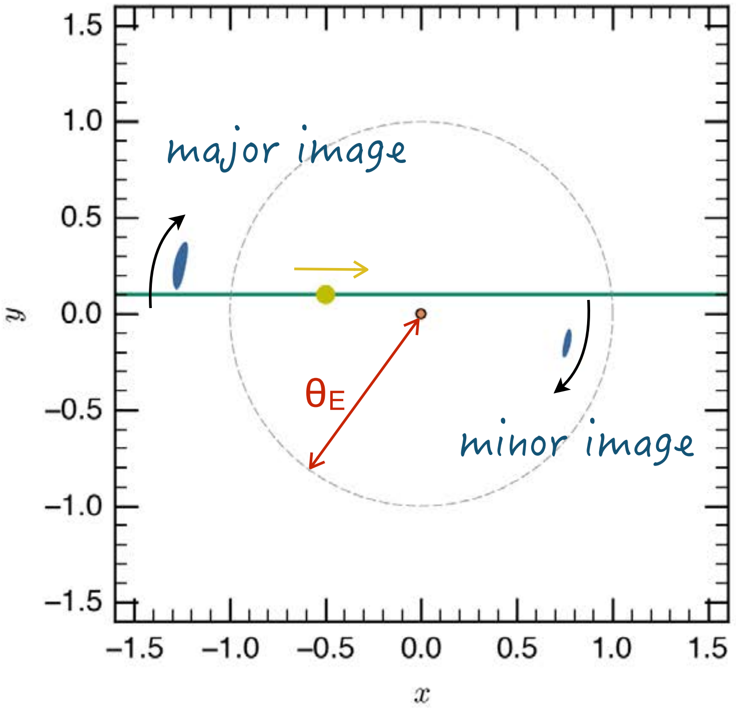
Point source: 2 isolated images.

Finite source: 2 isolated images per edge point.

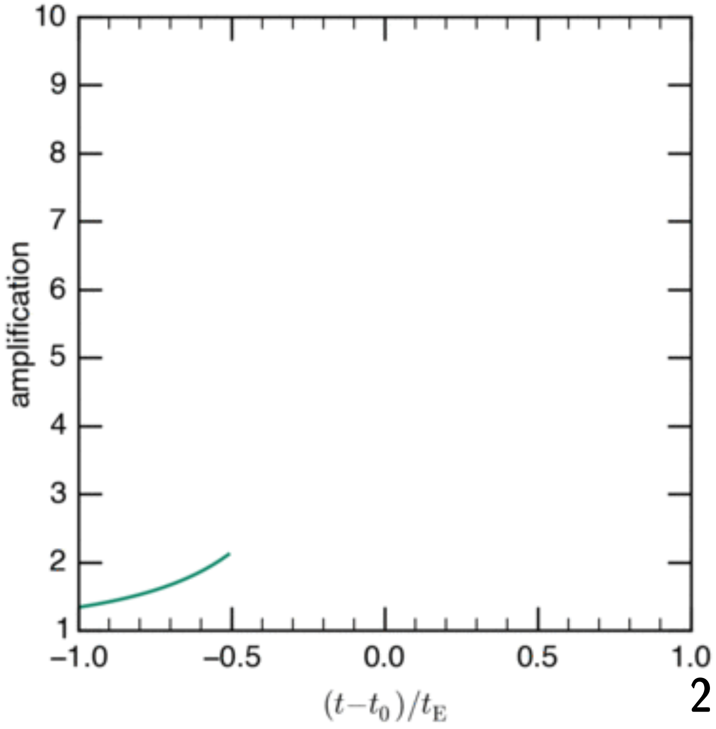
Angular scale: **Einstein radius θ_E**

- **Magnification as a function of time**

Multiple images

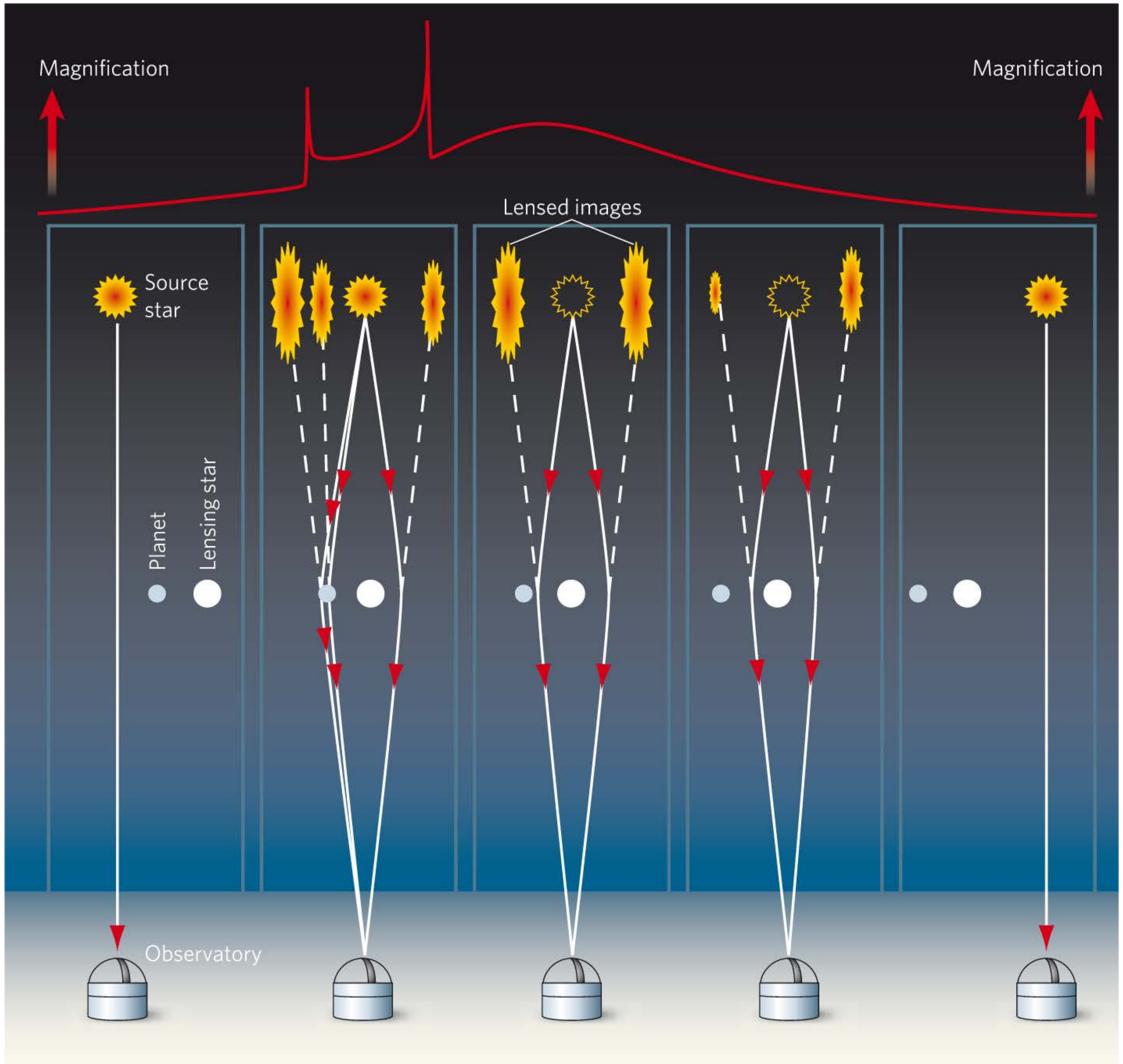


Amplification



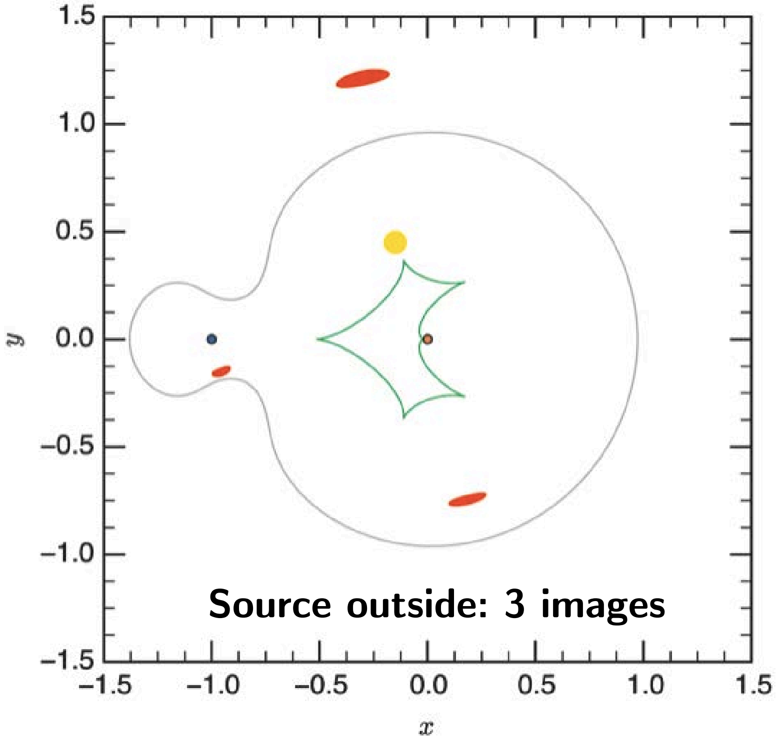
Planetary microlensing

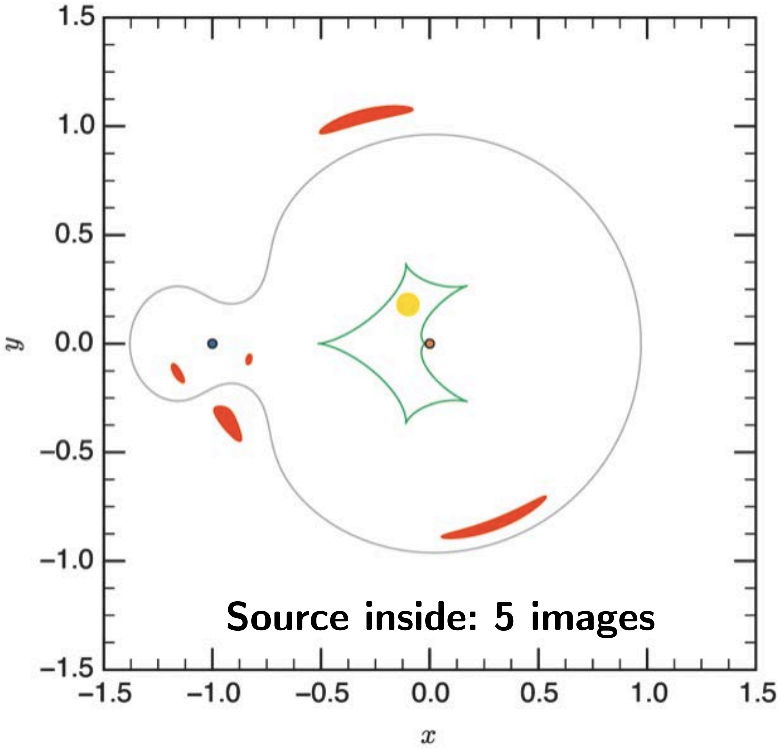
- **Binary lens equation: 3 or 5 images**



Queloz (2006)

- **Central role of the caustics**

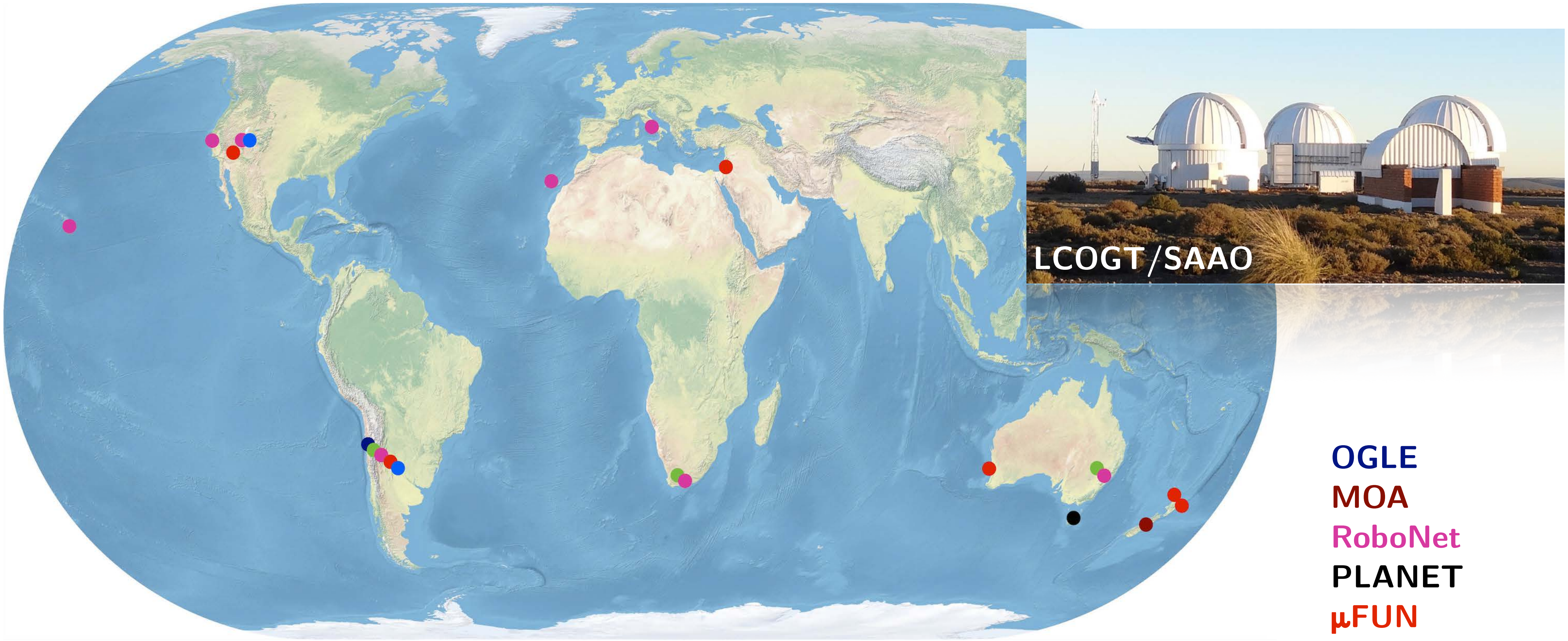




- **Images not resolved by one telescope**

Microlensing network of telescopes in 2015

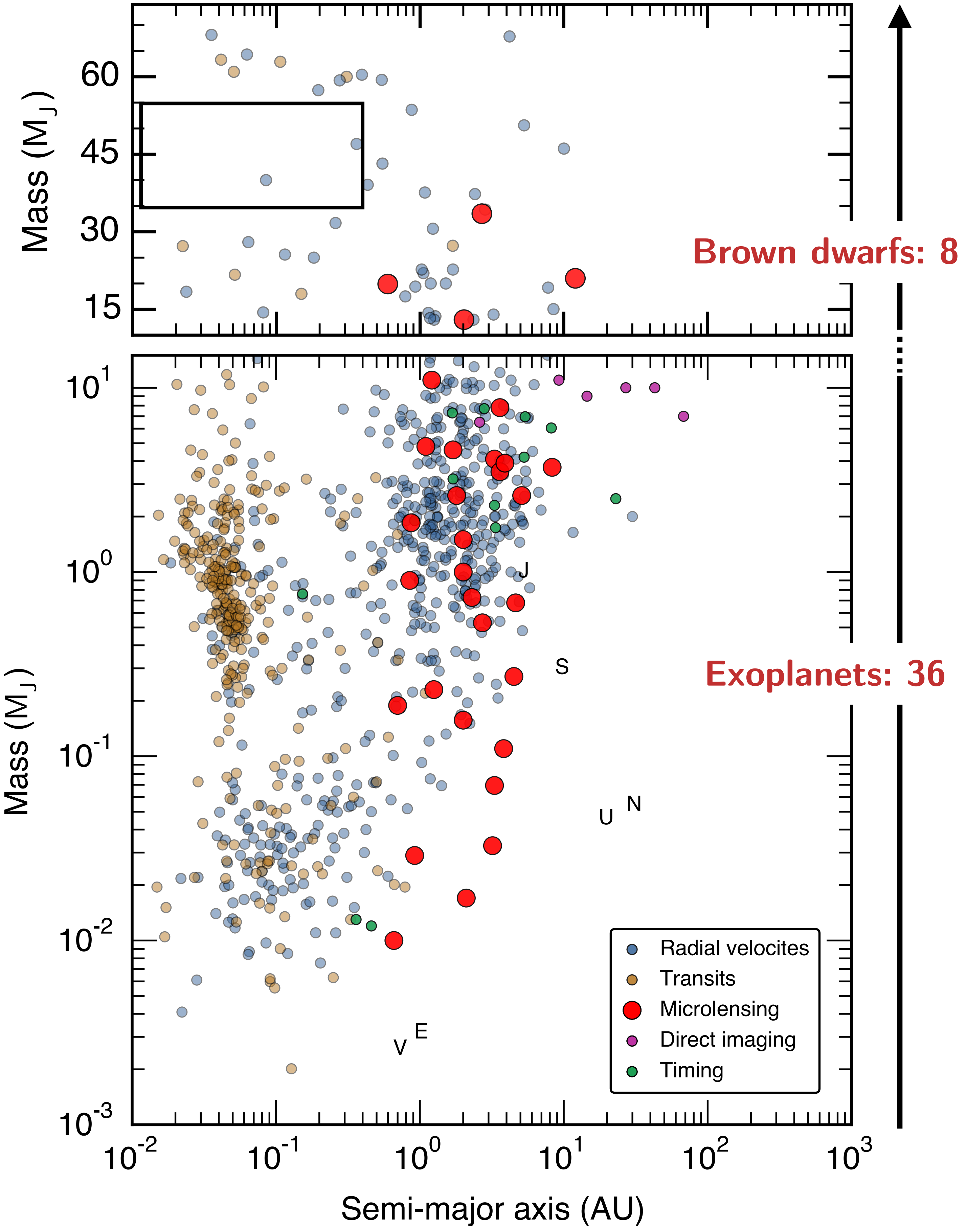
- A need for a continuous follow-up to catch the planetary features.



OGLE
MOA
RoboNet
PLANET
μFUN
KMTNet
MiNDSTEp

- **Light curve:** flux from the source as a function of time
- New networks and new network of robotic telescopes

Microlensing among exoplanets detection techniques



Brown dwarfs: 8

Exoplanets: 36

Microlensing detections:

- **orbits: 0.5-10 AU**
- **masses down to Earth**
- **masses up to binaries**
- **beyond the snow line**

... and free-floating planets!

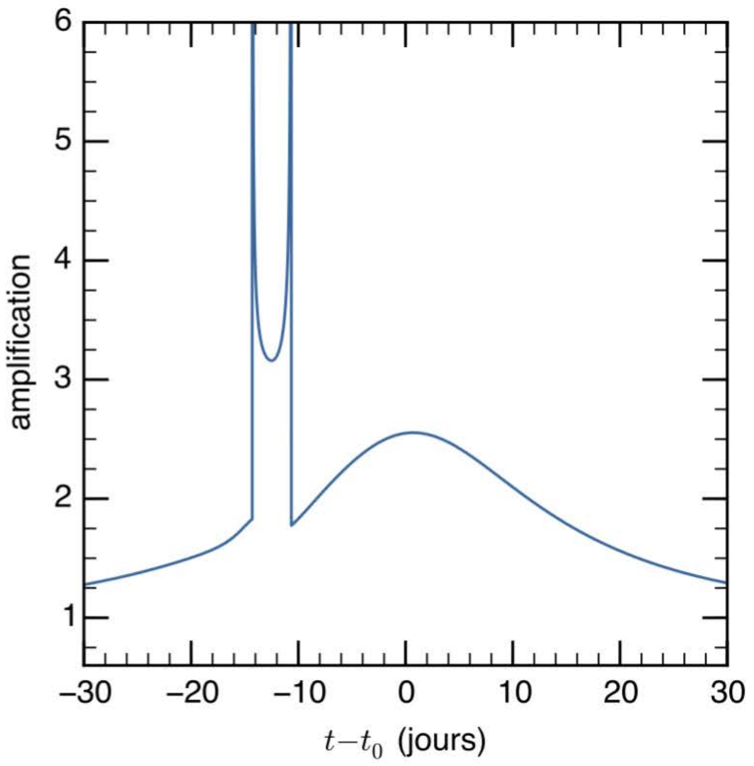
Data: Open Exoplanets Catalogue, and Ma & Ge (2014)

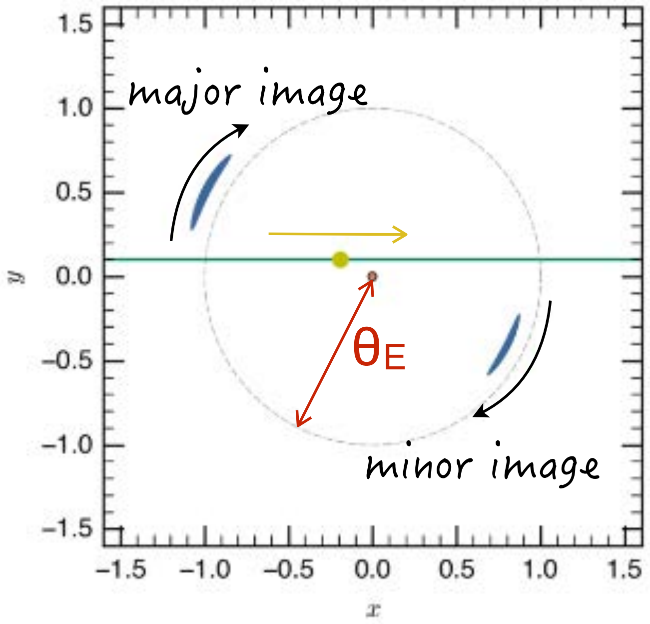
Parameters determination in microlensing

✦ **Parameters are affected by degeneracies:** $t_E = \frac{D_L \theta_E}{v}$ with $\theta_E = \sqrt{\frac{4\,G\,\mathcal{M}}{c^2}\left(\frac{1}{D_L} - \frac{1}{D_S}\right)}$

✦ **How can degeneracies be solved?**

- Measuring the source size
- Measuring parallax effects (annual, terrestrial, from Space...)
- Performing high resolution photometry
- **Resolving the multiple images using an interferometer**





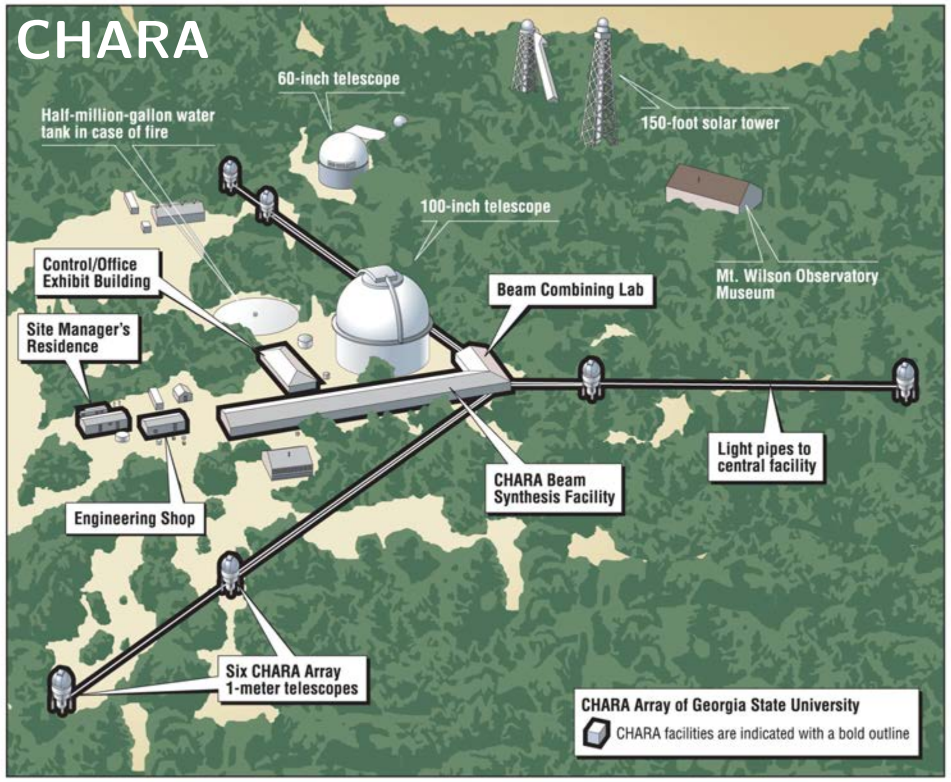
$$\theta_E \leq 1\,\text{mas}$$
$$t_E \approx 50\,\text{days}$$
$$D_L \approx 0.5 - 8\,\text{kpc}$$
$$D_S \approx 8\,\text{kpc}$$

Images cannot be resolved individually...

... but the separation between the images is at reach of 100m baseline interferometers

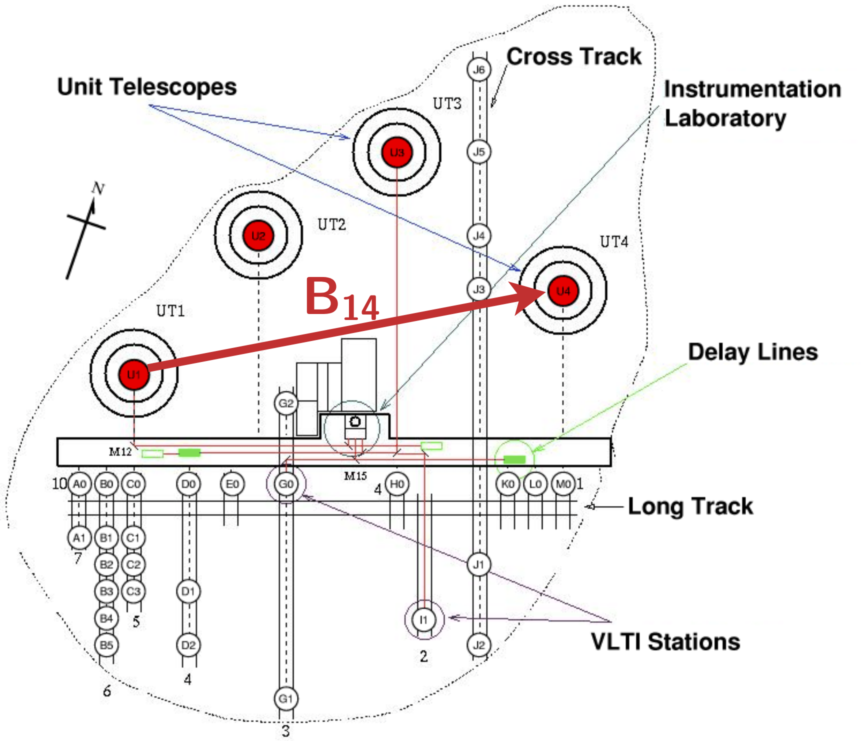
Probing the (u,v)-plane using interferometry

✦ An interferometer: N telescopes —> N(N-1)/2 baselines



Credit: CHARA website

VLTI



Credit: VLTI website

✦ Goal: measuring visibility of an extended source

Visibility related to the "source" intensity profile (van Cittern-Zernike theorem)

$$\mathcal{V}\left(\frac{B_x}{\lambda_0},\frac{B_y}{\lambda_0}\right)=\frac{\iint I(\theta_x,\theta_y)\,e^{-i2\pi\frac{\boldsymbol{B}\cdot\boldsymbol{\theta}}{\lambda_0}}\,d\theta_x d\theta_y}{\iint I(\theta_x,\theta_y)\,d\theta_x d\theta_y}=\frac{\mathrm{FT}\left[I\right](u,v)}{\mathrm{FT}\left[I\right](0,0)}$$

(u,v): spatial frequencies

$$\mathrm{FT}\left[I\right](u,v)=\iint I(x,y)\,e^{-i2\pi(ux+vy)}\,dxdy$$

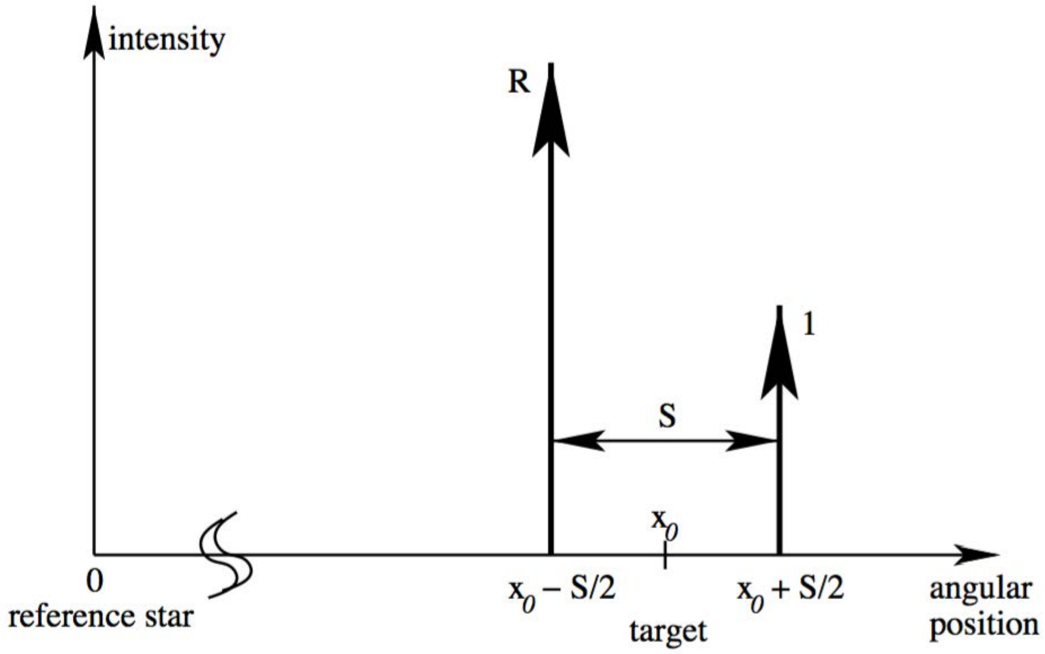
Single lens model

✦ **Previous study:** Delplancke et al. (2001)

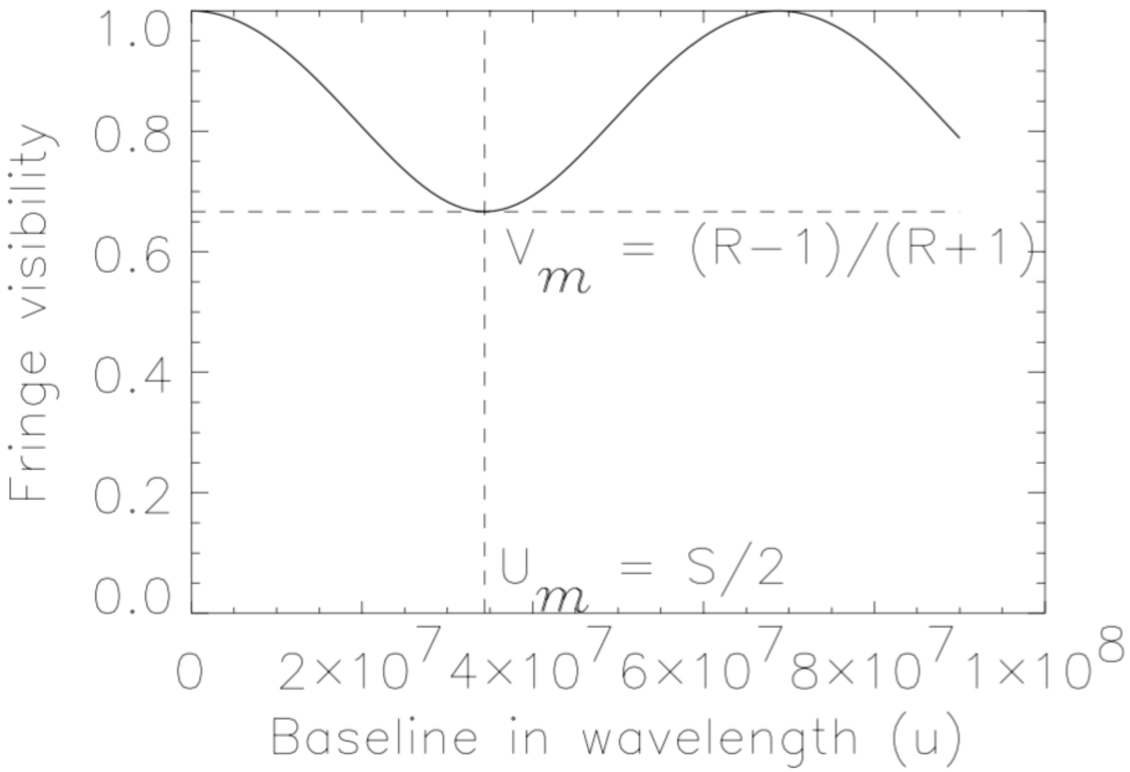
Two point-source images: $f(x) = R\,\delta(x_0 - S/2) + \delta(x_0 + S/2)$

Visibility: $V(u) = \dfrac{\sqrt{R^2 + 1 + 2\,R\,\cos(2\pi u S)}}{R+1}$ $\qquad R = \dfrac{A+1}{A-1}$ $\qquad u = B/\lambda$

Intensity profile



Visibility



✦ **For N point-images:**

$$\frac{I(x,y)}{I_S} = \sum_{i=1}^{N} A_i\,\delta(x - x_i, y - y_i)$$

$$V(\mathbf{k}) = \frac{\left[\sum_{1\le i\le N} A_i^2 + \sum_{1\le i<j\le N} 2A_iA_j\cos\left(\mathbf{k}\cdot\mathbf{r_{ij}}\right)\right]^{1/2}}{\sum_{1\le i\le N} A_i}$$

Closure phase

✦ **Previous study: Dalal & Lane (2003)**

One baseline : problem to determine phase of the visibility

$$\bar{V} = |\hat{V}|e^{i(\phi_{12}+\phi_1-\phi_2)}$$

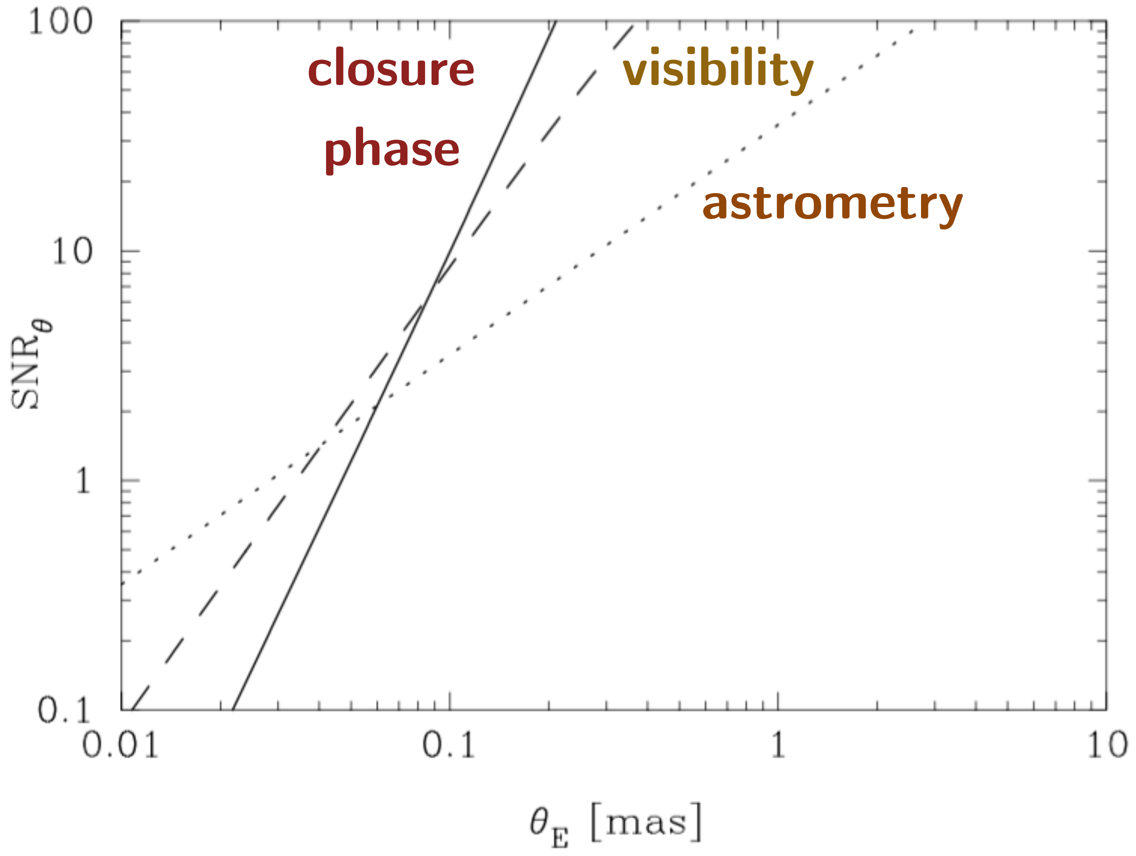
Φ_{12}: intrinsic phase difference between T1 and T2

Φ_1 and Φ_2: random phases

Closure phase with three baselines:

$$\begin{aligned}\bar{V}_{123} &= |\hat{V}_1||\hat{V}_2||\hat{V}_3|e^{i[\phi_{12}+\phi_{23}+\phi_{31}+(\phi_1-\phi_2)+(\phi_2-\phi_3)+(\phi_3-\phi_1)]}\\ &= |\hat{V}_1||\hat{V}_2||\hat{V}_3|e^{i(\phi_{12}+\phi_{23}+\phi_{31})} .\end{aligned}$$

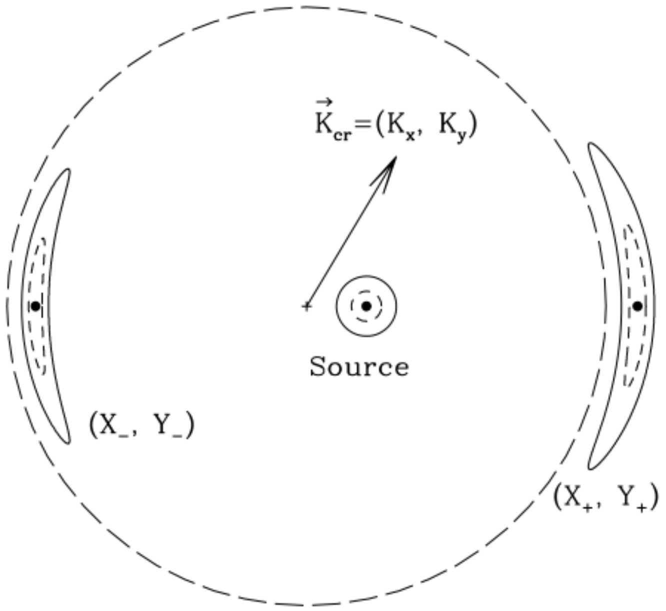
$$\phi_{123} = \arctan\left\{\frac{(R^2-R)\sum_{i=1,2,3}\sin[(2\pi/\lambda)\Delta\boldsymbol{s}\cdot\boldsymbol{B}_i]}{1+R^3+(R+R^2)\sum_{i=1,2,3}\cos[(2\pi/\lambda)\Delta\boldsymbol{s}\cdot\boldsymbol{B}_i]}\right\} .$$



S/N ratio obtained from astrometry, visibility and closure phase.

Finite source effects in a single lens

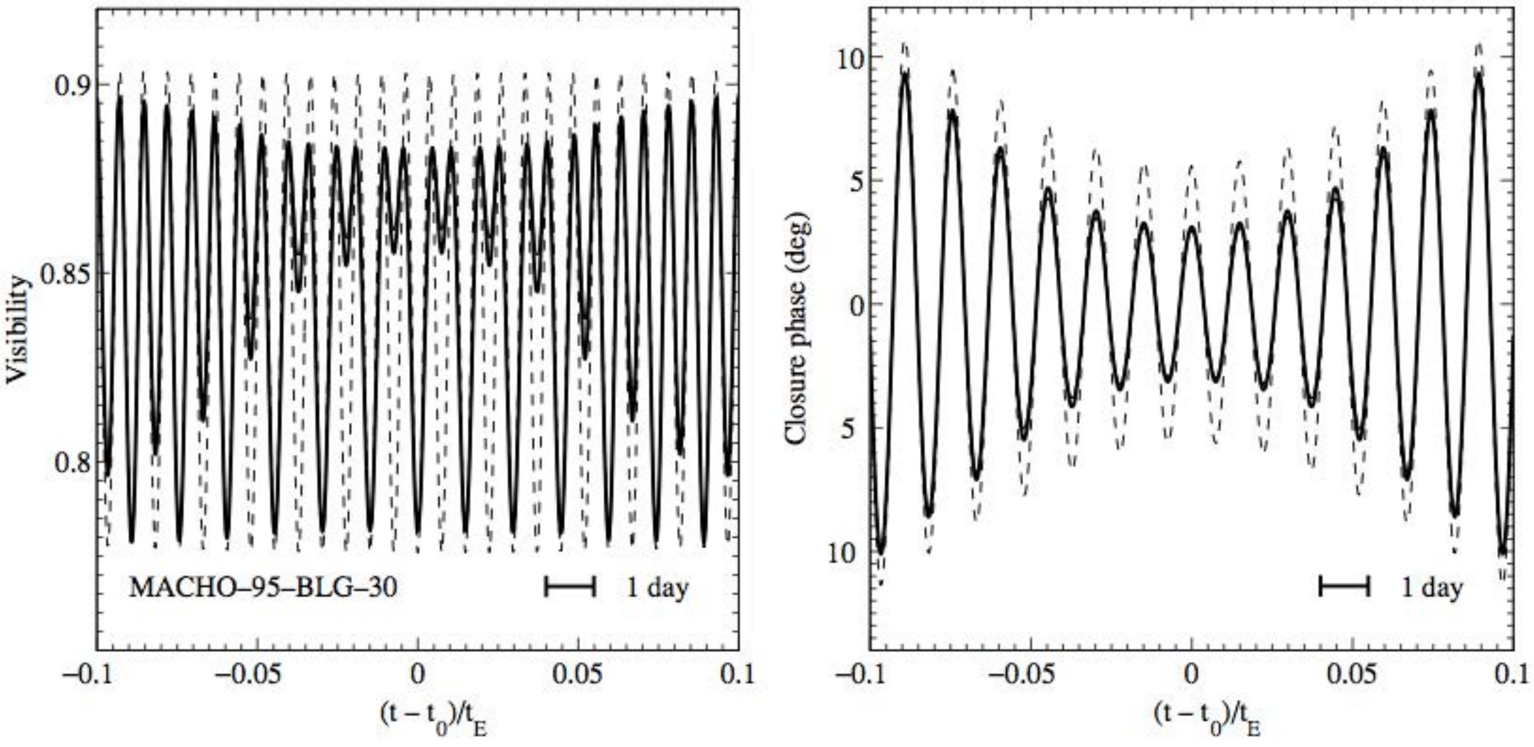
✦ **Previous study:** Rattenbury and Mao (2005)



$$z_{+,-}(r,\varphi) = \frac{z_{s,0}+re^{i\varphi}}{2}\left[1\pm\sqrt{1+\frac{4}{g(\varphi)}}\right]$$

$$\mu_{\rm tot} = \frac{1}{\pi\rho_\star^2}\int_0^{2\pi}\left[-Y_+(\varphi)\frac{\mathrm{d}X_+(\varphi)}{\mathrm{d}\varphi}+Y_-(\varphi)\frac{\mathrm{d}X_-(\varphi)}{\mathrm{d}\varphi}\right]\mathrm{d}\varphi$$

Point source (dashed) versus finite source (limb-darkening and uniform)



Visibility: when interferometry joins microlensing

Visibility related to the "source" intensity profile (van Cittern-Zernike theorem)

$$\mathcal{V}\left(\frac{B_x}{\lambda_0},\frac{B_y}{\lambda_0}\right)=\frac{\iint I(\theta_x,\theta_y)\,e^{-i2\pi\frac{\boldsymbol{B}\cdot\boldsymbol{\theta}}{\lambda_0}}\,d\theta_x d\theta_y}{\iint I(\theta_x,\theta_y)\,d\theta_x d\theta_y}=\frac{\mathrm{FT}\left[I\right](u,v)}{\mathrm{FT}\left[I\right](0,0)}$$

(u,v): spatial frequencies

$$\mathrm{FT}\left[I\right](u,v)=\iint I(x,y)\,e^{-i2\pi(ux+vy)}dxdy$$

- $\boldsymbol{\theta}_{\mathrm{E}}$ is now a **vectorial quantity** **(Gould & Yee, 2014)**
- Interferometry point of view: **visibility** is related to the **Einstein angular radius**

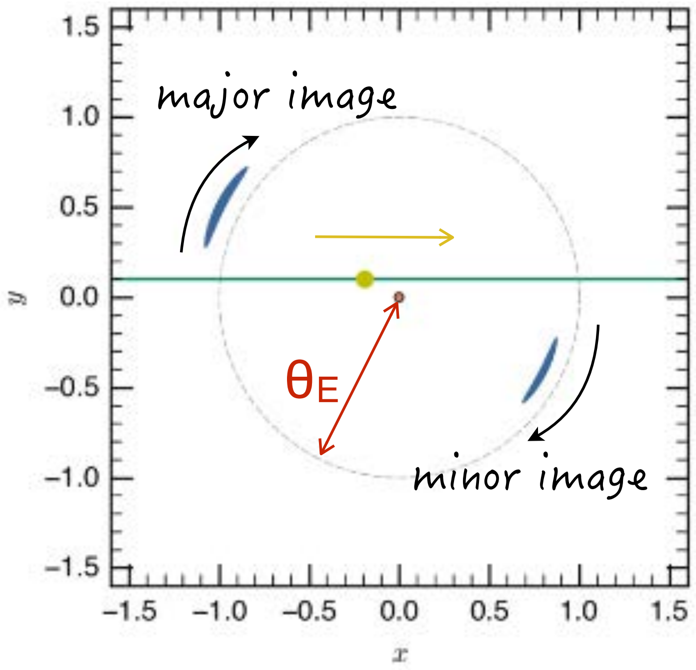
$$ux+vy\equiv\frac{\boldsymbol{B}}{\lambda_0}\cdot\boldsymbol{\theta}\equiv-\boldsymbol{k}\cdot\boldsymbol{\theta}$$

"Einstein (u,v) plane": link between microlensing and interferometry.

$$\begin{pmatrix}u\\v\end{pmatrix}\equiv\begin{pmatrix}\boldsymbol{\theta}_{\mathrm{E}}\cdot\boldsymbol{k}\\\boldsymbol{\theta}_{\mathrm{E}}\times\boldsymbol{k}\end{pmatrix}=\begin{pmatrix}\theta_{\mathrm{E},N}k_N+\theta_{\mathrm{E},E}k_E\\\theta_{\mathrm{E},N}k_E-\theta_{\mathrm{E},E}k_N\end{pmatrix}=\begin{pmatrix}\theta_{\mathrm{E},\parallel}k_\parallel+\theta_{\mathrm{E},\perp}k_\perp\\\theta_{\mathrm{E},\parallel}k_\perp-\theta_{\mathrm{E},\perp}k_\parallel\end{pmatrix}$$

$$\mathcal{V}_{\mathrm{E}}(u,v)=\frac{\mathrm{FT}\left[I\right](u,v)}{\mathrm{FT}\left[I\right](0,0)}$$

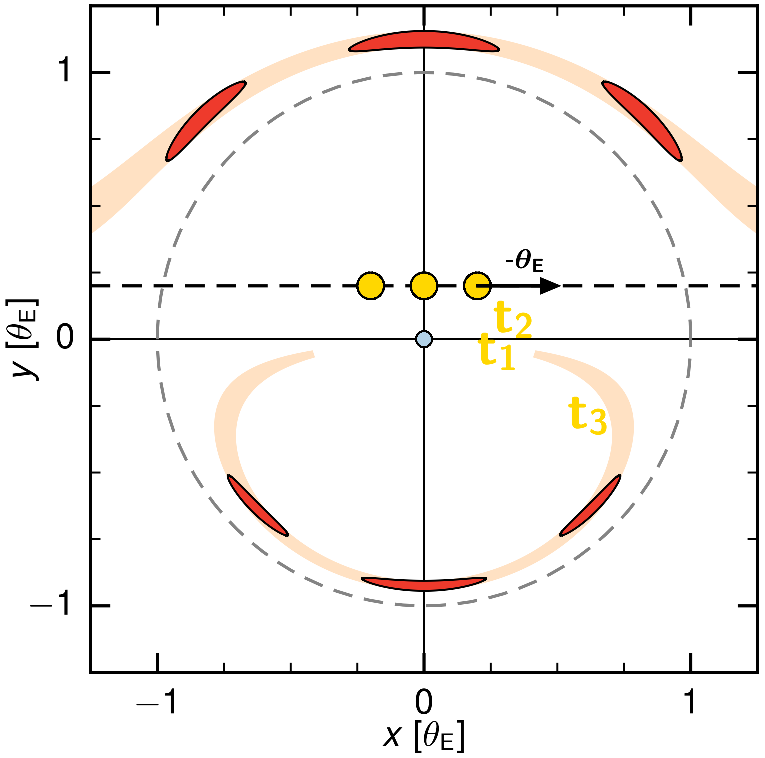
with spatial frequencies in units of θ_{E}^{-1}



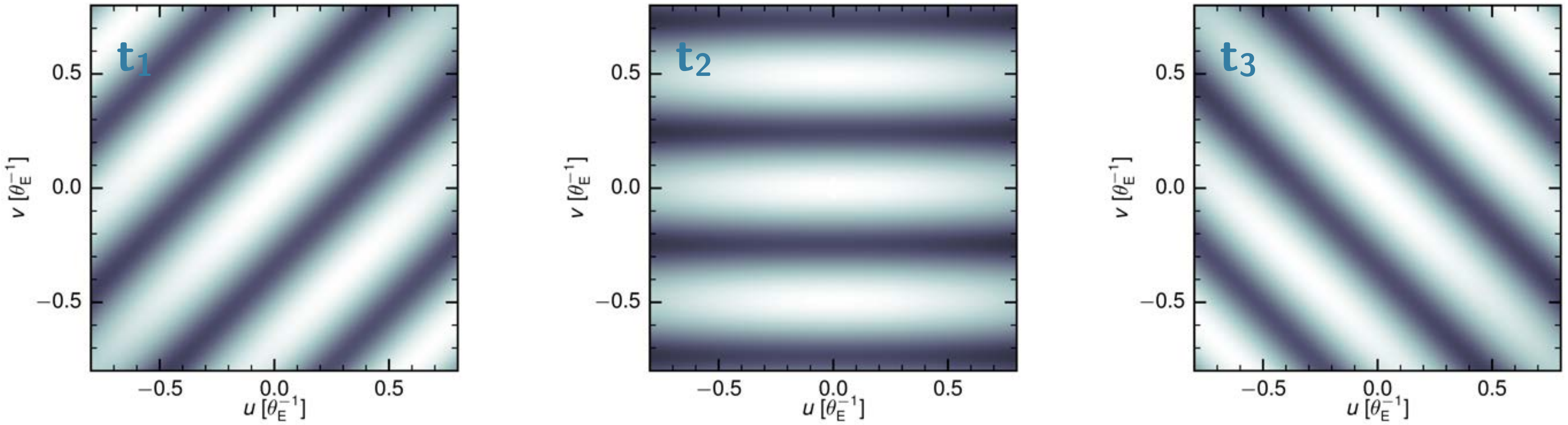
(Cassan & Ranc 2016, in press, MNRAS)

Examples of visibility patterns

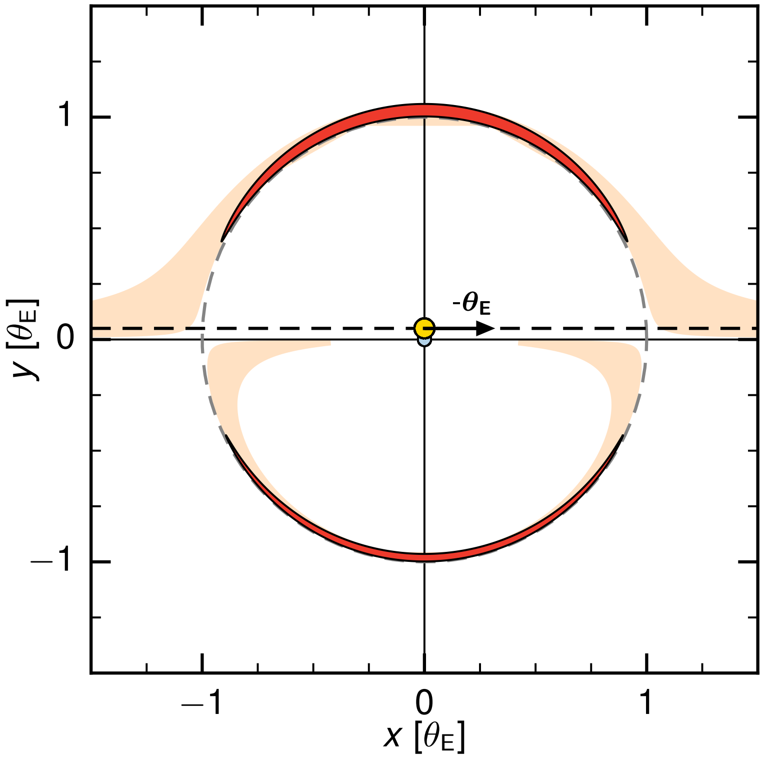
✦ Single lens: 2 images in motion

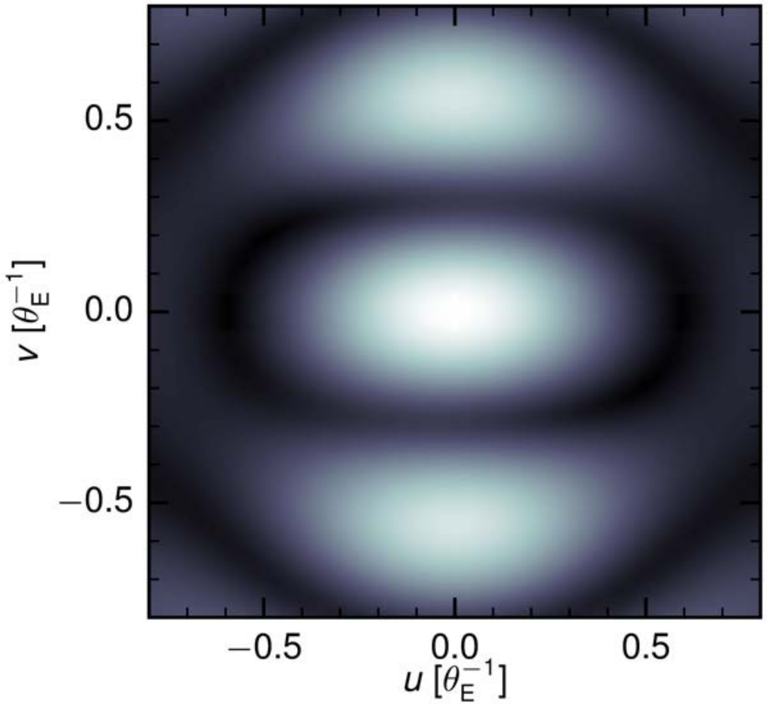


✦ Corresponding visibility patterns



✦ Single lens with strong finite source effects:

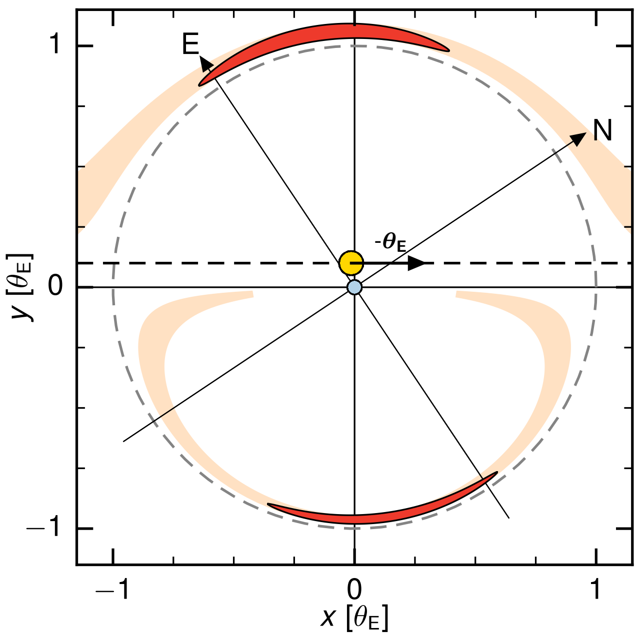


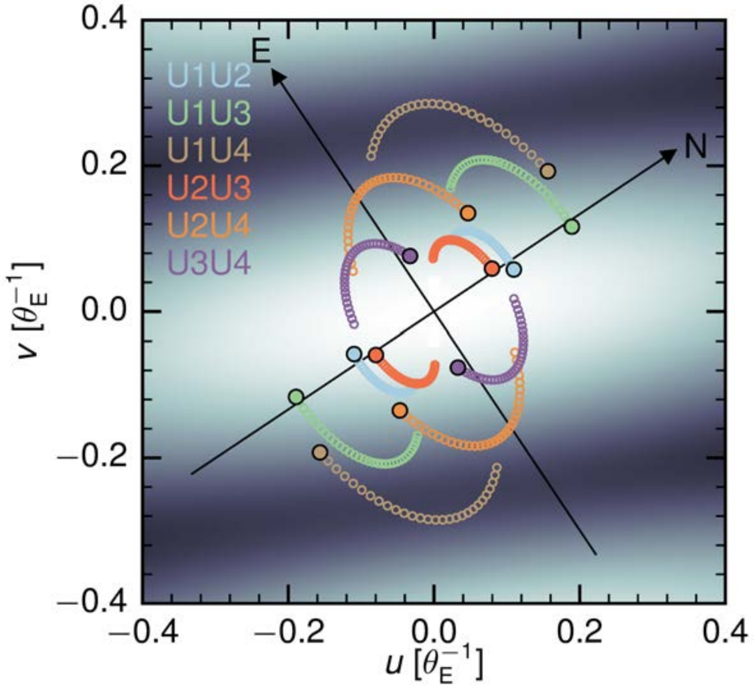


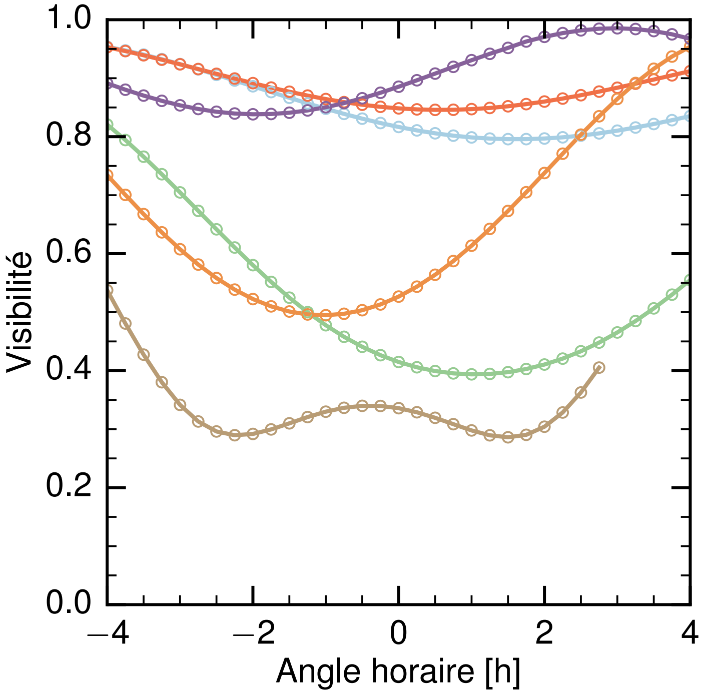
$$\mathrm{FT}\left[I\right](u,v) = -\frac{i}{2\pi}\oint_{\partial\mathcal{I}} \frac{e^{-i2\pi(uX+vY)}}{v} dX$$

Exploring the Einstein (u,v)-plane

- **B and V are a function of time**

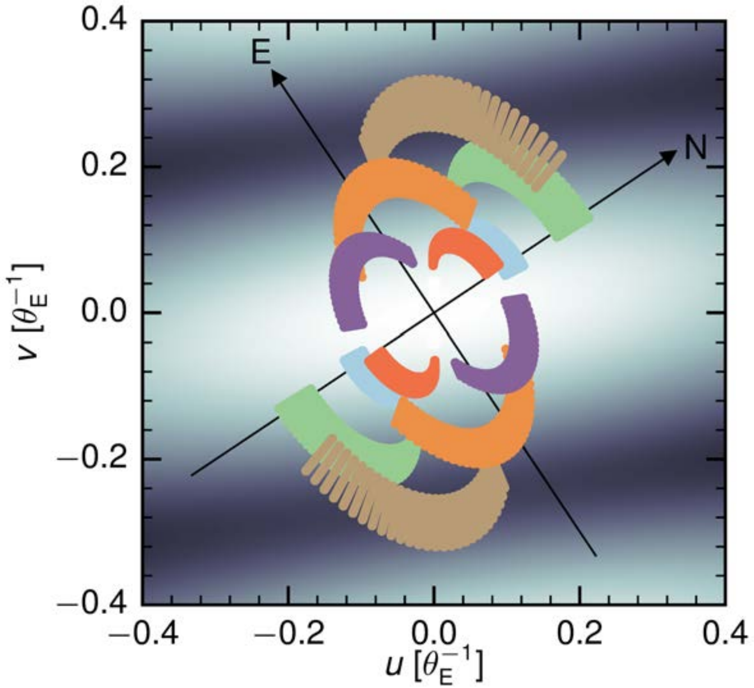






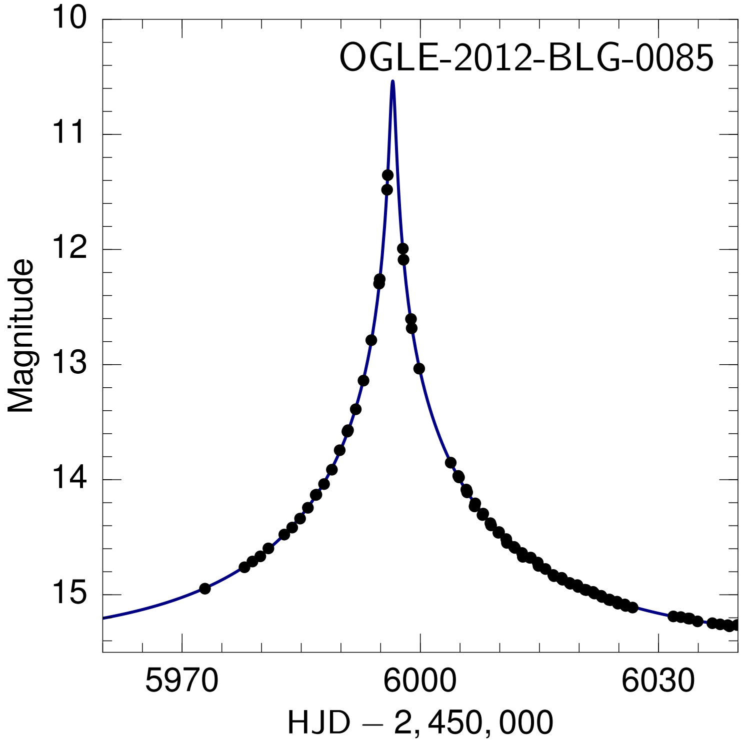
- **"Microlensing" supersynthesis: motion of the images**

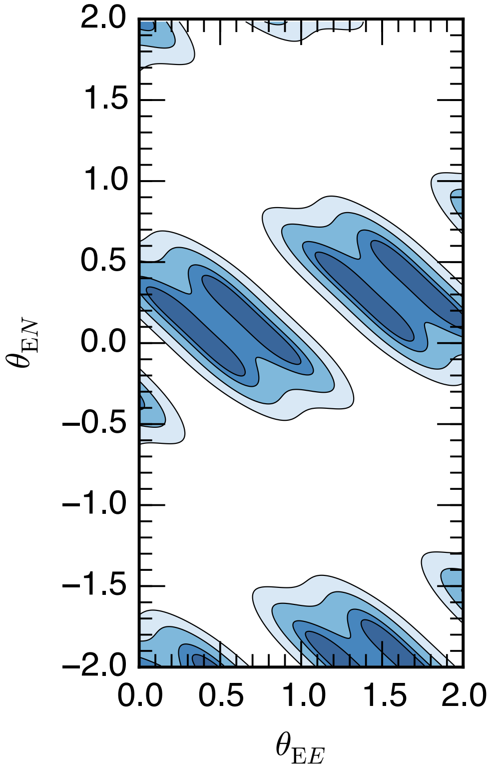
- **Spectral coverage**



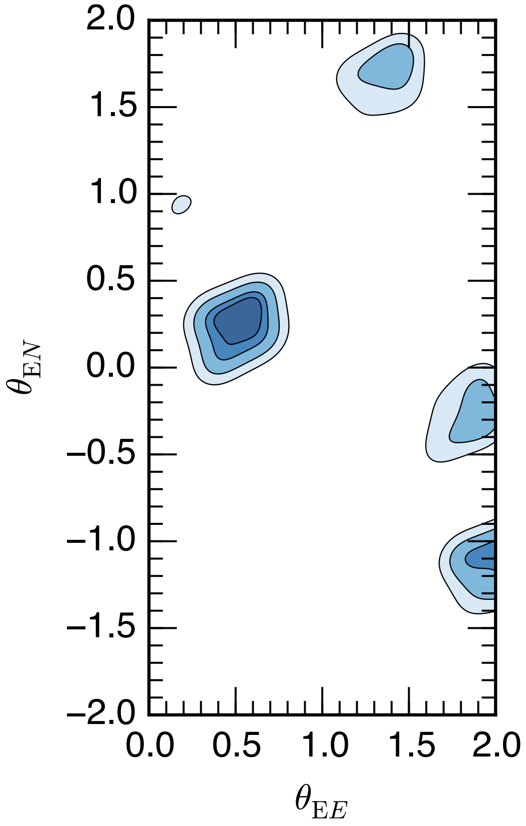
Simulated constrains on the Einstein radius

- **Both prediction AND parameters determining after observations.**





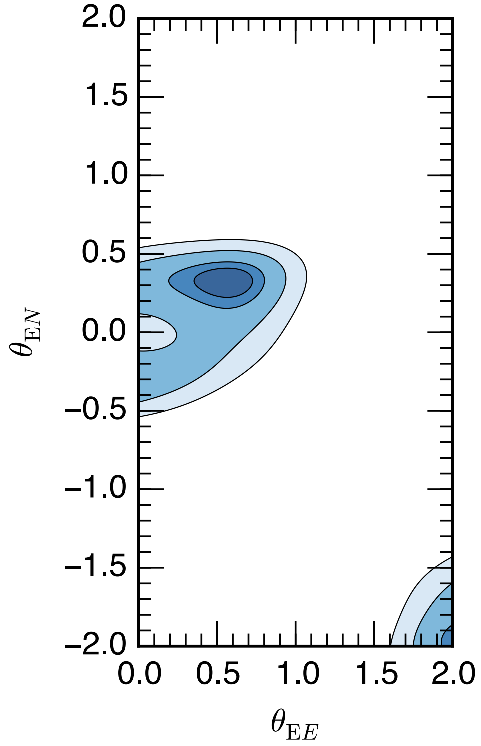
1 baseline
2 measurements



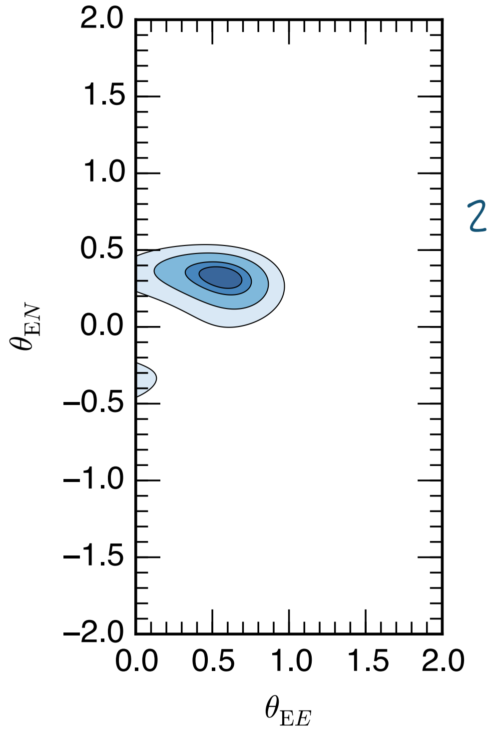
2 baselines
2 measurements

Confident intervals: 1σ , 2σ, 3σ, 4σ

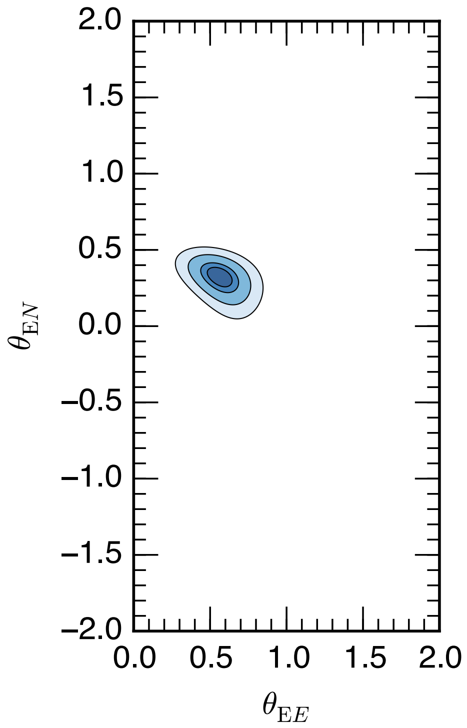
- **Simulating V^2 simultaneously from 6 baselines.**



1 measurement



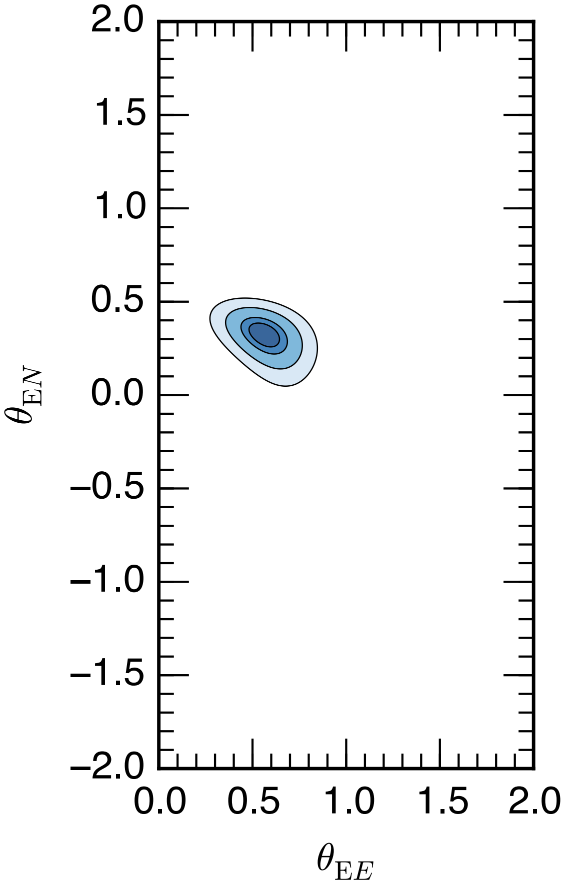
2 measurements



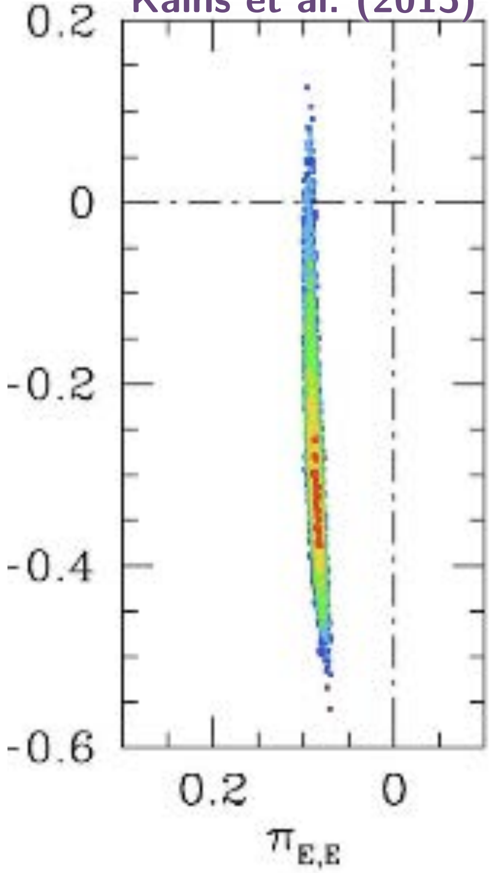
3 measurements

Simulated constrains on the Einstein radius

- **Key step: combining photometric measurements with interferometry**



Kains et al. (2013)

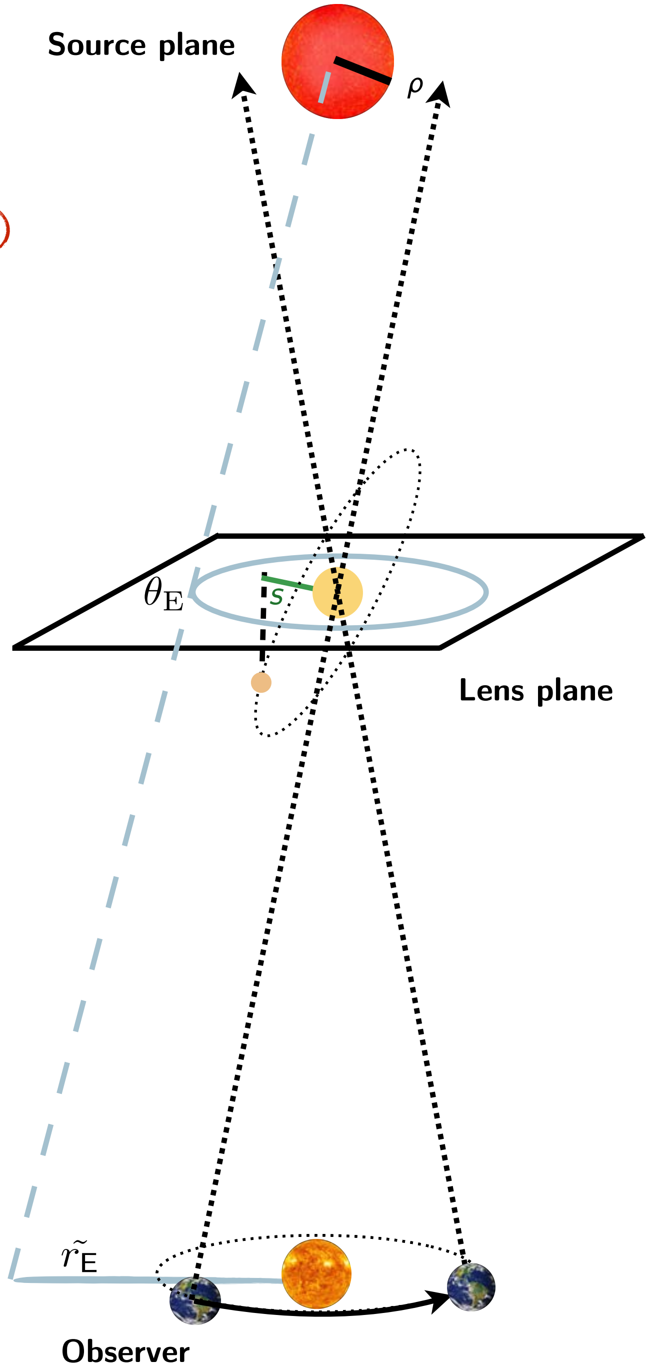


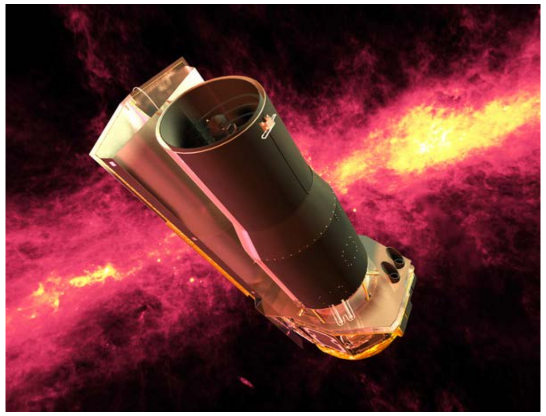
Confident intervals: 1σ , 2σ, 3σ, 4σ

Constrain from parallax: $\boldsymbol{\pi}_{\mathbf{E}} = \frac{\pi_{\rm rel}}{\theta_{\rm E}} \frac{\boldsymbol{\mu}_{\mathbf{rel}}}{\mu_{\rm rel}}$

Constrain on the mass: $M = \frac{\theta_{{\rm E},E}}{\kappa \pi_{{\rm E},E}} = \frac{\theta_{{\rm E},\parallel}}{\kappa \pi_{{\rm E},\parallel}}$

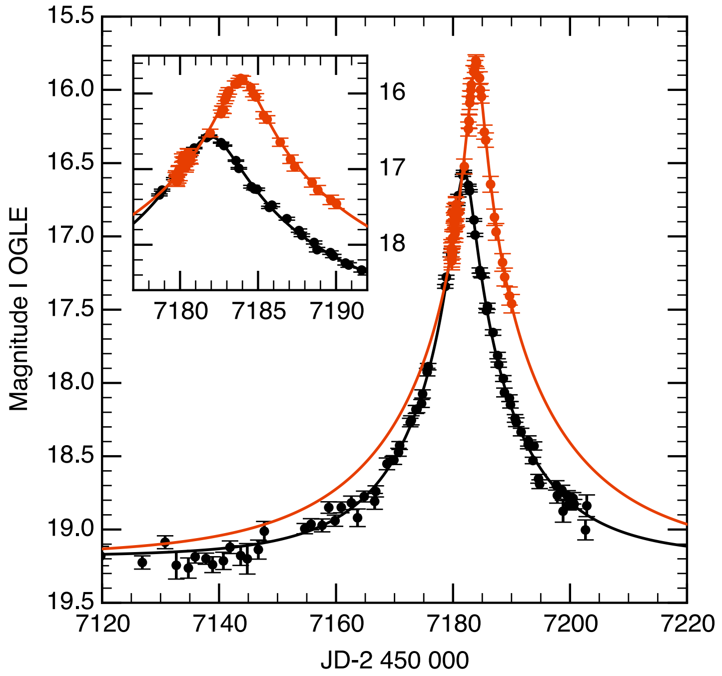
Constrain on the distance: $\pi_{\rm rel} = \theta_{\rm E}^2 \frac{\pi_{{\rm E},\parallel}}{\theta_{{\rm E},\parallel}}$





Credit: NASA/JPL-Caltech

Spitzer Space Telescope

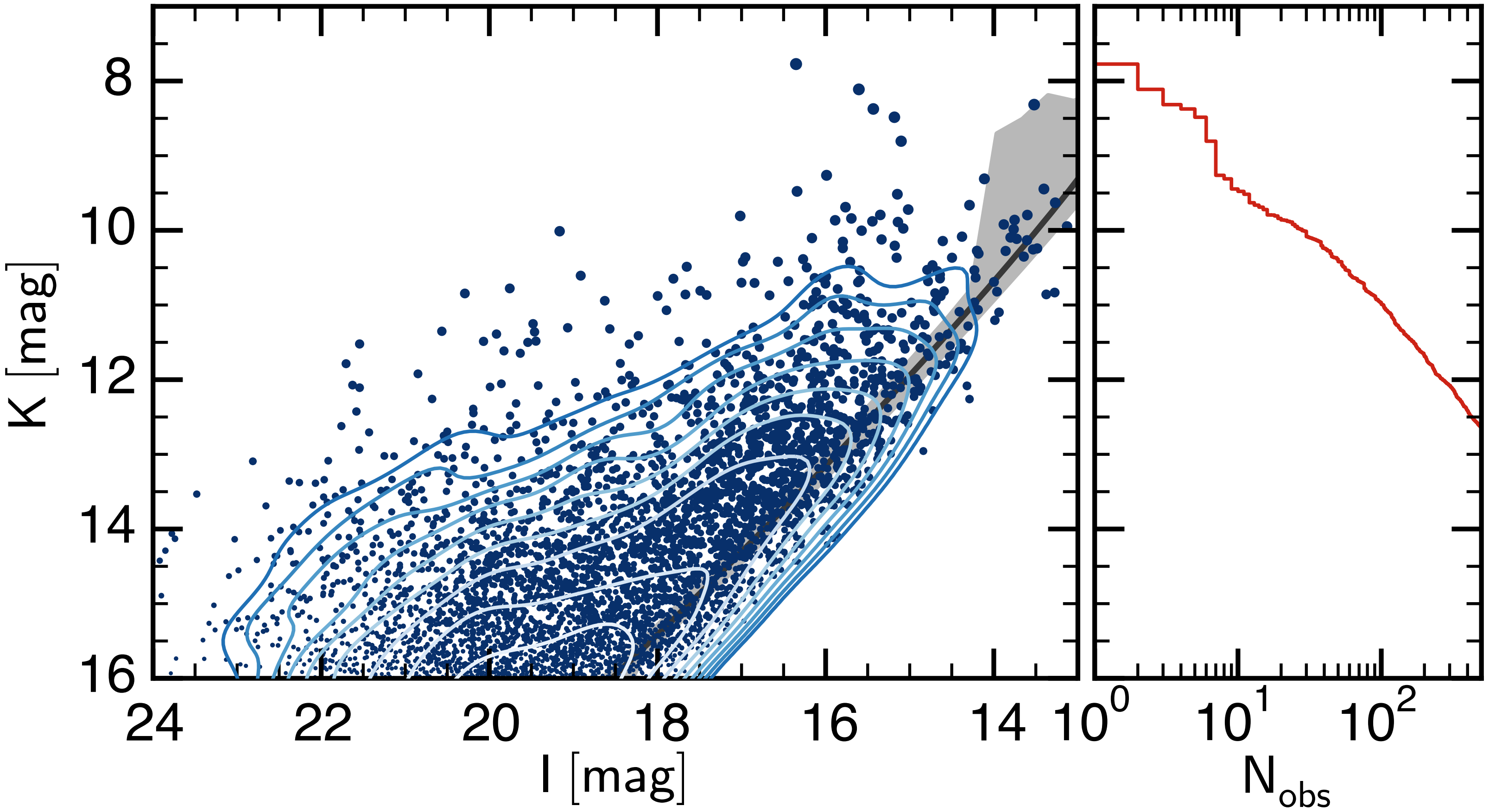


- **Interpretation of interferometric observations rely on the photometric light curve.**

How many targets can be observed?

✦ Statistics based on 2011-2014 seasons: 7342 observed events

Estimation of K-mag at the peak after identifying SL and binary lenses.



(Cassan & Ranc 2016, in press, MNRAS)

How many events in 4 years? 26 events with K<10

✦ Conversion I-magnitude to K-magnitude

- Microlensing light curve fits
- Absorption in K/I bands (Marshall et al. 2006/Nataf et al. 2013)
- K/I-mag conversion with stellar isochrones (Girardi et al. 2002)
- From microlensing model, K-mag at peak of the event

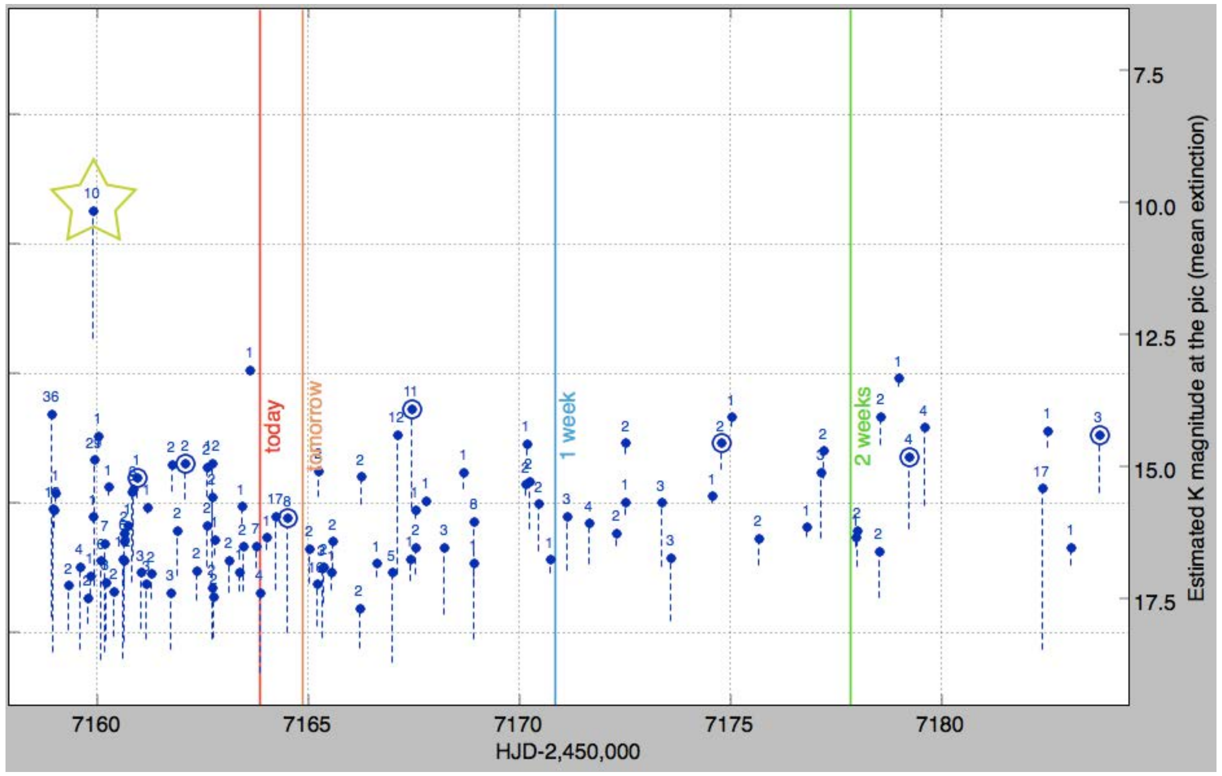
A first attempt with CHARA in 2015

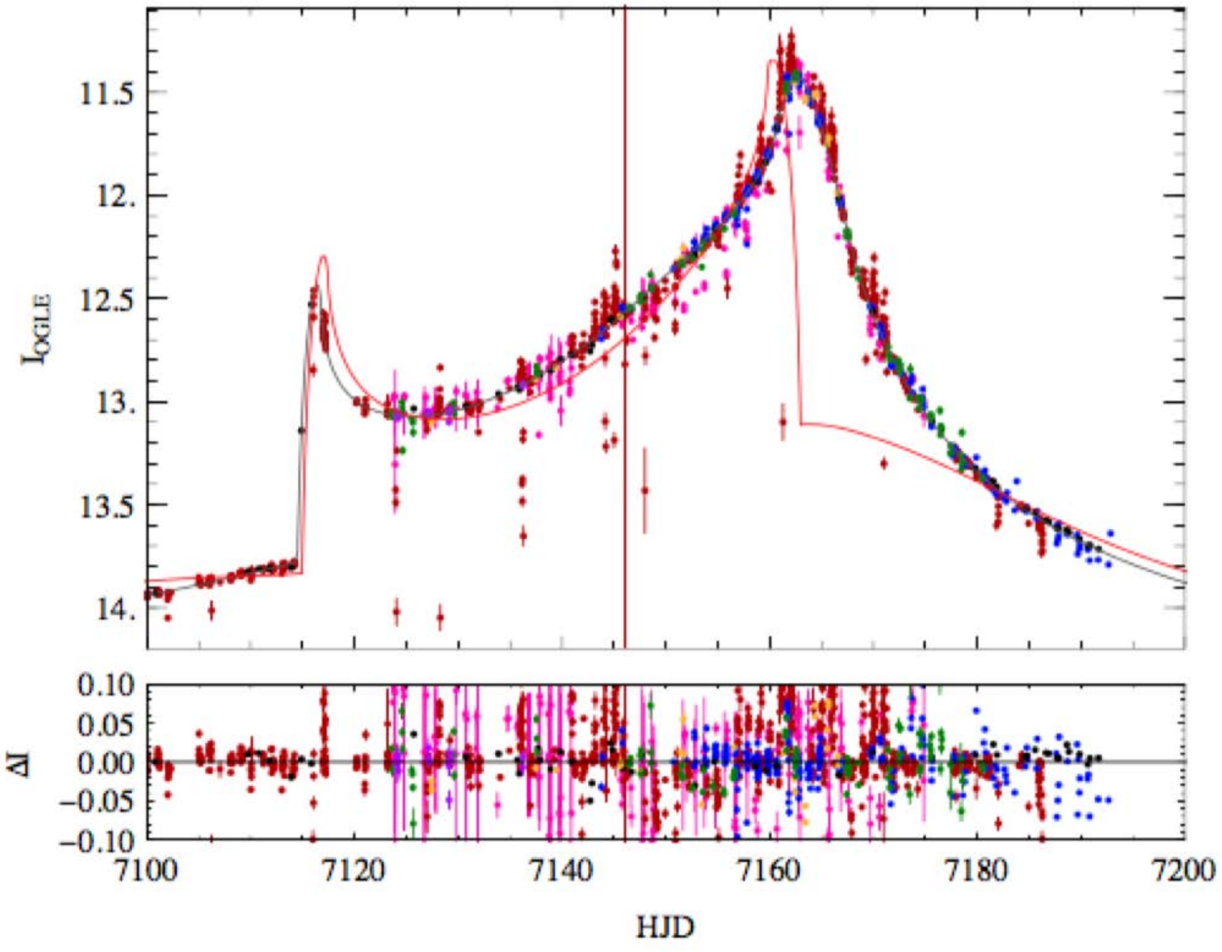
✦ **First test of the full observational strategy.**

✦ **The best target of the season (early).**

✦ **VisObs has identified it.**

- **First alert officially sent by Arnaud Cassan to Stephen Ridgway on May 21st (K<9) on MOA-2015-BLG-020/ OGLE-2015-BLG-0102.**
- **6.5 hours later, CHARA was preparing a try.**





Plot: RTModel, Valerio Bozza

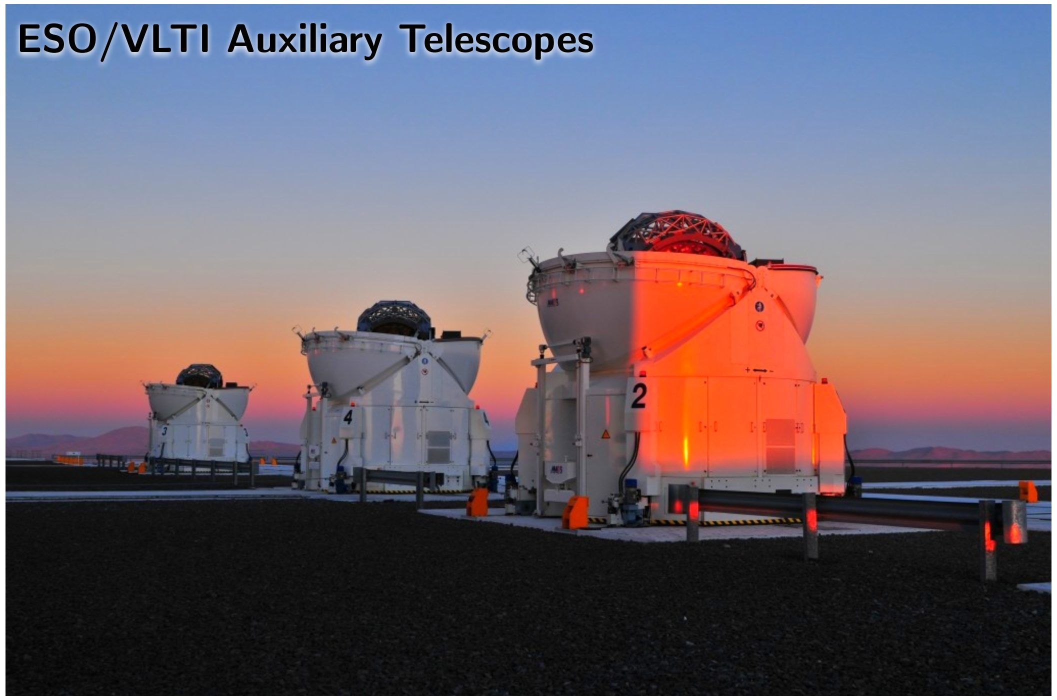
- **Back and forth during 3 days with updates. (K=10.5 on May 24th)**
- **No observations because of rain.**

✦ **Unique opportunity to test interactions**

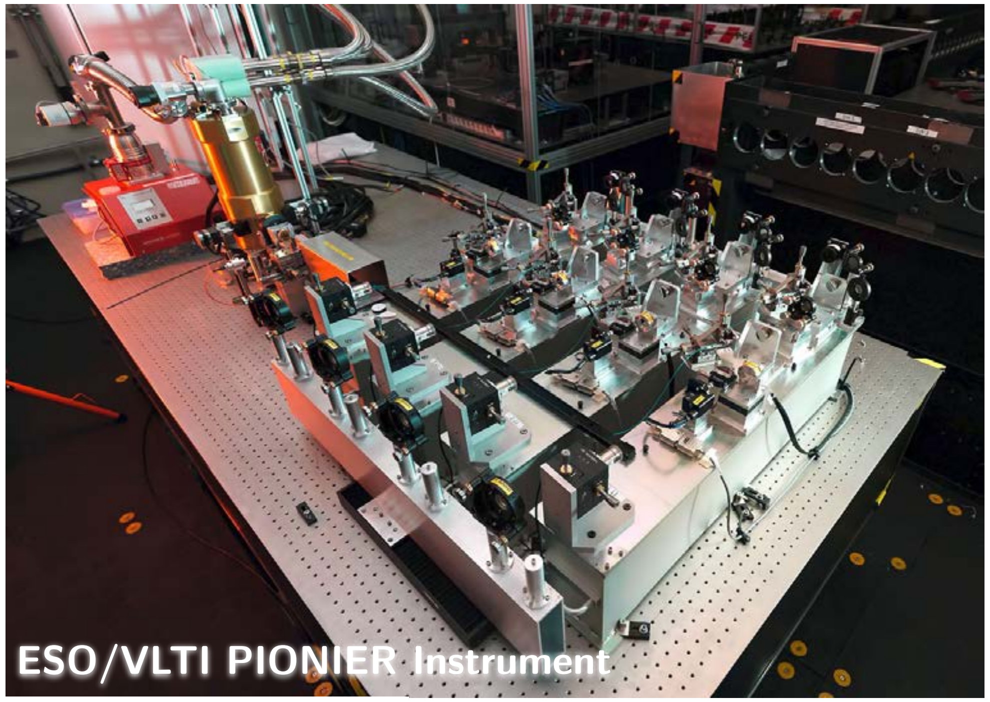
✦ **These events do exist!**

ESO VLTI Proposal

- **ESO VLTI Proposal, accepted in 2015**
  - PI: A. Cassan
    Co-PI: O. Absil, C. Ranc, R. Street, J. Surdej, O. Wertz, J.-B. Le Bouquin
  - Pilot project to demonstrate the feasibility of interferometric observations of microlensing events
  - VLTI location much better to observe the Galactic Bulge
- Target of Opportunity observing mode
- Observing period: April to October
- VLTI/PIONIER: the only instrument in the Southern hemisphere that combines a mas resolution with a high enough sensitivity


ESO/VLTI Auxiliary Telescopes

Credit: Max-Planck-Institut für radioastronomie website

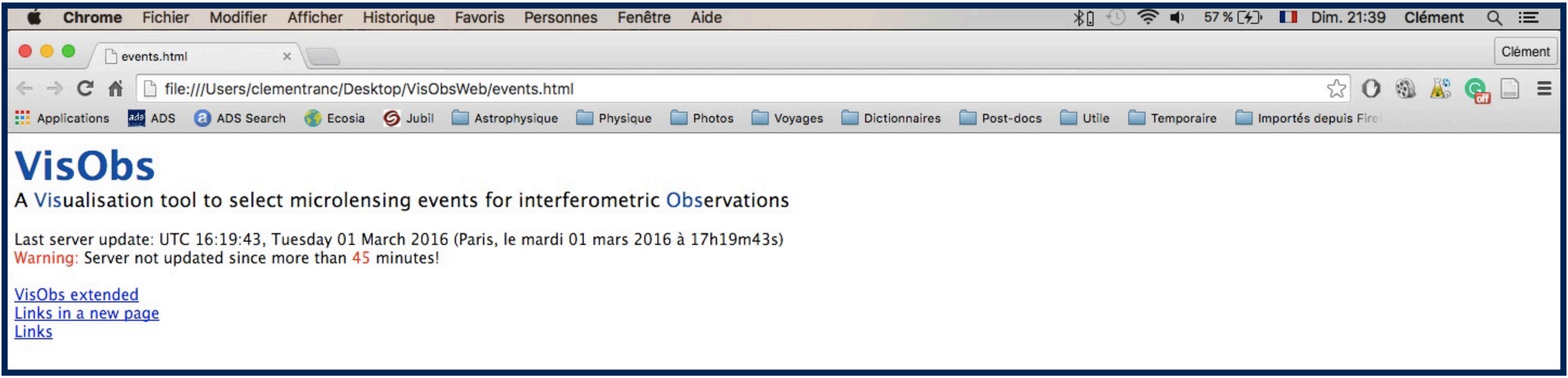

ESO/VLTI PIONIER Instrument

Credit: VLTI website

Online interactive observational tools

✦ **VisObs**: a tool to alert microlensing events for interferometric observations.

http://www.iap.fr/miiriads/VisObs/events.html



VisObs

A Visualisation tool to select microlensing events for interferometric Observations

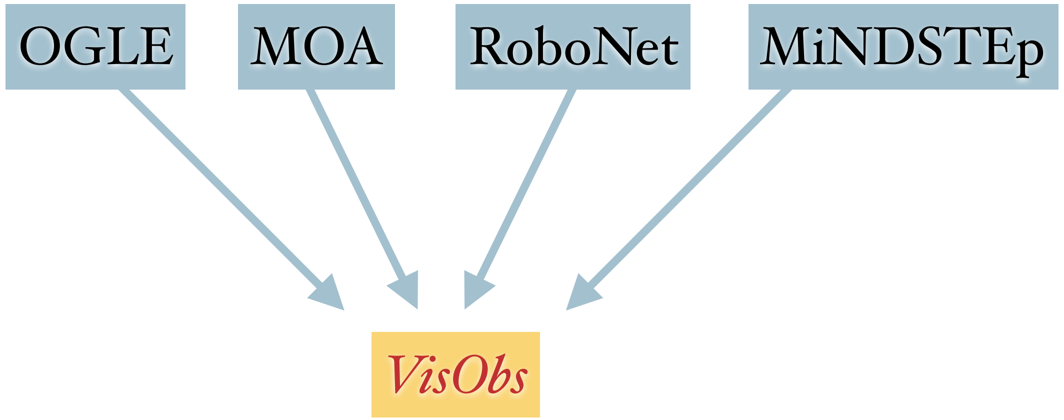
Last server update: UTC 16:19:43, Tuesday 01 March 2016 (Paris, le mardi 01 mars 2016 à 17h19m43s)
Warning: Server not updated since more than 45 minutes!

VisObs extended
Links in a new page
Links

✦ Code to colect, order and identify data

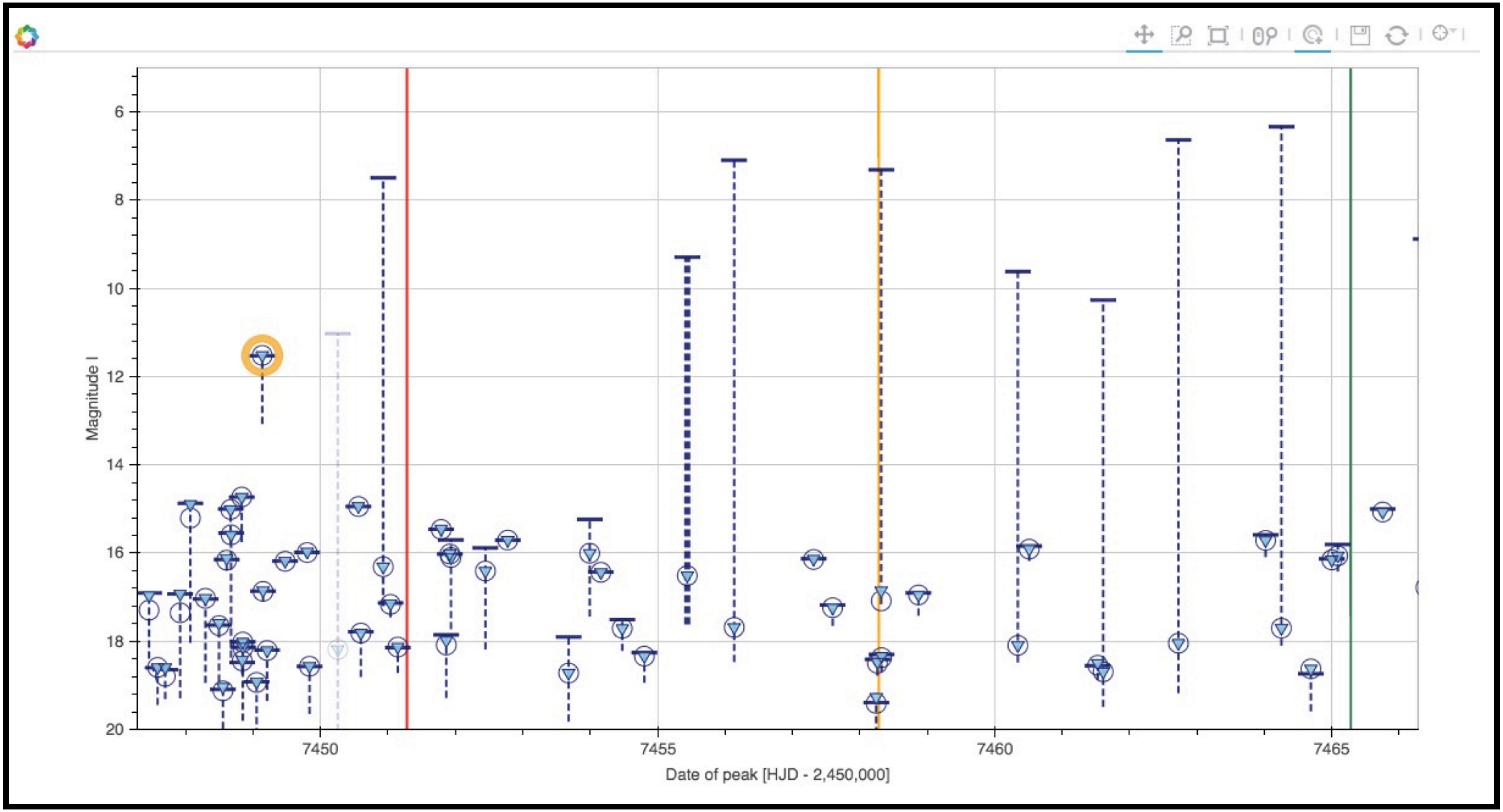
Requirements:

- Code to collect ongoing events data
- Identification of the promising events
- Order, prioritise, and summarise the current situation
- Predict I-magnitude at the peak
- Predict K-magnitude at the peak
- Bayesian framework


OGLE
MOA
RoboNet
MiNDSTEp
VisObs

✦ VisObs: a tool to alert microlensing events for interferometric observations.

http://www.iap.fr/miiriads/VisObs/events.html



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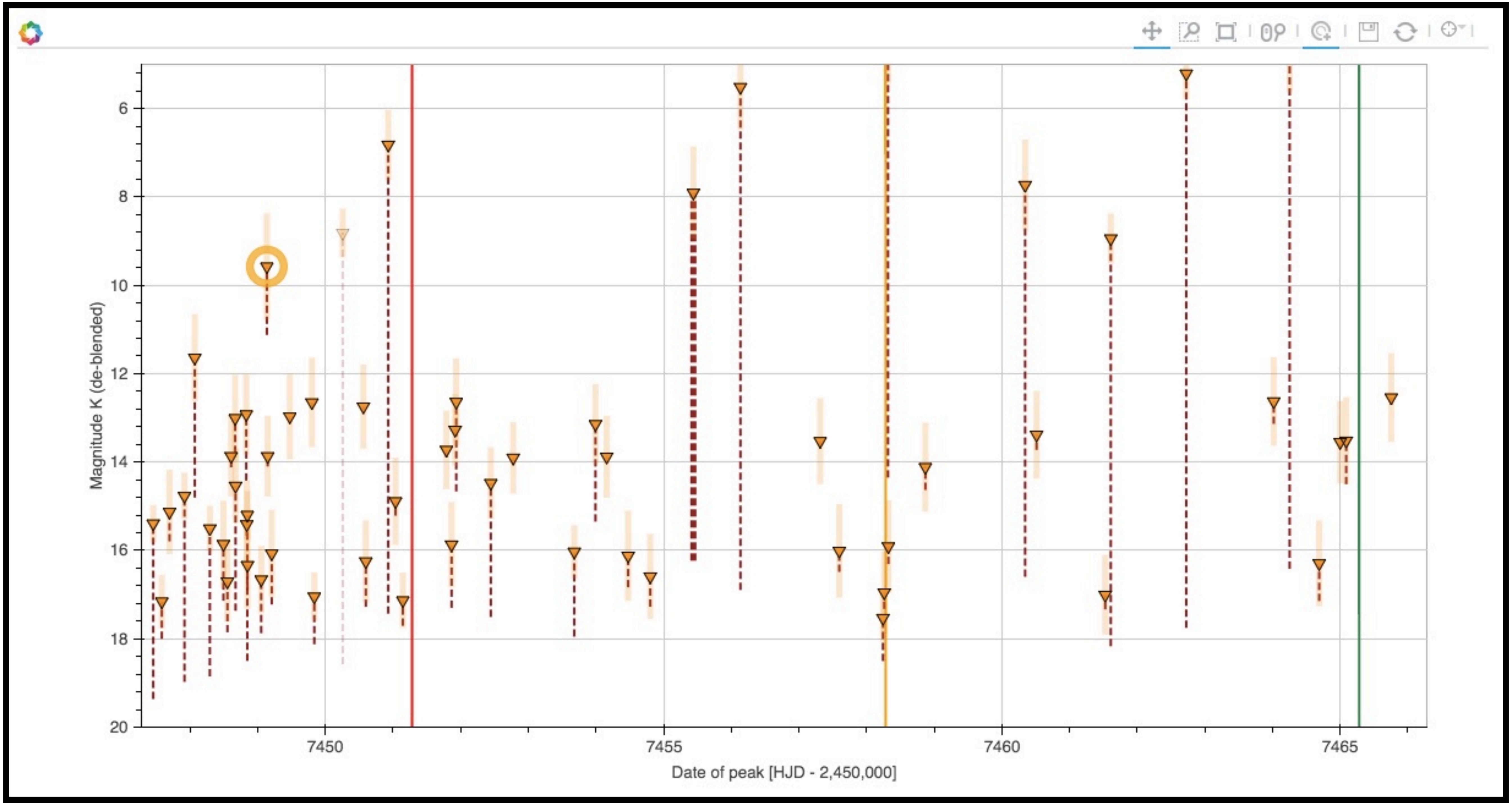

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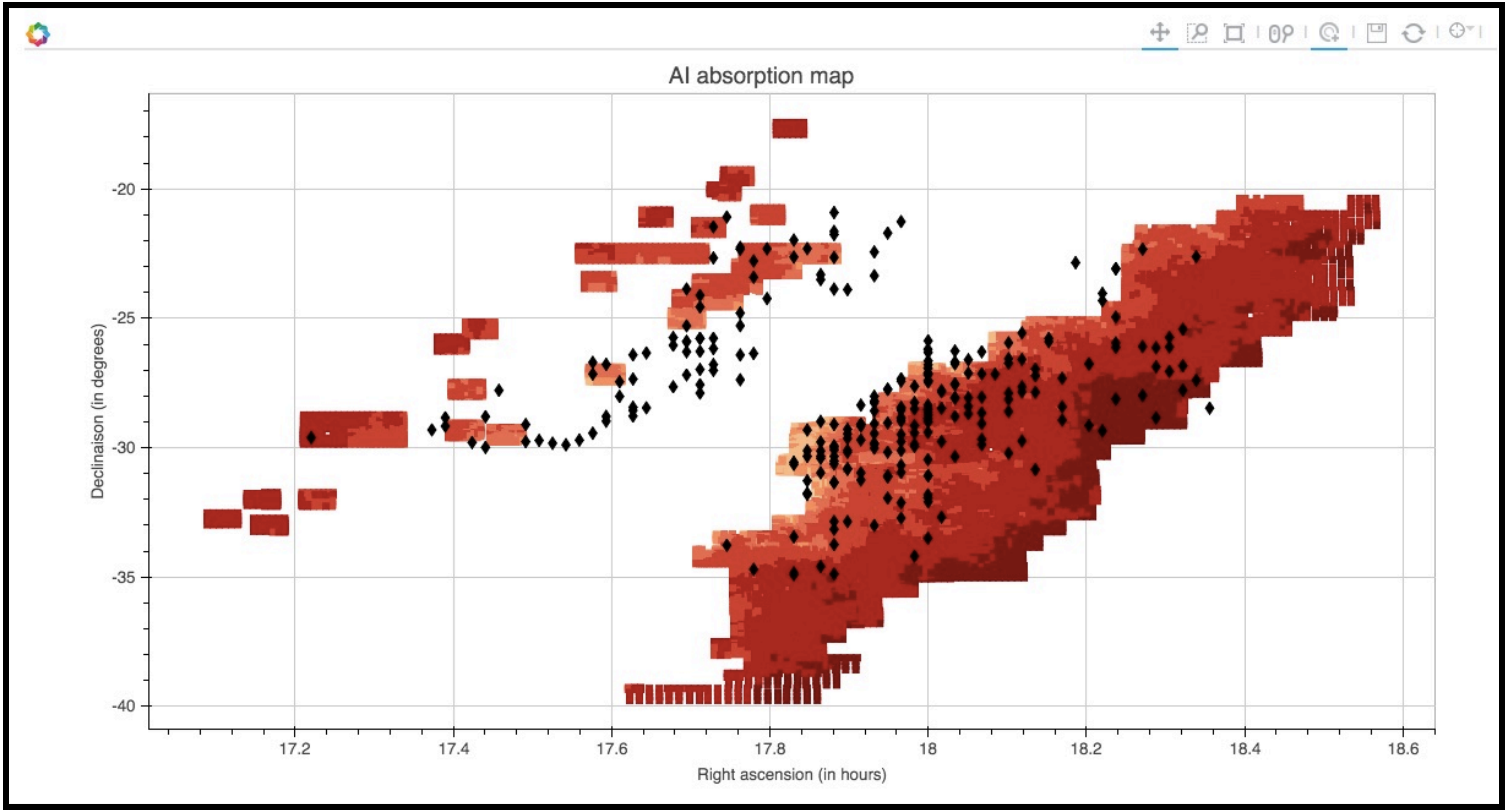

Conclusion

✦ Interferometry to solve degeneracies in microlensing

- Microlensing images can be in principle **resolved by 100m-baseline**.
- **Visibility** and **closure phase** allow an independent constrain on the **Einstein angular radius**.

✦ Observational challenges

- Limiting magnitudes.
- Short notice alert based on real-time modelling.
- Prediction of the peak magnitude in H and K.

✦ Now, let's try to observe

- Several events **can be observed**, in principle, every year by the **VLTI.**
- **A first good candidate identified in May 2015: test of the observing strategy.**
- **ESO/PIONIER/VLTI Proposal accepted.**
- Good perspectives for the instrument ESO/Gravity.

Thank you!