

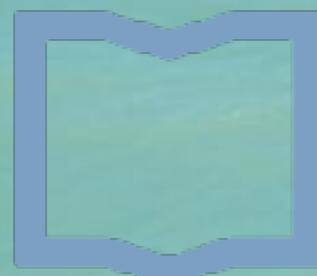
LENTES GRAVITACIONALES EN ASTROFÍSICA Y COSMOLOGÍA

SEMANA - 4

MARTÍN MAKLER

ICAS/IFICI/CONICET & UNSAM Y CBPF

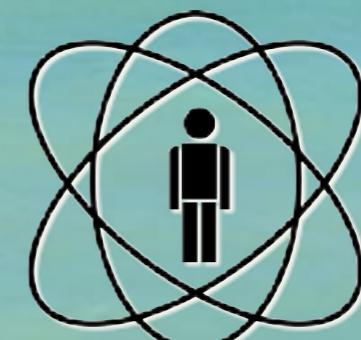
ICAS



Instituto de
Ciencias Físicas

ICIFI-ECYT_UNSAM-CONICET

CONICET



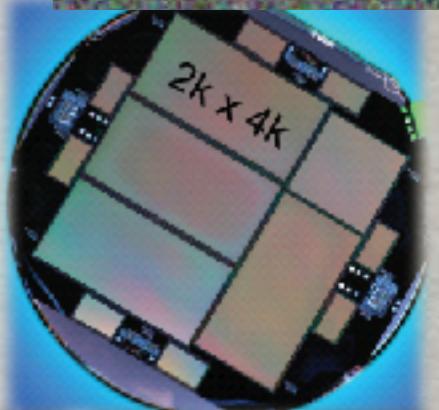
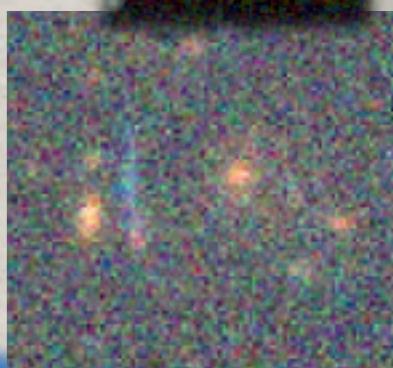
CBPF

ESTRUCTURA GENERAL DE LA MATERIA

Parte I: Introducción, visión general y microlentes gravitacionales

[GR, SL][lentes puntuales, astrofísica, materia oscura]

- Introducción a las lentes gravitacionales y sus aplicaciones actuales
- Deflexión de la luz y ecuación de la lente
- Lentes puntuales
- Mapeo de lentes, magnificación, cáusticas y curvas críticas
- Lentes binarias
- Curvas de luz de microlentes y microlentes por astrometria
- Mas allá de la curva de Paczynski
(efectos de segunda orden y lentes compuestas)
- Estadística de lentes



Hoy

Aplicaciones: descubierta de planetas y agujeros negros, búsqueda de materia oscura, caracterización de la distribución de objetos compactos...

- Eventos individuales

- Informaciones adicionales: romper degeneraciones
- Eventos de lentes binarias y múltiples (incluso exoplanetas y QSO *microlensing*)

Apéndice: sistemas con N lentes y microlensing de cuásares

- For a system of N -lenses we obtained:

$$z_s = z - \sum_{i=1}^N \frac{m_i}{z^* - z_i^*}$$

- Taking the conjugate:

$$z_s^* = z^* - \sum_{i=1}^N \frac{m_i}{z - z_i}$$

- We obtain z^* and substitute it back into the original equation, which results in a (N^2+1) th order complex polynomial equation

$$p(z) = \sum_{i=0}^N c_i z^i$$

- This equation can be solved only numerically, even in the case of a binary lens

Esta y próximas filminas extraídas de
http://pico.oabo.inaf.it/~massimo/teaching_2016.html

COMPLEX LENS EQUATION

Sistemas con N lentes

- For a system of N -lenses we obtained:

$$z_s = z - \sum_{i=1}^N \frac{m_i}{z^* - z_i^*}$$

- Taking the conjugate:

$$z_s^* = z^* - \sum_{i=1}^N \frac{m_i}{z - z_i}$$

- We obtain z^* and substitute it back into the original equation, which results in a (N^2+1) th order equation

$$p(z) = \sum_{i=0}^N c_i z^i$$

- Note that the solutions are not necessarily solutions of the lens equations (spurious solutions)
- One has to check if the solutions are solutions of the lens equation
- Rhie 2001,2003: maximum number of images is $5(N-1)$ for $N > 2$

- In the complex form, the magnification can still be derived from the lensing Jacobian:

$$\det A = \left(\frac{\partial z_s}{\partial z} \right)^2 - \frac{\partial z_s}{\partial z^*} \left(\frac{\partial z_s}{\partial z^*} \right)^* = 1 - \frac{\partial z_s}{\partial z^*} \left(\frac{\partial z_s}{\partial z^*} \right)^*$$

$$\frac{\partial z_s}{\partial z^*} = \sum_{i=1}^N \frac{m_i}{(z^* - z_i^*)^2}$$

$$\det A = 1 - \left| \sum_{i=1}^N \frac{m_i}{(z^* - z_i^*)^2} \right|^2$$

- Therefore the critical lines form where

$$\left| \sum_{i=1}^N \frac{m_i}{(z^* - z_i^*)^2} \right|^2 = 1$$

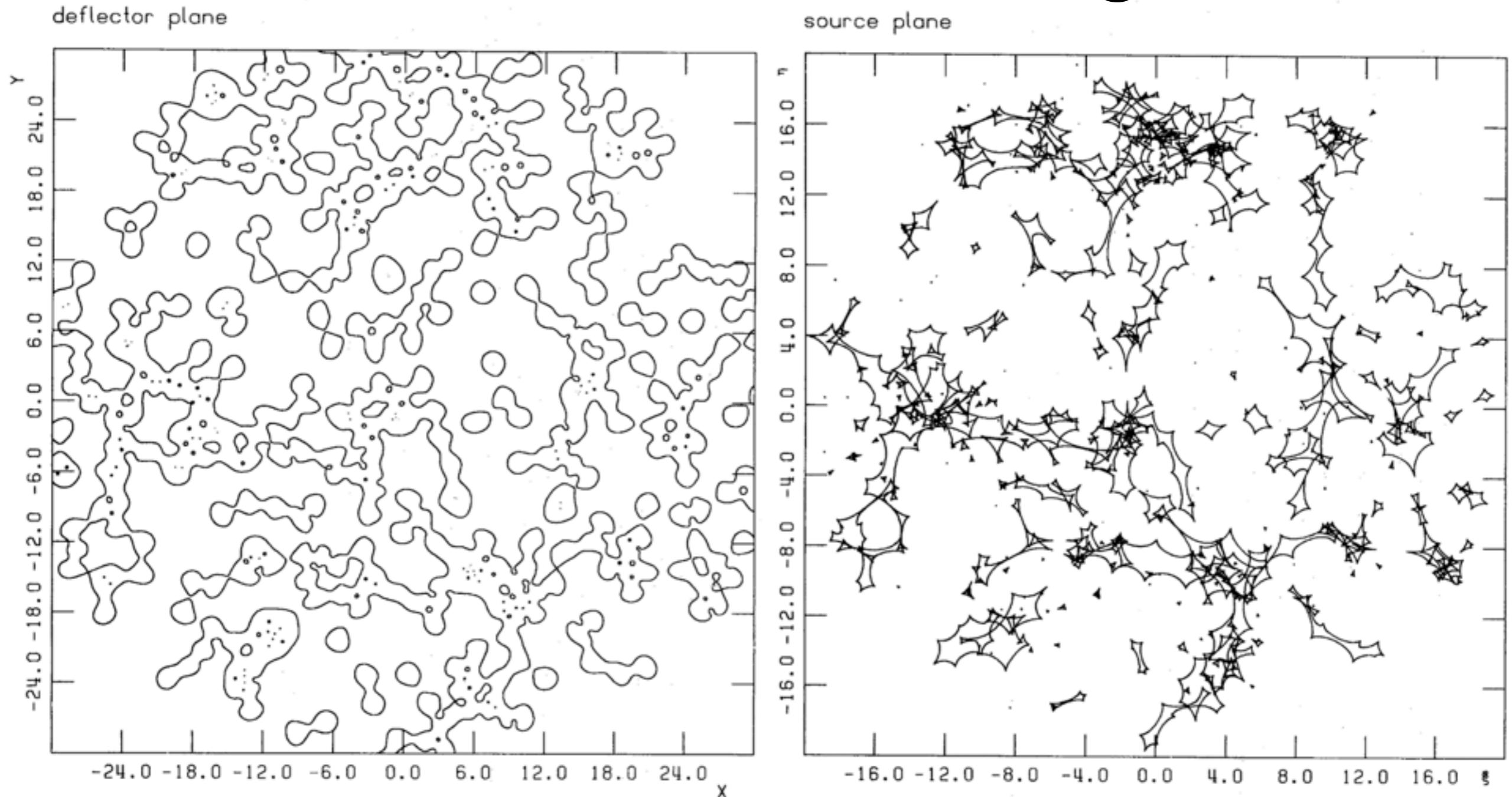
- Thus, to find the critical points we solve

$$\sum_{i=1}^N \frac{m_i}{(z^* - z_i^*)^2} = e^{i\phi} \quad \phi \in [0, 2\pi]$$

- Again, this can be turned into a complex polynomial of order $2N$: for N lenses, there are $2N$ critical lines and caustics. The solutions can be found numerically.

Sistemas con N estrellas

Quasar microlensing

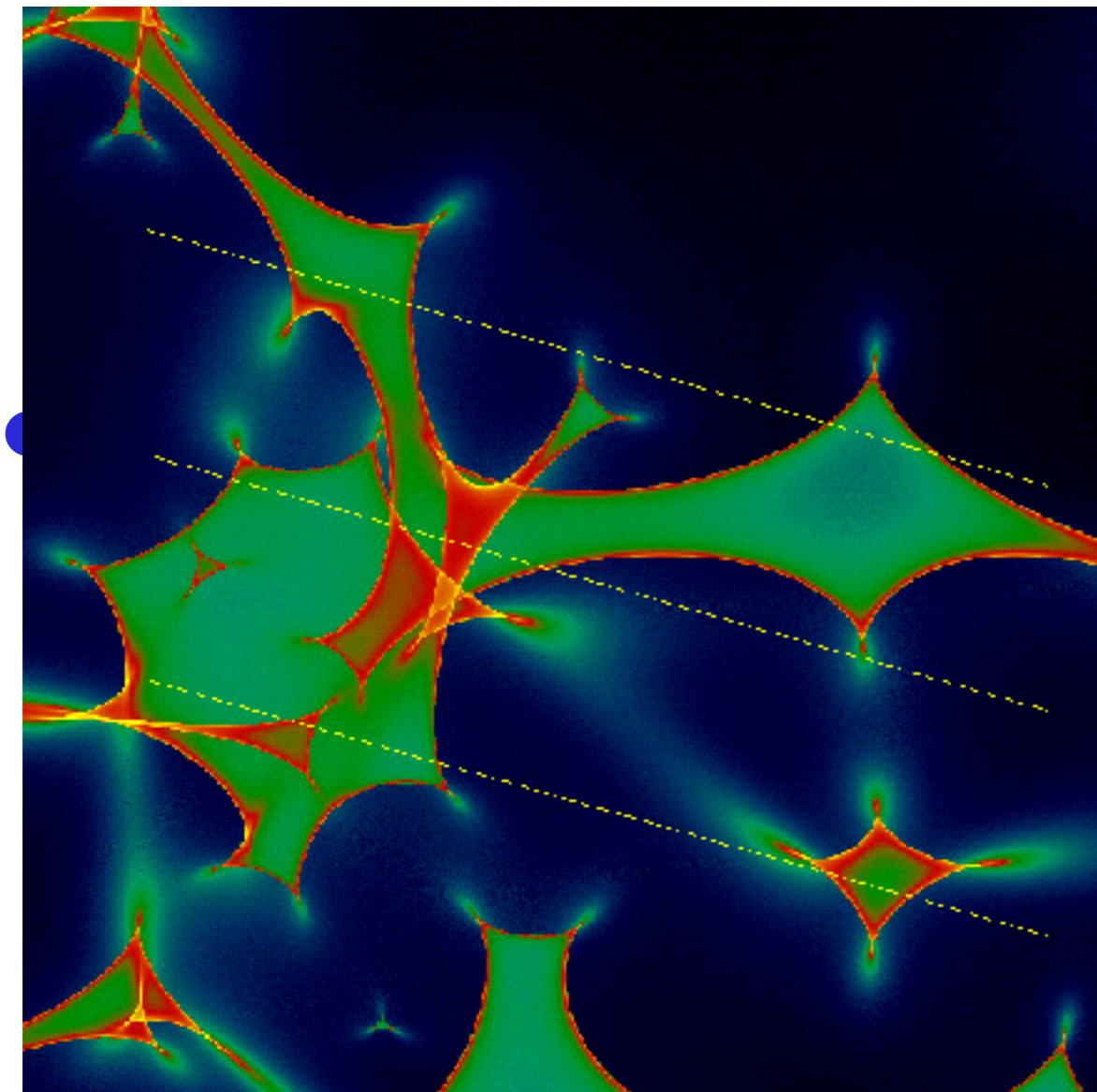


*critical lines and caustics originated by 400
stars*

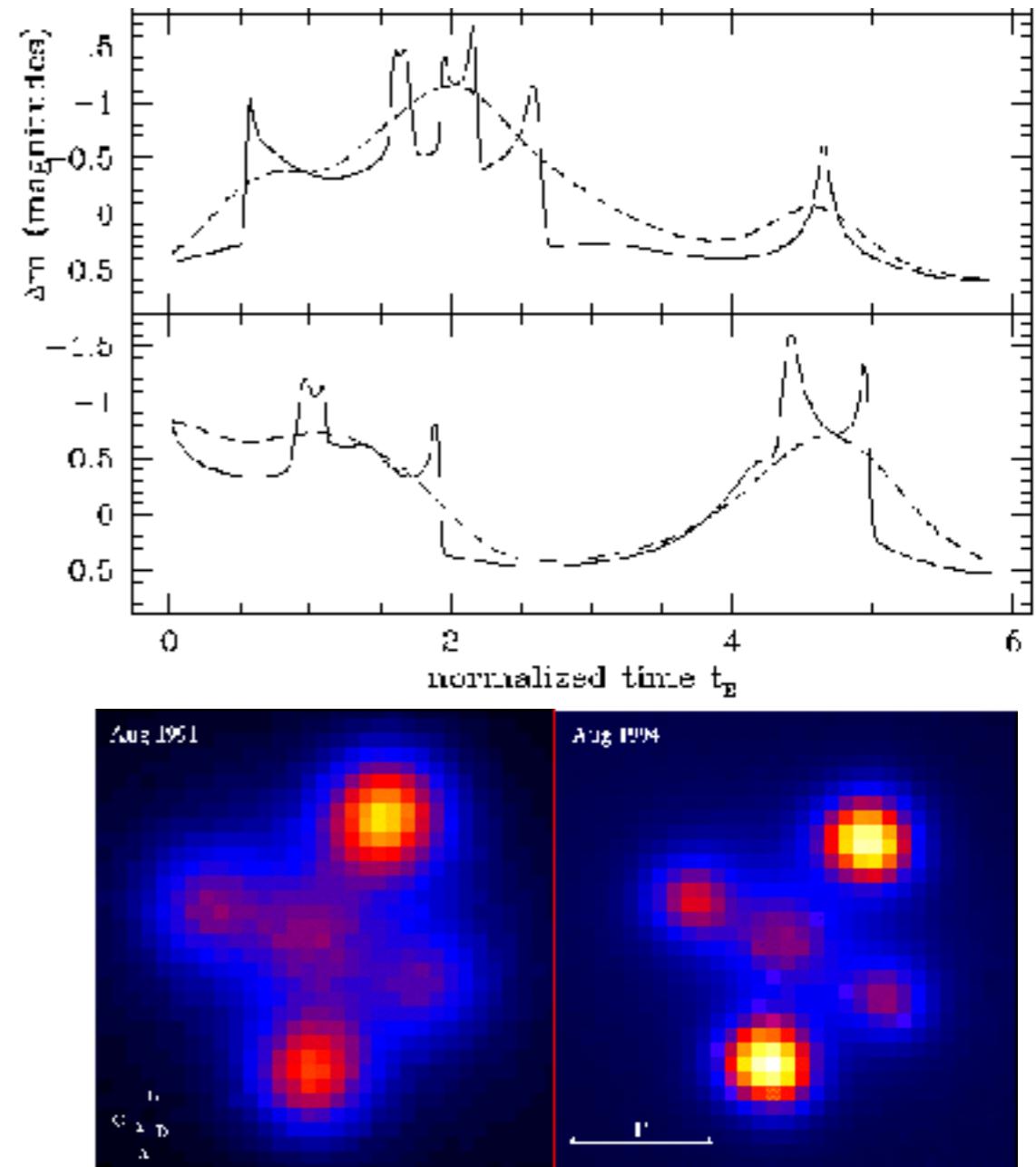
Witt, 1990, A&A, 236, 311

Mililentes de Cuasares

- Patrón de magnificación



- Curvas de luz

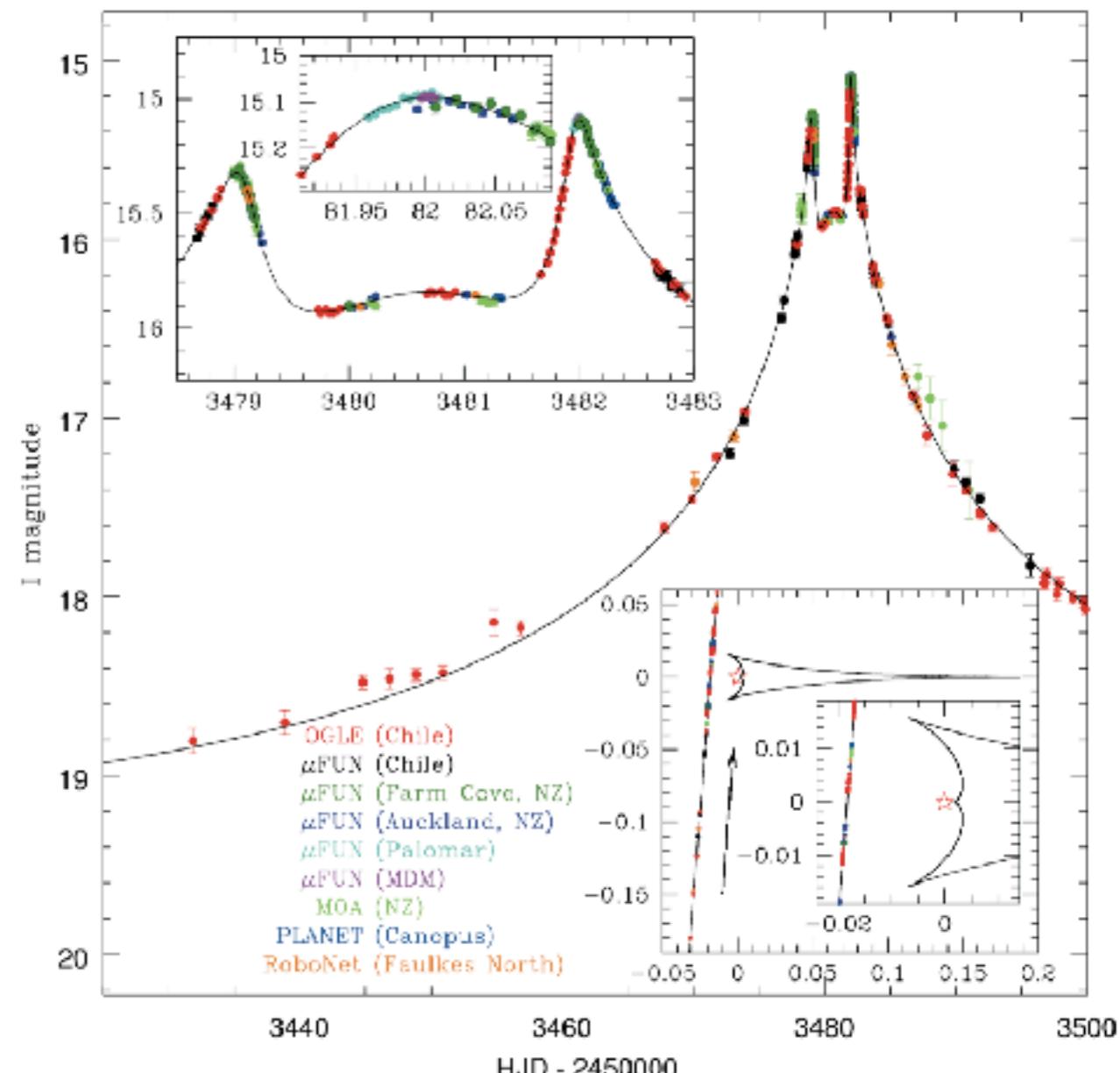


Exoplanetas

- Obtener los parámetros de curvas de luz con múltiples componentes (y/o shift astrométrico)
- En general binarias, pero sistemas múltiples
- Ecuación de la lente binaria $y = x - \frac{\mu_A}{\bar{x} - \bar{x}_A} - \frac{\mu_B}{\bar{x} - \bar{x}_B}$
 $q := \mu_A / \mu_B$
 $d := |x_A - x_B| = 2|x_A|$
 - Para un planeta como Júpiter: $q = 0.001$
 - Para un planeta como la Tierra: $q = 0.000003$
- Gran diversidad de curvas

INTERESTING CASES: MASSIVE COMPANIONS TO M-DWARFS

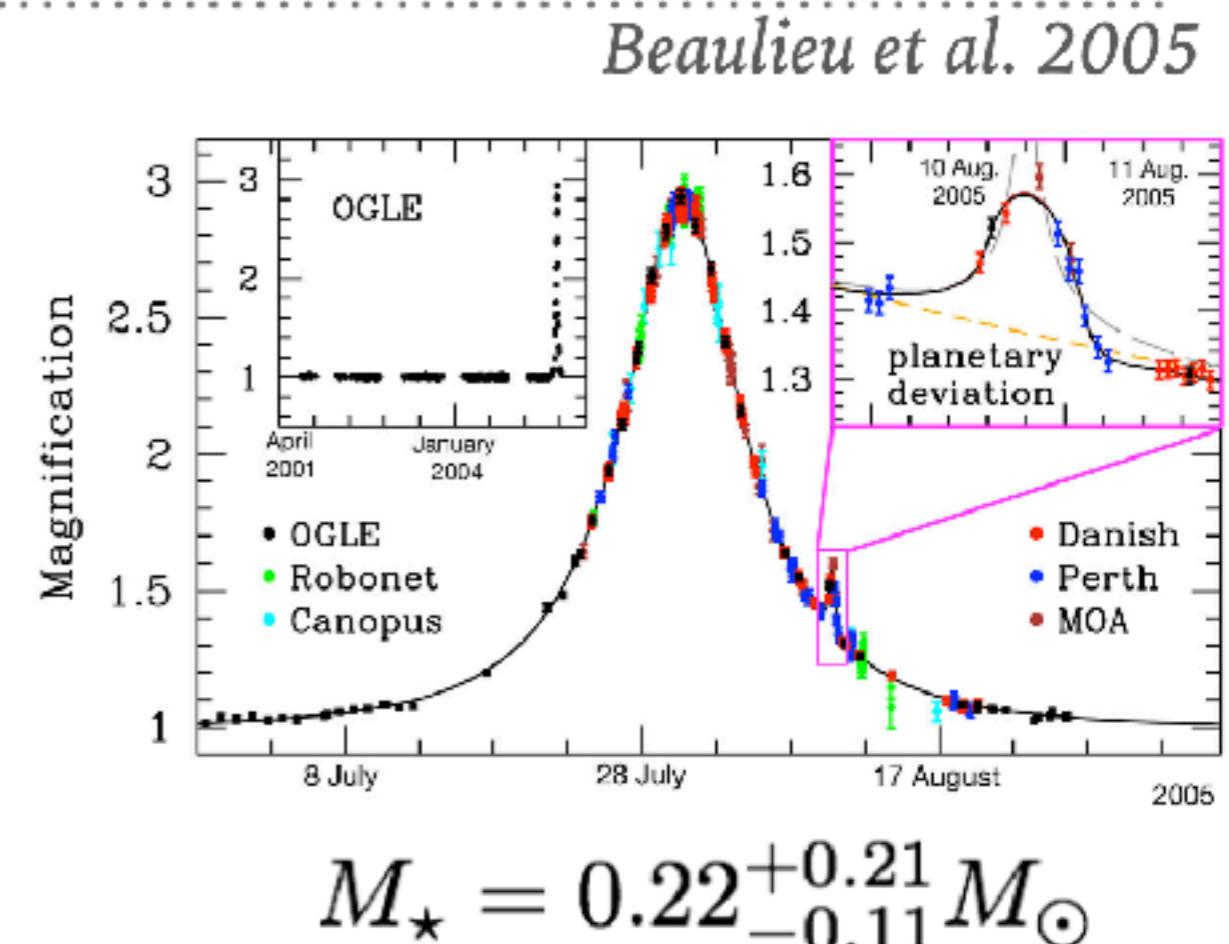
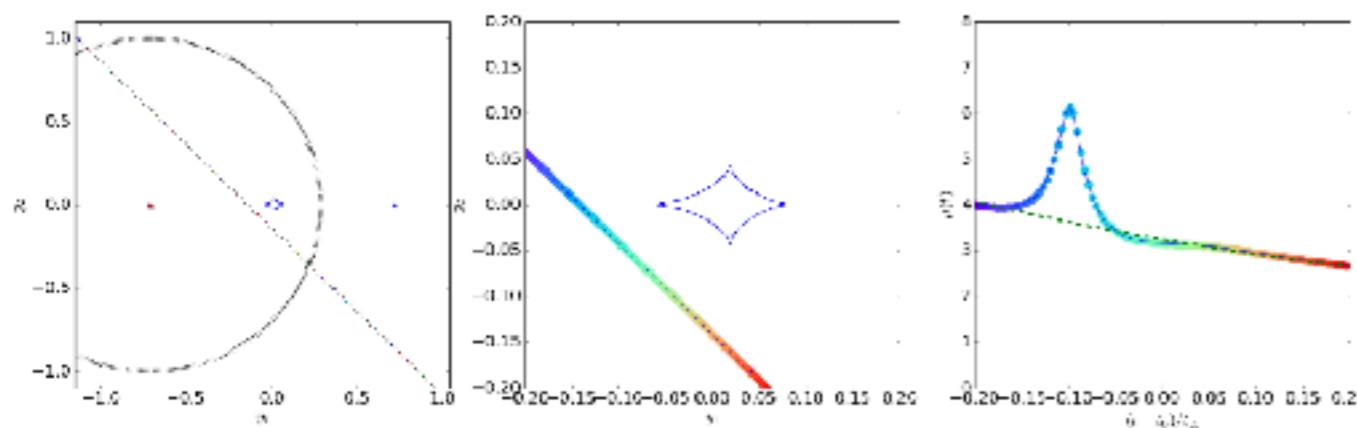
- OGLE-2005-BLG-071Lb: a Jovian-mass planet around a relatively small star
- Other cases: MOA-2009-BLG-387Lb, MOA-2011-BLG-293Lb
- At 2013: 3 out of 14 planets are Jovian companions of M-dwarf stars.
- they seem common, contrary to expectations



Udalski et al. (2005)

INTERESTING CASES: COLD SUPER-EARTHS

- OGLE-2005-BLG-390Lb: the first icy super-earth just beyond the snow line discovered via microlensing



$$M_{\star} = 0.22^{+0.21}_{-0.11} M_{\odot}$$

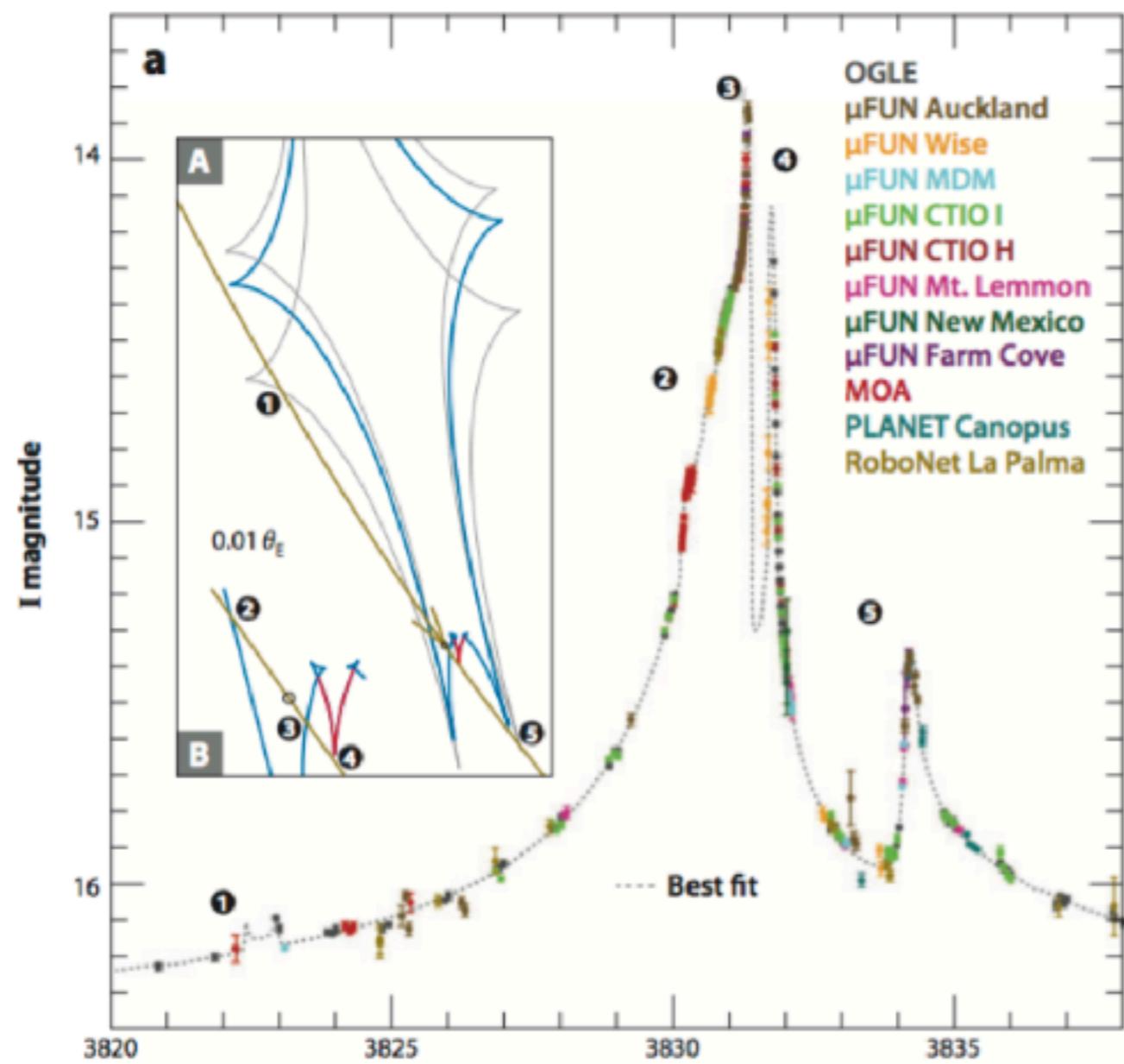
$$q \sim 8 \times 10^{-5} \quad M_p = 5.5^{+5.5}_{-2.7} M_{\oplus}$$

$$a = 2.6^{+1.5}_{-0.6} AU$$

Mas allá de la lente binaria

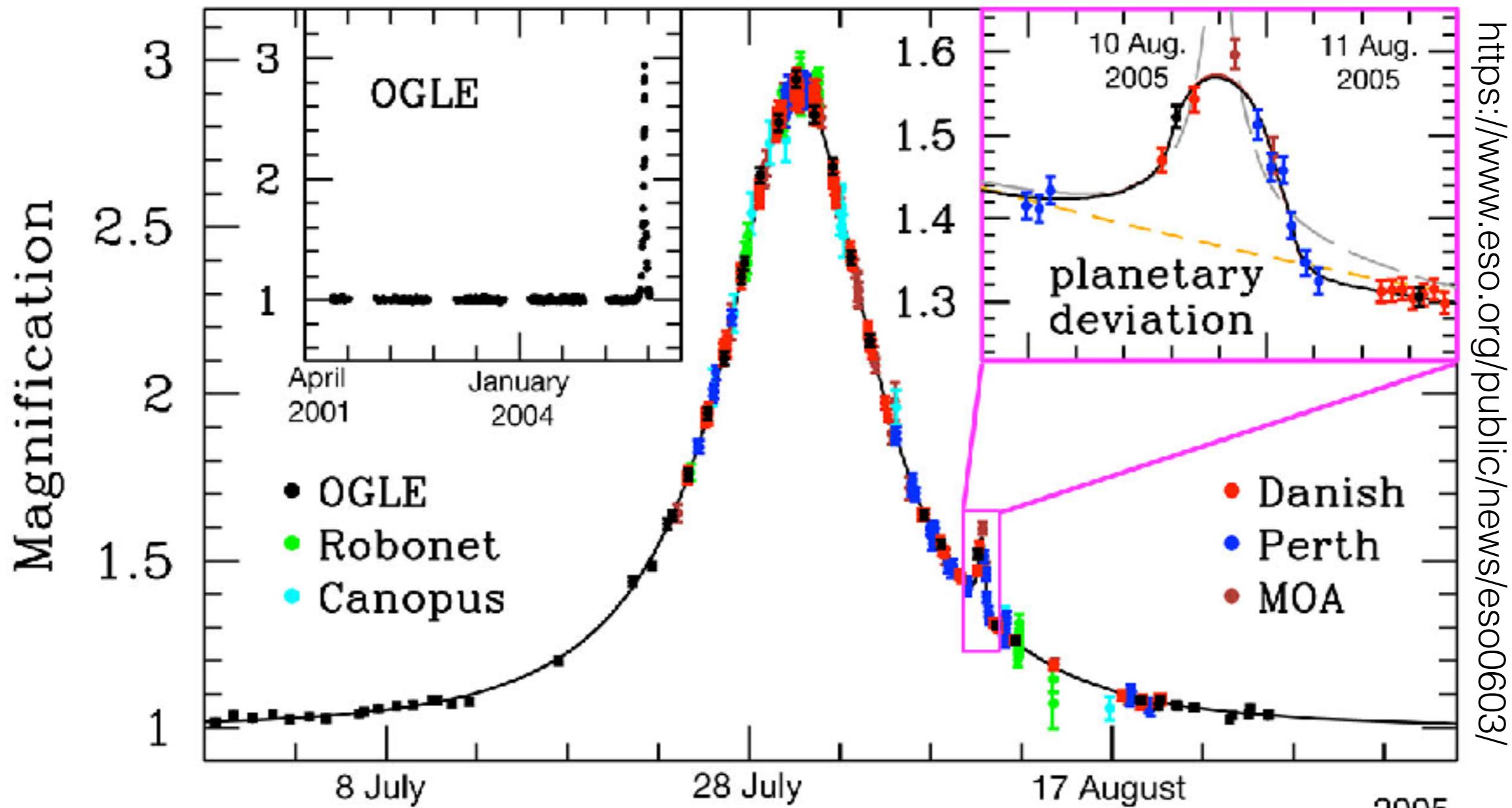
INTERESTING CASES: MULTIPLE PLANETS AND EVOLVING CAUSTIC

- OGLE-2006-BLG-109Lb,c: the first detection of a multiple planet system via microlensing
- M-dwarf star host star
- A Saturn-like planet generating a resonant caustic
- A Jupiter-like planet generating a small perturbation (central caustic)
- **There are indications for an evolution of the caustic of the Saturn-like planet due to its orbital motion**



Gaudi *et al.* (2008), Bennet *et al.* (2010)

Exoplanetas

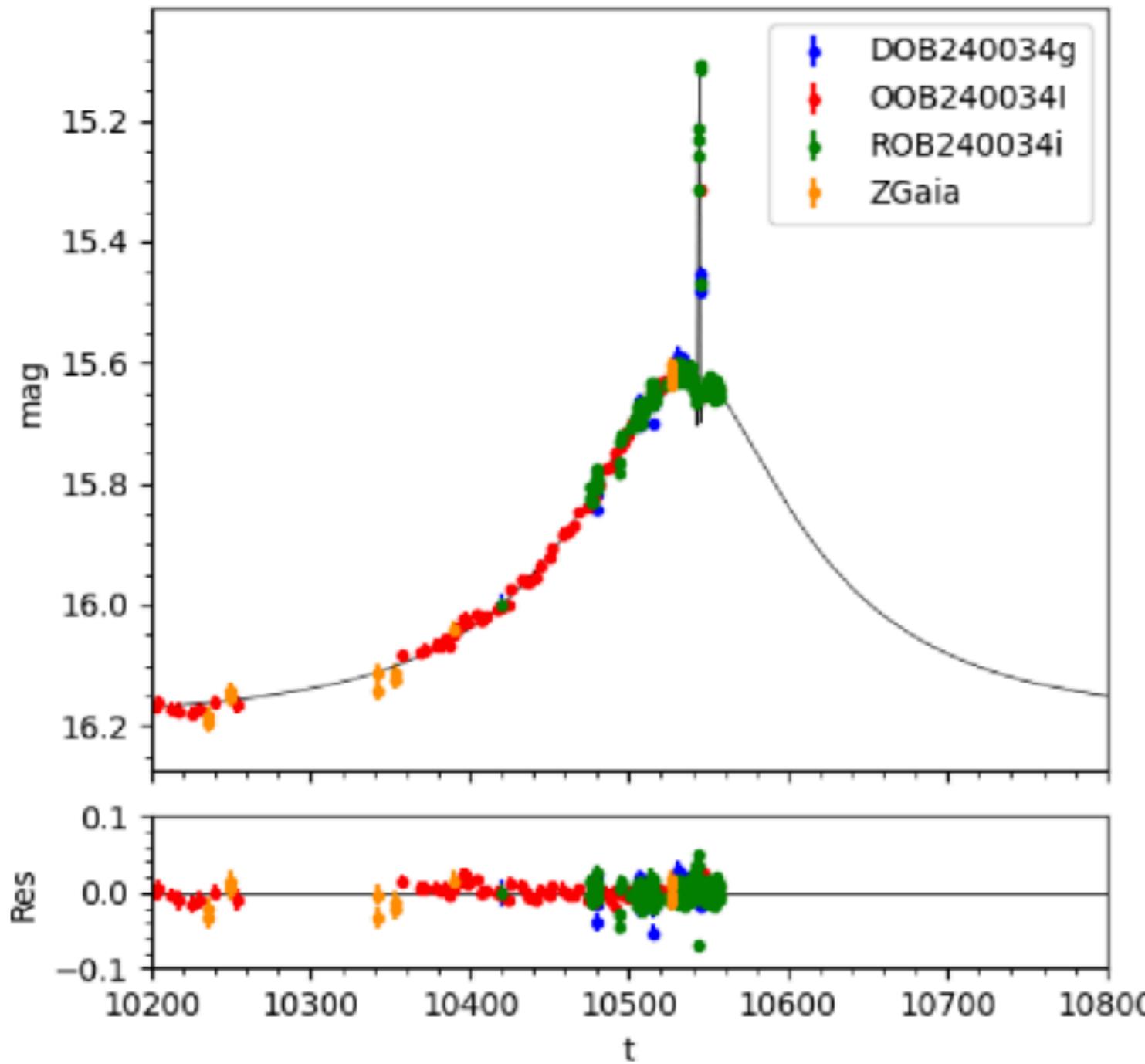


<http://exoplanet.eu/catalog/>

- 308 planetas / 10 sistemas con múltiples planetas (en 12/09/2024)
- Anomalías planetarias características
- Necesitan cadencia mayor

<https://www.eso.org/public/news/eso0603/>

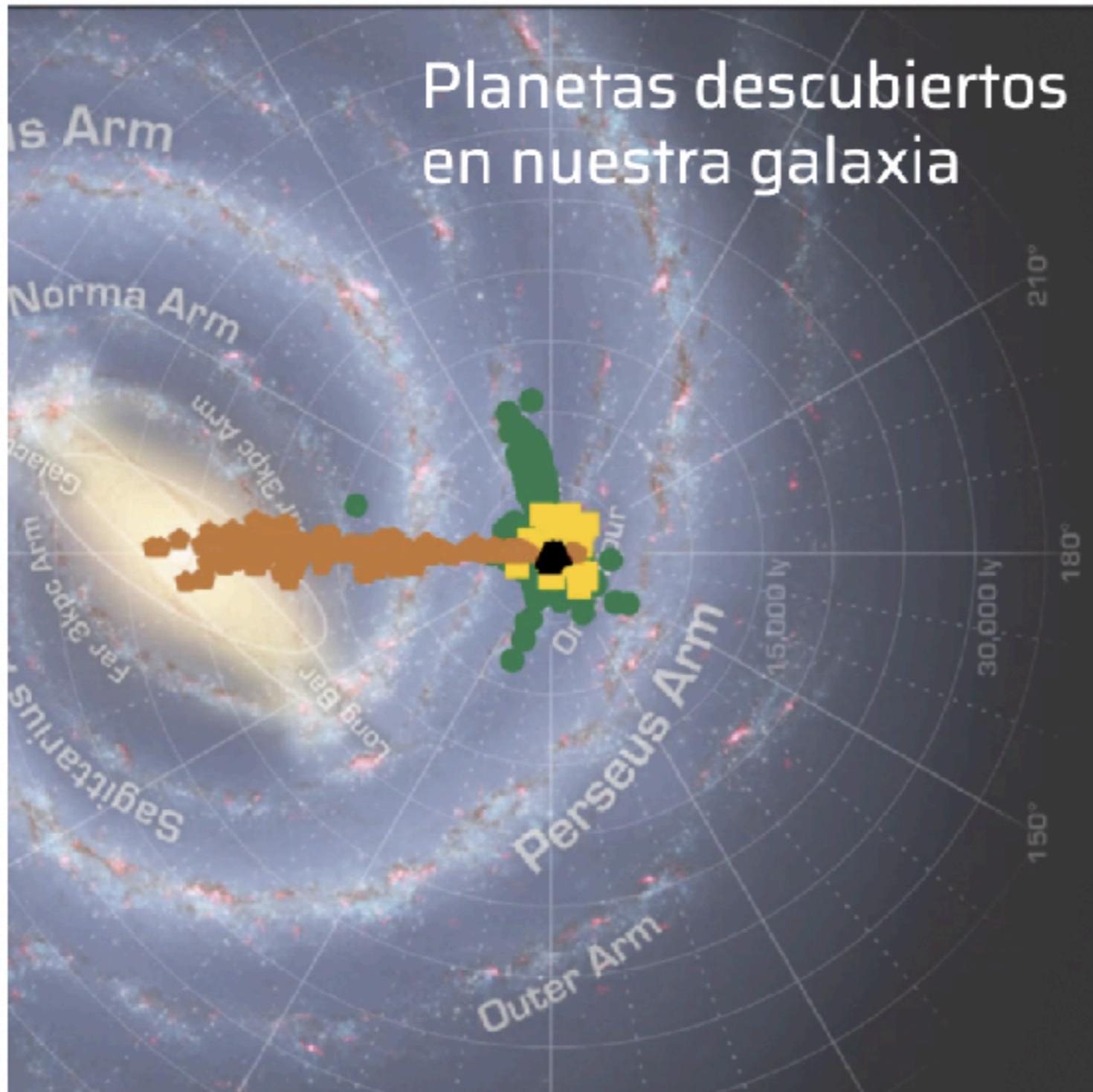
Evento 0034



Parámetros ajustados con RTModel
(en 12/09/2024)

$$\begin{aligned}s &= 1.1785475 \pm 0.0019 \\q &= 0.0001575027 \pm 0.00000063 \\u_0 &= 0.3432 \pm 0.0024 \\a &= 1.7161 \pm 0.0018 \\Q^* &= 0.002198 \pm 0.000081 \\t_E &= 164.28 \pm 0.71 \\- t_0 &= 10535.832 \pm 0.050\end{aligned}$$

Detección de exoplanetas

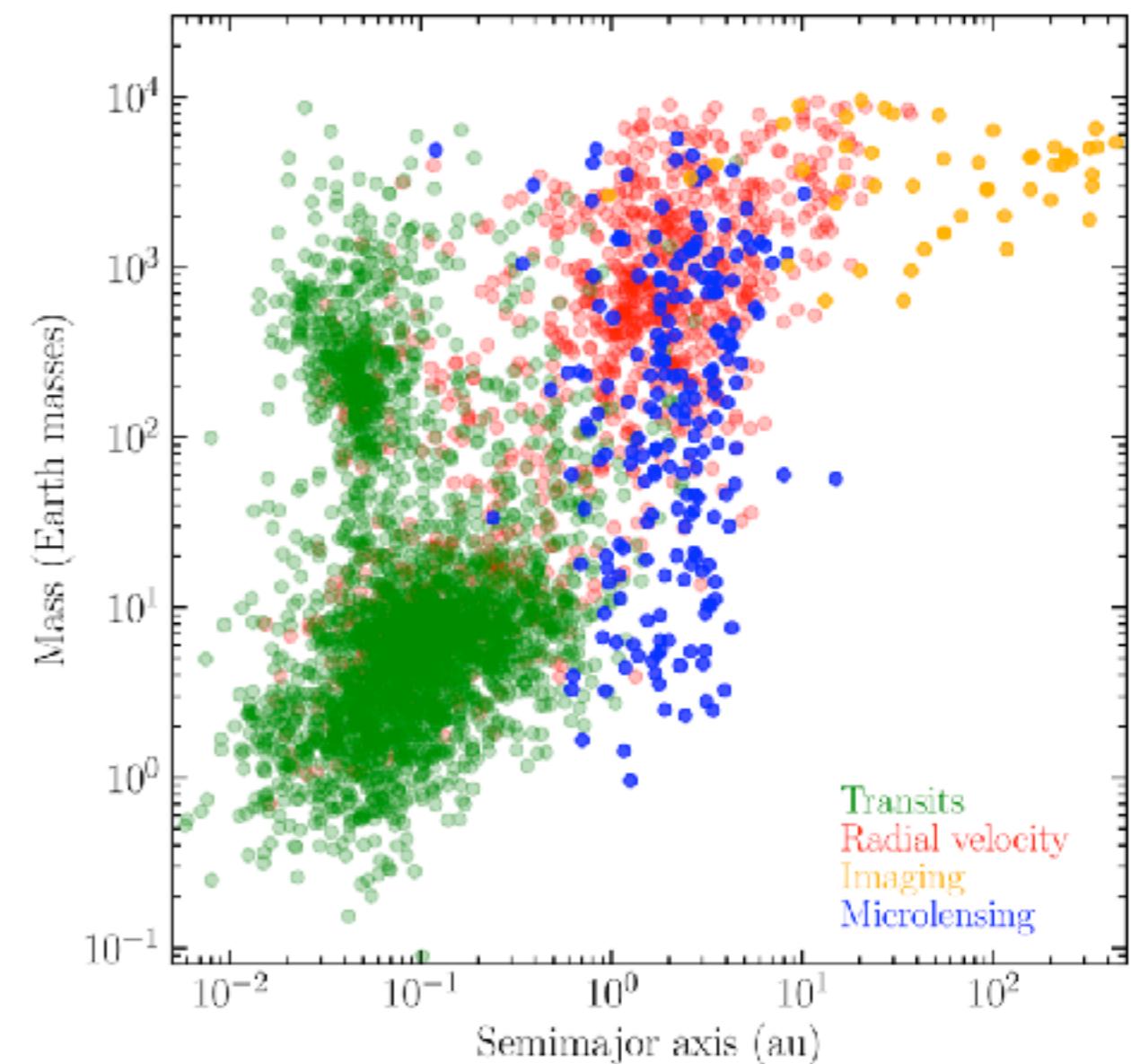
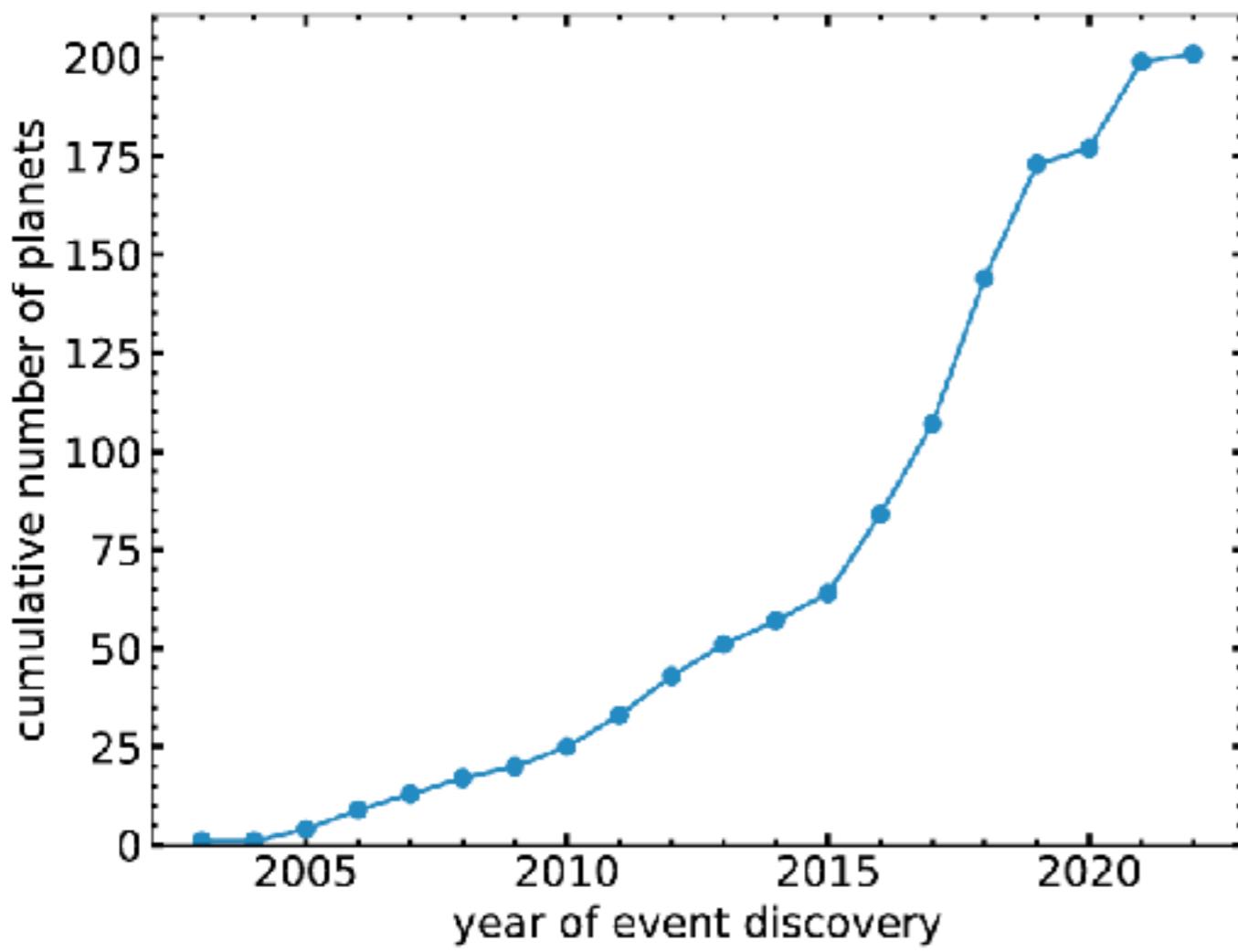


Descubiertas de exoplanetas

Exoplanet Occurrence Rates from Microlensing Surveys

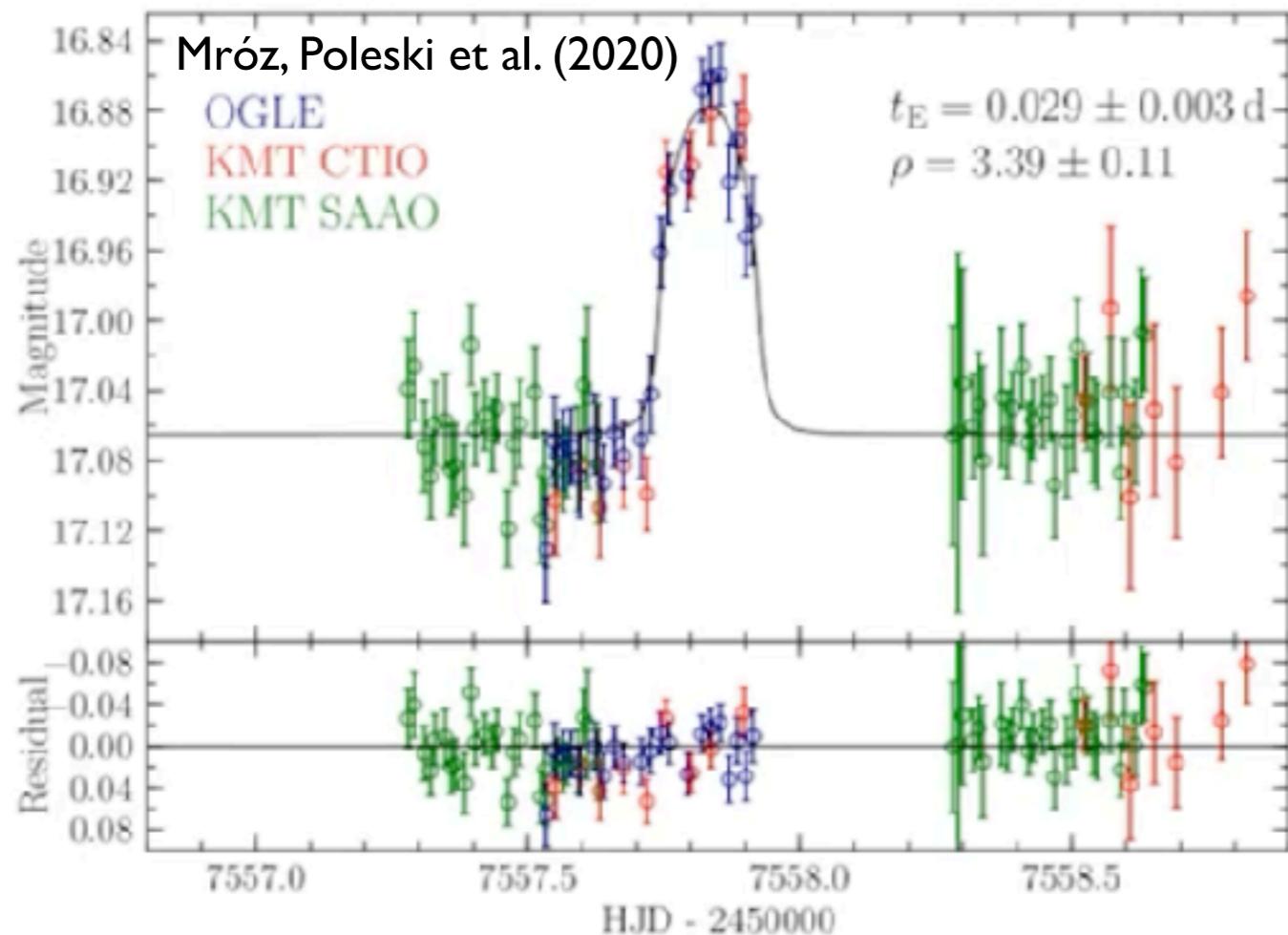
Przemek Mróz and Radosław Poleski

arXiv:2310.07502

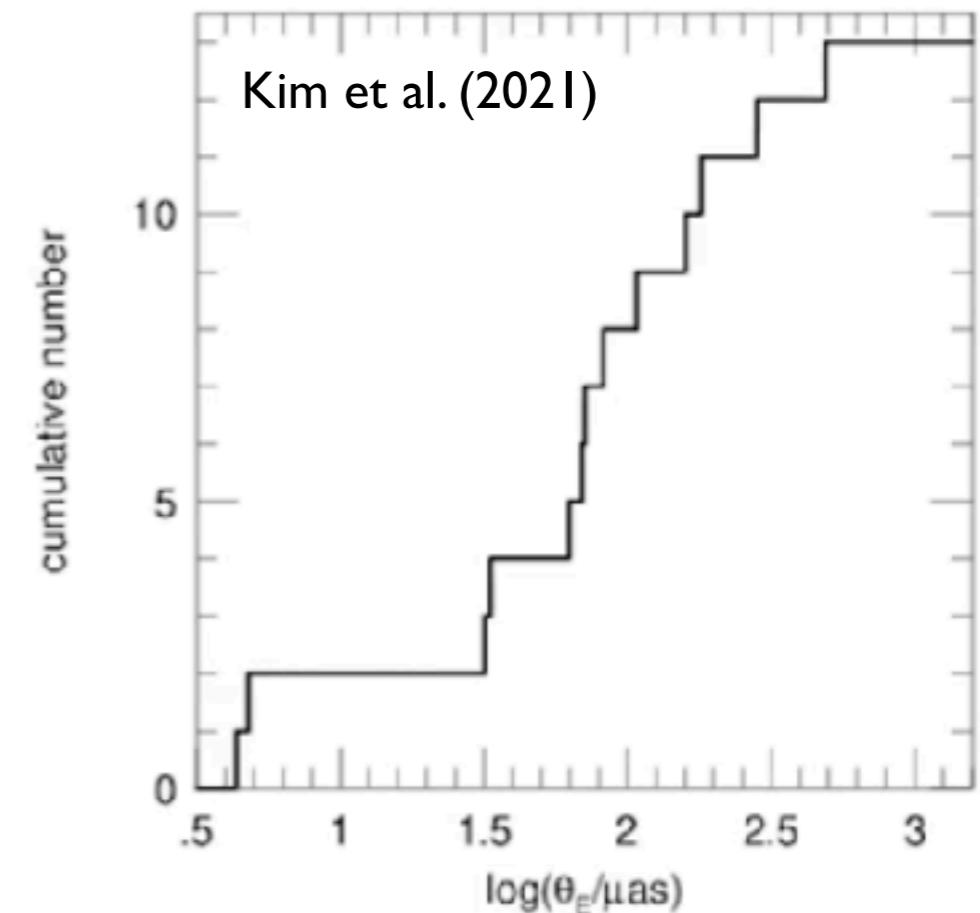


Detección de exoplanetas

- Sistemas binarios: medir q (también múltiples), mayor probabilidad
- eventos de planetas libres (*free floating, rogue*)



6 eventos de planetas libres
con efectos de funte finita



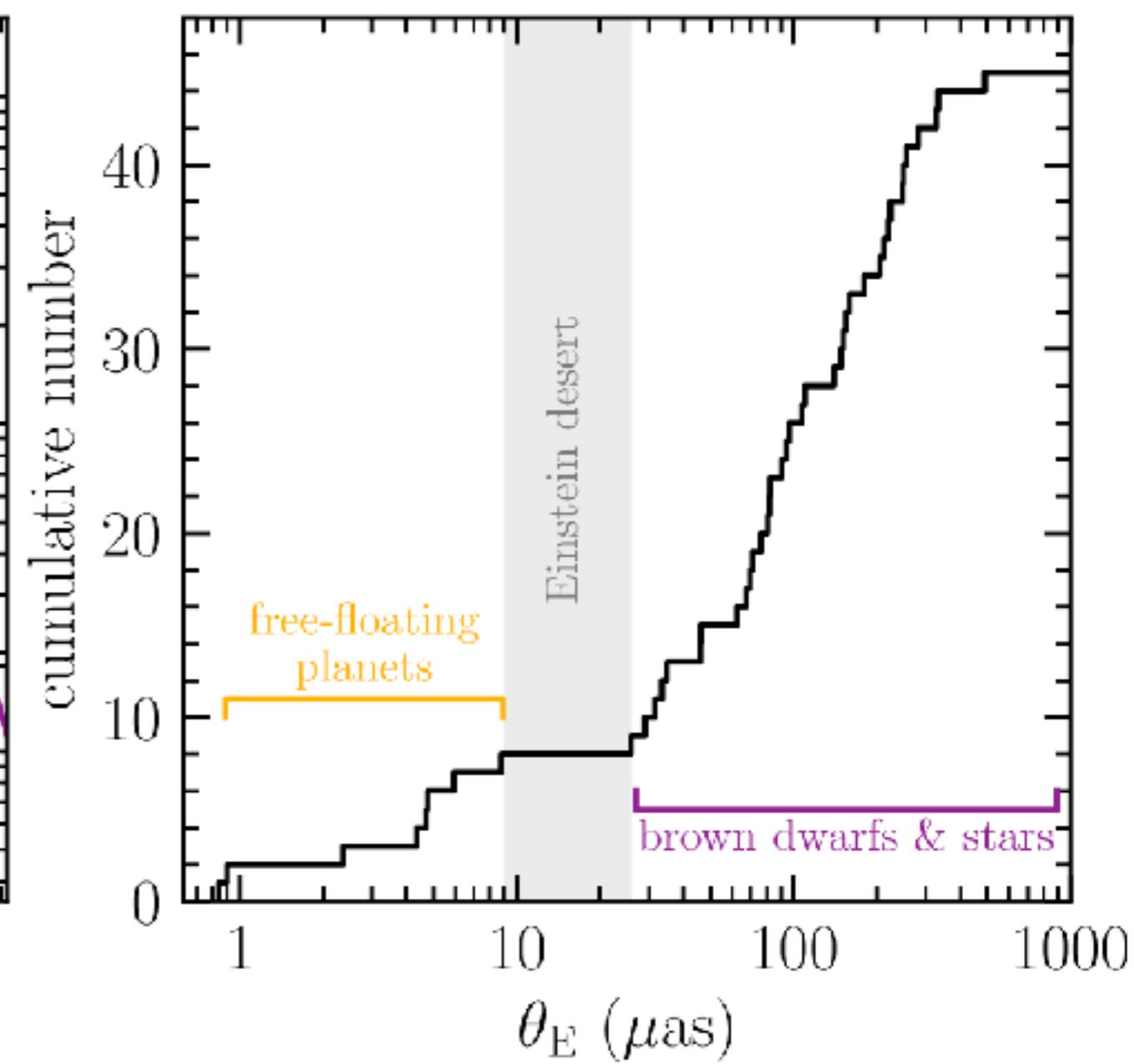
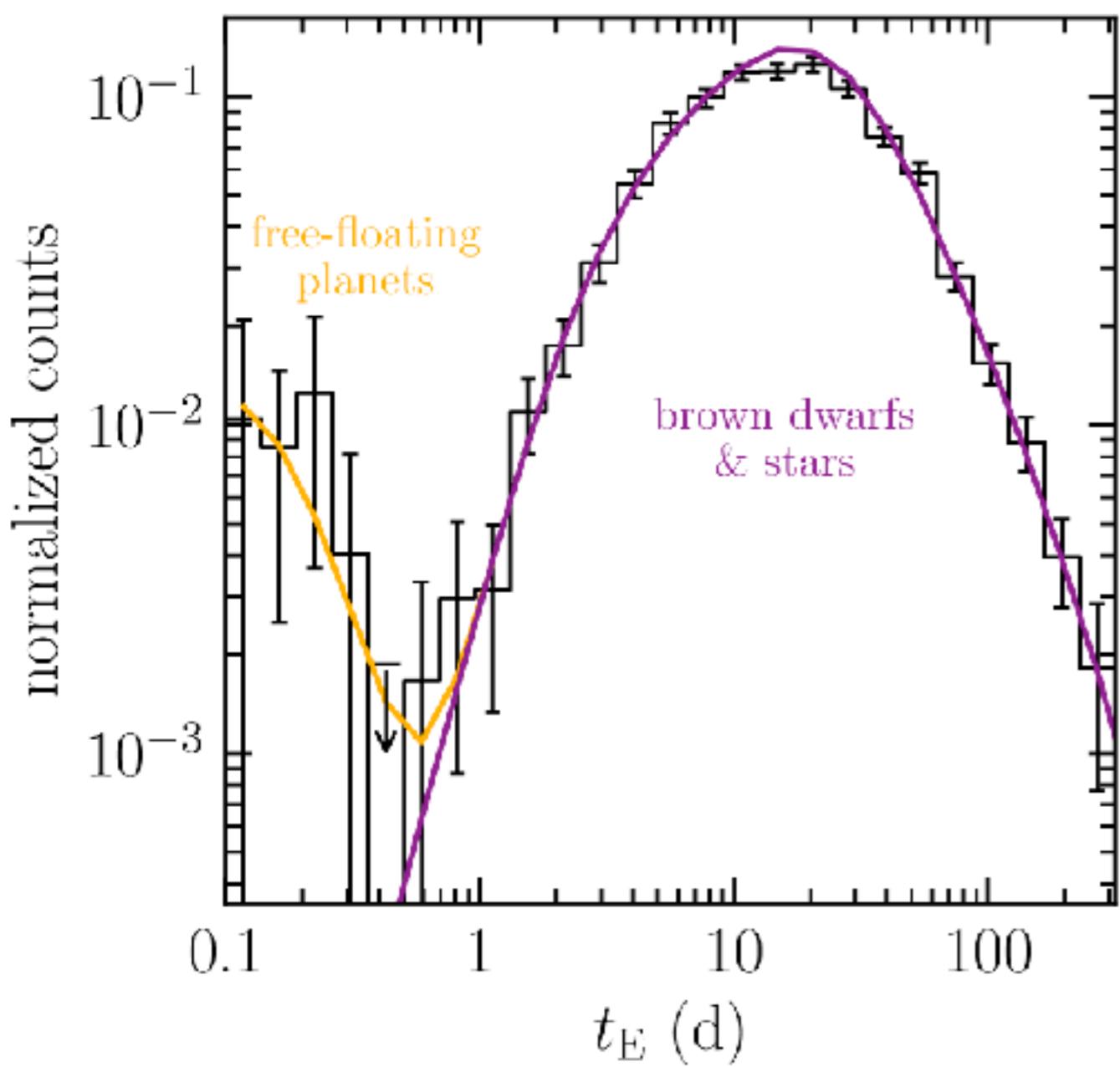
Se observa un “desierto de Einstein”
No se detectan eventos en el rango

$$5 \mu\text{as} < \theta_E < 30 \mu\text{as}$$

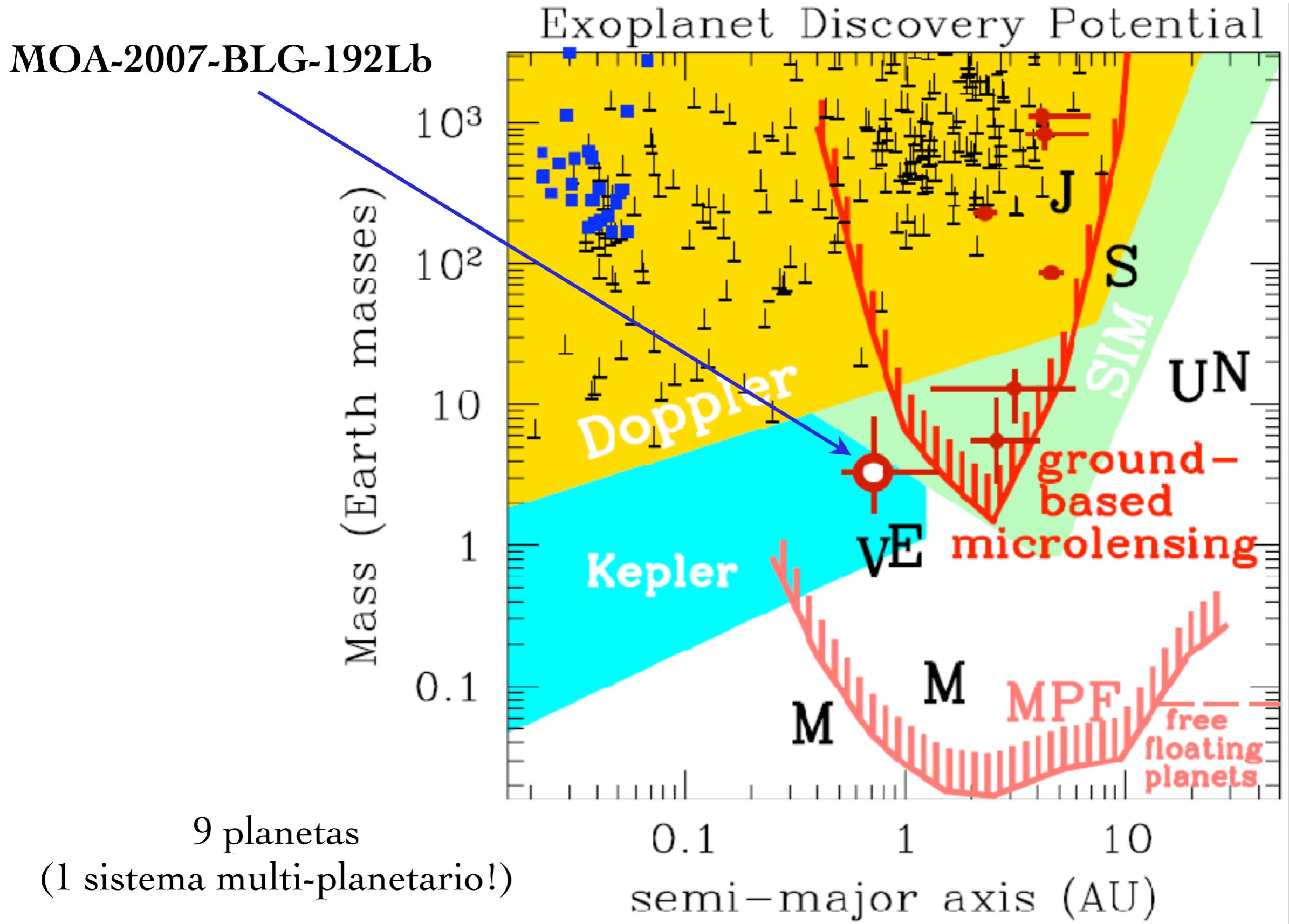
Población de exoplanetas libres

Przemek Mróz and Radosław Poleski

arXiv:2310.07502

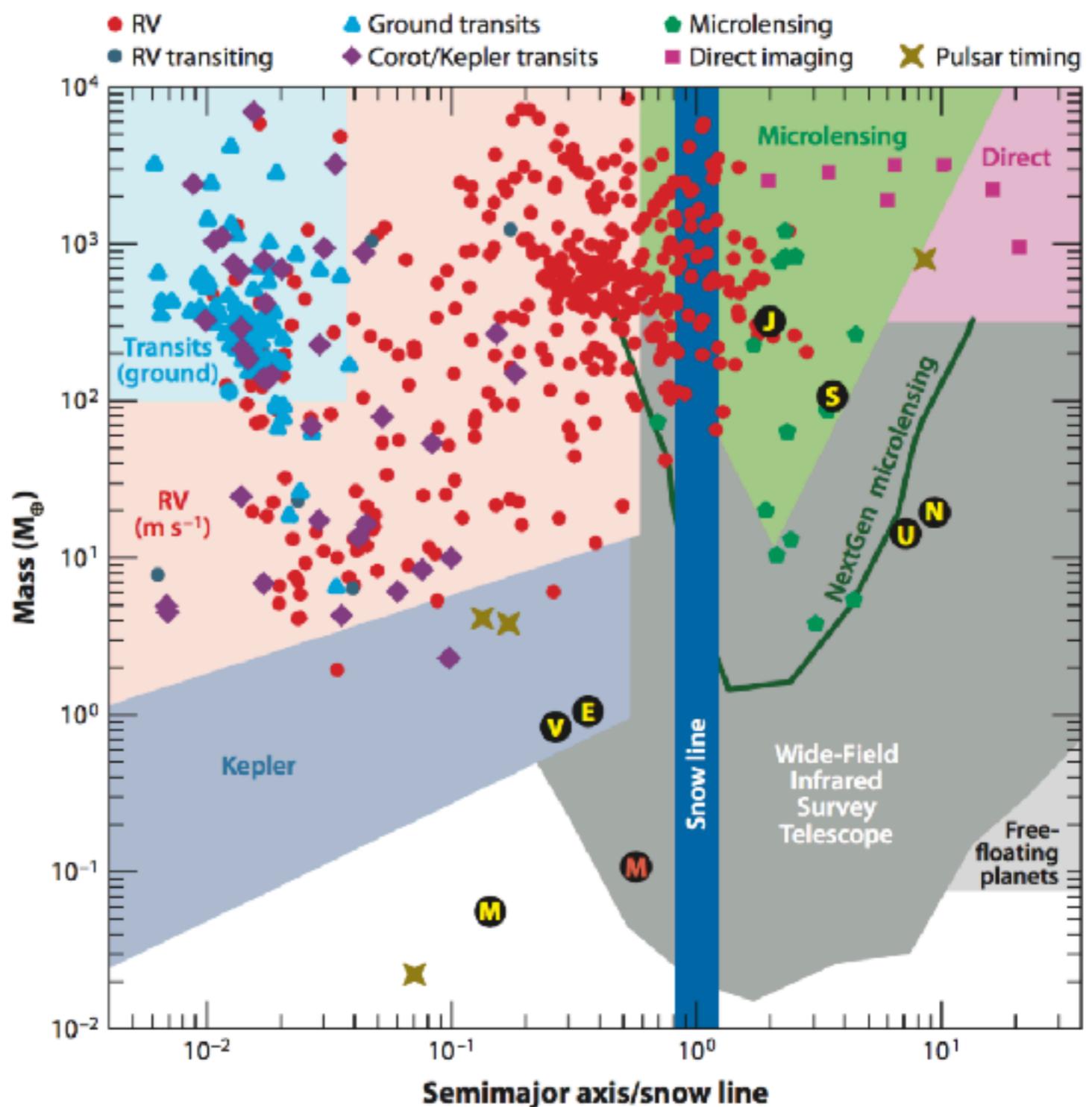


Exoplanetas



ADVANTAGES OF USING MICROLENSING FOR PLANET SEARCHES

- ~35 planets discovered via microlensing so far
- $d_{\min} = 0.66 \text{ AU}$
- bulk of planets at $d \sim 3 \text{ AU}$
- wide range of masses
- complementary technique to others that are most sensitive to planets near their host stars (transits, radial velocity)



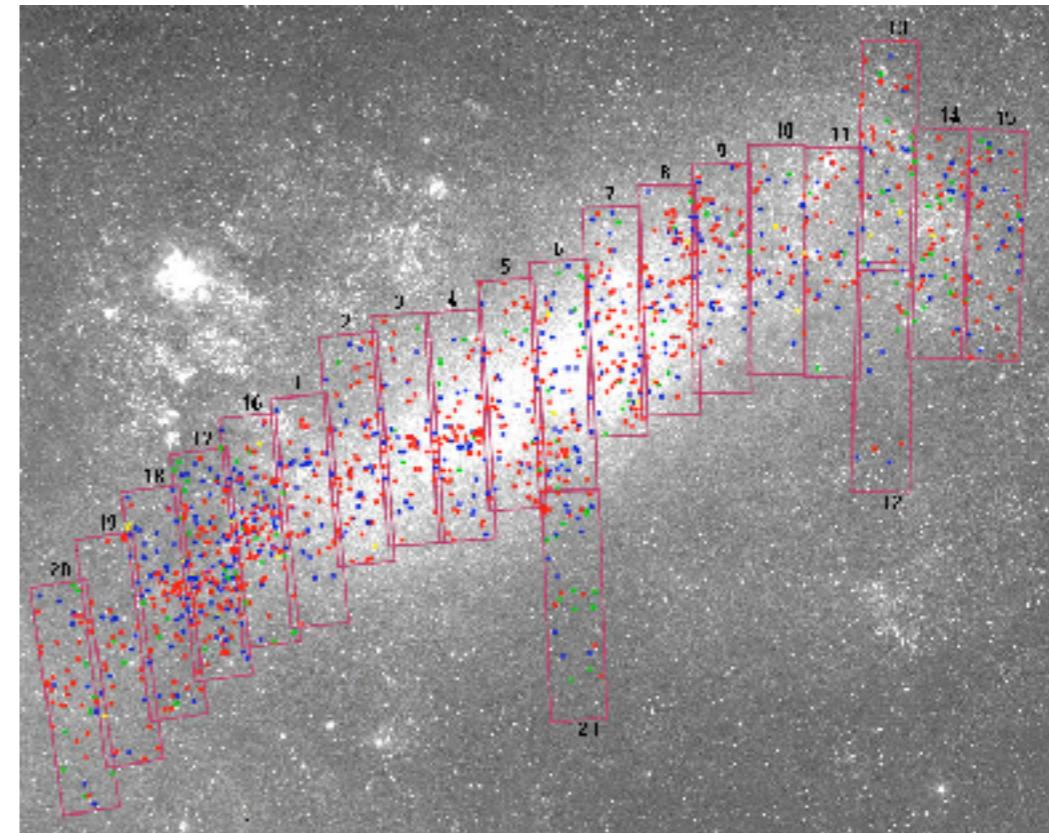
En la práctica

Proyectos de descubierta: fotometría, gran campo de visión

- proyectos dedicados (MACHO, OGLE, EROS...)
- *Time-domain surveys*: ZTF, LSST (+brokers...)

Seguimiento de eventos:

- Fotometría:
mayor cadencia,
profundidad, filtros
- Espectroscopia
- Óptica adaptativa
- Interferometría
- Observaciones del espacio (HST, Gaia, Spitzer...)
- Coordinación: redes globales (e.g. MOP)

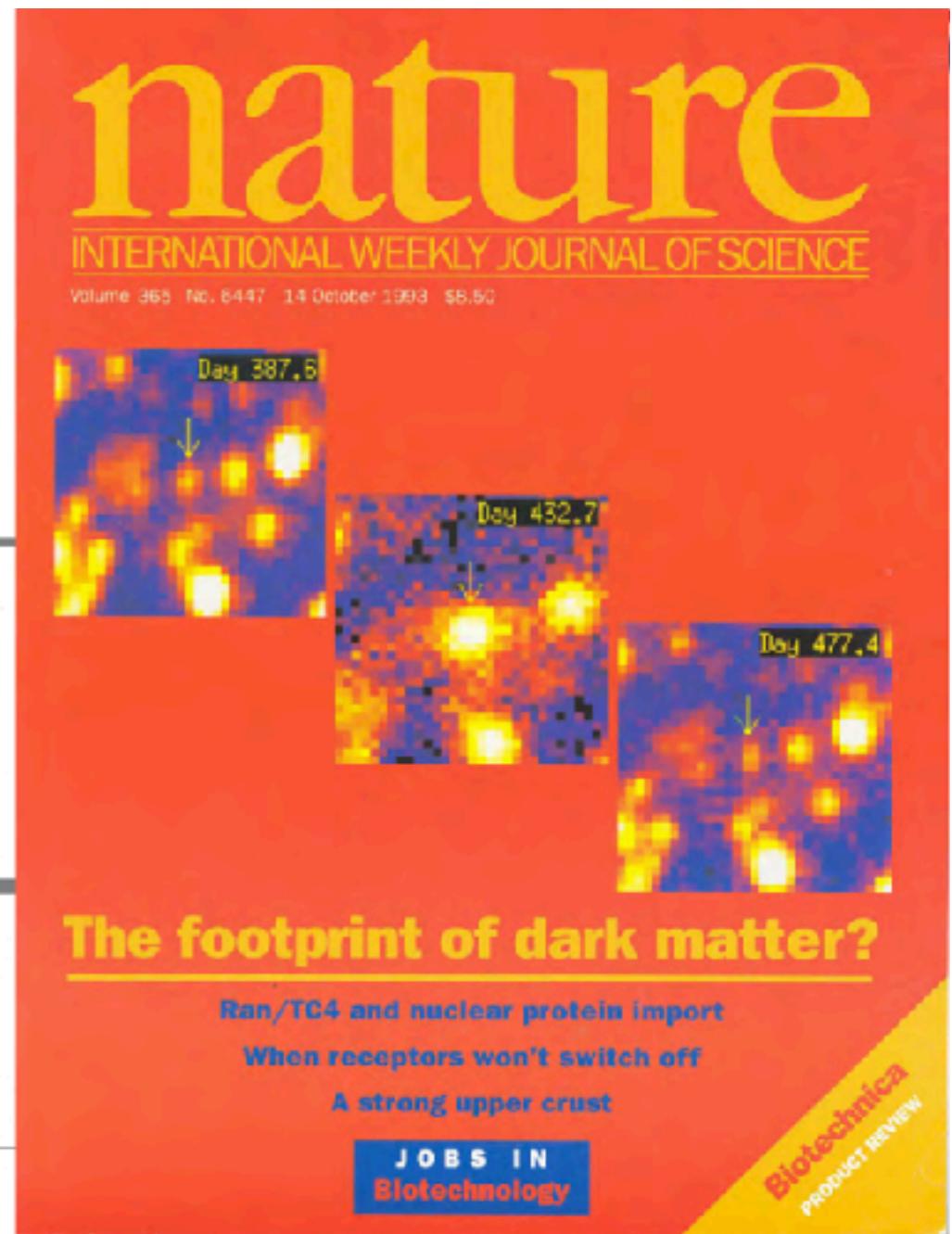
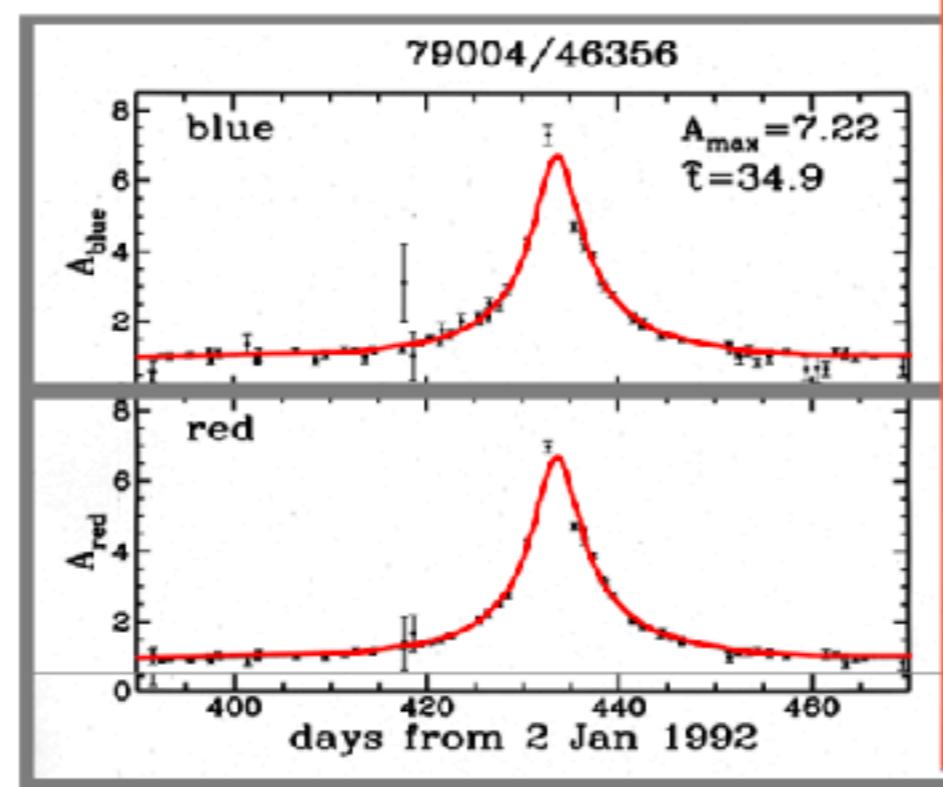


Algunos resultados de microlensing (visión OGLE)

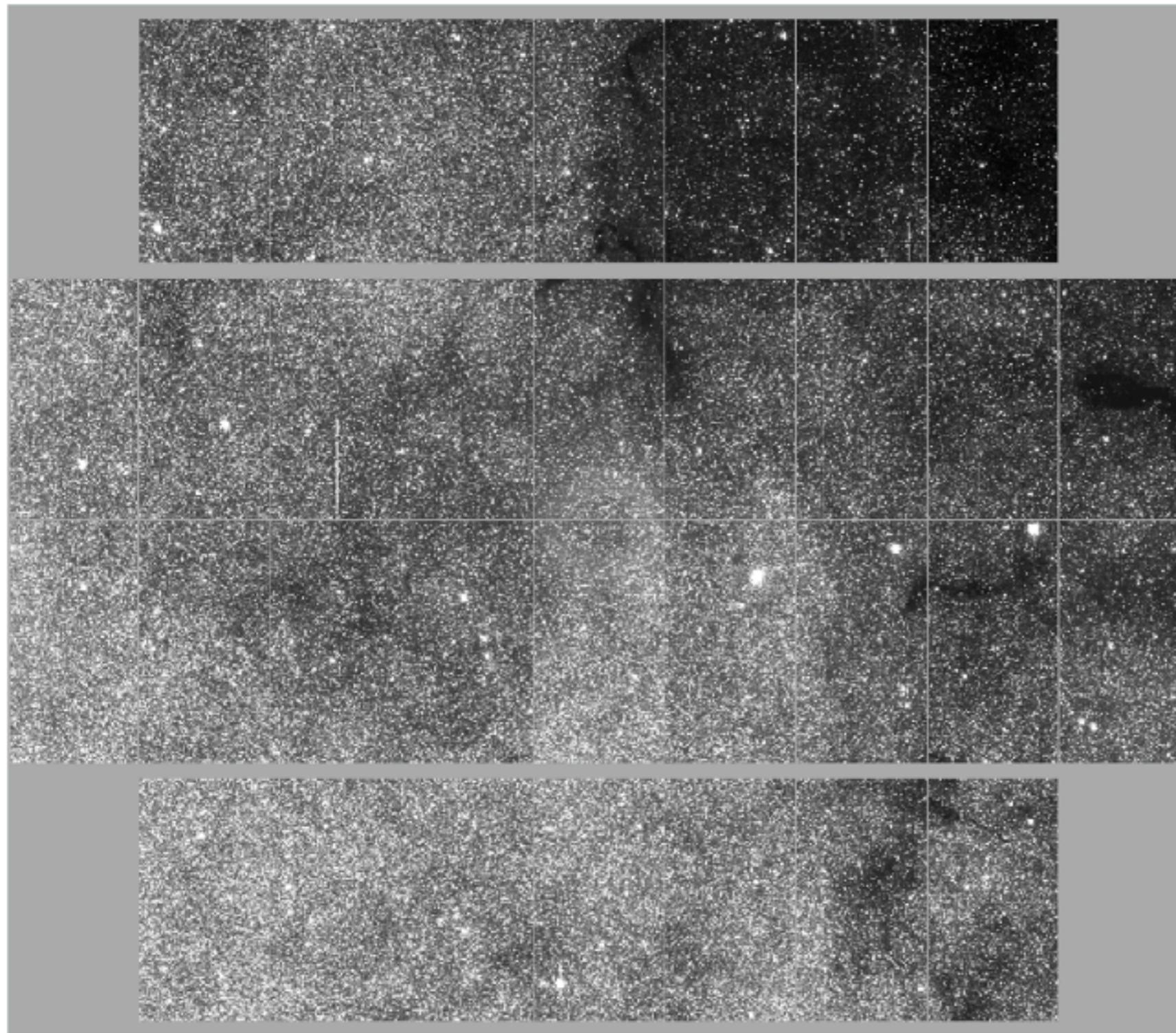
1993: First Microlensing Events

Alcock started the MACHO Project, including me, and the competing French EROS project was started based on a talk given by Alcock. In MACHO, we thought that OGLE was also started in response to discussions between Alcock and Paczyński.

- MACHO: LMC-1 event
 - Nature paper (and cover)
- OGLE: 1st bulge event
 - Acta Astronomica paper
- EROS: 2 microlensing “candidates”
 - (both later retracted)
- Discoveries came in the face of wide-spread skepticism of microlensing

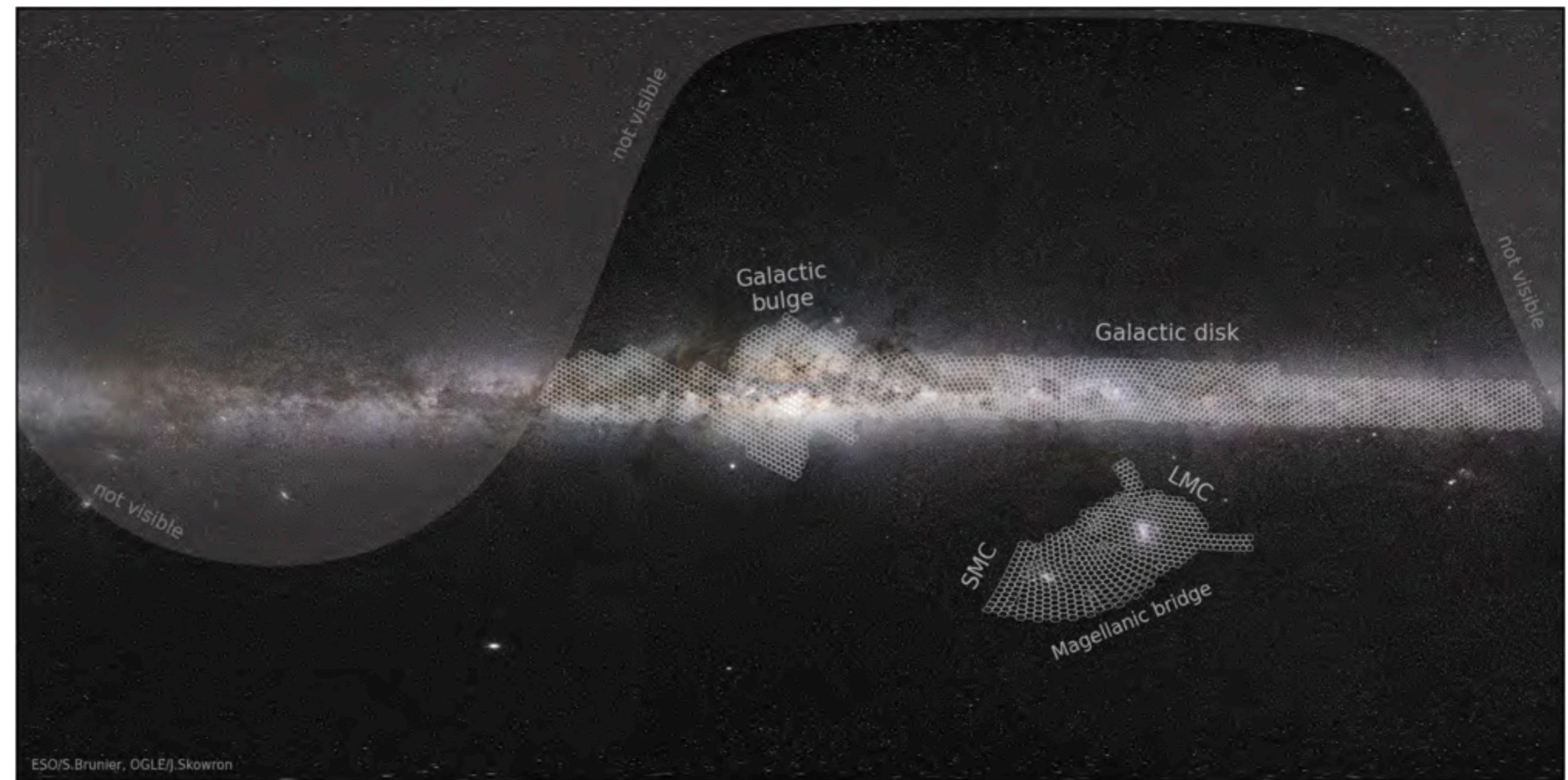


OGLE-IV SKY: 1.4 deg² FOV, I~21mag



*~6 million
stars in
this
picture!*

OGLE SKY

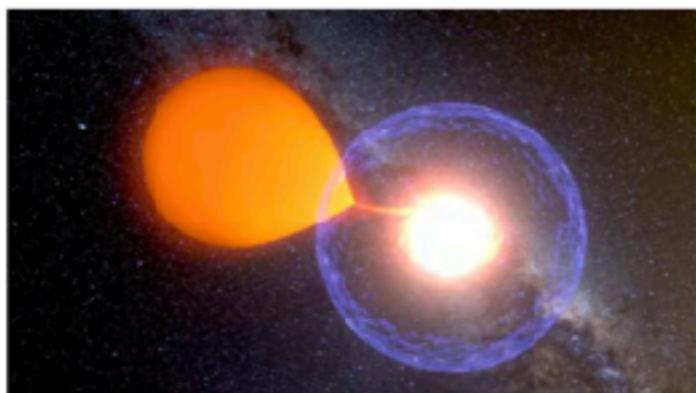
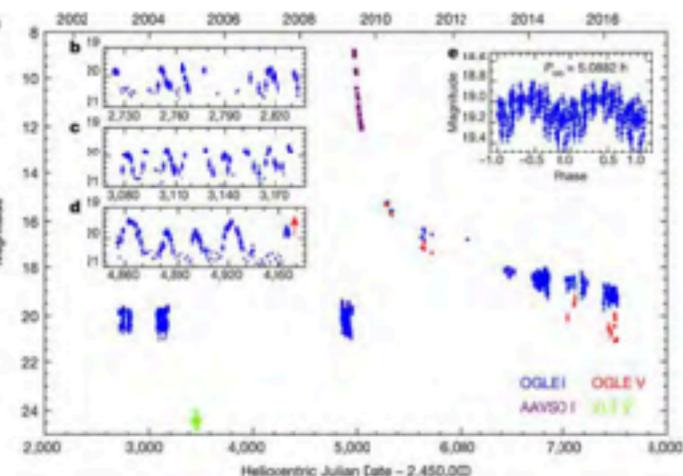


ESO/S.Brunier, OGLE/J.Skowron

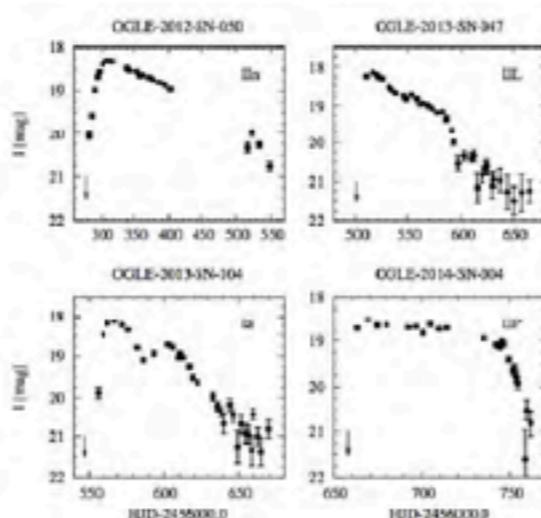
Andrzej Udalski, 26th microlensing conference

OGLE Transients

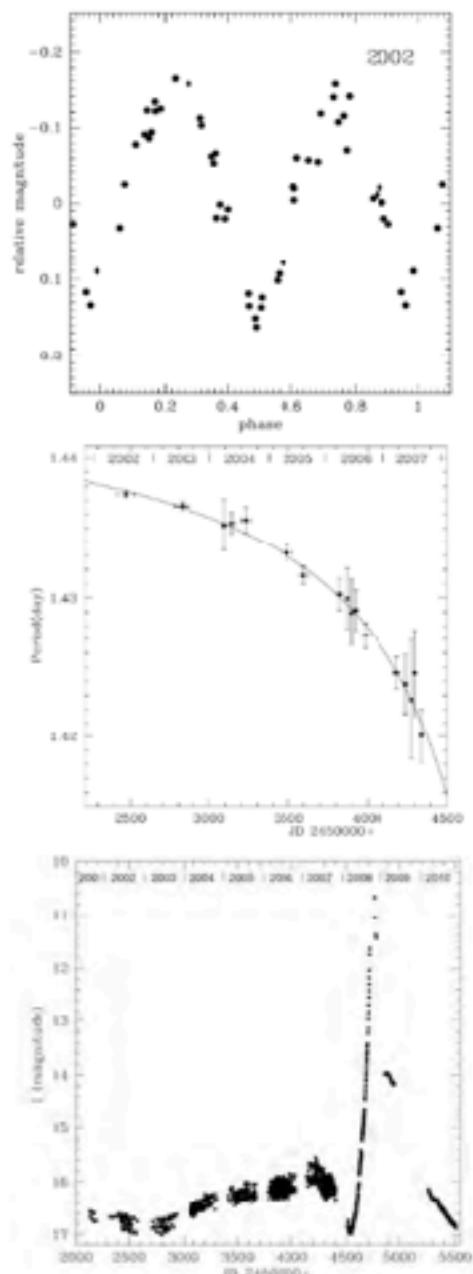
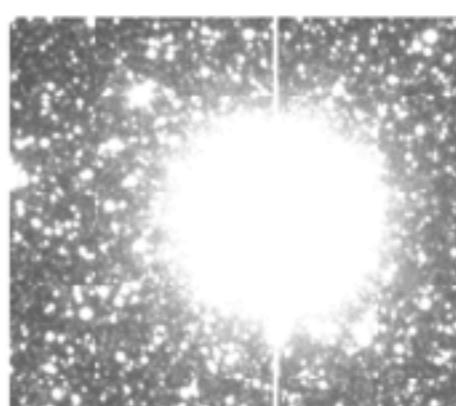
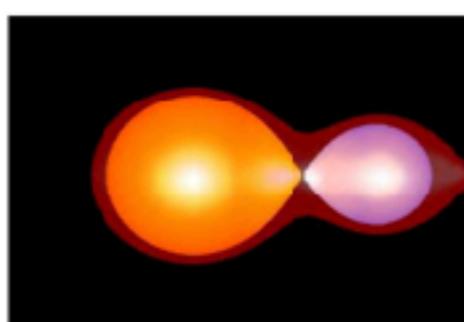
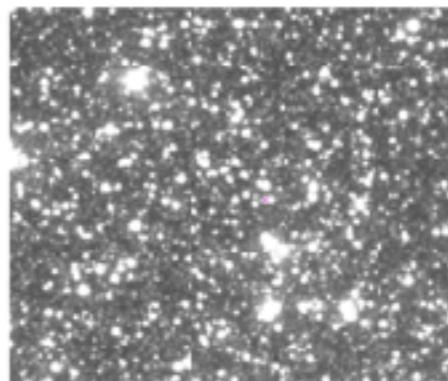
- ~2000 Microlensing Events / Season
- ~150 Novae
- >1000 Dwarf Novae
- >1000 SNe



Novae (**Nova Centauri 2009**)



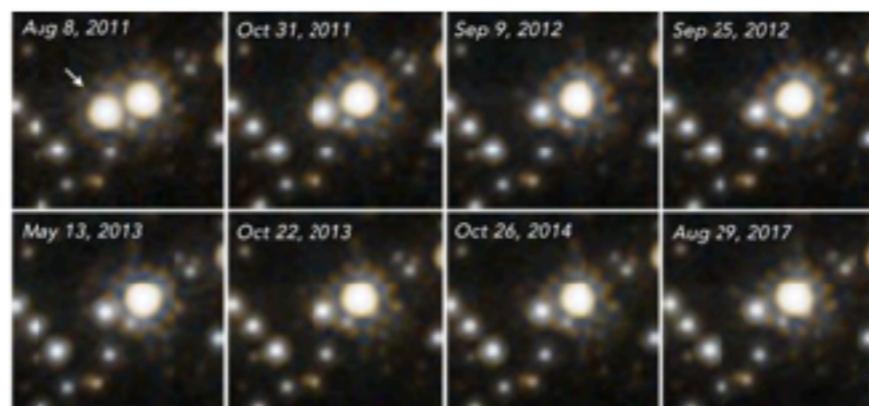
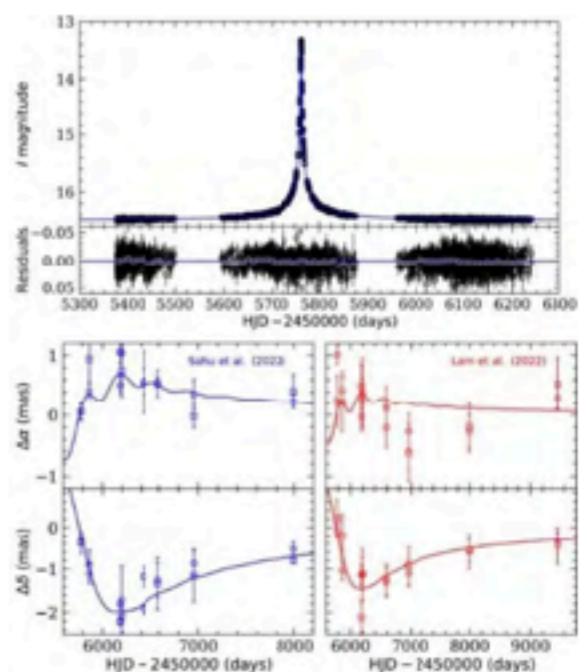
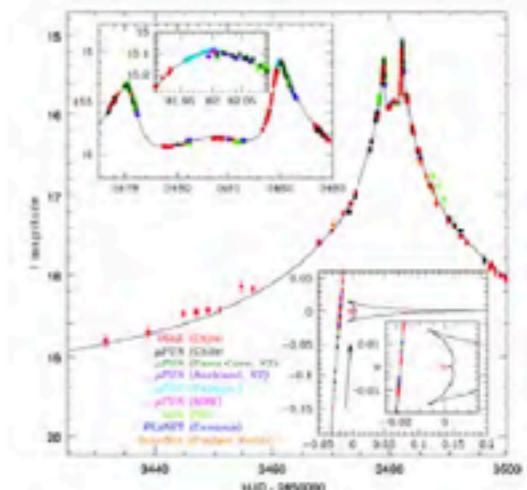
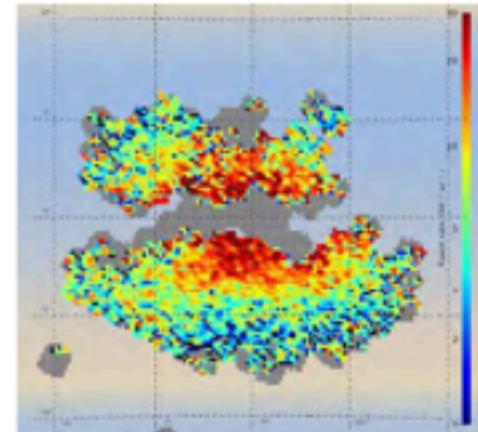
SNe



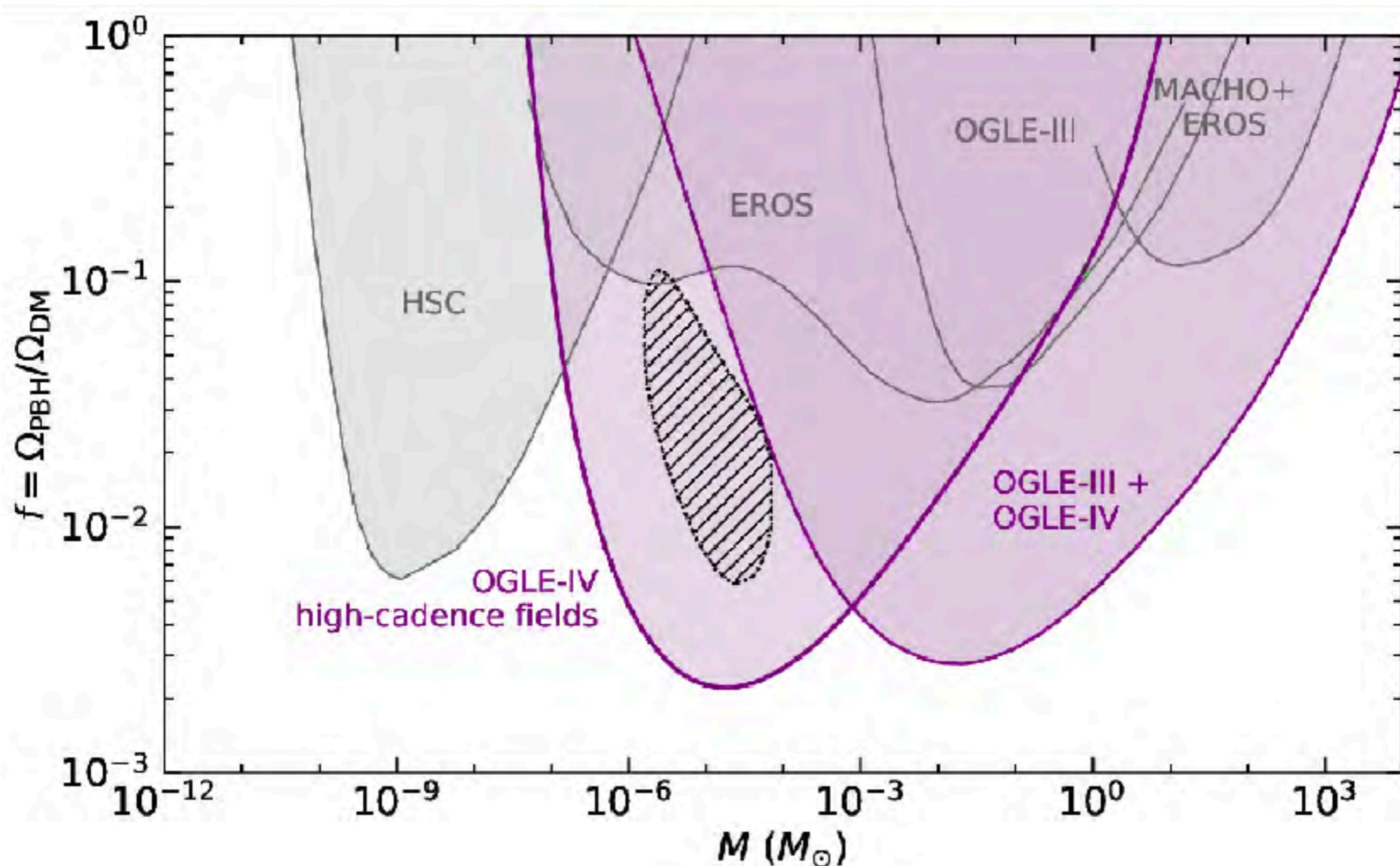
V1309 Sco Red Nova – the first well documented stellar merger

OGLE Microlensing

- **Galactic Structure Studies (1994 – 2020)**
(optical depth: Galactic center & disk)
- **Microlensing Exoplanets (2003 – ...)**
- **Free Floating Black Holes (2022 – ...)**



Límites en la abundancia de Materia Oscura



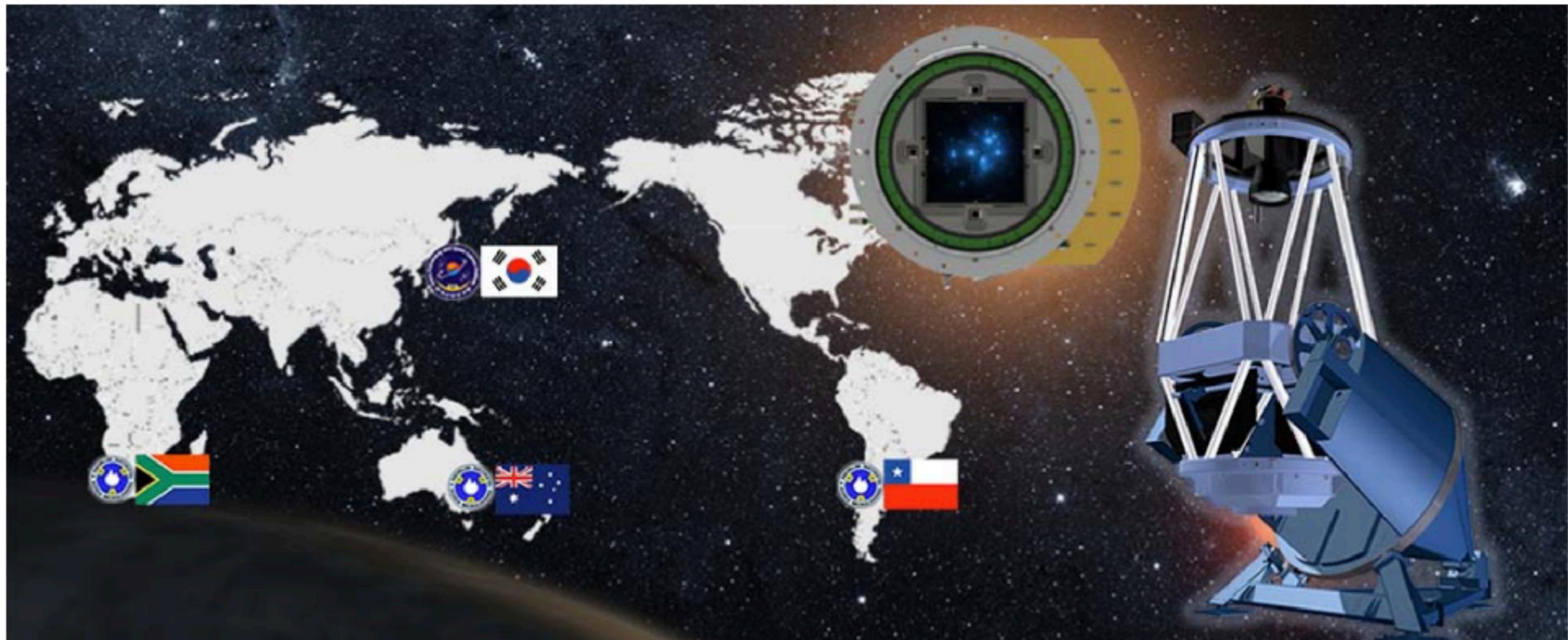
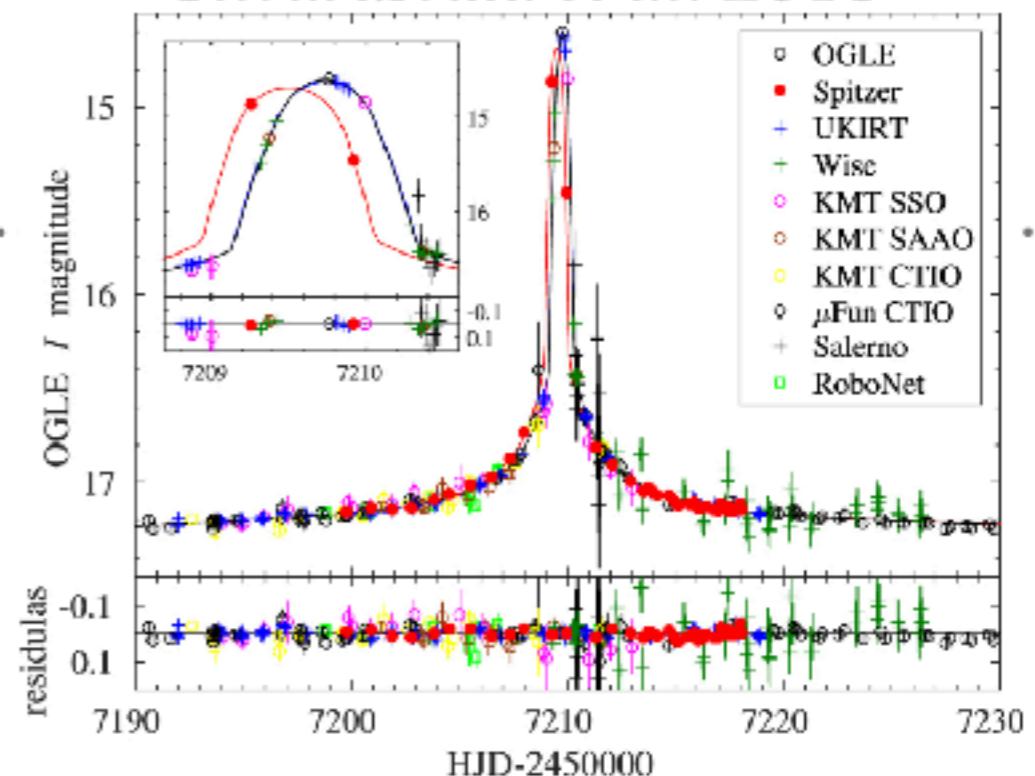
Redes Globales!

Adaptado de Meneghetti, 2016

THE FUTURE OF MICROLENSING

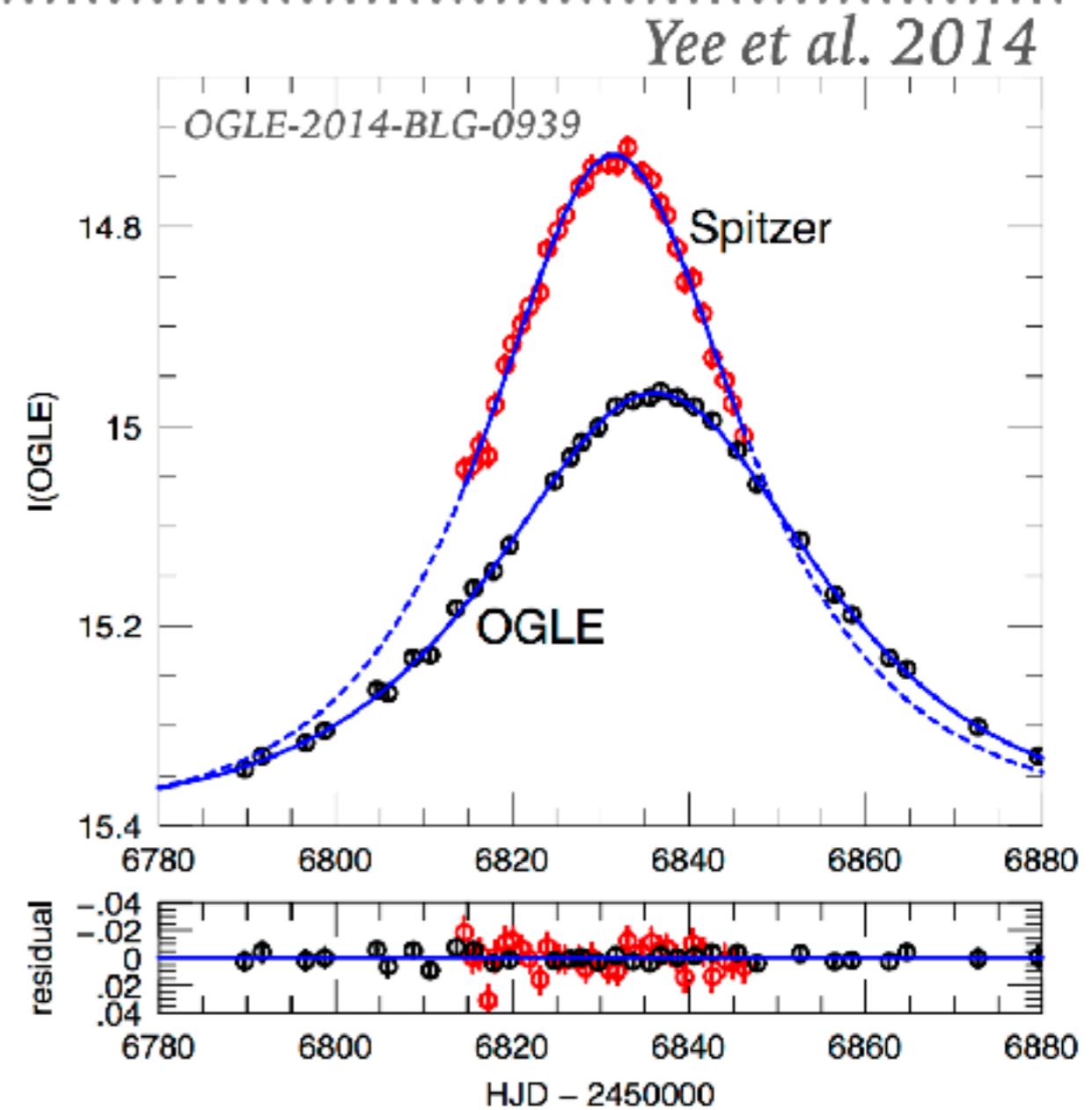
- Korean Microlensing Telescope Network (KMTNet, South Africa, South America, Australia, 3x1.6m, 4 sq. deg.)

Shvartzvald et al. 2015



THE FUTURE OF MICROLENSING

- microlensing searches from space
- possibility to resolve main sequence star lenses
- continuity of observations
- possibility to observe in the NIR-IR where several lenses are brighter
- satellite microlensing parallax
- currently: Spitzer (parallax measurements of 21 single-lens events)
- in 5-10 years: WFIRST, Euclid



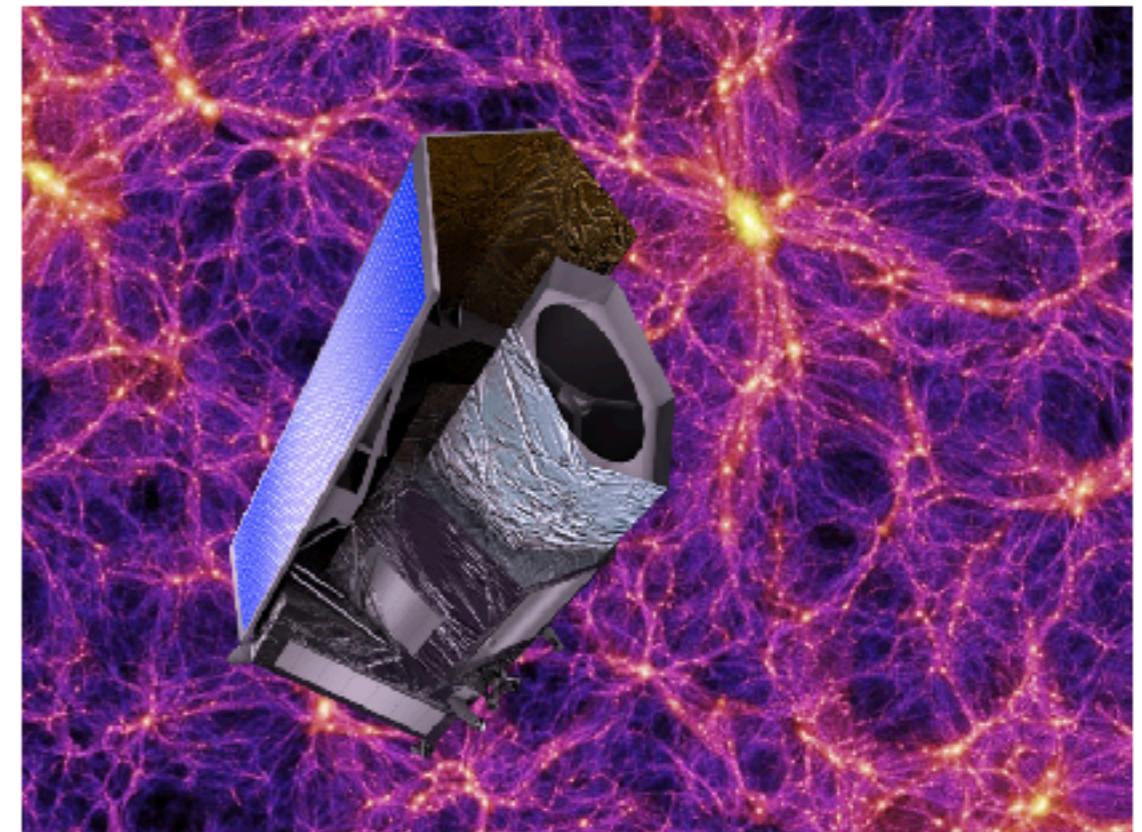
Microlentes con Gaia!!

THE FUTURE OF MICROLENSING: EUCLID

- Lanzado en 2023

1.2m telescope with 0.5 sq. deg FOV;
riz (VIS, 0.1"), Y, J,H (NIR,
0.3")

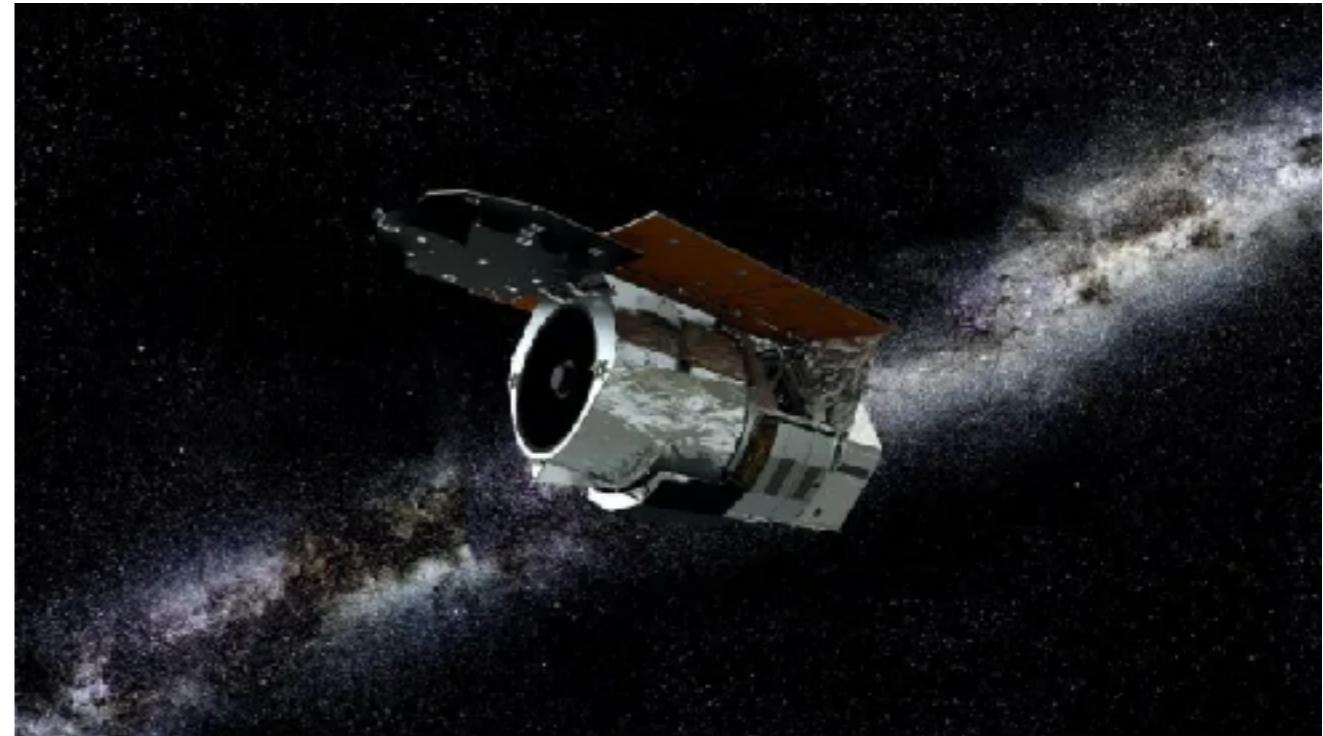
- primary science: cosmology
(growth of the cosmic
structures, dark energy)
- likely, it will perform secondary
surveys for other science goals:
planet searches via microlensing
- limited view over the galactic
bulge: can observe for about a
month twice a year



- expected performance:
 - Cold earths and neptunes: 35 planets/month
 - Free-floating planets: 15 planets/month

THE FUTURE OF MICROLENSING: WFIRST

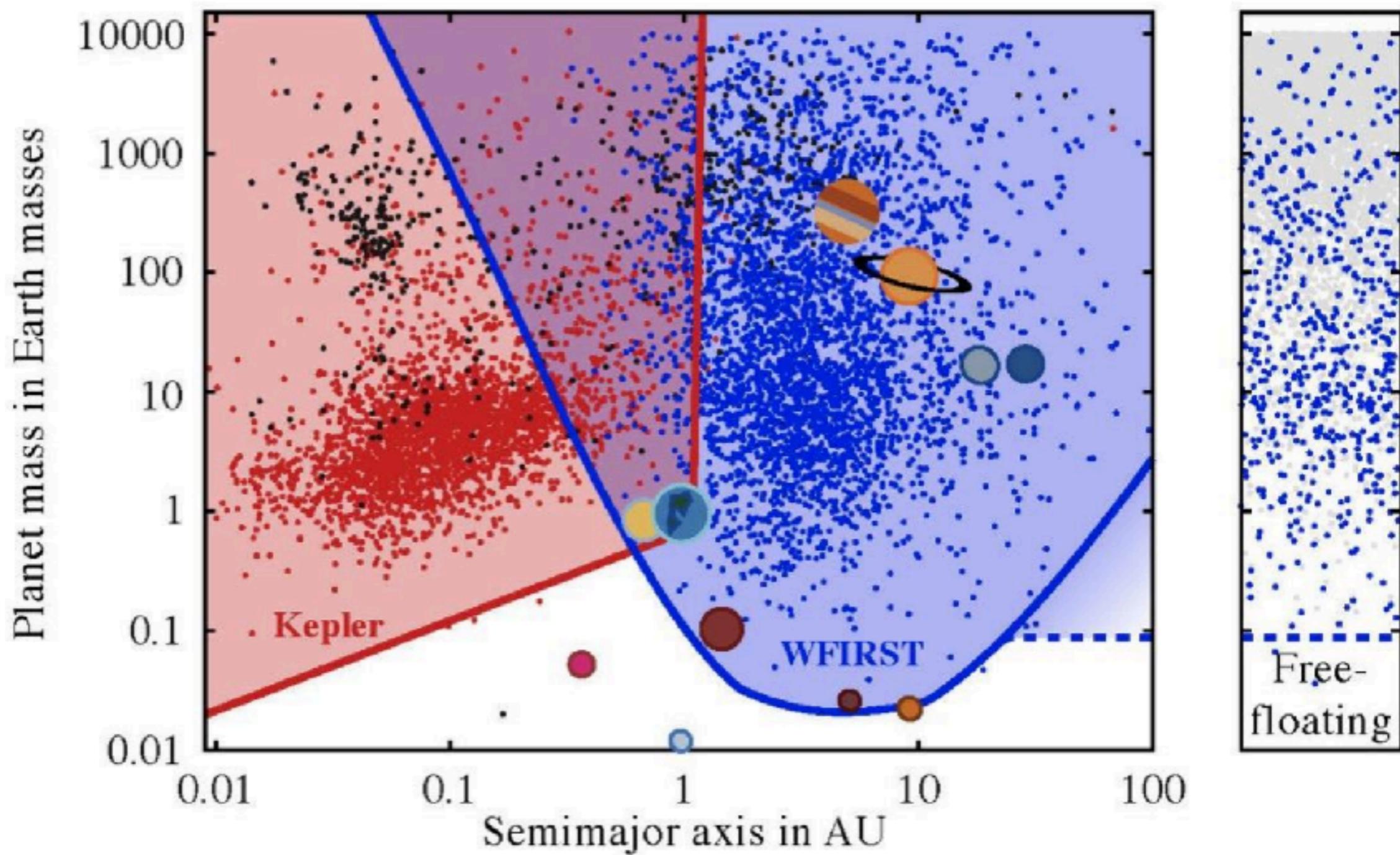
- Roman (WFIRST), exp 2027: 2.4m telescope with 0.28 sq. deg FOV; NIR, 0.76-2.0 μm , $\sim 0.2''$ res.
- primary science: cosmology and planets
- NIR imaging for microlensing
- Chronograph for characterizing the planets and their atmospheres (via direct imaging)
- more flexible telescope: will perform several surveys and will host a GO program



Cadencia de 15 minutos por 72 días!

- expected performance (5 years survey)
- 3250 bound exoplanets in the range 0.1-1000 Earth mass, 0.1-40 AU
- 2080 free-floating planets

Detección de planetas con Roman



Telescopio Vera Rubin y su LSST

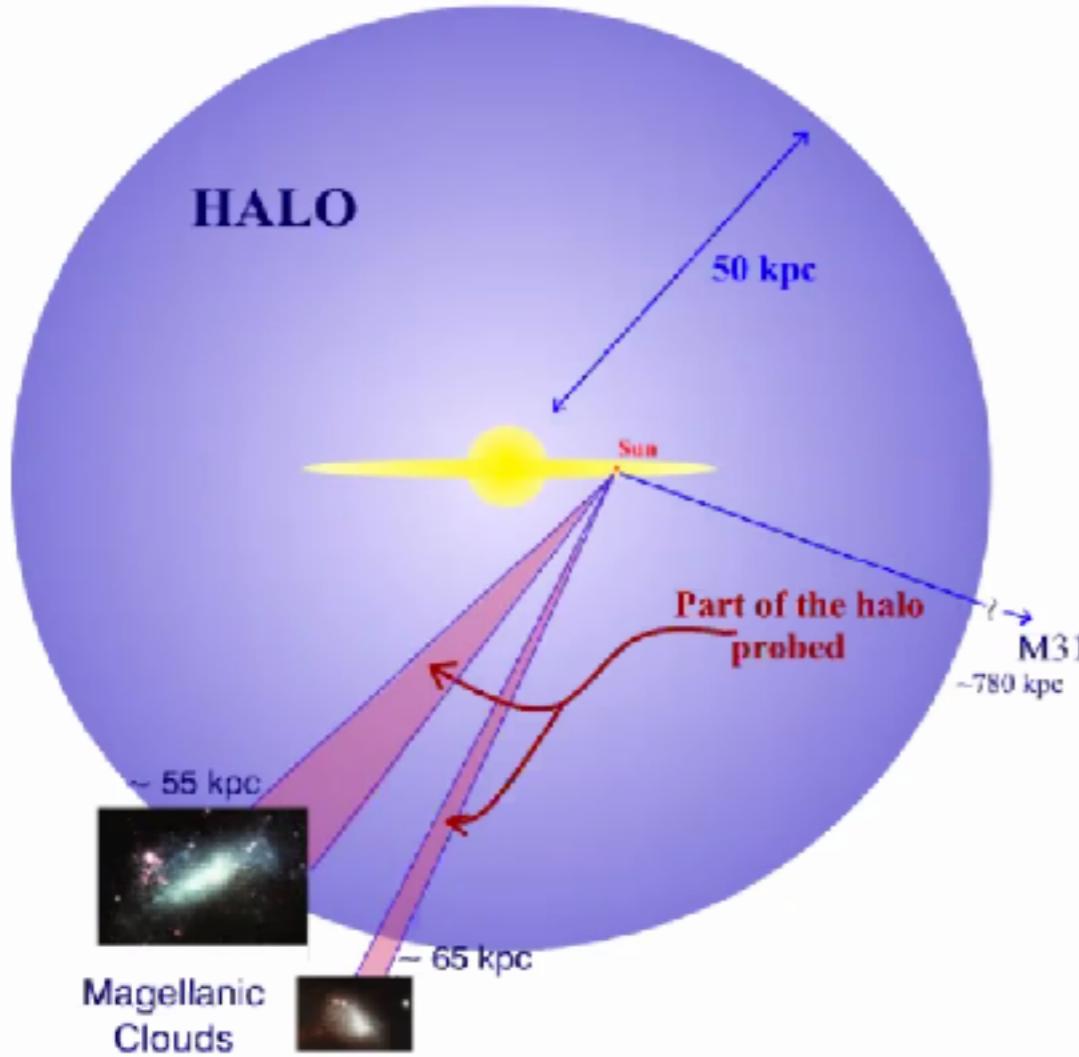
Estado del arte de la astronomía por imágenes con *seeing* natural

- Observatorio completamente nuevo en Cerro Pachón, Chile (con Gemini y SOAR)
- Gran apertura, luminosidad y campo de visión: espejo primario de 8.4 m, nuevo diseño óptico $f/1.2$
- Cámara de 10 sq-deg en 3.2 Gpx (mayor cámara del mundo)
- **CCDs gruesas (sensible al rojo) y de lectura rápida (2s!)**
- Habilidad de exposiciones cortas, totalmente automatizado
- Instrumento **ideal y único para relevamientos**
- **No solo el próximo paso: nueva dimensión temporal!**
- 1 millón de alertas por noche!
- Inicio del *survey* con la cámara completa: 2024
- Contribución *in-kind* del IATE/AOC/UNC: membresía en LSST!



Microlentes con Vera Rubin LSST

Adaptado de Tristan Blaineau



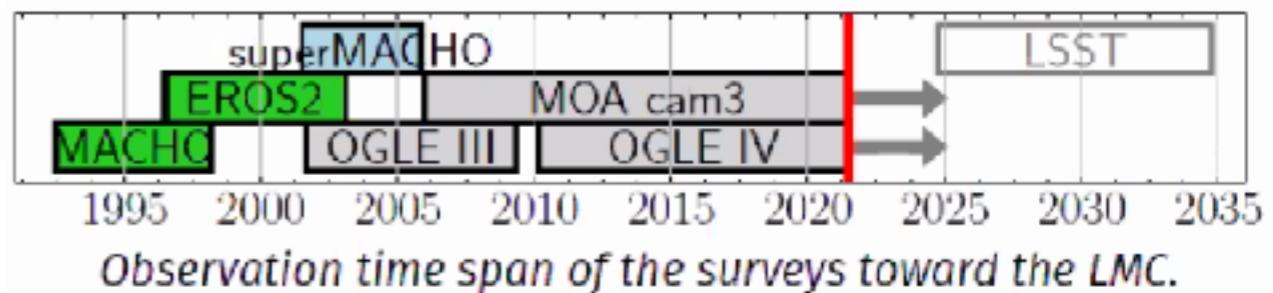
+ Efecto fuerte por galáxias y cúmulos, lensing de supernovas, kilonovas, ondas gravitacionales, microlensing de cúasares, etc.

Hasta el presente:

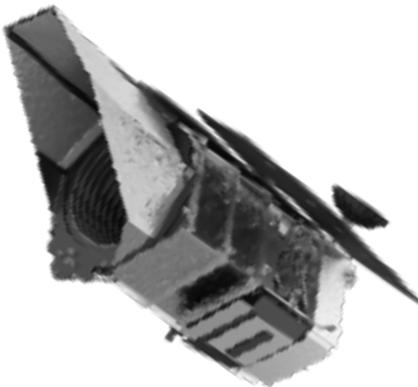
- Búsqueda restringida a regiones con mayor densidad de estrellas de fondo: nubes de Magallanes, M31, bulbo de nuestra galaxia
- Uso de telescopios pequeños ($\sim 1\text{m}$)

Con LSST:

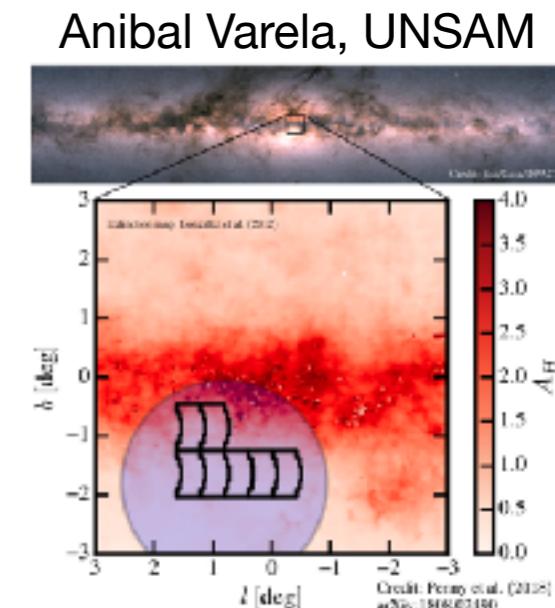
- Búsqueda en toda la esfera celeste! (particular atención al disco de la galaxia y a cúmulos globulares)
- Telescopio moderno de gran apertura efectiva (6,67 m) en un sitio excelente!
- Amplia gama de cadencias accesibles: amplio rango de masa!



Microlensing con Rubin y Sinergía con Roman



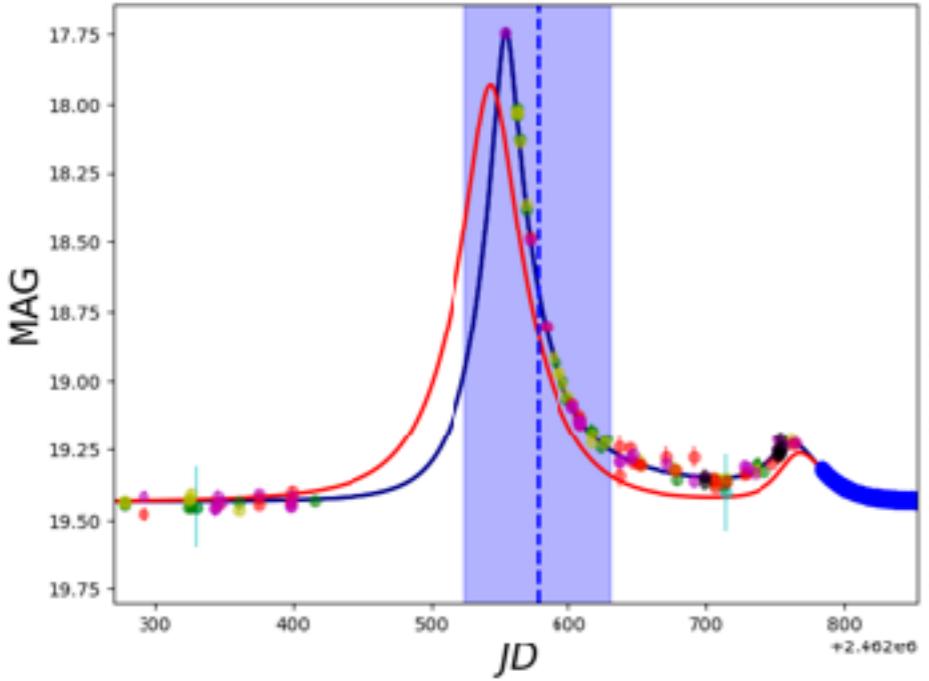
- Planetas flotantes, lentes binarias, agujeros negros
- Distribución realista de fuentes con movimientos propios
- Incluye modelos de errores y cadencias de ambos relevamientos
- Incluye efectos de tamaño finito y paralaje(s)
- Ajuste extenso de curvas de luz con pyLima



Event: 8253 - Roman and RR fits

Red: Roman

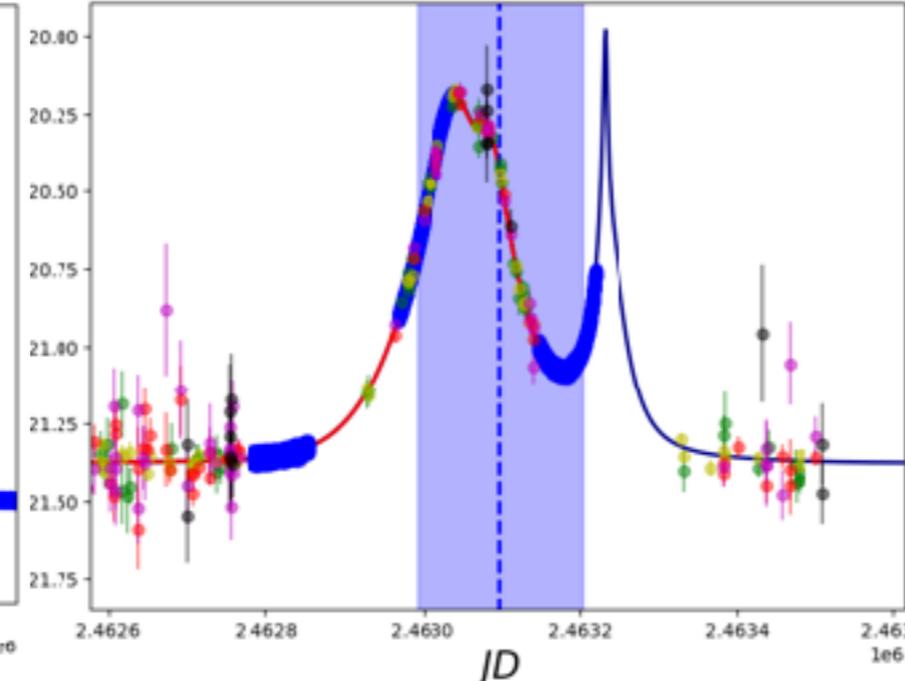
Blue:Roman+Rubin



Event: 14 - Roman and RR fits

Red: Roman

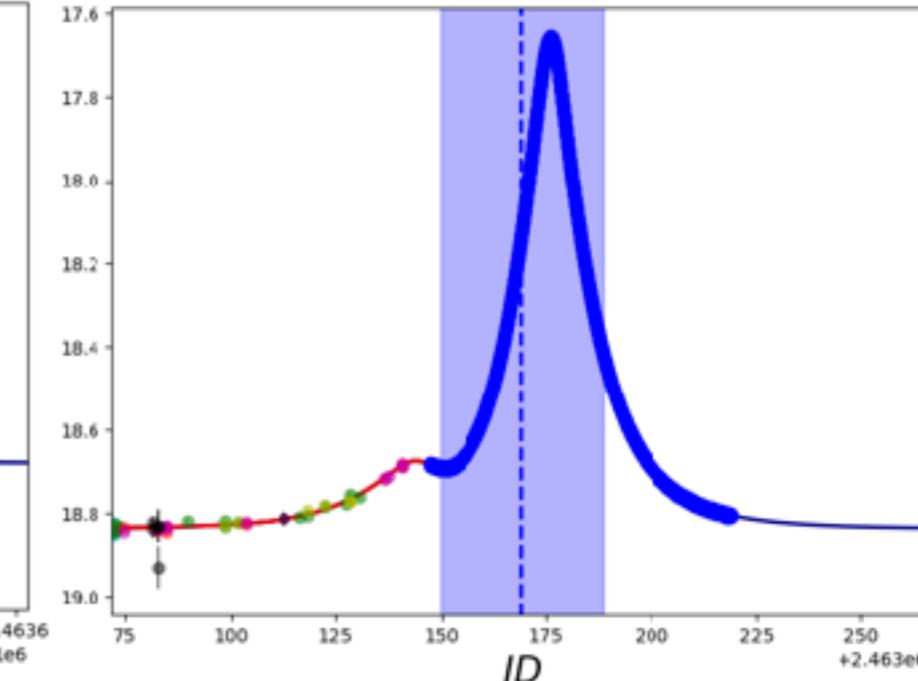
Blue:Roman+Rubin



Event: 214 - Roman and RR fits

Red: Roman

Blue:Roman+Rubin



Case for Rubin-Roman coordination

arXiv:2306.13792

- Proporcionar una línea de base para Roman
- Rellenar los vacíos en las observaciones de Roman
- Determinar el paralaje para una fracción de los eventos

Y CASLEO??

Un telescopio de 2.15 m ya fue....

Rubin/LSST

- Diámetro efectivo: 6.67 m
- Tiempo de exposición: 30s (2x15s), en 6 filtros (u, g, r, i, z, y)



Jorge Sahade



- Diámetro efectivo: 2.06 m
- Tiempo de exposición para profundidad equivalente a LSST: ~ 300 s
- 6 filtros de LSST en 30 min! (mientras LSST observa en noches distintas)
- Match perfecto para LSST, usando pequeña fracción del tiempo
- Propuesta de una camera sensible al rojo: *skipper* CCDs/Fermilab

HSH

- buen match para observaciones actuales de *microlensing*

Microlensing desde CALEO

Andrea Buccino, Mariano Dominguez, Juan Luna, Luis Mammana, Martin Makler, Damián Mast,
Karen Nowogrodzki, Rachel Street, Anibal Varela

Máquinas de descubrimiento: fotometría de campo amplio y baja cadencia (Rubin, ZTF, OGLE)
Necesitan seguimiento: mayor cadencia, anomalías, espectroscopía (para deconvolución y
caracterización)



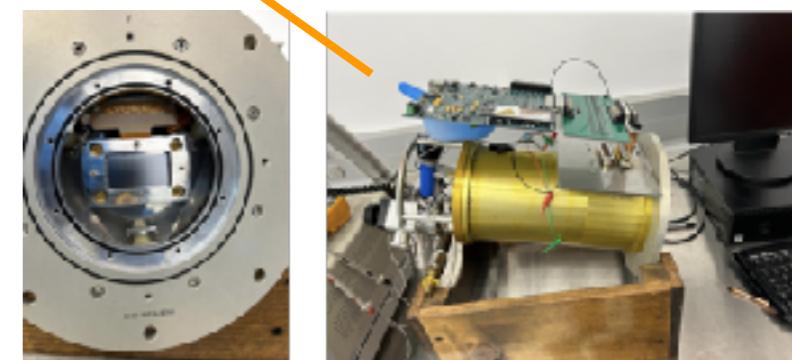
Seleccionar sistemas usando MOP (nuevas características para nuestro programa), red Omega

Fotometría con HSH (0.6m), espectros ToO con JS (2.15m)

Futuro: filtro para FINK (Godines, Nowogrodzki, et al.),
también ALeRCE

Bonus: nueva cámara Skipper-CCD para JS (Fermilab)

Sensibilidad en el rojo, 16 canales (lectura rápida), se
espera en el cielo: ¡2024/2!



Microlensing online platform

MOP Home Targets ▾ Alerts Active Obs Data Users Martin Makler Logout

OGLE-2024-BLG-0669

RA: 18:20:21.390 Dec: -18:16:09.80
l: 13.1964° b: -1.6435°
Outside HCZ

No TNS infomation

Current time: 2024-09-08 22:53:30 UTC, JD=2460562.454

Update Delete

Alive	True
Observing mode	No
TAP priority	2.33174±0.26454
TAP priority longtE	8.78388±0.74256
Interferometry candidate	False
t_0 [HJD]	2460523.35435±0.29478
u_0	0.3056±0.03786
t_E [days]	65.95088±5.56917
Mag now	15.59940871236068
Latest data HJD	2460544.6938
Latest data UTC	2024-08-22 04:39:04
Last fit JD	2460550.9388157306
Classification	Microlensing PSPL
Category	Microlensing stellar/planet

Observe Observations Manage Data Manage Groups Photometry Spectroscopy pyLIMA Results

Interferometry Gaia Comments

Photometry

● OGLE_L
● r_ZTF
● g_ZTF
— Model

Mag

JD: 2460454 (2024-09-08)

JD: 2460562.454 (2024-09-09)