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The MACHO Project: A historical perspective

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GRAVITATIONAL MICROLENSING BY THE GALACTIC HALO

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ABSTRACT

The massive halo of our Galaxy has an optical depth to gravitational microlensing $\tau \approx 10^{-6}$. If the halo is made of objects more massive than $\sim 10^{-8}\ M_\odot$, then any star in a nearby galaxy has a probability of 10^{-6} to be strongly microlensed at any time. The lensing events last ~ 2 hr if a typical "dark halo" object has a mass of $10^{-6}\ M_\odot$, and they last ~ 2 yr for objects of $100\ M_\odot$. Monitoring the brightness of a few million stars in the Magellanic Clouds over a time scale between 2 hr and 2 yr may lead to a discovery of "dark halo" objects in the mass range 10^{-6}–$10^2\ M_\odot$ or it may put strong upper limits on the number of such objects.
Subject headings: galaxies: Magellanic Clouds — gravitation — stars: variables

I. INTRODUCTION

The possibility of gravitational microlensing by stars in distant galaxies has been suggested and studied by many authors (Liebes 1964; Refsdal 1964; Chang and Refsdal 1979, 1984; Gott 1981, Young 1981; Vietri and Ostriker 1983; Nityananda and Ostriker 1984; Subramanian, Chitre, and Narasimaha 1985; Paczyński 1985). Unfortunately, in most cases the time scale of intensity changes of a distant quasar subject to microlensing by a solar mass star located at a cosmological distance is very long, and therefore it is not likely to be observed unless many lensed quasars are monitored for many years. If we want to make the time scale much shorter, we have to consider stars which are much closer to us, such as those in the halo of our own Galaxy. The price we pay for the shortened time scale is rather high: optical depth to gravitational lensing on known stars in the halo of our Galaxy is very small. However, most of the halo mass is believed to be, not in stars, but in some unknown form of "dark matter;" possibly black holes, Jupiters, snowballs, or some elementary particles. If the "dark matter" is made of massive objects, then it may give rise to gravitational lensing with an optical depth of $\sim 10^{-6}$, which is substantially higher than the optical depth for the known halo stars.

The aim of this paper is to present a simple model of microlensing by massive objects that might be present in the halo of our Galaxy. We calculate the probability of the effect, and we discuss some possible observations that may lead to a discovery of the effect or put interesting limits on the masses of individual objects that contribute to the mass of the halo.

II. A MODEL

Vietri and Ostriker (1983) and Nityananda and Ostriker (1984) introduced and developed a very useful concept of optical depth to gravitational microlensing. When optical depth is small, it gives a probability that one star strongly affects the intensity of a distant source of radiation. We consider here a case of a very small optical depth, and therefore gravitational microlensing is always due to just a single point with some mass M. We consider a flat space and a point source of radiation. The equation of gravitational lensing may be written in the deflector's plane as

$$r^2 - r_0 r - R_0^2 = 0 , \qquad (1)$$

where the coordinate system is centered on the lensing point mass, the source is at r_0, the image is at r, and

$$R_0^2 = \frac{4GMD}{c^2}, \quad D = \frac{D_d D_{ds}}{D_s}, \qquad (2)$$

and all symbols have their usual meaning. The quantity R_0 is the radius of the annular image that is formed when the source and the point mass are perfectly aligned.

The equation (1) has two solutions corresponding to the positions of two images:

$$r_{1,2} = [r_0 \pm (r_0^2 + 4R_0^2)^{1/2}]/2 . \qquad (3)$$

Their amplifications are given by

$$A_{1,2} = \mathrm{abs}\left(\frac{r_{1,2}}{r_0}\frac{dr_{1,2}}{dr_0}\right) = \mathrm{abs}\left(\frac{r_{1,2}^4}{r_{1,2}^4 - R_0^4}\right), \qquad (4)$$

and their combined amplification is

$$A \equiv A_1 + A_2 = \frac{u^2+2}{u(u^2+4)^{1/2}}, \quad u \equiv \frac{r_0}{R_0} . \qquad (5)$$

If the optical depth is τ, then the probability that the source is found within a radius R_0 of some point mass is also τ. According to equation (5) the combined amplification of the two images is, in that case, larger than 1.34. Of course, the probability of a smaller amplification is larger, while the probability of a larger amplification is smaller. Let the probability that the amplification is larger than A be $p(A)$. The ratio $p(A)/\tau$ is given as

$$\frac{p(A)}{\tau} = \frac{r_0^2}{R_0^2} = u^2 , \qquad (6)$$

and its variation with A is shown in Figure 1.

When a point mass passes between the observer and the source, the apparent intensity of the source varies in proportion to the variation of the combined amplification of the two microimages. This may be easily calculated with equation (5). The variation of a combined intensity with time is shown in Figure 2 for 12 values of the impact parameter d: $d/R_0 = 0.1$,

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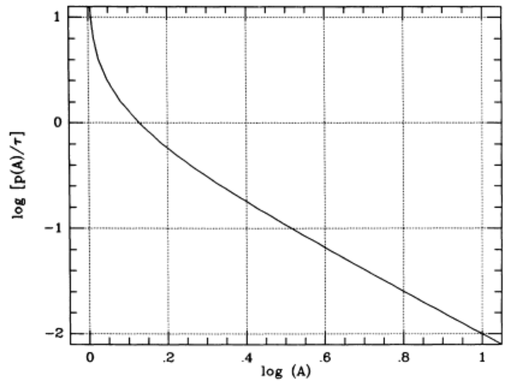


FIG. 1.—Variation of the ratio $p(A)/\tau$ with amplification A. The value $p(A)$ is the probability that a particular source is amplified by a factor larger than A as a result of gravitational microlensing, τ is the optical depth to microlensing, $p(A) = \tau$ for $A \geq 1.34$.

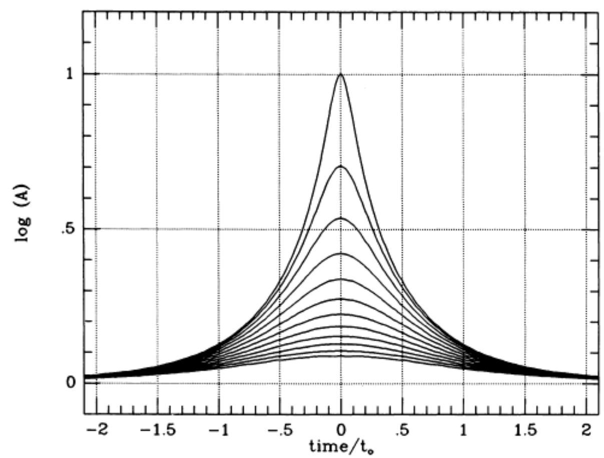
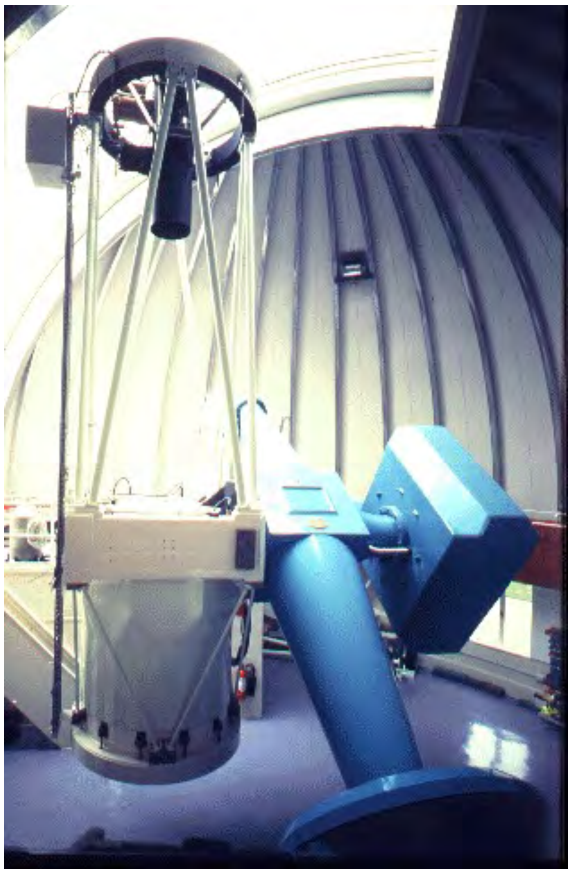


FIG. 2.—Time variation of the amplification due to gravitational microlensing for events with the impact parameter d/R_0 equal 0.1, 0.2, ..., 1.1, 1.2. The largest amplitude corresponds to the smallest impact parameter. The unit of time is given as $t_0 \equiv R_0/v$, where R_0 is the radius of ringlike image formed when the source, the lensing mass, and the observer are perfectly aligned (see eq. [2] and [16]) and v is the relative tangential velocity of the lensing object.

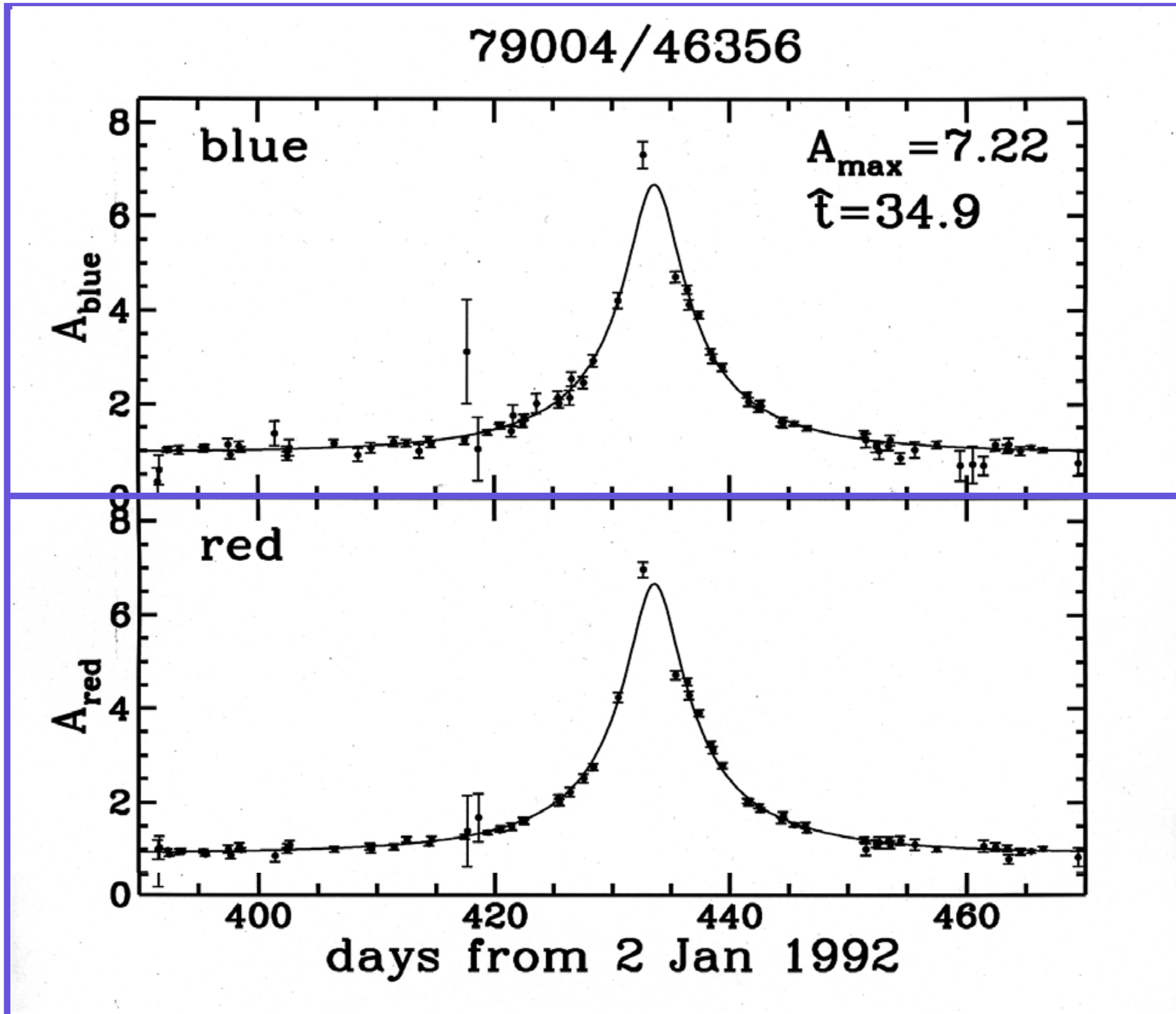
The MACHO Project:



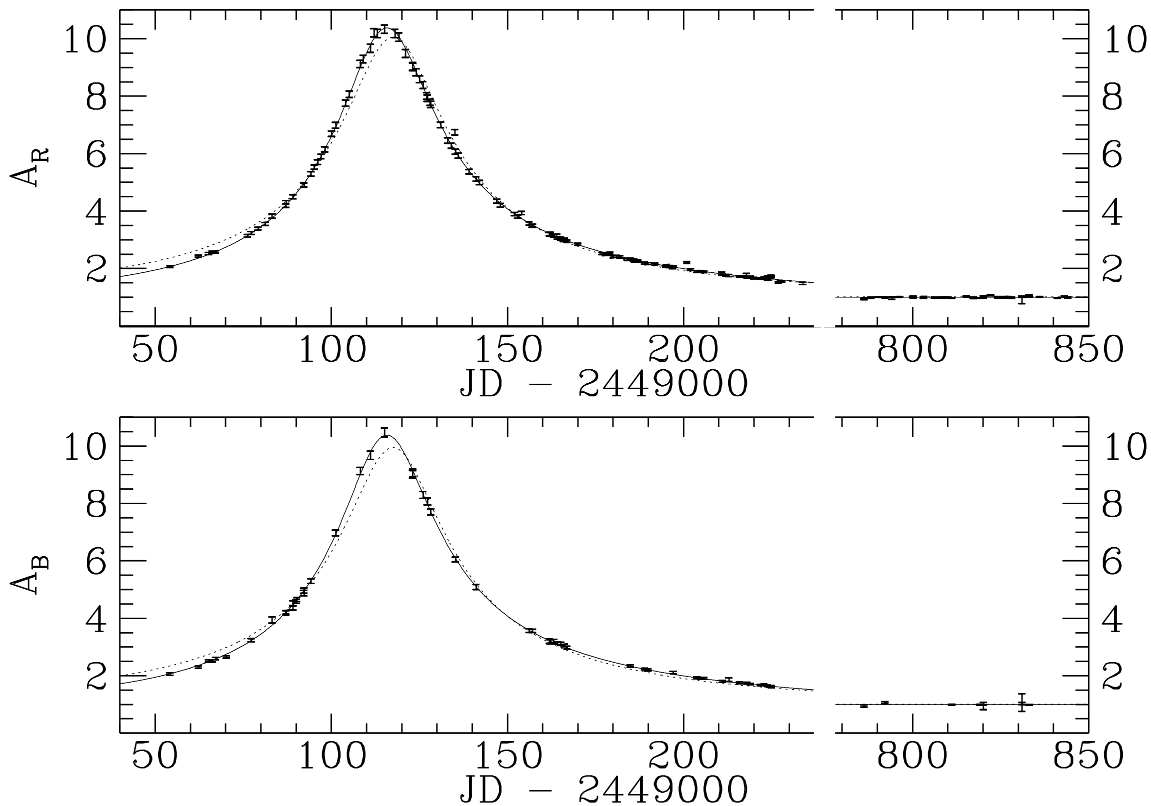
1.3 meter telescope
at Mt. Stromlo

- Two CCD cameras with a dichroic beam-splitter
- Team of 22 from:
  - Lawrence Livermore National Lab
  - Center for Particle Astrophysics
  - Mount Stromlo & Siding Spring Observatories
- With competition from EROS and OGLE

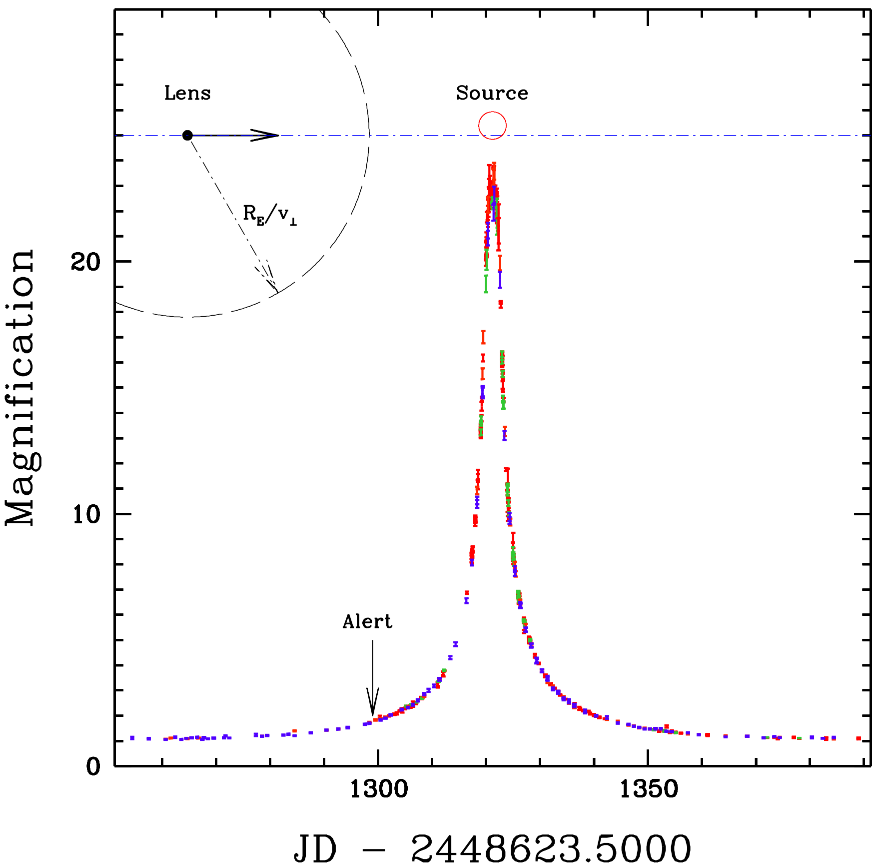
The lightcurve for the first MACHO event:



First detection of parallax in a microlensing event:

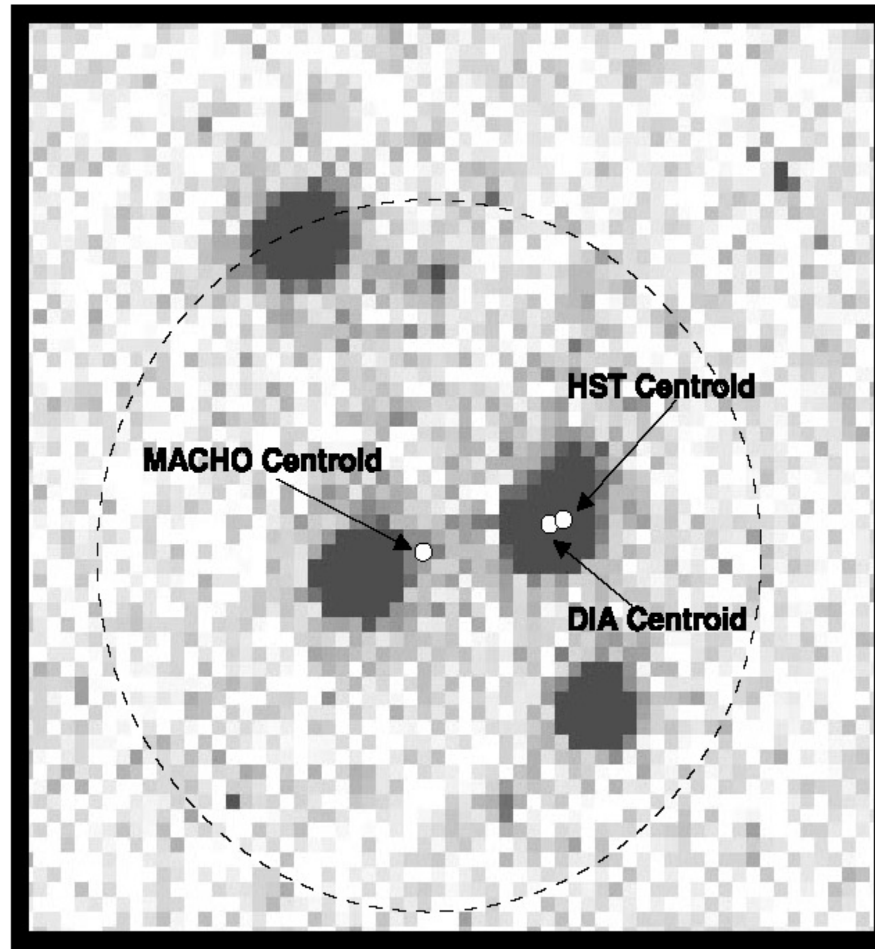


Finite size of source stars limit magnification:



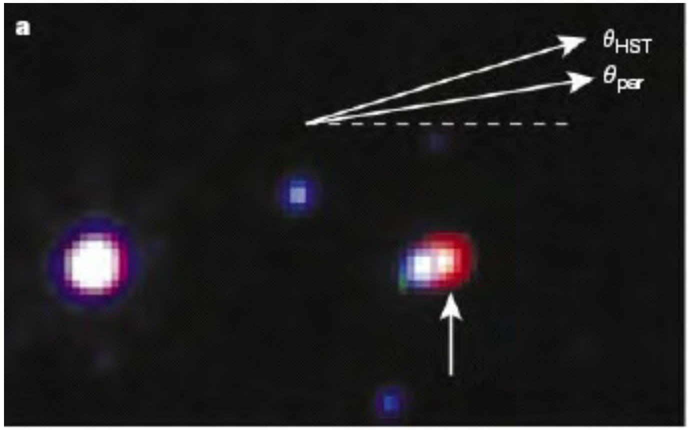
“Sources”may comprise multiple stars:

- Images do not typically resolve LMC stars (e.g. LMC-4)
- Apparent magnification can be reduced
- Number of microlensing targets is increased
- Model the survey using stellar luminosity functions from *HST*



The LMC-5 story as seen with *HST and Spitzer:*

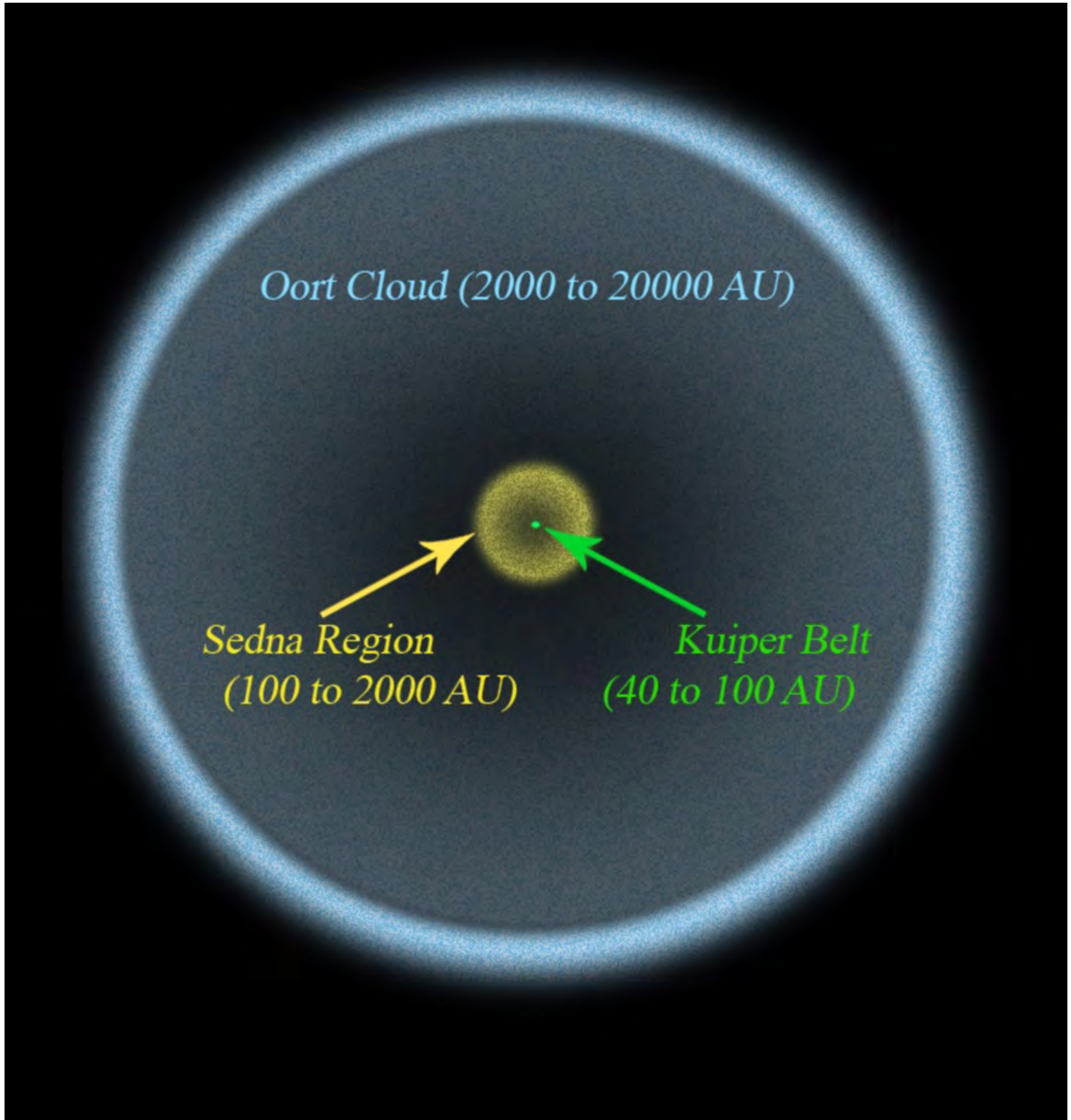
- LMC-5 had a high magnification (~50). Peak was in February 1993.
  - *HST* follow-up showed that the microlensing system was composed of a faint, red object displaced by 0.134” from the center of the source star.
- Further follow-up with HST confirmed the proper motion.



And now for something different:

Most of the volume of the solar system is unexplored:

- “Outer edge” is not well-defined, but reasonably >50,000 AU
- The Oort Cloud certainly extends to ~20,000 AU
- Most of this region is unexplored because objects are too faint for direct detection:
  - Small in size
  - Flux of reflected sunlight $\sim r^{-4}$


Oort Cloud (2000 to 20000 AU)
Sedna Region
(100 to 2000 AU)
Kuiper Belt
(40 to 100 AU)

“Sedna region” specific goals for a survey of the outer solar system:

- Detect and characterize small bodies on orbits related to Sedna
- The processes that placed Sedna where it is should have placed also many smaller objects
  - Compact “Oort Cloud” (Brasser et al)
  - Clear predictions regarding the spatial distribution
- Size spectrum not understood

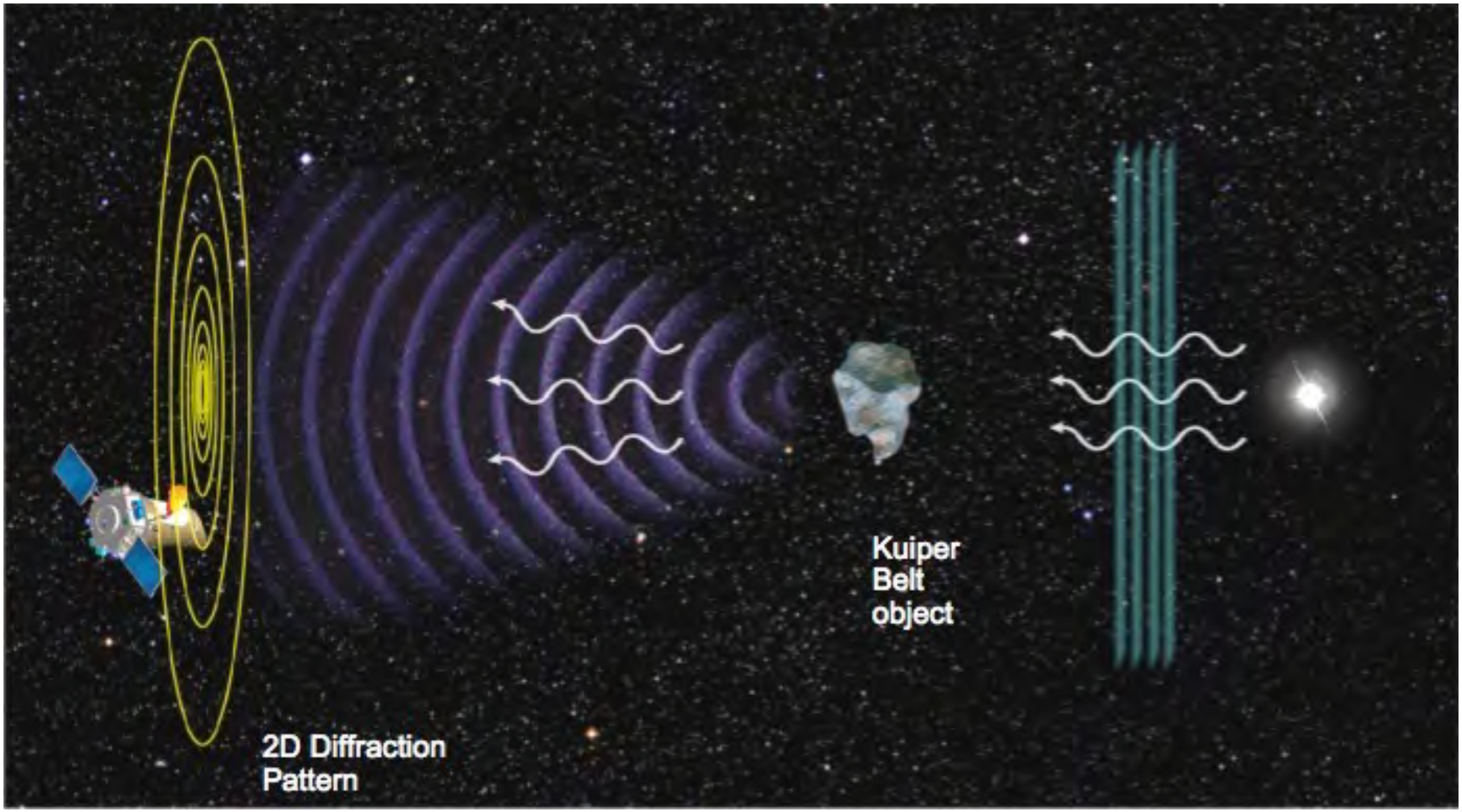
Oort Cloud specific goals for a survey of the outer solar system:

- Detect the inner cloud in objects similar in size to the nuclei of long period comets
  - Should see the transition from flattened to ~spherical produced by Galactic tides
- Detect the outer cloud (>10,000 AU)
  - Thought to be the source of the long period comets
  - Very challenging to detect!
  - May only be able to detect objects with D>10 km

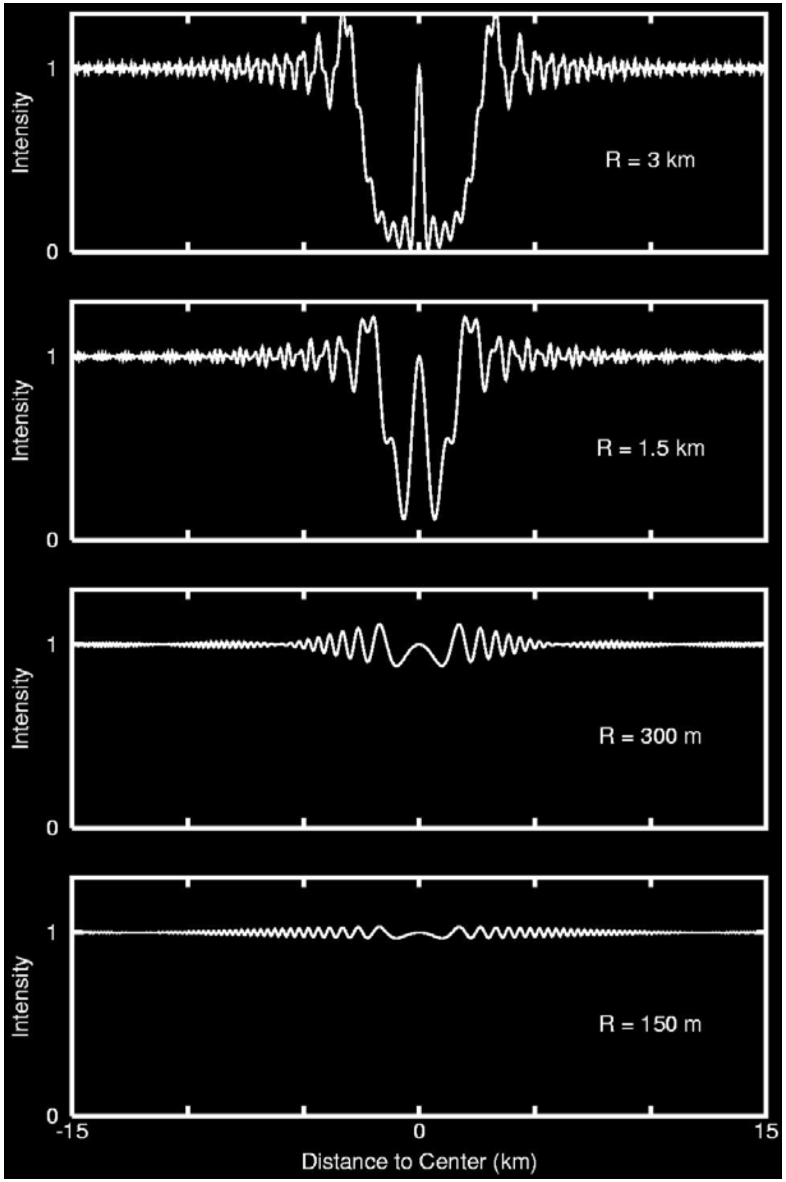
Surveying the outer solar system (beyond Neptune) is challenging

- Objects fainter than magnitude 29.5 are effectively invisible
- Most of the projected area is in “small” objects
- Most of the volume of the solar system is inaccessible to direct surveys

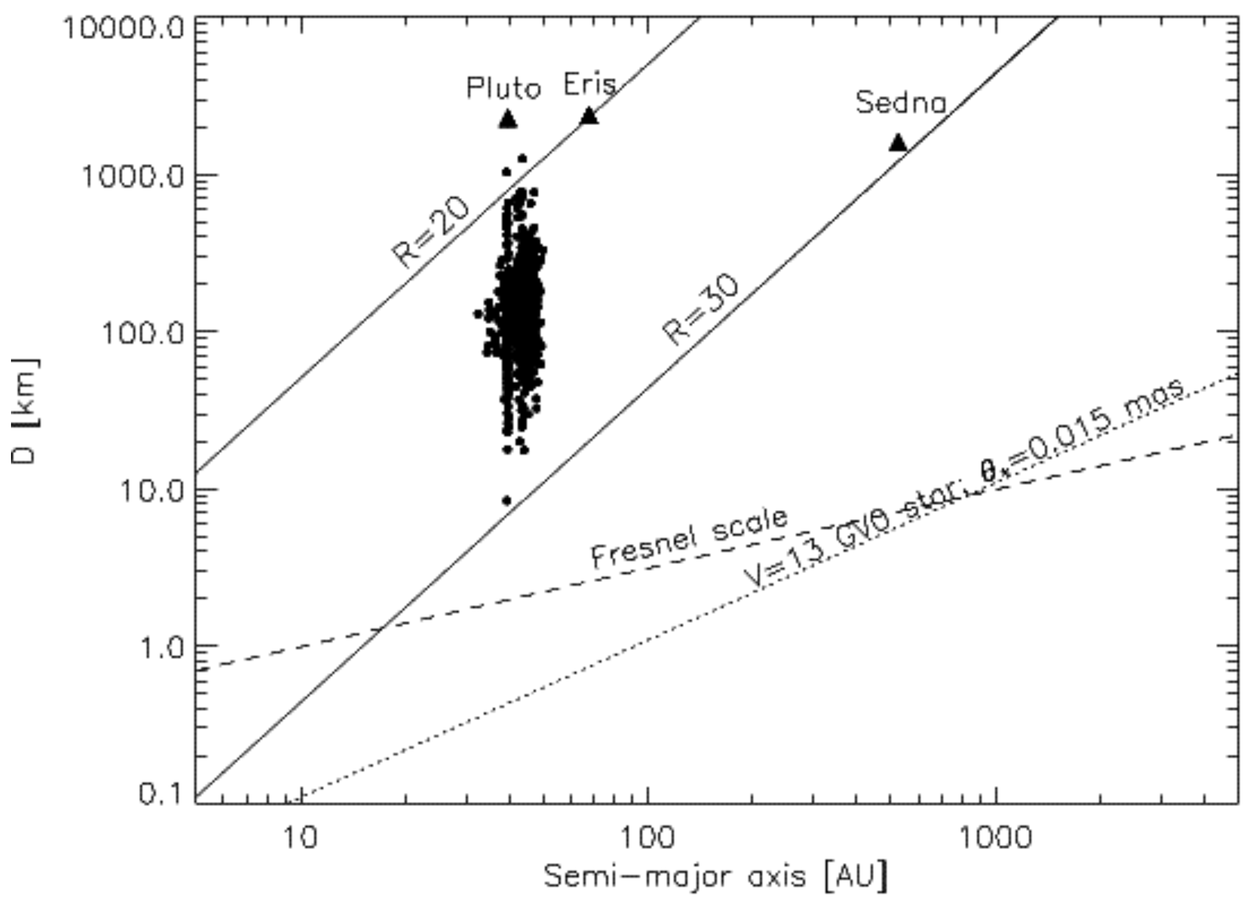
Use occultations of background stars:



Occultation events exhibit striking diffraction fringes:



The finite angular size of the target star can also be important :



Rate estimates are straightforward, for a given model population:

- Rate ~ (Objects/sq. deg.)$\times$(angular velocity)$\times$(angular size)   per “star-hour”

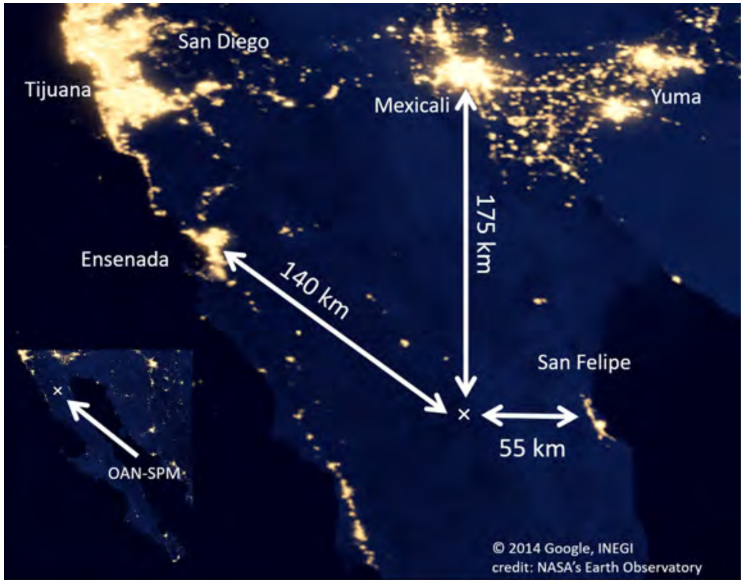
- KBO rate ~ 3.6×10^{-11} (KBOs/sq. deg.) per “star-hour”

TAOS I:

TAOS II:

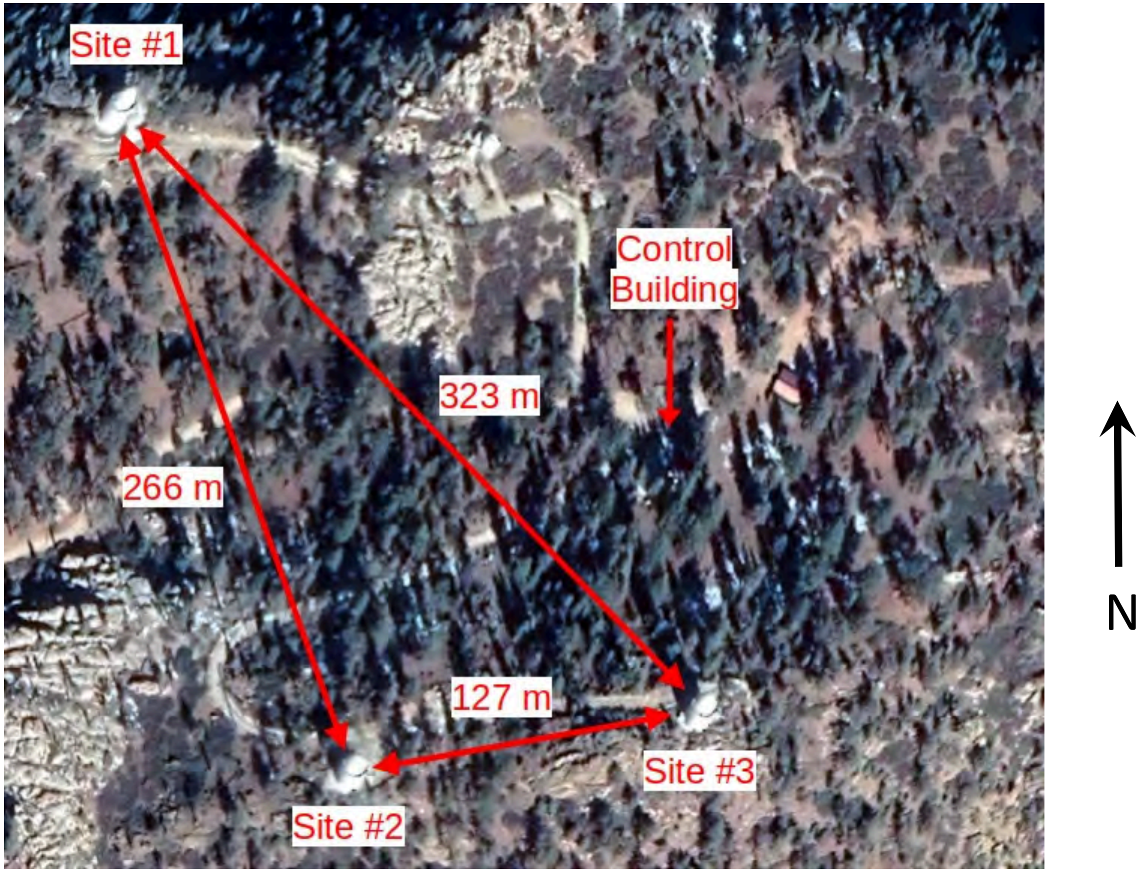
Shiang-Yu Wang and Matt Lehner

Site: San Pedro Mártir, Baja California:



- Baja California, Mexico
- ~300 clear nights per year
- Good seeing (median 0.57")
- Dark sky
  - V: 21.5 mag/arcsec^2
  - R: 20.7 mag/arcsec^2
- Light pollution ordinance in effect for Baja California

Three Telescopes



Telescopes

- Three telescopes from DFM Engineering
- F/4 1.3m modified Richey Chretien
  - Single Schmidt corrector plate
  - Same model as USNO, FLWO 1.3m telescopes
  - F/4 version of OGLE telescope
- 1.7° FOV over 154 mm diameter
- r_{lim} = 18.5 at 20 Hz
  - SNR = 1.2, good enough for 20 – 30 km objects
  - Enough for our target of ≈10,000 stars
- Telescopes installation completed 2017 October

Cameras

- Custom CMOS imagers from e2v

  1920×4608 16 μm pixels

  3-edge buttable

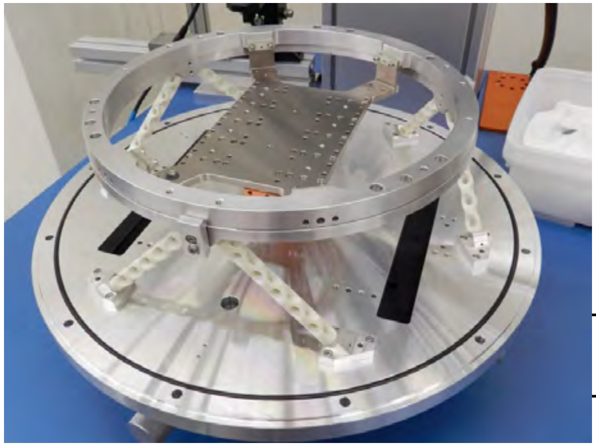
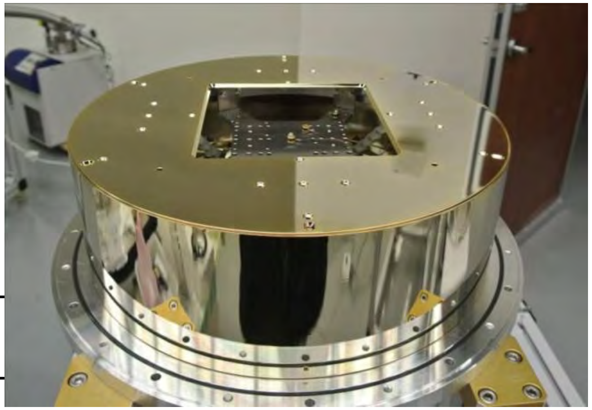
  Focal plane composed of 2×5 array of imagers

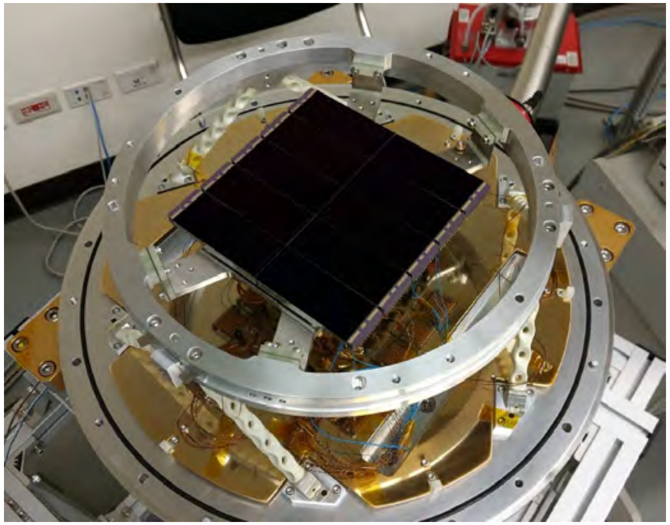
  Back illuminated 100% photosensitive

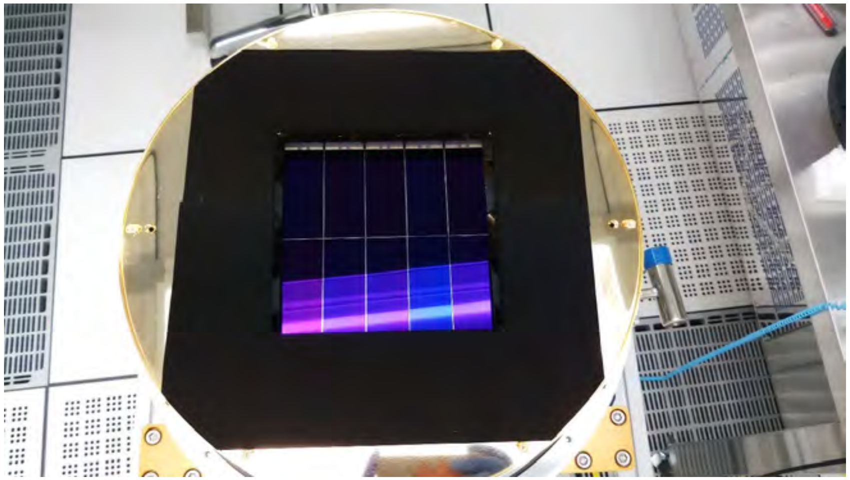
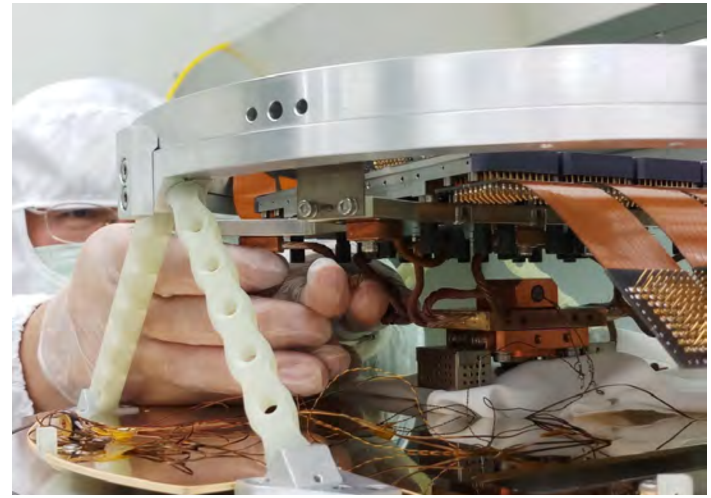
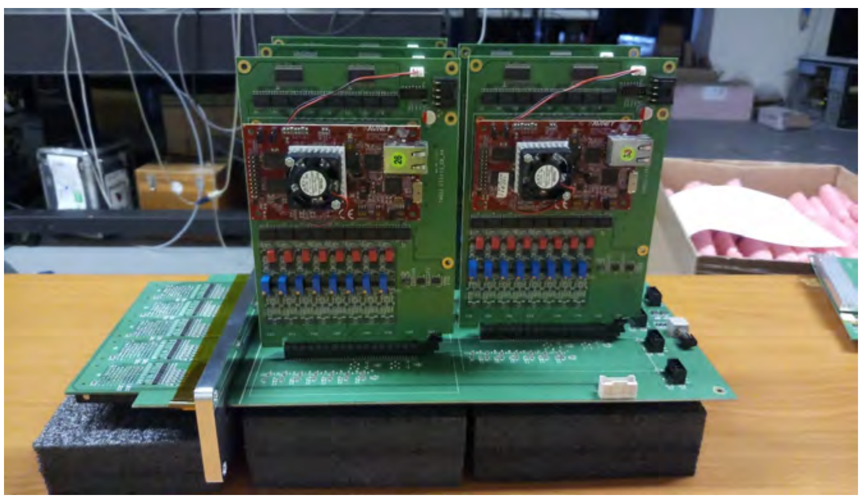
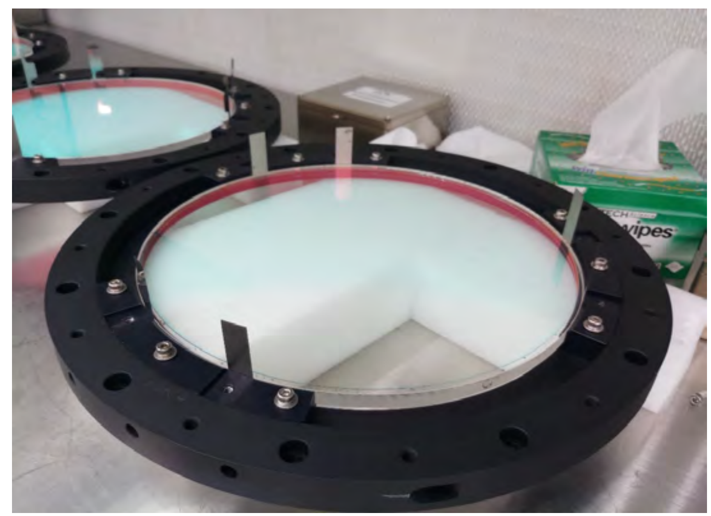
  Onboard correlated double sampling (CDS)

  - Read noise 2.7 e^-

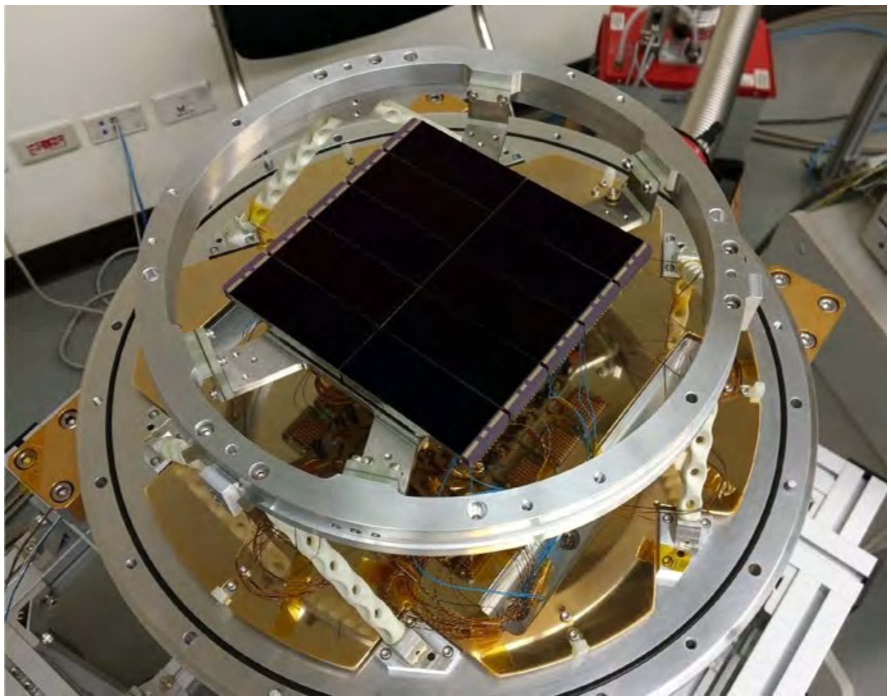
  Readout on multiple sub-frames (>1200 per imager)

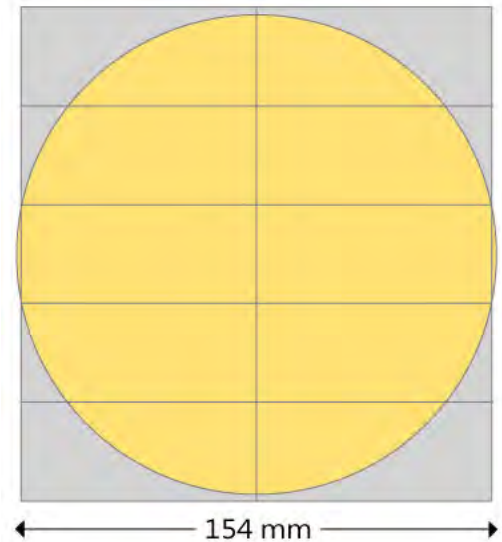





TAOS II:





TAOS II: First light expected this year.