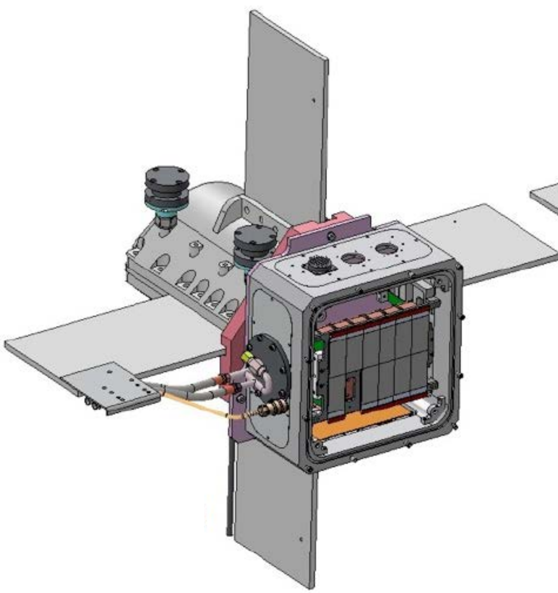
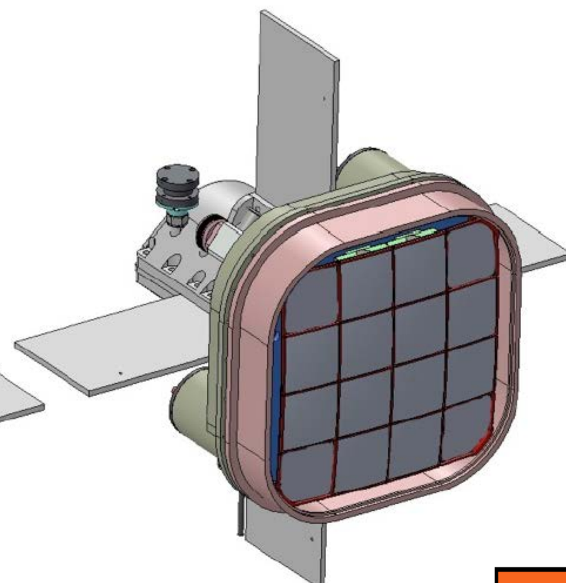
Wide and Fast:
A new Era of EMCCD and CMOS?

???

ZTF

PTF





	PTF	ZTF	???
Active Area	7.26 deg^2	47 deg^2	47 deg^2
Readout Time	36 sec	10 sec	Negligible
Exposure Time	60 sec	30 sec	1 sec

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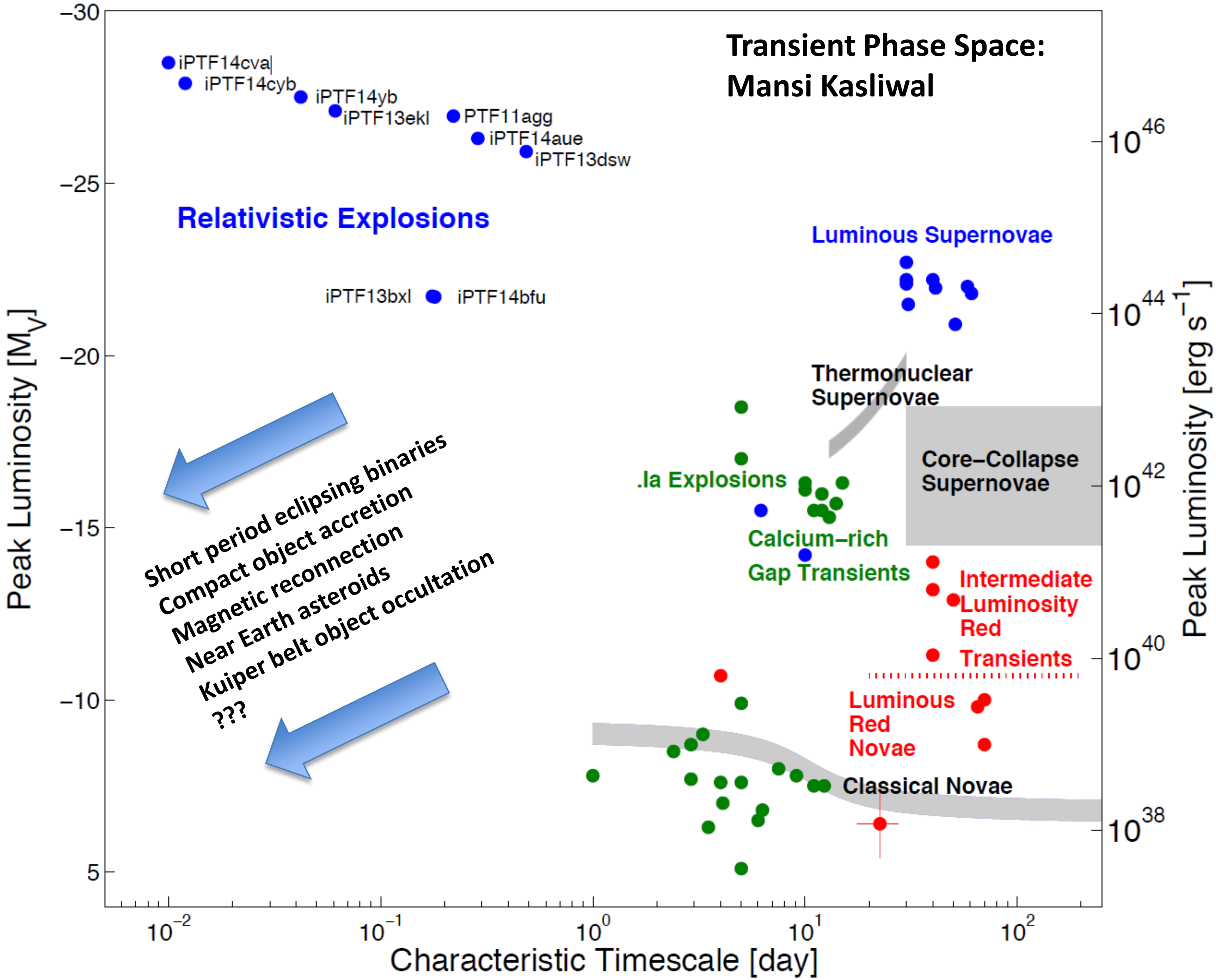


Transient Phase Space:
Mansi Kasliwal
iPTF14cva
iPTF14cyb
iPTF14yb
iPTF13ekl
PTF11agg
iPTF14aue
iPTF13dsw
Relativistic Explosions
Luminous Supernovae
iPTF13bxl
iPTF14bfu
Thermonuclear Supernovae
Core–Collapse Supernovae
.Ia Explosions
Calcium–rich
Gap Transients
Intermediate Luminosity Red Transients
Luminous Red Novae
Classical Novae
Short period eclipsing binaries
Compact object accretion
Magnetic reconnection
Near Earth asteroids
Kuiper belt object occultation
???
Peak Luminosity [M_V]
Peak Luminosity [erg s^{-1}]
Characteristic Timescale [day]

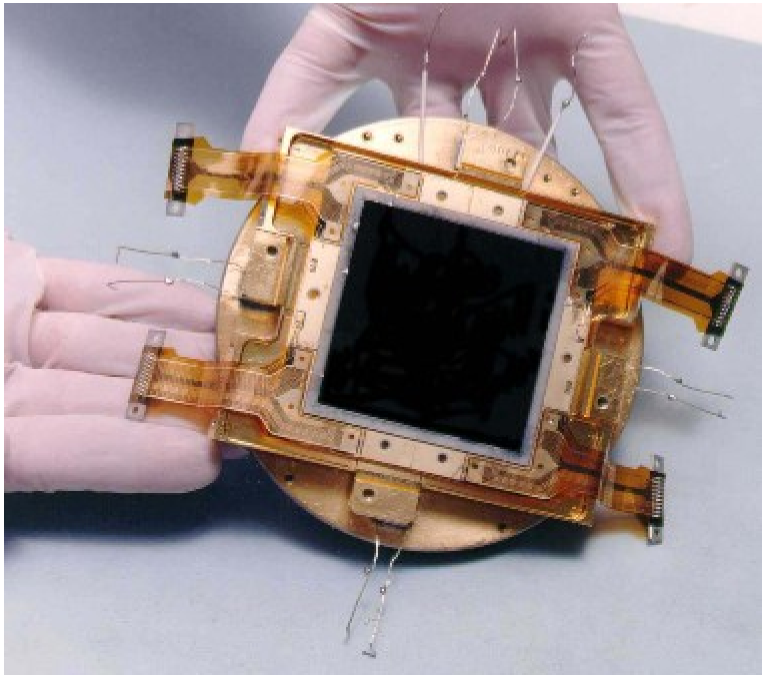
Conventional CCDs

Conventional CCDs are not suitable for high-speed astronomy

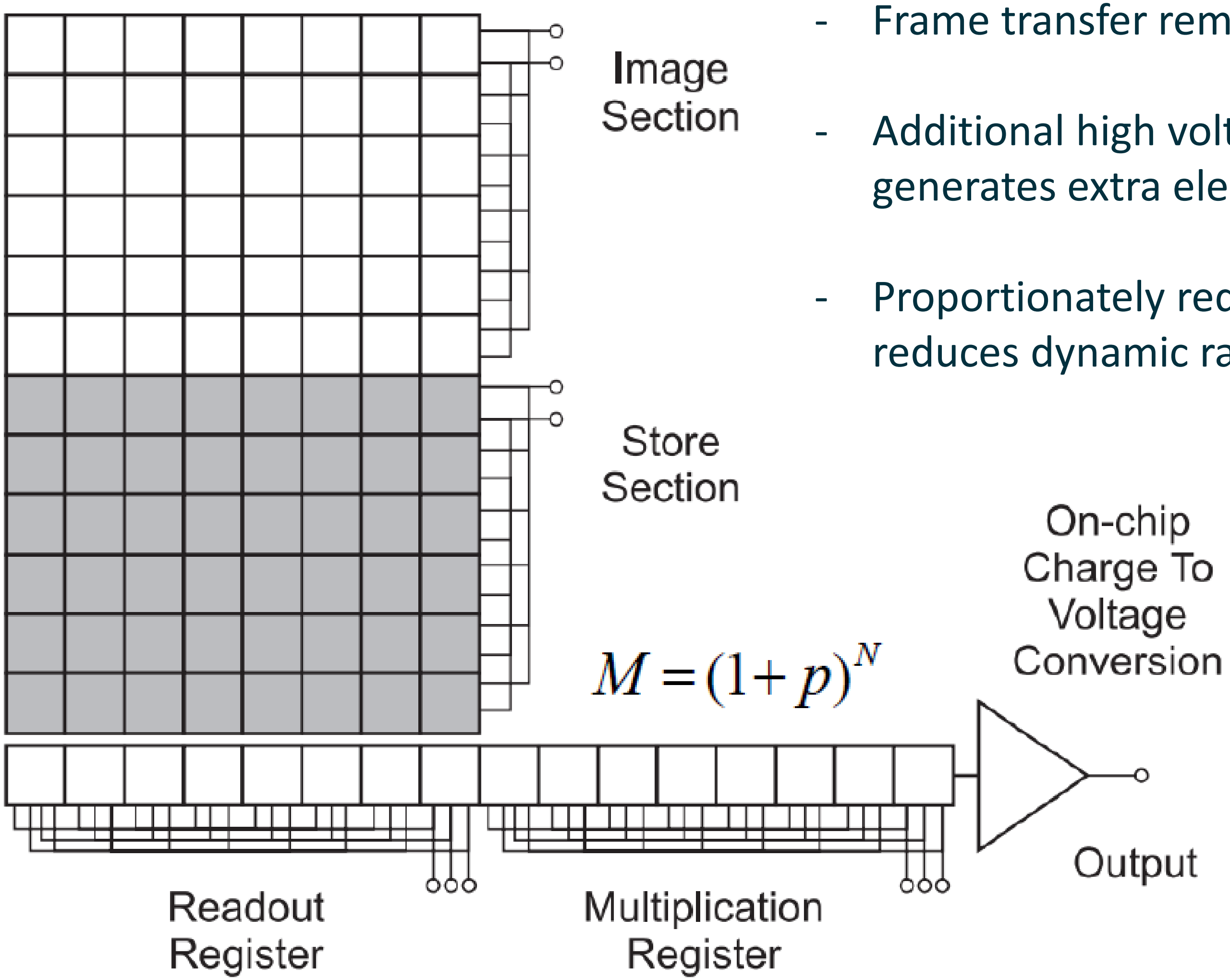
- Readout via a serial register and a single on-chip amplifier

- Read-out requires CCD dead time – loss of duty cycle and survey speed

- Higher speed readout -> higher read noise!



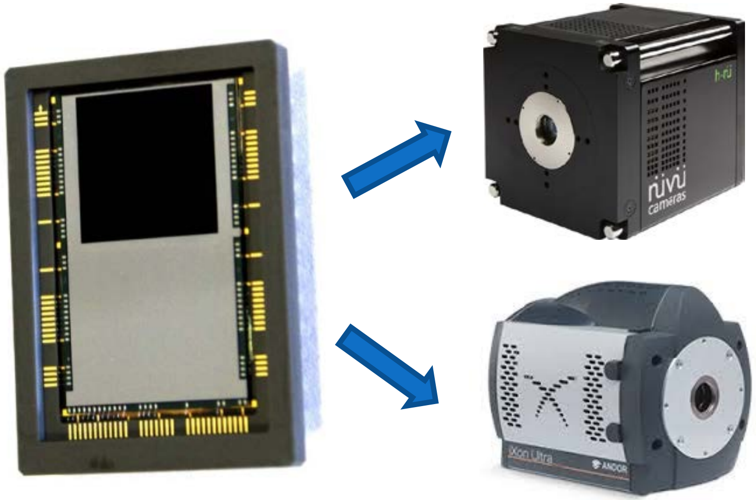
Electron Multiplying CCDs



$$M = (1+p)^N$$

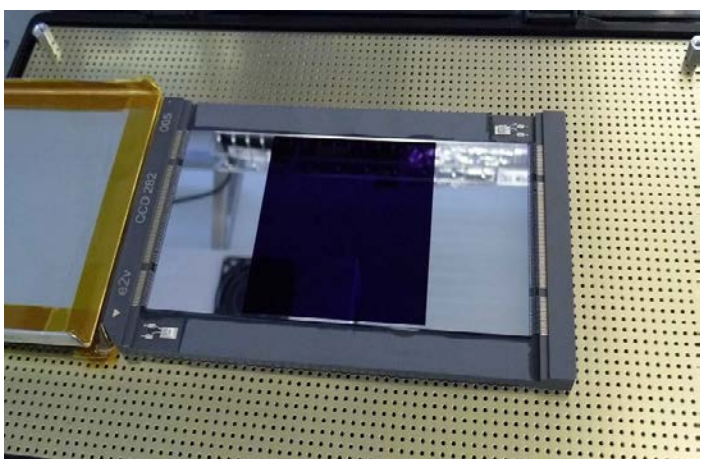
- Frame transfer removes readout dead time
- Additional high voltage gain stage – generates extra electrons
- Proportionately reduces read noise, but also reduces dynamic range

EMCCDs in Astronomy



- **e2v CCD201-20**
- 1K x 1K / 13.3 x 13.3 mm
- 13 µm pixels
- 26 FPS full frame

CHIMERA
GEONIS
Palomar Cosmic Web Imager (CWI)
Fireball
WFIRST-AFTA



- **e2v CCD282 (2015?)**
- 4K x 4K
- > 5 FPS full frame

MeerLicht?

CMOS in Astronomy

CMOS dominates the commercial sensor market

First generation "scientific CMOS" now on the market

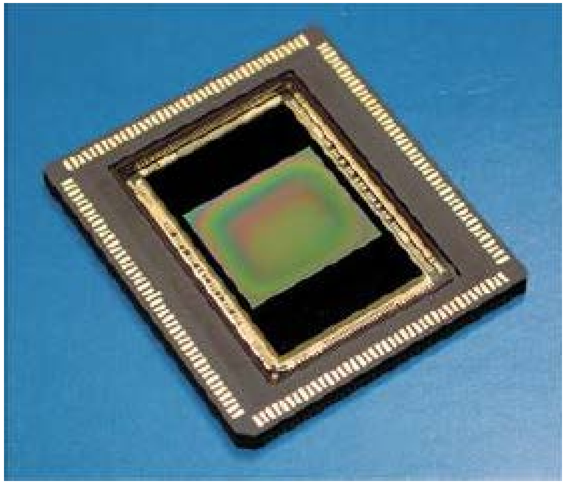
Lots of problems:

- Low quantum efficiency
- Small pixel pitch
- Difficult to mosaic
- Additional pixel and amplifier noise, non-linear charge-to-voltage conversion – **difficult to calibrate**

However, each pixel has its own readout electronics – very fast!

Second generation sensors promise large form factor (4K x 4K), with 80 FPS full frame readout

Better QE, bigger pixels and better performance



Fairchild Imaging CIS2521

2560(H) x 2160(V) pixels
16.6 x 14 mm
6.5 μm pixels
~55% QE
<2 e- read noise

100 FPS full frame!

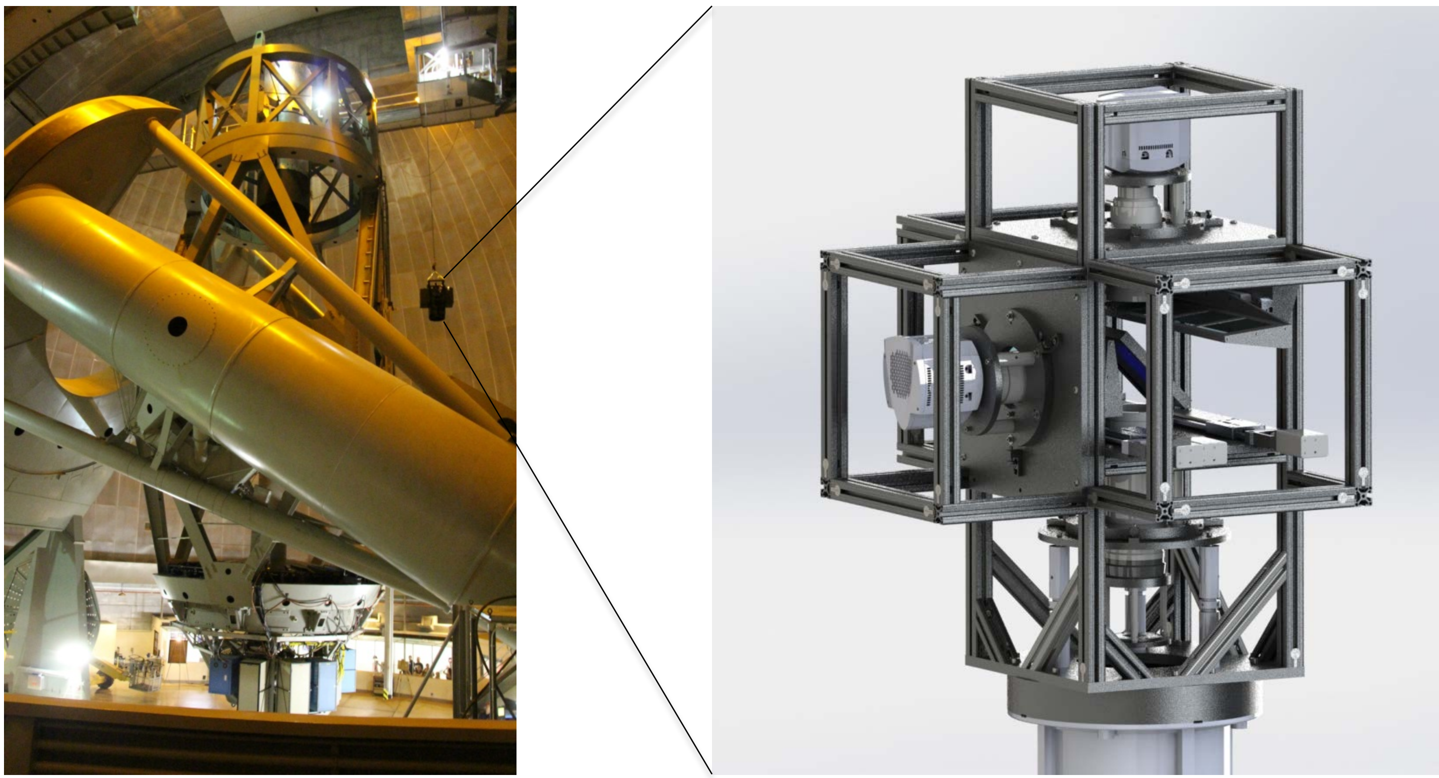
Caltech

CHIMERA

Jet Propulsion Laboratory

Caltech High-speed Multi-color camERA

Caltech: Gregg Hallinan (PI), Navtej Singh, Jennifer Milburn, Nick Konidaris, Paul Gardner, Gillian Kyne
JPL: Leon Harding (Instrument Scientist), Mike Shao, Jagmit Sandhu
MIT: Hilke Schlichting



Concept

Unique imaging system for the Prime focus of the Palomar 200-inch:

- *1) High-speed (<< 1 FPS)* Unique to US
- *2) Multi-color*
- *3)* ***Wide field*** *Unique worldwide*

Instrument to grow in iterative generations to eventually image the entire mechanically limited FOV at the P200 focus (~0.5 x 0.5 degrees)

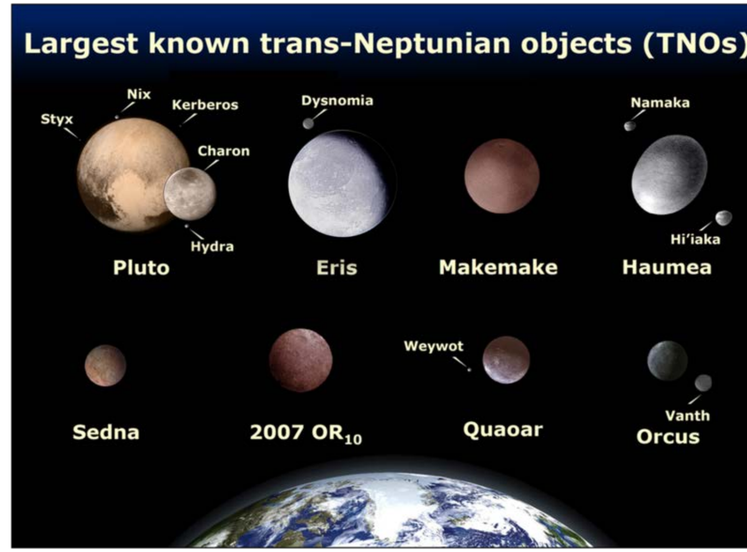
- **<u>Utilizes EMCCDs and CMOS to go wide and fast</u>**

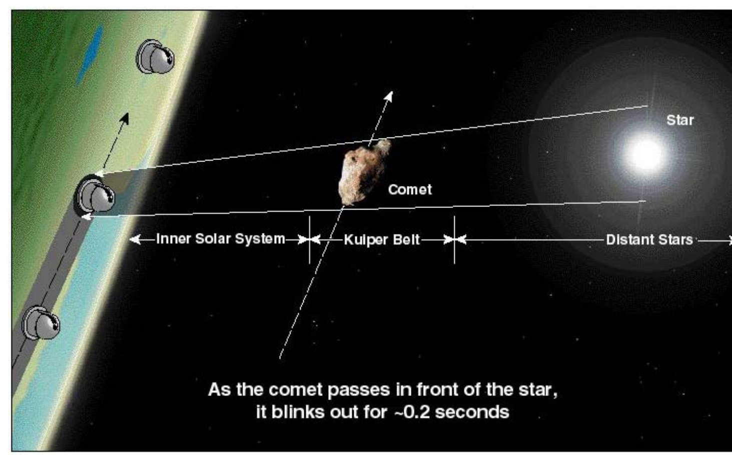
<u>Science</u>

- 1) **Kuiper Belt Object (KBO) detection via occultation**
- 2) Low mass Near Earth Asteroid (NEA) detection
- 3) iPTF and ZTF follow up
- 4) Additional wide-field, high speed transient surveys (e.g. Galactic Bulge)

The Kuiper Belt

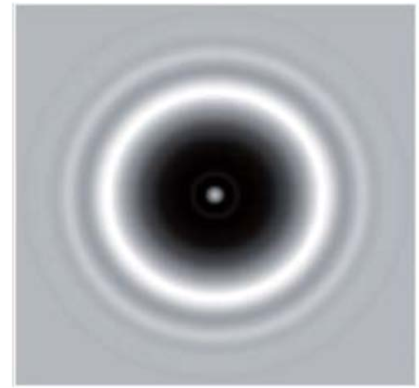
- Kuiper belt is a remnant of the primordial solar system
- >1000 KBOs have been detected since 1992
- The size distribution of small (< 10 km) Kuiper Belt Objects is poorly constrained…
- Important questions to be answered:
  - **Is the Kuiper Belt undergoing collisional evolution?**
  - **Are sub-km KBOs held together by their own gravity, or by material strength?**
  - **Is the Kuiper Belt the source of the Jupiter Family comets?**
- <u>**Sub-km population too small for direct detection**</u>
- -> can be detected via occultation

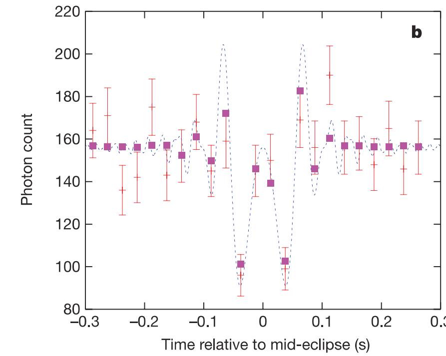




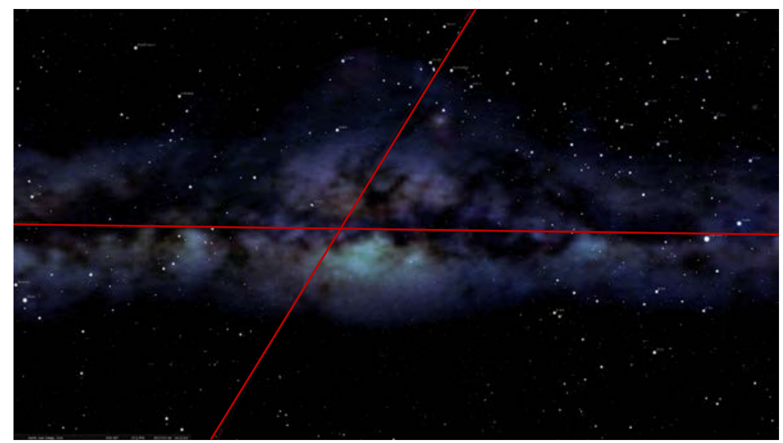
Detecting Occultations of Kuiper Belt Objects

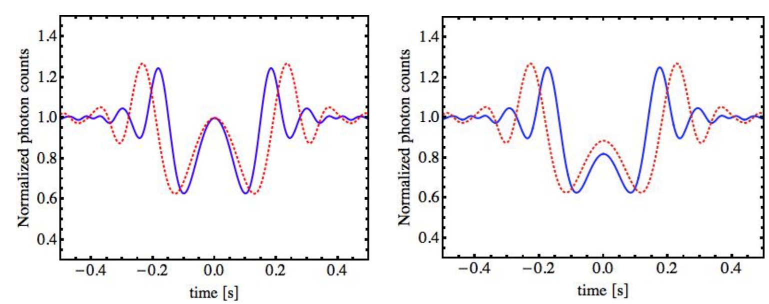
- Can only be detected through the occultation signature as they pass in front of background star
- **Requires ~40 Hz sampling to fully characterize** [need EMCCDs or CMOS]
- Only two detections thus far from HST FGS data (Schlichting et al. 2009, 2012)
- Ground-based efforts ongoing – e.g. TAOS II: Dedicated 3 x 1.3 m telescope system
- **CHIMERA uses a large telescope and simultaneous observing in two bands to overcome scintillation**
- Targets dense fields in the ecliptic (Galactic Center, Globular Clusters) - > monitor 1000s of stars simultaneously





Schlichting et al. Nature 462, 895, (2009)





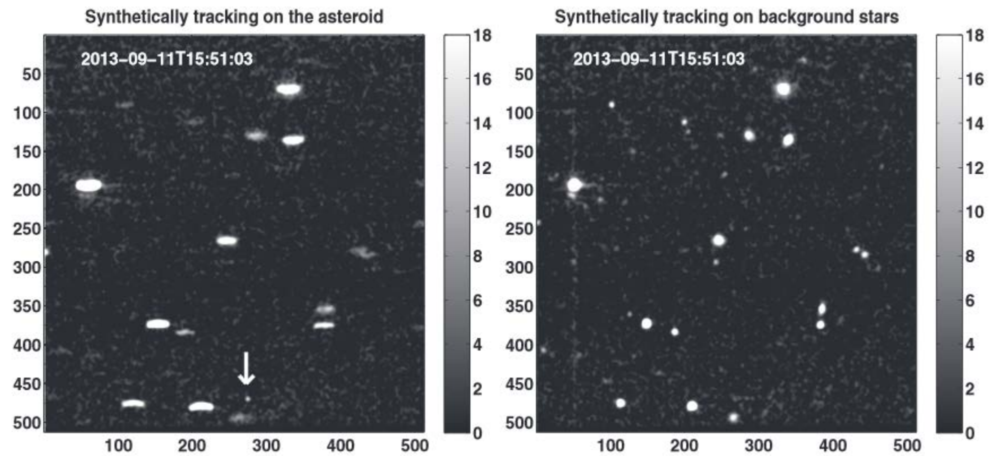
Detecting Near Earth Asteroids via Synthetic Tracking

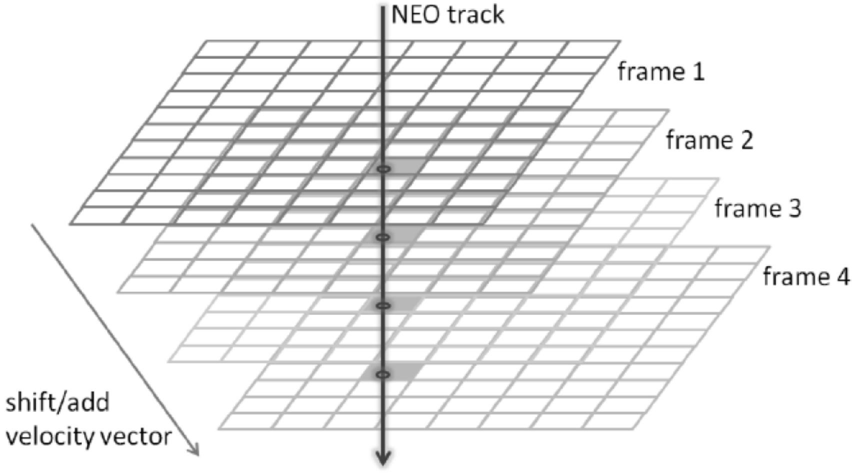
- Synthetic Tracking technique developed at JPL to detect small NEAs **[see talk by Mike Shao]**

CHIMERA Mk I:

1) Finding Very Small Near-Earth Asteroids using Synthetic Tracking – *Shao et al. – (2014 ApJ, **782**, 1S)*

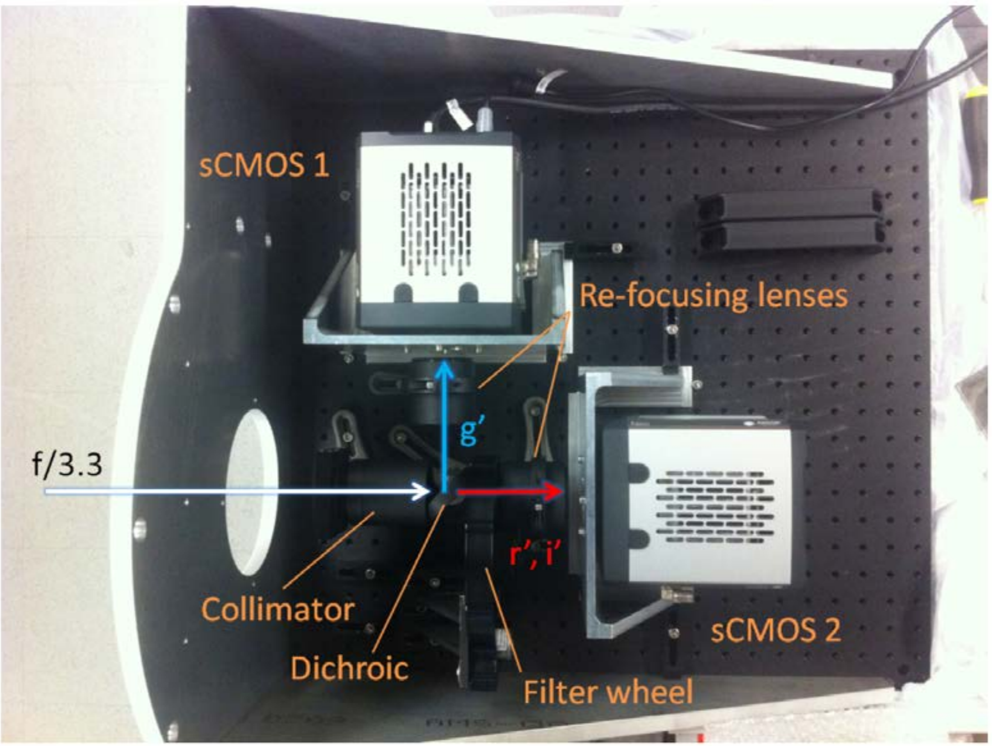
2) Detection of a faint fast moving asteroid using synthetic tracking – *Zhai et al. (2014 ApJ, **792**, 60Z)*





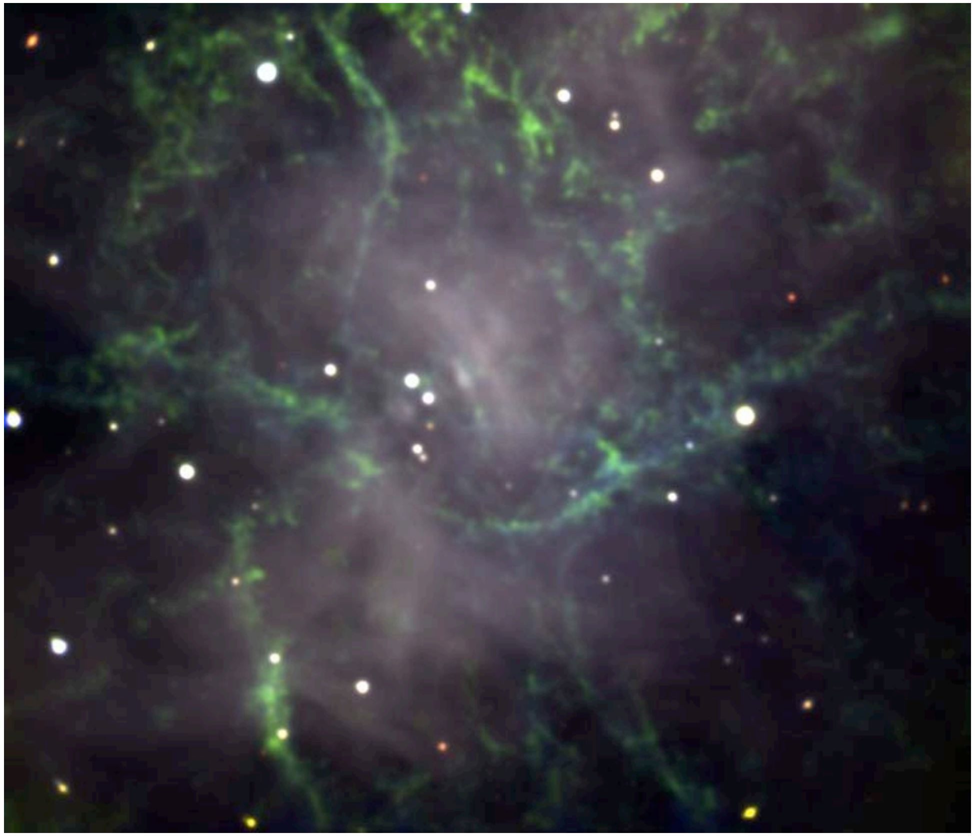
Shao et al. 2014; Zhai et al. 2014

Gen I: Prototype



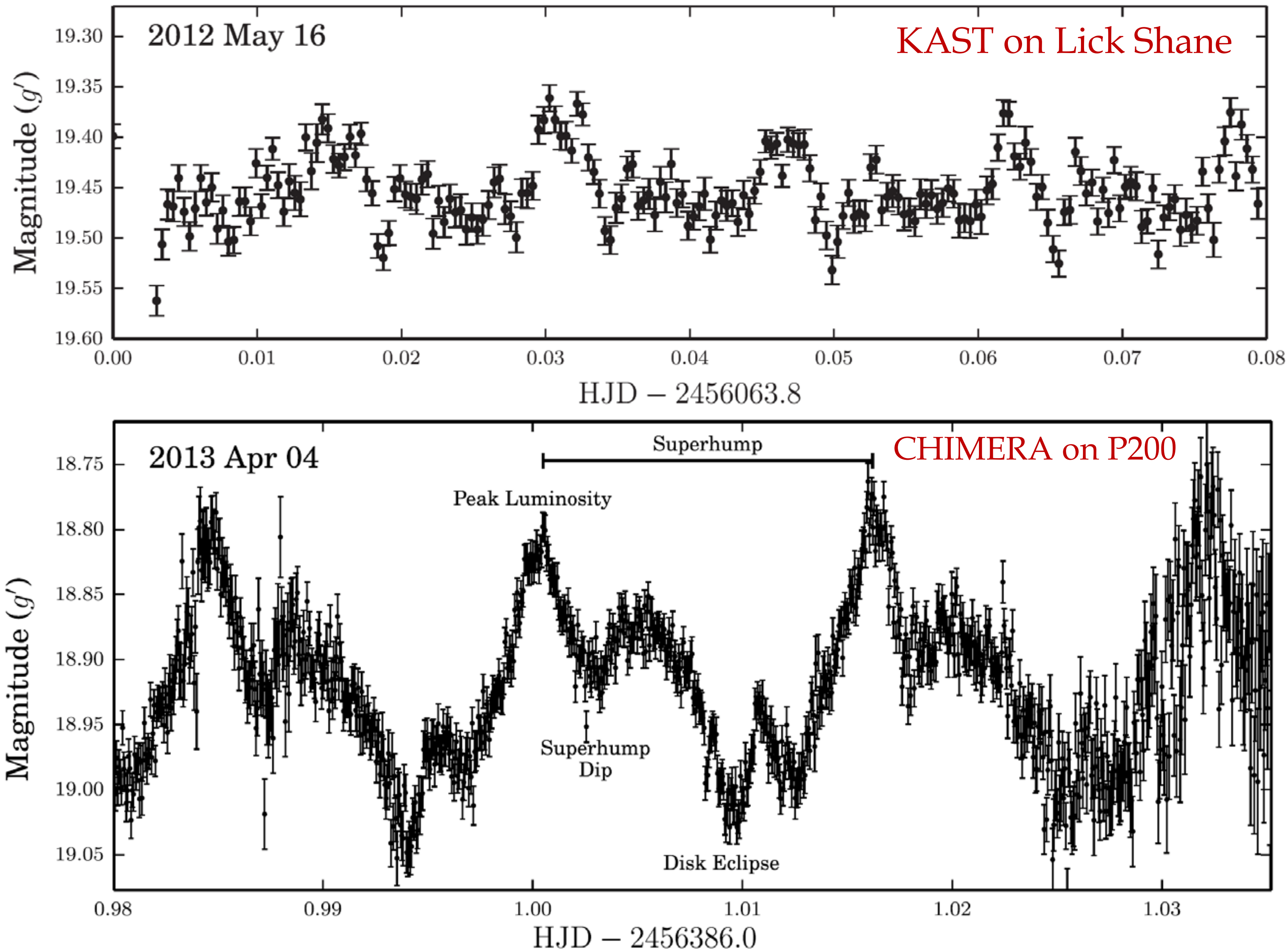
- Proof of concept: Conceived in Mar 2012; Built from Mar-July 2012; First Light August 2012
- Total hardware costs < $50K
- Largely constructed on campus by postdoc Leon Harding with off-the shelf optics
- Uses two low-noise 5.5 Mpix CMOS detectors
- Single 8-core, 8TB RAID data processing node

CHIMERA MK I First Light (August 2012)



- Single engineering night in August 2012
- First light image of the Crab pulsar (300 sec exposure in g’, r’, i’ bands)
- Field of view ~2.5 x 2.5 arcminutes

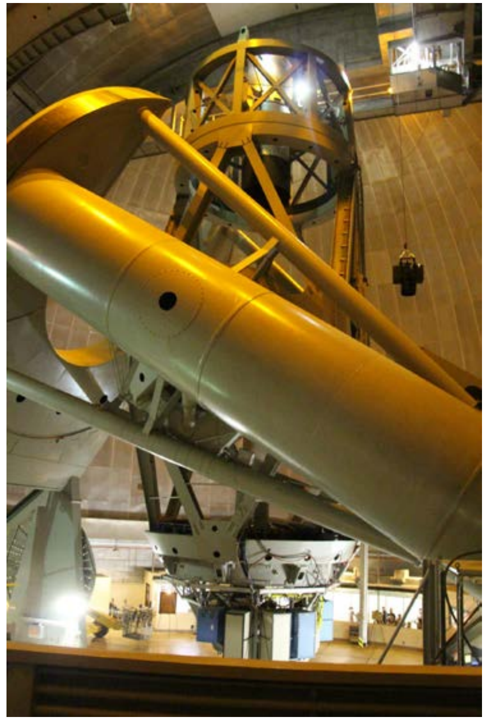
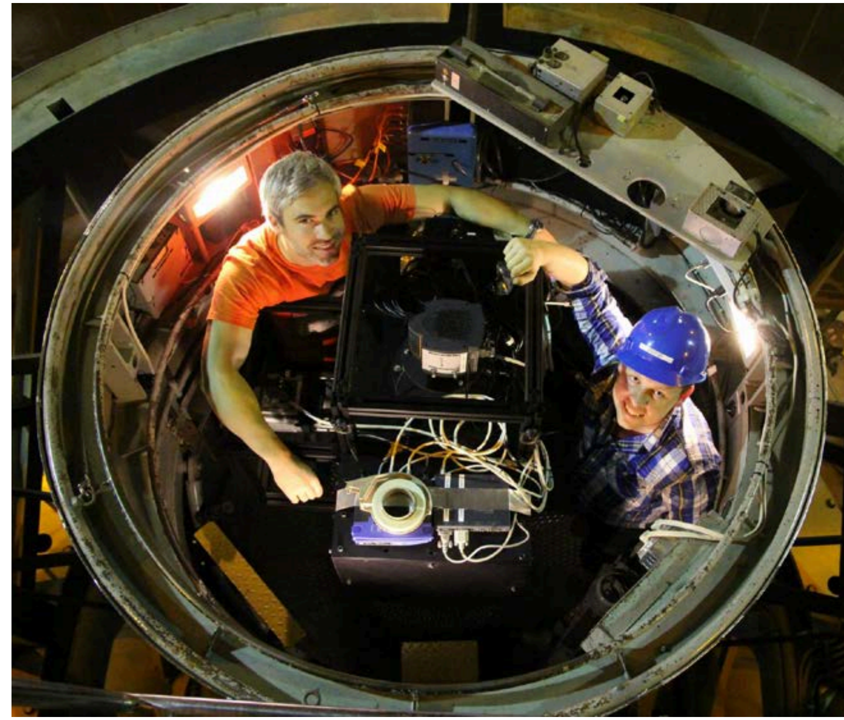
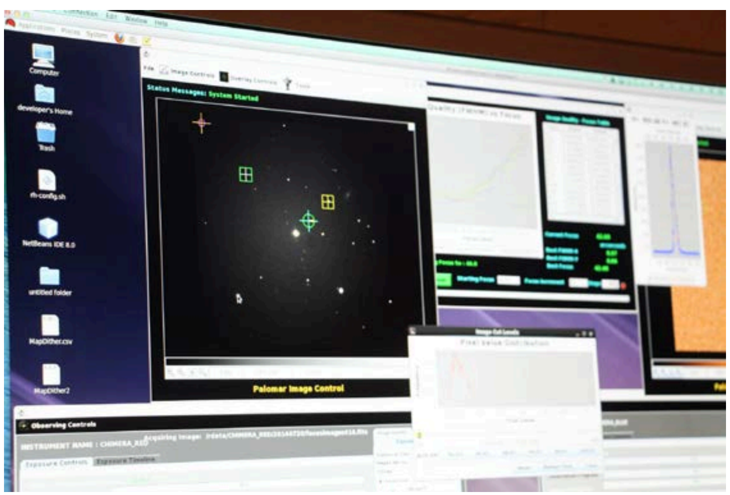
Eclipsing AM CVn: Levitan et al. 2014



CHIMERA Mk II

- Designed and built in 2014
- A new (f1.8) optical system delivering a 5 x 5 arcminute FOV
- Completely new mechanical system
- Total hardware cost of <$60K
- Reused EMCCDs sensors
- **Harding et al. 2015 (MNRAS submitted)**

First Light: July 19 2014 (Harding et al. 2015)

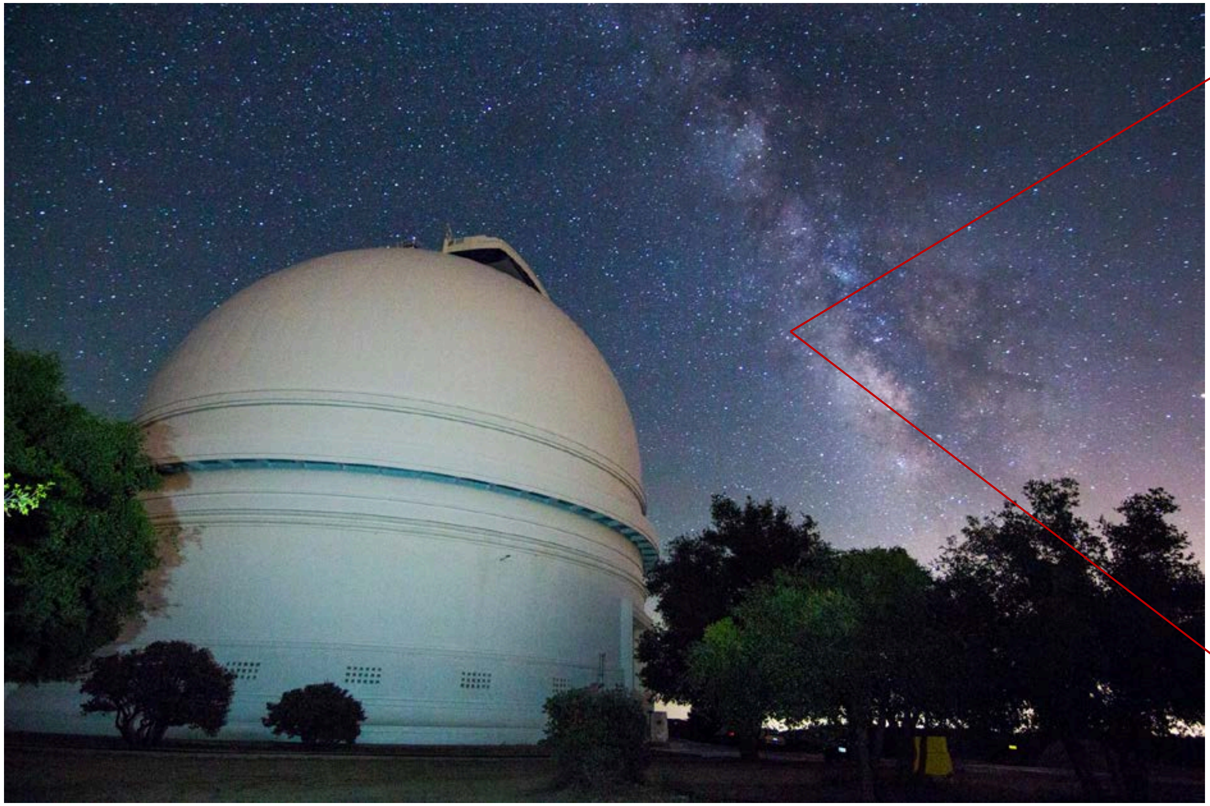





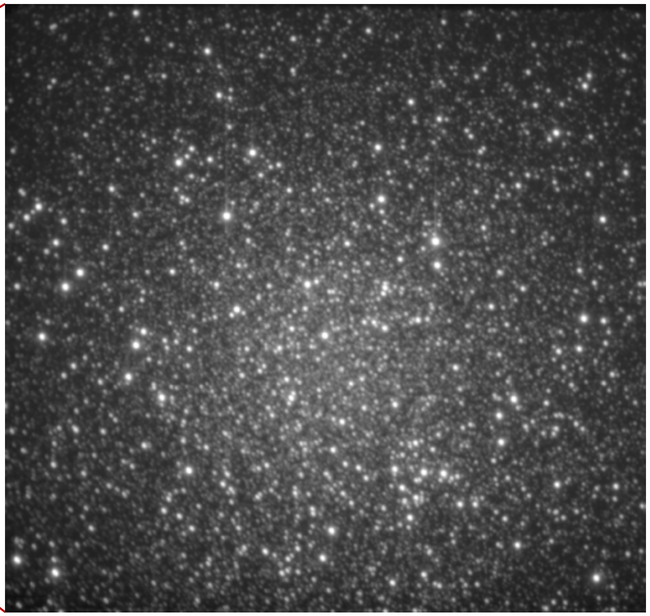
First Light Image

CHIMERA Mk I

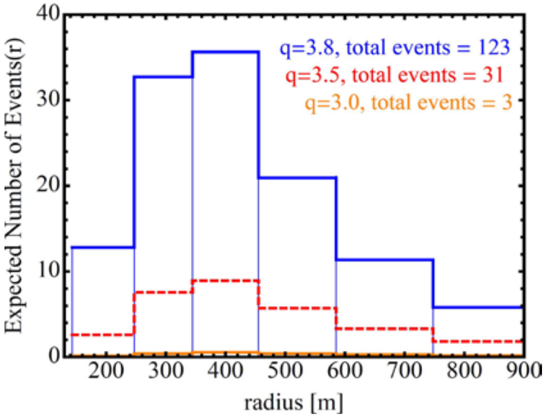
CHIMERA Mk II

CHIMERA science Runs 2015+





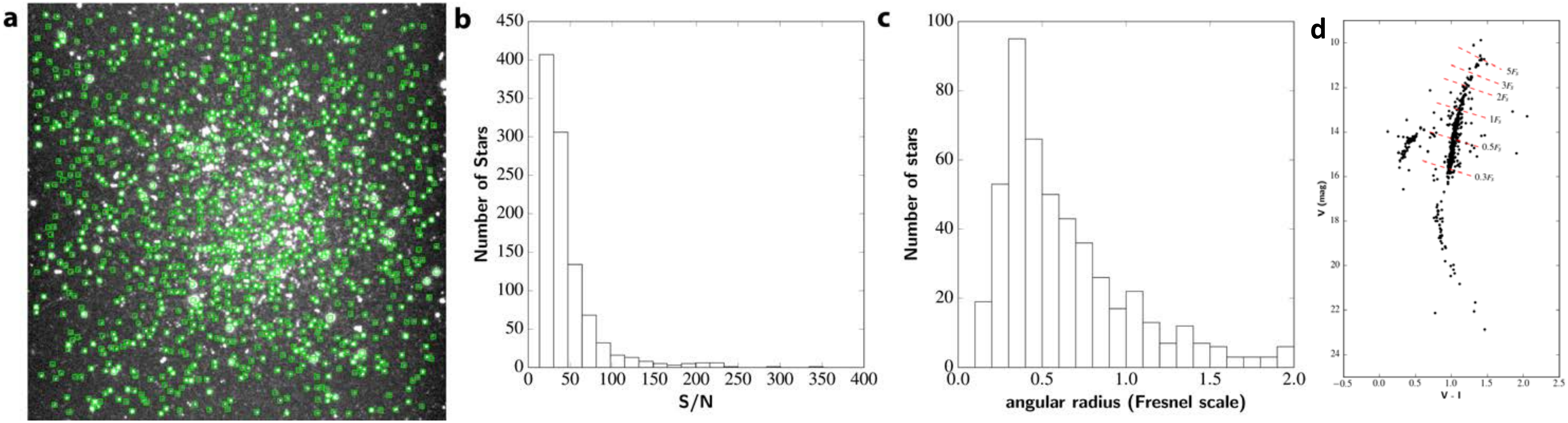
Name	RA and Dec	Ecliptic Latitude	Planned Observations	No. Stars per Field	Total No. Hours	Total No. Star hours
M22	18:36:23.94 -23:54:17.1	-0.4°	June-Aug 2015 - 2018	5,000	115	575,000
NGC 2158	06:07:25 +24:05:50	+0.4°	Sept-Feb 2015 - 2017	1,000	60	60,000
1850-1800	18:50:00 -18:00:00	+5°	June-Aug 2015 - 2018	2,000	50	100,000
1843-0647	18:43:00 -06:47:00	+15°	June-Aug 2015 - 2018	1,500	65	100,000



Movie available at
http://www.astro.caltech.edu/~gh/chimera/KBOM2261b.mkv

Movie available at
http://www.astro.caltech.edu/~gh/chimera/science_182.mp4

CHIMERA science Runs 2015+



- 5,000 stars can be monitored continuously in 2 colors at ~40 Hz
- 1 TB of image data each night!
- ~100,000 star-hours collected thus far
- 95% of stars have angular scale < 1 Fresnel scale (good!)
- Aperture photometry, PSF photometry and light curve extraction – *Navtej Singh*
- KBO search algorithm – *Hilke Schlichting*

CHIMERA Mk III

- 4Kx4K CMOS sensor under development at Andor Technologies
  - 12μm pixels
  - < 2 e- rms read noise
  - 80 fps from 4kx4k (rolling shutter)
  - ~ 60% QE (> 80% back-illuminated)
  - > 75K e- pixel well depth

- Front illuminated sensor – 18 months
- Back illuminated sensor – 24 months

- CHIMERA MK III will image ~0.5 deg x 0.5 deg

- Will monitor 50,000 stars simultaneously for KBO occultations

Summary

- EMCCD and CMOS sensors offer the opportunity to monitor relatively wide fields at high speed, opening up the transient sky on second and sub-second timescales
- EMCCDs offer excellent QE and extremely low read noise, and are easy to mosaic
- CMOS sensors have had problematic noise characteristics but offer the only avenue to truly wide-field, high-speed synoptic surveys
- The CHIMERA instrument has been used as a testbed for EMCCD and CMOS technology at Palomar
- The current system uses two EMCCDS to image a 5 x 5 arcminute FOV at 40 Hz in two photometric bands to search for KBO occultations
- A future system will use two 4K x 4K CMOS sensors to image 0.5 x 0.5 degrees at 40 Hz