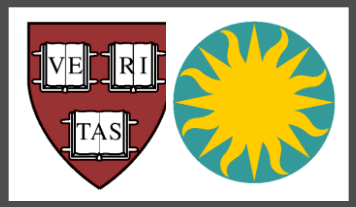
The Taiwanese-American Occultation Survey (TAOS I)

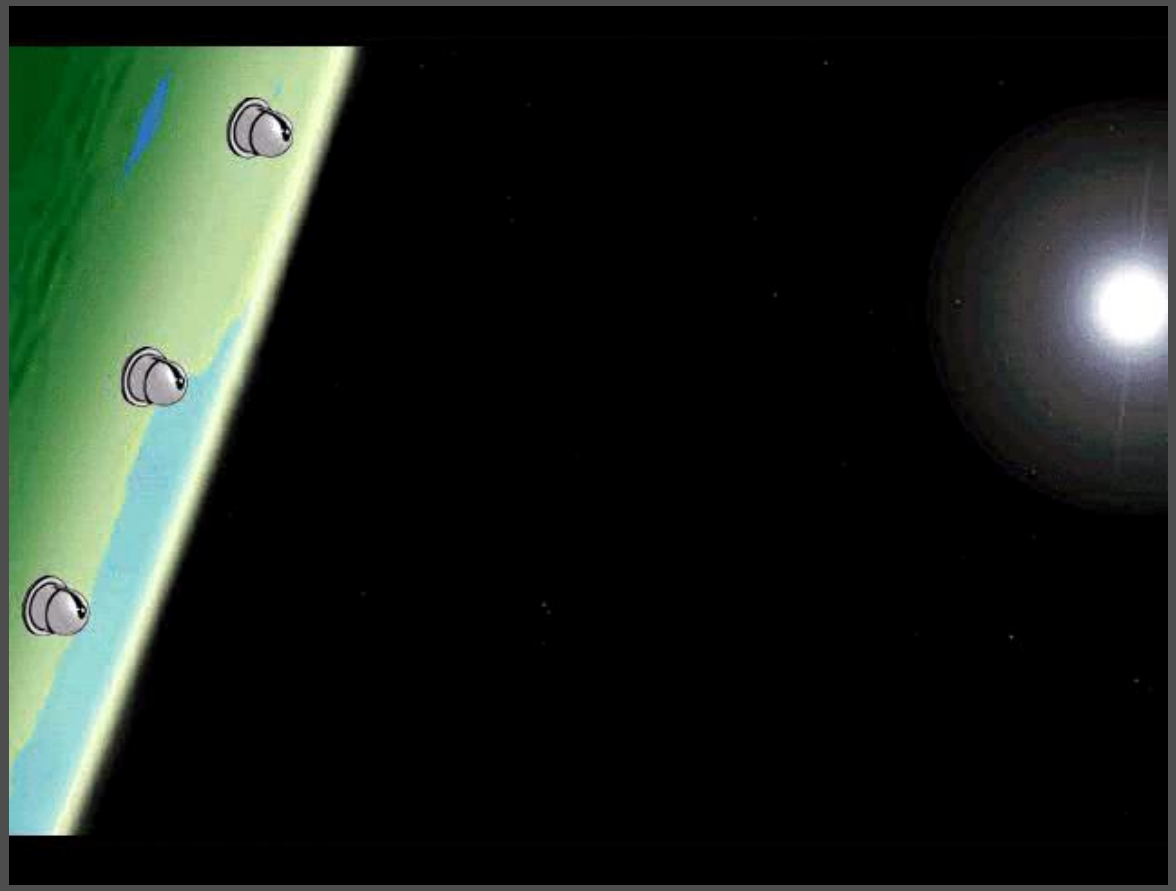
Matthew Lehner

ASIAA

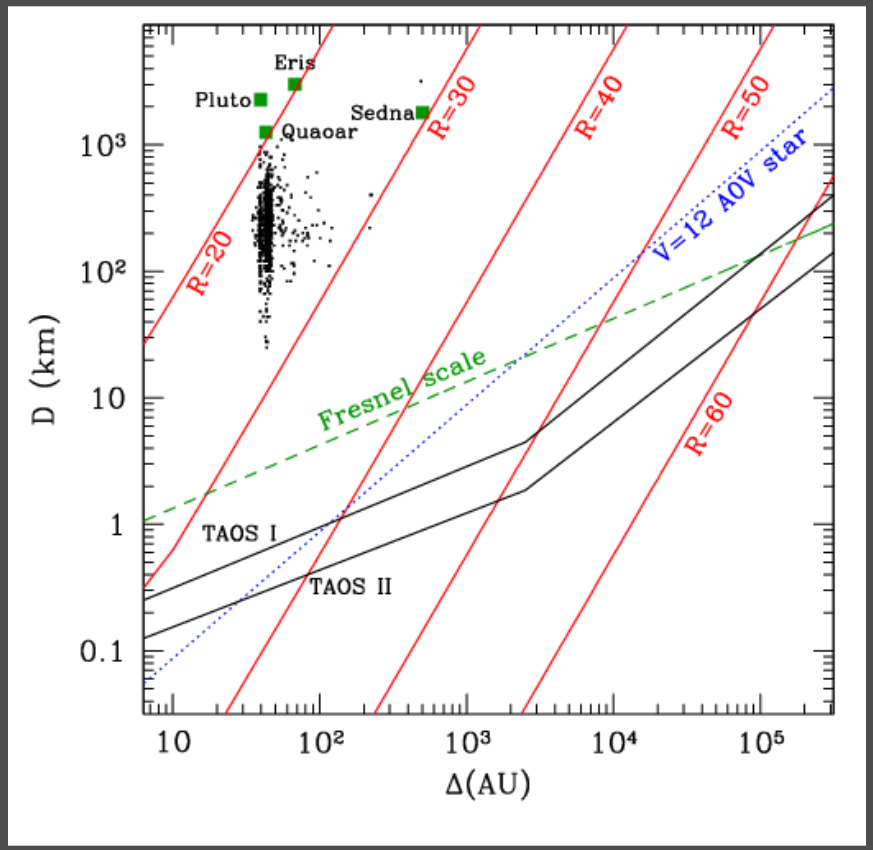
The TAOS Institutional Partners:



Occultations of stars by KBOs



Why attempt an occultation survey?



- Direct searches well-suited to objects larger than R ~30 km
- Much of the mass may be in smaller objects
- Models predict a major change in size distribution for smaller objects
- Occultations of bright stars can reveal smaller and/or more distant objects!
- No orbital information!
  - Can measure inclination distribution if enough events.

Challenges

- Rapid photometric measurements (5 Hz)
- Follow enough stars (500 - 1000) for significant rate
- Credible result

Occultation Events

Fresnel Scale:

$$F = \sqrt{\lambda a / 2}$$

F = 2 km at 50 AU

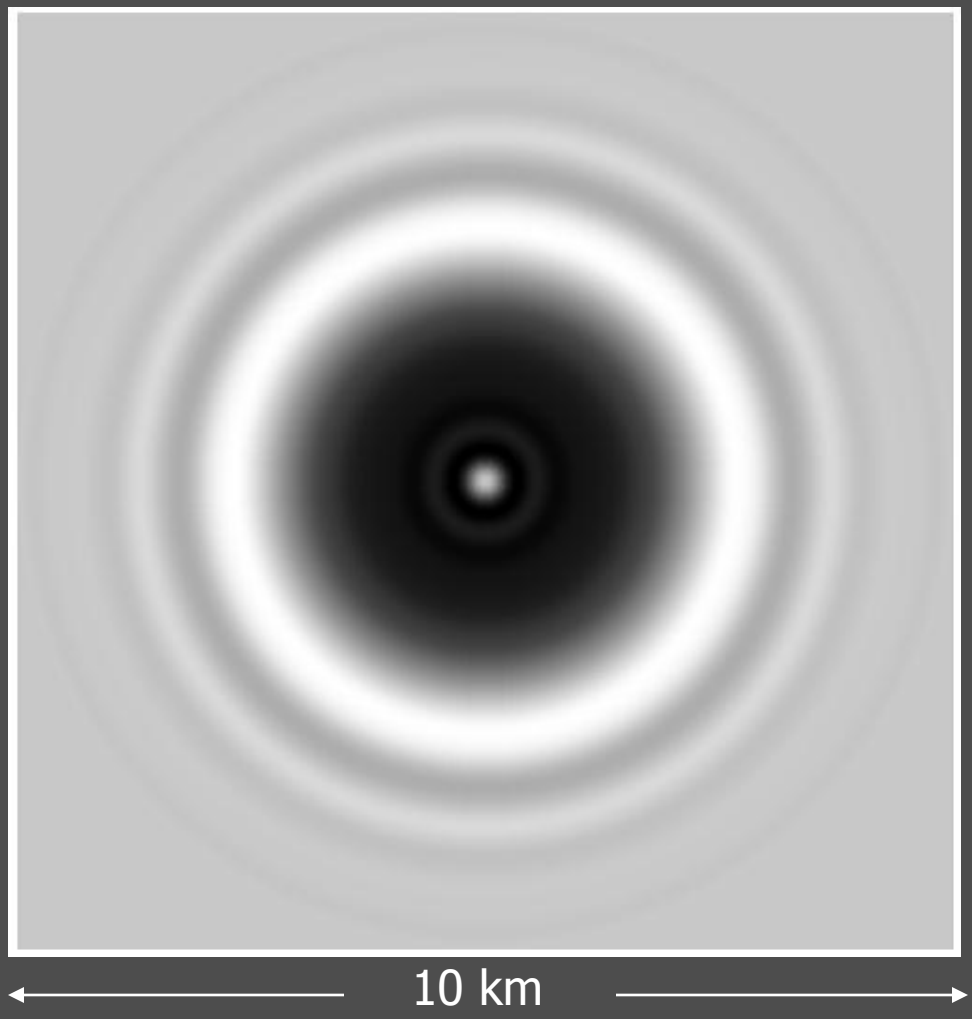
Minimum event width:

$$W = 2\sqrt{3}F$$

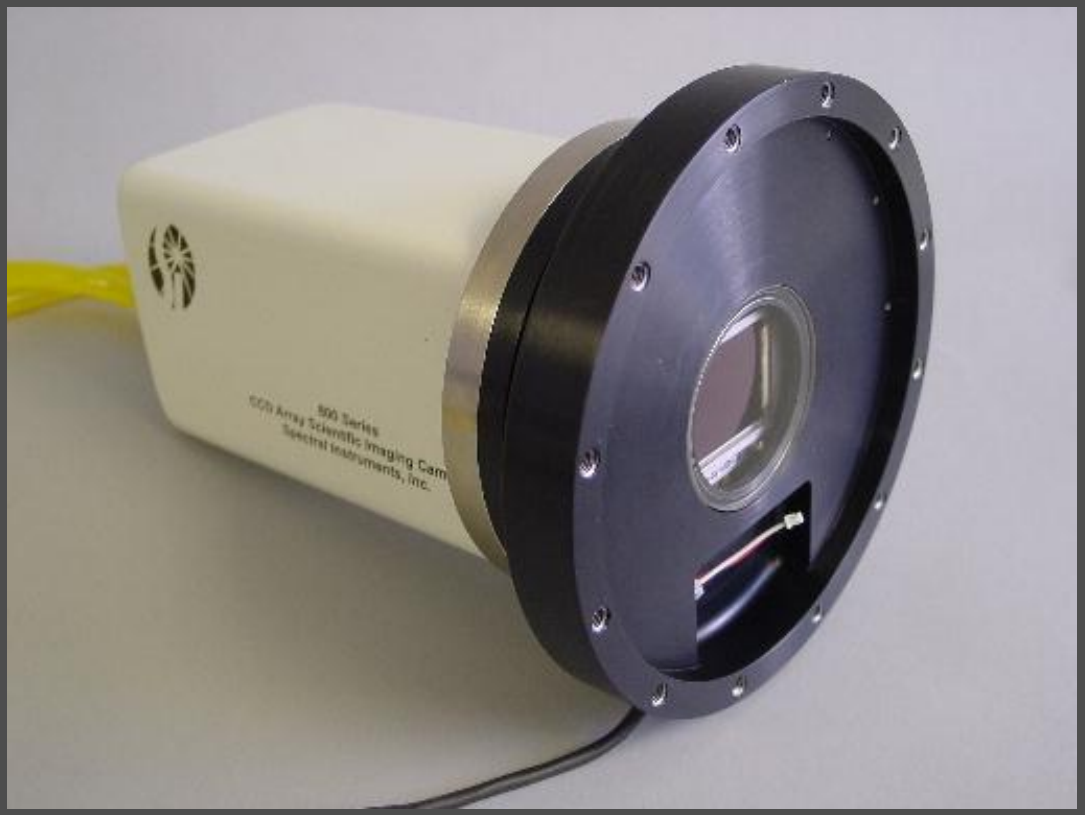
Objects in relative motion,

$v \sim$ 25 km/sec

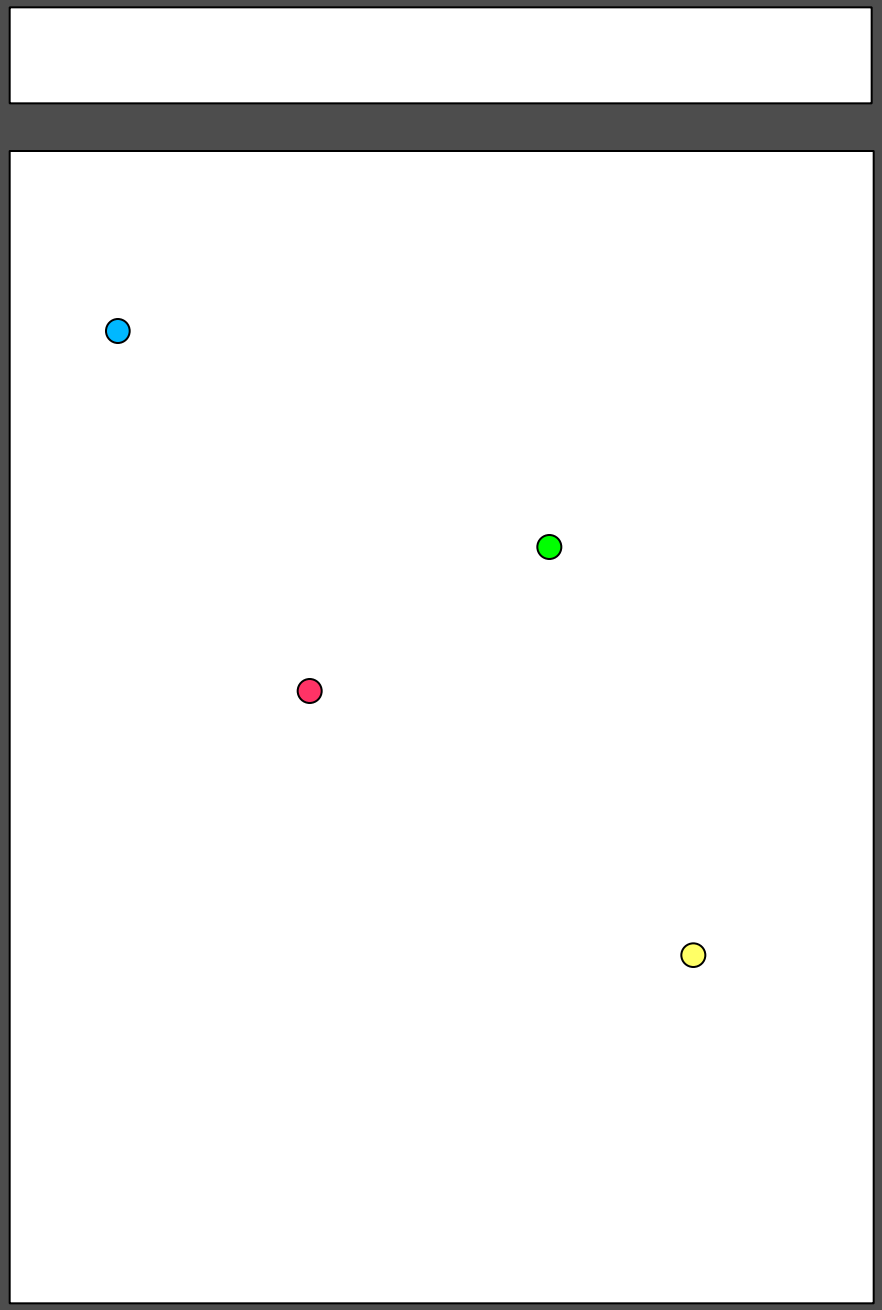
Event timescale ~200ms!

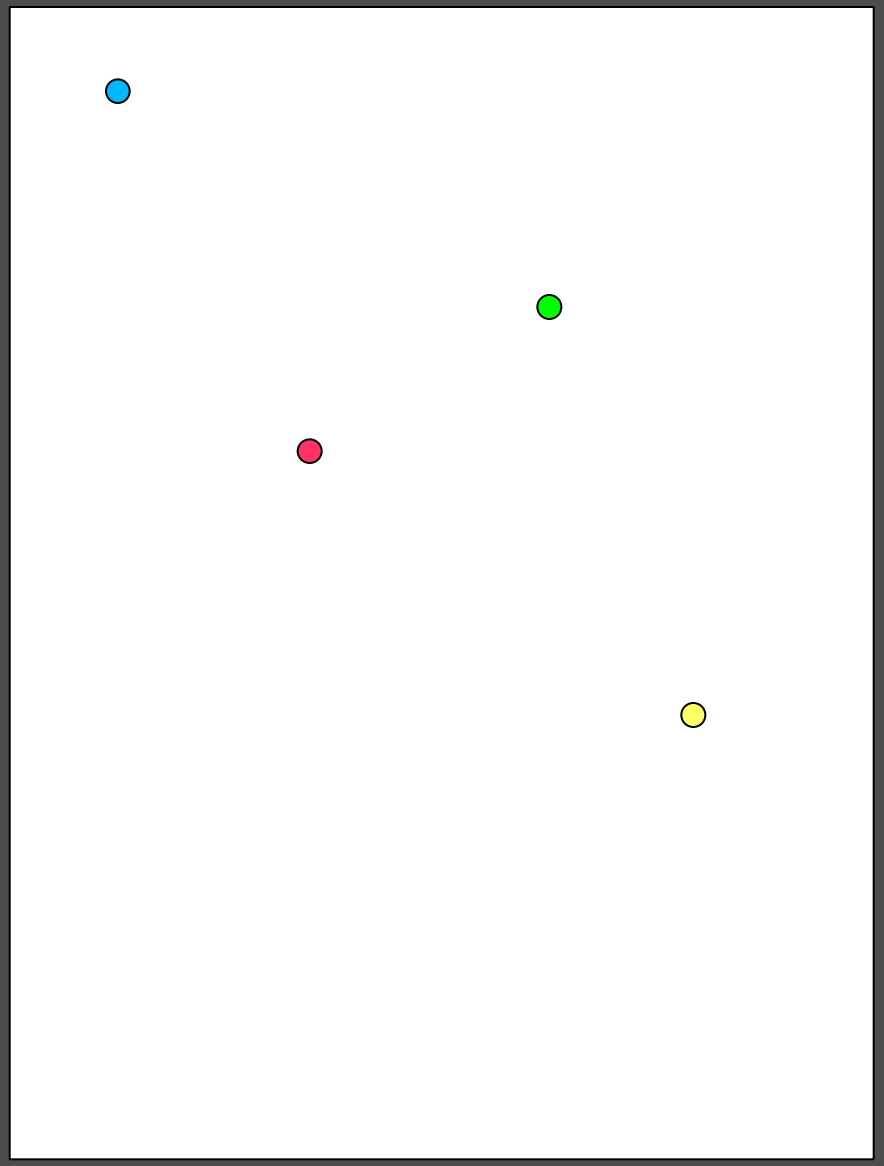


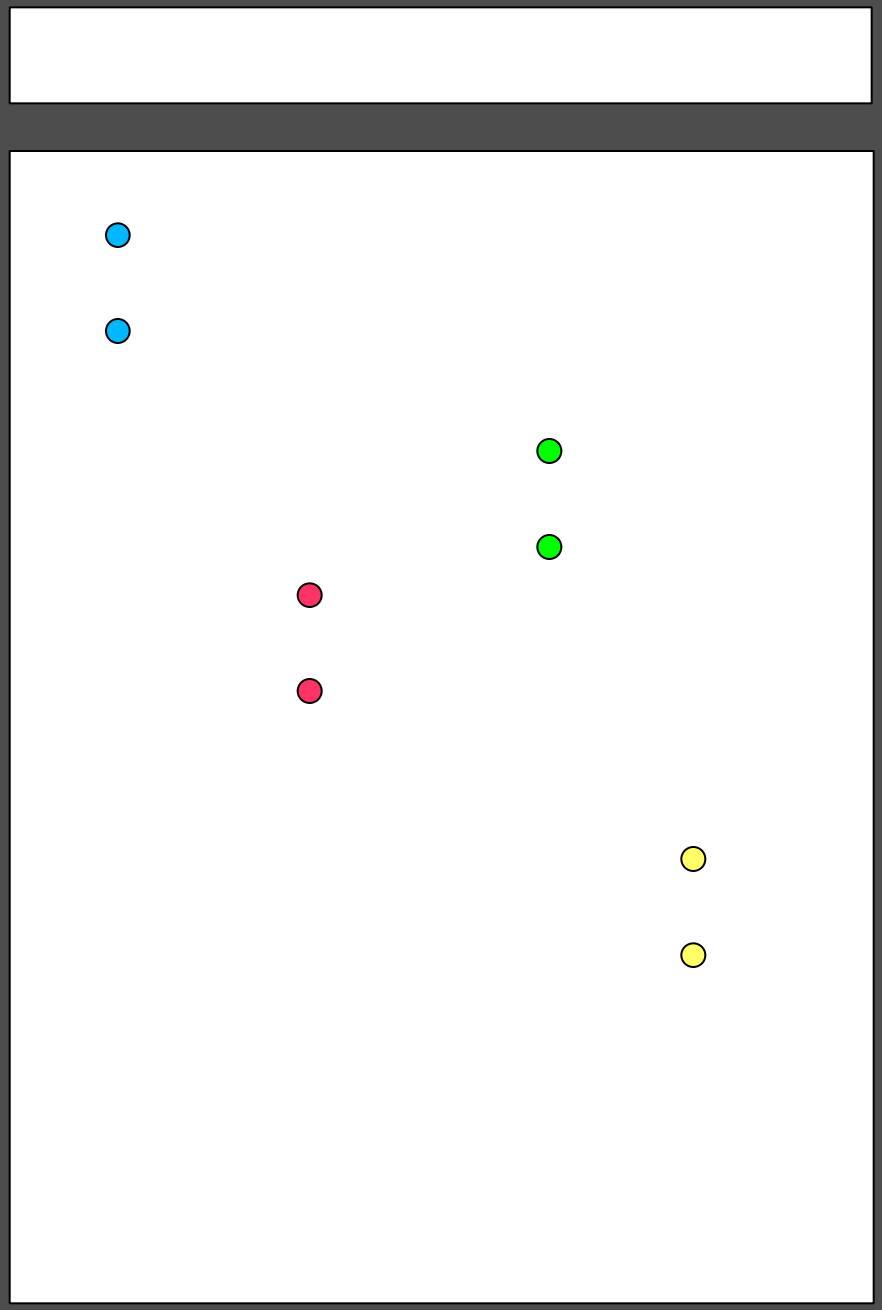
Spectral Instruments SI-800 thinned, backside illuminated, 2048×2052 CCD cameras:

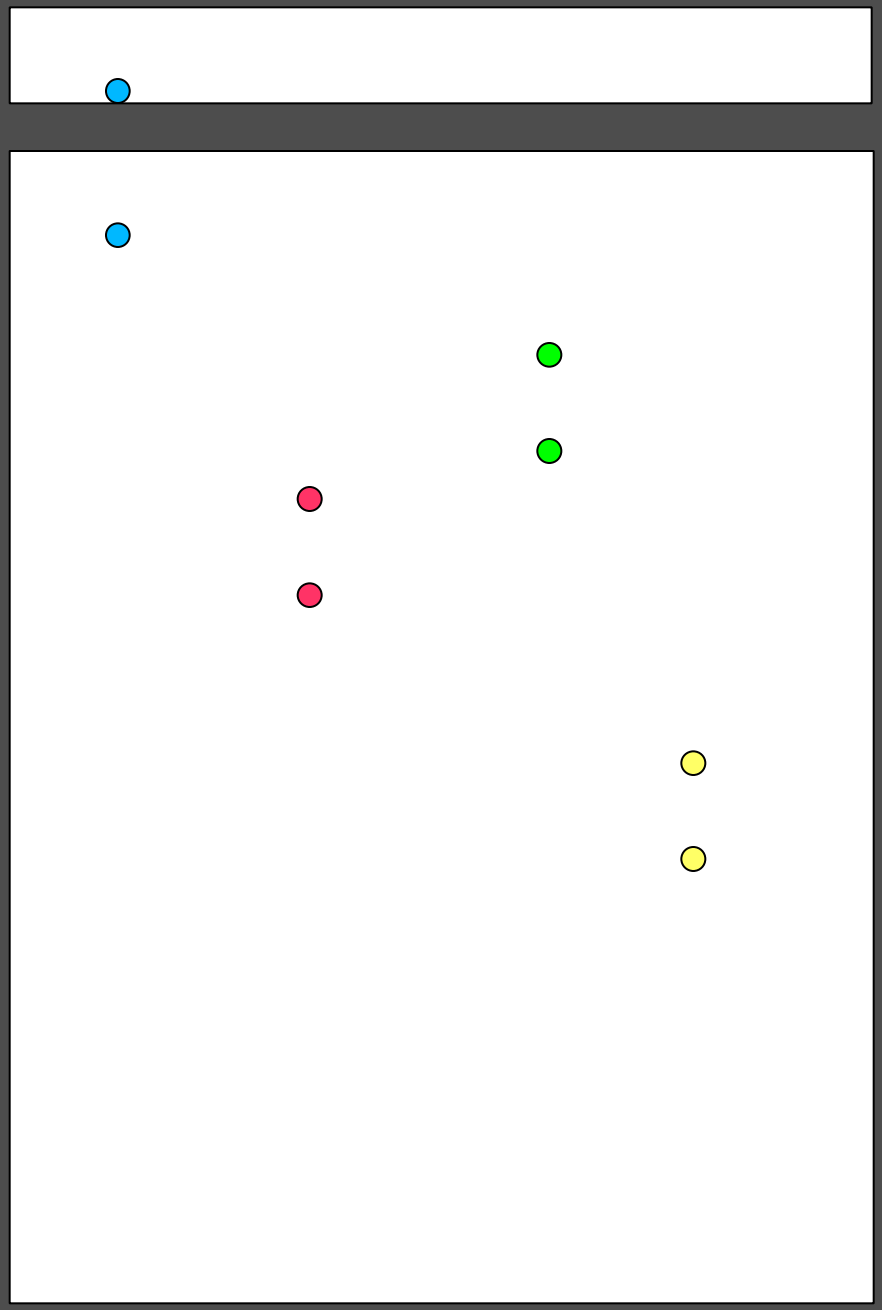


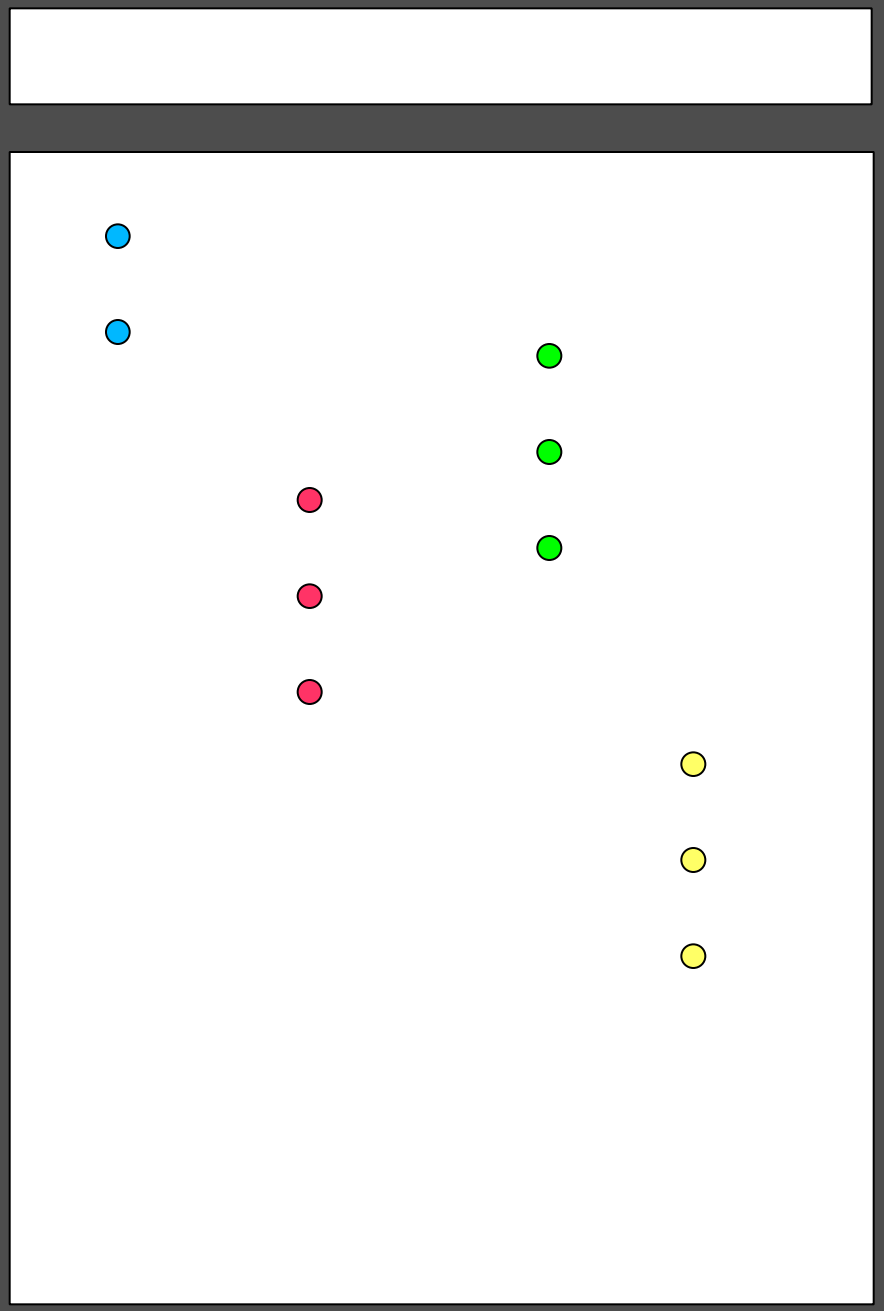
Readout time of 2.5 seconds, want 5 Hz sampling

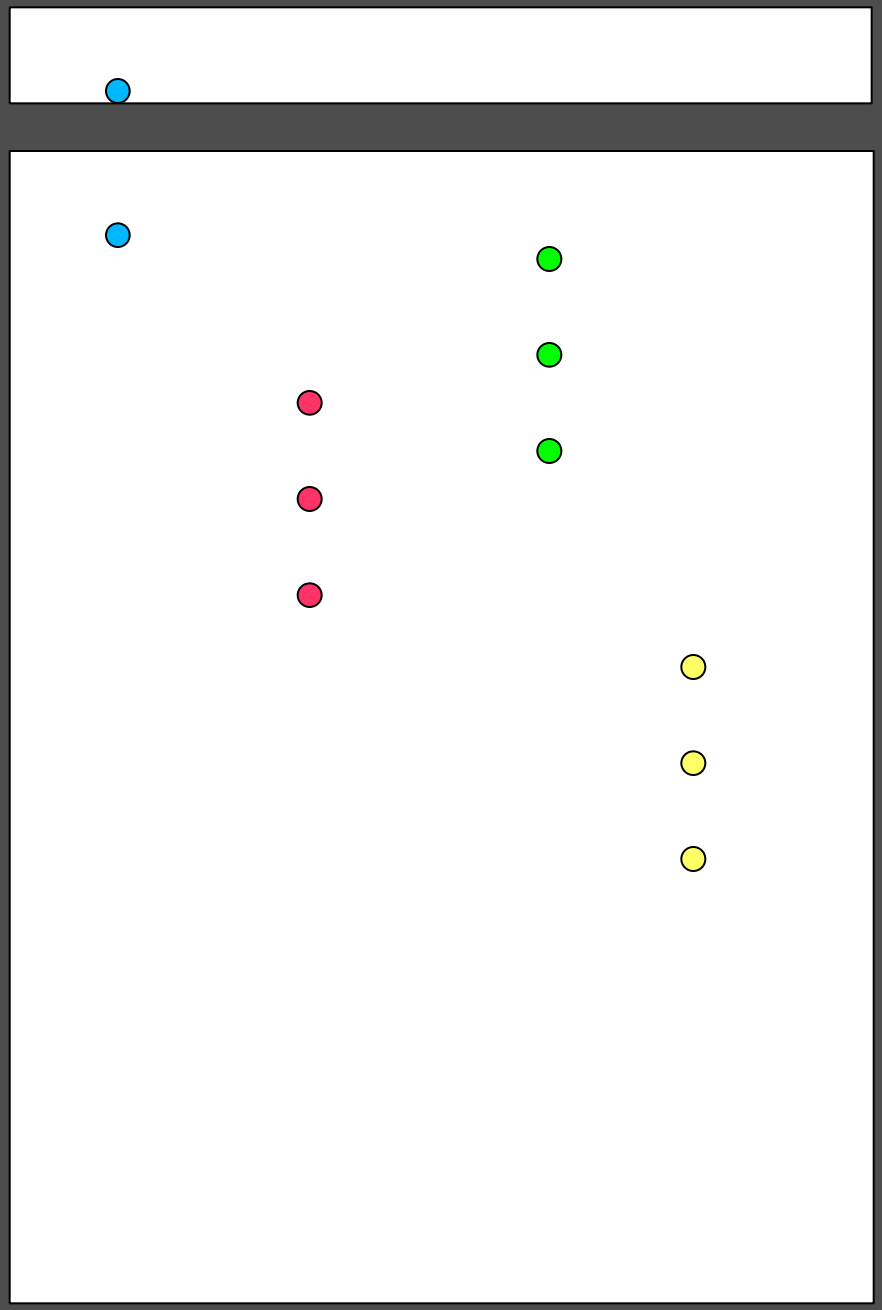


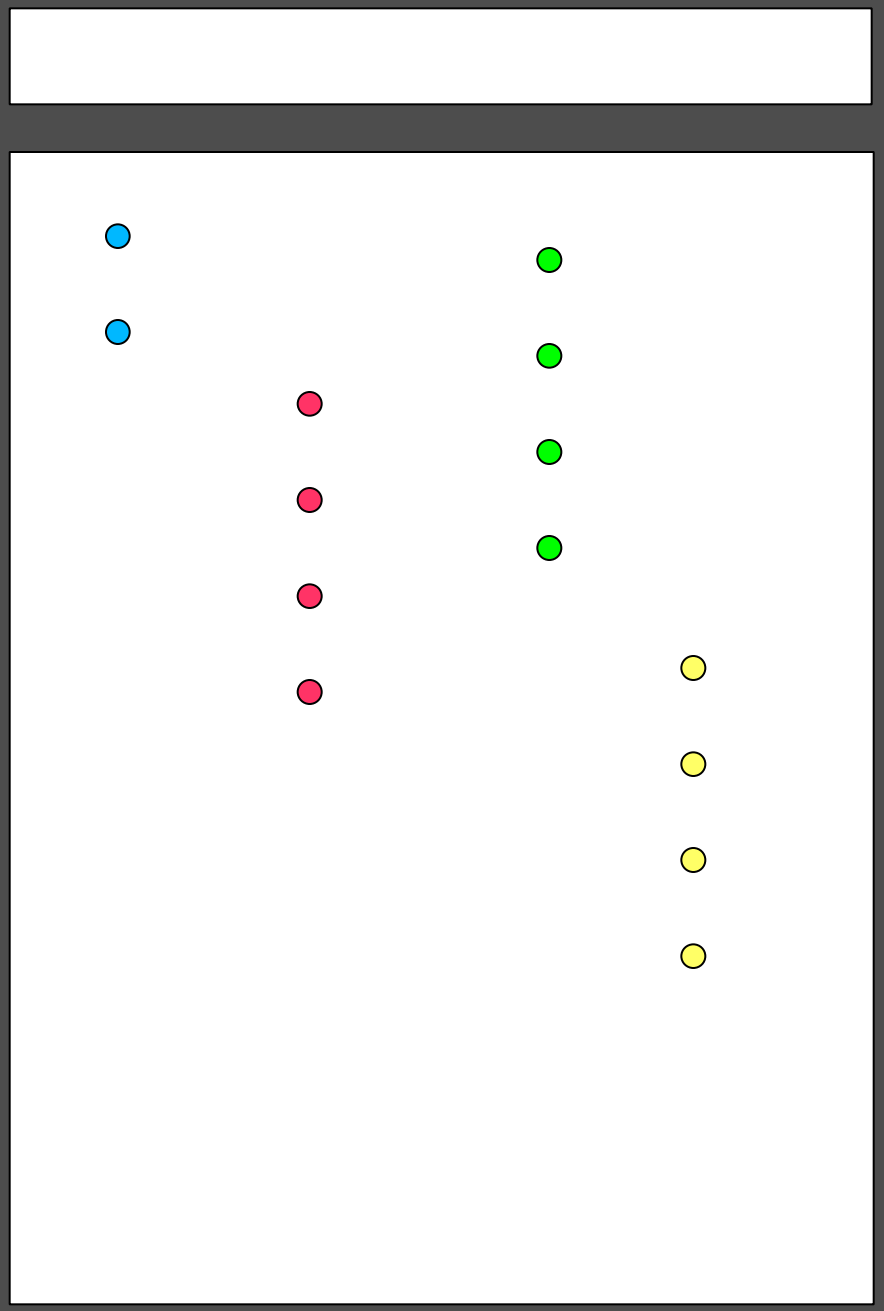


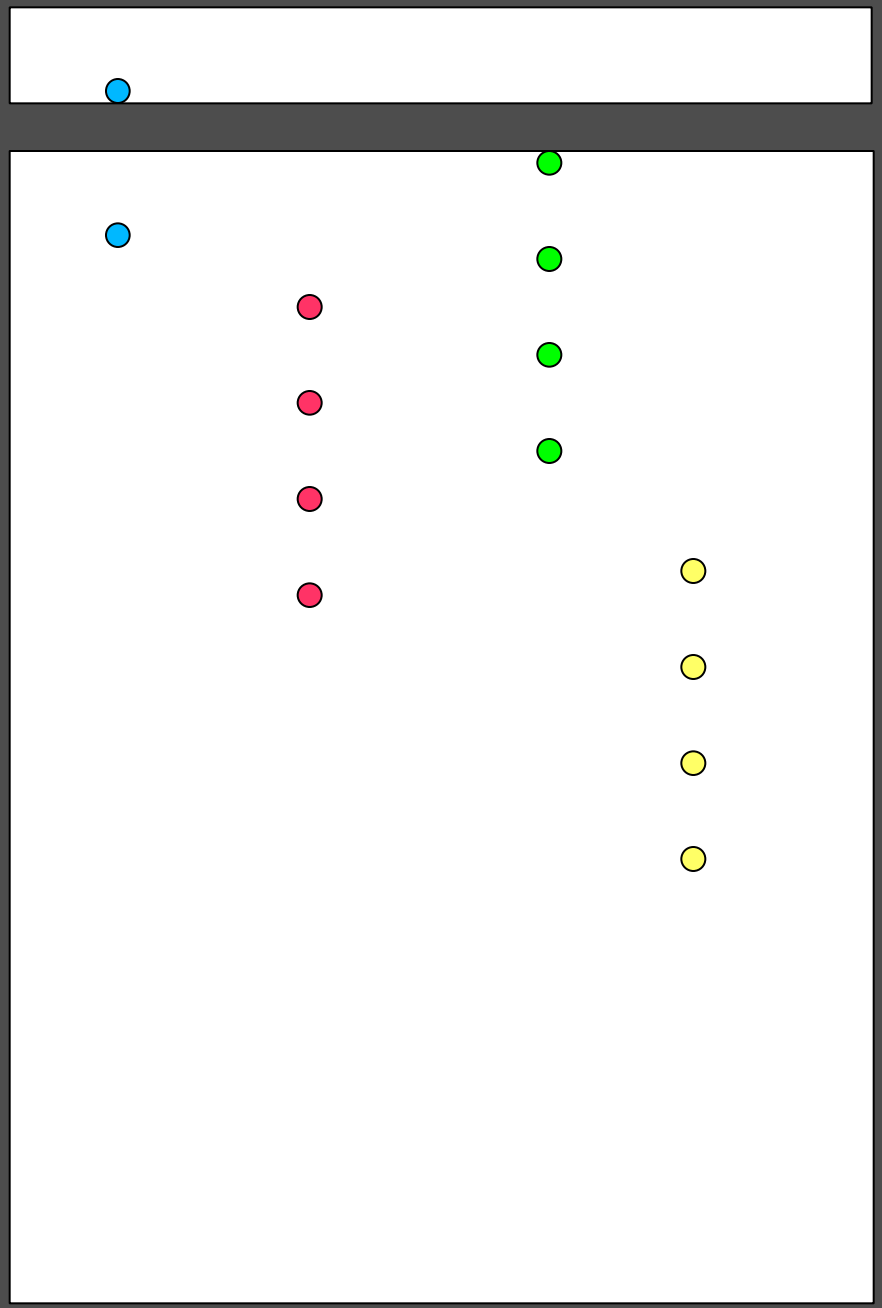


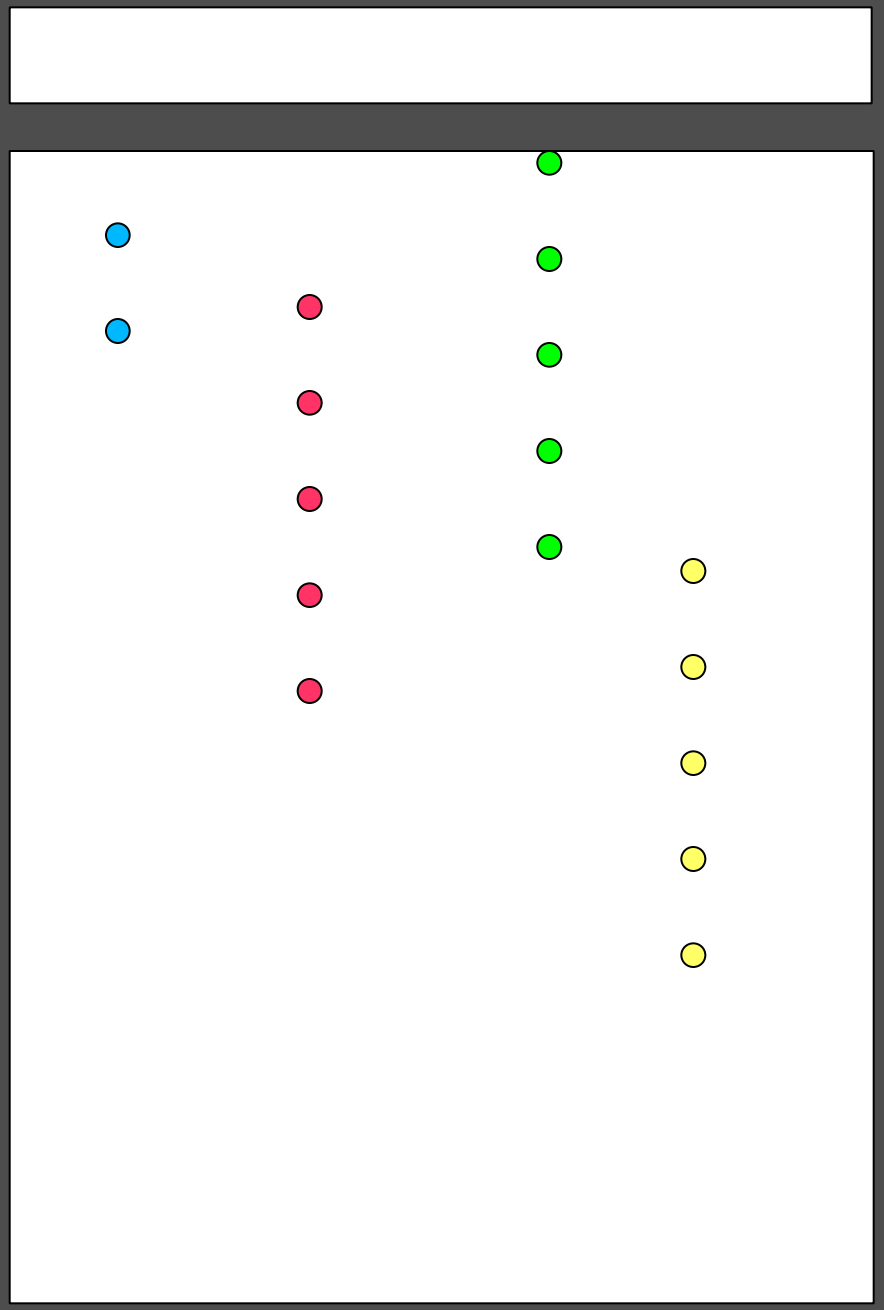


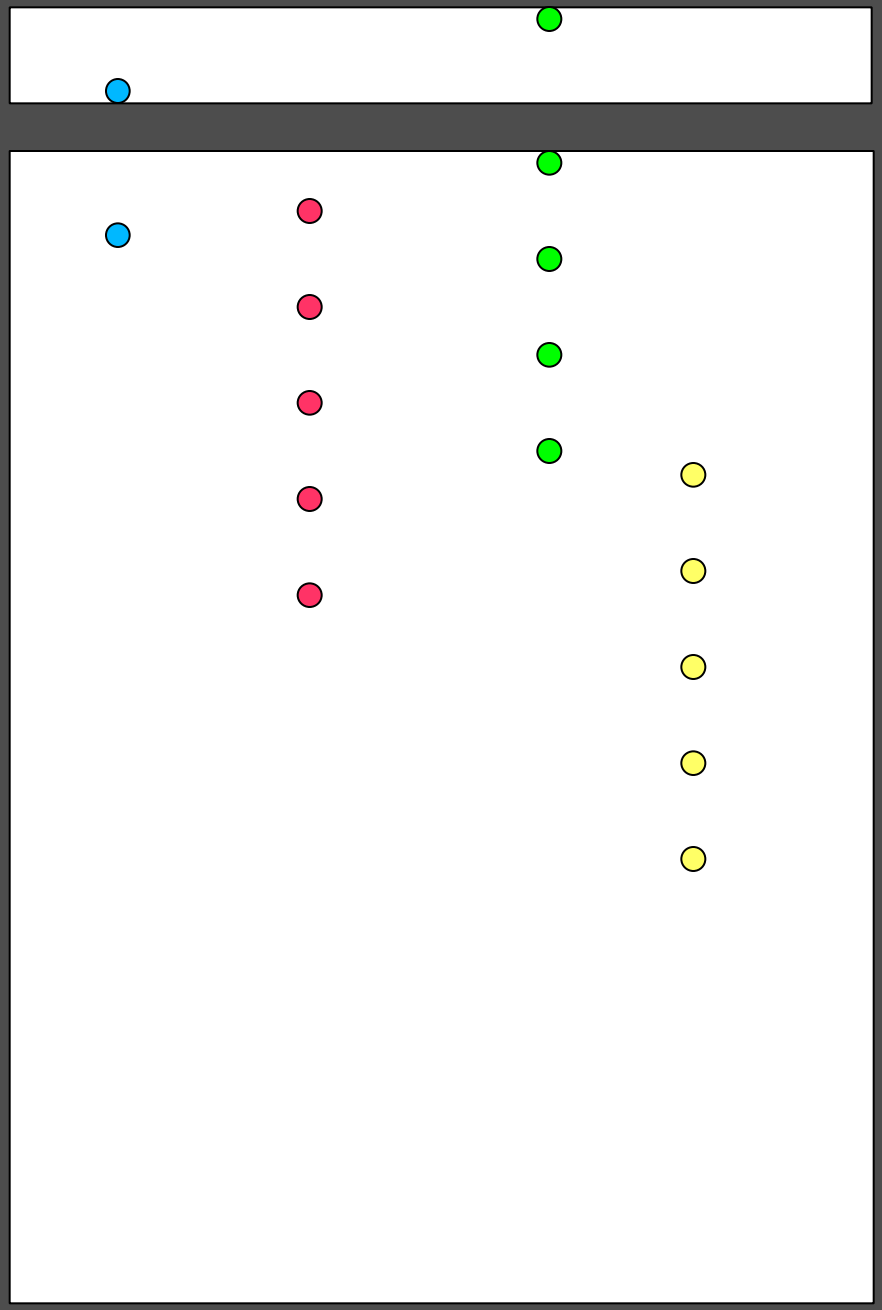


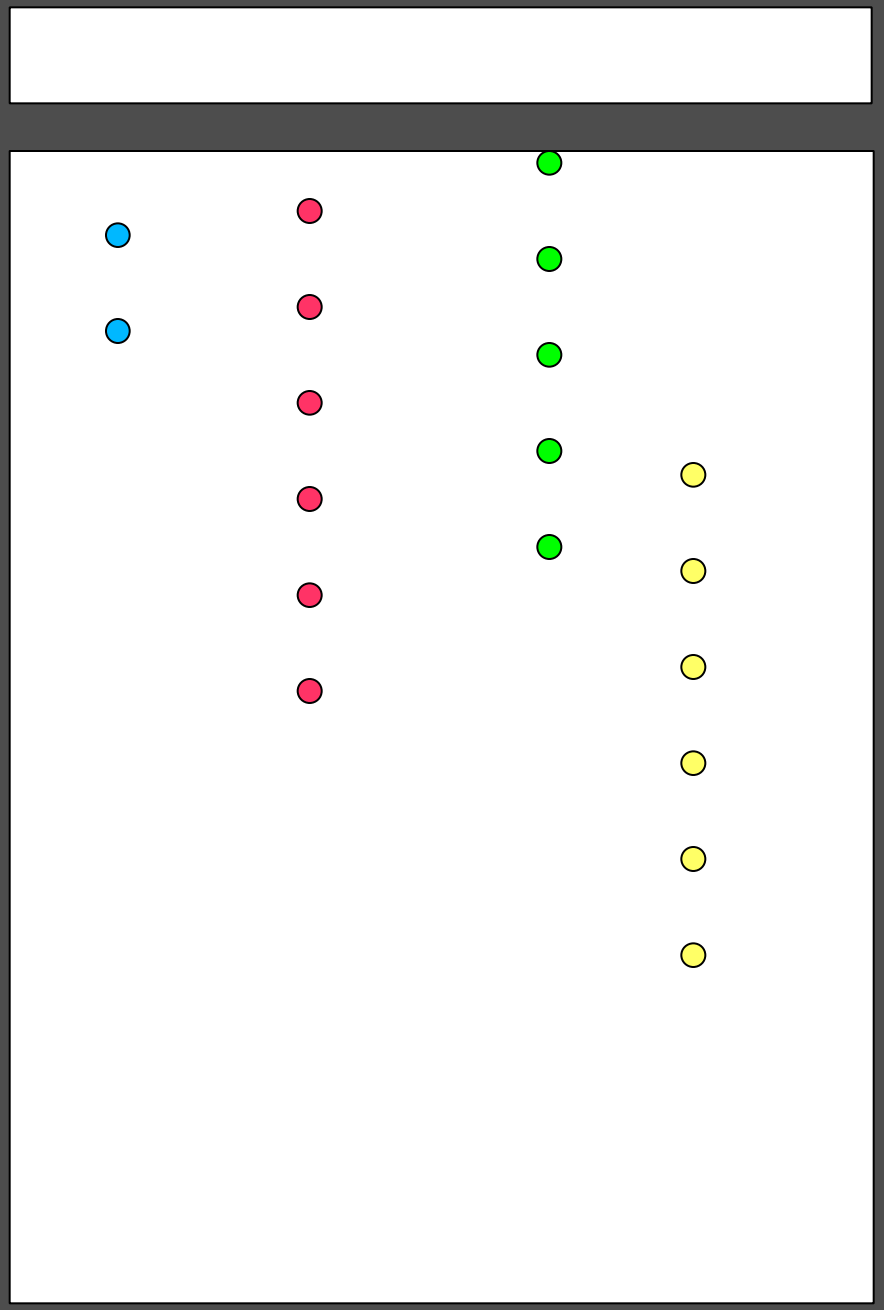


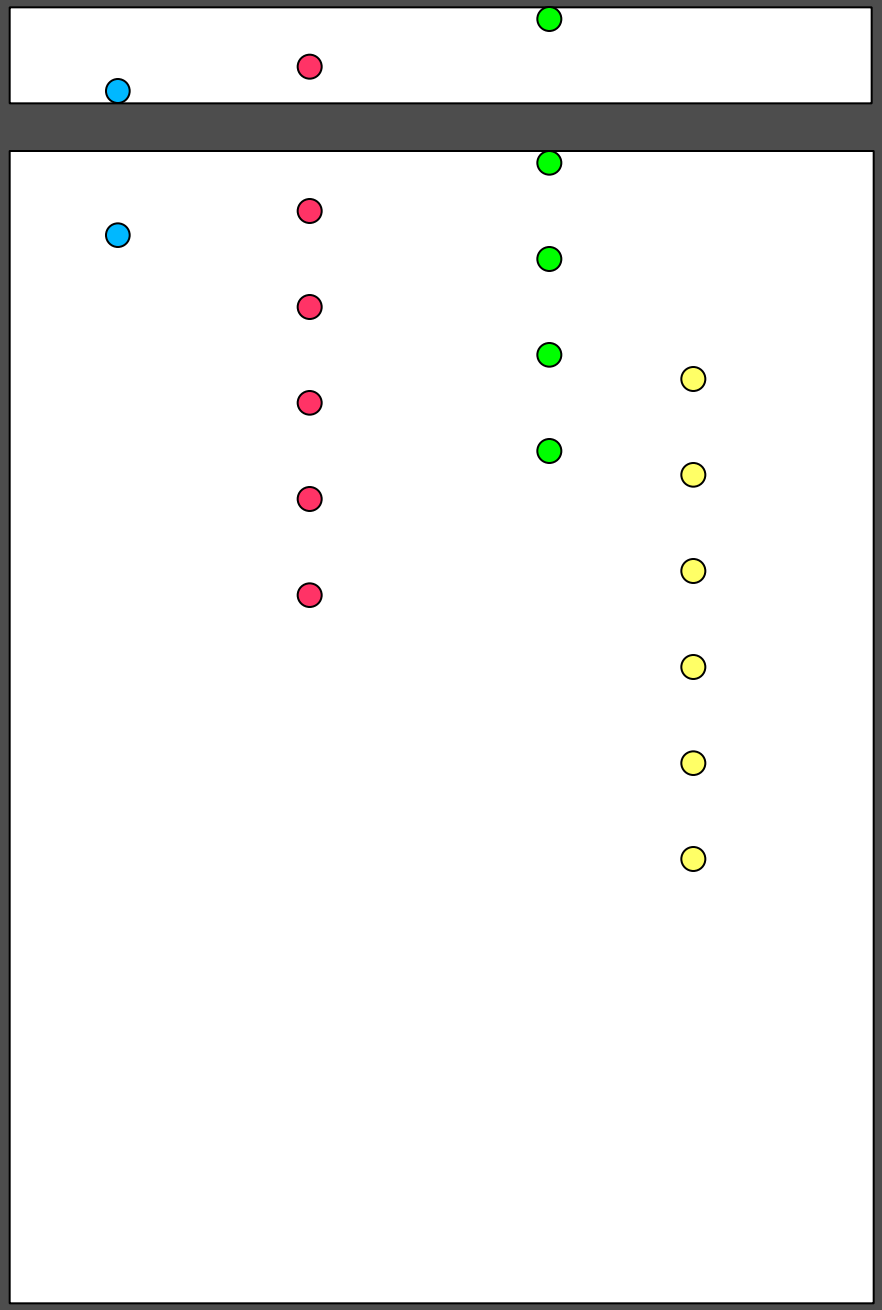


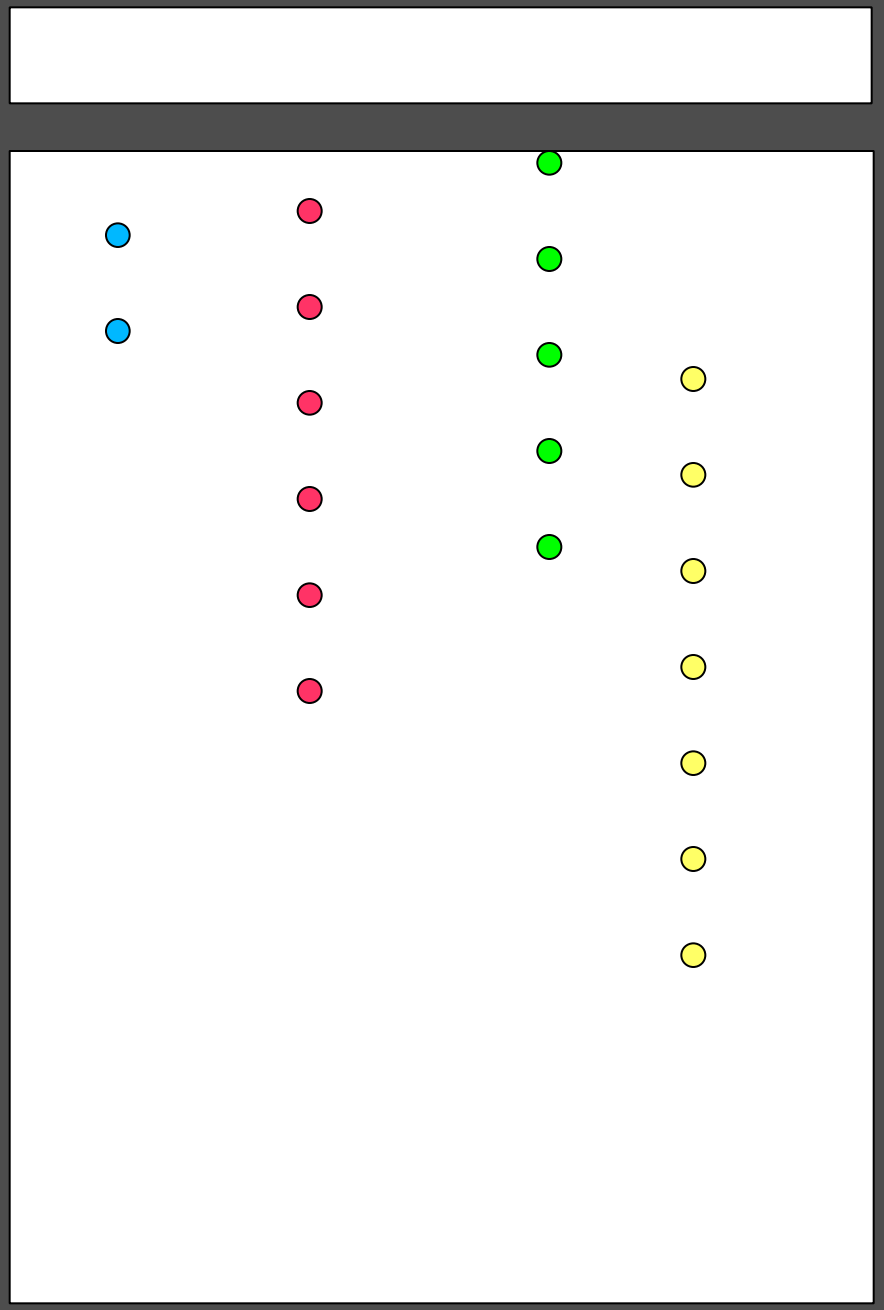


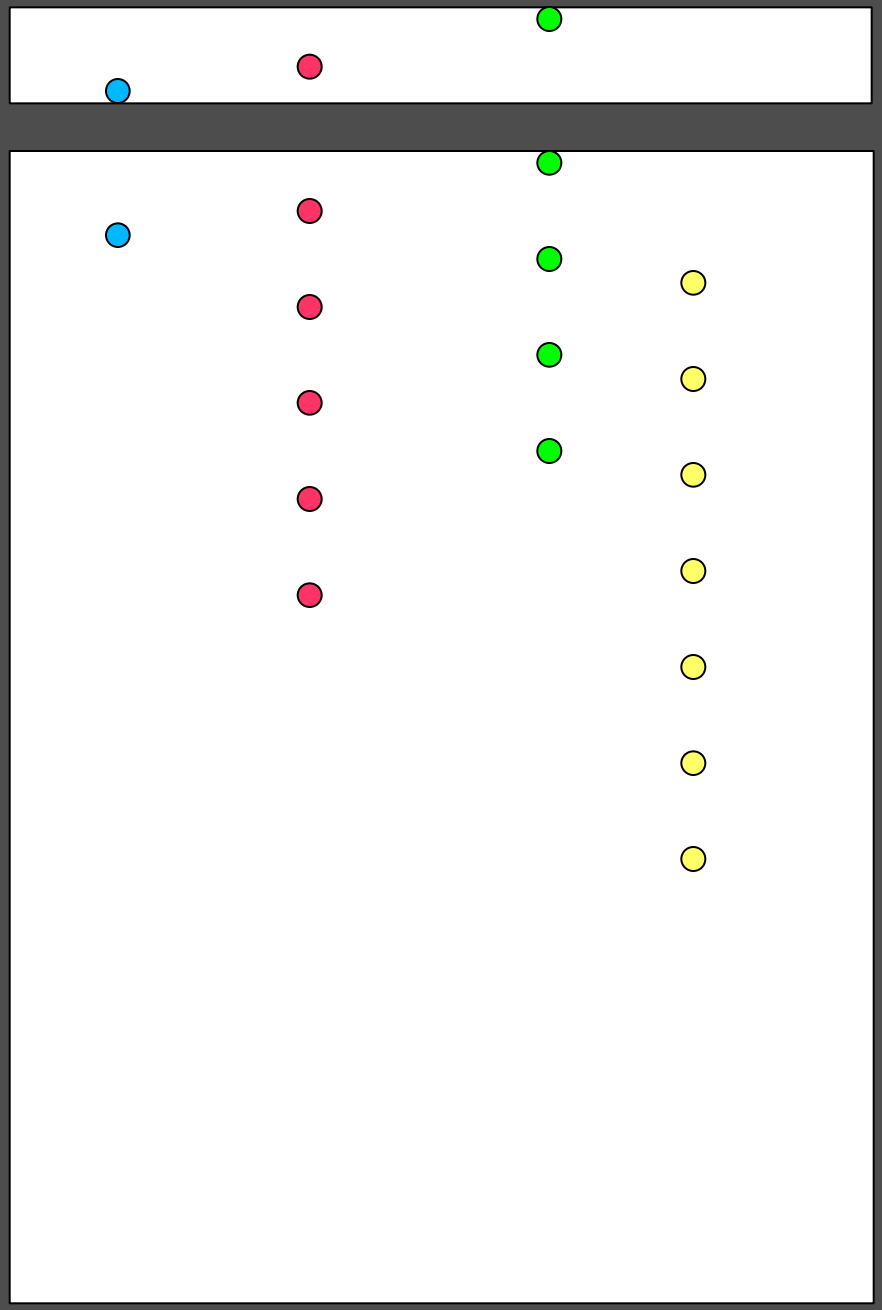


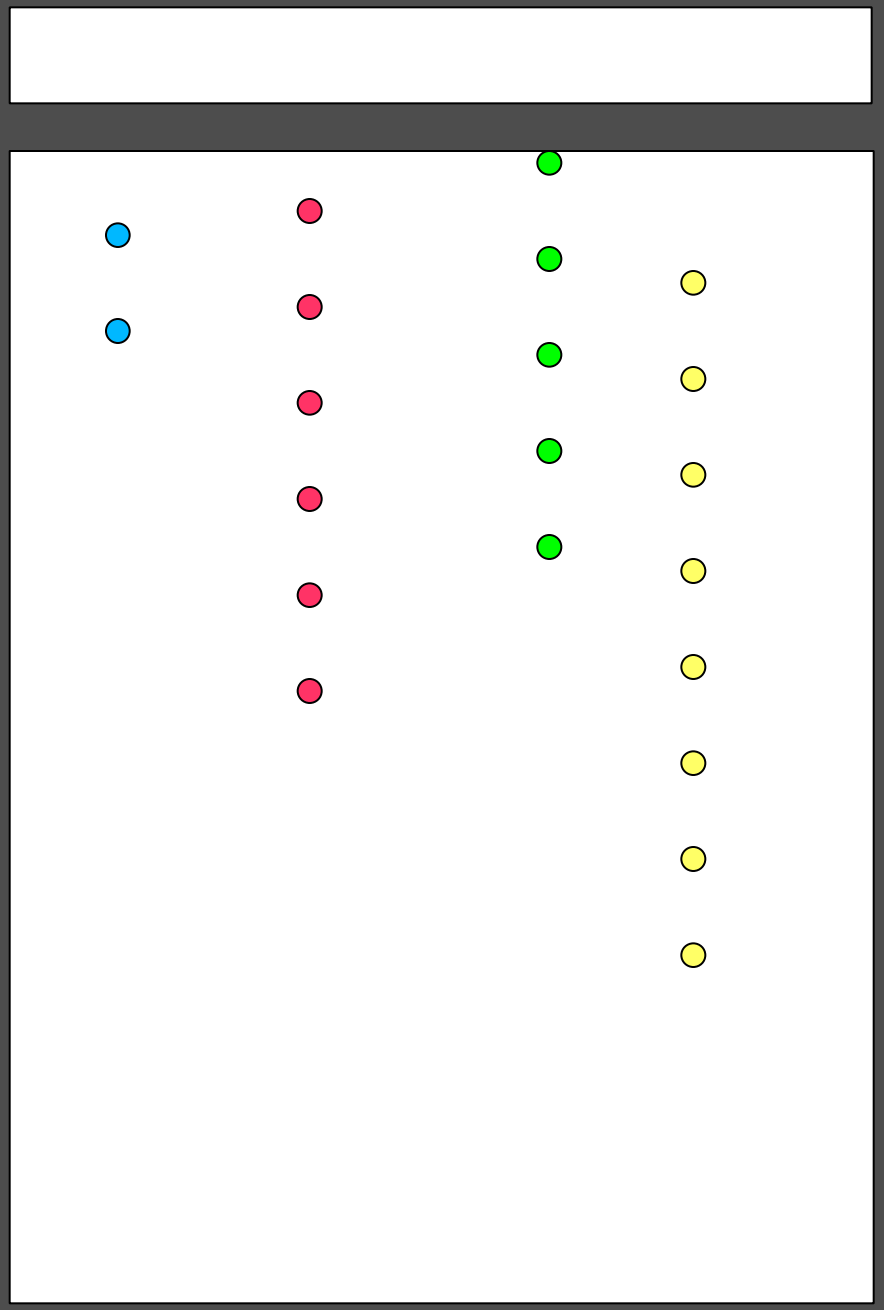


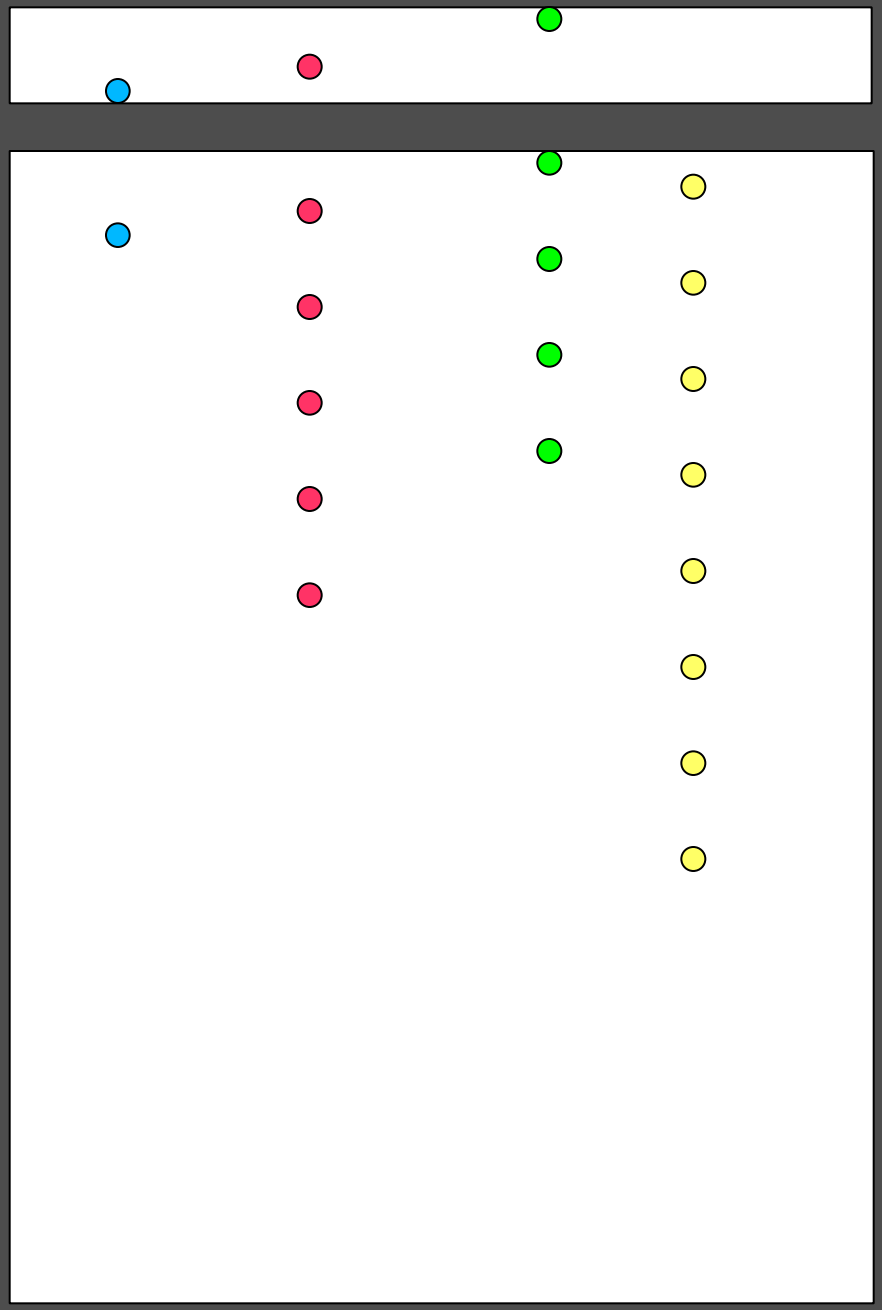


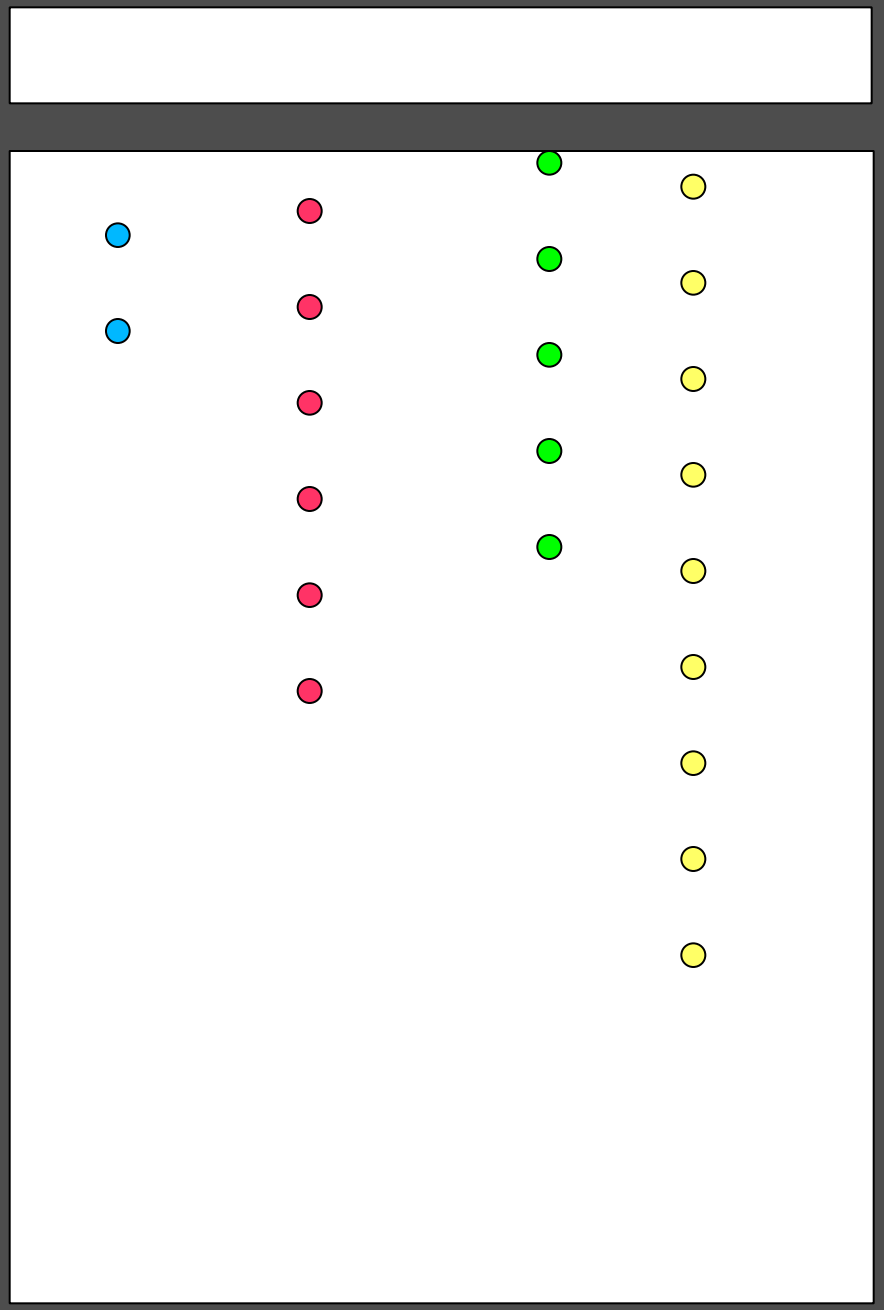


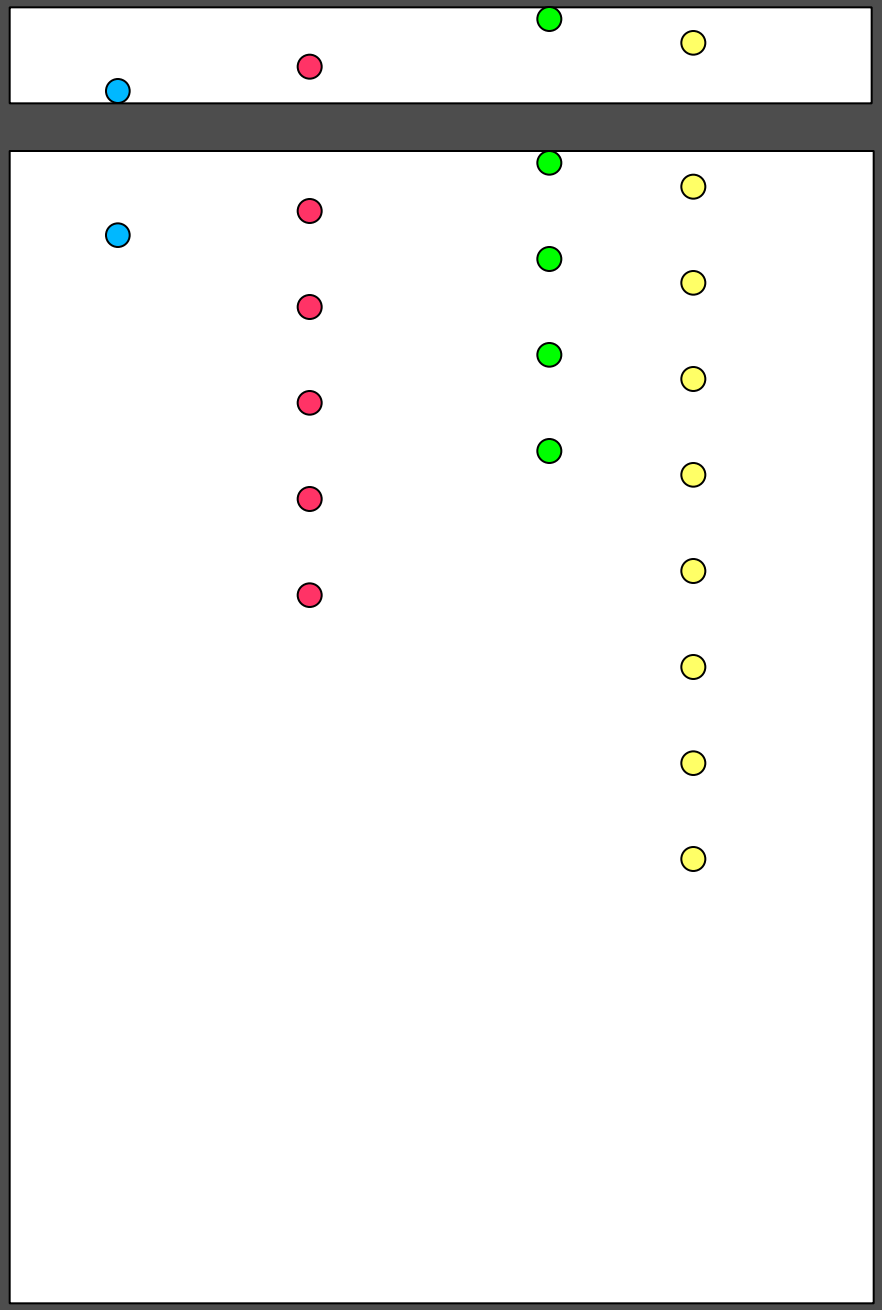






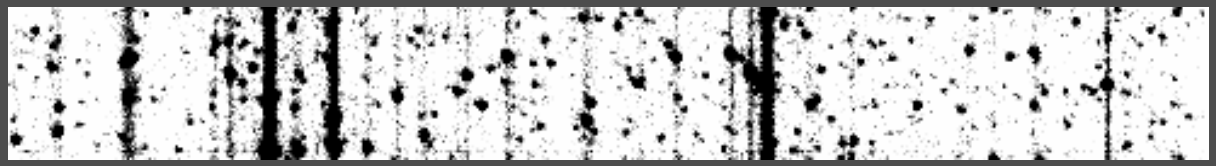






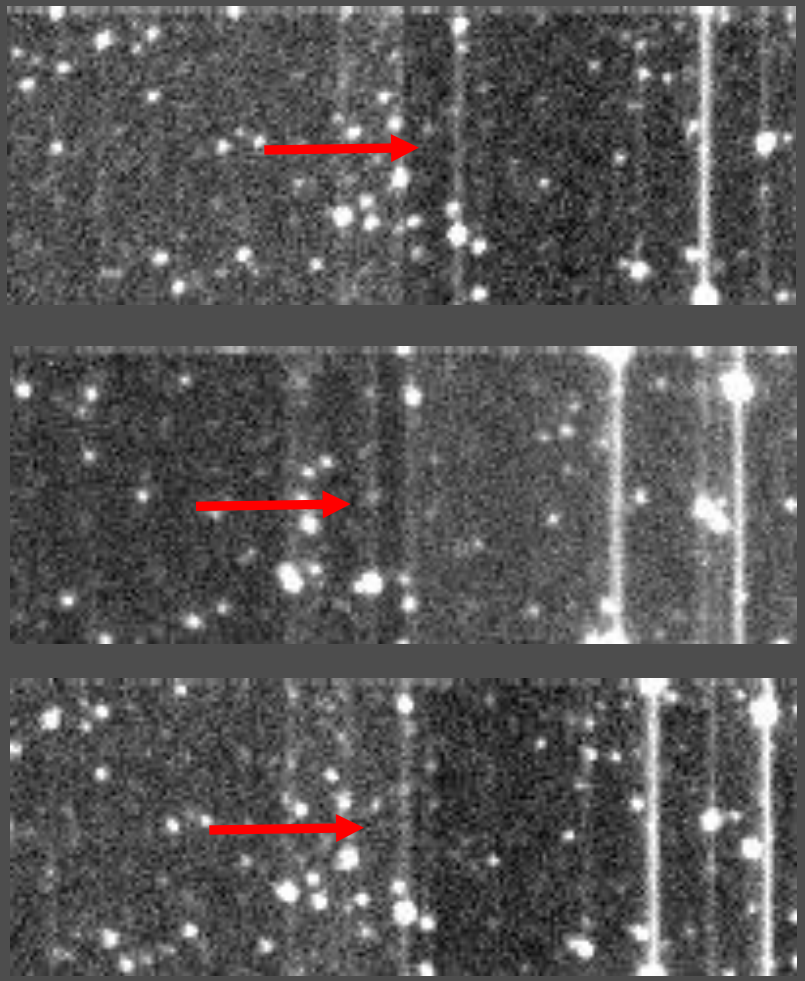
“Zipper Mode”

- “rowblocks” of 76 rows
- Sky background 27 times as bright
- Streaks from bright stars
- **Readout every star in image at 5 Hz**



512×76 rowblock

Occultation by (286) Iclea
2006 February 6



TAOS: four small robotic telescopes

- 50 cm aperture
- F/2.0
- 3 square degree field
- Synchronized imaging

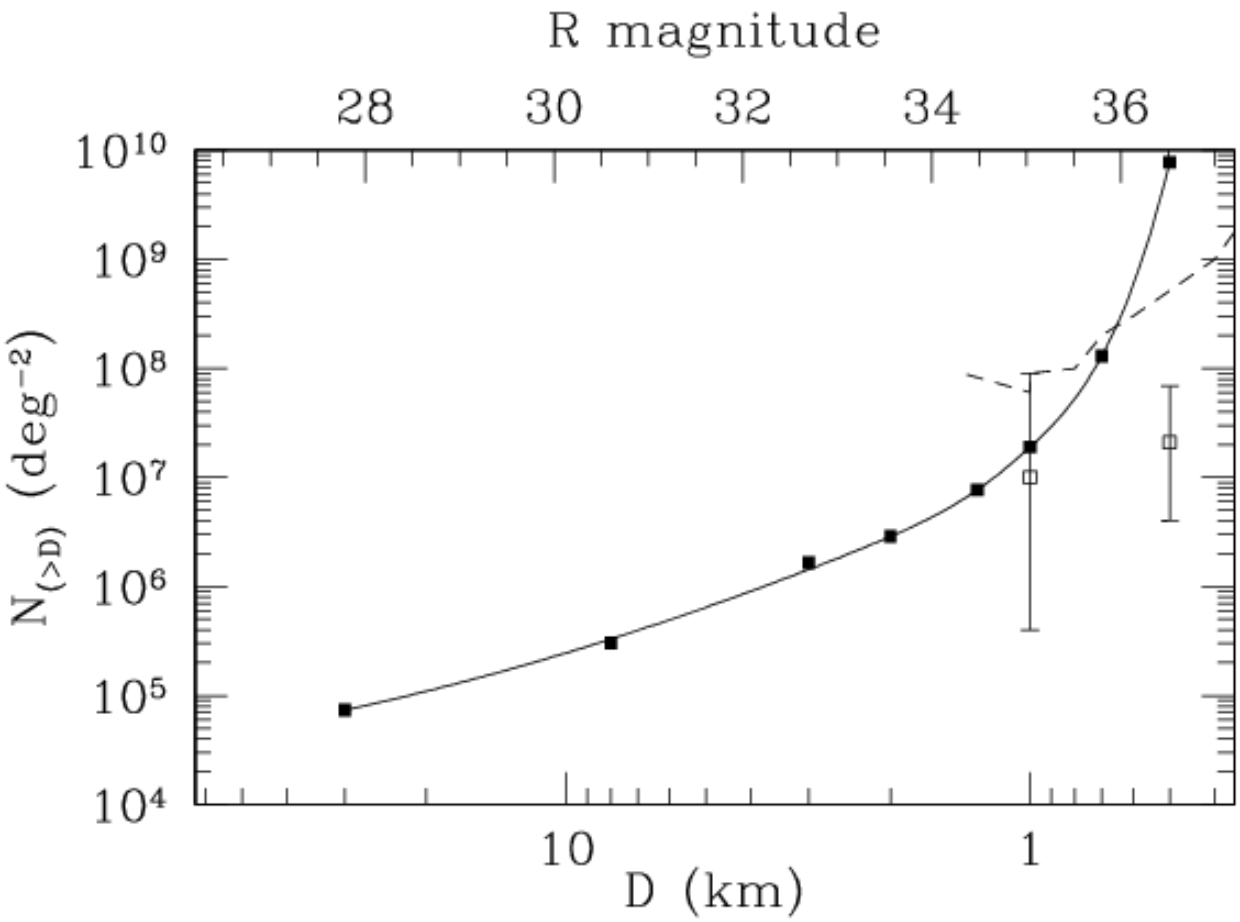
The telescopes operate at the Lulin Observatory in Central Taiwan

- Moderate elevation (2850 meters)
- Dark sky (comparable to Kitt Peak)
- 200 50 clear nights per year

The telescopes operate at the Lulin Observatory in Central Taiwan

The telescopes operate at the Lulin Observatory in Central Taiwan

TAOS Results from 2009



The Taiwanese-American Occultation Survey (TAOS I)

Matthew Lehner

ASIAA

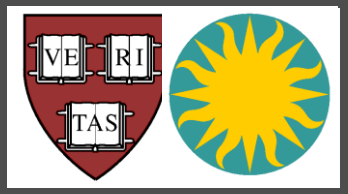
The Trans-neptunian Automated Occultation Survey (TAOS II)

Matthew Lehner

ASIAA

The TAOS II Partners:

Academia Sinica Institute of Astronomy and Astrophysics



Harvard-Smithsonian Center for Astrophysics

Yonsei University

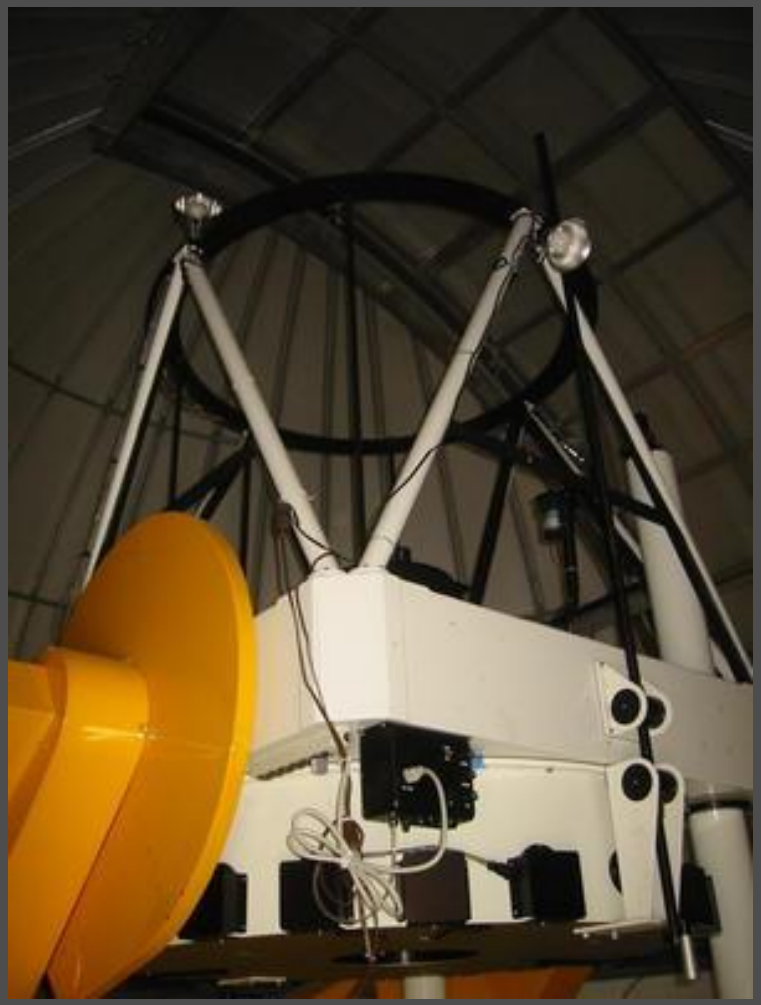
Universidad Nacional Autónoma de México

Design Goal: 100×Event Rate

- 5 times more of observing time
  - 250 observable nights/yr
- 1-10 times higher event rate (model dep.)
  - 20 Hz sampling, higher S/N
  - smaller objects
- 10 times more stars monitored
  - R_{limit}= 17.5 with 1/2 FOV
  - 40 times higher SNR needed
    - Larger aperture
    - Better seeing & sampling
    - No zipper mode!

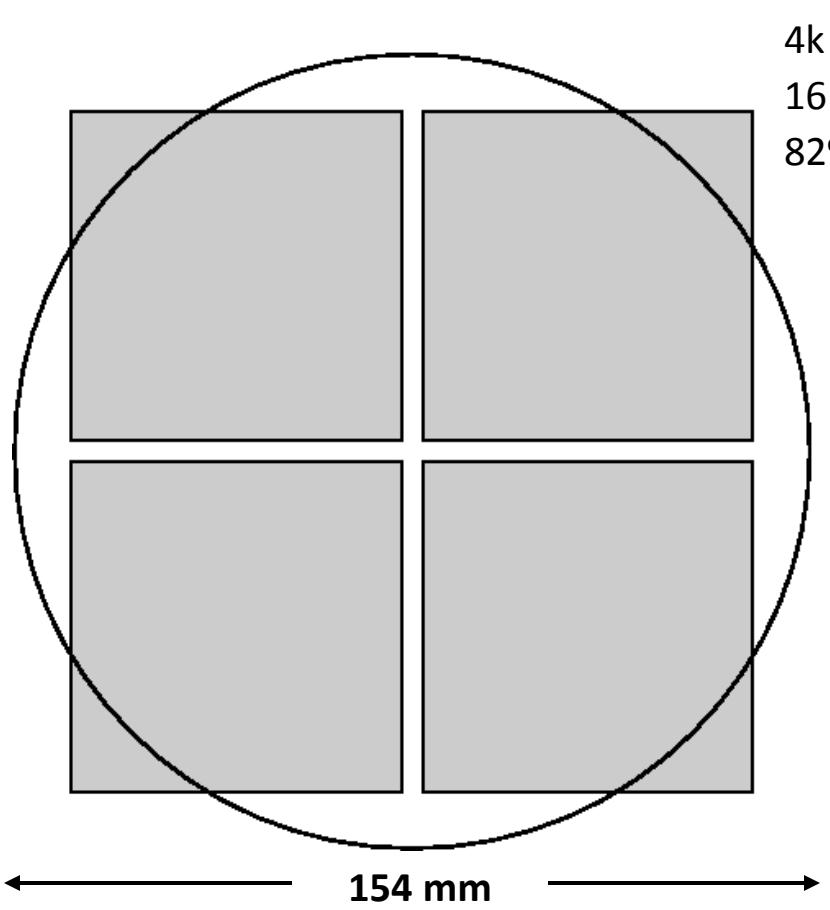
Telescopes

- DFM Engineering
- F/4 1.3 m
- 1.7° FOV over 154 mm diameter
- 3 telescopes
- Contracts signed
- First delivery in summer 2011



Camera

- High speed readout with ultra low noise
- High duty cycle

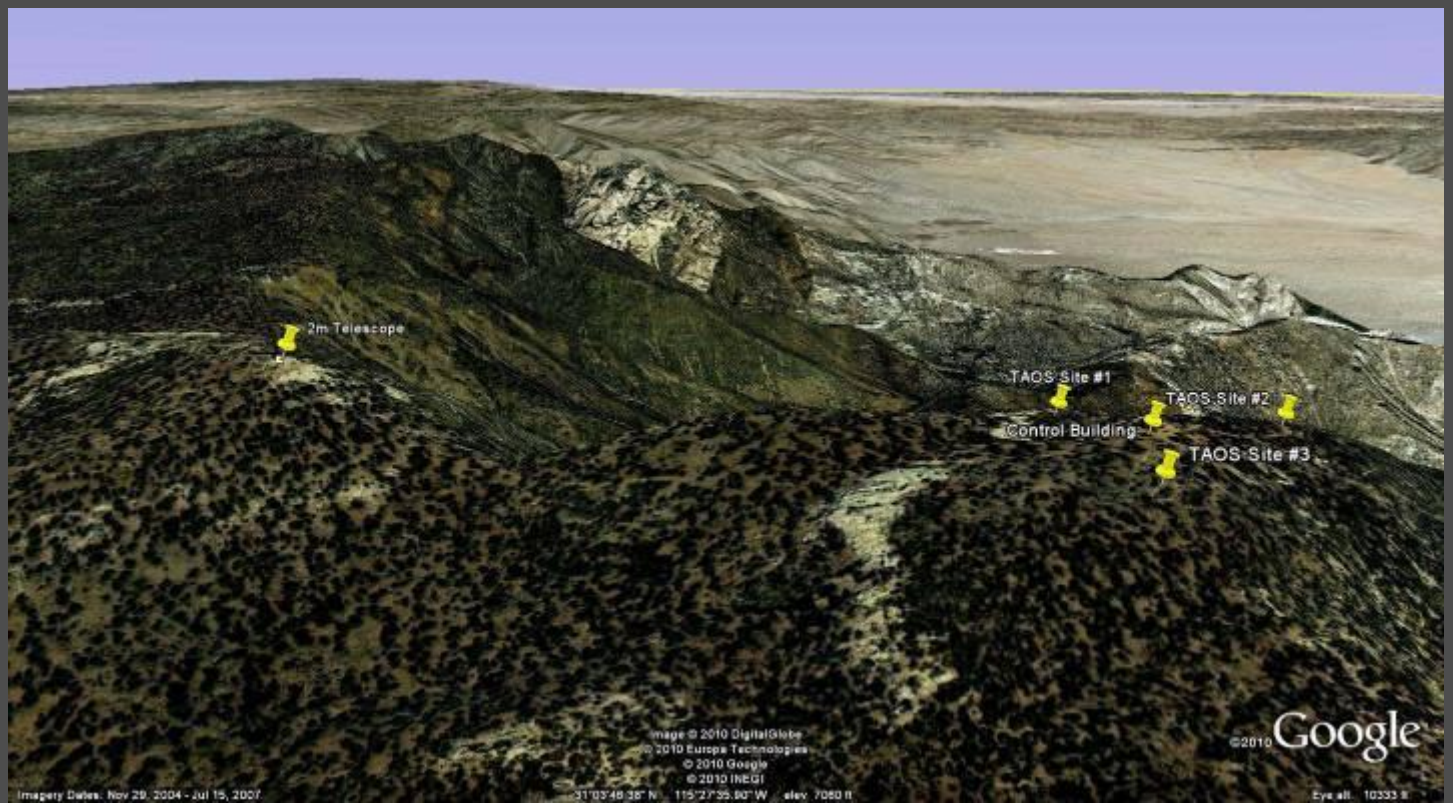


Monolithic CMOS

- New technology
  - Back-illuminated
- 200 KHz readout
- $2e^-$ read noise
- Sub-aperture readout mode
- Large format now available

TAOS II Site

- San Pedro Màrtir
  - Baja California
- >250 clear nights per year
- 0.6” median seeing
- Dark sky
  - R: 20.7 mag/sq. arc sec.
- Large baseline (>100 m)



TAOS II: Schedule

- Site preparation to begin in 2012
  - Weather monitors, enclosures, domes
- Telescope #1 delivered in summer of 2011, #2 and #3 early 2013
- Prototype camera this summer
- Completed system operation mid 2013

“Robotic” Observatory

- What are we really talking about?
  - Automated scheduling of observations, standard operations, remote observations
  - Automatic “safe mode”, recovery from hardware, software problems
- No human intervention!
  - Some intervention inevitable
  - Amount of intervention inversely proportional to cost, complexity

Automated Scheduling

- Maximize observing time
- Use complex algorithm when many observations in queue
- Minimize slewing, filter changing
- No dead time
- Minimize chance of human error
- TAOS: motivation is boredom
  - Pick a field
  - Image for 90 minutes
  - Repeat
  - Spend most of your time watching dew point
  - Dedicated survey: always need someone there

TAOS Scheduler

- Automated initialization of system
  - Check weather, open lids if OK
  - Initialize camera, take darks
- Focus sequence after dark
- Pick a field near zenith, zipper mode observations for 90 minutes
- Repeat until dawn or bad weather
- Close lids
- Other capabilities:
  - Automated response to GRB alerts
  - Manual scheduling of observations (asteroid occultations, etc.)

“Safe Mode” and Recovery

- Automatically close lids during bad weather
- Need to alert staff in case of hardware problem (like if the lid fails to close)
- System needs to be robust in case of software, hardware failures
  - Daemons go into safe mode, shutdown if hardware problem
  - Automatically restart daemons in case of shutdown or crash
  - But not always….

Automatically close lids during bad weather

- Need reliable lids!
  - Resist the urge to reinvent the wheel
- Need reliable weather monitoring
  - Need to operate in high (but not too high) humidity at Lulin
    - Want quality sensors (Vaisala HMT337)
    - *Need to keep them calibrated!*
  - Rain detection
    - Total area of sensors << 1% of the area of our telescopes and electronics
    - Looking into cloud sensors

Need to alert staff in case of hardware problem

- Observer on call in Taipei
- Monitor system with iPhone/Android web browser
- Support staff at Lulin
  - Non-technical, non-scientist, non-English speaking
  - Have simple web interface to close lids, shut down other operations
- Not “fully robotic”
  - Still occasionally have problems the require human intervention
  - But, we’re robotic enough!

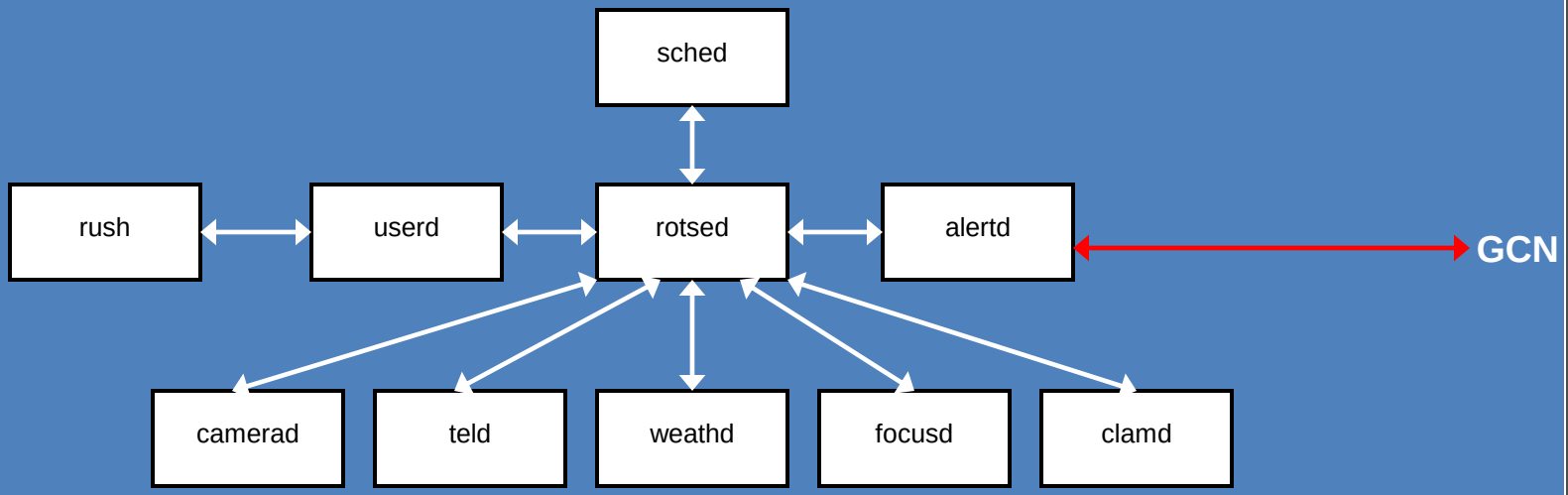
System needs to be robust in case of software, hardware failures

- Watchdog card in control computers
  - Automatically close lids using hardware override in case of computer crash
- Scheduler can automatically restart crashed or shutdown daemons
  - Best thing is to write daemons that don't crash!
- Auto-recovery from hardware failures
  - Depends on the failure mode
  - Only possible when you have the same problem repeatedly (in which case you fix the problem!)

Lessons Learned

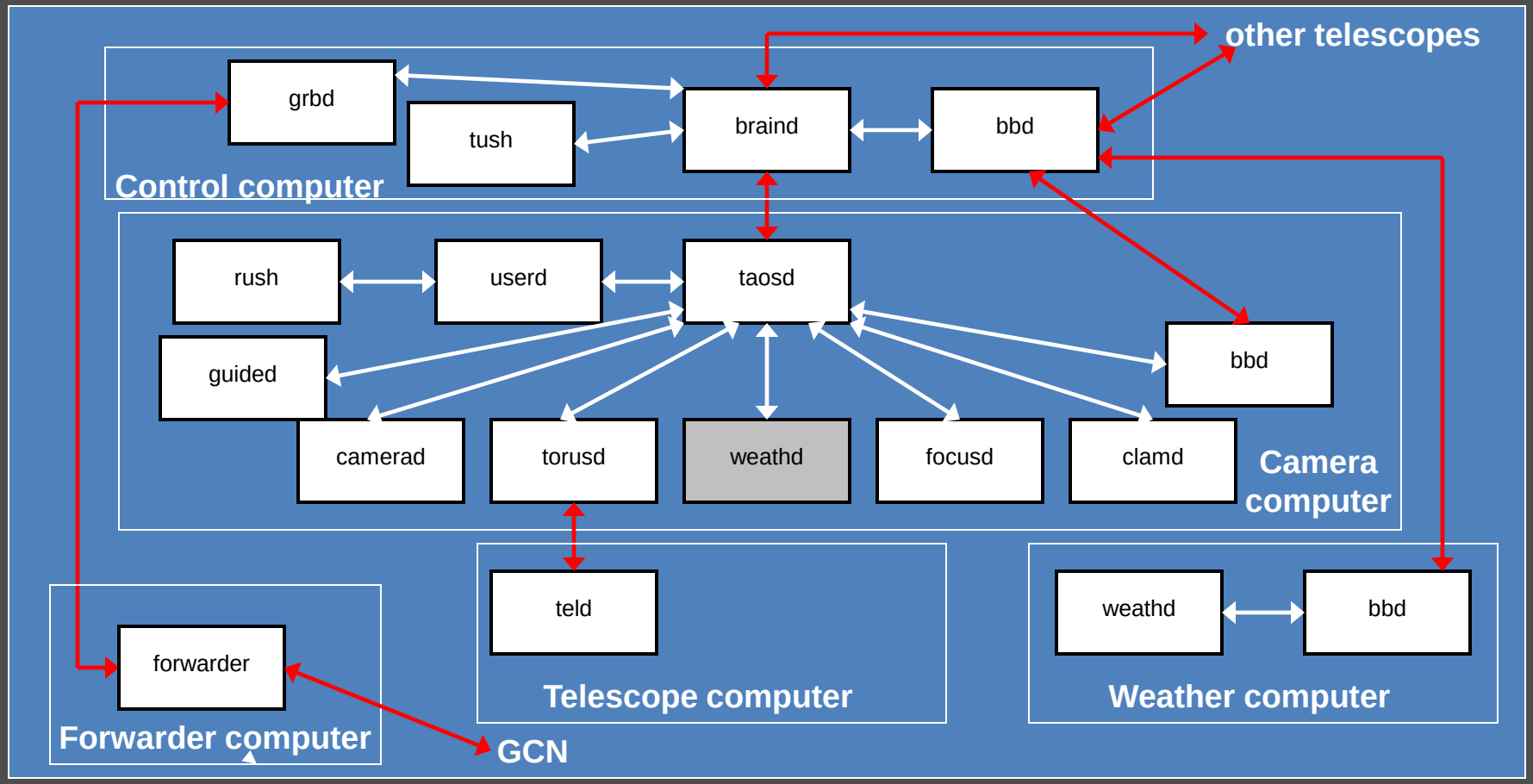
- Quality software design
  - Robust IPC
  - Error checking on every system call
  - Verbose logging (log every command)
    - Use __FILE__, __FUNCTION__, and __LINE__ macros
  - Stick with POSIX compatible code
    - Makes system upgrades much easier
    - Avoid third party software packages if possible
  - Simple macro facility
- Control software will take much longer than you think!

TAOS I Software



Courtesy of ROTSE

TAOS I Software



Lessons Learned

- Quality hardware
  - Reliable lids
    - Ashdome
    - ROTSE
    - ROVOR (neither bullet-proof nor bull-proof)
  - Reliable weather stations
    - Vaisala
    - Have some redundancy
    - Keep calibrated
  - Watchdog timer
- Have people available for emergencies