Kepler and Kuiper (K&K)
Addressing Key Questions in Astrophysics and Planetary Science

Charles Alcock, Center for Astrophysics

Principal Investigator

Matt Holman, Center for Astrophysics

Eric Agol, University of Washington

Joshua Carter, Center for Astrophysics

Jason Rhodes, JPL/Caltech

Michael Werner, JPL/Caltech

Co-Investigators

Picture

- **Charles, Matt**
- **Johnny Kwok suggests we add a colorful graphic either here or on the cover page…something illustrating transit timing would be good, or just gravitationally interacting planets**

K&K – Mission Overview

- **K&K addresses decadal science questions in:**
  - Astrophysics
    - Masses of terrestrial zone exoplanets via timing variations
      - Extends effective duration of Kepler Mission
    - Deep surveys in support of Dark Energy missions Euclid/WFIRST
  - Planetary Science – Size and spatial distribution of small Kuiper Belt Objects
- **Uses large, multi-band CMOS focal plane:**
  - 0.25 sq deg, 300 million pixels in each of four visible/nearir bands
  - Simultaneous viewing through series of dichroics
  - Sensitivity, sky coverage, image quality not available from the ground
- **Spacecraft in L2 orbit with continuous viewing of Kepler field**
- **Single Observing Mode – no moving parts in payload**
- **5 year lifetime [basically dictated by Kepler program]**

Science

- **K&K is a survey/imaging instrument with three major science investigations and one parallel mode program**
- **Investigation #1. Transit timing studies of Kepler planets, to determine the masses of dozens of exoplanets, some smaller than the Earth (50% of time).**
- **Investigation #2. Deep imaging surveys searching for Kuiper Belt Objects (KBOs) as small as 10km in size. (25%).**
- **Investigation #3. Deep surveys in support of survey missions such as Euclid and WFIRST. (25%)**
- ***Parallel Mode Program. While any of the three major investigations is under way*, observe bright stars throughout the field at high cadence to detect transits by small (~1 km) KBOs.**

Transit Timing Studies

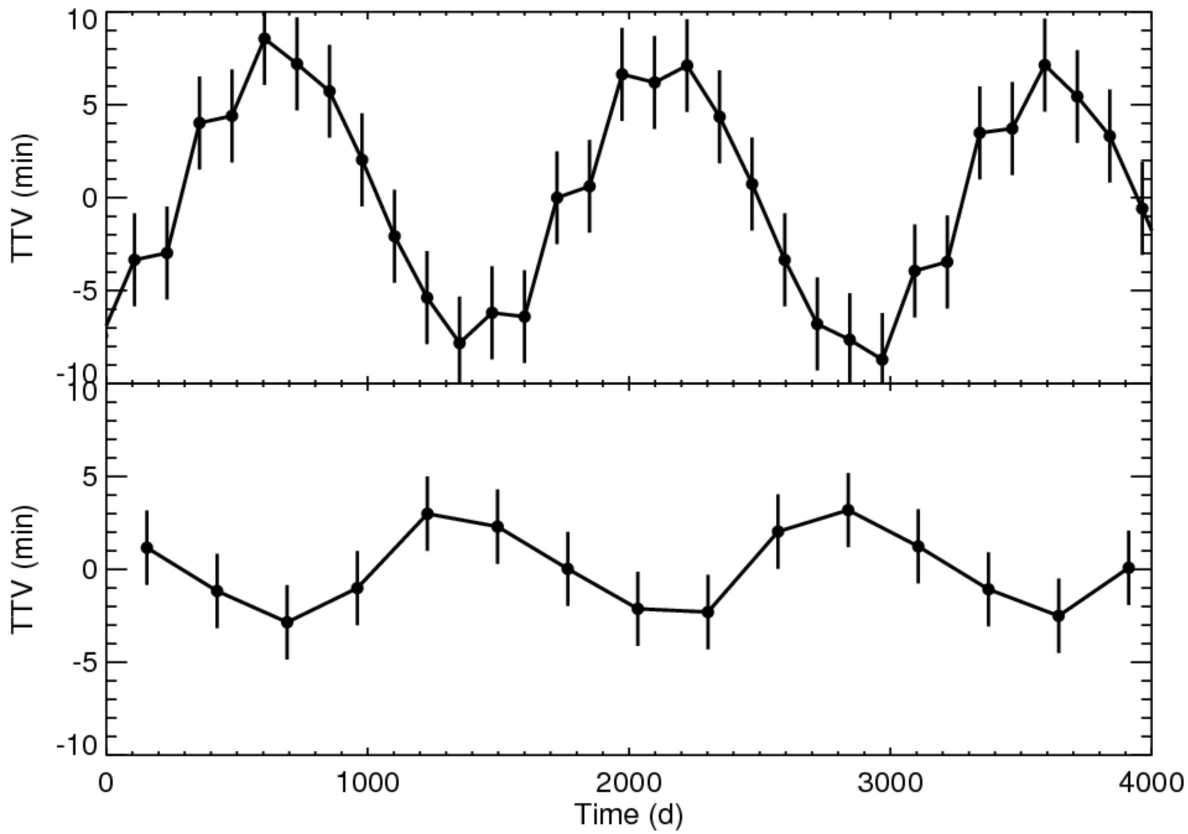
The theoretical TTV curves of an actual Kepler two-planet system, both of which are in the habitable zone. The timing uncertainties are estimated for K&K to be a factor of 2.4 smaller than those achieved by Kepler. These planets have masses ~3.5$M_{E.}$

The mass sensitivity is directly proportional to the timing precision.

The mass sensitivity also improves with time baseline t as $t^{3/2}$. One factor of t comes from the baseline. The remaining factor of $t^{1/2}$ comes from the number of observed transits.

By extending the Kepler time baseline by a factor of 2 and exploiting the improved timing precision, **we expect an overall improvement of 3-4 in mass sensitivity.**

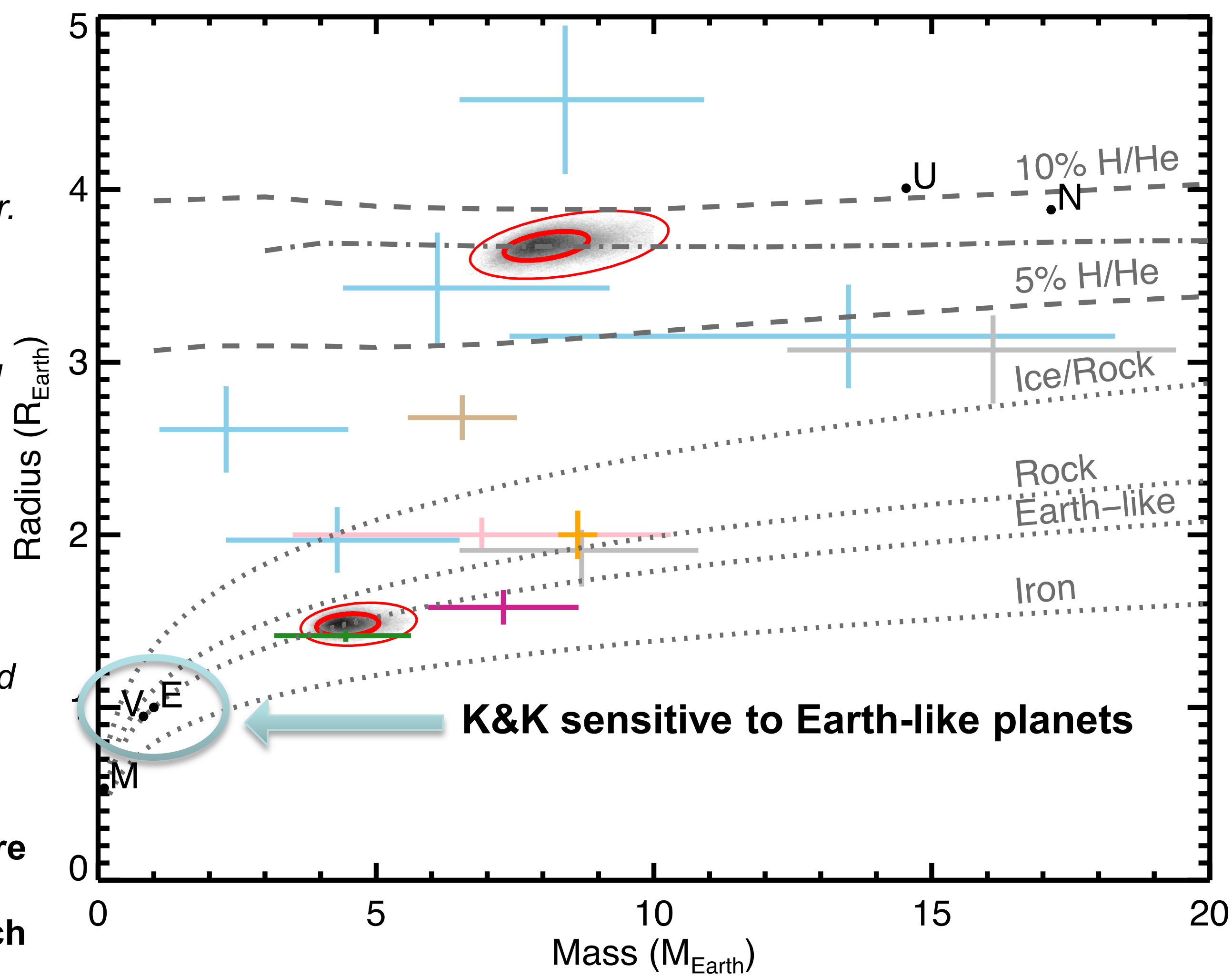
TTV are the only currently available way of determining the masses of planets too low in mass or too distant to produce RV signals



Transit Timing Studies

Estimates of masses and radii for a number of exo-planets, mostly from Kepler. The error ellipses refer to the well-studied Kepler 36 system. K&K will provide mass estimates for upward of 100 Kepler exoplanets with known radii, determining their densities, placing them on the theoretical curves, and revealing the frequency of planets of different type and composition (Carter et al., 2012).

At present TTV studies are the only means of obtaining masses for such low-mass planets.



Transit Timing Studies

- **Target Selection**
  - There are more than 1000 Kepler planet candidates in systems with more than two transiting bodies. In each of these systems, at least one planet is smaller than Neptune.
  - 10% of these show TTVs detectable by Kepler. K&K can establish precise masses and radii for all of these, and search for TTVs in other systems as well.
  - 20 of the Kepler planets have periods greater than 100 days and may be viable habitable zone candidates

Outer Solar System Surveys:

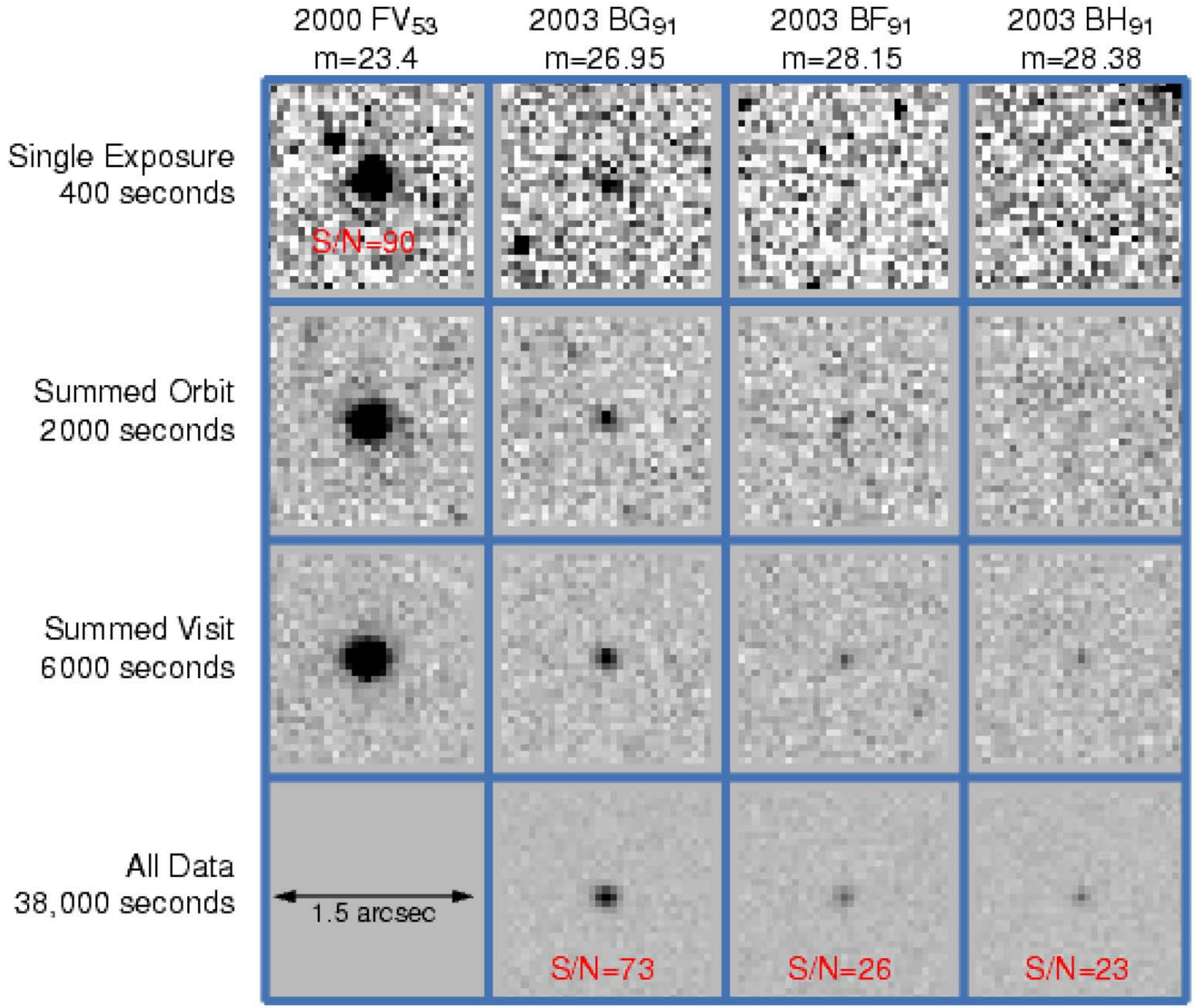
- **The early history of planet migration in the Solar System populated and shaped the regions beyond Neptune: the Kuiper Belt, Sedna, and the Oort Cloud are the known relics**
  - The rich resonance structure of the Kuiper Belt is sensitive to the timing and rate of Neptune's outward migration
  - The size spectrum of Kuiper Belt bodies reflects their history of formation through agglomeration and later erosion through collisions
- **These populations occupy >99.9999% of the volume of the Solar System**
- **K&K could survey the Kuiper Belt to unprecedented depth, revealing the resonance structure and size spectrum for objects as small as ~1 km**

Outer Solar System Surveys:

- **Investigation #2a:**
  - Survey a strip 0.5° wide along the entire (360°) invariable plane for slow moving objects: Kuiper Belt Objects
  - Employ the technique of digital tracking to probe for faint objects and mitigate tracking losses; this has been demonstrated successfully with HST by Bernstein et al (2004 AJ, 128, 1364)
  - Expected yield (scaling from Bernstein et al) of 10,000 – 40,000 KBOs with $r<28.5$
  - Good orbital elements for all objects will reveal the resonance structure with unprecedented detail
- **Investigation #2b:**
  - Survey 12 selected 2×2 mosaics (each 1 sq. deg.) to $r \sim 30$
  - Anticipated yield >20,000 objects

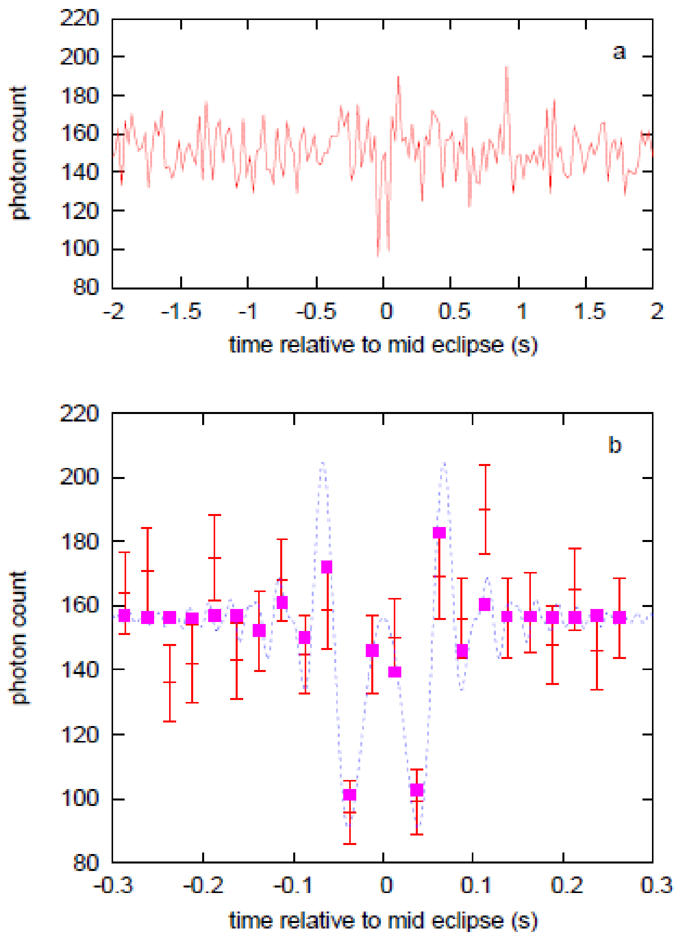
Outer Solar System Surveys:

- **Investigation #2:**
- Four KBOs in HST images combined by digital tracking by Bernstein et al (2004):
- Need to say how small these puppies are



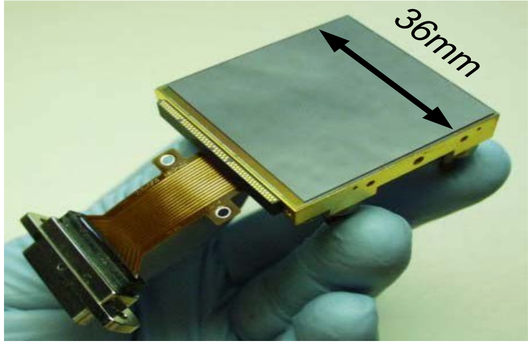
Outer Solar System Surveys:

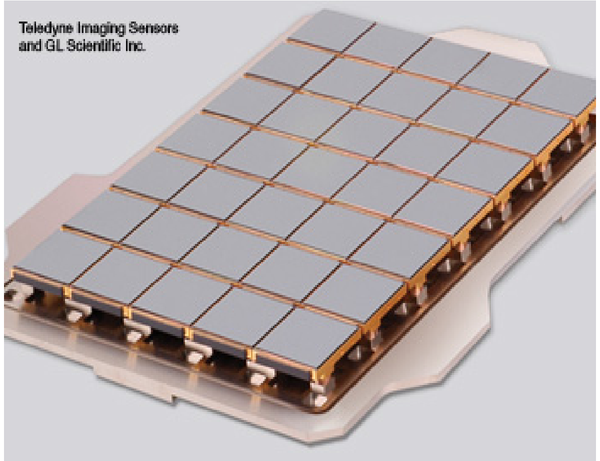
- **Parallel Mode Program:**
  - Exploit the CMOS capability to read out small windows around all bright stars (r<16; possibly fainter depending on detailed simulations) at high cadence (10-40 Hz)
  - Perform on-board photometry of these stars and search for occultations by small (>1 km diameter) KBOs. Expect to detect ~ 2000
  - Occultation technique has been demonstrated by Schlichting et al using the Fine Guidance Sensors on HST
  - Plots are data, model for ~1km object discovered by Schlichting et al in HST data



Outer Solar System Surveys:

- **Maturity of the CMOS devices:**
  - Optical analogs of widely-used infrared devices
    - E.g. Teledyne H2RG+HyViSi with SIDECAR is electronically almost identical to the infrared devices to be used on Euclid. We are baselining H4RGs similar to the WFIRST devices
  - Presently available devices compete well with CCDs on QE but not on read noise (~18 electrons)
    - This is an active area of development and new devices with ~6 electron read noise are expected within two years; further improvement may be possible





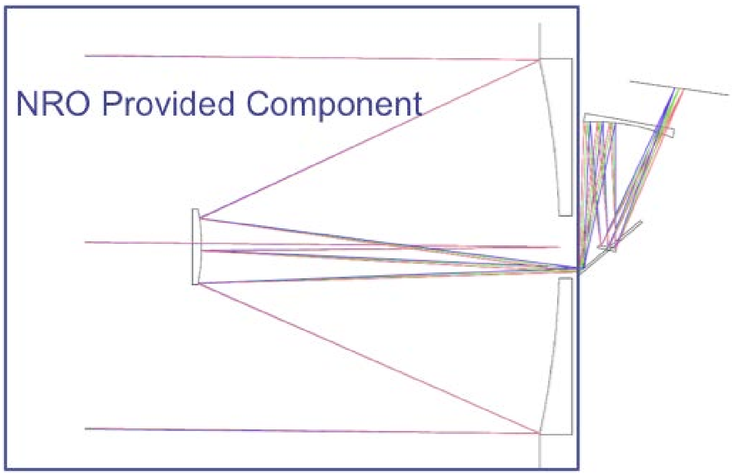
Cosmological Surveys

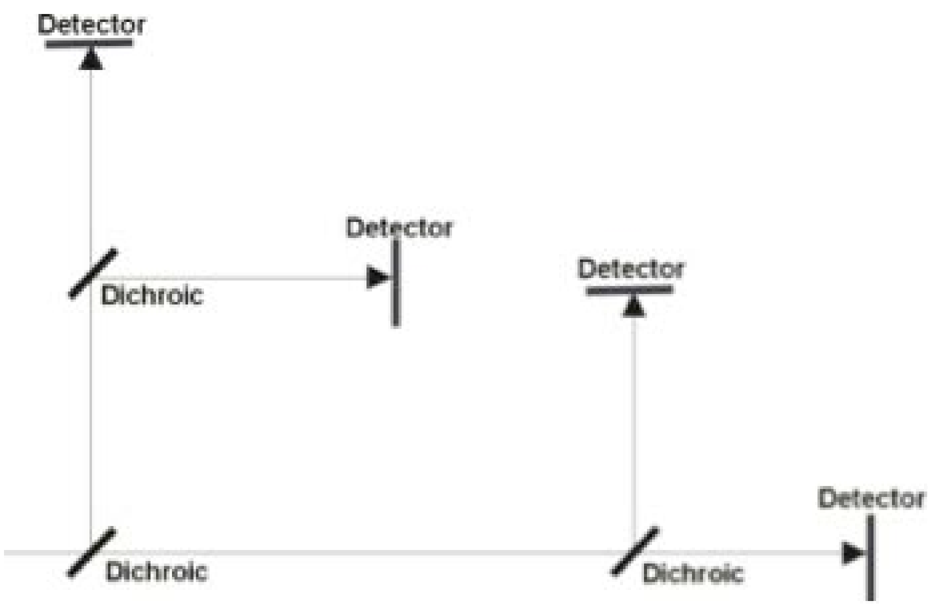
- **K&K could cover significant chunks of Euclid, LSST, and WFIRST surveys in several optical bands, providing high resolution optical imaging**
- **Better Photometric Redshifts- A Use Case**
  - Could cover the 40 square degree Euclid deep survey area to mag ~26.5 in several optical bands; survey could be done in a few months
  - This cannot be done with any other planned hardware in the 2020s
  - The millions of galaxies in this region will thus have the best possible photometric data and thus offer the highest precision photo-zs
  - The resulting photo-z will provide a 'truth set' for calibration photo-zs in the full Euclid, LSST, and WFIRST surveys
  - This enhances the cosmological parameter determination possible with those data sets (e.g. Ω_M, Λ σ_8, *w*, *w*'), since photo-z errors are a signifcant source of uncertainty

Scientific Instrument – Requirements Traceability:

Science Theme	Wide Field	Multiband	Rapid Readouts	Pointing Performance	Data Rate
Exoplanets		x		x	
KBO Imaging	x	x			x
Deep Surveys	x	x			x
KBO Occultations	x	x	x		

Instrument Description





- **Rodger Thompson WNEW inspired four fold dichroic multiplexing photometer.**
  - 450 – 850 nm Bandwidth
  - 0.1 arcsec/10µm Plate Scale
  - ¼ square degree FOV
  - 20 4k X 4k CMOS arrays per band with SIDECAR ASICS
  - Total Mass ~ 300 kg
  - Total Power ~ 900 W
  - Data Rate ~ 161 Mbps (raw)
  - Cost ~ $300 M

Spacecraft Description

- **Spacecraft mass based on the following assumptions developed by JPL A-Team**
  - 3000 W solar power system for the entire observatory
  - 100 Mbps telecom from E-S L1/L2 with a 0.5 m high-gain antenna, 20 W Ka to DSN (similar to James Webb)
  - Chandra-class pointing and stability => approximately 30 arc-sec control, 0.25 arc-sec over 10 sec. stability (includes star tracker, IMU, Reaction Wheels). Additional mass required to achieve Kepler class pointing can be accommodated within launch vehicle capability
  - 150 m/s delta-v capability for chemical burn orbit-insertion and maintenance
- **Total mass (excluding instruments): 2700 kg dry, 2900 kg wet including the telescope parts; then add 200 kg to the wet mass (180 kg to dry mass, 20 kg to propellant mass) for each 100 kg of the 300 kg instrument - 2,900 + 600 = 3,500 kg.**
  - This includes all JPL design principle requirements in terms of margin for this stage of concept maturity.

Data Rate is a Potential Issue

- **Data rate averages 80 Mbps assuming 100 sec integrations, 12 bits A/D, and 2x lossless compression**
- **SOLUTION: Mix low data rate Kepler field observations with deep surveys to bring average rate below ~40 Mbps, roughly consistent with downlink capabilities [100 Mpbs for 8 hrs/day]**
  - Occultation data analyzed on orbit using protocols developed for Whipple

Pointing and Control – Further Study Needed

- **The proposed pixel scale (0.1”) undersamples the PSF and could compromise the photometric precision, even for small intrapixel sensitivity variations (1-10%) and pointing jitter of.**
- **By implementing a means of broadening the PSF by a factor of 2-3 over a small portion of the focal plane and upgrading to Kepler quality pointing the photometric uncertainty due to pointing variation would be negligible.**
- **Mitigation options include:**
  - Raising one or more detectors to be out of focus.
  - Adding an optical element on the detector (similar to Kepler).

Conclusions

Kepler and Kuiper:

- Addresses decadal science priorities in both astrophysics and solar system exploration
- Requires no unusual modifications of the NRO telescopes
- Relies on large focal plane[s] making full use of state of the art detectors
  - Basic observing protocols and analysis techniques established by previous missions and laboratory simulations
- Can be accommodated by existing spacecraft and launch vehicles
- Builds on the success of previous NASA missions – HST and Kepler – while supporting the missions of the future – WFIRST and Euclid
- Presents several separate science investigations which might be combined with other investigations in a single SALSO mission –