Serendipitous Detection of Transiting Planets in Future Synoptic Surveys

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Special Thanks To…

- Thomas Beatty (CfA,MIT)
- Cullen Blake (CfA)

Detecting Transiting Planets

Properties of current transit surveys

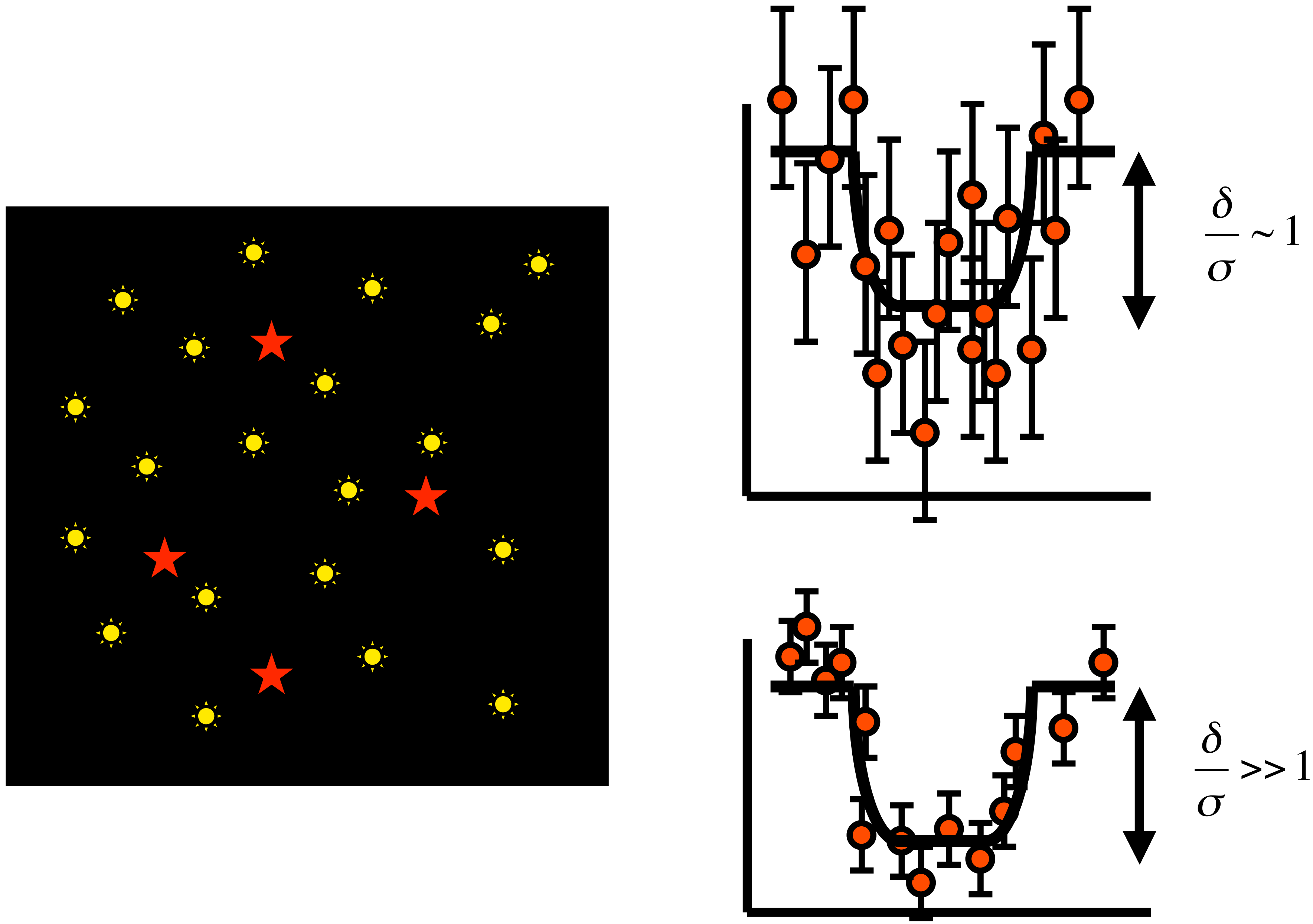
- Reach a required S/N on enough main-sequence stars to detect a transiting planet

- For a given type of star (i.e. FGK dwarfs):
  - At what depth (i.e. limiting magnitude) do you have enough stars in your survey area?
  - S/N should be larger than some required minimum value at that depth

$$\frac{S}{N} \approx N^{1/2} \frac{\delta}{\sigma}$$

Properties of current transit surveys

- Reach a required S/N on enough main-sequence stars to detect a transiting planet
- For current dedicated surveys for transiting planets:
  - At the depth where there enough stars to detect a planet:
  - S/N per point is low
  - Detection achieved using many points

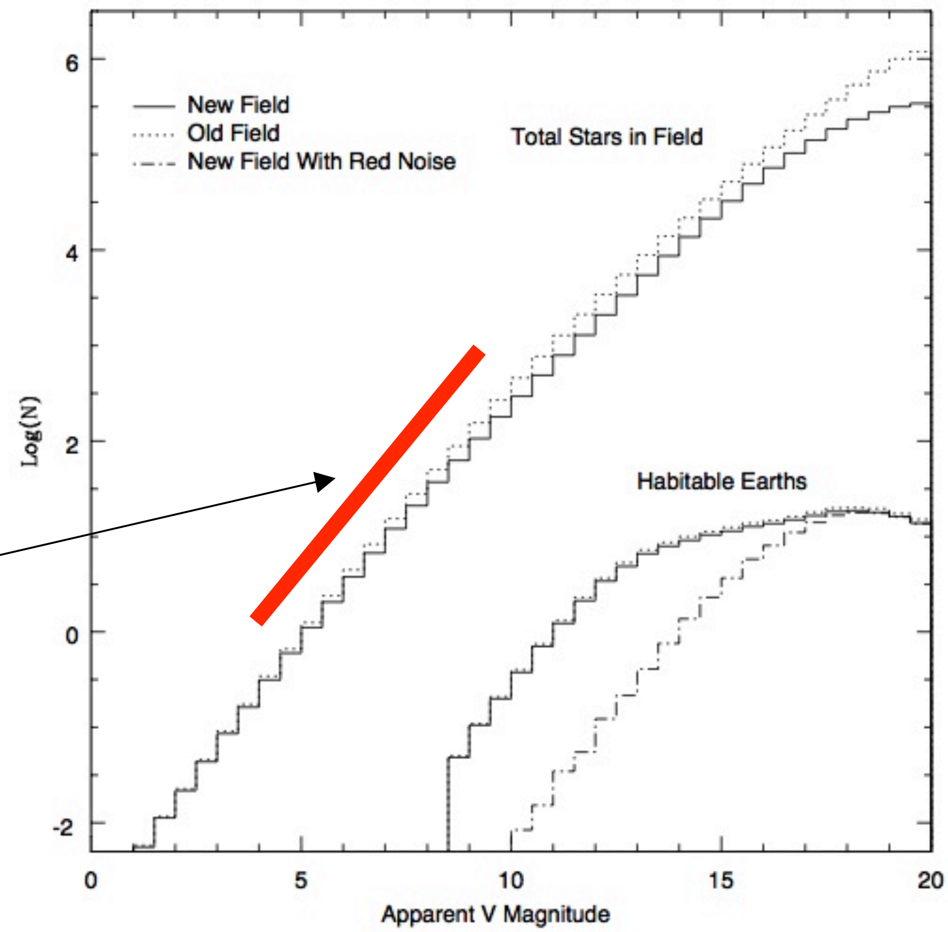


$\frac{\delta}{\sigma} \sim 1$
$\frac{\delta}{\sigma} >> 1$

Brighter Stars?

- For brighter stars, detection could be achieved with fewer points, but…
  - Correlated noise
  - Not enough stars

$$N \propto 10^{-0.6\Delta m}$$



A Different Regime:
Sparse Sampling, Large Area, Few Observations

Avoid correlated noise:
- **Sample on timescales >> correlation timescale**

Sufficient number of stars:
- **Very wide area**

This is the precisely the regime of future large synoptic surveys!!

Synoptic Surveys

Future Synoptic Surveys

Synoptic*, adj,*

1. pertaining to or constituting a synopsis; affording or taking a general view of the principal parts of a subject.

2. *Meteorology* Of or relating to data obtained nearly simultaneously over a large area of the atmosphere.

Astronomer's definition: Repeated observations of a large area of the sky.

Current/Future Synoptic Surveys

SDSS-II
- now

Pan-STARSS
- Early 2008

LSST
- 2012

MPF
- ?

Estimating the Yields of Synoptic Surveys

(with Thomas Beatty)

Estimating the Yields

- Accurate estimates difficult.
- Depend on:
  - survey strategy
  - equipment specifications
  - data analysis methods

- Approximate yields
  - Estimate total number of main-sequence stars in survey area
  - Estimate the number of transiting planets
  - Estimate limiting magnitude

Estimating the Sky Densities

Present-Day Mass Function

M-L, M-R relations

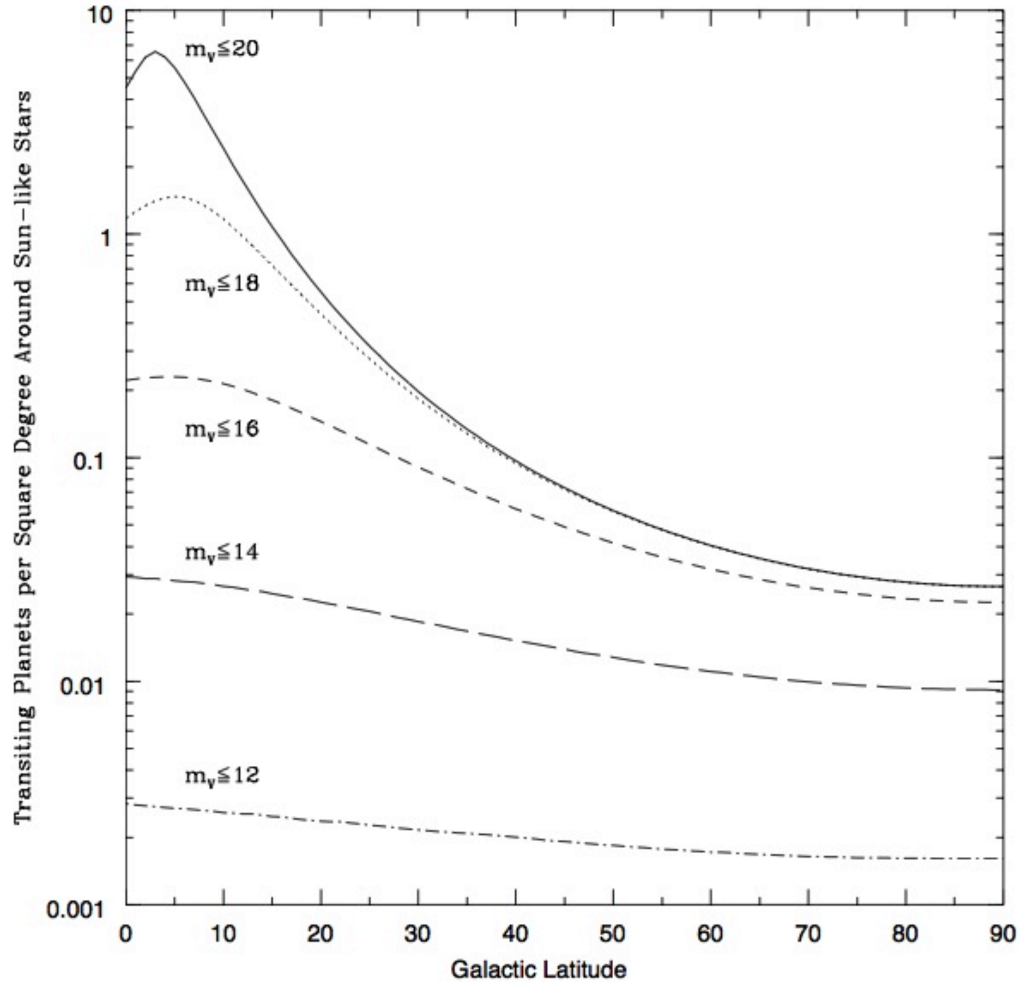
Double Exponential Thin Disk

M_V-dependent scale height

Extinction

Transit Probability

Gould et al (2006) frequencies



Beatty & Gaudi (in prep)

Sky Densities, Sun-like Stars

V Mag. Limit	Gal. Plane	Gal. Poles	All-Sky Average
V<12	0.003	0.002	0.002
V<14	0.029	0.009	0.017
V<16	0.219	0.025	0.087
V<18	1.125	0.026	0.293
V<20	4.052	0.027	0.800

Sky Densities, M Dwarfs

V Mag. Limit	Gal. Plane	Gal. Poles	All-Sky Average
V<12	0.00001	0.00001	0.00001
V<14	0.00017	0.00015	0.00016
V<16	0.0047	0.0015	0.0028
V<18	0.0257	0.0105	0.0169
V<20	0.2081	0.0368	0.0989

Limiting Magnitudes

$$\frac{S}{N} \approx N^{1/2} \frac{\delta}{\sigma}$$

(white noise)

$$N \approx \frac{R}{\pi a} N_{total}$$

$$N_{total} = \frac{\varepsilon T}{t_{\exp} N_{fields}}$$

$$N_{fields} = \frac{\Omega_{survey}}{\Omega_{FOV}}$$

$$\frac{S}{N} = \left(\frac{\varepsilon T}{t_{\exp}} \frac{\Omega_{FOV}}{\Omega_{survey}} \frac{R}{\pi a} \right)^{1/2} \frac{\delta}{\sigma}$$

Limiting Magnitudes

$$\frac{S}{N} = \left(\frac{\varepsilon T}{t_{\exp}} \frac{\Omega_{survey}}{\Omega_{FOV}} \frac{R}{\pi a} \right)^{1/2} \frac{\delta}{\sigma}$$

$$\sigma = \sigma_0 \left(\frac{t_{\exp}}{t_{\exp,0}} \right)^{1/2} \left(\frac{D}{D_0} \right) 10^{0.2(V - V_0)}$$

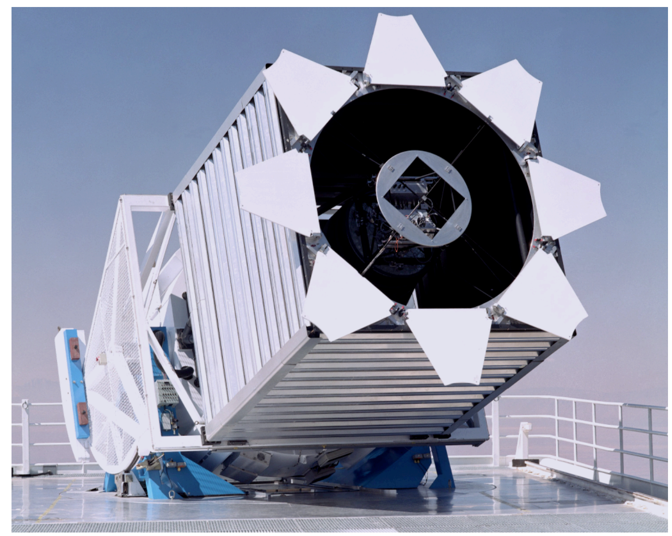
$$V_{\lim} = 5 \log \left[\left(\frac{\varepsilon T}{t_{\exp,0}} \frac{\Omega_{FOV}}{\Omega_{survey}} \frac{R}{\pi a} \right)^{1/2} \frac{D}{D_0} \frac{\delta}{\sigma} \left(\frac{S}{N} \right)^{-1} \right] + V_0$$

Magnitude Limits and Yields

SDSS Magnitude Limits and Yields

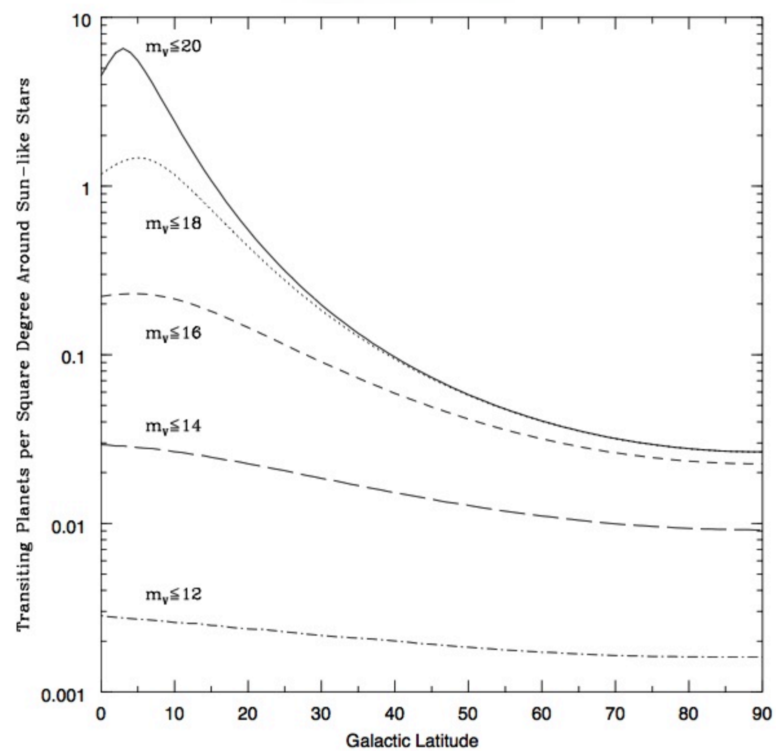
- **SDSS-II**
  - Observation time = 37.5 days
  - Telescope Diameter = 2.5m
  - Efficiency = 0.5
  - Field of View = 6.25 deg^2
  - Area Surveyed=300 deg^2
- **Magnitude limits**
  - Sun-like stars = 15.6
  - M dwarfs = 20.2
- **Total Yields for S/N=20**
  - Sun-like stars = 6
  - M-dwarfs = 12

Sloan Digital Sky Survey
Mapping the Universe



Pan-STARRS Magnitude Limits and Yields

- **Pan-STARRS (Medium-Deep)**
  - Observation time = 5 months
  - Telescope Diameter = 1.8m
  - Efficiency = 0.5
  - Field of View = 7 deg^2
  - Area Surveyed=1200 deg^2
- **Magnitude limits**
  - Sun-like stars = 14.99
  - M dwarfs = 19.61
- **Total Yields for S/N=20**
  - Sun-like stars = 19
  - M-dwarfs = 37



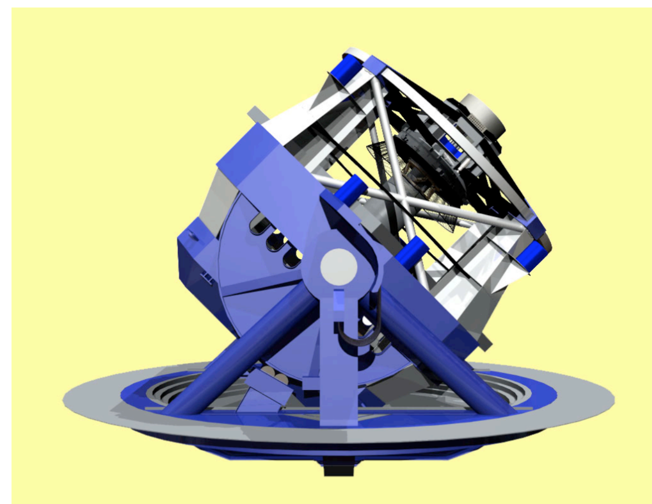
Pan-STARRS Magnitude Limits and Yields

- **Pan-STARRS (Wide??)**
  - Observation time = 5 months
  - Telescope Diameter = 1.8m
  - Efficiency = 0.5
  - Field of View = 7 deg^2
  - Area Surveyed=12,000 deg^2
- **Magnitude limits**
  - Sun-like stars = 12.5
  - M dwarfs = 17.1
- **Total Yields for S/N=20**
  - Sun-like stars = 48
  - M-dwarfs = 82

LSST Magnitude Limits and Yields

Large Synoptic Survey Telescope

- **LSST**
  - Observation time = 10 years
  - Telescope Diameter = 6.5m
  - Efficiency = 0.5
  - Field of View = 9.6 deg^2
  - Area Surveyed=20,000 deg^2
- **Magnitude limits**
  - Sun-like stars = 18.5
  - M dwarfs = 23.1
- **Total Yields for S/N=20**
  - Sun-like stars = 7700
  - M-dwarfs = 15500 (4000 to V~20)



A Worked Example

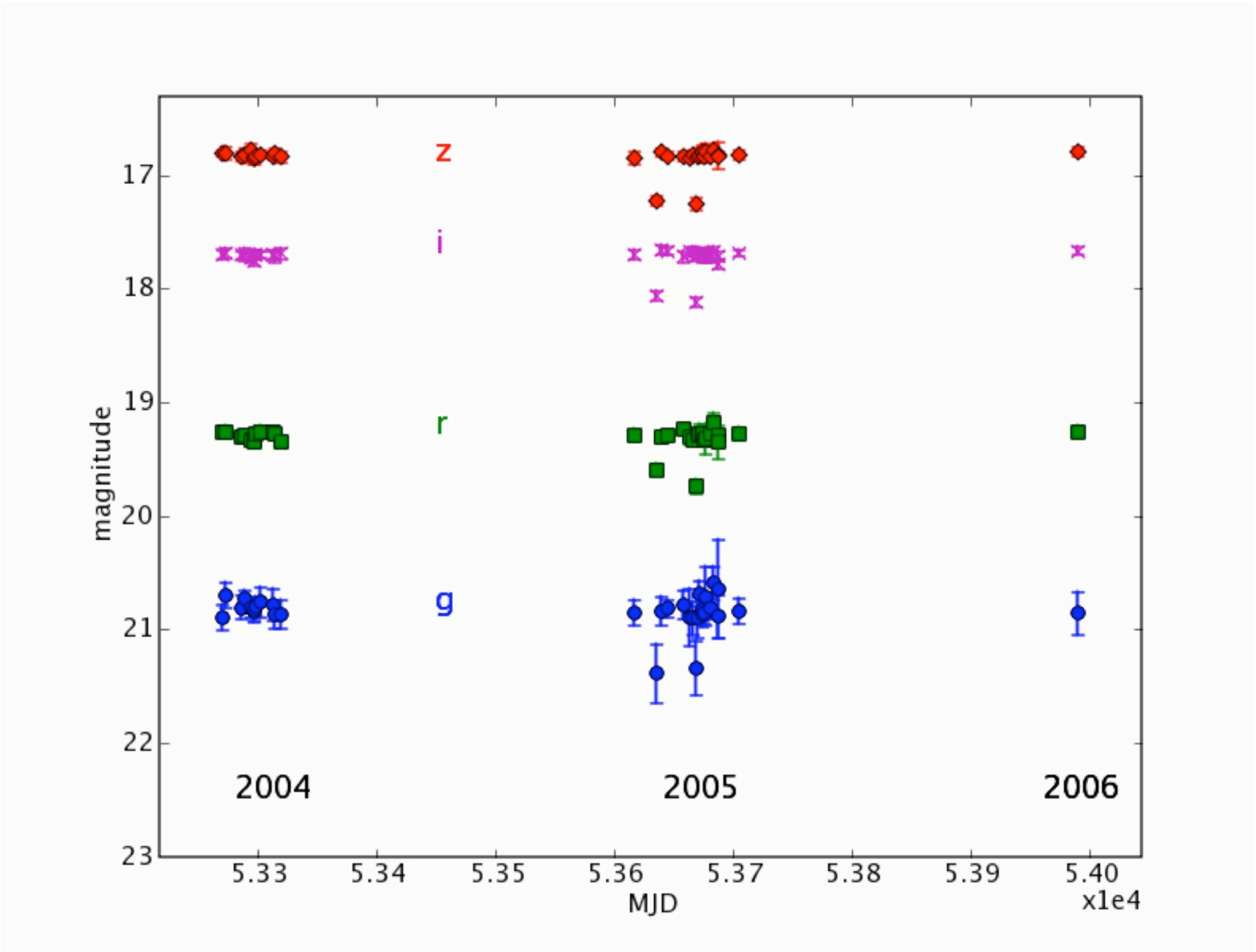
(with Cullen Blake, Guillermo Torres, Josh Bloom)

SDSS-II Transit Search

- **SDSS-II M dwarfs**
  - 300 deg^2
  - Point sources
  - *i-z* > 0.84
  - *r* < 21.2 (5% precision)
  - M4 and later
  - *r,i,z* light curves for 19,000 M dwarfs
  - 10-30 observations in each band
  - *At most a few points in transit*
- **Transit Search**
  - Flux decreases of > 0.2 mag
  - All three bands
  - Jupiter radii companions for $R<0.2R_\odot$

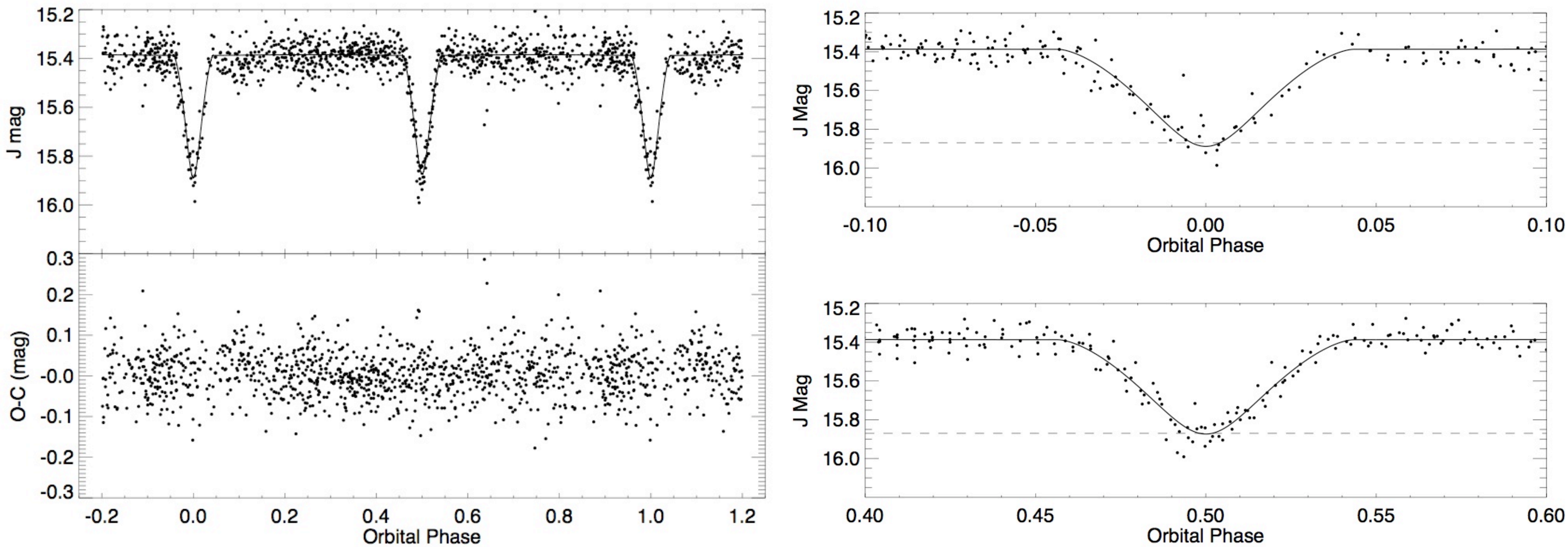
Best Candidate

SDSS031824-010018
***g*=20.818**
***r*=19.290**
***i*=17.681**
***z*=16.792**
Depth > 0.3 mag



(Blake et al. 2007)

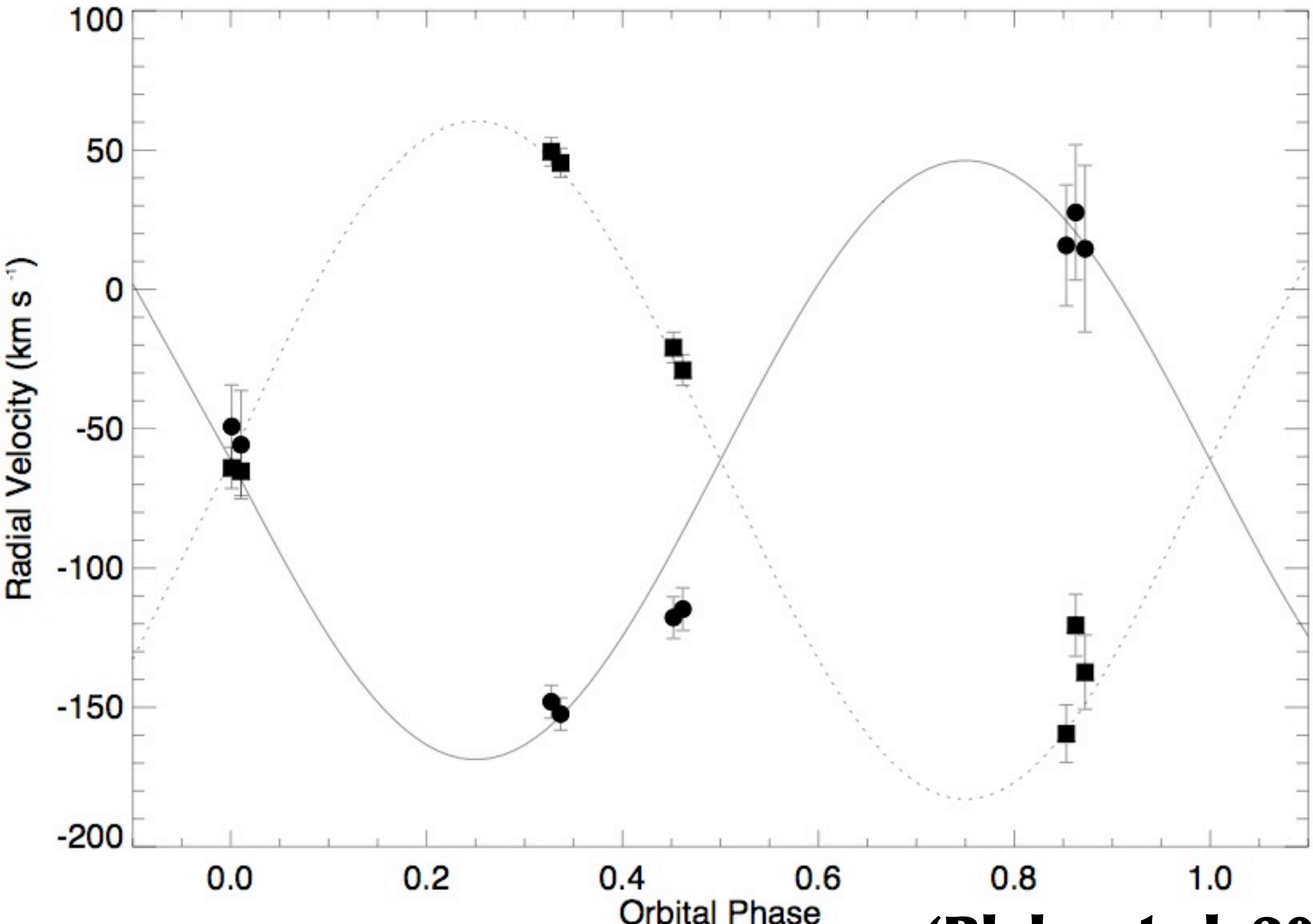
PAIRITEL Follow-Up



937 JHK measurements

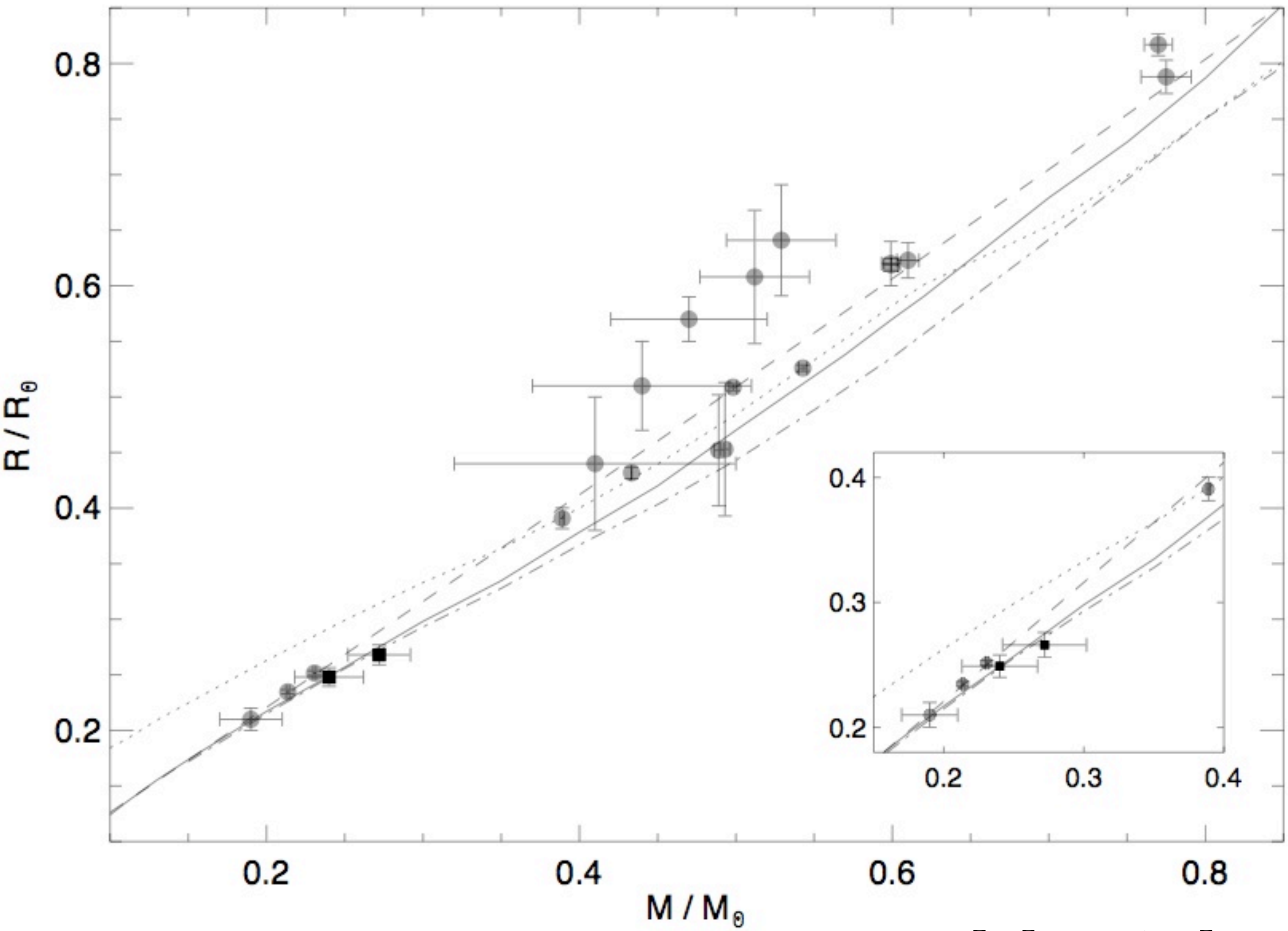
(Blake et al. 2007)

LRIS Keck Spectra



(Blake et al. 2007)

Mass-Radius Constraints

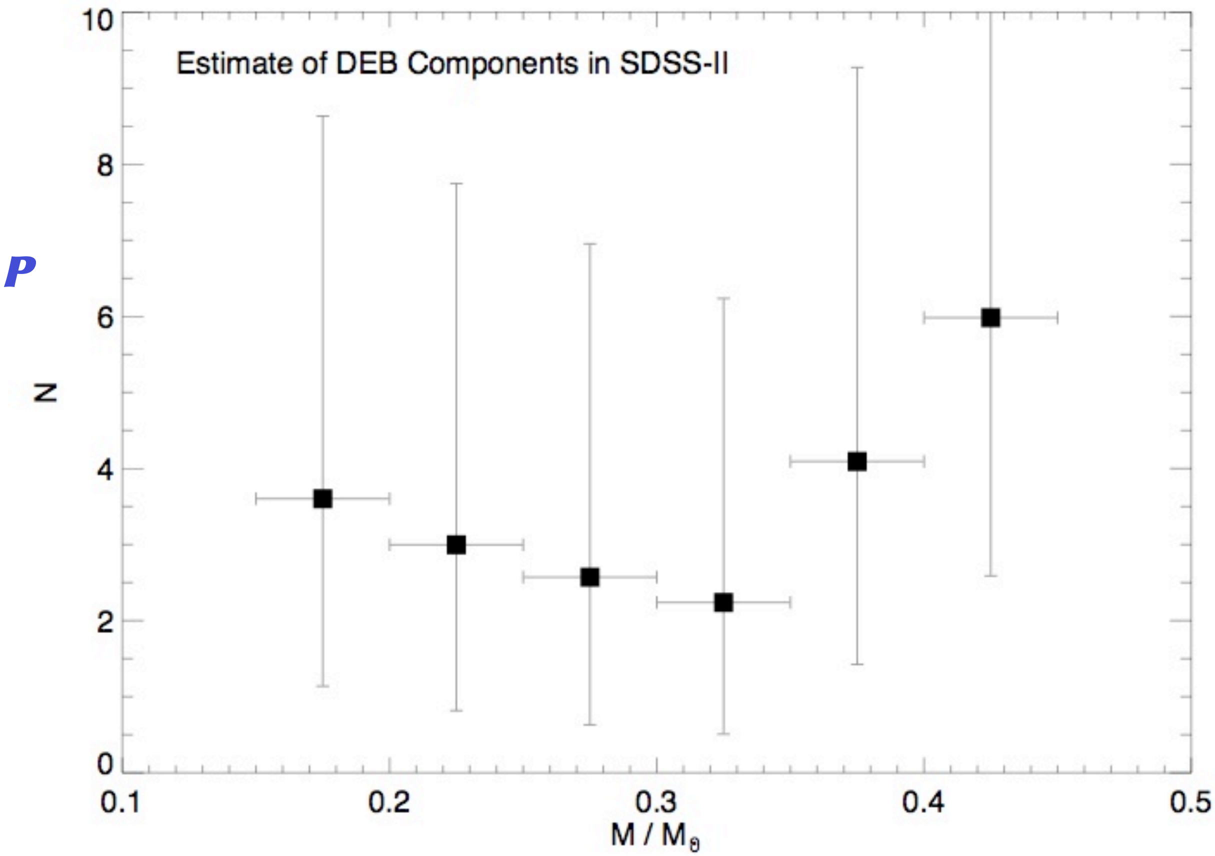


(Blake et al. 2007)

Other DEB in SDSS-II

Estimate:

- **Color-magnitude relations**
- **Mass-magnitude relation**
- **30% binary fraction**
- **Duquennoy & Mayor *q* and *P* distributions.**
- ***i*<19**
- **Double lined, K>30 km/s**
- **Luminosity ratio > 0.1**
- **10% duty cycle**
- **Eclipse depth > 10%**



(Blake et al. 2007)

Planets?

Targets:

- i-z > 0.37, i < 19
- 40,000 targets with $R < 0.3R_{\odot}$
- Depths > 10% for Jupiters

Planet Yield:

- 21 HJ+VHJ

Follow-up:

- K>30 km/s
- $M \sin i > 95 M_J$ for P<3 days
- IR spectroscopy?

Smaller Planets?

- Depths > 1% for Neptunes
- Calibrate SDDS to better than 1%?

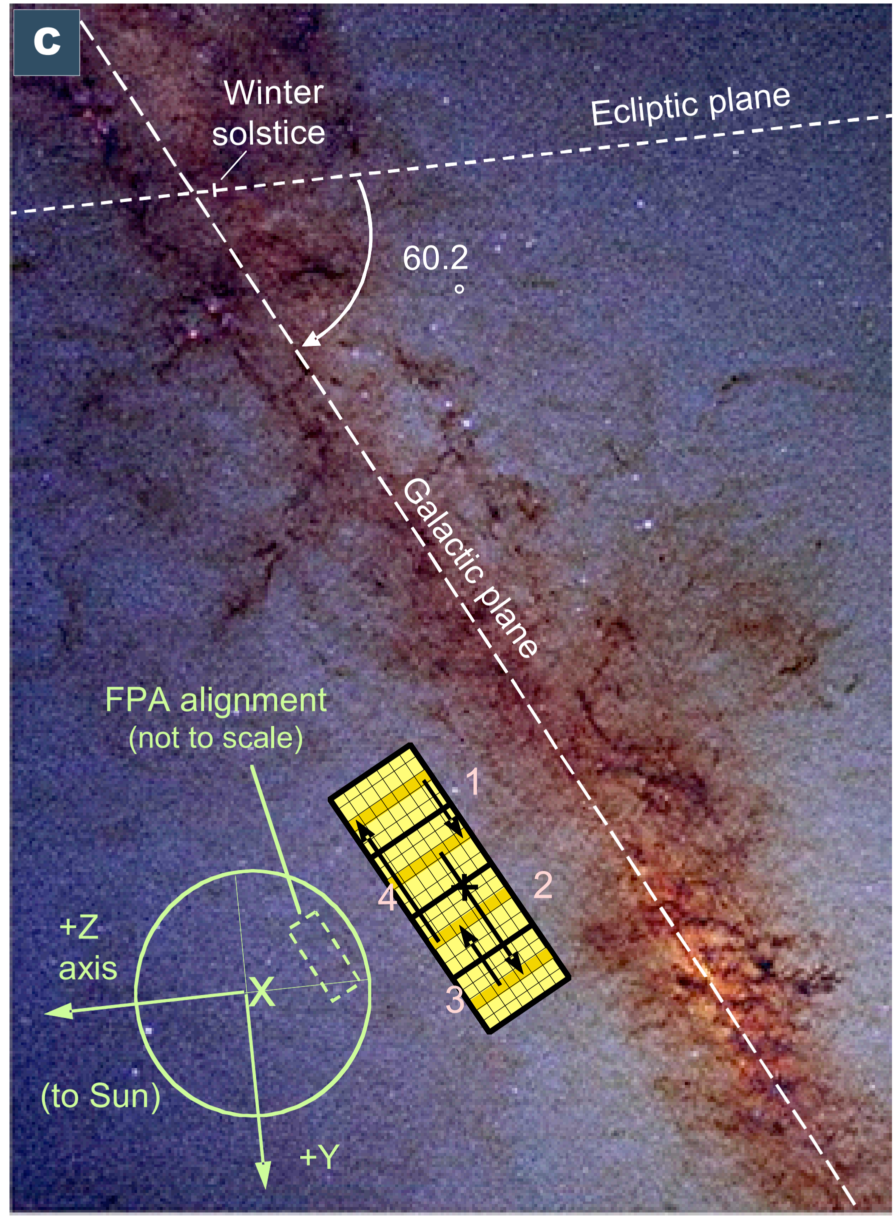
The Coming Storm

An Embarrassment of Riches?

- LSST
  - Sun-like stars = 7700
  - M-dwarfs = 15500 (4000 to V~20)
- Calibrate photometry to ~0.1%?
- All fainter than V=16
- 10^5-10^6 false positives?
- Is there anything we can do with these planets?

Microlensing Planet Finder

- Monitor ~10^8 MS stars
- 9 months/year, 4 years
- 15 minute sampling
- S/N~90 for 3 days
- ~30,000 Hot Jupiters
- S/N~$P^{-1/3}$ → Thousands of planets out to P~2 years
- Single Transits to tens of AU
- All will have I>20!



Statistical Analysis of Transit Candidates?

SWEEPS experience (Sahu et al. 2006)

- Statistical determination of the frequency of false positives
- Also model of Brown (2003)

More needs to be done:

- What are the uncertainties in these models?
- Variations in the binary fraction with environment?
- Do Kozai-created hierarchical triples (Fabrycky & Tremaine, Wu et al) change the results?
- Can we determine $f(M_*,r,P)$ robustly from a statistical analysis?

Can we rule out false positives without RV (for shallow transits)?

- How useful are planet detections without planet mass?

?