Expectations from Next Generation Microlensing Planet Searches from the Ground and Space

Scott Gaudi
(The Ohio State University)

The Challenge of Detecting Earths

- Short Timescale

$$t_{E,p} = 2\text{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}$$

- Low Probability (Planetary Caustics)

$$P \approx A_0 \frac{\theta_p}{\theta_*} \approx 1\% \left(\frac{M_p}{M_E}\right)^{1/2}$$

Three Approaches

1. Alert/Follow-Up, Low Magnification

   PLANET

2. Alert/Follow-Up, High Magnification

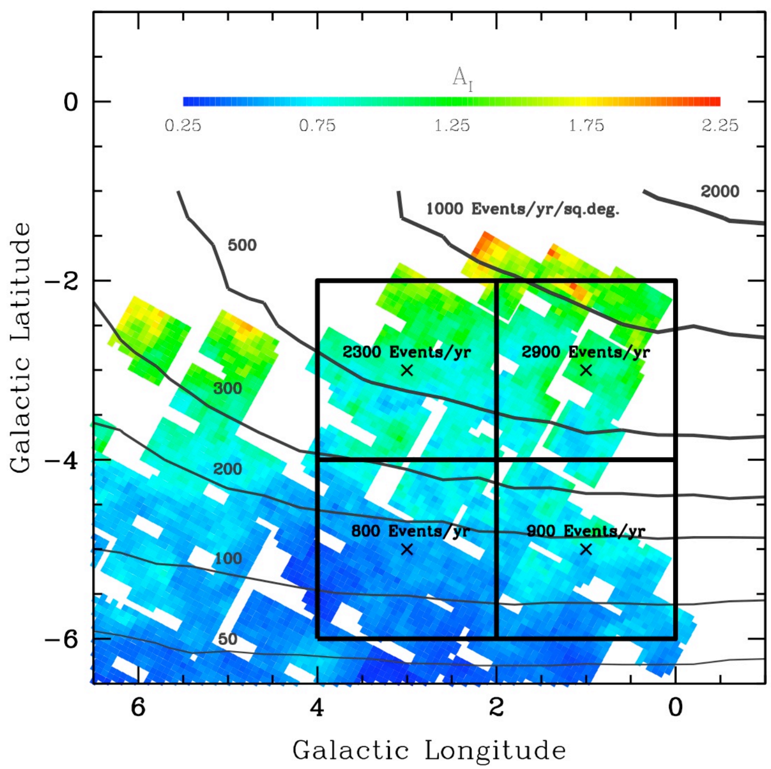
   MicroFUN

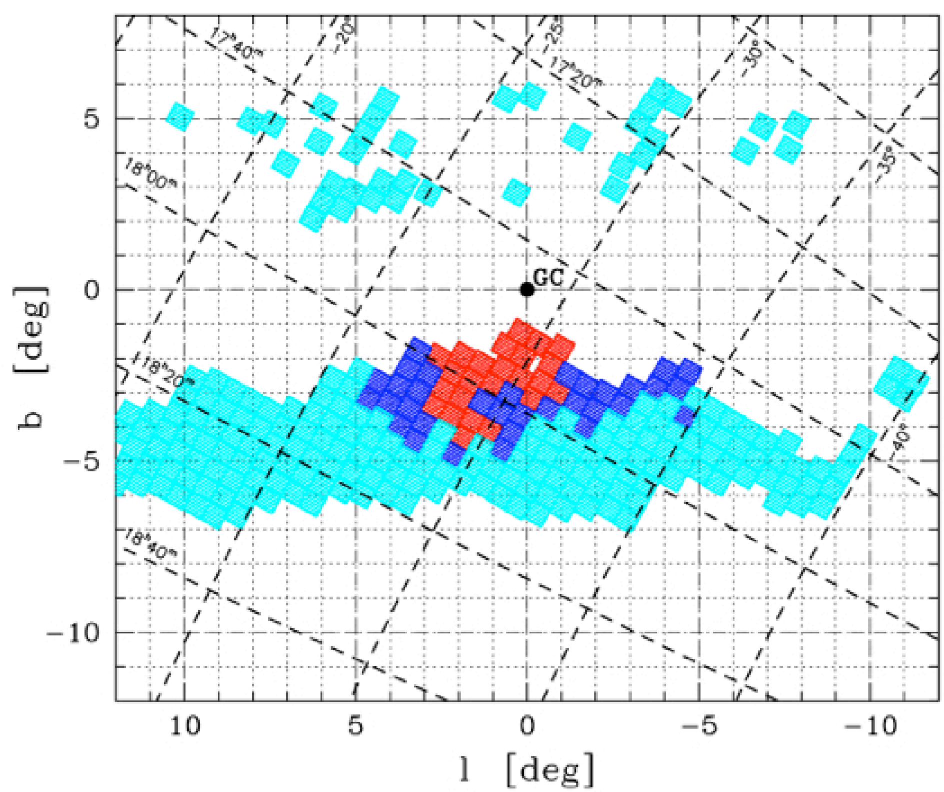
3. Wide-Field Network

   Future

Alert/Follow-Up

- Alerts Saturated
- 1000 Events/Year





High Magnification

- Detection Probability
  - 100% for A>500

$$N \approx 100\% \times \frac{1}{500} \times 1000 \approx 2$$

Low Magnification

- Detection Probability
  - 1% for A>1.34
- How Many Events?
  - Timescale = 20 days
  - Season = 8 months
  - Concurrent Events =1000 Events x 2 x 20 days / 8 months ~ 170 Events
- How Many Telescopes?
  - Sampling = 1 hour
  - Exposure Time = 5 minutes + 1 minute overhead
  - Number Events per Telescope = 1 hour / 6 minutes = 10 Events
  - Number of Telescopes per Site = 170 Events / 10 Events = 17!

$$N \approx 1\% \times 1000 \times \frac{N_{telescopes}}{17} = 0.6 N_{telescopes}$$

Order-of-Magnitude Estimates

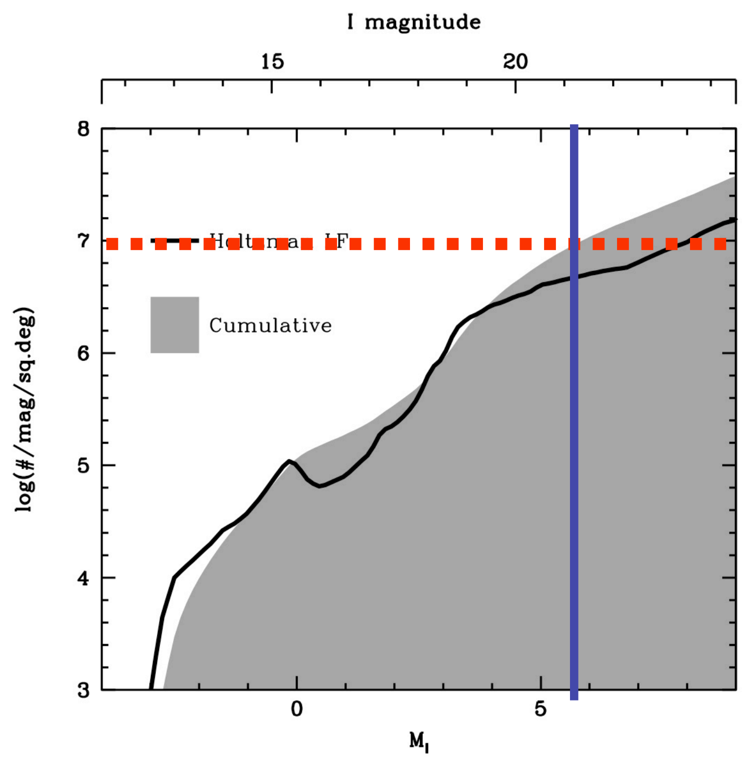
- Event Rate
  - Primary Event Rate

$$\Gamma \approx 10^{-5}\,\mathrm{yr}^{-1}$$

  - Detection Probability

$$P \approx 1\% \left(\frac{M_p}{M_E} \right)^{1/2}$$

  - Detections Per Year



$$N \approx n_F \Omega \Phi \Gamma P \approx 10\ \mathrm{yr}^{-1} \left(\frac{n_F \Omega}{10\square^\circ} \right) \left(\frac{\Phi}{10^7\ /\square^\circ} \right) \left(\frac{\Gamma}{10^{-5}\,\mathrm{yr}^{-1}} \right) \left(\frac{P}{1\%} \right)$$

Order-of-Magnitude Estimates

- Detecting the Perturbations
  - Duration

$$t_{E,p} = 2\text{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}$$

  - Signal Magnitude
    - >5% for Earth-mass planets

$$\rho = \frac{\theta_*}{\theta_E} \approx \left(\frac{M_p}{M_E}\right)^{-1/2}\left(\frac{R_*}{2R_\odot}\right)$$

  - Photometric Uncertainty
    - few % photometry for I~12 on ~1-2m class telescopes for few minute exposure times

NextGen μLensing Survey

- Requirements to detect ~10 Earth-mass planets per year
  - Monitor ~10 square degrees of the Galactic bulge continuously with ~10 minute sampling using 1-2m class telescopes

- Monte Carlo simulation
  - Survey specifications
    - Four 2m telescopes in Hawaii, Chile, South Africa and Australia
    - 4 square degree cameras
    - 4 fields in the bulge (16 square degrees, 7000 events per year)
  - *Most* ambitious survey ➔ degrades gracefully

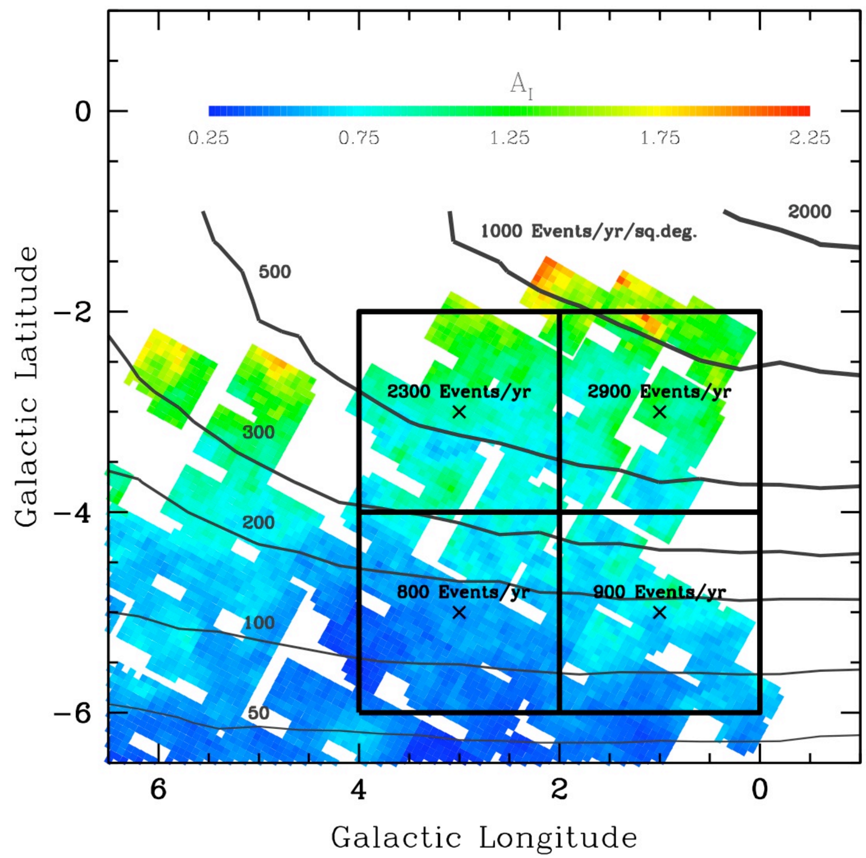
Observatory Parameters

	Hawaii	South Africa	La Silla	Siding Springs
Longitude	204.5º	20.80º	289.27º	149.06º
Latitude	19.83º	-32.38º	-29.25º	-31.27º
Mean Seeing	0.75”	1.00”	0.75”	1.75”
Seeing Variance	0.25”	0.25”	0.25”	0.5”

- Visibility
  - Airmass < 2
  - Sun > 15° below horizon

Target Fields

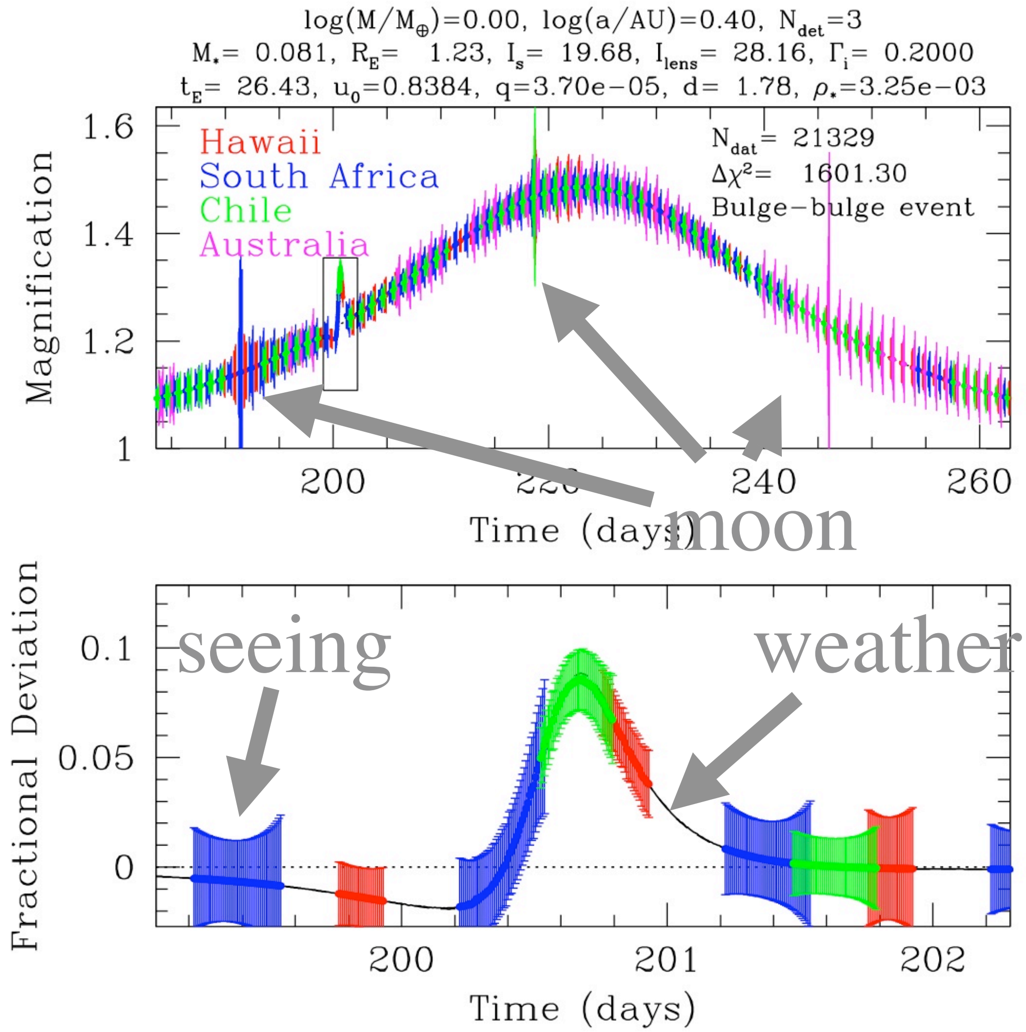
- Four Fields
  - (l,b)=(1,-3)
    - ~2900 Events/yr
  - (l,b)=(3,-3)
    - ~2300 Events/yr
  - (l,b)=(1,-5)
    - ~900 Events/yr
  - (l,b)=(3,-5)
    - ~800 Events/yr



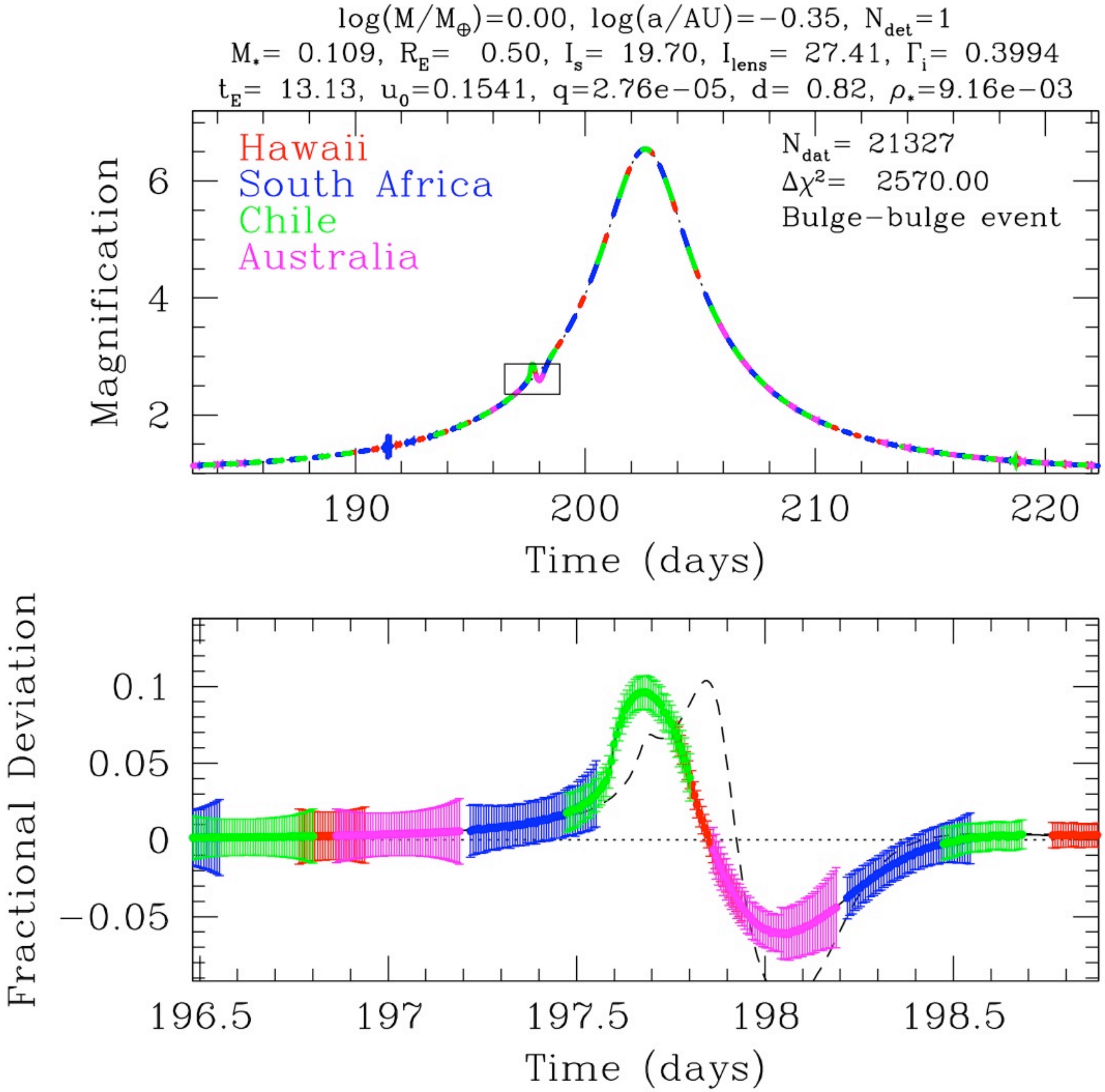
Simulation Ingredients

Monte Carlo Simulation

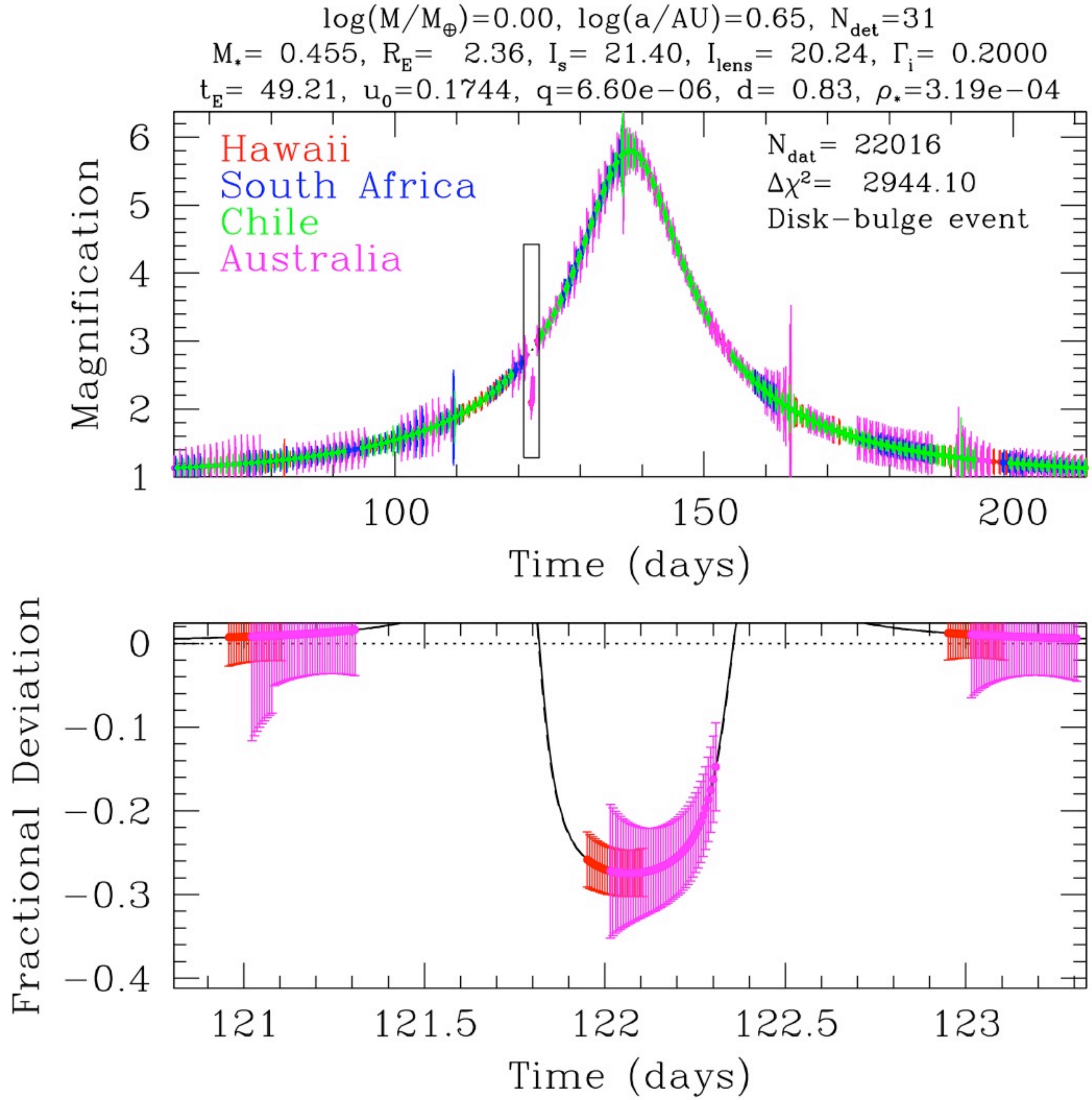
- µLensing Event Model
- Blending Model
- Moon + Sky
- Weather
- Seeing



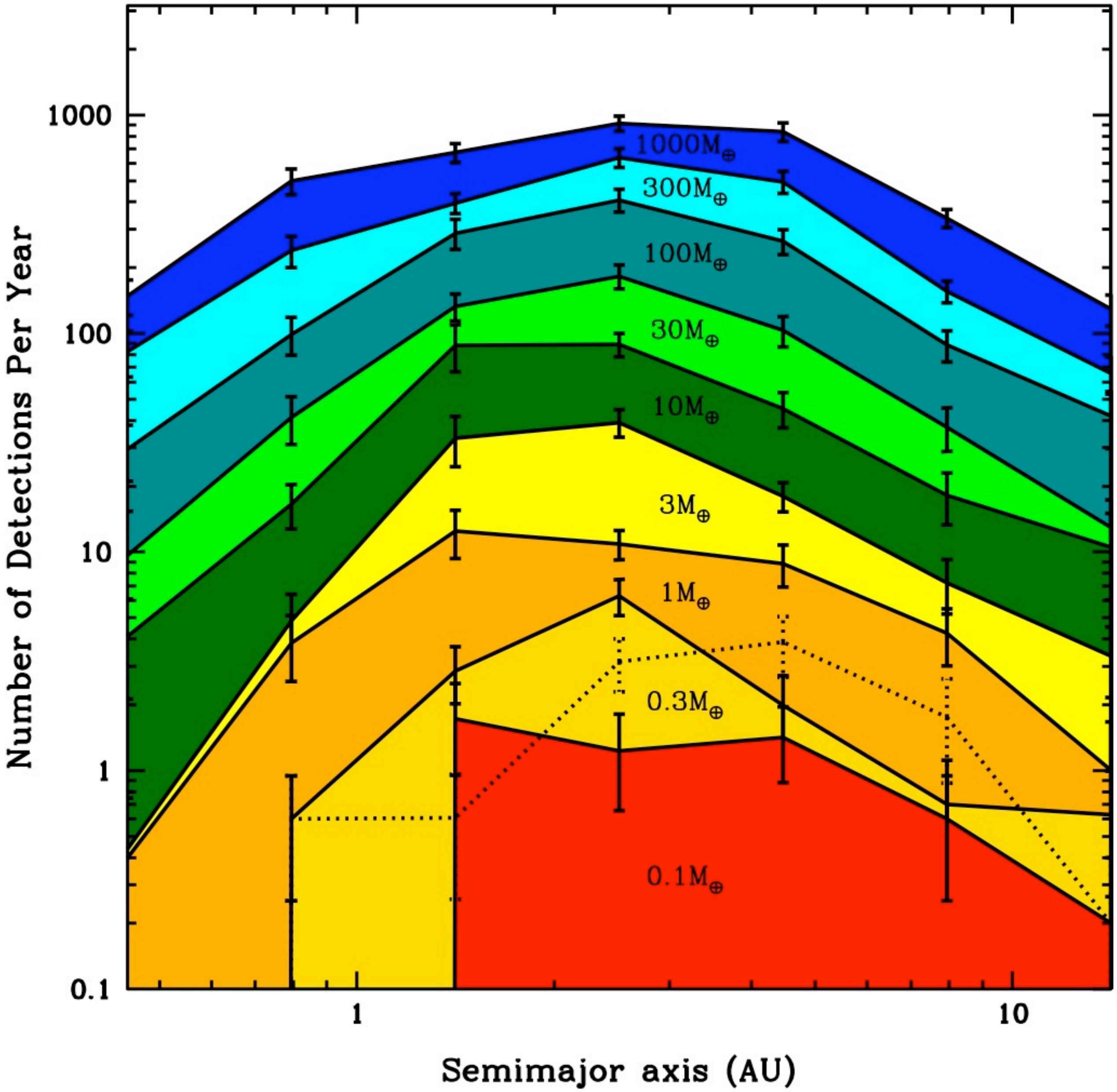
(w/ Han & Andy)



log(M/M$_\oplus$)=0.00, log(a/AU)=−0.35, N$_{det}$=1
M$_*$= 0.109, R$_E$= 0.50, I$_s$= 19.70, I$_{lens}$= 27.41, Γ$_i$= 0.3994
t$_E$= 13.13, u$_0$=0.1541, q=2.76e−05, d= 0.82, ρ$_*$=9.16e−03
Hawaii
South Africa
Chile
Australia
N$_{dat}$= 21327
Δχ²= 2570.00
Bulge−bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

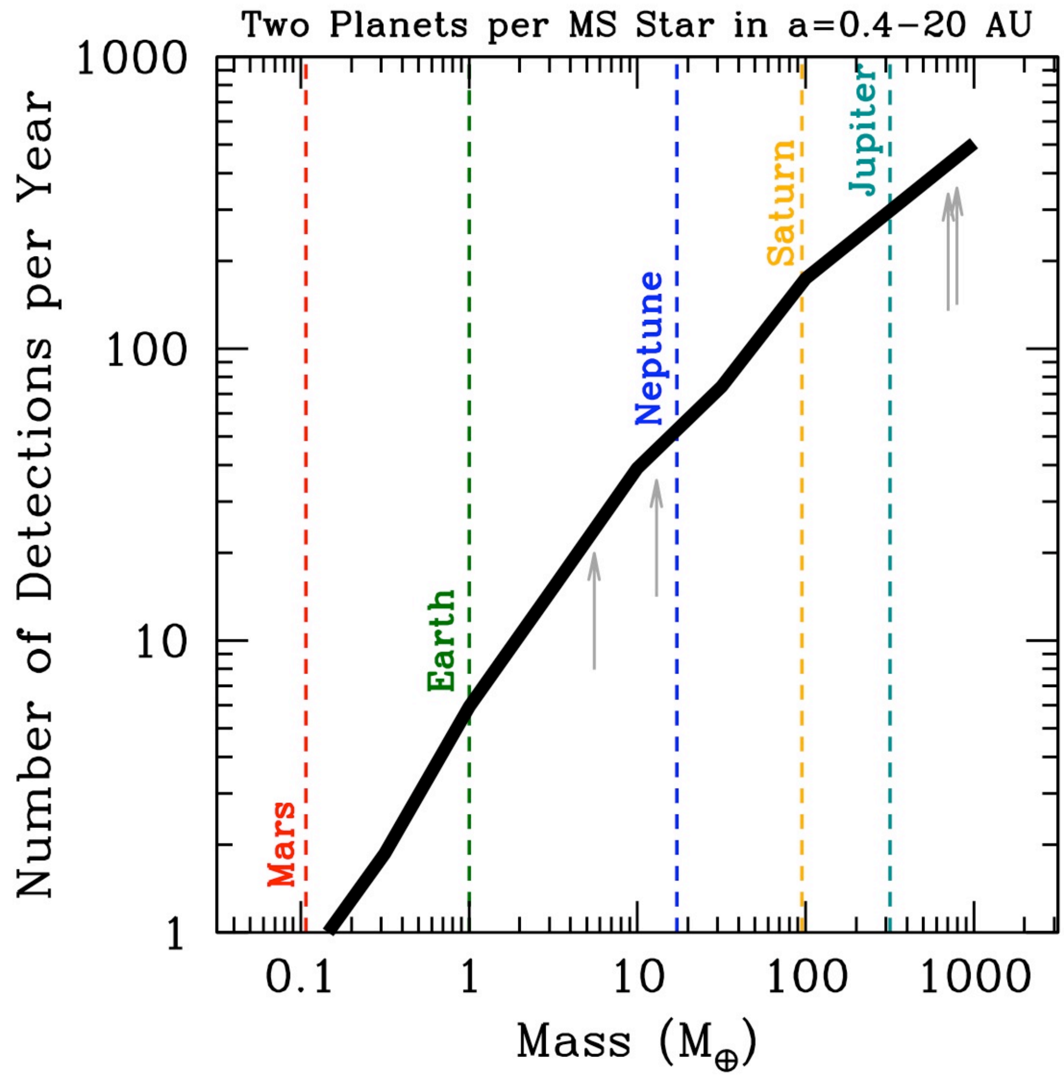


log(M/M⊕)=0.00, log(a/AU)=0.65, N_det=31
M*= 0.455, R_E= 2.36, I_s= 21.40, I_lens= 20.24, Γ_i= 0.2000
t_E= 49.21, u_0=0.1744, q=6.60e−06, d= 0.83, ρ*=3.19e−04
Hawaii
South Africa
Chile
Australia
N_dat= 22016
Δχ²= 2944.10
Disk−bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)



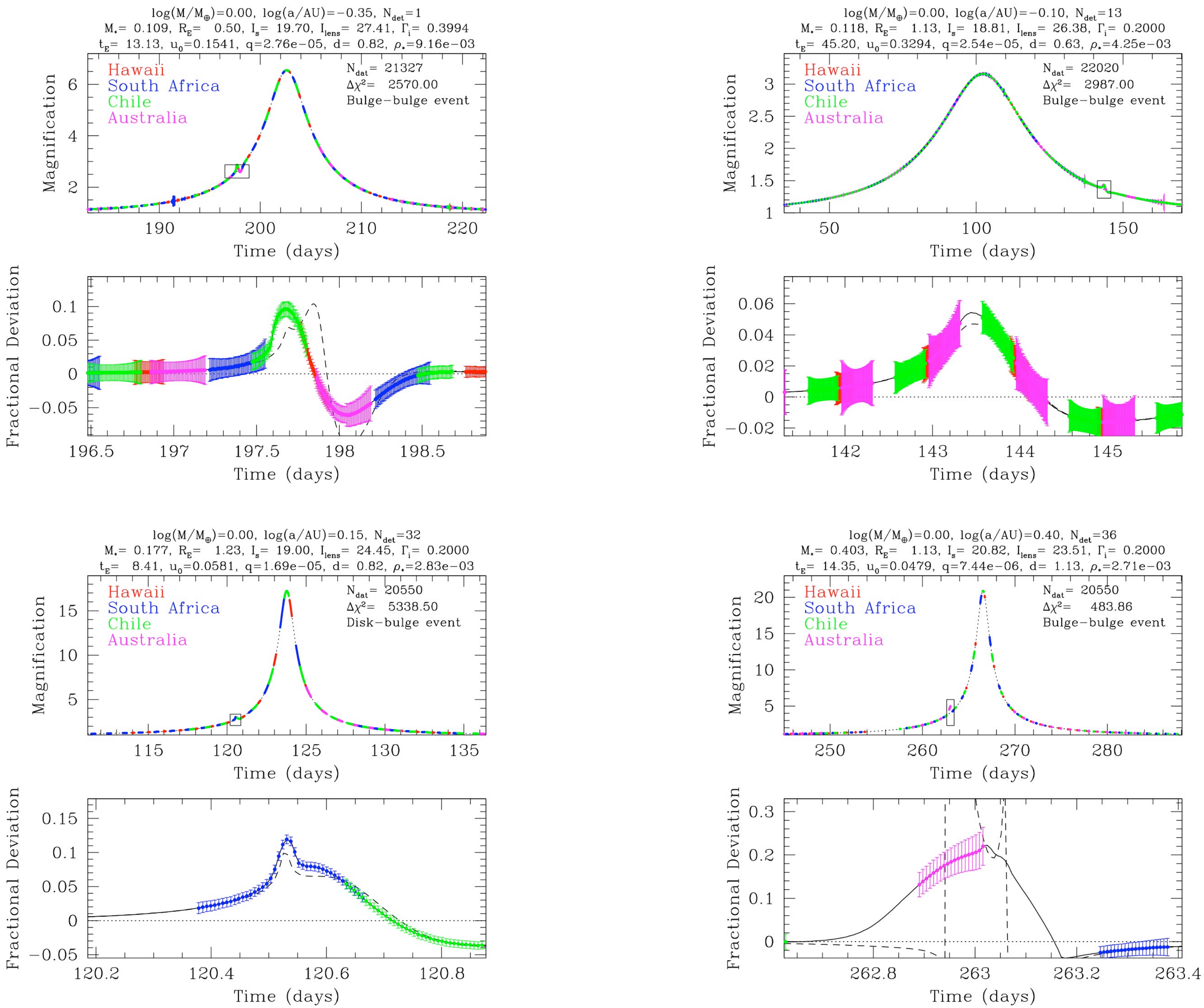
1000
100
10
1
0.1
1
10
Number of Detections Per Year
Semimajor axis (AU)
1000M⊕
300M⊕
100M⊕
30M⊕
10M⊕
3M⊕
1M⊕
0.3M⊕
0.1M⊕

- Average over *a*
  - -0.35<log(a/AU)<1.15
  - Two planets per star

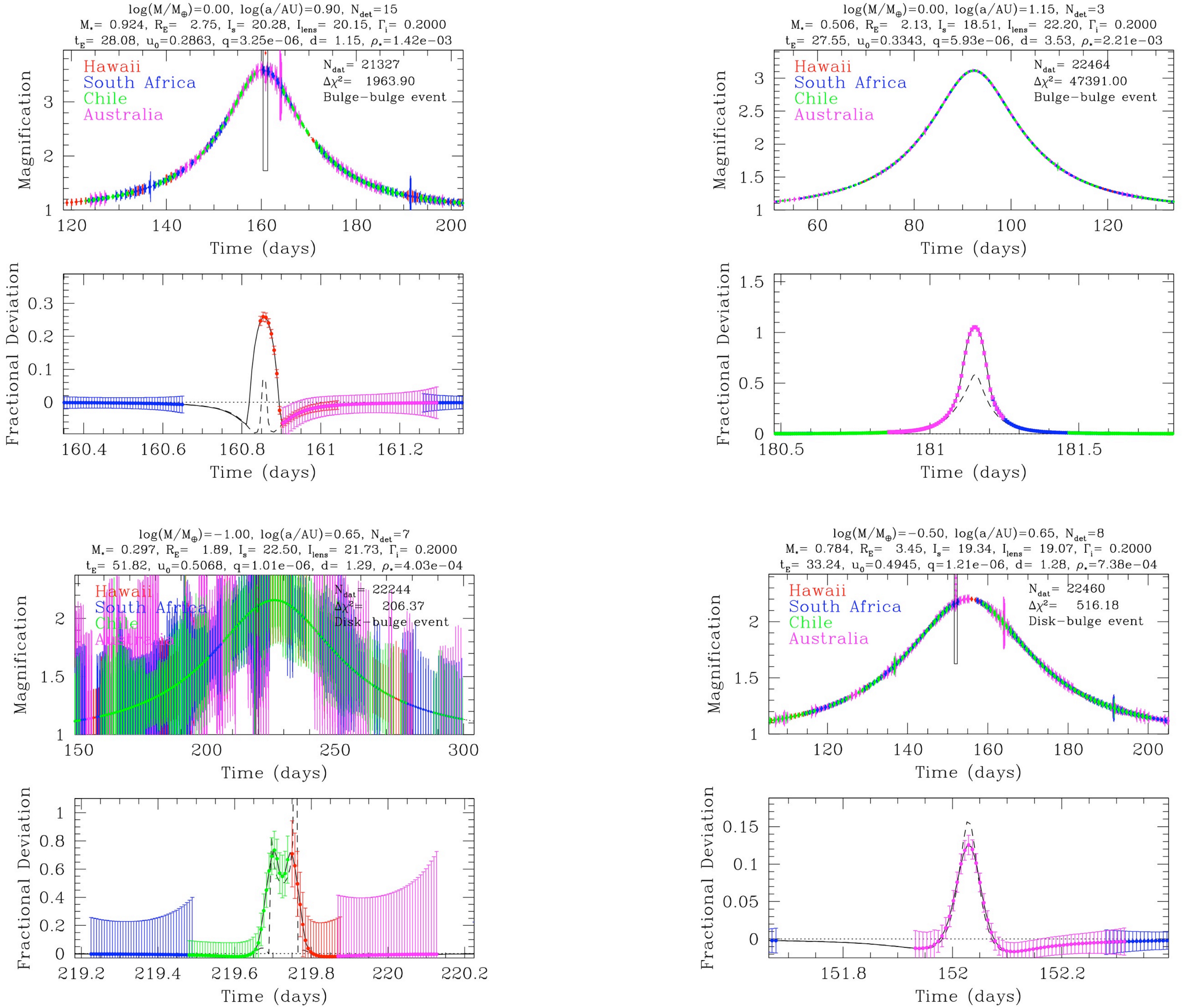


$\log(M/M_\oplus)$	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Γ (yr^{-1})	1.5±0.3	3.7±0.5	12±1	30±3	78±8	150±10	350±20	590±30	1012±40

2 planets per star, uniformly distributed in log a in the range 0.4-20 AU



log(M/M⊕)=0.00, log(a/AU)=−0.35, Ndet=1
M*= 0.109, RE= 0.50, Is= 19.70, Ilens= 27.41, Γi= 0.3994
tE= 13.13, u0=0.1541, q=2.76e−05, d= 0.82, ρ*=9.16e−03
Hawaii
South Africa
Chile
Australia
Ndat= 21327
Δχ2= 2570.00
Bulge−bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)
log(M/M⊕)=0.00, log(a/AU)=−0.10, Ndet=13
M*= 0.118, RE= 1.13, Is= 18.81, Ilens= 26.38, Γi= 0.2000
tE= 45.20, u0=0.3294, q=2.54e−05, d= 0.63, ρ*=4.25e−03
Ndat= 22020
Δχ2= 2987.00
Bulge−bulge event
log(M/M⊕)=0.00, log(a/AU)=0.15, Ndet=32
M*= 0.177, RE= 1.23, Is= 19.00, Ilens= 24.45, Γi= 0.2000
tE= 8.41, u0=0.0581, q=1.69e−05, d= 0.82, ρ*=2.83e−03
Ndat= 20550
Δχ2= 5338.50
Disk−bulge event
log(M/M⊕)=0.00, log(a/AU)=0.40, Ndet=36
M*= 0.403, RE= 1.13, Is= 20.82, Ilens= 23.51, Γi= 0.2000
tE= 14.35, u0=0.0479, q=7.44e−06, d= 1.13, ρ*=2.71e−03
Ndat= 20550
Δχ2= 483.86
Bulge−bulge event



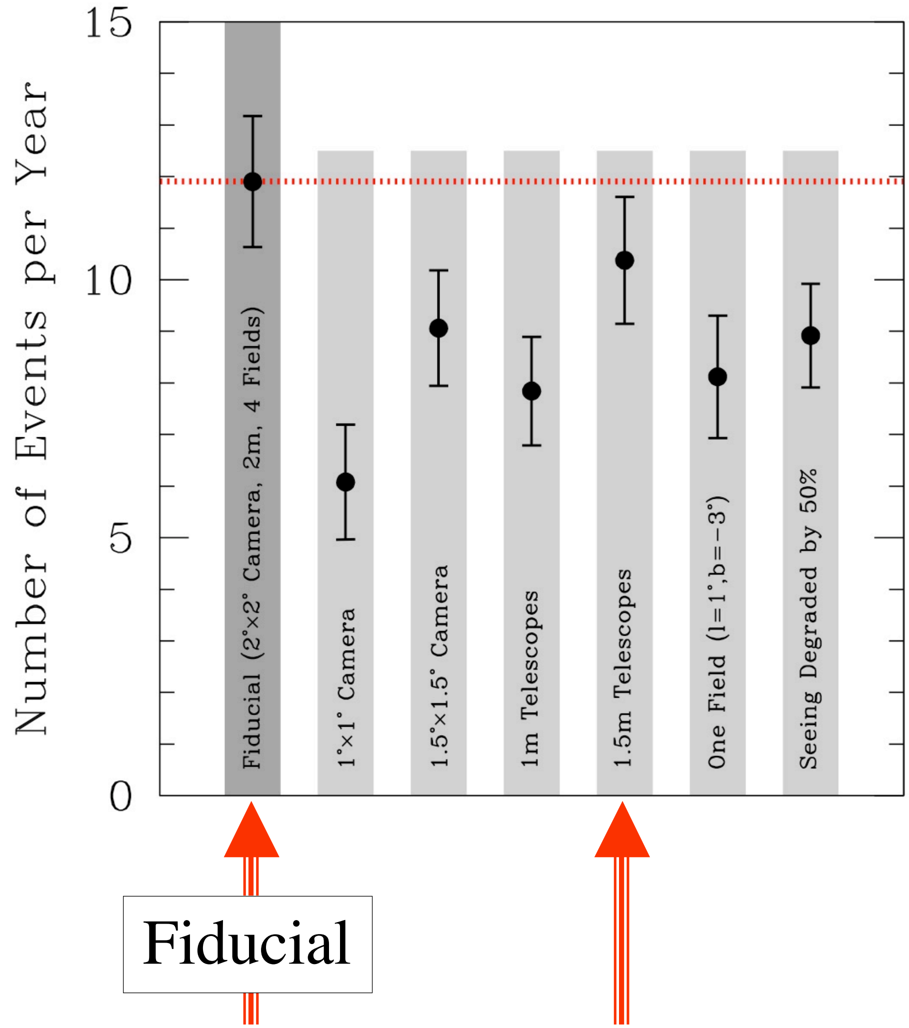
log(M/M⊕)=0.00, log(a/AU)=0.90, N_det=15
M*= 0.924, R_E= 2.75, I_s= 20.28, I_lens= 20.15, Γ_I= 0.2000
t_E= 28.08, u_0=0.2863, q=3.25e-06, d= 1.15, ρ*=1.42e-03
Hawaii
South Africa
Chile
Australia
N_dat= 21327
Δχ²= 1963.90
Bulge-bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)
log(M/M⊕)=0.00, log(a/AU)=1.15, N_det=3
M*= 0.506, R_E= 2.13, I_s= 18.51, I_lens= 22.20, Γ_I= 0.2000
t_E= 27.55, u_0=0.3343, q=5.93e-06, d= 3.53, ρ*=2.21e-03
Hawaii
South Africa
Chile
Australia
N_dat= 22464
Δχ²= 47391.00
Bulge-bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)
log(M/M⊕)=−1.00, log(a/AU)=0.65, N_det=7
M*= 0.297, R_E= 1.89, I_s= 22.50, I_lens= 21.73, Γ_I= 0.2000
t_E= 51.82, u_0=0.5068, q=1.01e-06, d= 1.29, ρ*=4.03e-04
Hawaii
South Africa
Chile
Australia
N_dat= 22244
Δχ²= 206.37
Disk-bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)
log(M/M⊕)=−0.50, log(a/AU)=0.65, N_det=8
M*= 0.784, R_E= 3.45, I_s= 19.34, I_lens= 19.07, Γ_I= 0.2000
t_E= 33.24, u_0=0.4945, q=1.21e-06, d= 1.28, ρ*=7.38e-04
Hawaii
South Africa
Chile
Australia
N_dat= 22460
Δχ²= 516.18
Disk-bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

Toward a NextGen Survey

- MOA-II
  - 1.8m telescope, 2.18 sq. degree camera, NZ
- OGLE -IV
  - 1.3m telescope, upgrade to 1.4 sq. degree camera
- KMN - Korean Microlensing Network
  - $30M to build three telescopes and cameras
  - South Africa, Chile, Australia

Ok, What About Reality?

- Detection Threshold
- Systematic Error
- Diameter
- Area of Detector
- Seeing
- One Field
- Different Sites



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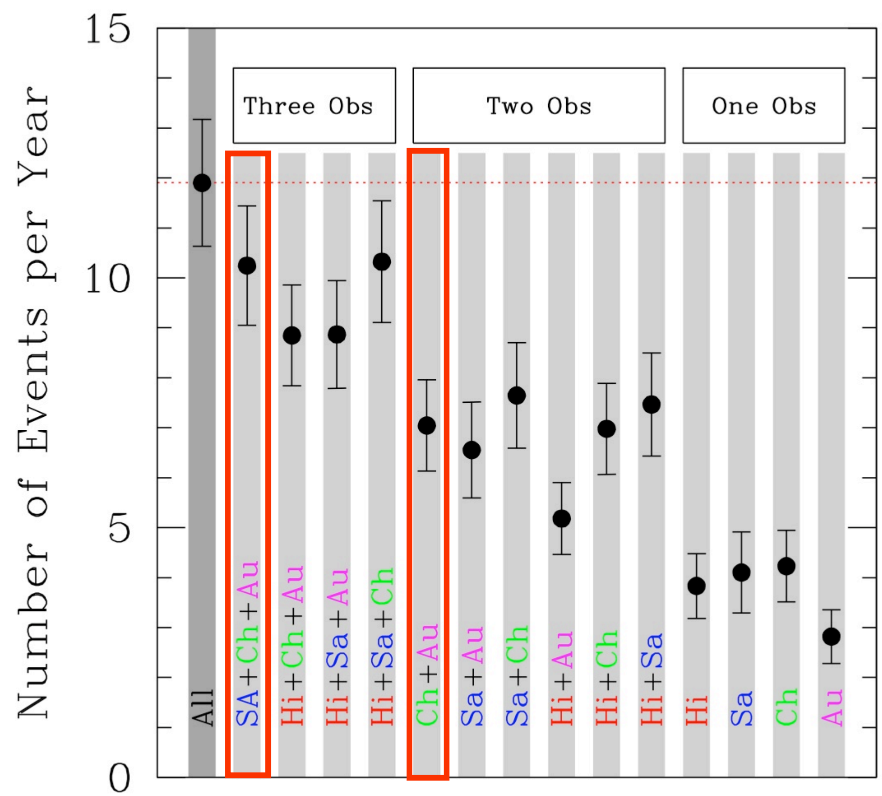


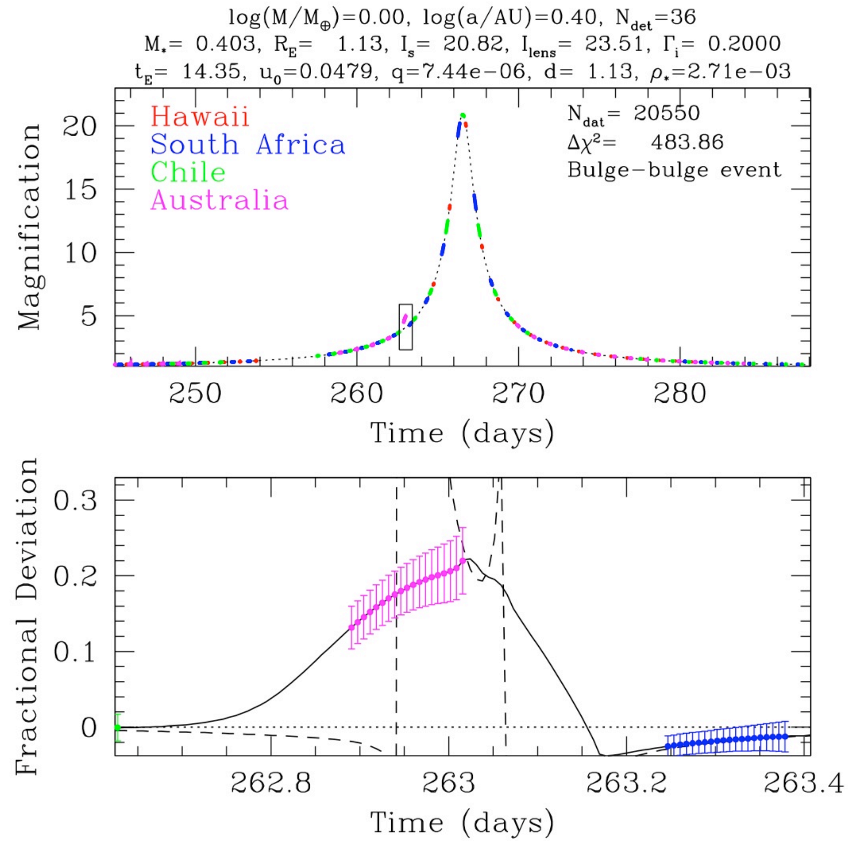
High Magnification Events?

- A>200 *ignored* in simulation.
  - ~ 10 per year
- Also saturated and finite source events.
- Will be alerted $\rightarrow$ potential for follow-up.
- High magnification events have advantages that the survey events do not.

Why Space is Better

From the ground:

- MS sources severely blended
- Getting constraints on hosts is expensive
- Perturbations can be poorly sampled



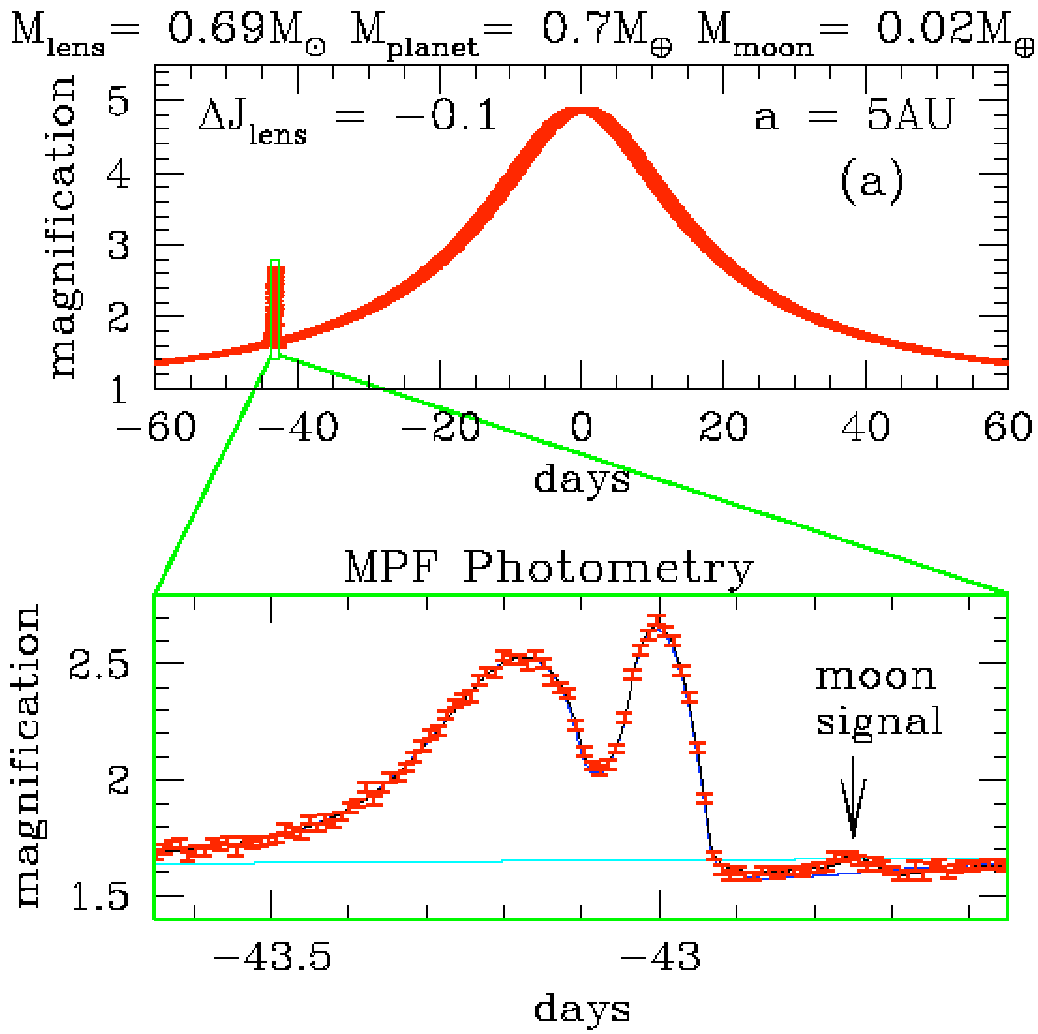
What can we expect from Space?

A worked example: Microlensing Planet Finder (Bennett PI)

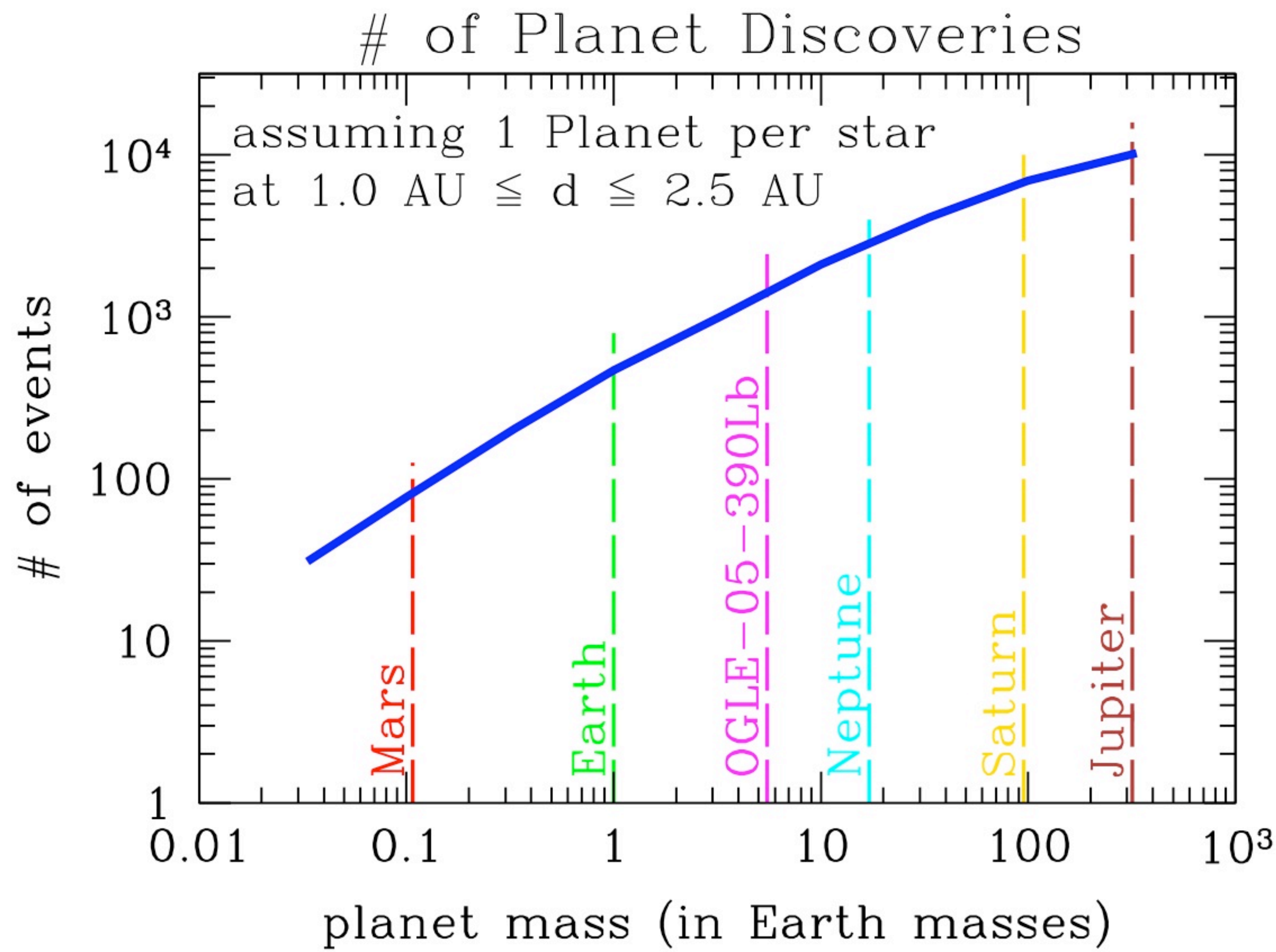
- Simulations from Bennett & Rhie (2002)
- Basic results confirmed by independent simulations.
- Continuous observations of 4 × 0.66 sq. deg. central Galactic bulge fields: ~2×10^8 stars
- Observations in near IR to increase sensitivity
- ~15,000 events in 4 seasons

Simulated Planetary Light Curves

- Exposures every 10-15 minutes
- Strong signal
- Unambiguous information
- Moons detectable! (1.6 lunar masses)

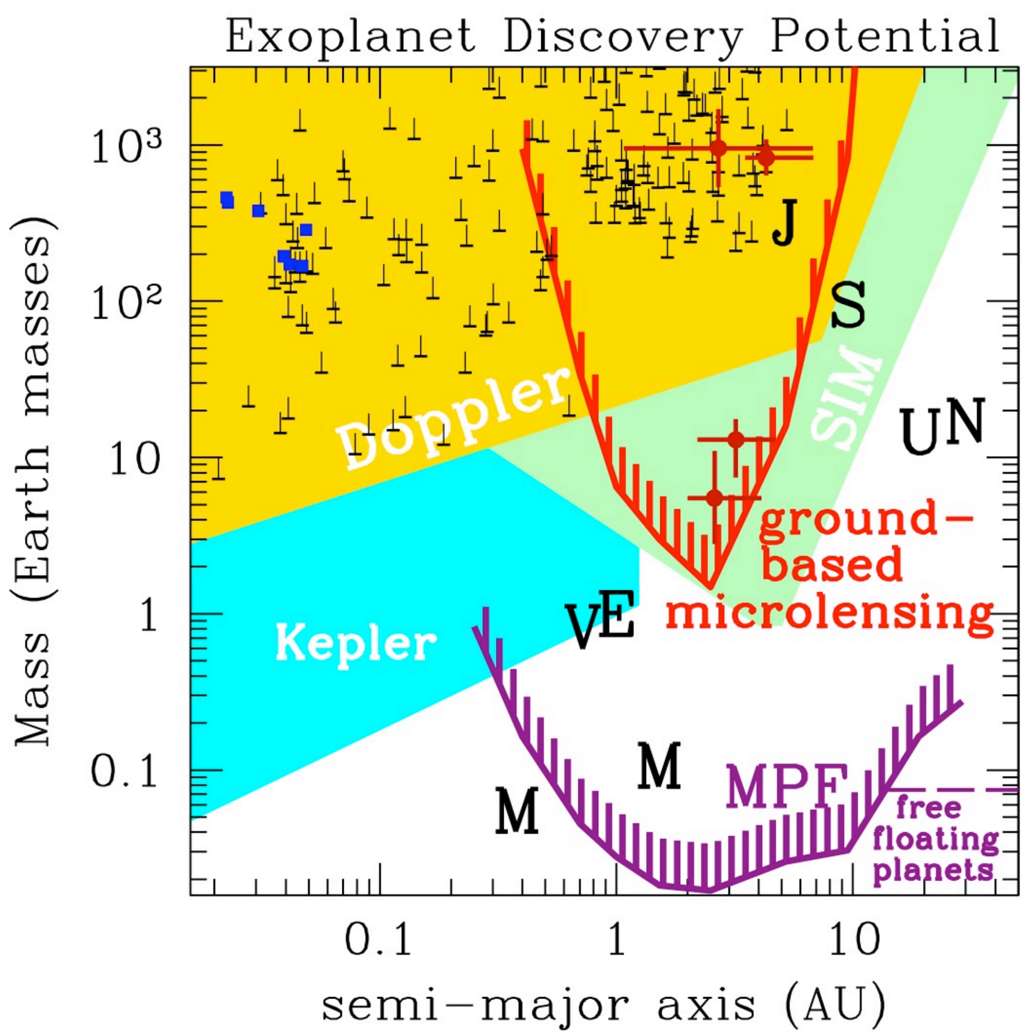


MPF Discoveries



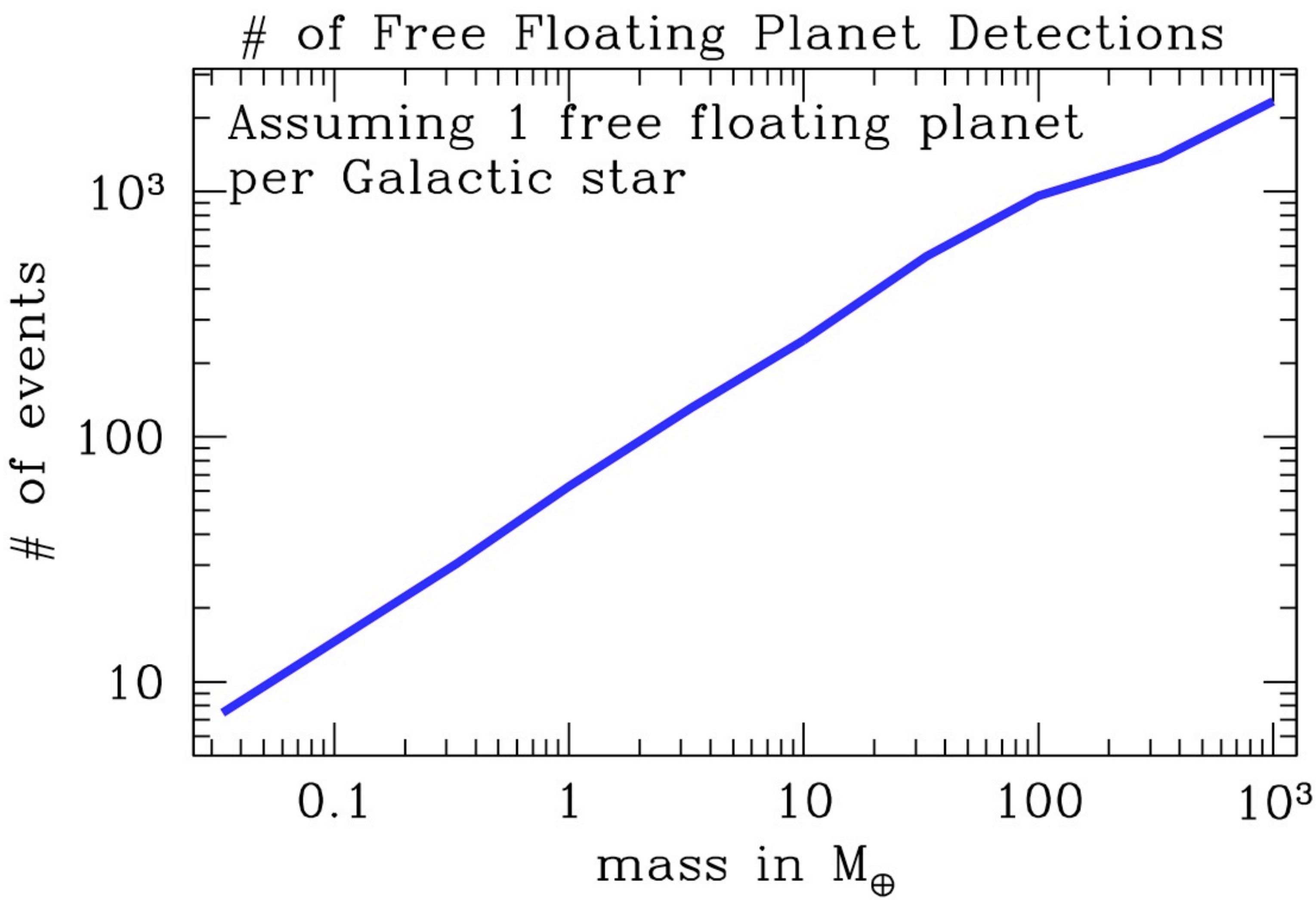
Planet Detection Sensitivity

- Sensitivity to all Solar System-analogs except Mercury
- most sensitive technique for a ≥ 0.5 AU
- Good sensitivity to "outer" habitable zone (Mars-like orbits) where detection by TPF is easiest
- Assumes $\Delta\chi^2 \geq 80$ detection threshold
- Can find moons and free floating planets



Updated from Bennett & Rhie (2002) ApJ 574, 985

Free Floating Planets



Planet formation theories generically predict many free-floating planets.

Summary

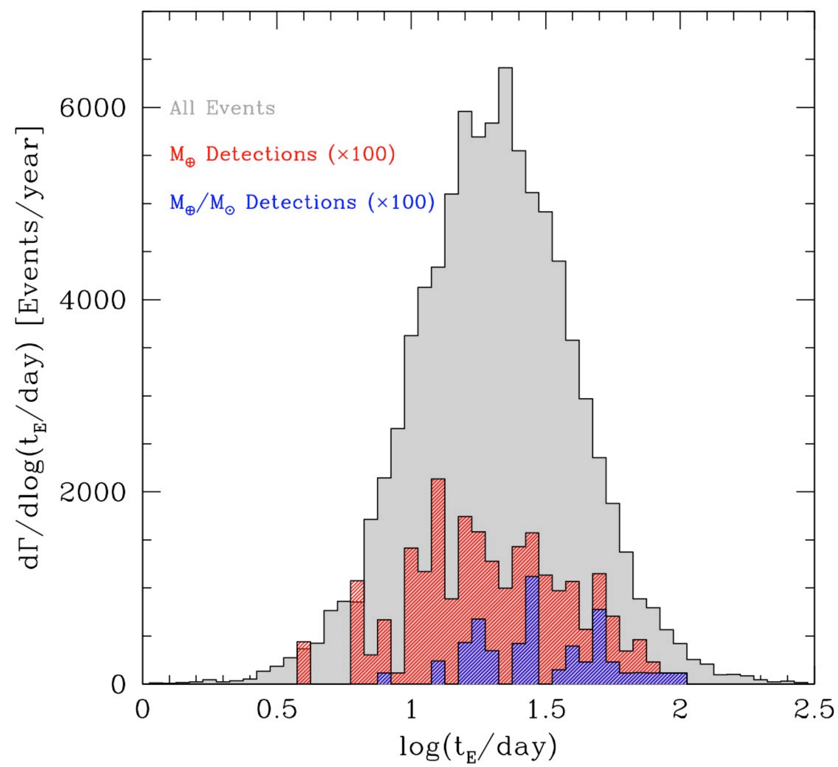
- Earth-Mass planets require new approach.
- Next Generation experiment - 12 Earths/year.
- MOA II (III?), OGLE IV, *KMN*
- High-magnification events will keep those interested in follow-up busy.
- A space survey will increase the detection rate by at least an order of magnitude.

Summary

- Order of Magnitude Estimates
  - ~ 20 events/year
  - Main-sequence source stars
  - Requires ~2m telescopes
  - Severe Blending / Background Limited
- Detailed Simulation
  - Han & Gould Model
  - Weather, Sky, Background, Moon, Visibility
- Basic Results
  - 10 Earth-mass planets per year
    - 2 planets per MS lens with 0.4AU $< a <$ 20 AU
- Sensitivity to Assumptions
  - Reasonably robust to systematics, seeing, diameter.
  - Need camera with at least $1.5^\circ \times 1.5^\circ$
  - Need at least three sites
- Agrees reasonably well with Dave’s simulations
  - (when similar assumptions are used)
- Parameter Uncertainties
  - Average:
    - Mass ratio to 10%
    - Source size to 30%
    - Timescale and impact parameter to 1%

Simulation Ingredients-I

- Event Model
  - Han & Gould (1995, 2003) Galactic model
  - Gould (2000) mass function
  - Vertically exponential dust disk
  - Cox (1999) Mass-Luminosity Relation
  - Holtzman et al. (1998) bulge luminosity function
  - 10Gyr Isochrone radius-luminosity relation
- Monte Carlo Simulation



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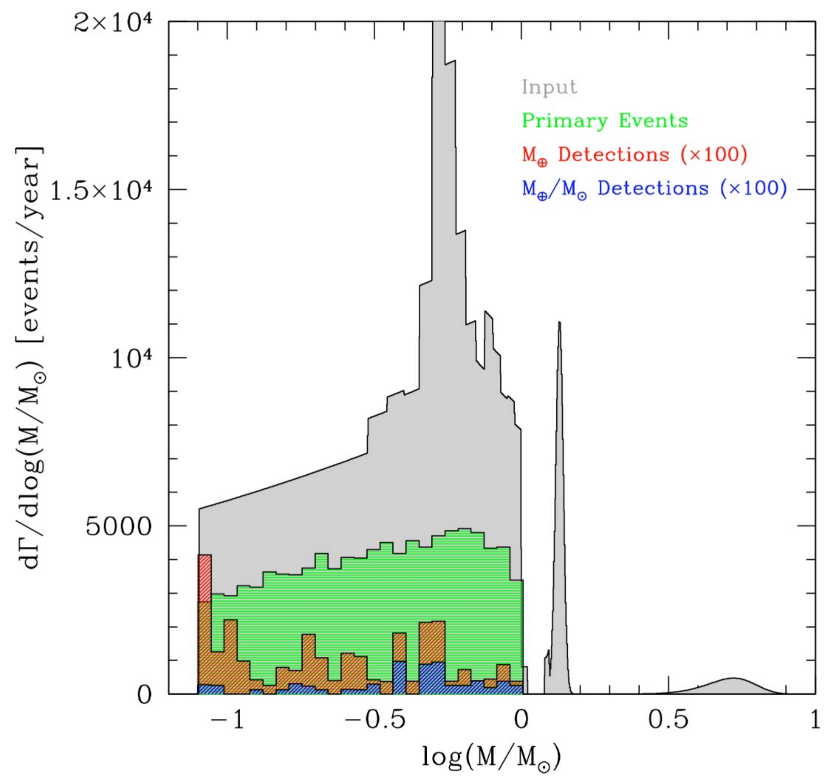

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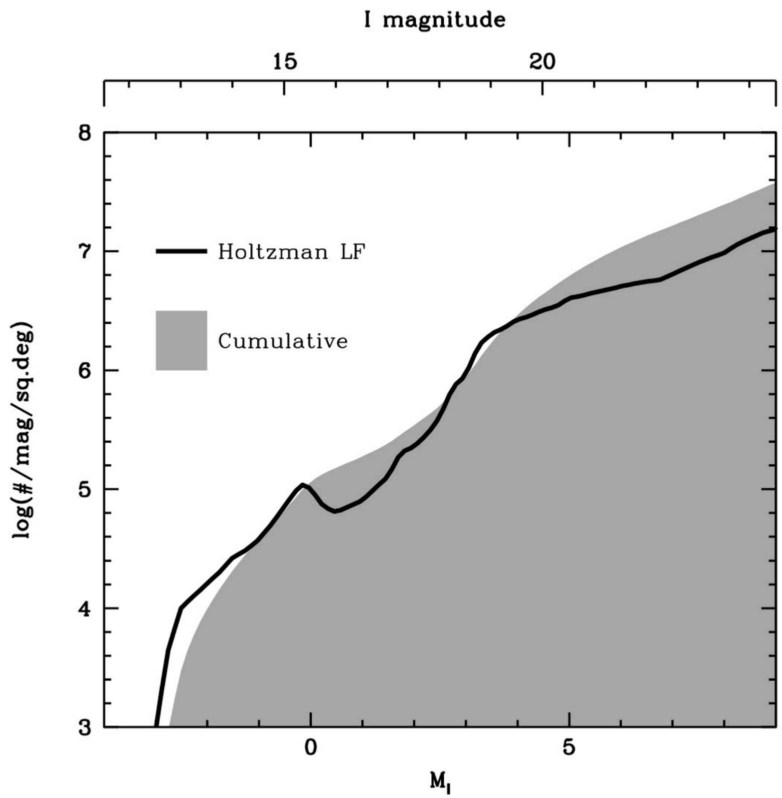
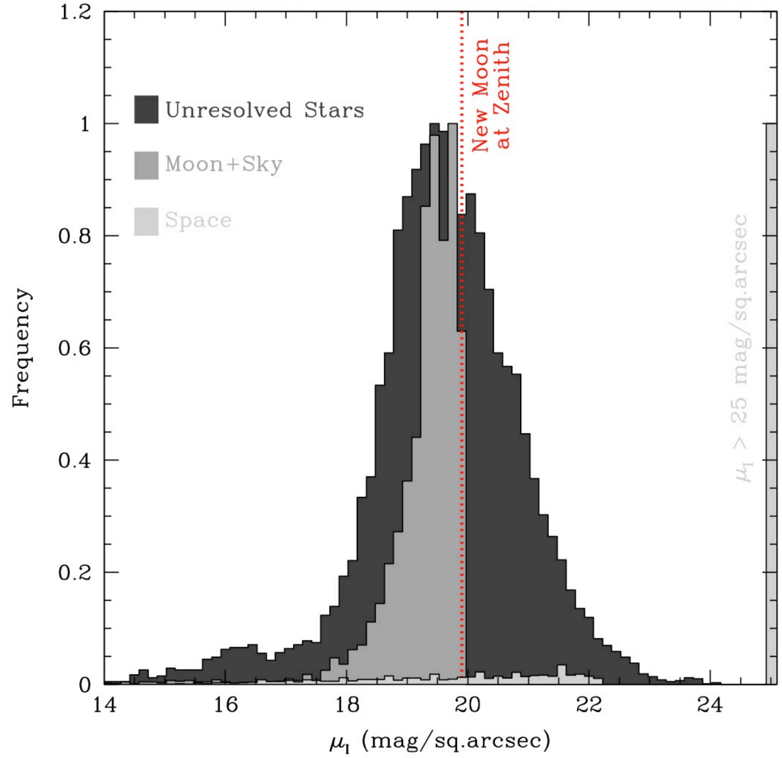


Simulation Ingredients-II

- Blending Model
  - Holtzman LF
  - Monte Carlo simulation
    - Mean Seeing 1.2”
  - Scaled to $\Sigma(l,b)$ and $A_I(l,b)$
- Moon + Sky
  - Krisciunus & Schaefer (1991)
  - Dark Sky (I=19.9 mag/□”)
- Weather
  - ‘Weather pattern’
  - Poisson, mean = 4 days
  - Average from Peale (1997)
- Seeing
  - Seeing at Zenith constant for ‘weather pattern’
  - Gaussian, Minimum = 0.5”
  - Seeing $\propto$ airmass$^{0.6}$



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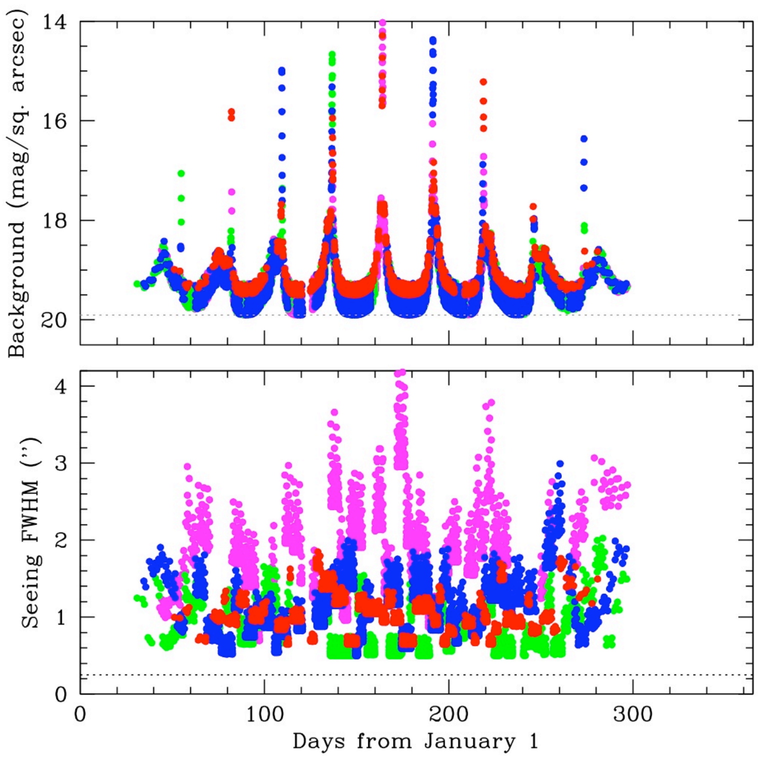

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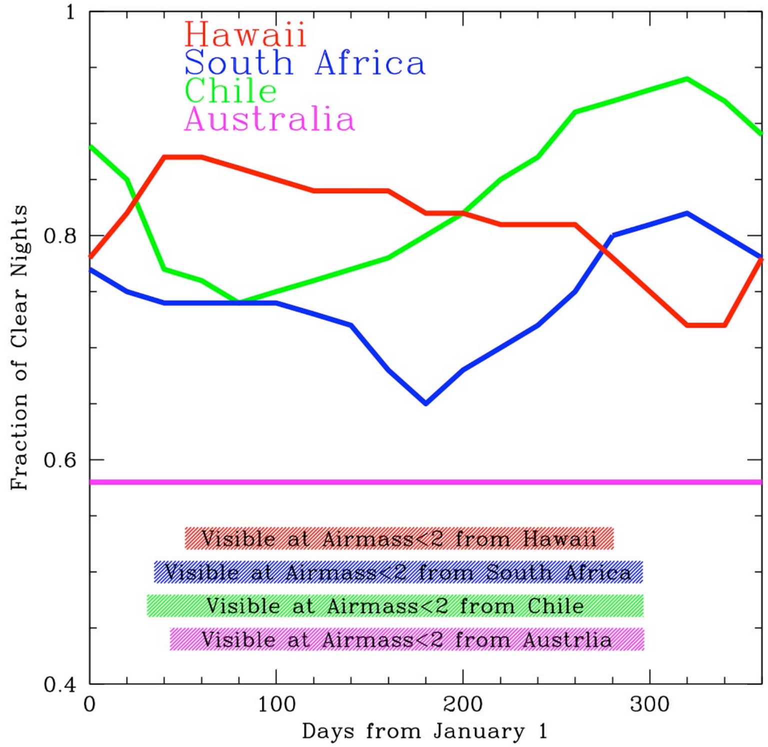

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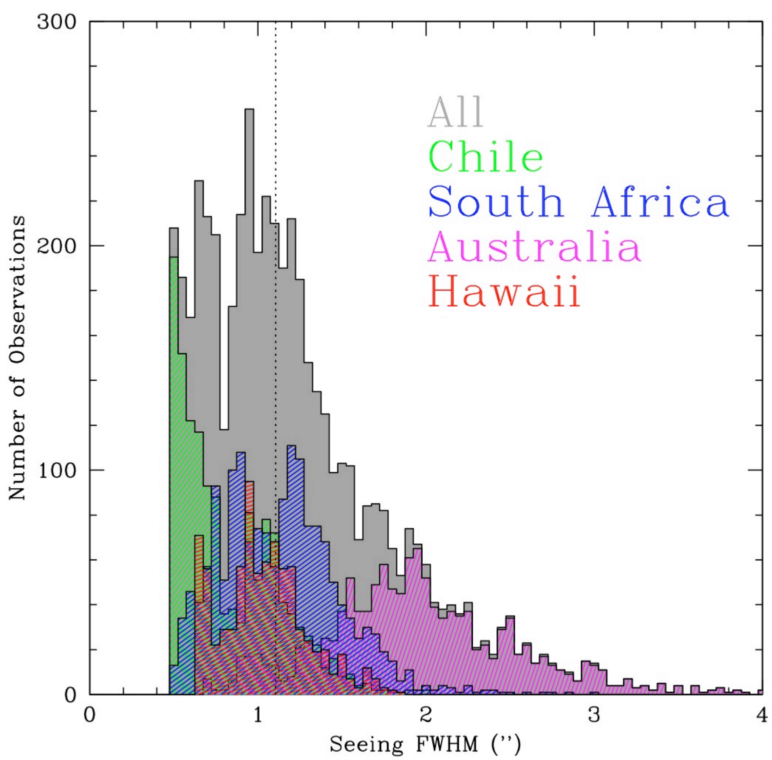


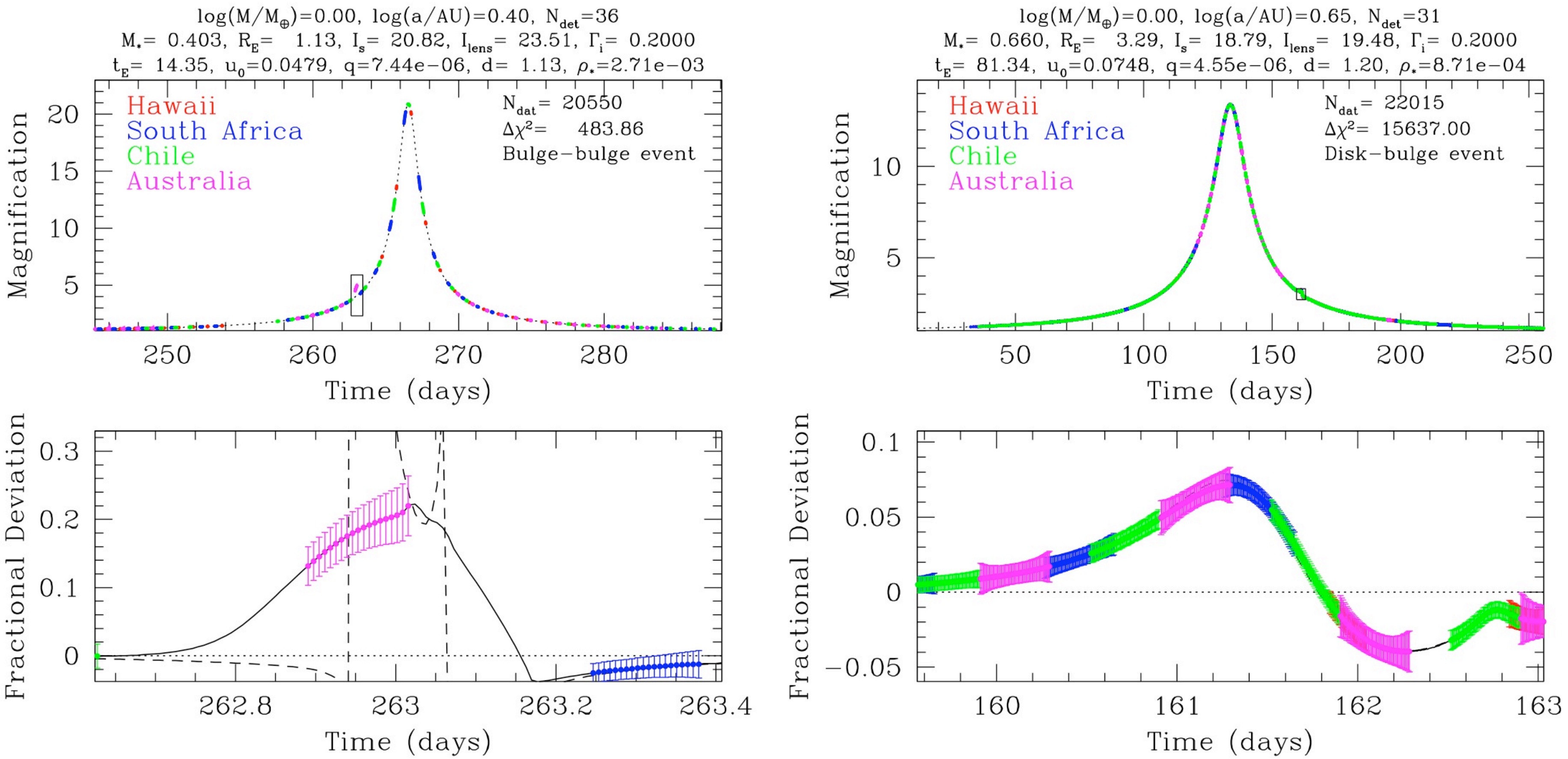
Simulation Ingredients-III

- Photometry
  - Poisson

$$N = 10\gamma/\mathrm{s}\left(\frac{D}{2\mathrm{m}}\right)^2 10^{-0.4(I-22)}$$

  - Source + Blend + Lens
  - Systematic - 0.2%
  - Saturation

Parameter Uncertainties



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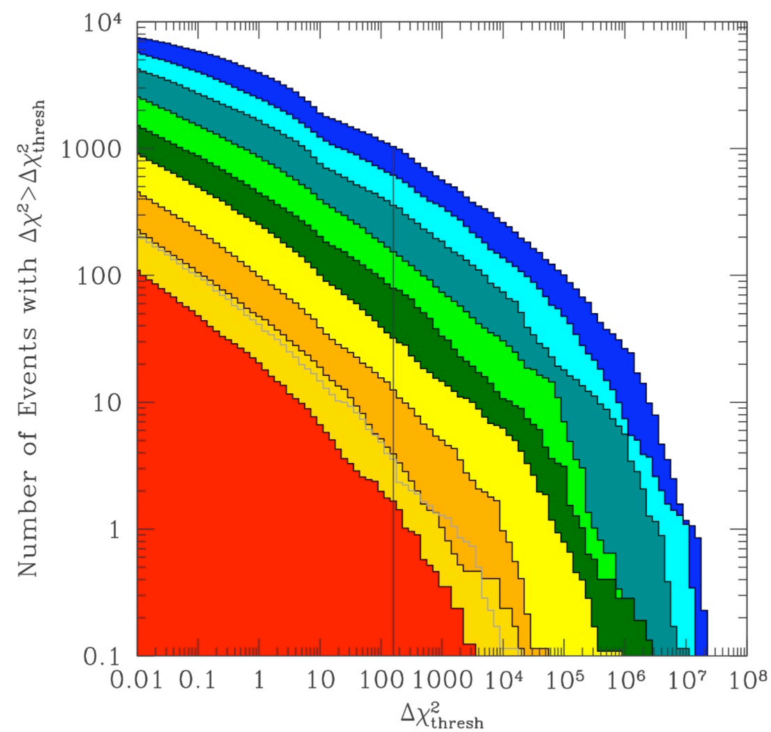

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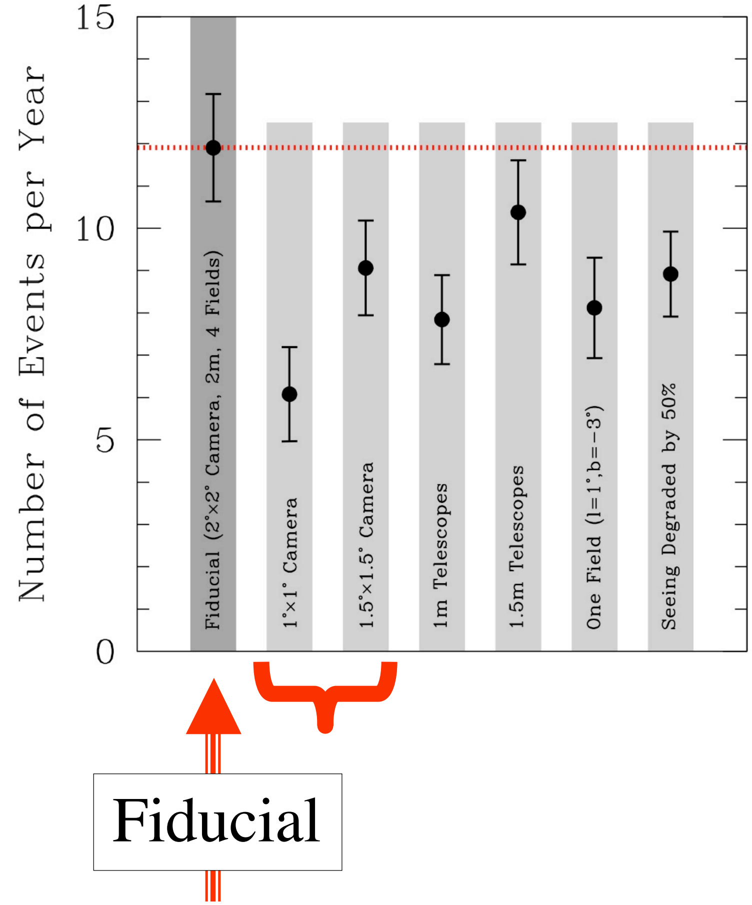

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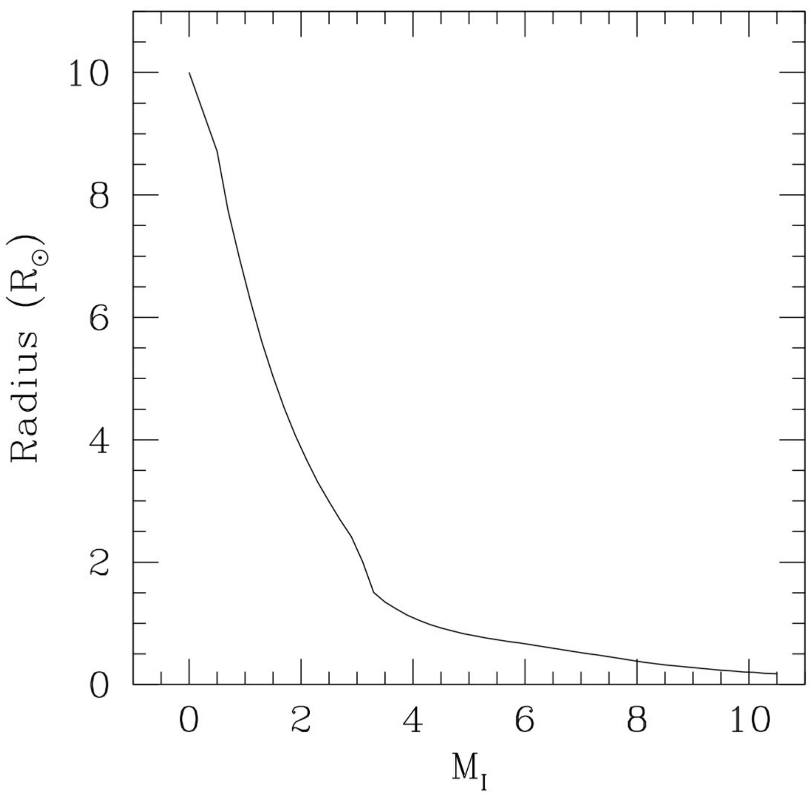
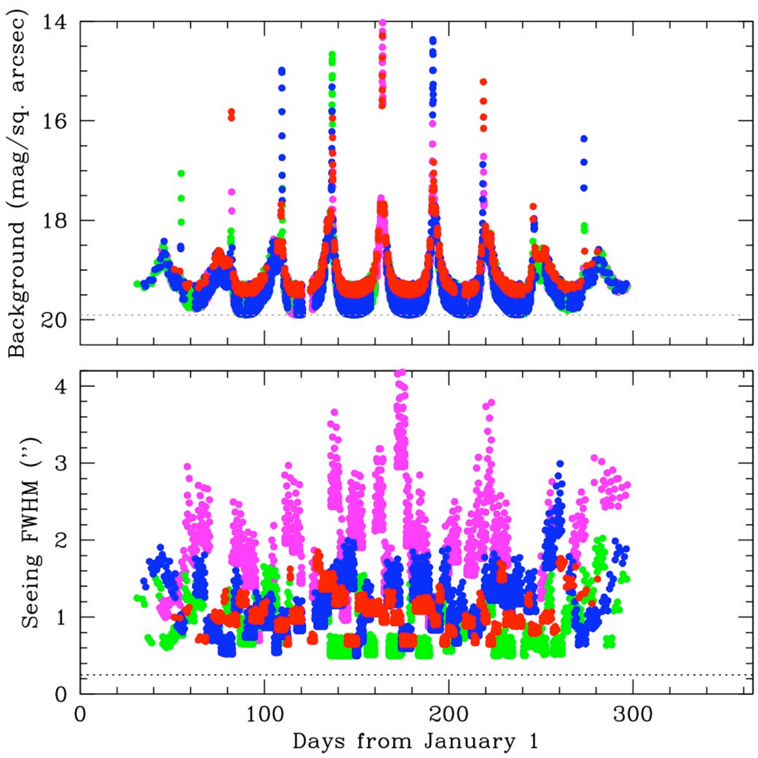
  - 10Gyr Isochrone radius-luminosity relation
- Monte Carlo Simulation



Simulation Ingredients-II

- Blending Model
  - Holtzman LF
  - Monte Carlo simulation
    - Mean Seeing 1.2”
  - Scaled to Σ(l,b) and A_I(l,b)
- Moon + Sky
  - Krisciunus & Schaefer (1991)
  - Dark Sky (I=19.9 mag/☐)
- Weather
  - ‘Weather pattern’
  - Poisson, mean = 4 days
  - Average from Peale (1997)
- Seeing
  - Seeing at Zenith constant for ‘weather pattern’
  - Gaussian, Minimum = 0.5”
  - Seeing $\propto$ airmass$^{0.6}$

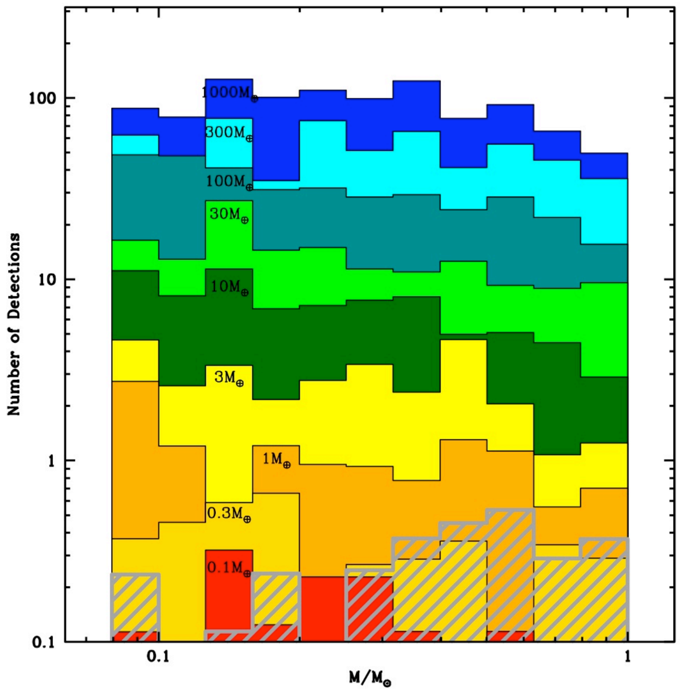


Fiducial Simulation Parameters

Diameter of Telescopes	2m
Number of Fields	4
Size of Detector	$2° \times 2°$
Size of Pixel	0.2”
Full Well Depth	50,000 e^-
Photon Rate	10/s at I=22 for D=2m
Systematic Error	0.2%
Exposure Time	2 minutes
Overhead	30 seconds
Sampling Interval	10 minutes
Primary χ^2 Threshold	500
Planetary χ^2 Threshold	160
Minimum Impact Parameter	0.005
Maximum Impact Parameter	3
Average Weather Pattern Duration	4 days
Minimum Seeing	0.5”

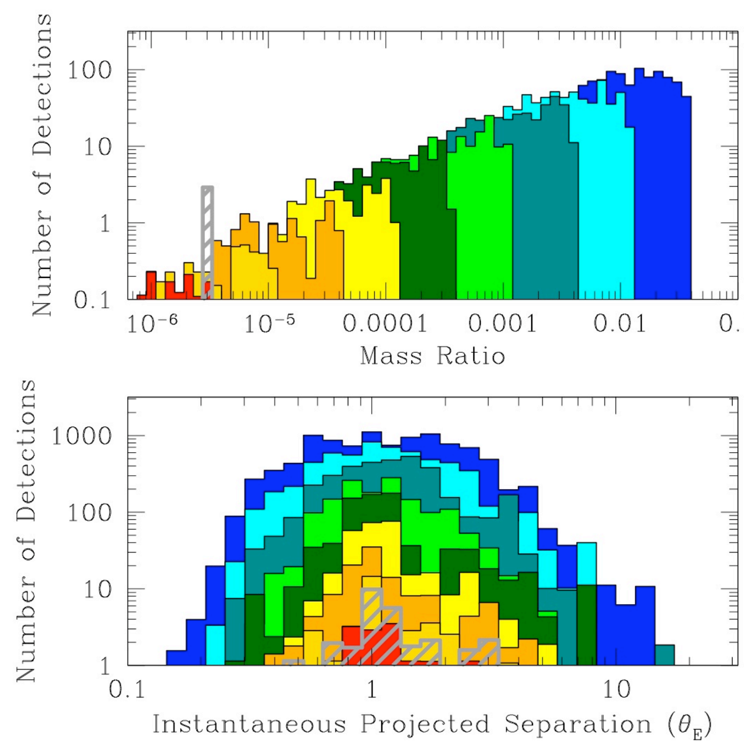
Baseline Results

- Number vs. Primary Mass
  - Approximately flat, with small preference for lower masses
  - Fixed mass ratio more skewed toward higher mass primaries



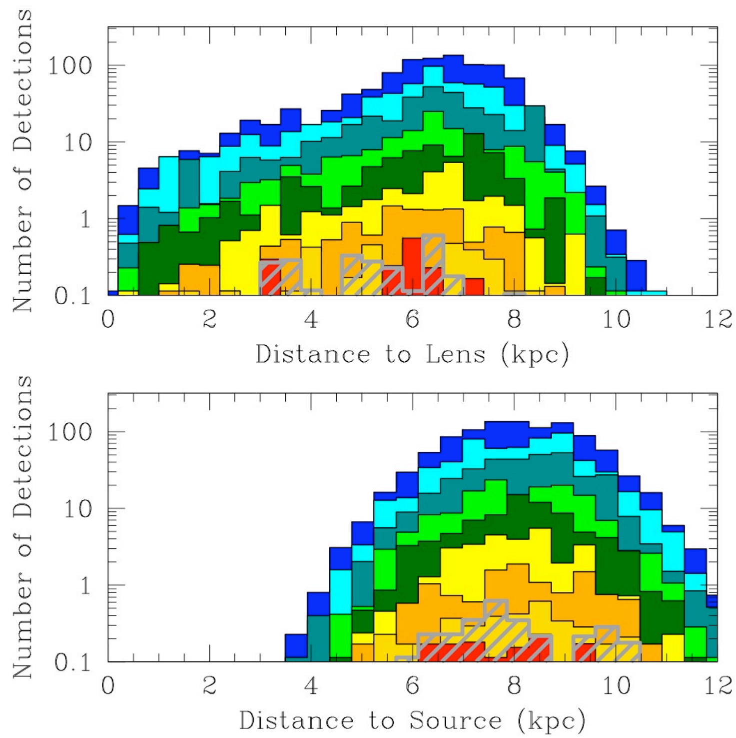
Baseline Results

- Number vs. Mass Ratio
  - ~ 1 dex dispersion in q at fixed planet mass
- Number vs Separation
  - Planets detected at a range of $0.1 < d < 10$
  - Concentrated at d~1
  - Preference for d>1
  - d<1 suppressed for low mass planets



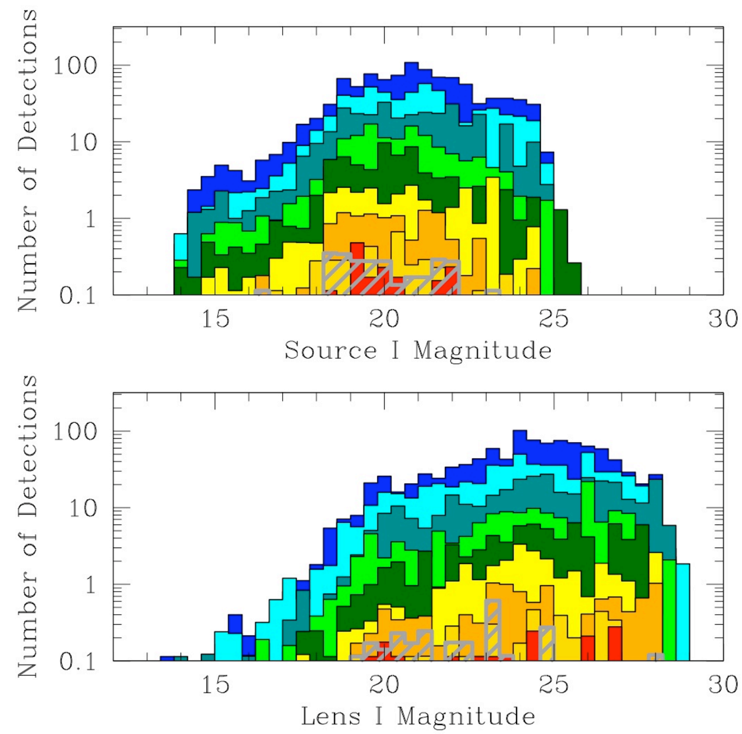
Baseline Results

- Number vs. D_l
  - Disk + Bulge Lenses
    - $0 < D_l < 10$ kpc
    - Median ~ 6 kpc
- Number vs. D_s
  - Bulge Sources ~ 8kpc
  - Weak preference for far side



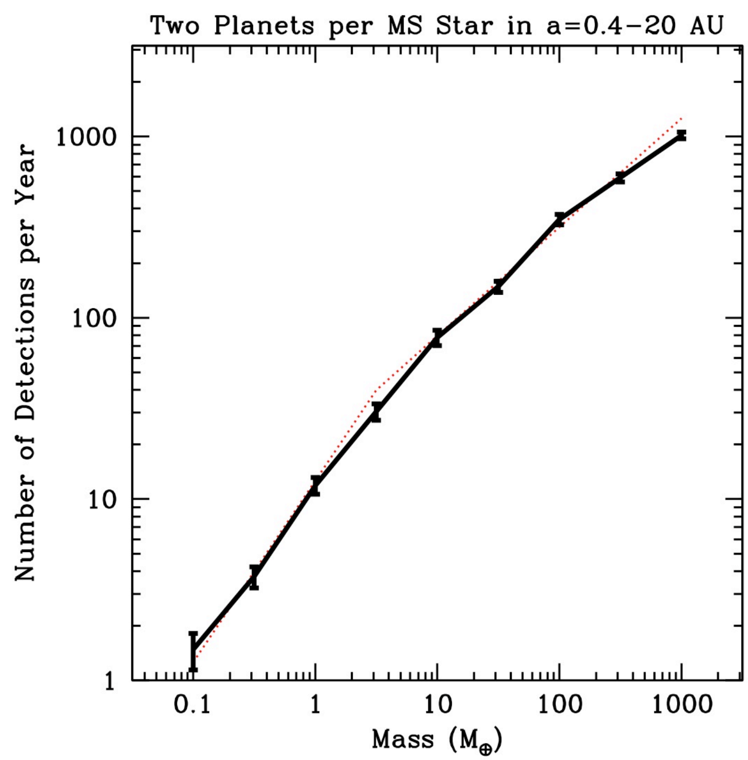
Baseline Results

- Number vs. I_S
  - $\langle I_S \rangle \sim$ 20-21
  - Smaller mass⇔ brighter source
- Number vs. I_L
  - $\langle I_L \rangle \sim$ 24
  - Smaller mass ⇔ fainter lens



Parameter Variations

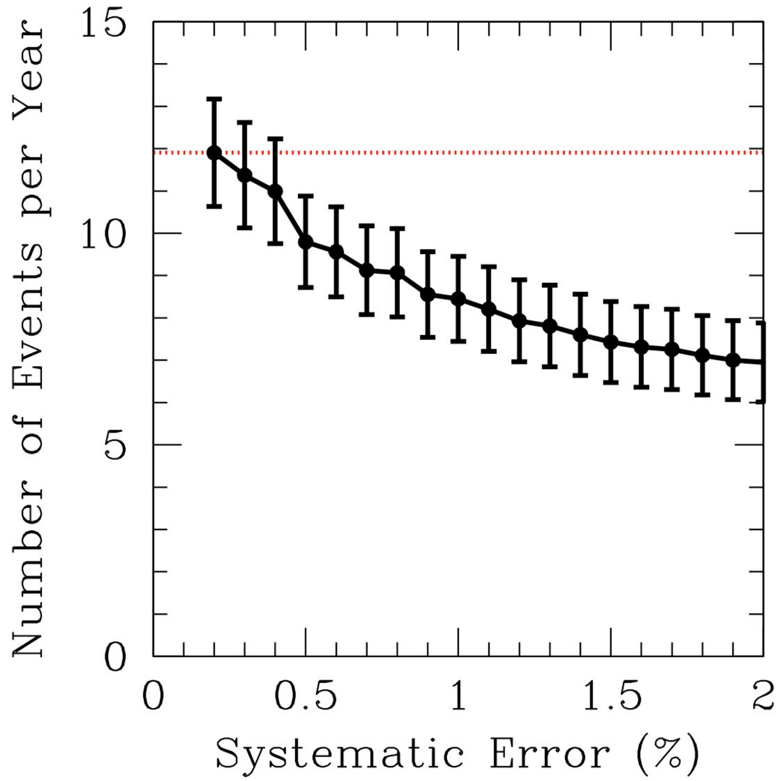
- Detection Threshold
- Systematic Error
- Diameter
- Area of Detector
- Seeing
- One Field
- Different Sites



- Average over *a*
  - –-0.35<log(a/AU)<1.15
  - Two planets per star

Parameter Variations

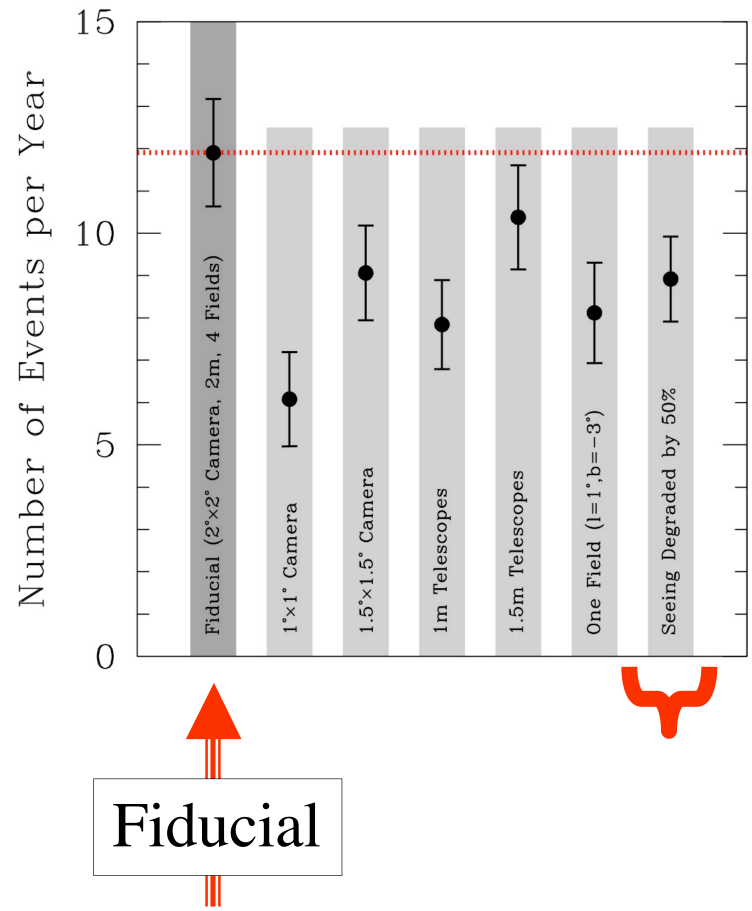
- Detection Threshold
- Systematic Error
- Diameter
- Area of Detector
- Seeing
- One Field
- Different Sites



Rate for σ_{sys}=0.7% is ~77% of the rate for σ_{sys}= 0.2%

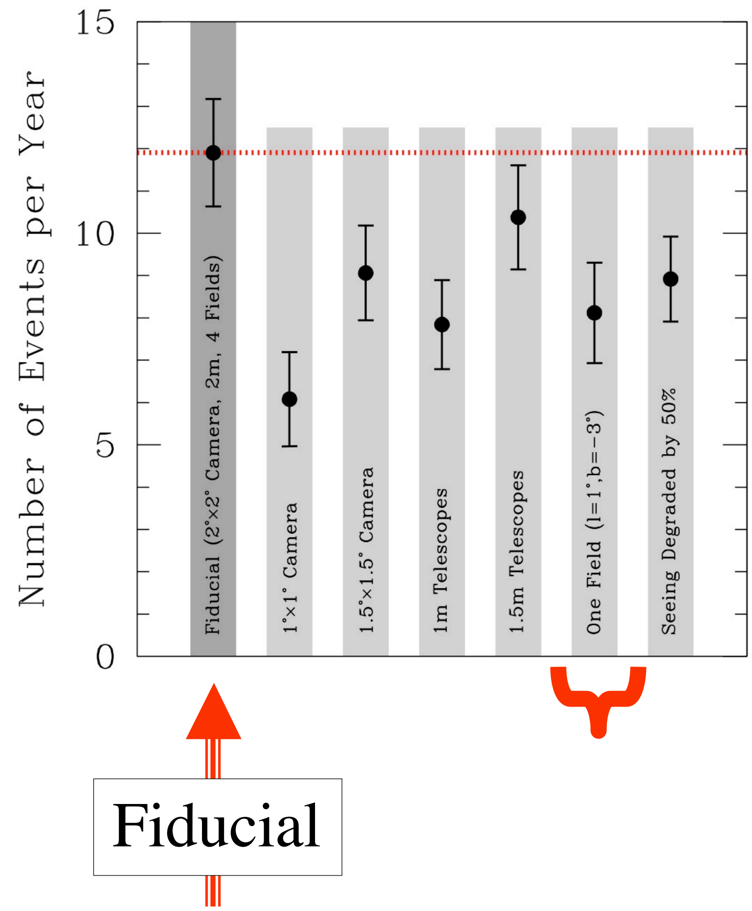
Parameter Variations

- Detection Threshold
- Systematic Error
- Diameter
- Area of Detector
- Seeing
- One Field
- Different Sites



Parameter Variations

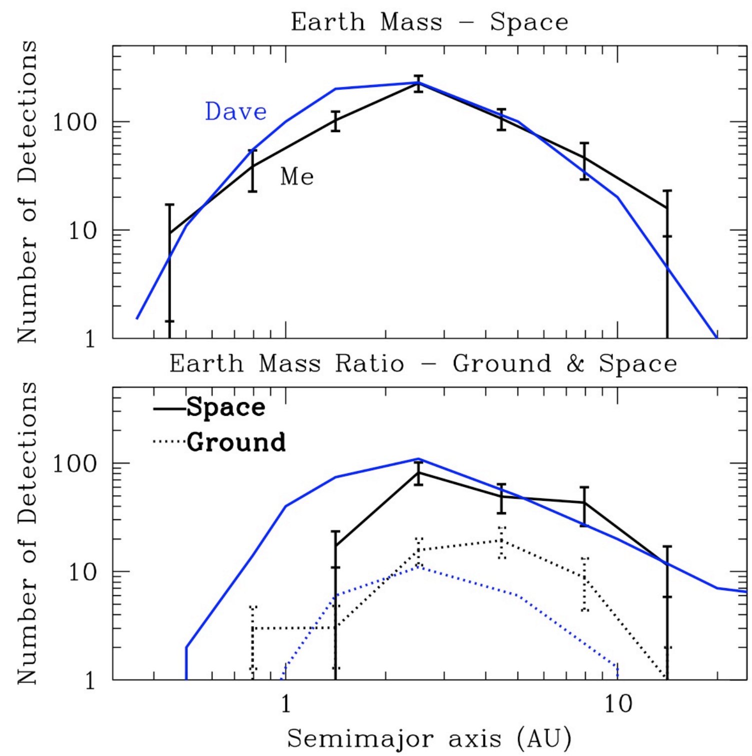
- Detection Threshold
- Systematic Error
- Diameter
- Area of Detector
- Seeing
- One Field
- Different Sites



Comparison with Dave

- MPF Simulation
  - Optical depth (× 2)
  - Four years (× 4)

- Ground-Based
  - Optical depth (× 2)
  - Four years (× 4)
  - Systematic Error (× 0.78)
  - No Hawaii (× 0.86)



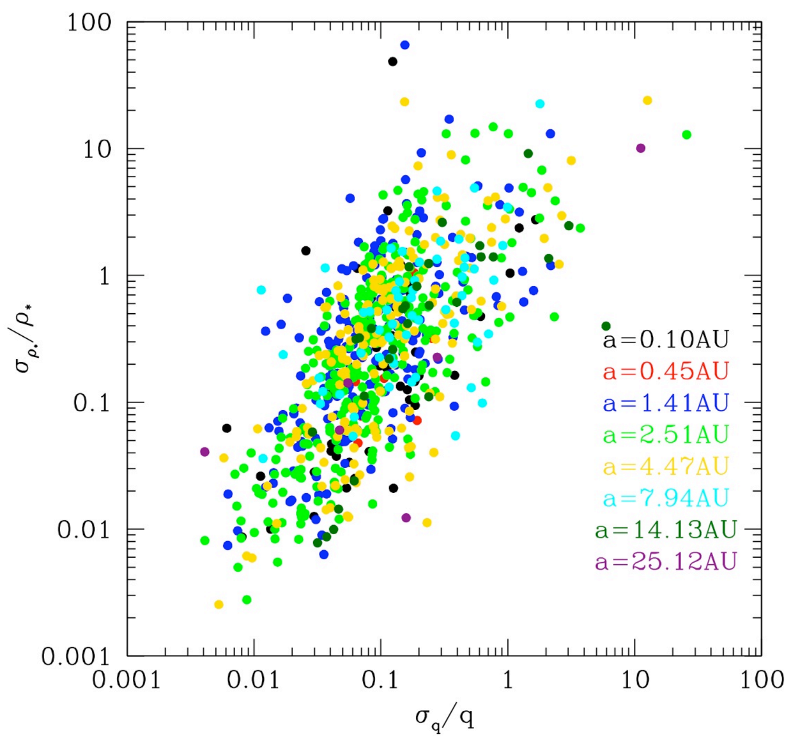
Parameter Uncertainties

- Fisher Errors

$$\left\langle \frac{\sigma_\rho}{\rho} \right\rangle \approx 30\%$$

$$\left\langle \frac{\sigma_q}{q} \right\rangle \approx 10\%$$

- Basically Confirmed by MCMC
  - Uncertainties in ρ underestimated (upper limits only)



Parameter Uncertainties

- Primary Parameters

$$\left\langle \frac{\sigma_{t_E}}{t_E} \right\rangle \approx 1\%$$

$$\left\langle \frac{\sigma_{u_0}}{u_0} \right\rangle \approx 1\%$$