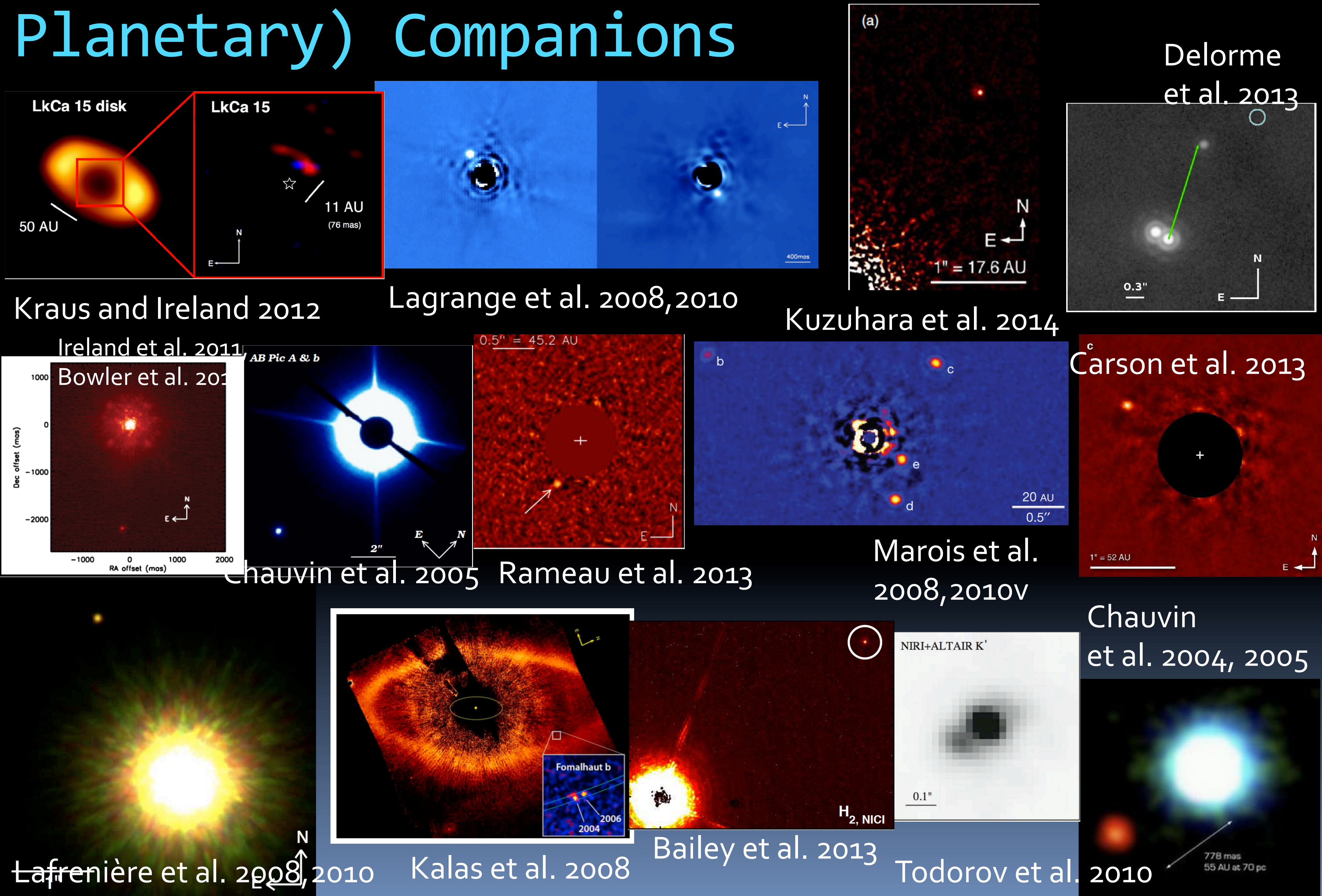
DIRECT IMAGING SURVEYS

Beth Biller

Mariangela Bonavita, Ken Rice, University of Edinburgh, Duncan Forgan, St. Andrews, Markus Feldt, MPIA, Arthur Vigan, LAM, Michael Liu, University of Hawaii, Zahed Wahhaj, ESO, Eric Nielsen, SETI Institute, Tom Hayward, Gemini, and the NICI Campaign Team

Directly Imaged Planetary (or Nearly Planetary) Companions



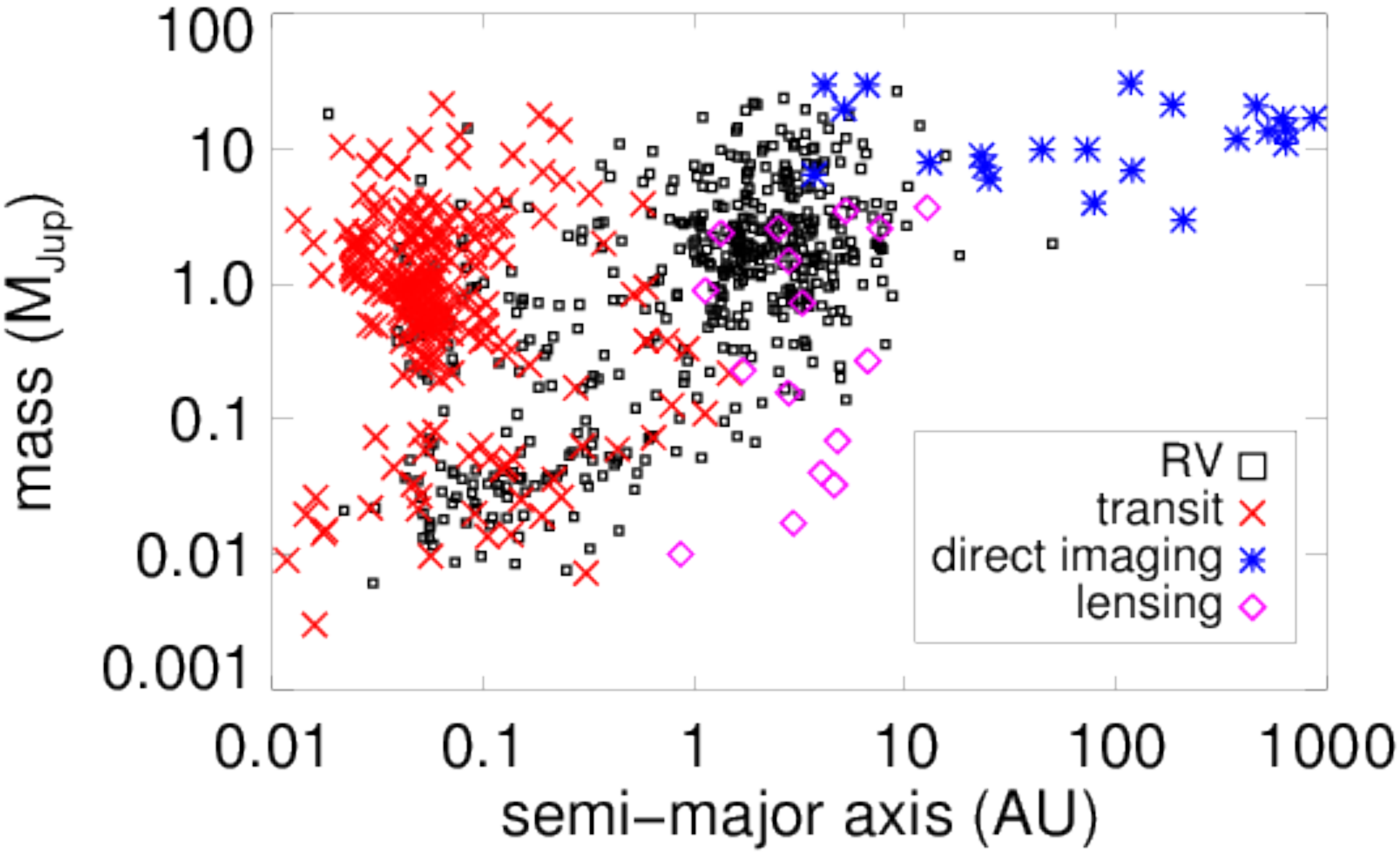
Some Fundamental Questions of Comparative Exoplanetology

Physical Properties

Orbits, masses, atmospheric properties

Architecture

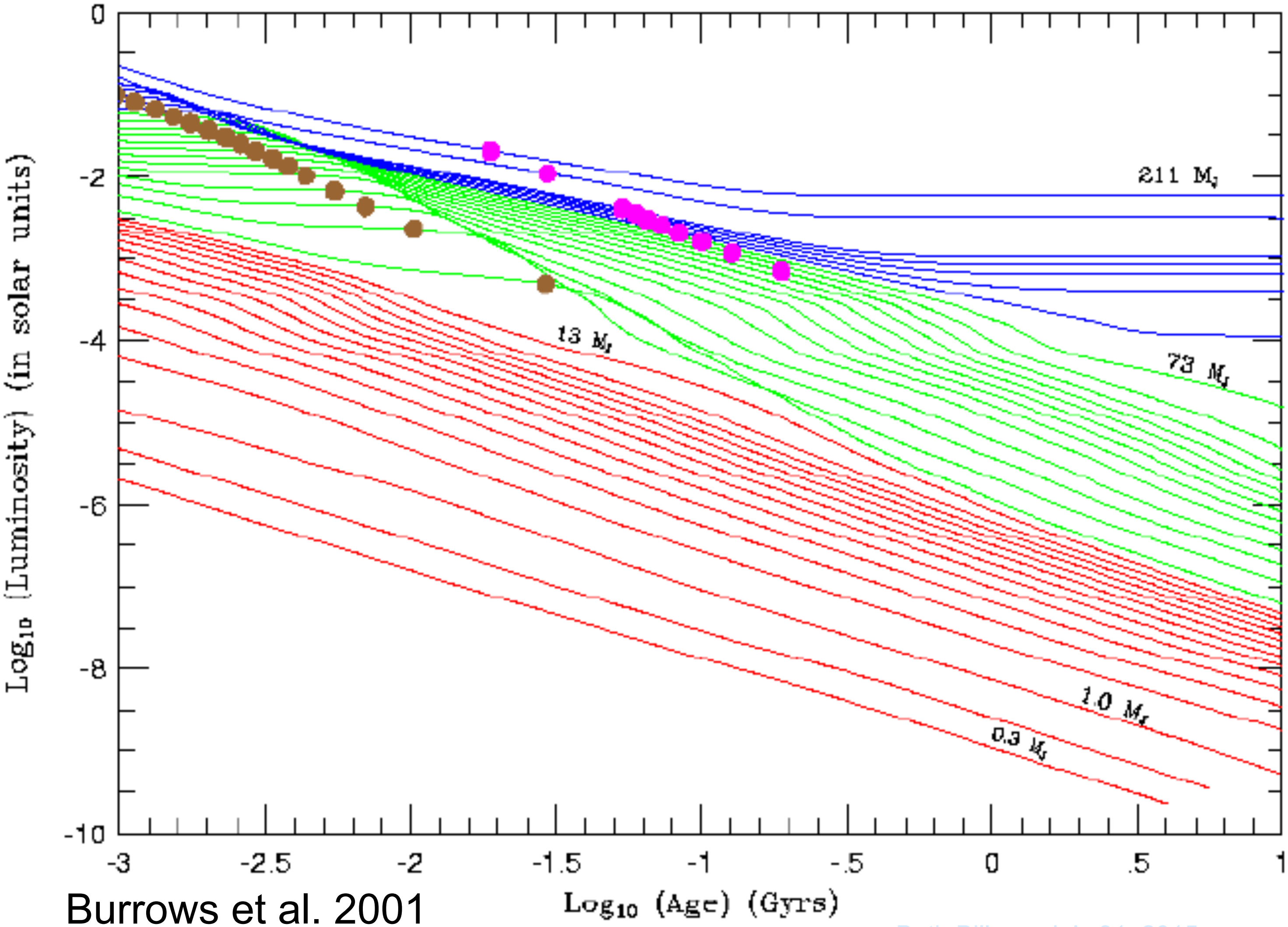
Where do planets live in their stellar systems?



Data from exoplanet.eu

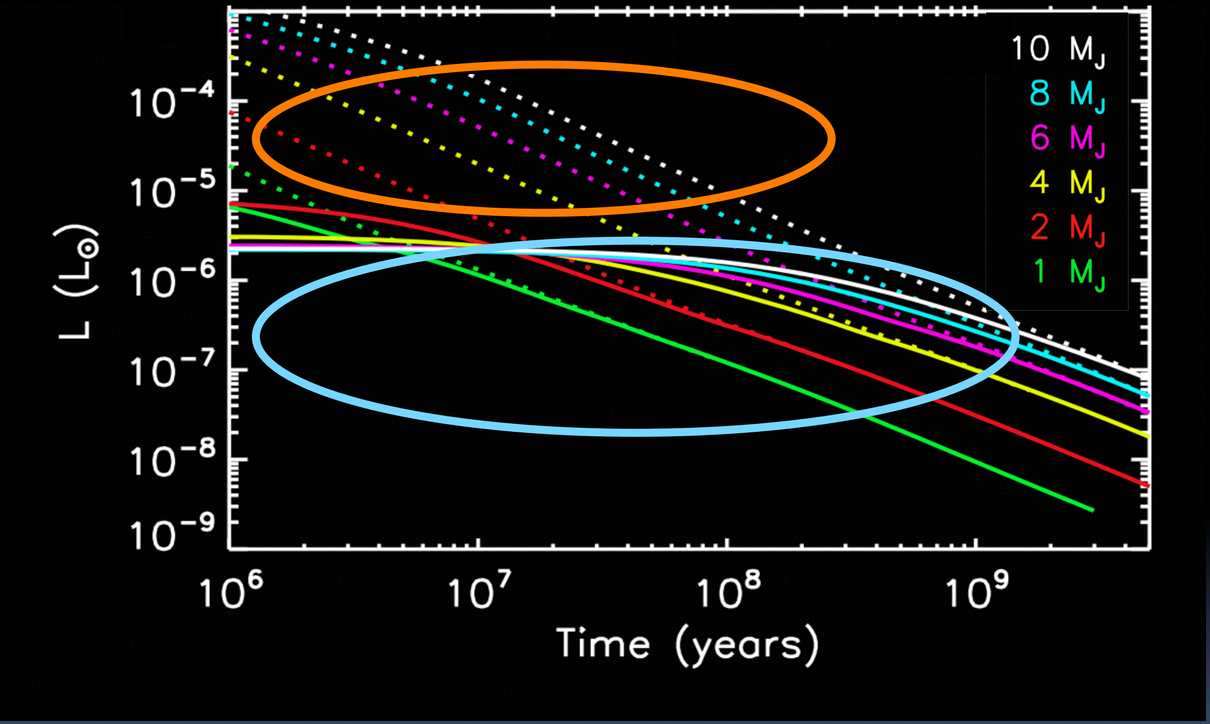
How do we open up the parameter space for exoplanet imaging?

Step 1) Focus on Young Stars



Burrows et al. 2001

Planet Properties can depend on initial conditions



hot-start models

cold-start models

Marley et al (2006), Fortney et al (2008)

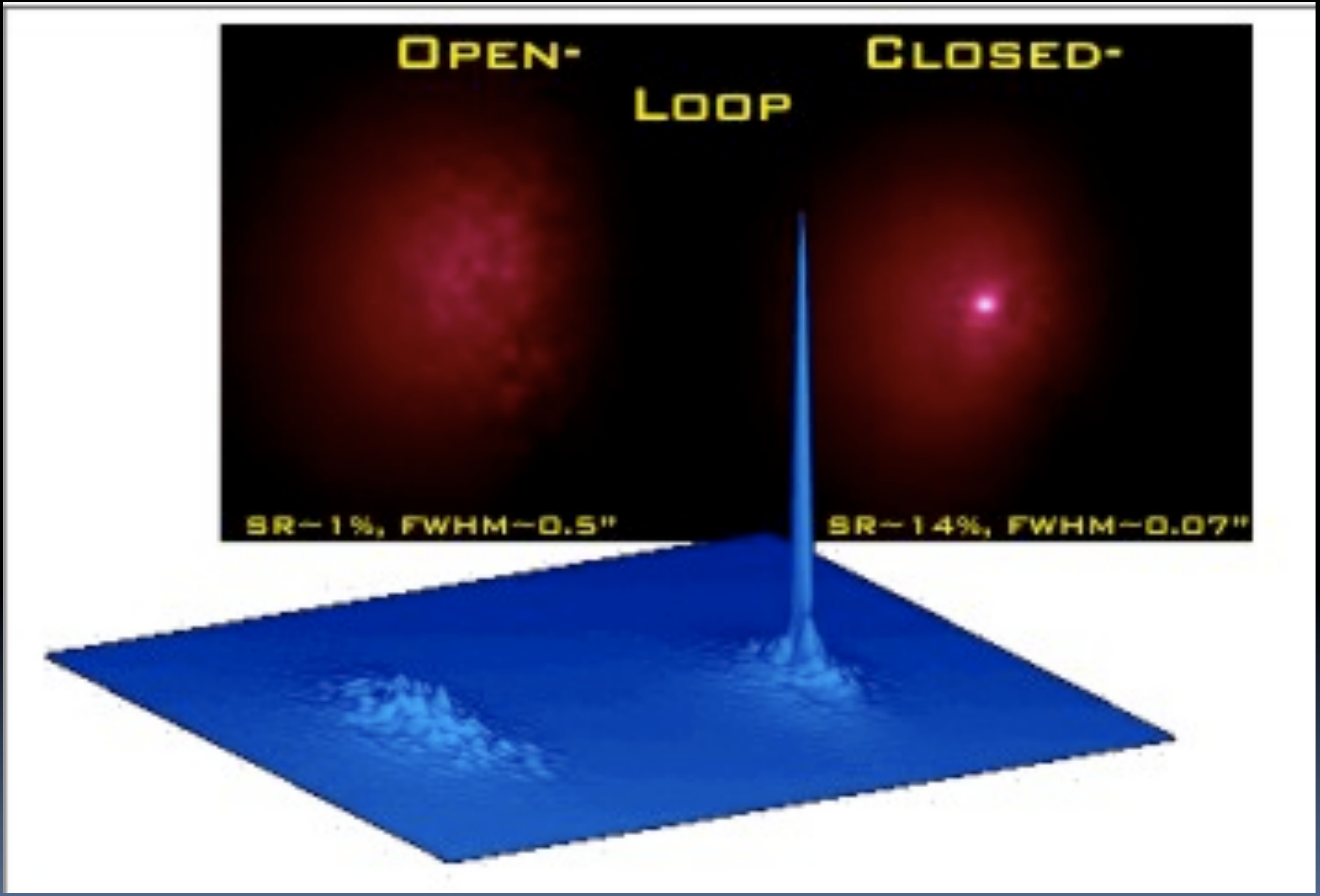
Step 2:
Overcoming Technical Hurdles

Difficulties with Direct Detection (1)

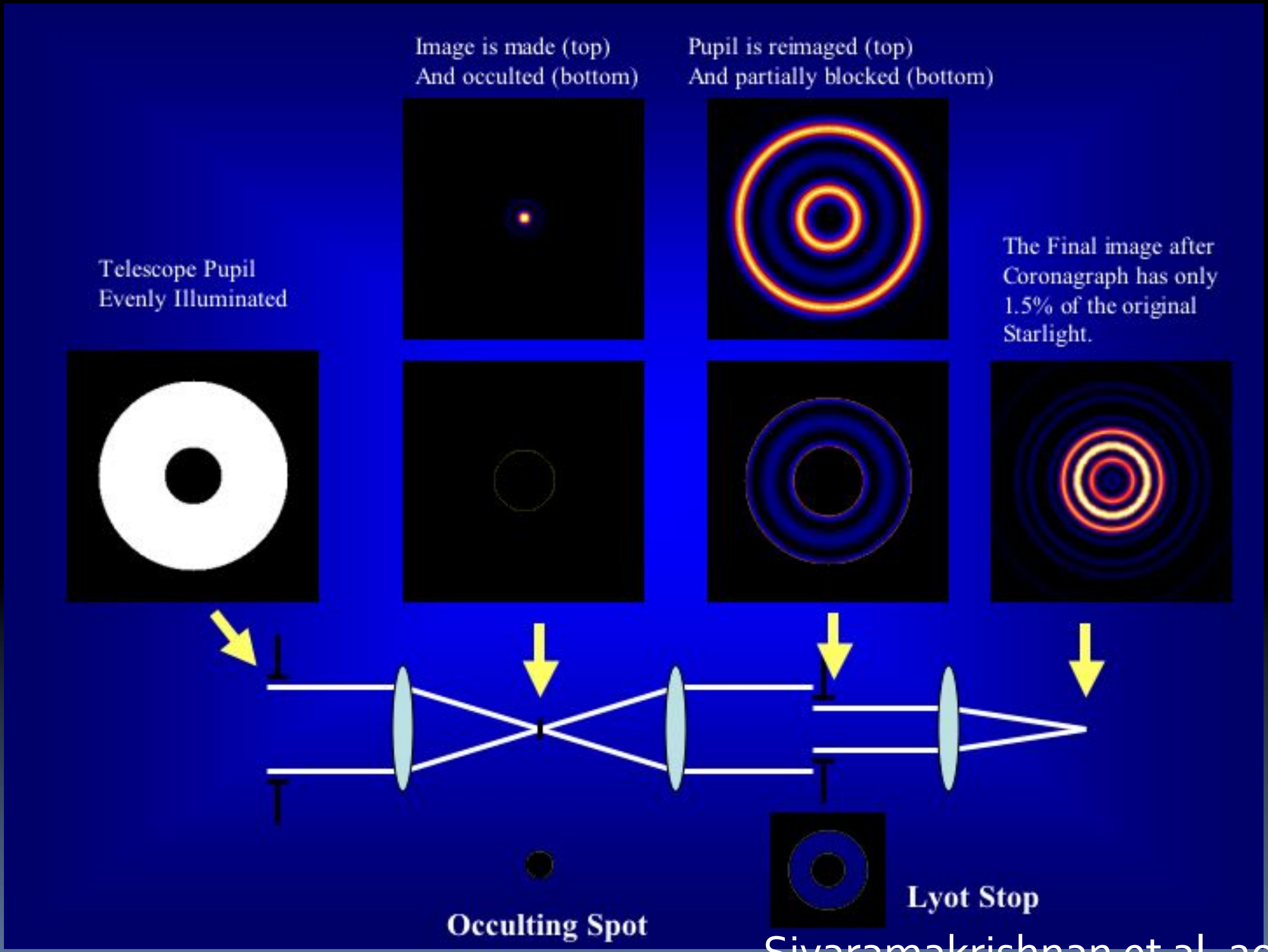
Huge contrast ratio between planet and star

- >2 Gyr gas giant planets $>10^8$ fainter than primary.
- Young planets $\sim10^{4-7}$ times fainter than primary.

Adaptive Optics



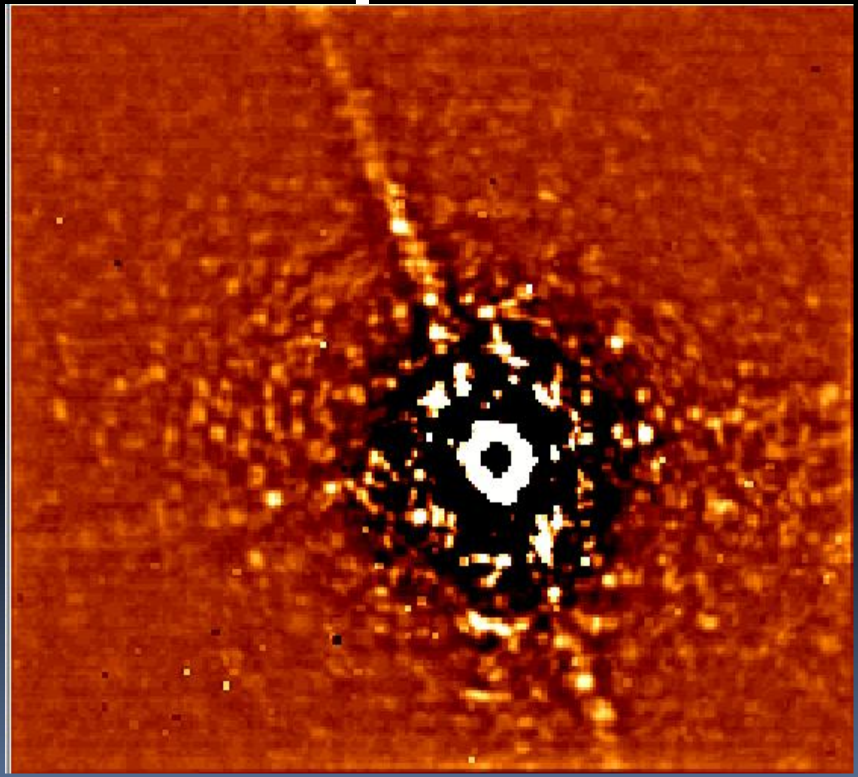
Coronagraphy



Sivaramakrishnan et al. 2001

Difficulties with Direct Detection (2)

Speckle Noise



For photon-noise limited data:

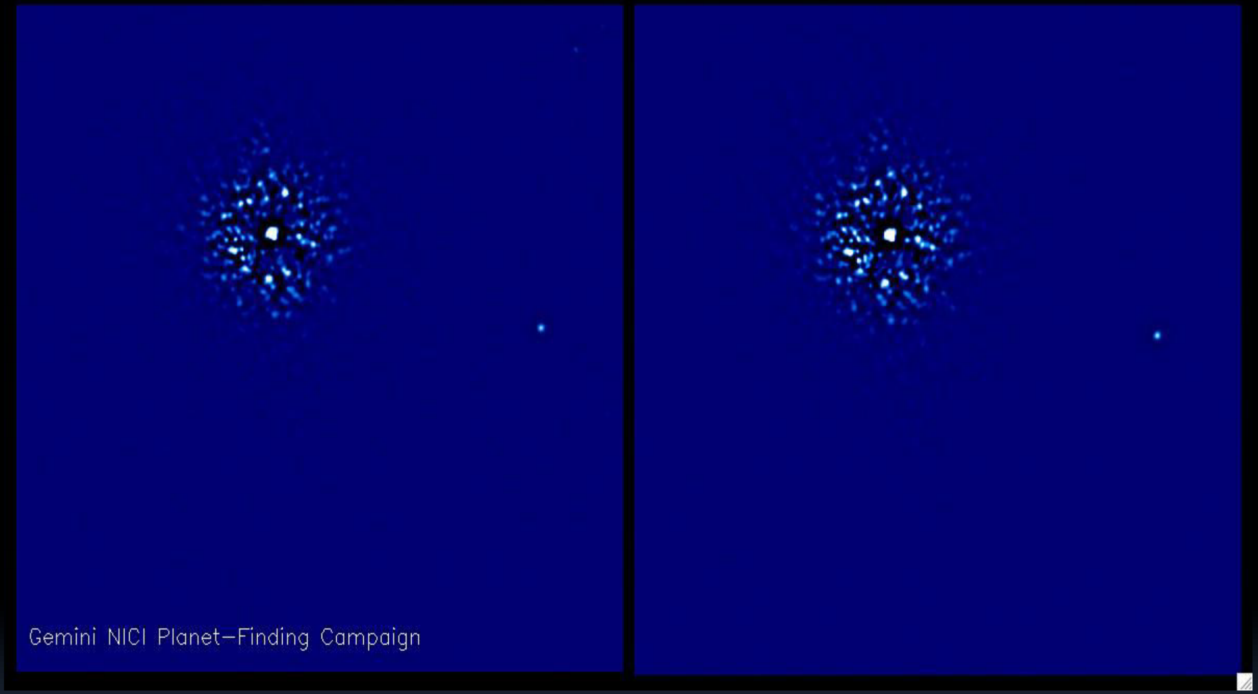
$S/N \sim t_{exp}^{0.5}$

For speckle-noise limited data:

S/N does not increase with time past a speckle noise floor.

Angular Differential Imaging

e.g. Schneider et al 2003, Liu 2004, Marois et al 2006, Heinze et al 2008



Rotation on sky decorrelates real objects from speckles

Elements of Exoplanet Imaging

1. **Adaptive optics**
   - *Increasing the contrast*

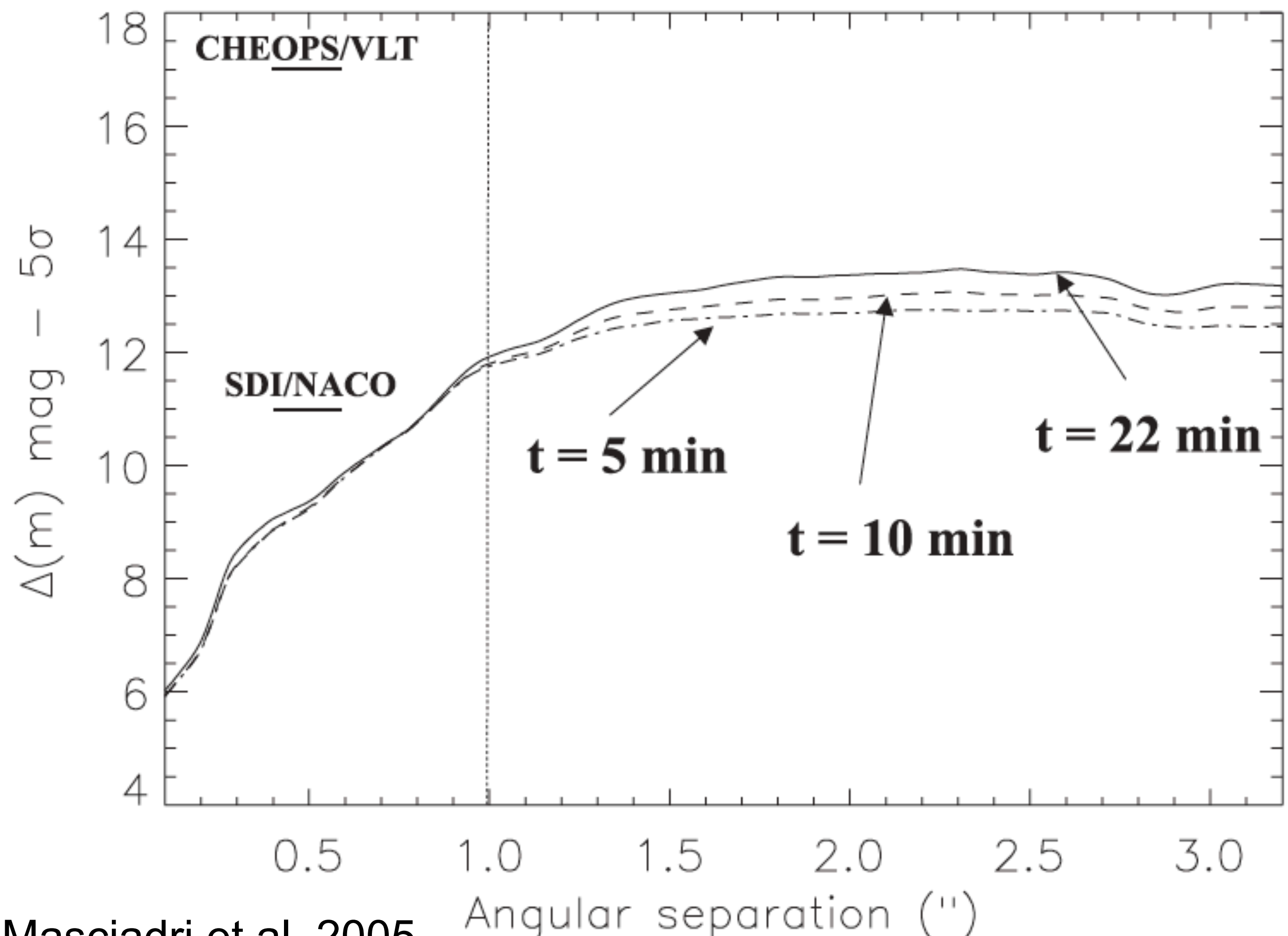
2. **Coronagraphy**
   - *Boosting dynamic range and contrast*

3. **Speckle Suppression Techniques**

Spectral Differential Imaging (SDI), Angular Differential Imaging (ADI), etc.

- *Removing quasi-static speckles*

Generation 1
AO enabled and HST efforts



Masciadri et al. 2005

Generation 1
AO enabled and HST efforts

- Typical sample size: <50 stars
- Typical contrast: Δmag ~ 8 @ 0.5"
- VLT: Masciadri et al. 2005
- ESO 3.6 m: Chauvin et al. 2003
- HST: Lowrance et al. 2005

Generation 2
large telescope + AO + speckle suppression techniques

- Typical sample size: 50-100 stars
- Typical contrast: Δmag ~ 10 @ 0.5"
- VLT: Biller et al. 2007, Chauvin et al. 2010
- Gemini: Lafreniere et al. 2007

Generation 3

large telescope + AO + coronagraphs + speckle suppression techniques

- Typical sample size: 100-300 stars
- Typical contrast: Δmag ~ 12-13 @ 0.5"

Recently Completed (or soon-to-be completed) Surveys:

NICI Science Campaign, Biller et al. 2013, Wahhaj et al. 2013, Nielsen et al. 2013, Nielsen et al. in prep

NACO Large Program, Desidera et al. 2014, Chauvin et al. 2014, Vigan et al. in prep

IDPS, Vigan et al. 2012

SEEDS, Brandt et al. 2014, Janson et al. 2013, Carson et al. in prep

PALMS, Bowler et al. 2013

LEECH, Skemer et al. 2013

Some Fundamental Questions of Comparative Exoplanetology

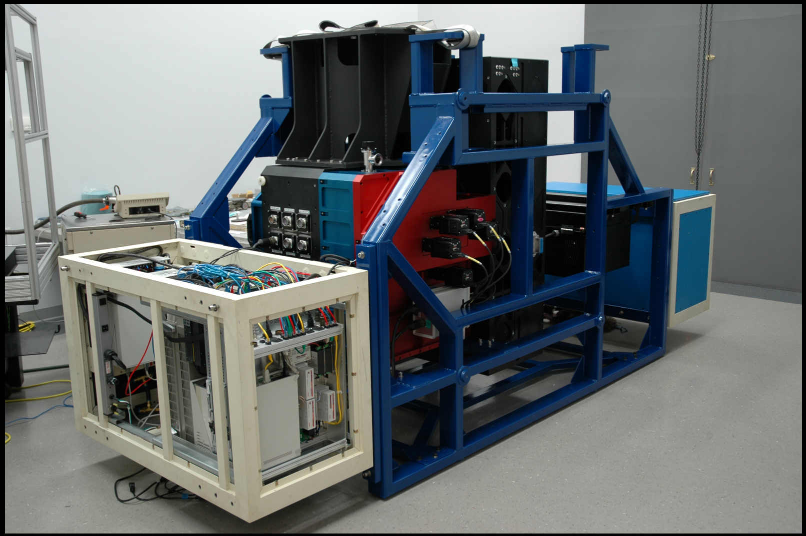
Physical Properties

Orbits, masses, atmospheric properties

Architecture

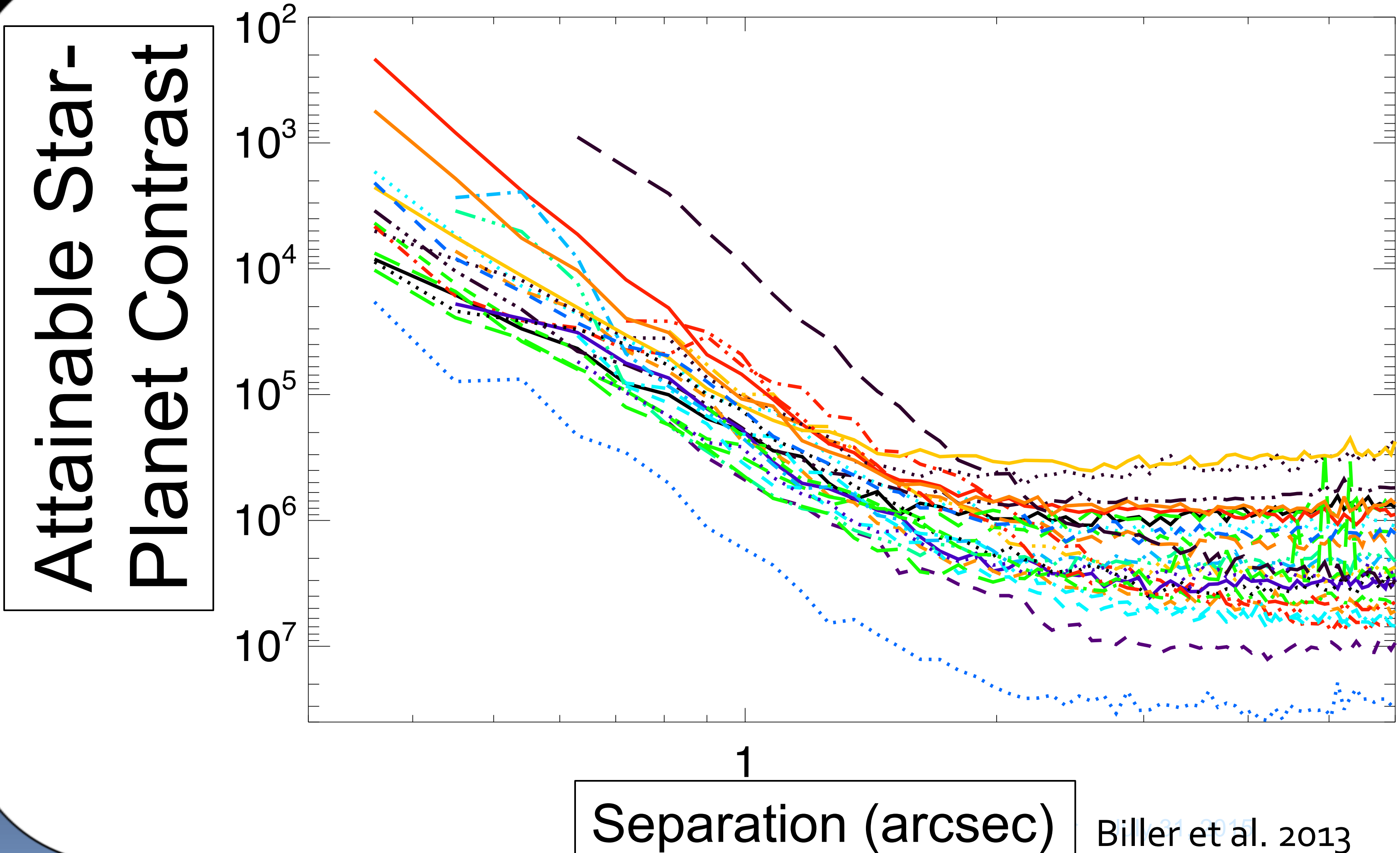
Where do planets live in their stellar systems?

Gemini/NICI Planet-Finding Campaign



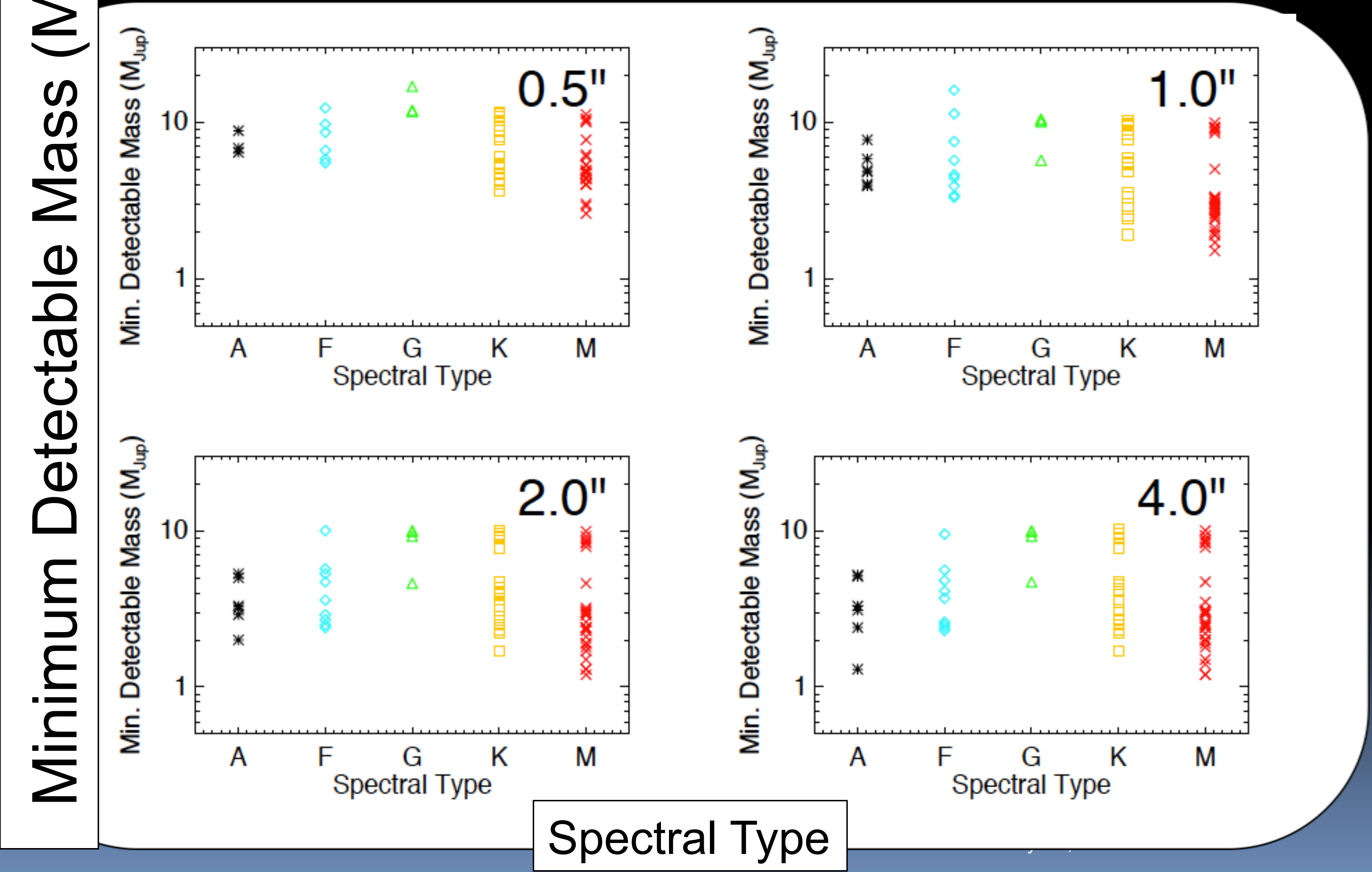
Major campaign (PI Michael Liu) @ Gemini-South for direct imaging of exoplanets from 2008-2012: 500 queue hrs, ~230 stars.

Excellent contrasts achieved

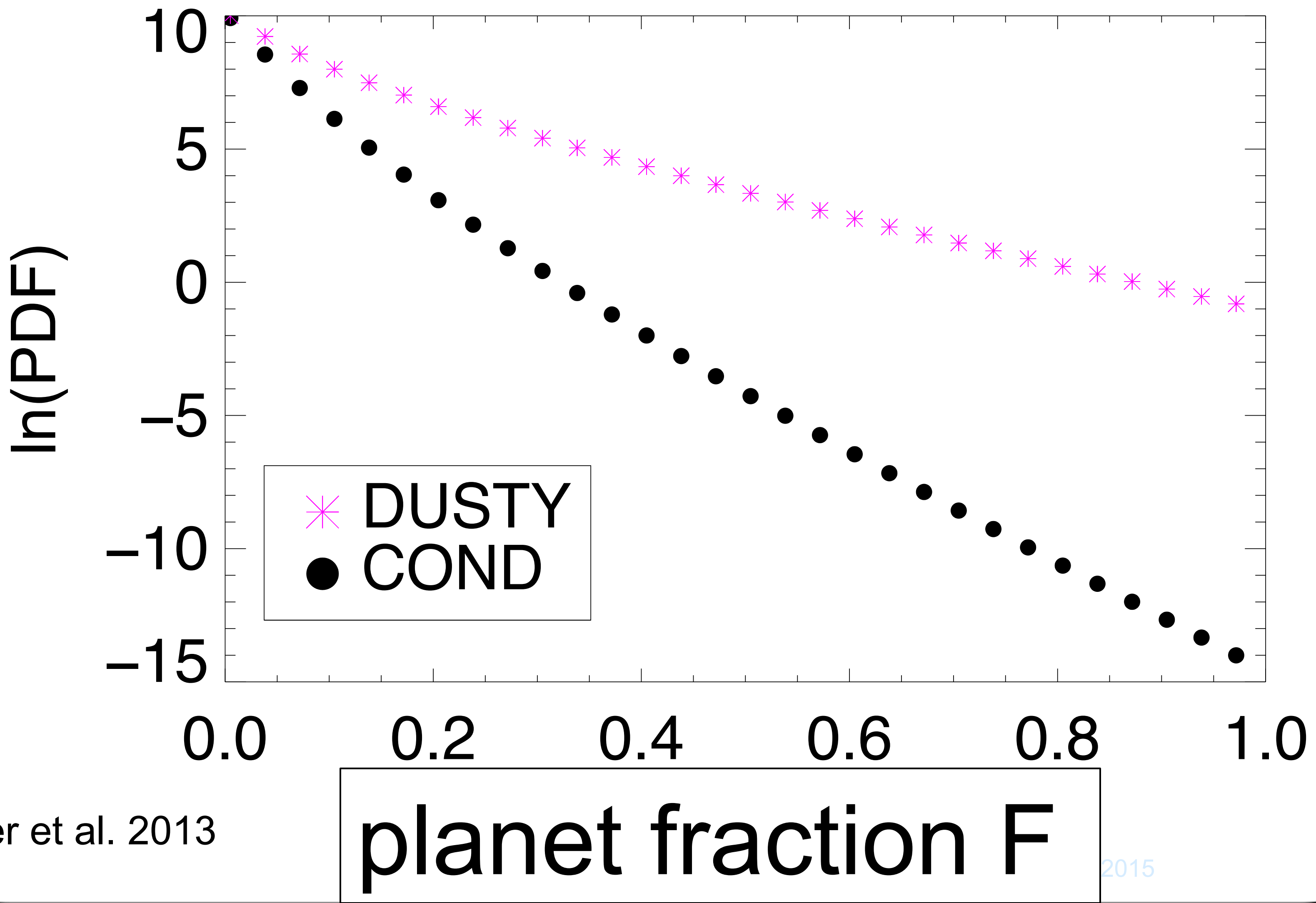


Biller et al. 2013

Mass Sensitivity



Survey Statistics place strong constraints on planet populations



Biller et al. 2013

2015

Constraints on Planet Fraction from 78 NICI Campaign stars:

$\leq$8% host 1-20 Mjup planets at semi-major axes of 10-150 AU

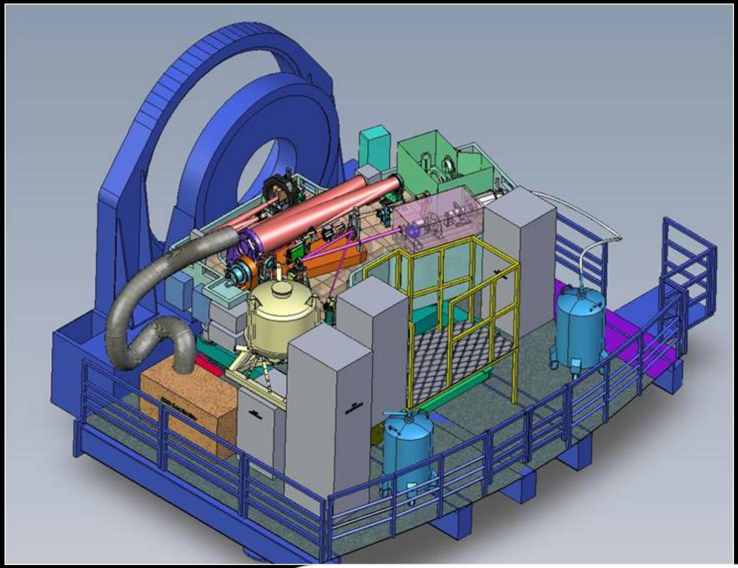
(95% confidence level, COND models)

Biller et al. 2013

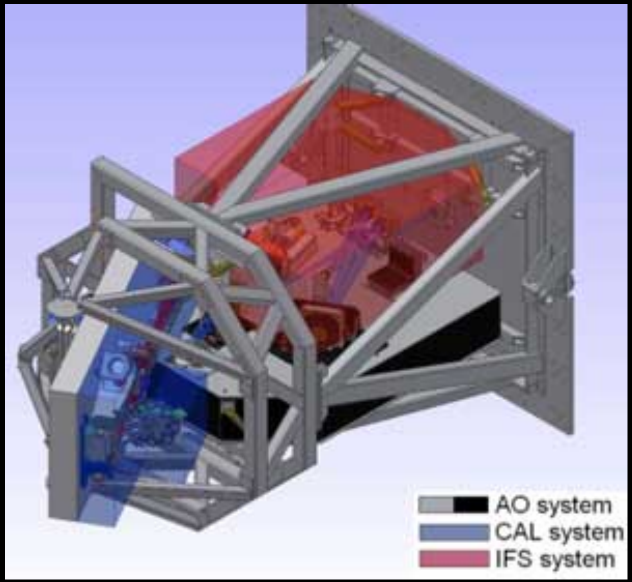
Current Direct Imaging Efforts

New Instruments

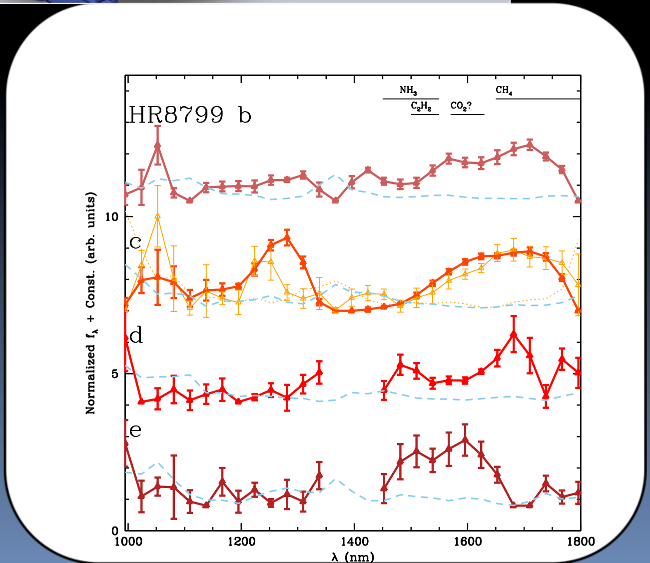
SPHERE @ VLT



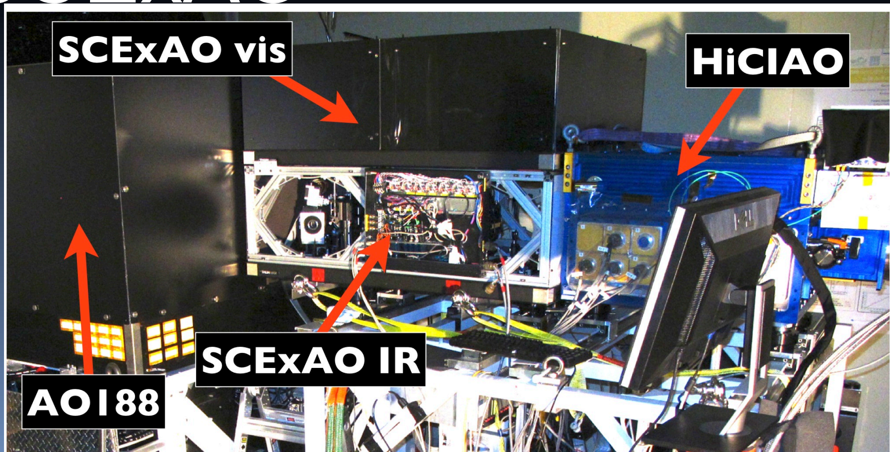
GPI @ Gemini



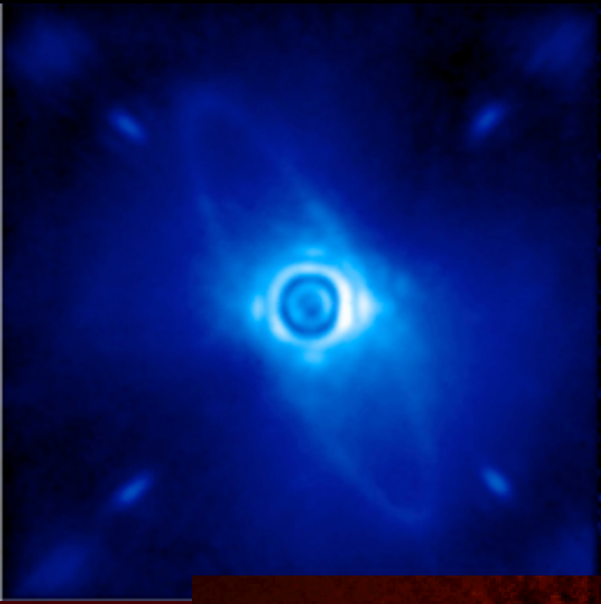
Project 1640

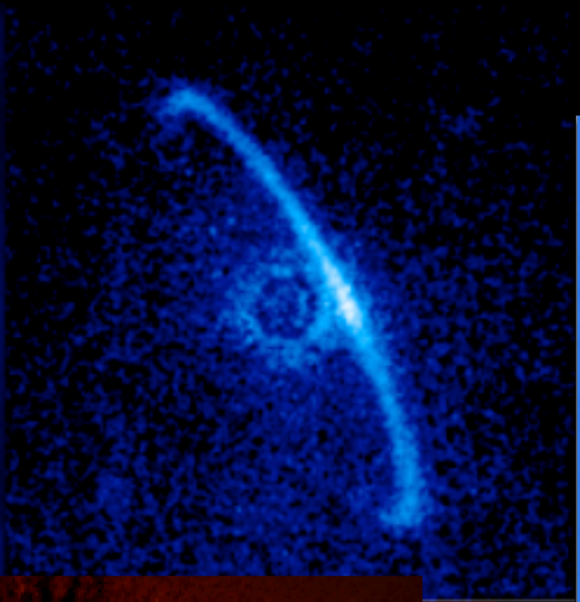


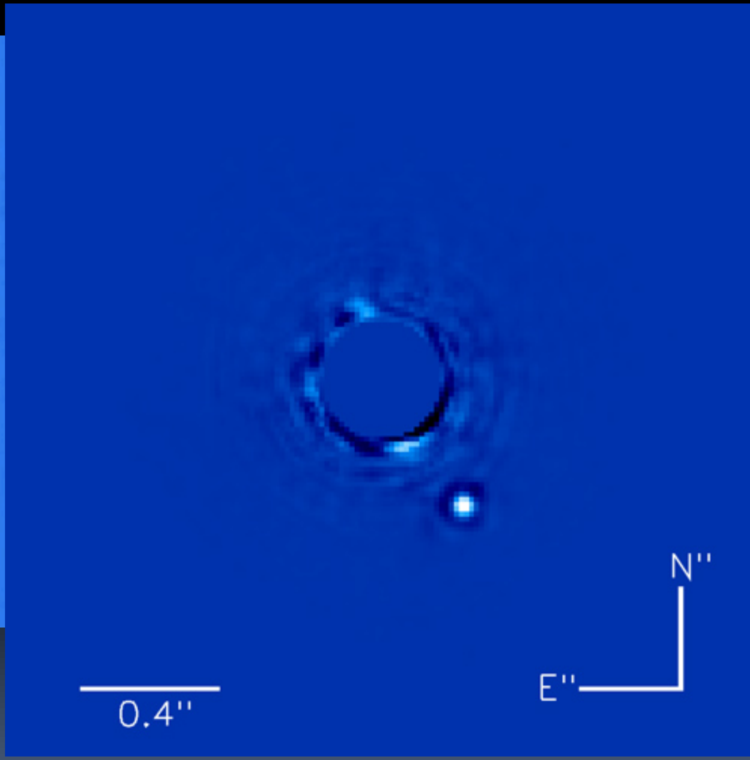
SCExAO

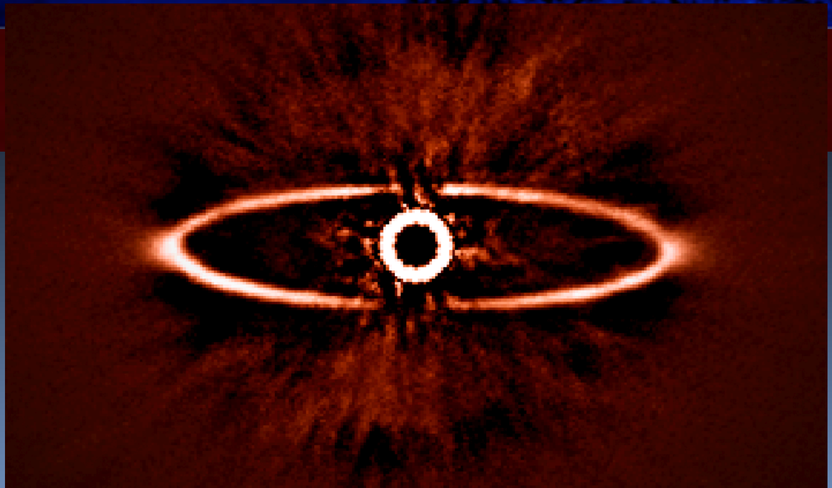


Unprecedented contrasts with SPHERE and GPI

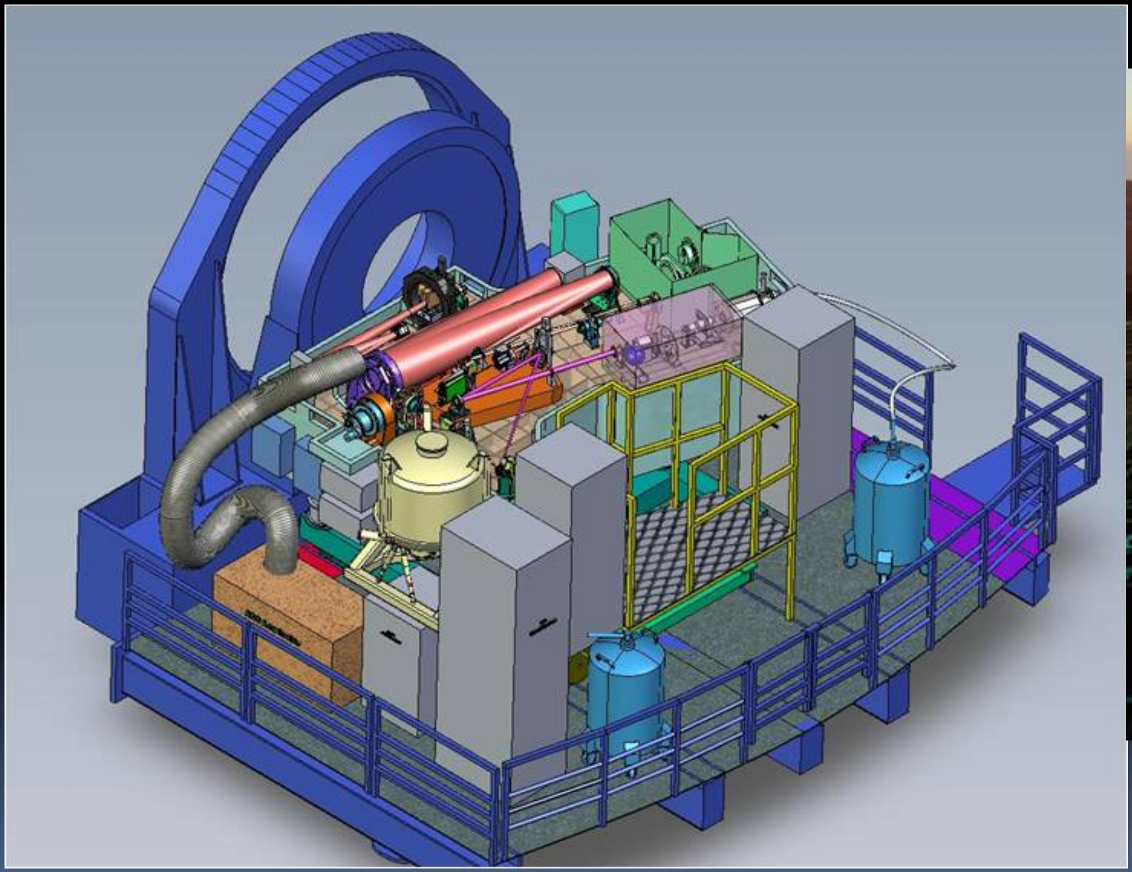




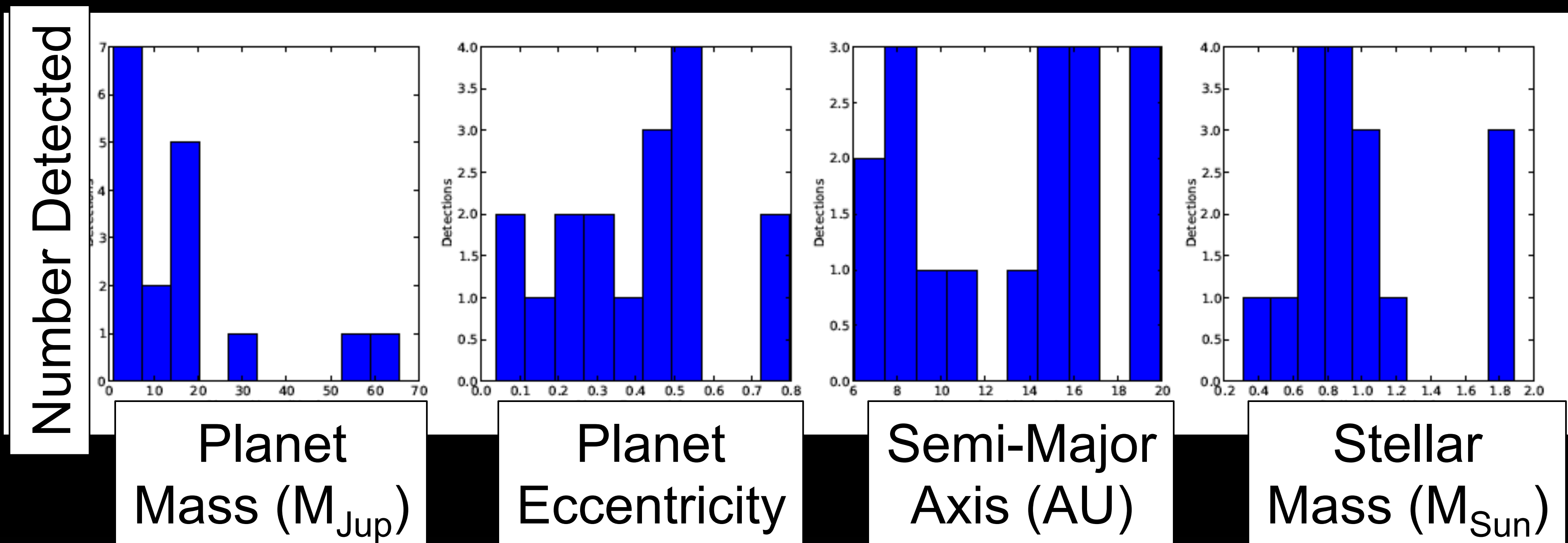




NIRSUR with SPHERE @ VLT – started in February 2015



Simulated Surveys for SPHERE NIRSUR



Monte Carlo simulation following the approach of Nielsen & Close, 2010 and Bonavita et al. 2012.

Assumed Planet Distribution

$$dN/dm \propto m^{\alpha},\ \alpha = -0.63$$

$$dN/da \propto a^{\beta},\ \beta = -1.16$$

until cutoff radius

Cumming et al. 2008 found $\alpha \sim -0.63$ and $\beta \sim -1.16$ for RV planets out to ~8 AU

$R(a, M \mid \alpha, \text{cutoff}, \beta, C) = CM^{\beta}a^{\alpha}$

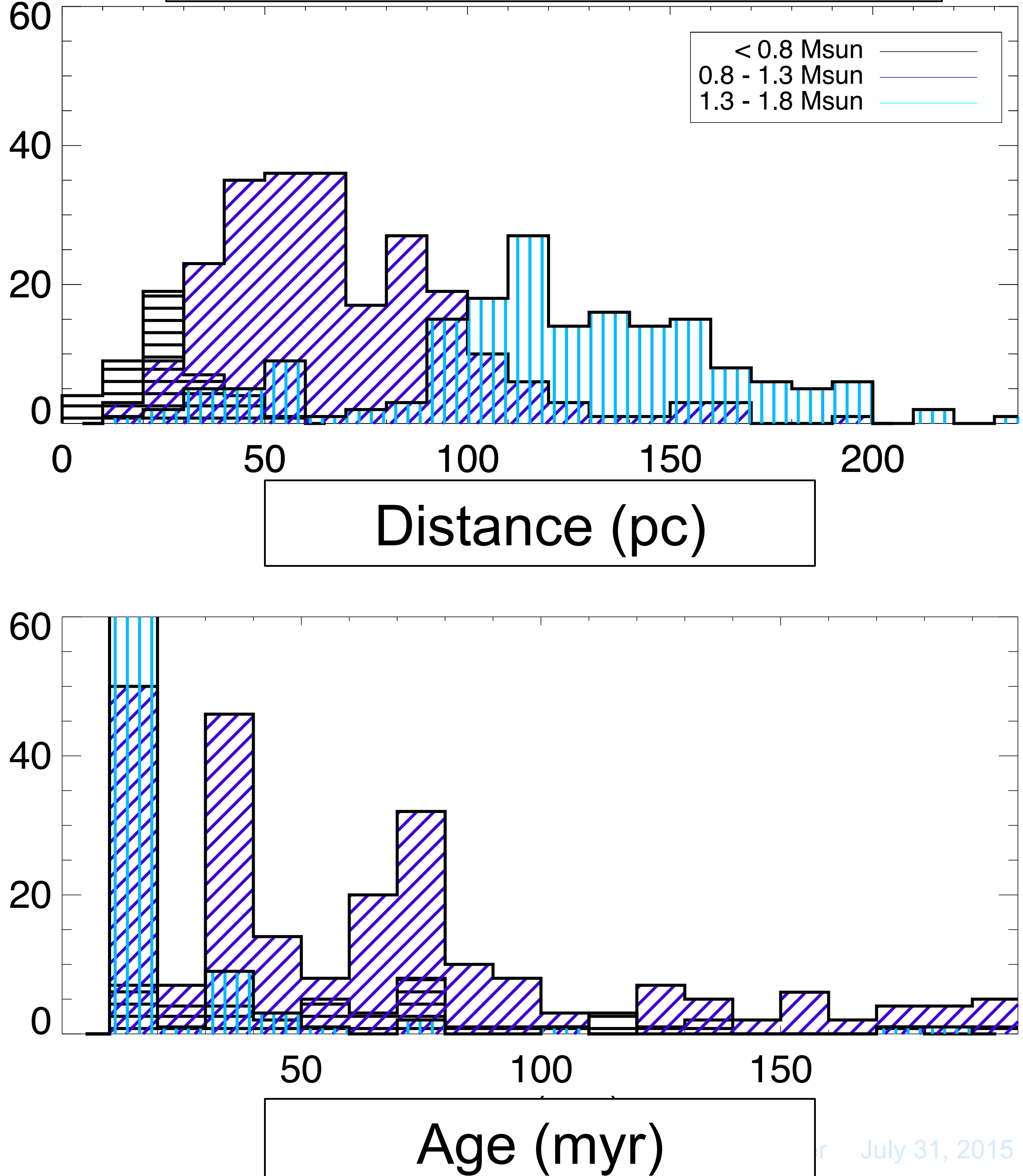
(until cutoff, where C is a normalization factor related to planet frequency F)

Normalize to known RV planets

Fischer and Valenti 2005 find a planet frequency of 3.94% for planets with:

- Mass 1-13 Mjup
- separations 0.3 – 2.5 AU
- stellar mass: 0.7 – 1.6 Msun
- [Fe/H]: -0.5 – +0.5

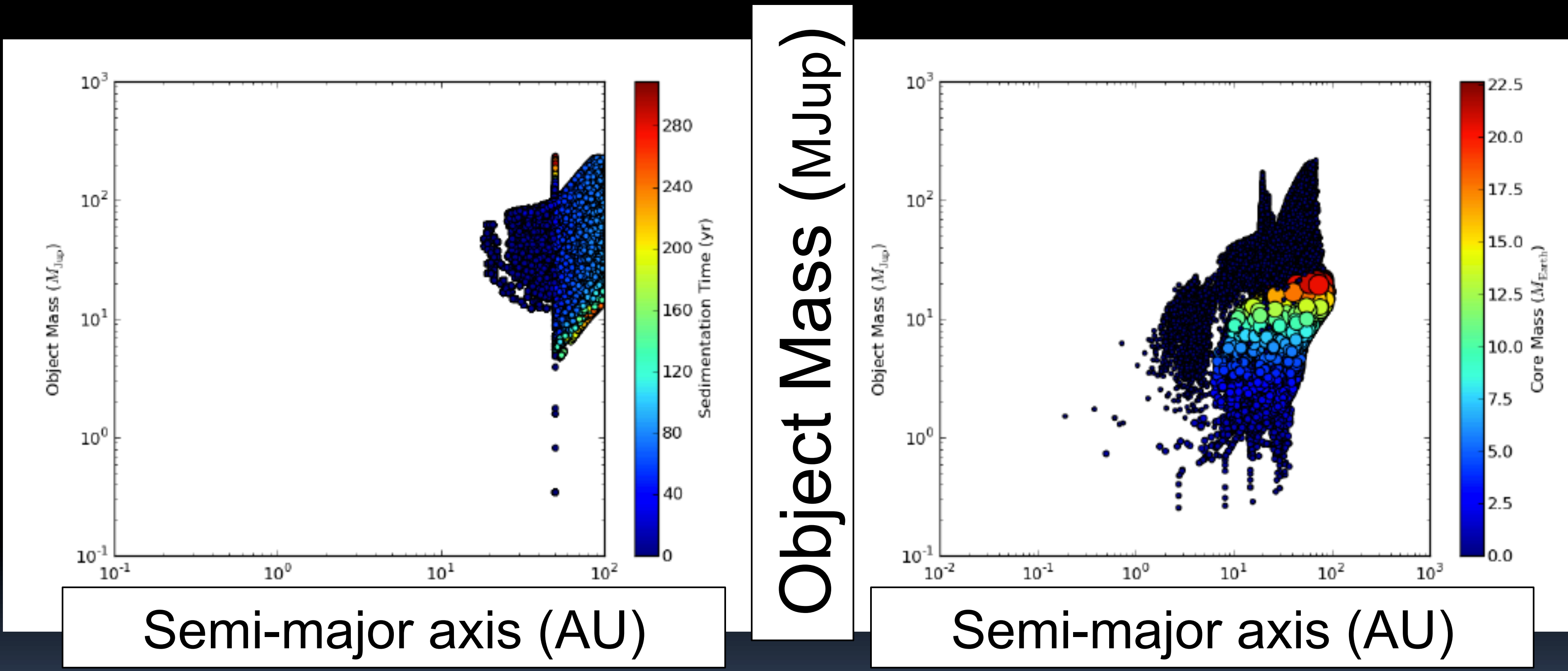
400 star 8 – 200 Myr sample



Predicted # of detections vs. cutoff

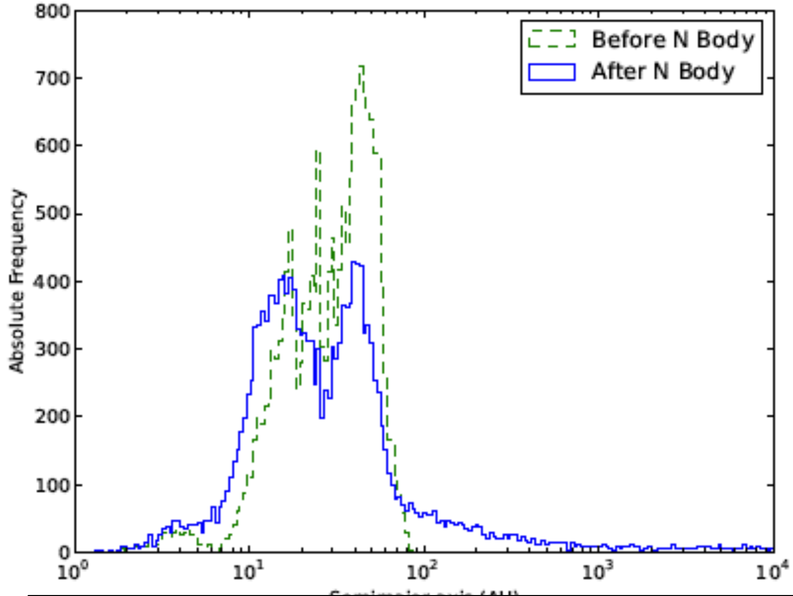
SMA Cutoff	Unscaled	Mass-Scaled
20 AU	17 ± 4	27 ± 6
30 AU	26 ± 7	46 ± 3
40 AU	34 ± 5	57 ± 5
50 AU	43 ± 4	66 ± 5

Comparing with Population Synthesis Models

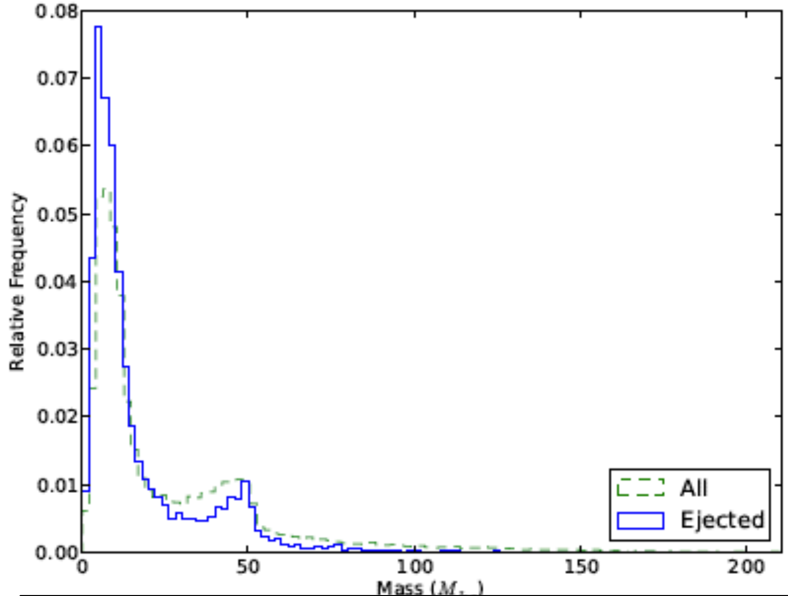


Disk Instability models from Forgan & Rice 2013

Disk Instability + Planet-Planet Scattering



Semi-major axis (AU)



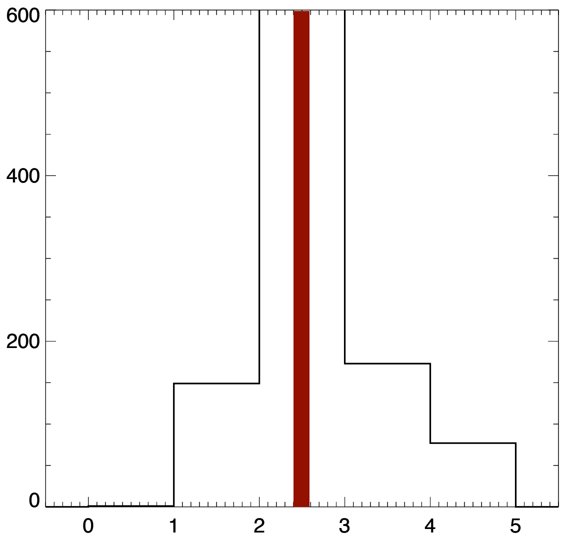
Object Mass (MJup)

Forgan,Rice, and Parker 2015

Expected Planet Yield

% of stars that host planetary systems

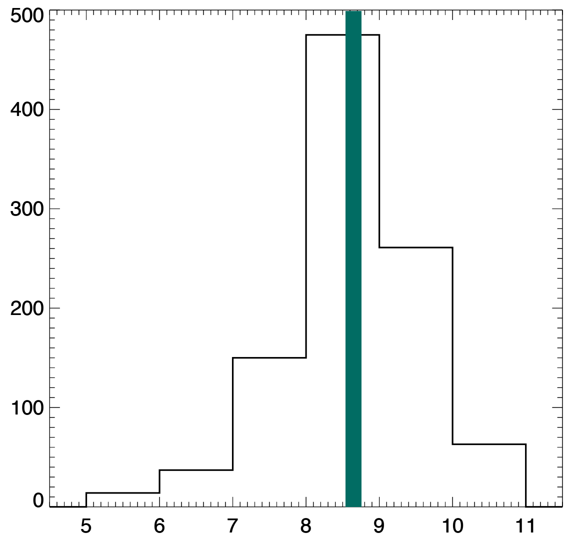
1%



planets detected

~2-3

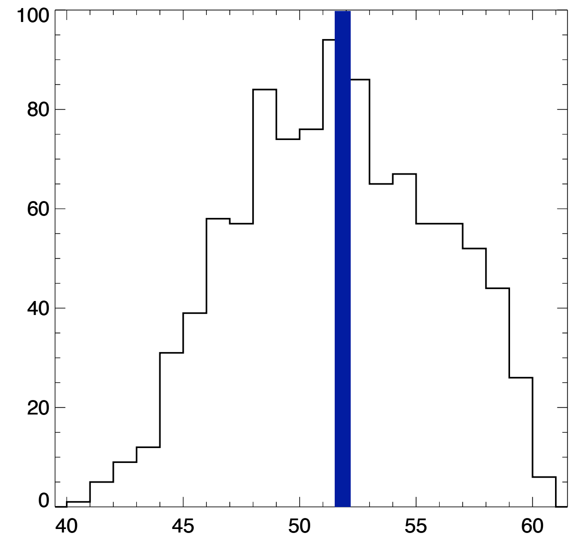
2.5%



planets detected

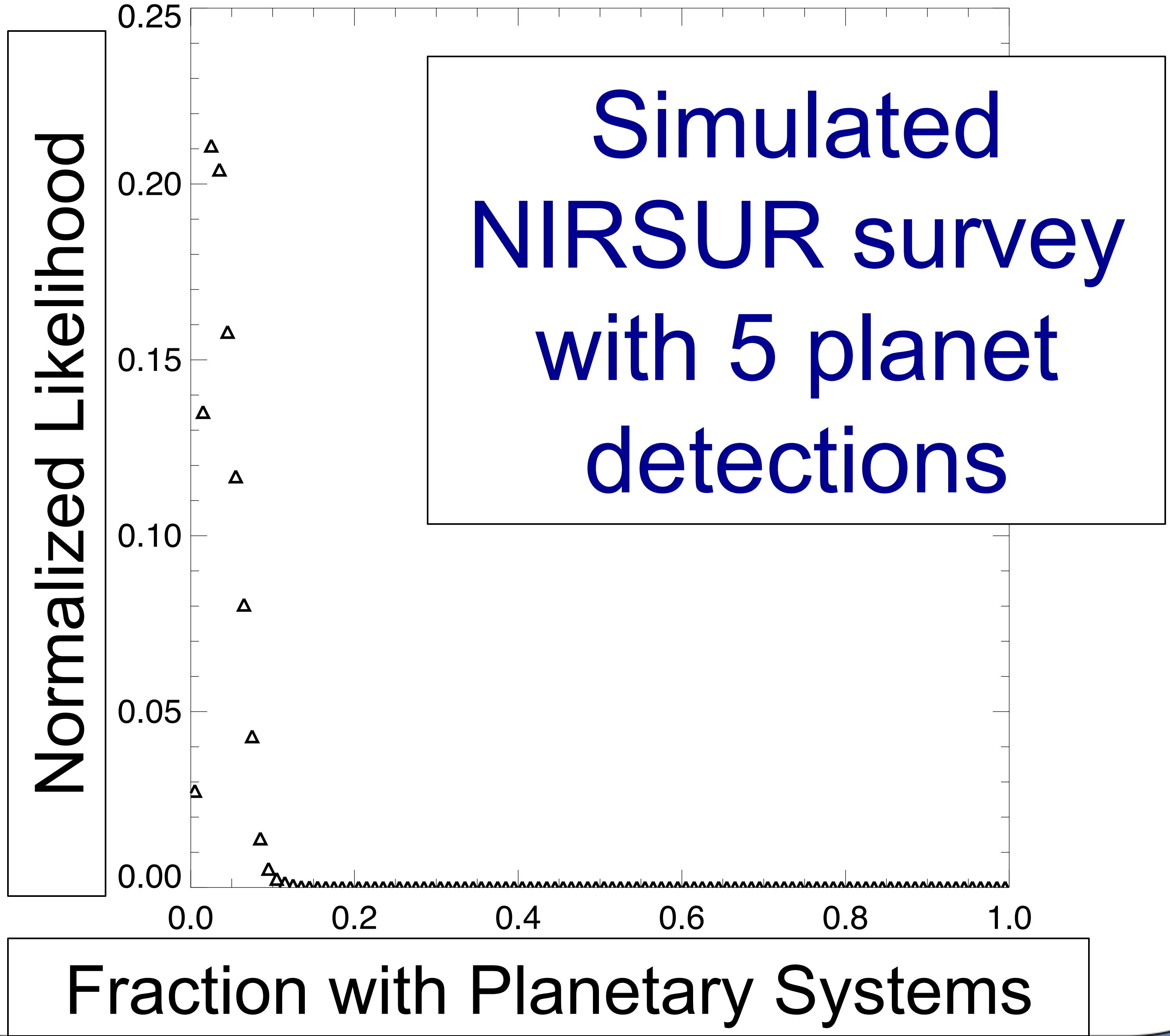
~8-10

10.5%



planets detected

~50-55



Simulated NIRSUR survey with 5 planet detections
Normalized Likelihood
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.2
0.4
0.6
0.8
1.0
Fraction with Planetary Systems

Conclusions

Physical Properties

Direct imaging yields vital information on young planets in formation or which have recently formed.

Architecture

Hot-start gas-giant (>4 M_{jup}) planets are rare at >10 AU.