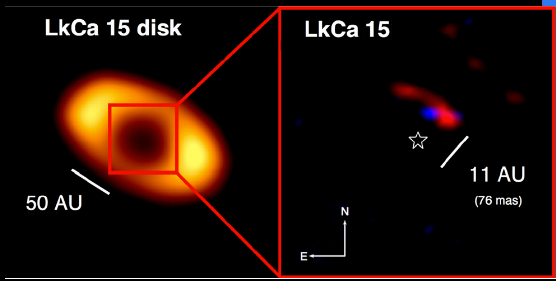
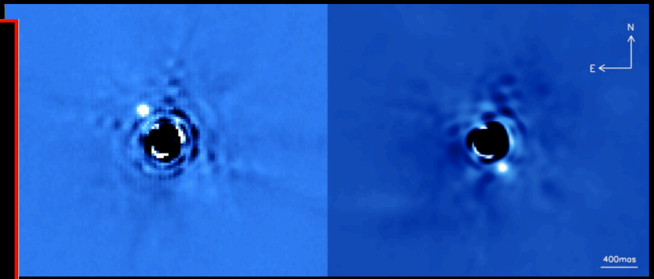
SURVEY OF SURVEYS AROUND YOUNG STARS

Beth Biller, University of Edinburgh

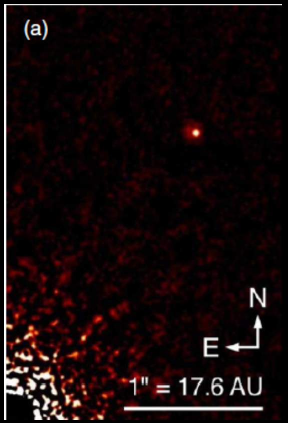
Directly Imaged Planetary (or Nearly Planetary) Companions



Kraus and Ireland 2012

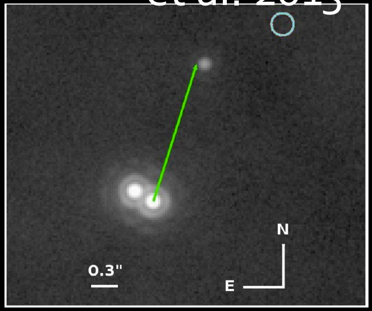


Lagrange et al. 2008,2010

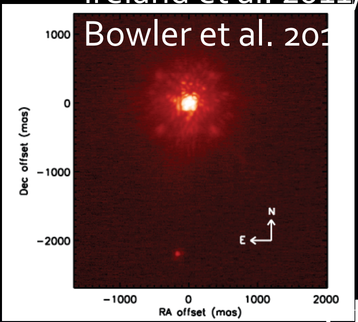


Kuzuhara et al. 2014

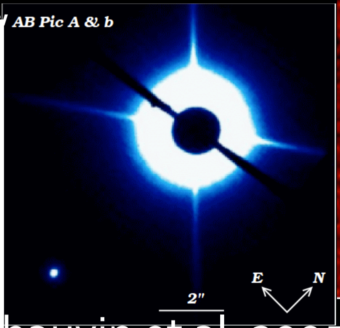
Delorme et al. 2013



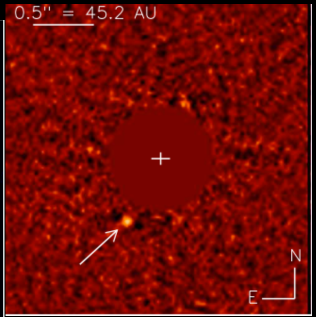
Ireland et al. 2011,



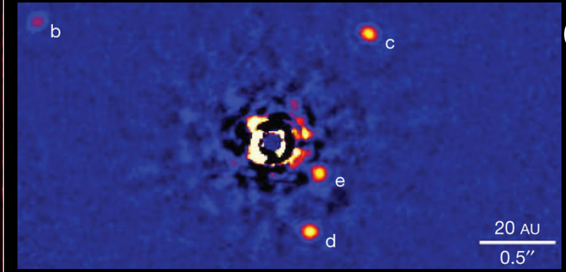
Bowler et al. 201



Chauvin et al. 2005

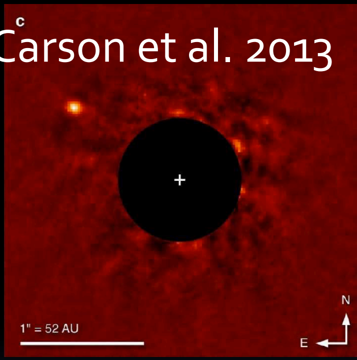


Rameau et al. 2013



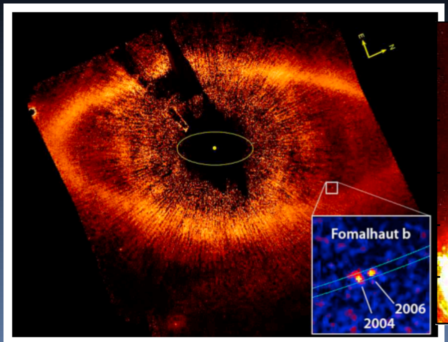
Marois et al. 2008,2010v

Carson et al. 2013

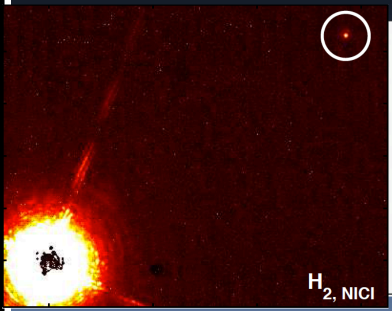


Chauvin et al. 2004, 2005

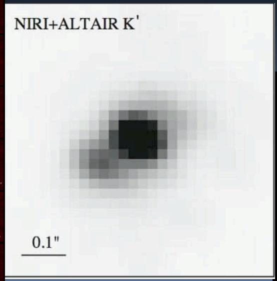
Lafrenière et al. 2008,2010



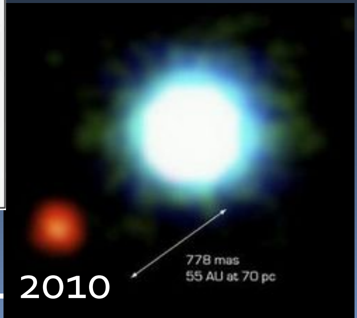
Kalas et al. 2008



Bailey et al. 2013



Todorov et al. 2010



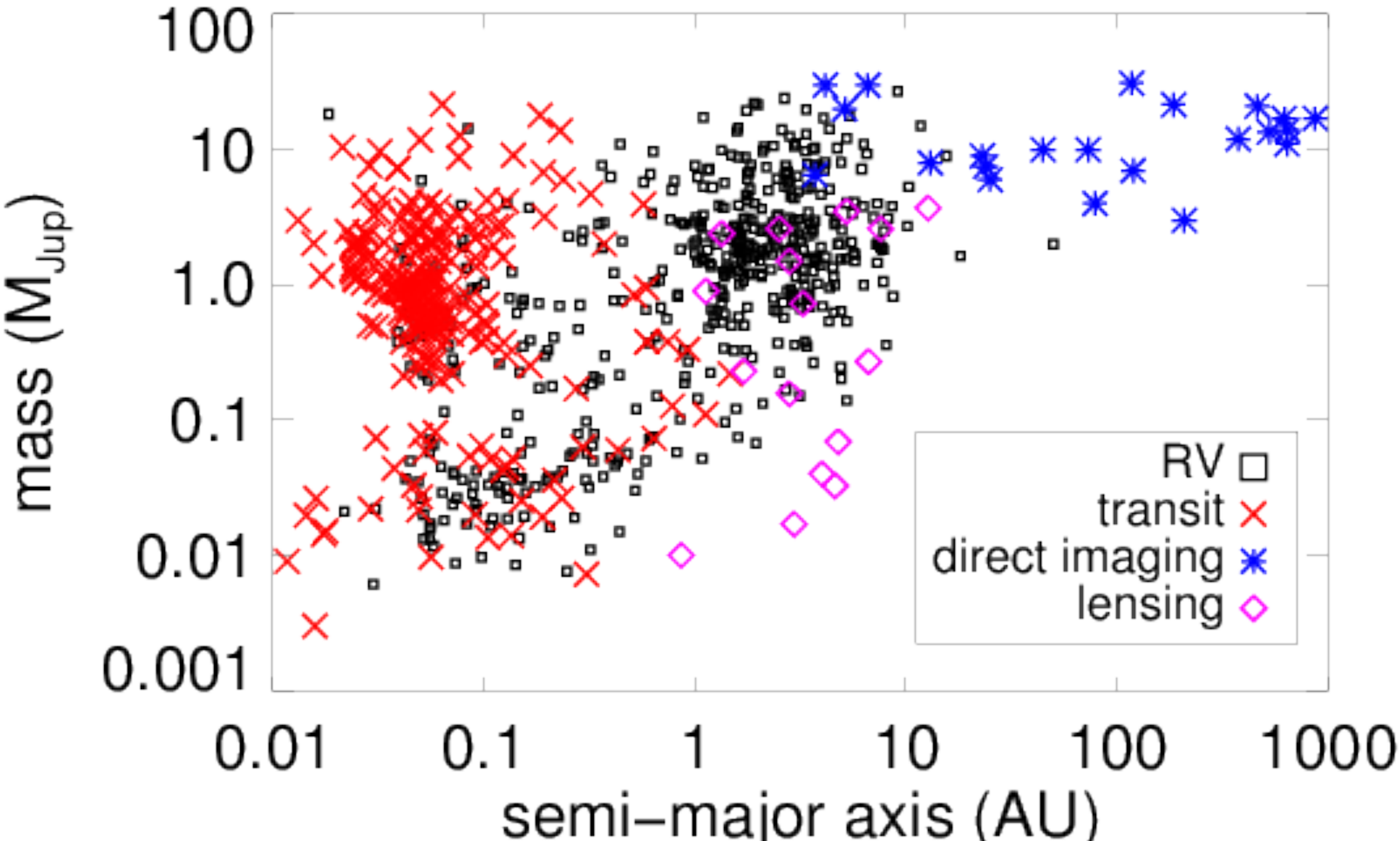
Some Fundamental Questions of Comparative Exoplanetology

Physical Properties

Orbits, masses, atmospheric properties

Architecture

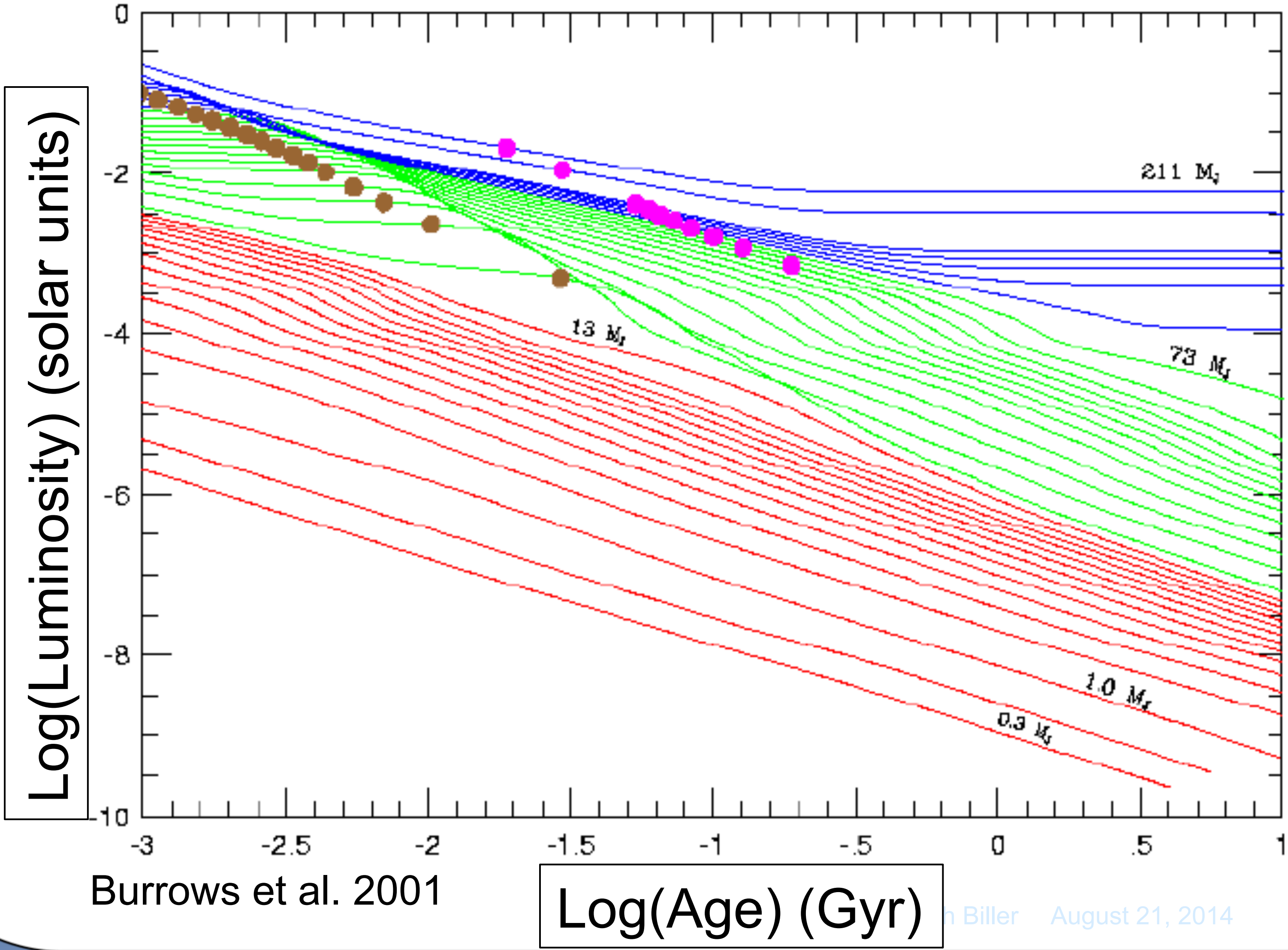
Where do planets live in their stellar systems?



Data from exoplanet.eu

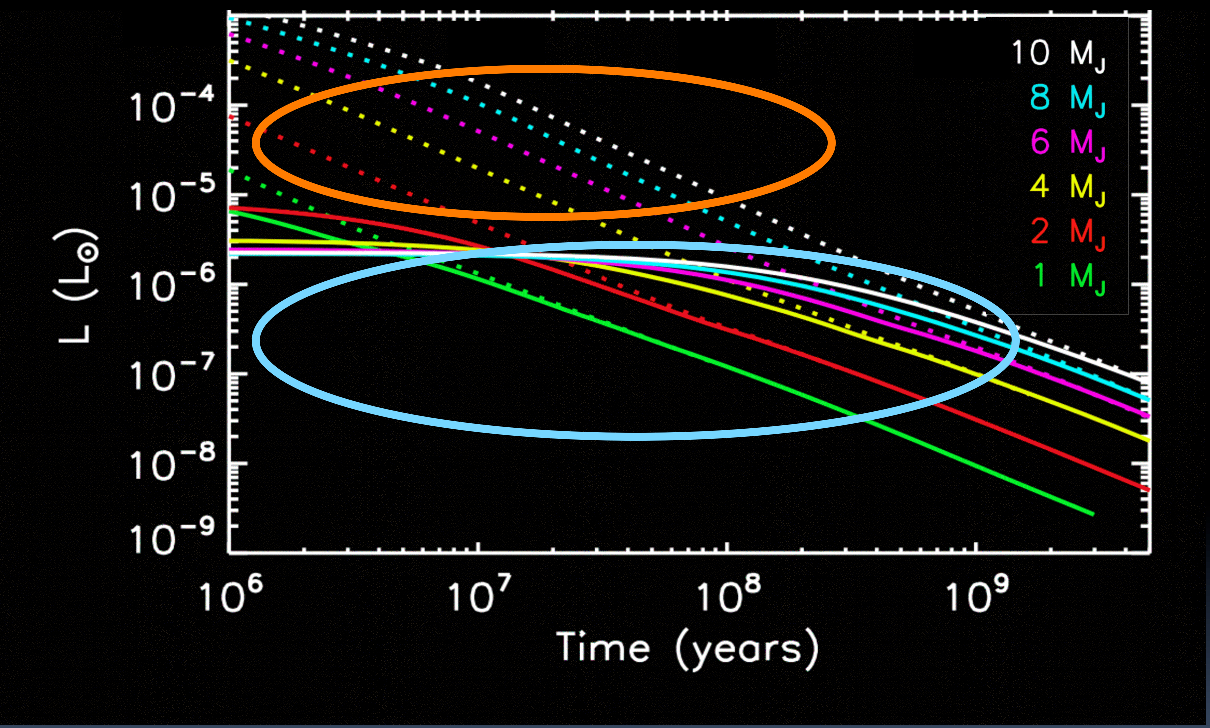
How do we open up the parameter space for exoplanet imaging?

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)

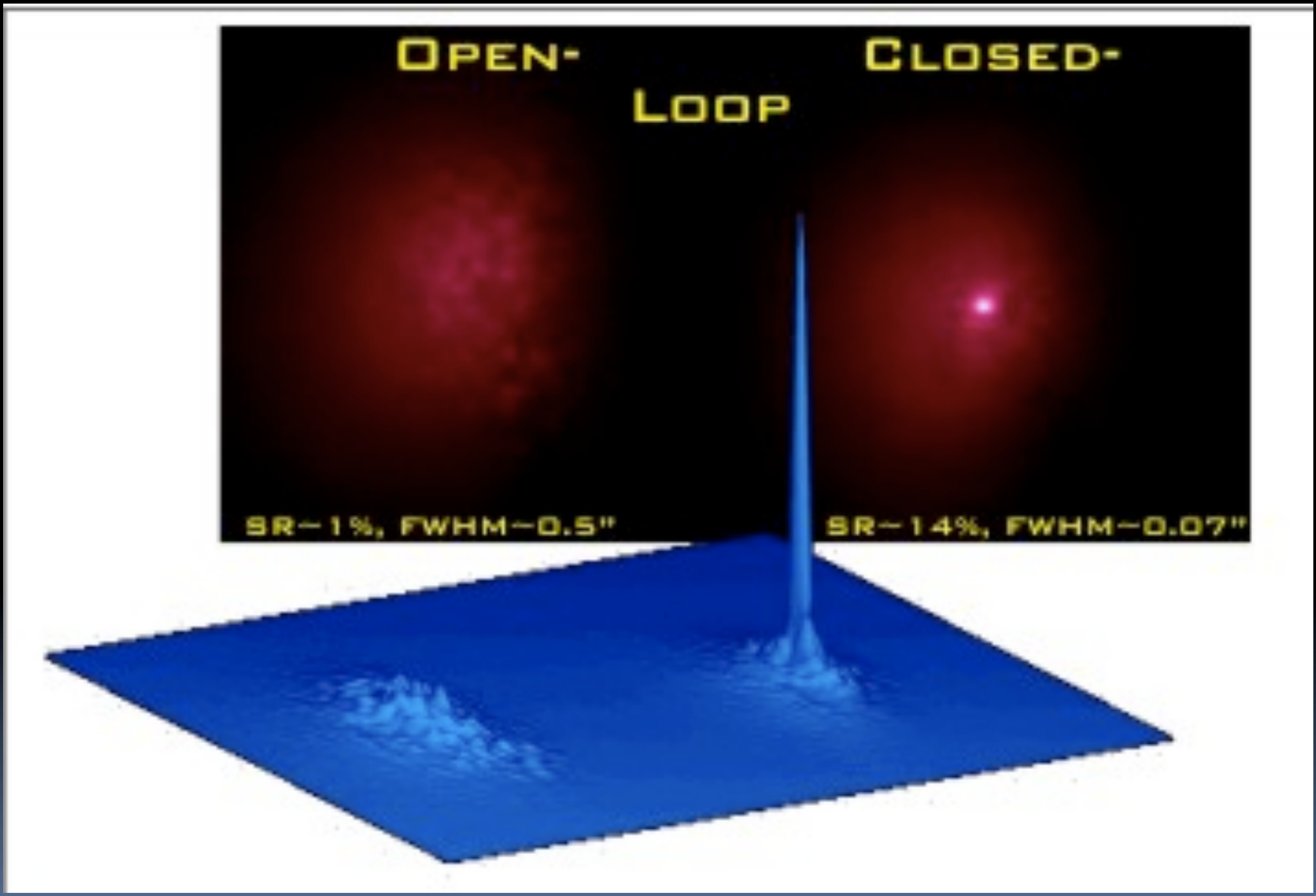
Step 2:
Overcoming Technical Hurdles

Difficulties with Direct Detection (1)

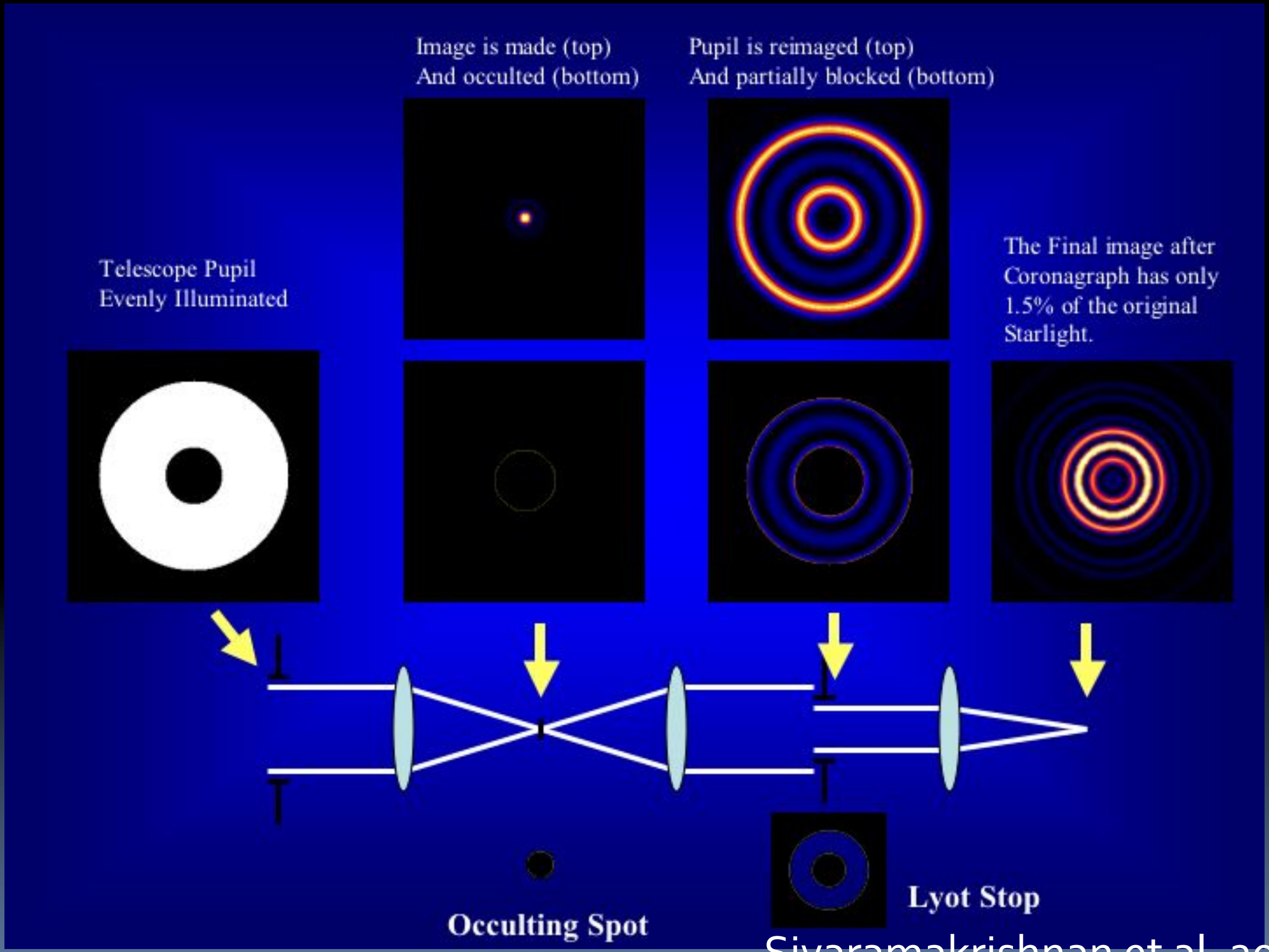
Huge contrast ratio between planet and star

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

Adaptive Optics



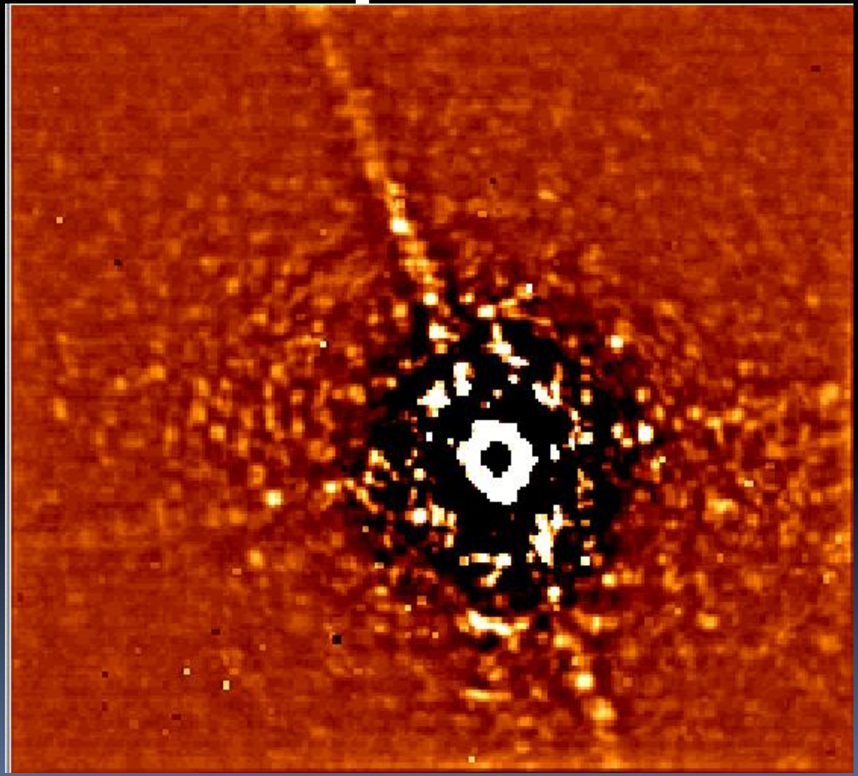
Coronagraphy



Sivaramakrishnan et al. 2001

Difficulties with Direct Detection (2)

Speckle Noise



For photon-noise limited data:

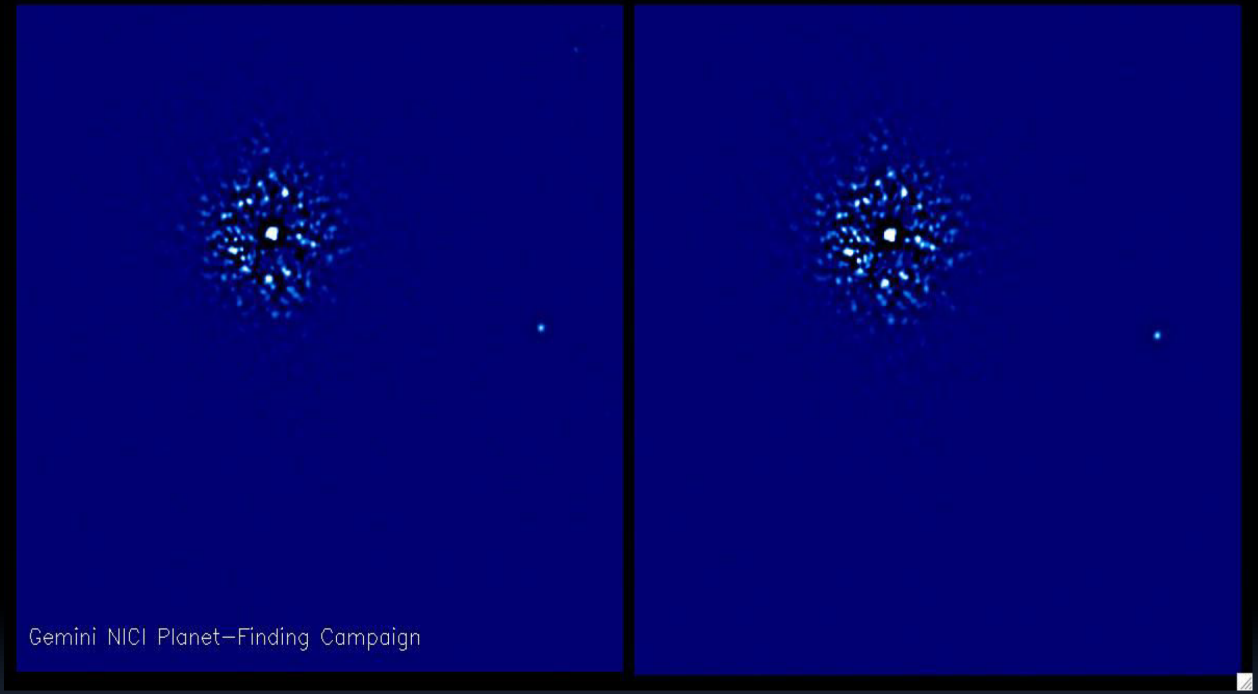
$S/N \sim t_{exp}^{0.5}$

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*

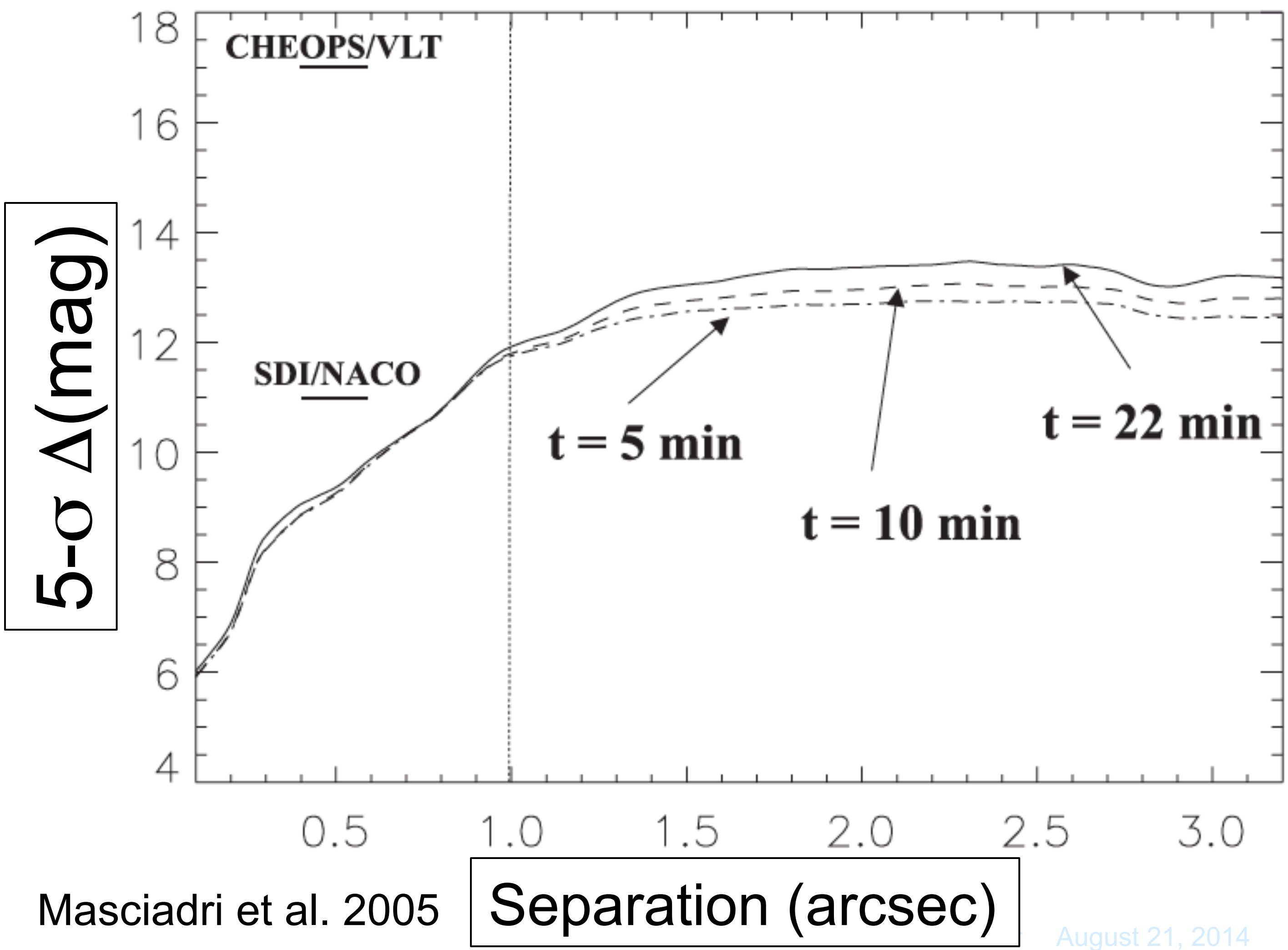
2. **Coronagraphy**
   - *Boosting dynamic range and contrast*

3. **Speckle Suppression Techniques**

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

- *Removing quasi-static speckles*

Generation 0
AO enabled and HST efforts



Masciadri et al. 2005

Generation 0
AO enabled and HST efforts

- Typical sample size: <50 stars
- Typical contrast: Δmag ~ 8 @ 0.5″

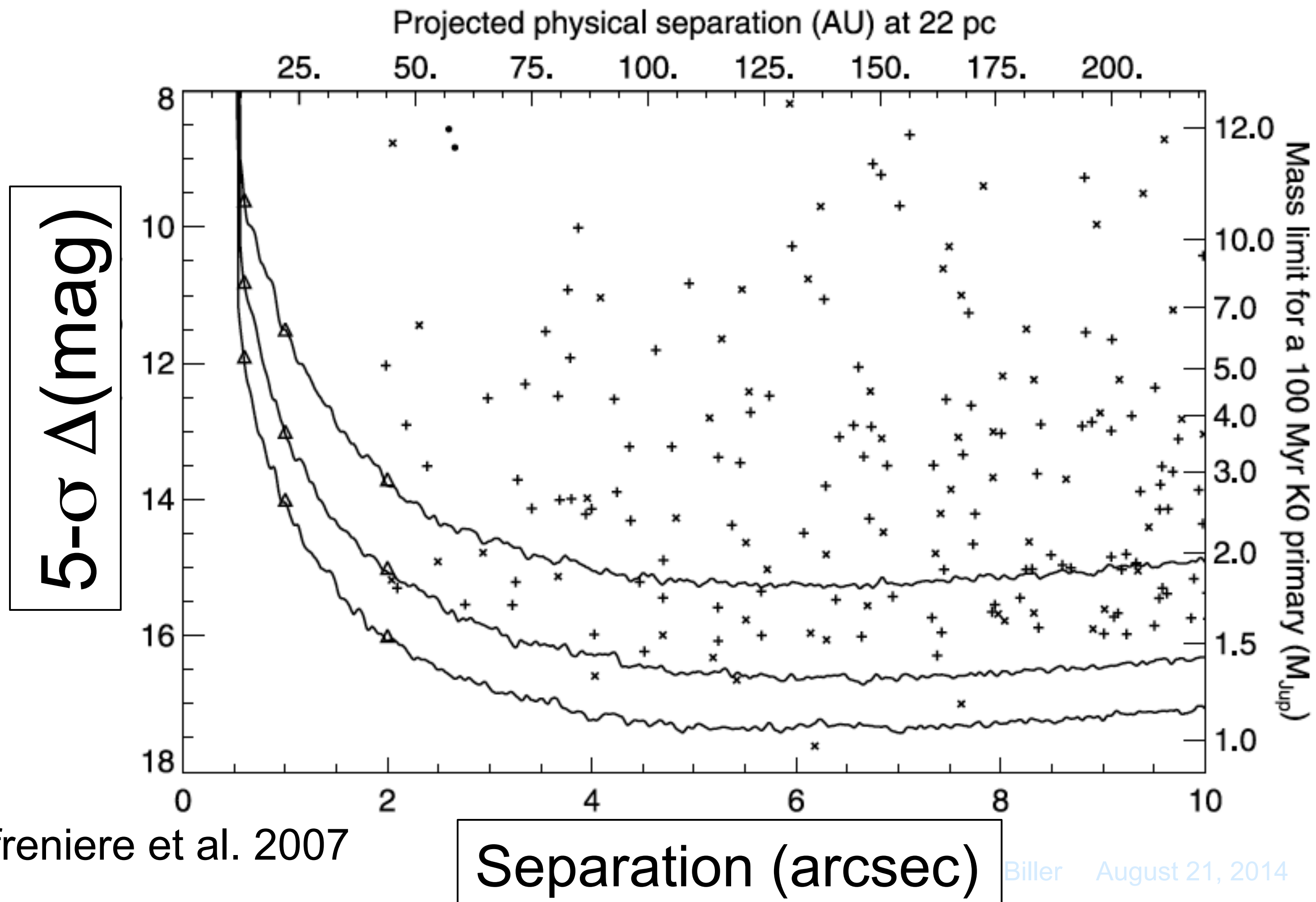
- VLT: Masciadri et al. 2005
- ESO 3.6 m: Chauvin et al. 2003
- HST: Lowrance et al. 2005

Generation 1
large telescope + AO + speckle suppression techniques

- Typical sample size: 50-100 stars
- Typical contrast: Δmag ~ 10 @ 0.5″

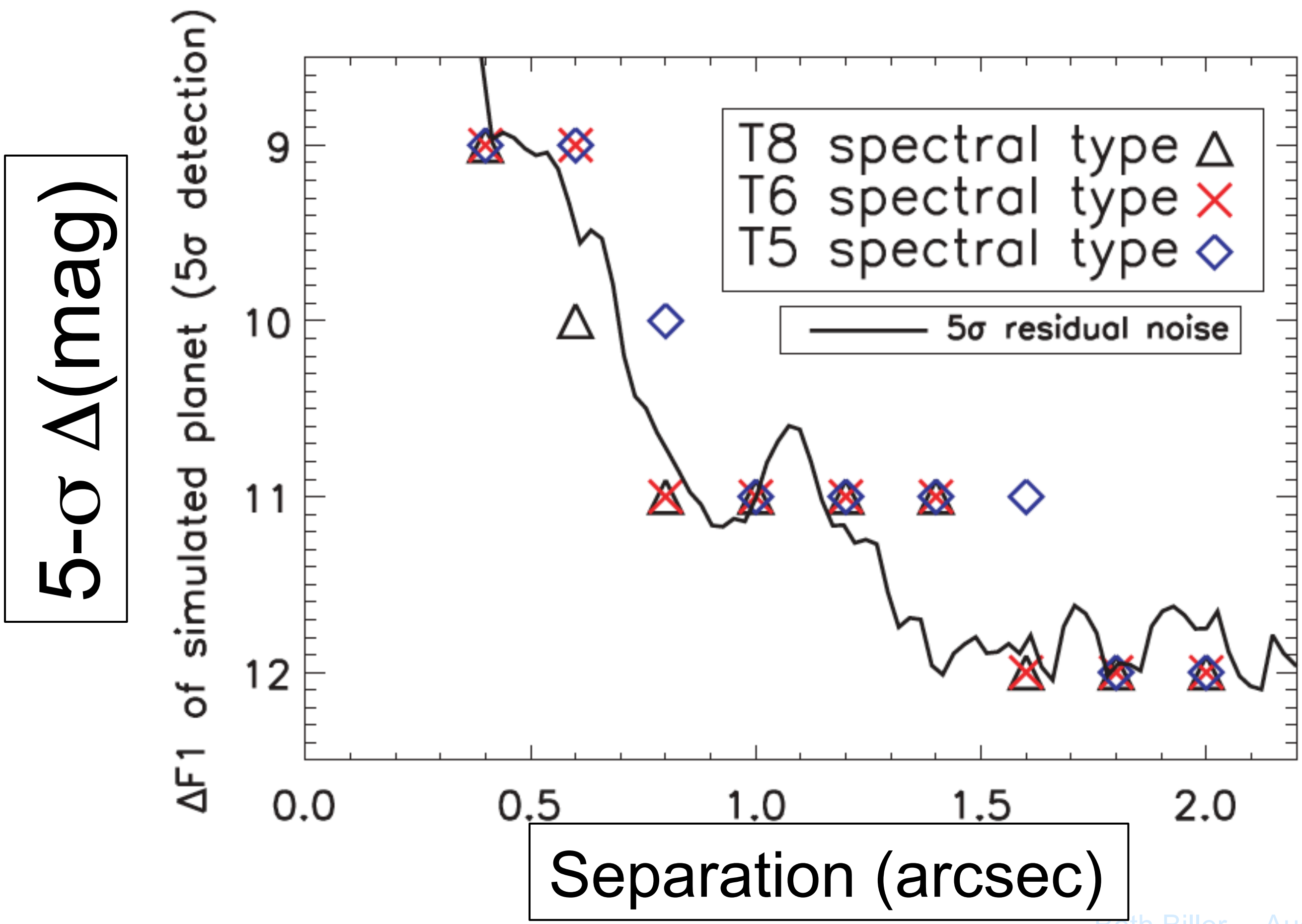
- VLT: Biller et al. 2007, Chauvin et al. 2010
- Gemini: Lafreniere et al. 2007
- Keck: Metchev et al. 2009
- Palomar: Carson et al. 2006, 2009, Metchev et al. 2009
- 3.6 AEOS + Lyot coronagraph: Leconte et al. 2010
- MMT: Heinze et al. 2010a, 2010b, Biller et al. 2007

Generation 1
large telescope + AO + speckle suppression techniques



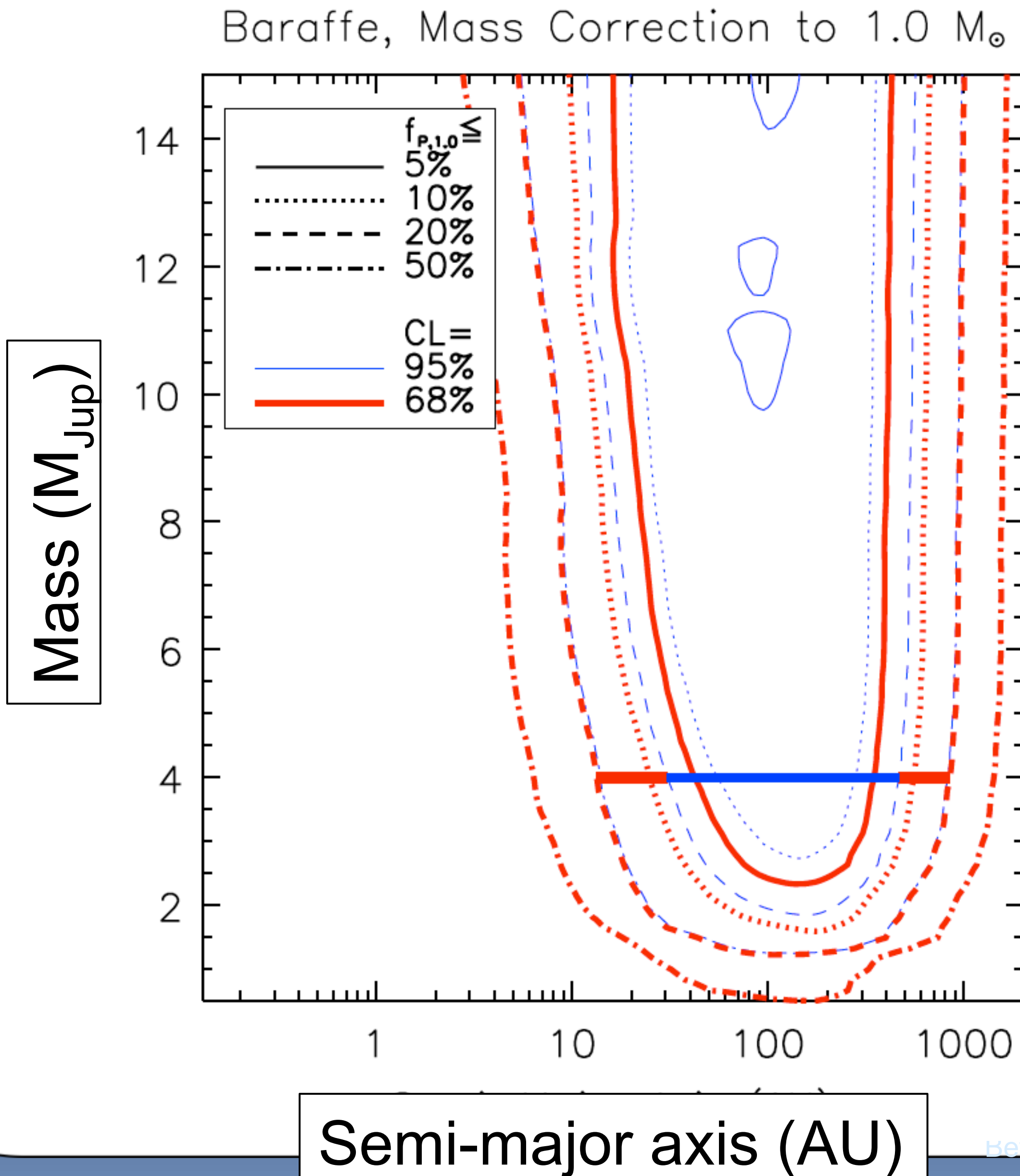
Lafreniere et al. 2007

Generation 1
large telescope + AO + speckle suppression techniques



Biller et al. 2007

Generation 1 survey statistics



Results from Nielsen and Close 2010, compiling data from 118 stars from Masciadri et al. 2005, Biller et al. 2007, and Lafrenière et al. 2007

Current Direct Imaging Efforts

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*

Current State of the Art:

large telescope + AO + coronagraphy + speckle suppression techniques

- Typical sample size: >100 stars
- Typical contrast: Δmag ~ 14.5 @ 1″

Ongoing and Recently Completed Surveys:

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

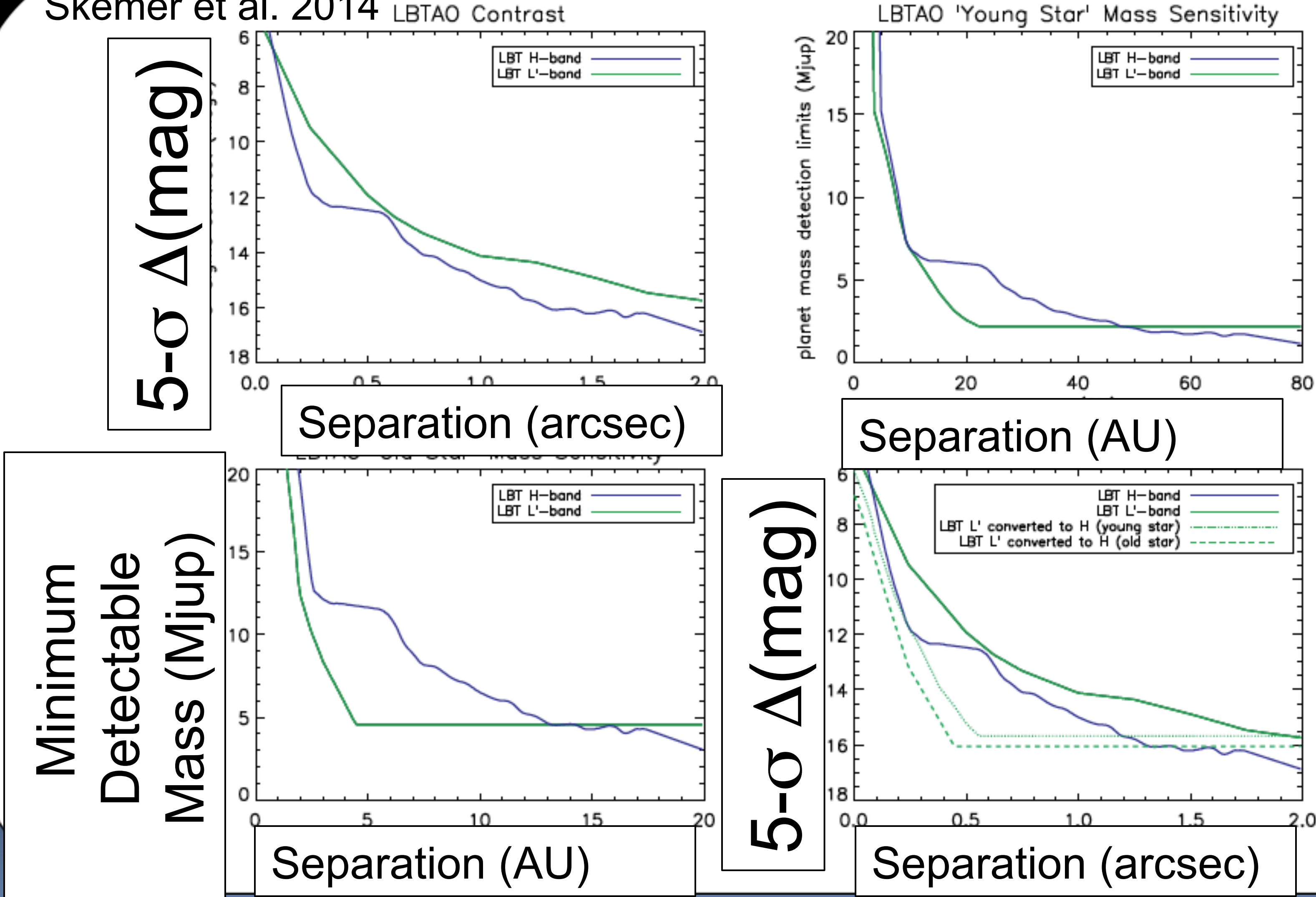
SEEDS, Brandt et al. 2014, Janson et al. 2013, Carson et al. in prep

M star based surveys, Bowler et al. 2013, Delorme et al. 2013

LEECH, Skemer et al. 2013

Near-IR vs. Mid-IR?

Skemer et al. 2014



Some Fundamental Questions of Comparative Exoplanetology

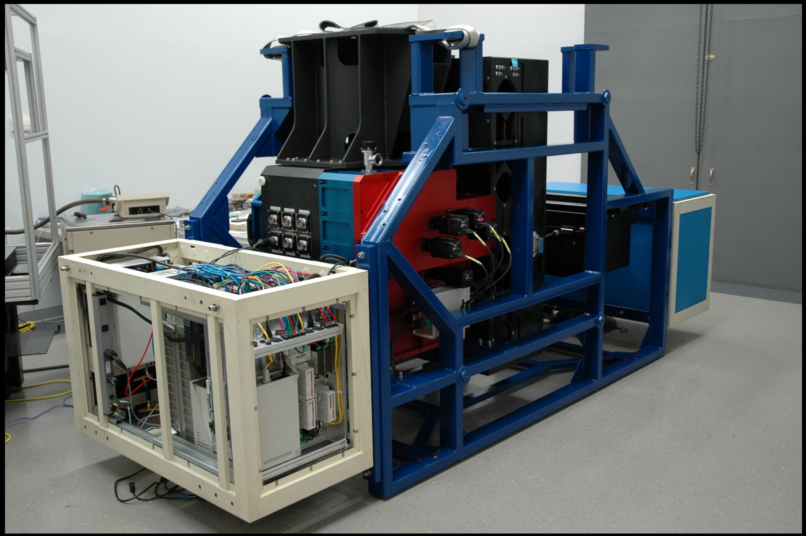
Physical Properties

Orbits, masses, atmospheric properties

Architecture

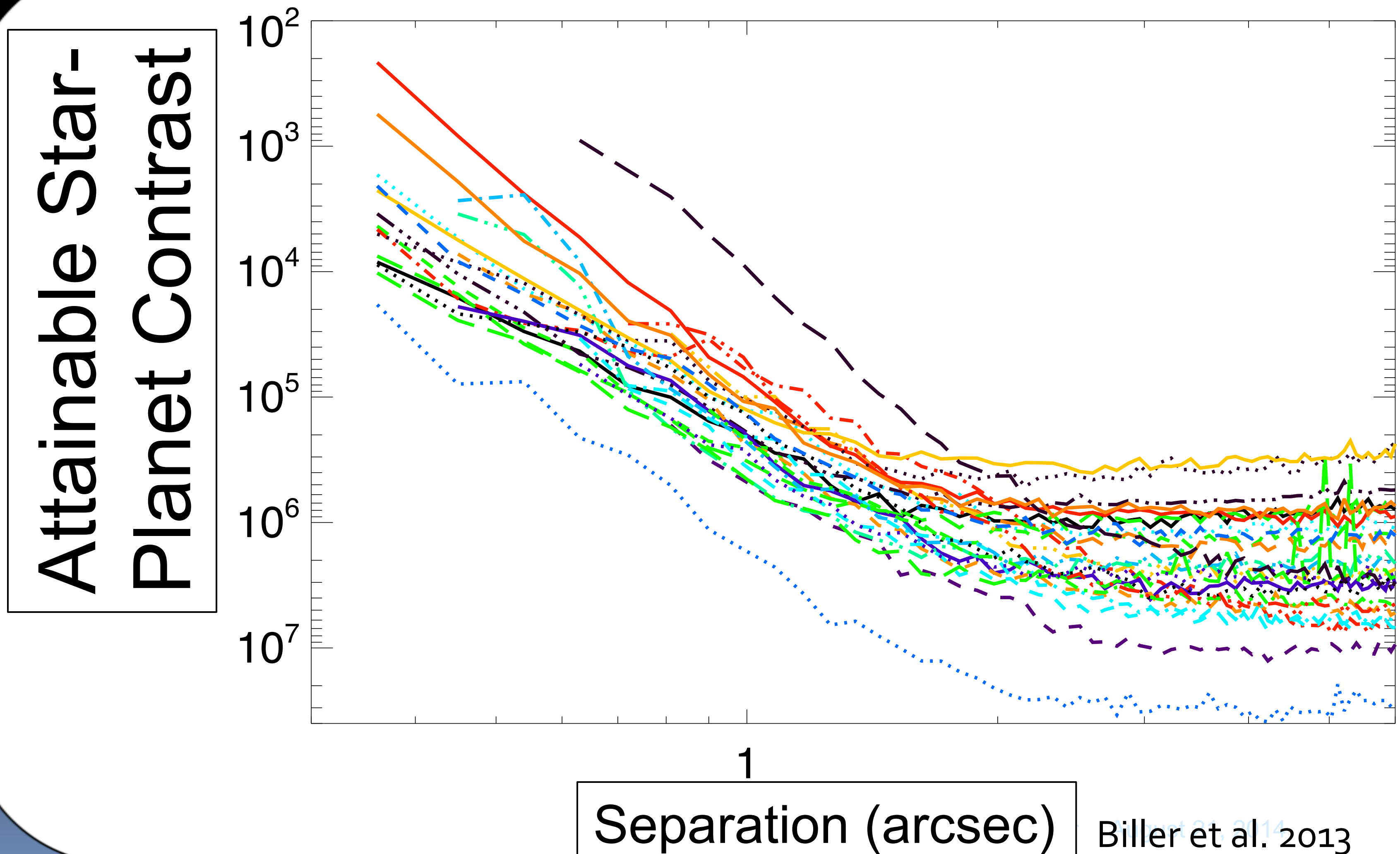
Where do planets live in their stellar systems?

Gemini/NICI Planet-Finding Campaign



- Recently completed major campaign (PI Michael Liu) @ Gemini-South for direct imaging of exoplanets: 500 queue hrs, ~230 stars.

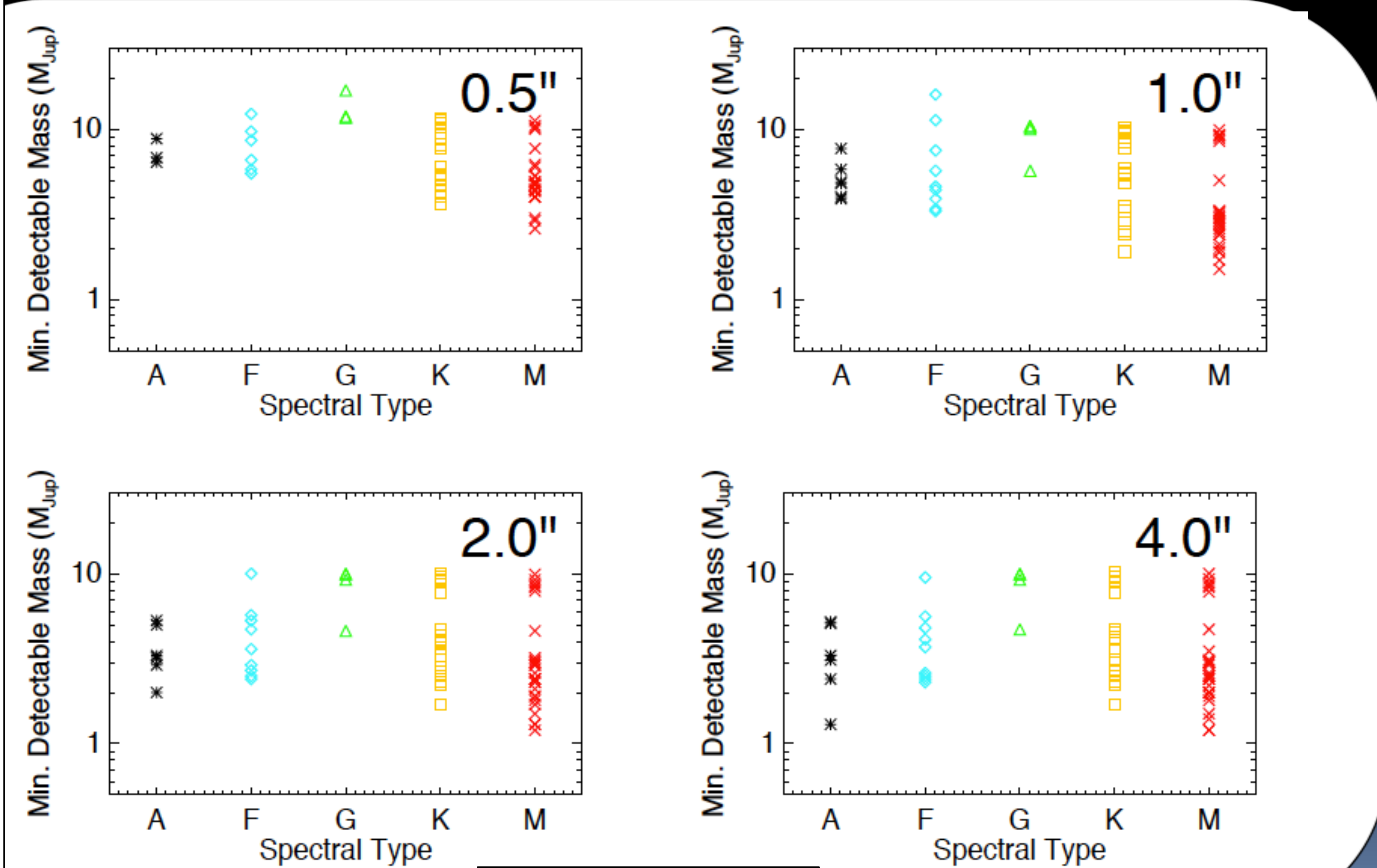
Excellent contrasts achieved



Biller et al. 2013

Mass Sensitivity

Minimum Detectable Mass (Mjup)



Spectral Type

Strongest Constraint on Planet Fraction to date 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

Summary

Hot-start gas-giant planets are rare at >10 AU.

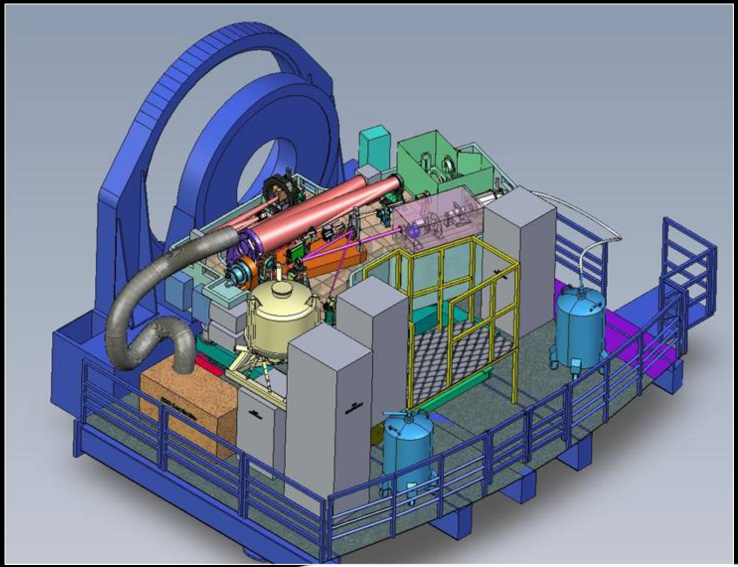
- *HR 8799b planets are rare, β Pic b could be common.*
- *If hot start corresponds to gravitational instability (GI), then GI planets must rarely occur.*
- *If wide planets are due to scattering, this happens rarely.*

Next Generation Direct Imaging Efforts

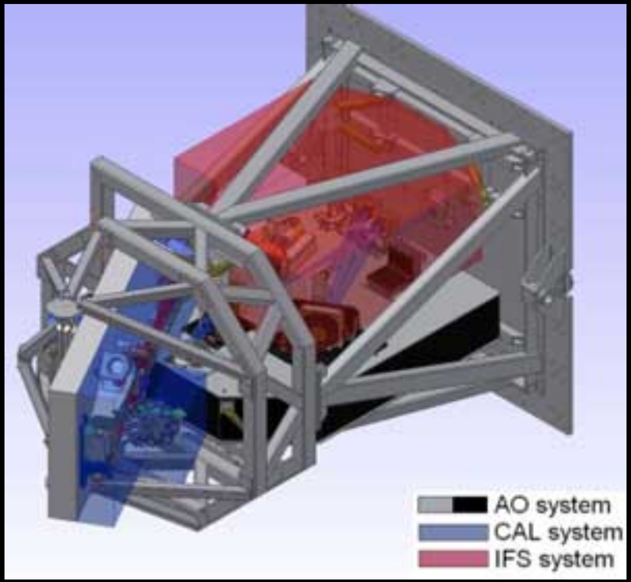
Beth Biller August 21, 2014

New Instruments

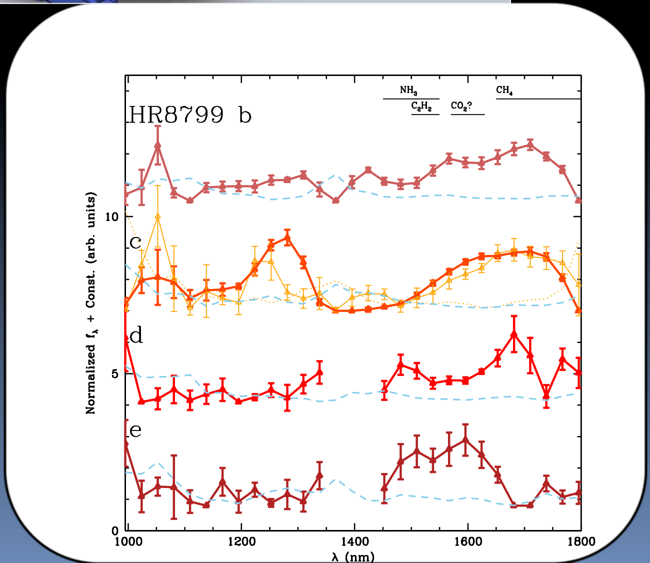
SPHERE @ VLT



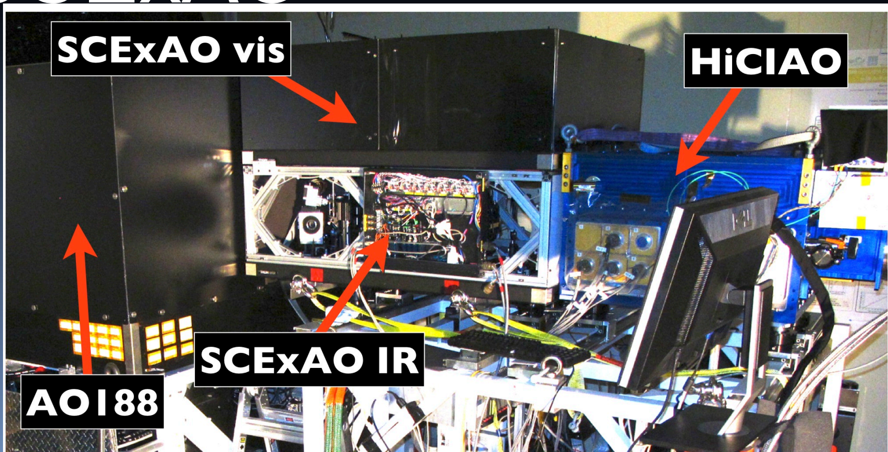
GPI @ Gemini



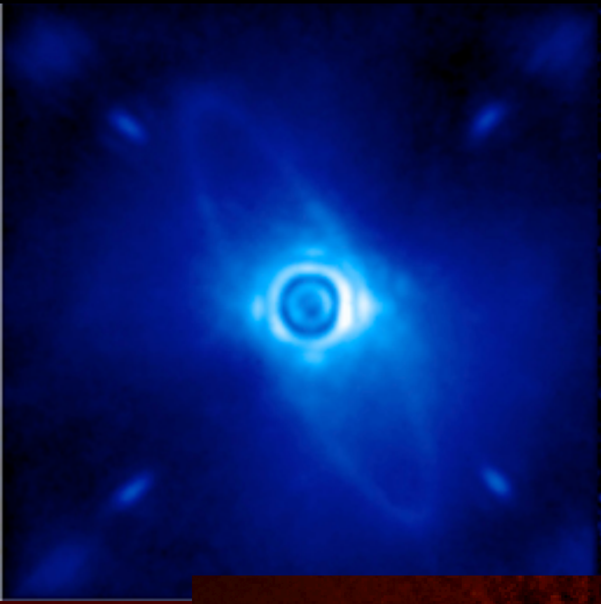
Project 1640

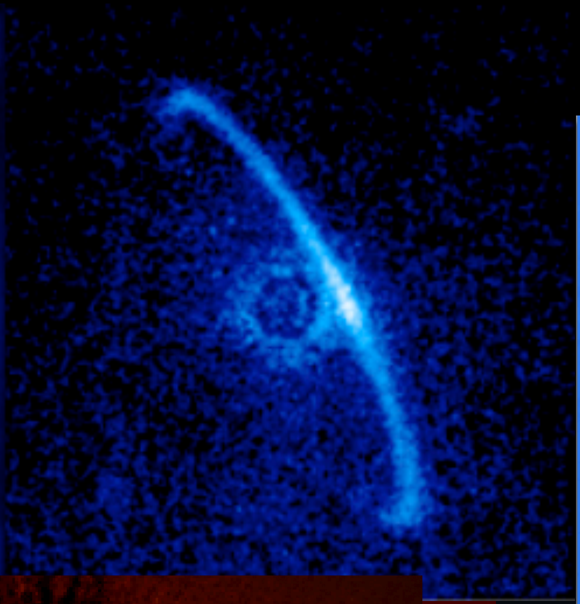


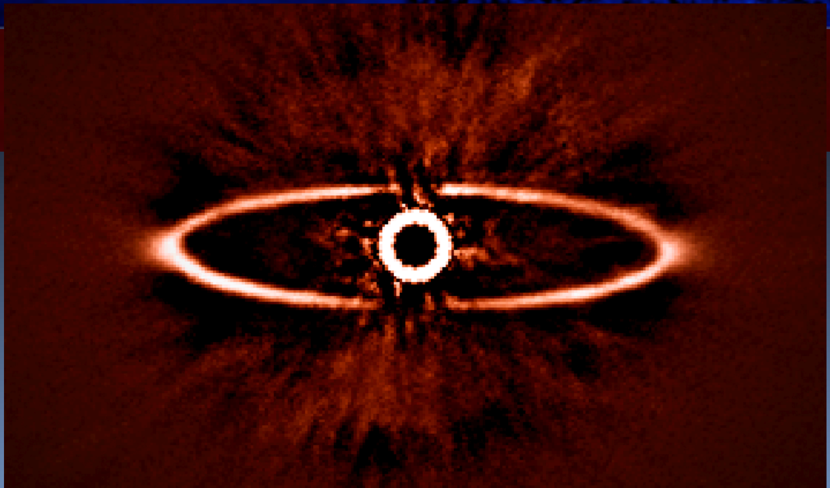
SCExAO

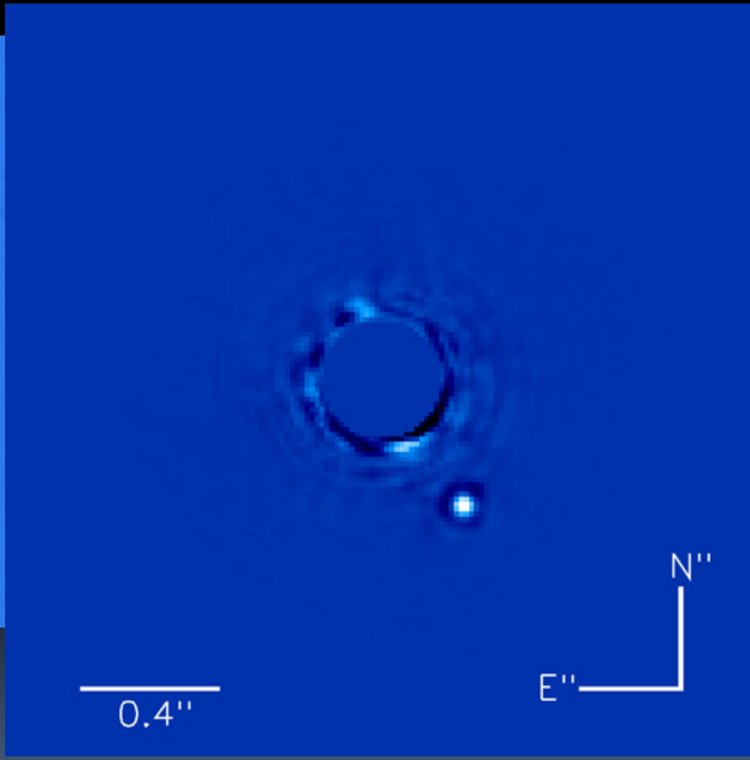


Unprecedented contrasts with SPHERE and GPI

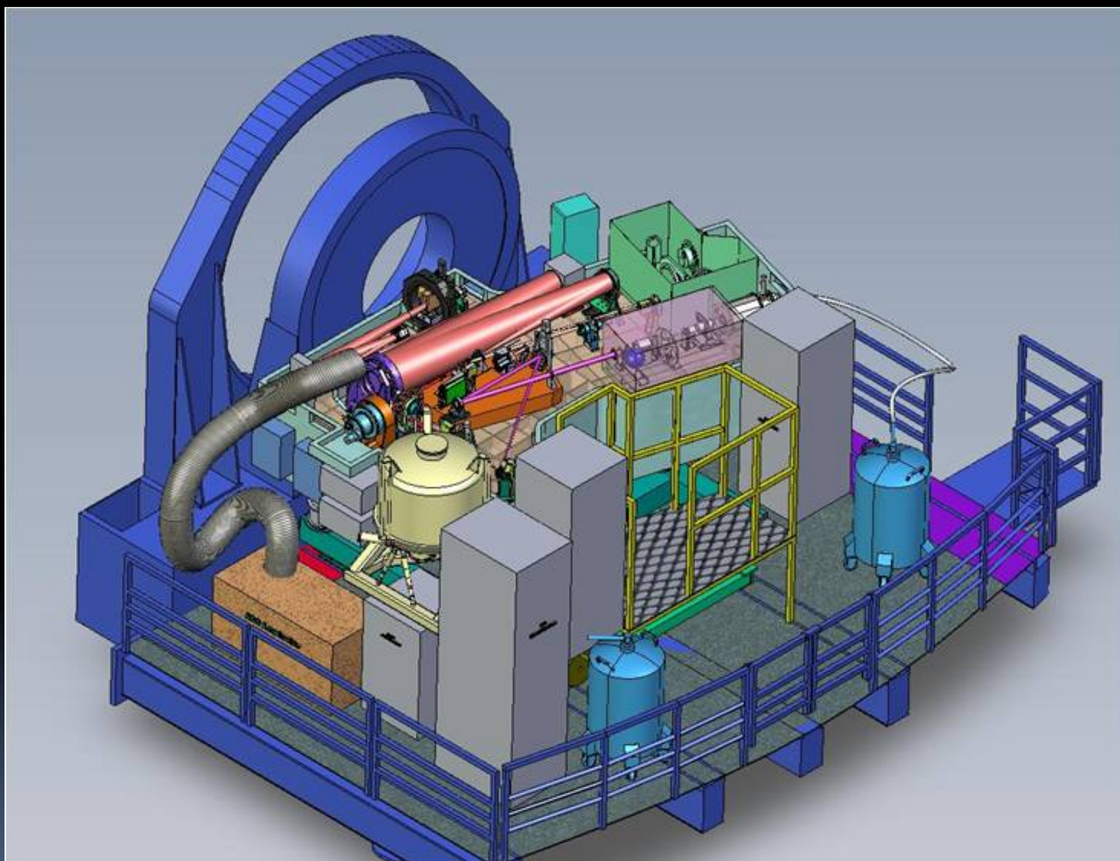








NIRSUR with SPHERE @ VLT – predicted start in 2015



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

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

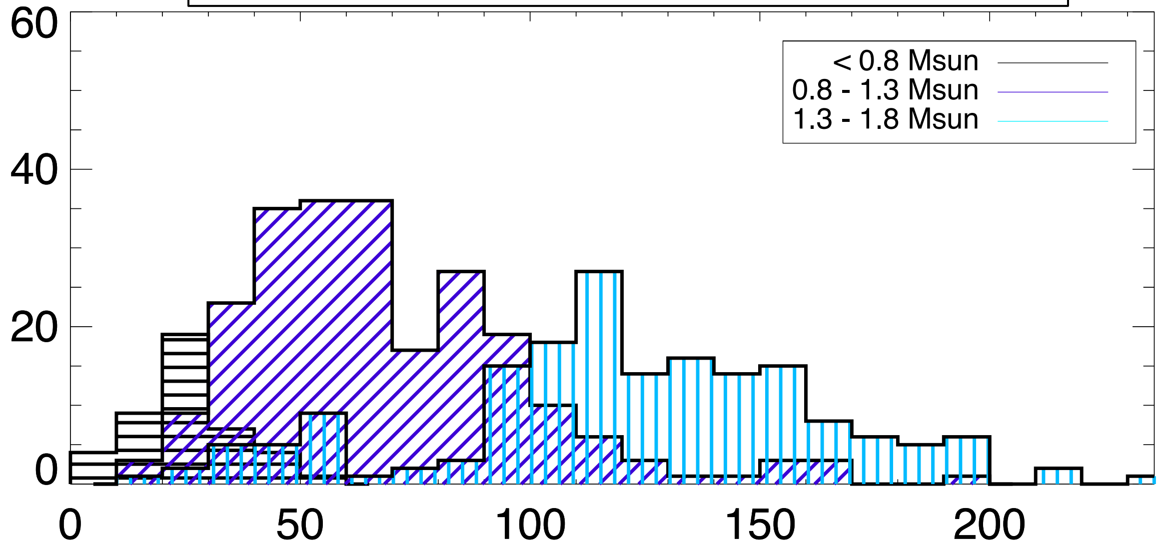
(until cutoff, where C is a normalization factor related to planet frequency F)

Normalize to known RV planets

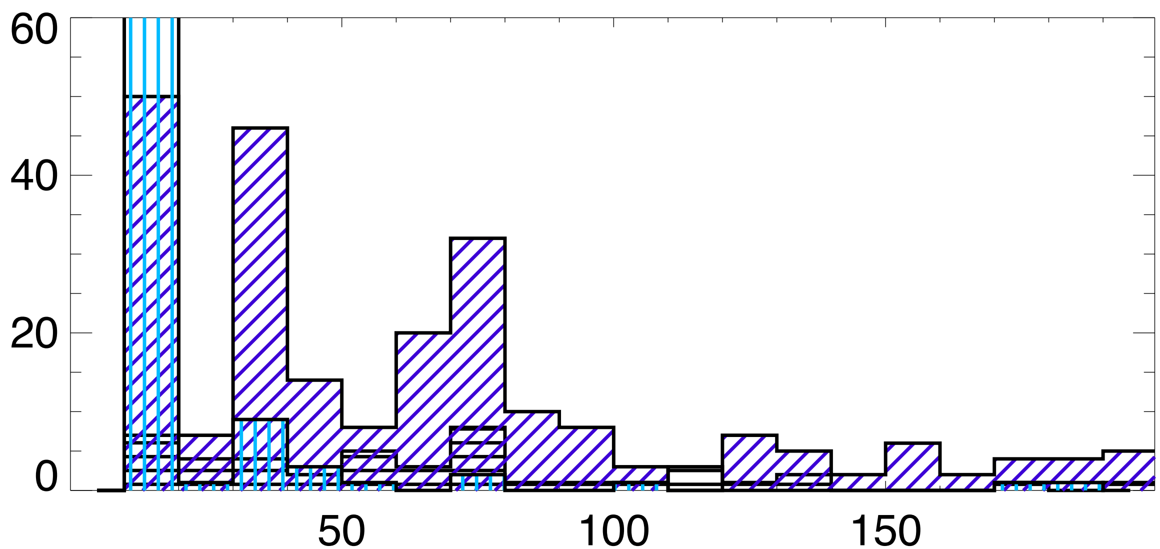
Fischer and Valenti 2005 find a planet frequency of 3.94% for planets with:

- 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



Distance (pc)



Age (myr)

Conclusions

Physical Properties

Direct imaging yields vital information on atmospheres of young planets

Architecture

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