Science yield modeling with the Exoplanet Open-Source Imaging Mission Simulator (EXOSIMS)

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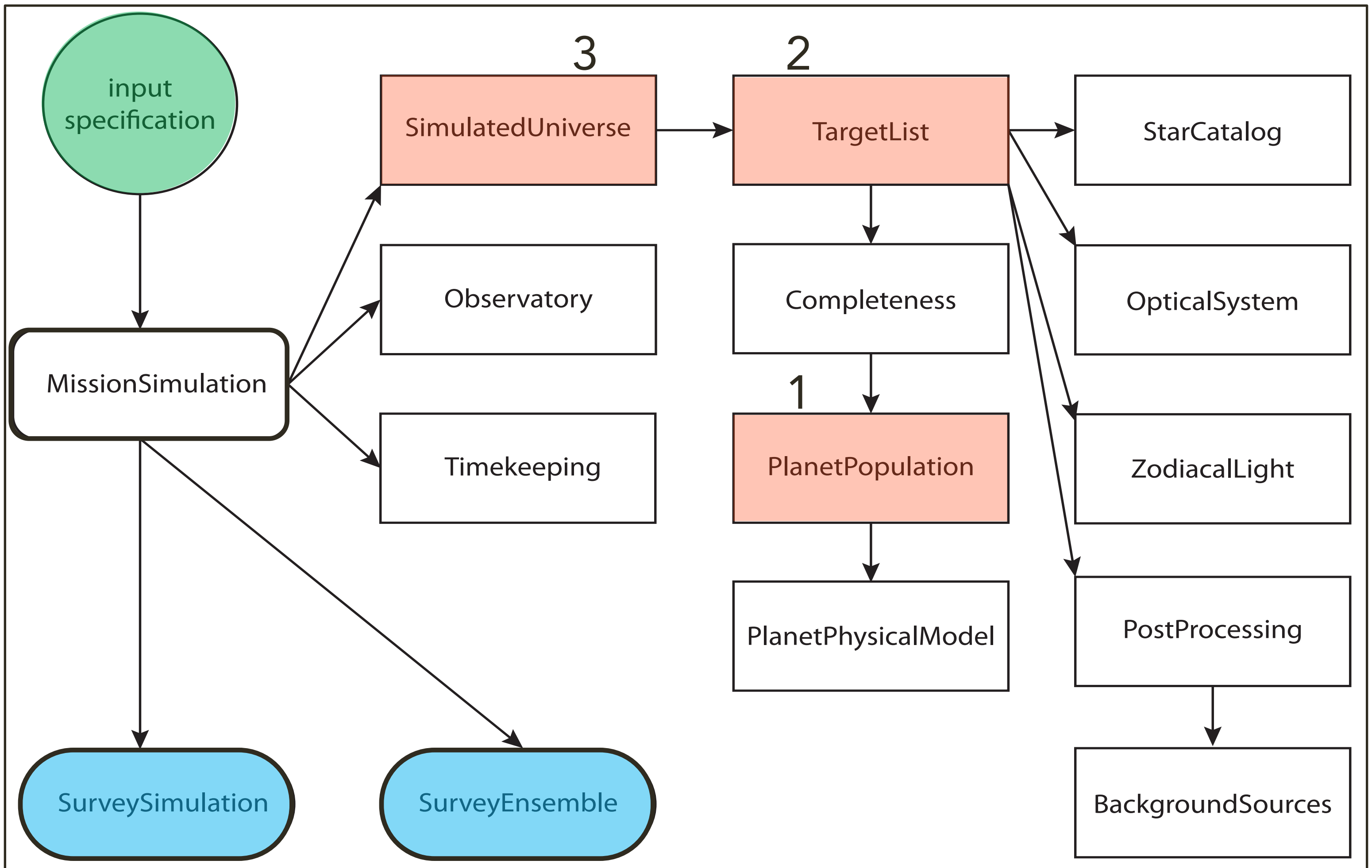
EXoplanet Open-Source Imaging Mission Simulator

- EXOSIMS - developed as part of WFIRST Preparatory Science
- Performs ensembles of simulations to determine science yield distributions
- Modular architecture, allows multiple mission designs
- https://github.com/dsavransky/EXOSIMS

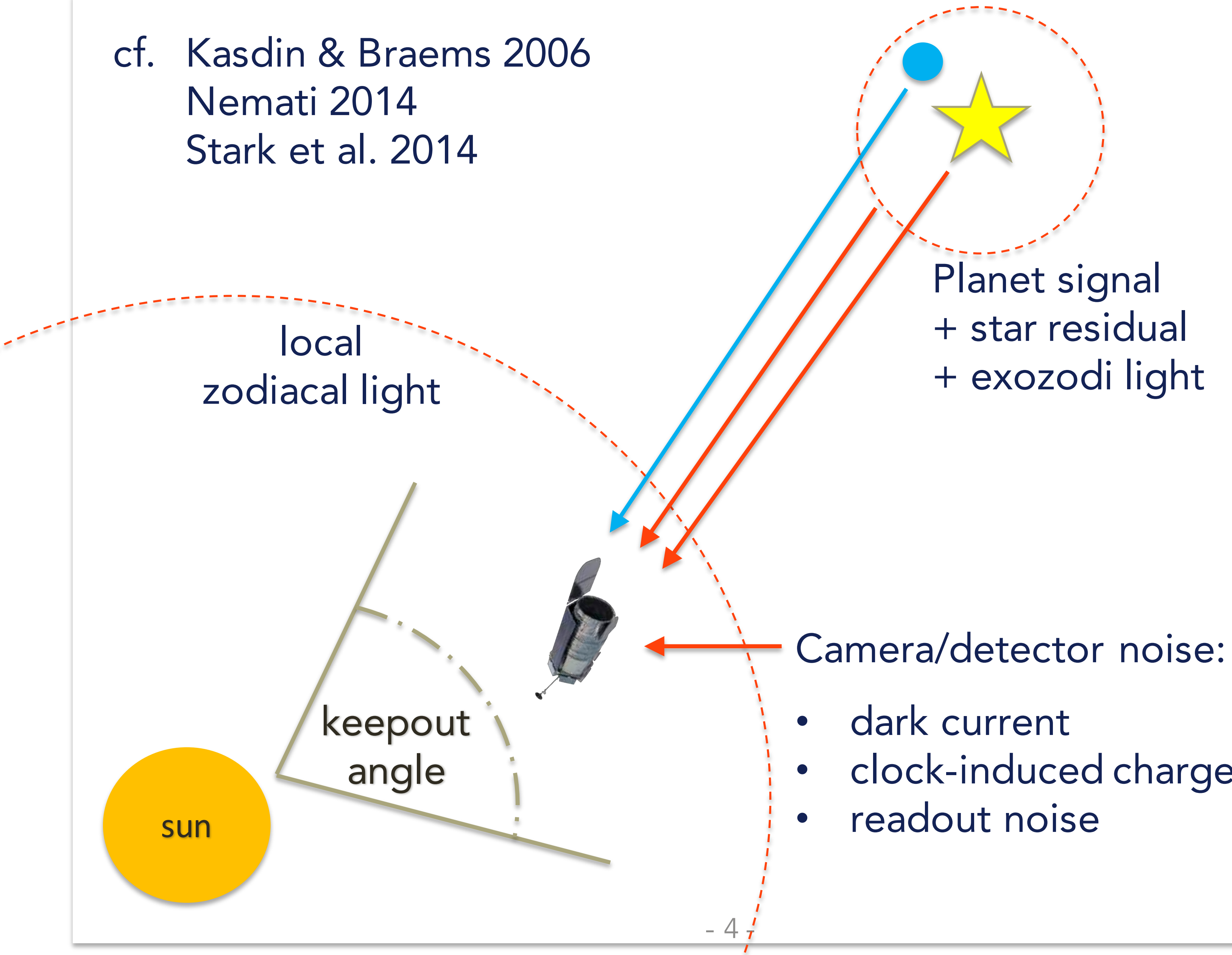


The Scheduler – which target to observe ?

- Find spacecraft orbital START positions and filter out unavailable targets (including settling time, occulter slew time)
- Calculate **integration times** for the preselected targets and filter out t > threshold (arbitrary)
- Find spacecraft orbital END positions and filter out unavailable targets
- Filter out all previously visited targets, unless in revisit list (e.g. detected planets, but not yet characterized)
- From remaining, choose the target with **highest completeness**

Planet integration time – noise budget

cf. Kasdin & Braems 2006
Nemati 2014
Stark et al. 2014



How do we determine integration time?

- spectral flux density electron count rate

$$C_{\mathcal{F}0}(\lambda) = \epsilon \, A \, \Delta\lambda \, \boldsymbol{T(\lambda)} \, \mathcal{F}_0(\lambda) \quad \text{with } \mathcal{F}_0(\lambda) = 10^{\left(4.01 - \frac{\lambda - 550}{770}\right)}$$

Total throughput

- planet signal

$$C_p(\lambda) = C_{\mathcal{F}0}(\lambda) \, 10^{-0.4\,(v\text{mag}+\Delta\text{mag})}$$

- star residual

$$C_{sr}(\lambda) = C_{\mathcal{F}0}(\lambda) \, 10^{-0.4\,v\text{mag}} \, \boldsymbol{Q(\lambda)}$$

Instrument contrast

- background noise

$$C_b(\lambda) = C_{sr}(\lambda) + C_{zl}(\lambda) + C_{dc} + C_{cc} + C_{rn}$$

zodiacal light

dark current

clock-induced charge

read noise

- SNR

$$SNR = \frac{C_p t}{\sqrt{C_p t + C_b t + \left(\boldsymbol{f_{pp} C_{sr} t}\right)^2}}$$

speckle residuals (systematic error)

with $\boldsymbol{f_{pp}}$ = post-processing factor

Implemented detection methods

- From Nemati SPIE 2014

$$t(\lambda) = \frac{(c_p + c_b)\,\mathrm{SNR}^2}{c_p{}^2 - \left(\mathrm{SNR}\, f_{\mathrm{PP}}\, c_{sr}\right)^2}$$

- From Kasdin & Braems 2006

$$t(\lambda) = \frac{C_b}{C_p{}^2\,\overline{\Delta\alpha}} \left(z_{\mathrm{FA}} - z_{\mathrm{MD}} \sqrt{1 + \frac{C_p \sum \overline{\mathrm{PSF}}_{\mathrm{ij}}^3}{C_b \sum \overline{\mathrm{PSF}}_{\mathrm{ij}}^2}} \right)^2$$

where $\overline{\Delta\alpha}$ is the dimensionless pixel size, and $\overline{\mathrm{PSF}}$ is the normalized PSF

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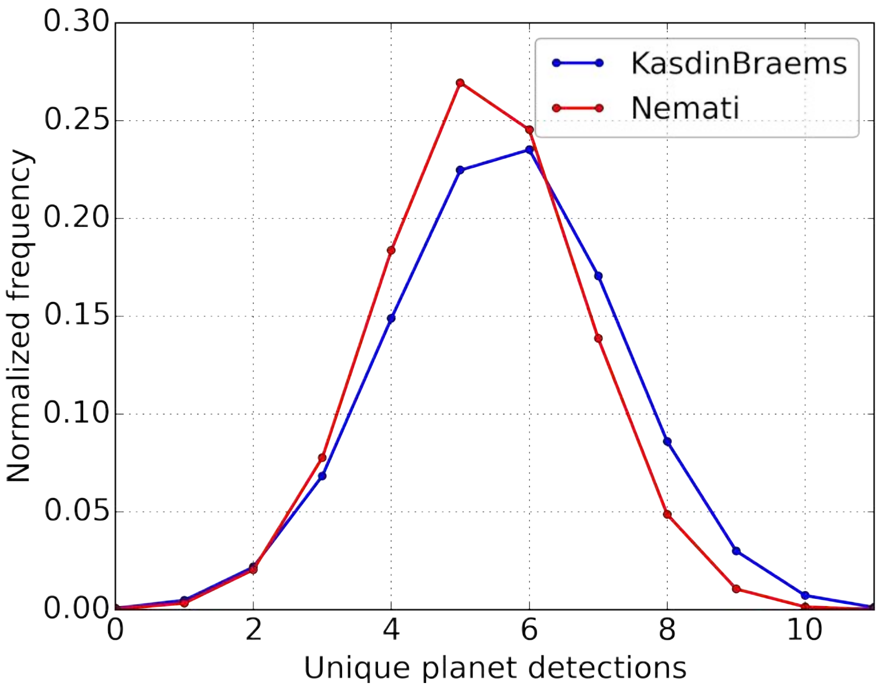
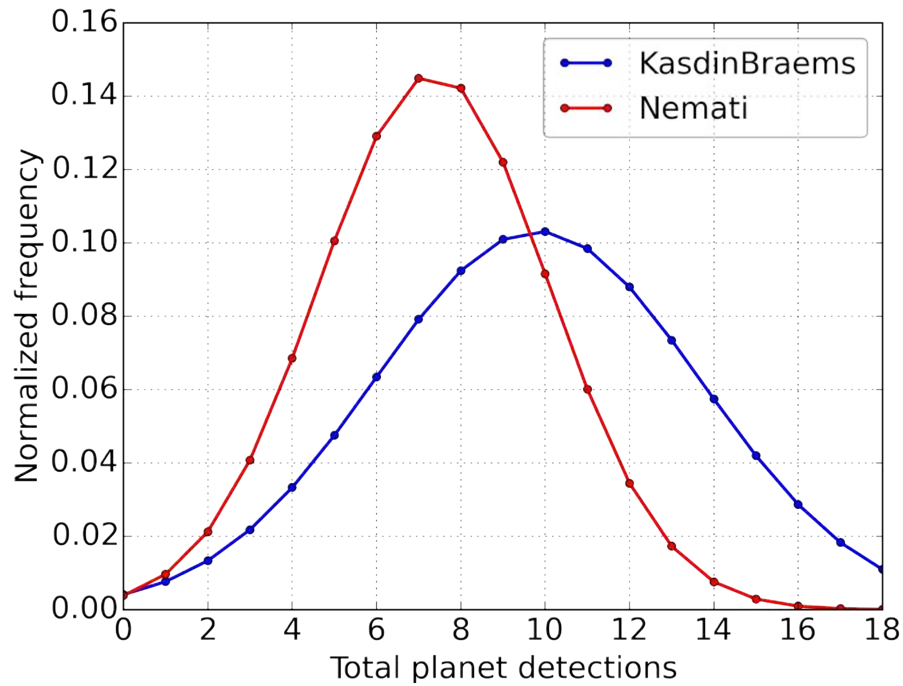
Comparison using EXOSIMS

- method 1, Nemati 2014: setting a **SNR = 5**
- method 2, Kasdin 2006: P_{FA} **= 3E-5** and P_{MD} **= 1E-3**





Null hypothesis H_0: there is no planet.

Alternative hypothesis H_1: there is a planet.

- Fail to reject H_0 while true (True Negative):

  $P(\text{no detection}) = P(Z < z_{FA}) = F_Z(z_{FA}) = 1 - p_{FA}$

- Reject H_0 while true (type I error, False Positive):

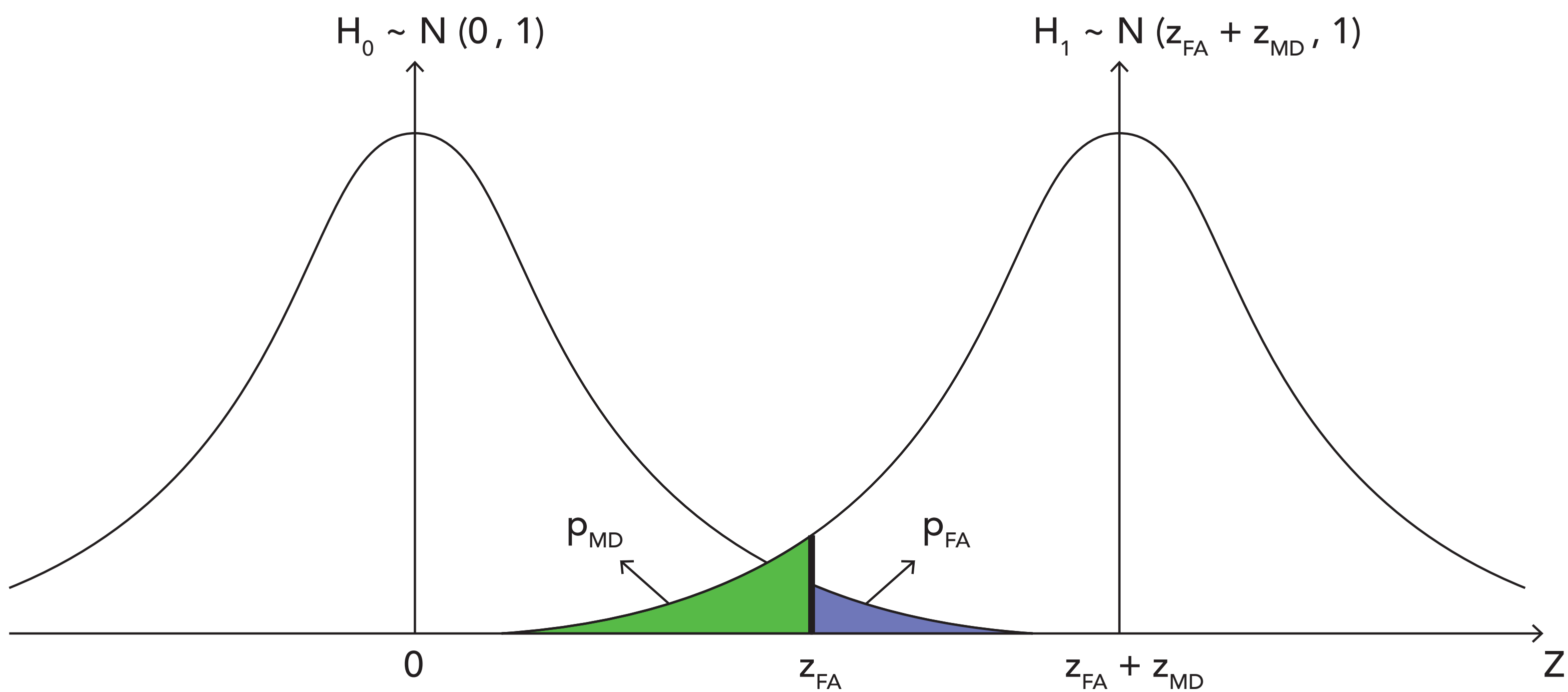
  $P(\text{false alarm}) = p_{FA}$

- Reject H_0 while false (True Positive):

  $P(\text{detection}) = P(Z < z_{MD}) = F_Z(z_{MD}) = 1 - p_{MD}$

- Fail to reject H_0 while false (type II error, False Negative):

  $P(\text{missed detection}) = p_{MD}$

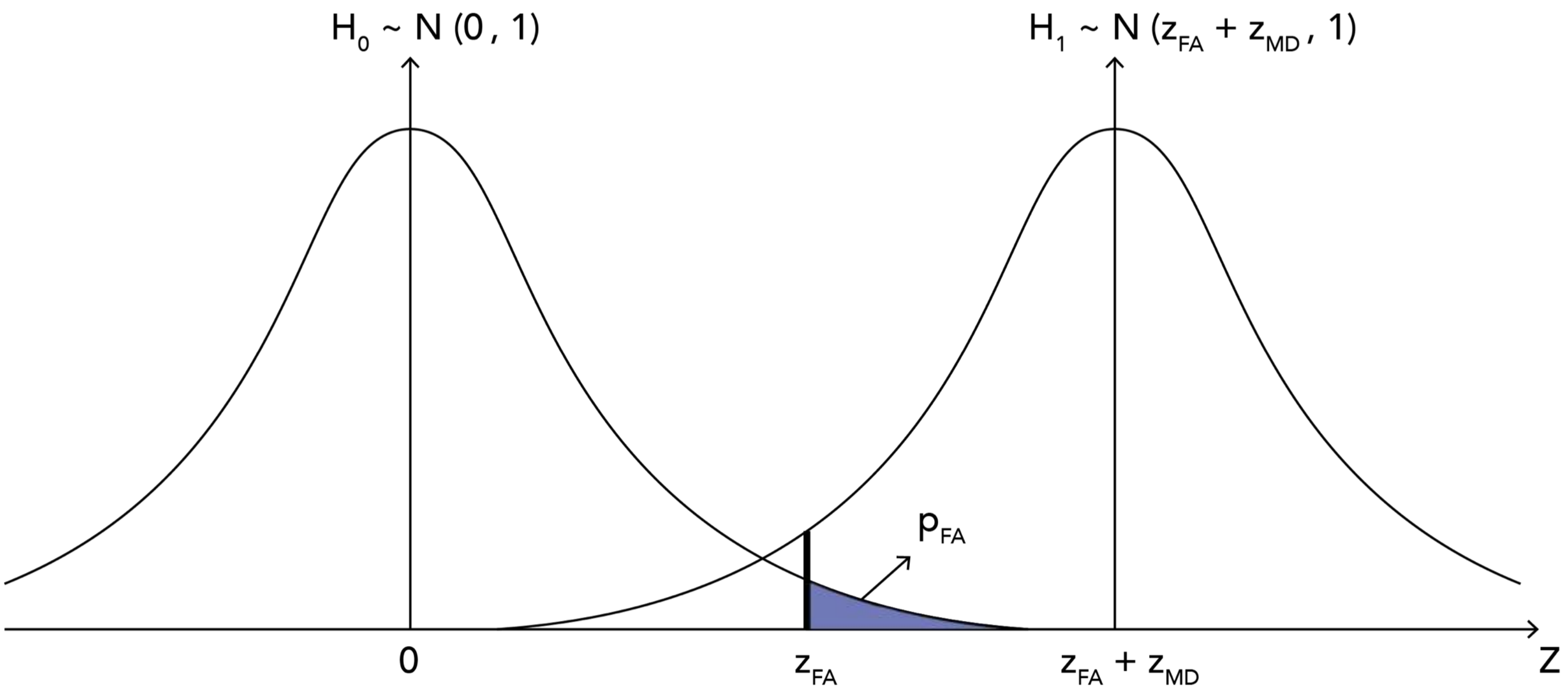


Probabilistic case

Case 1, no calculated SNR.

For the whole system:

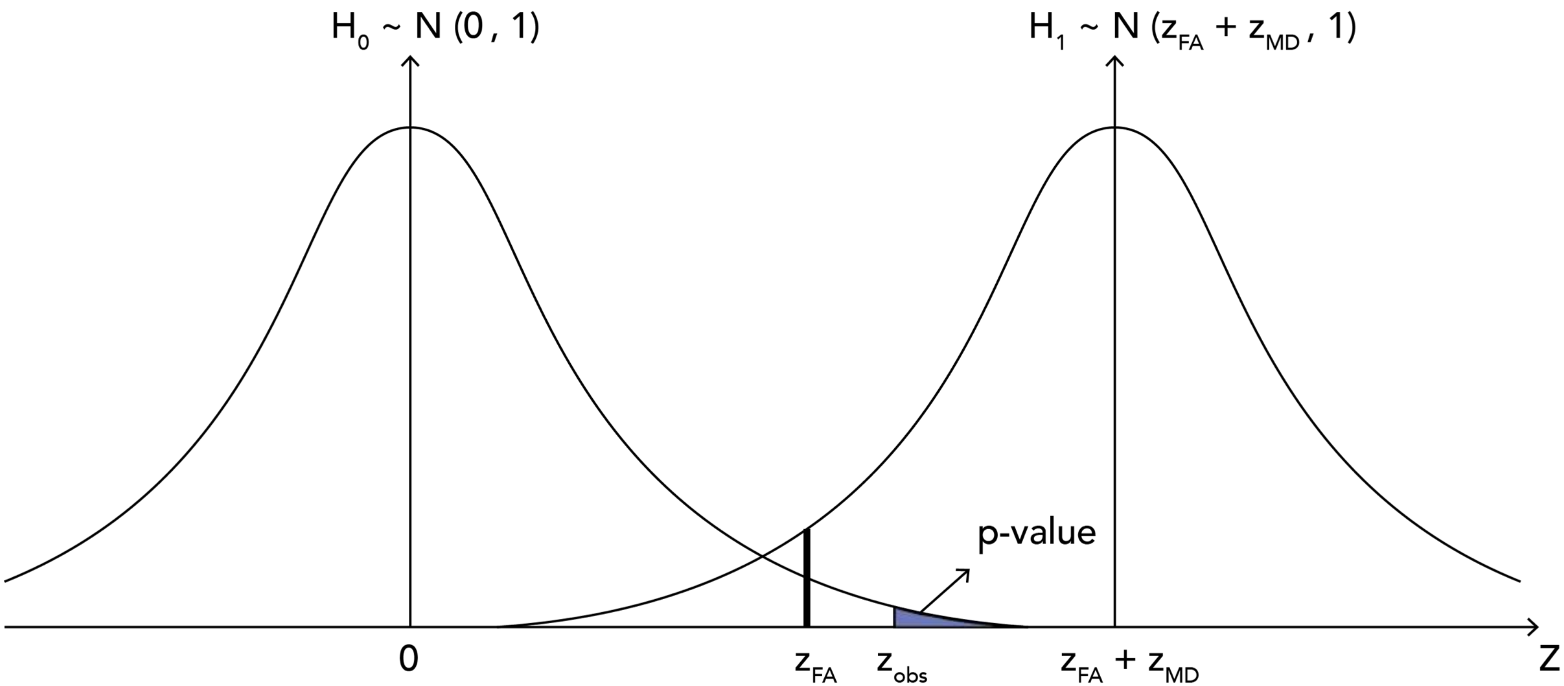
- True Negative: P(no detection) = $F_Z(z_{FA}) = 1 - p_{FA}$
- False Positive: P(false alarm) = p_{FA}



Probabilistic case (cont'd)

Case 2.1, calculated SNR = $z_{obs} > z_{FA}$ --> reject H_0.

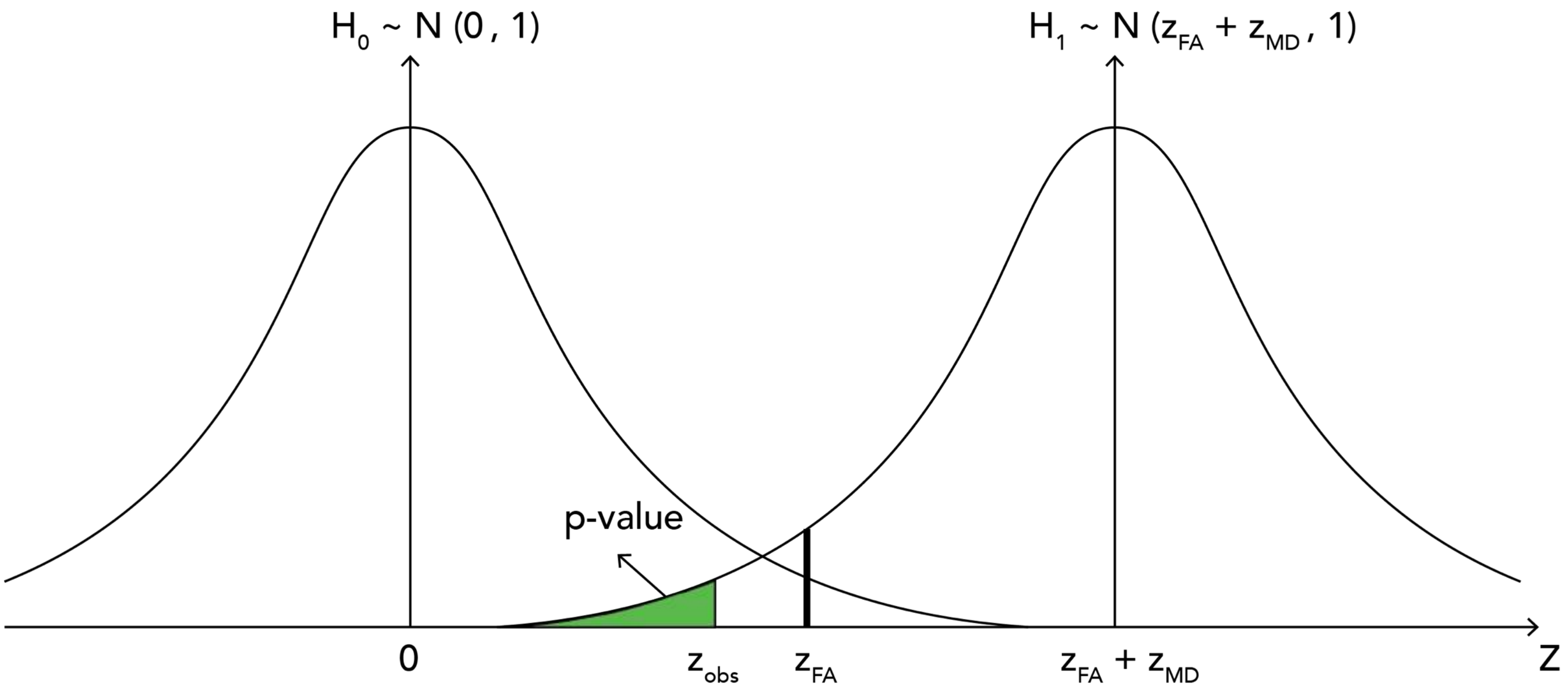
- True Positive: P(detection) = $P(Z < z_{obs}) = F_Z(z_{obs})$
- False Positive: P(false alarm) = $1 - F_Z(z_{obs})$ = p-value



Probabilistic case (cont'd)

Case 2.2, calculated SNR = $z_{obs} < z_{FA}$ --> fail to reject H_0.

- True Negative: P(no detection) = $P(Z < z_{FA} + z_{MD} - z_{obs}) = F_Z(z_{FA} + z_{MD} - z_{obs})$
- False Negative: P(missed detection) = $1 - F_Z(z_{FA} + z_{MD} - z_{obs})$ = p-value



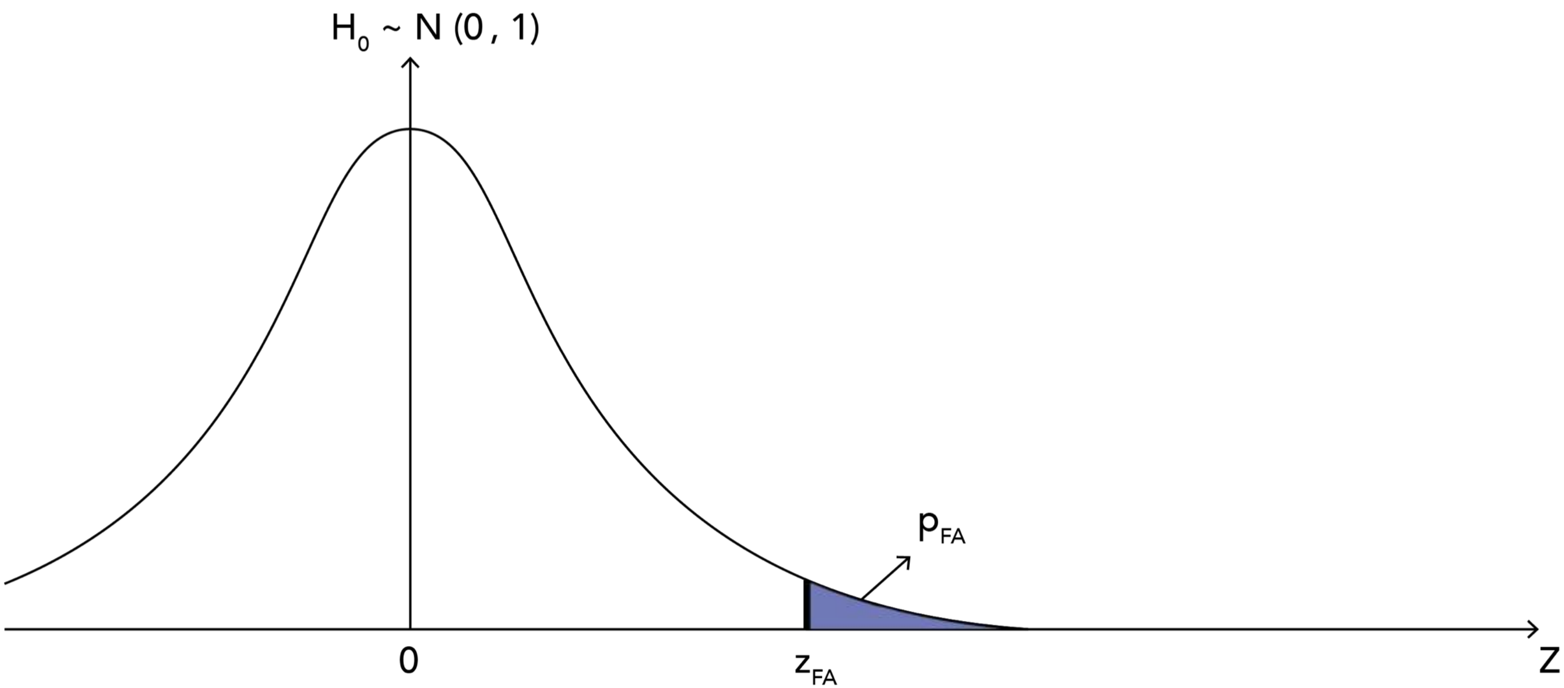
Backup slides

Deterministic case
We ‘know’ if there is a planet or not

Case 1, there is no planet, H_0 is true.

For the whole system:

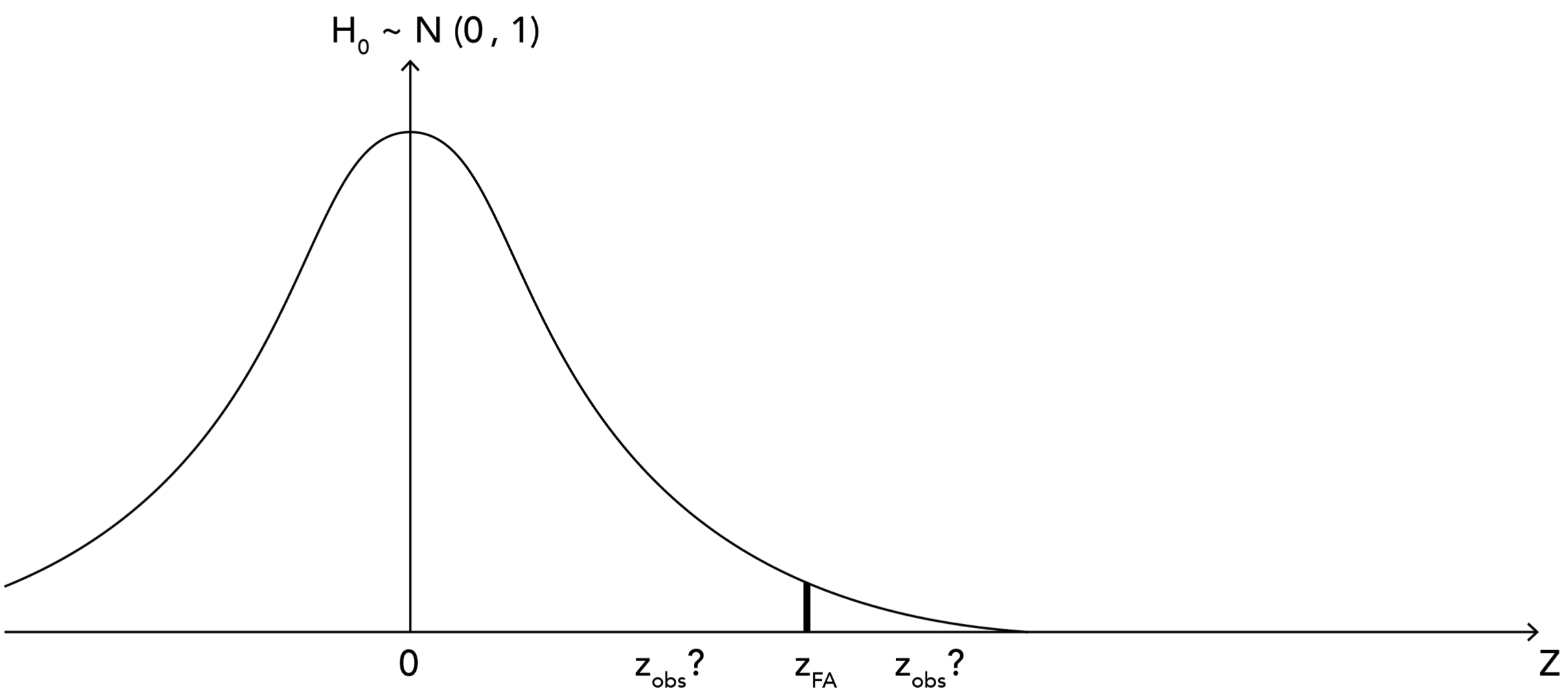
- True Negative: P(no detection) = $F_Z(z_{FA}) = 1 - p_{FA}$
- False Positive: P(false alarm) = p_{FA}



Deterministic case (cont'd)

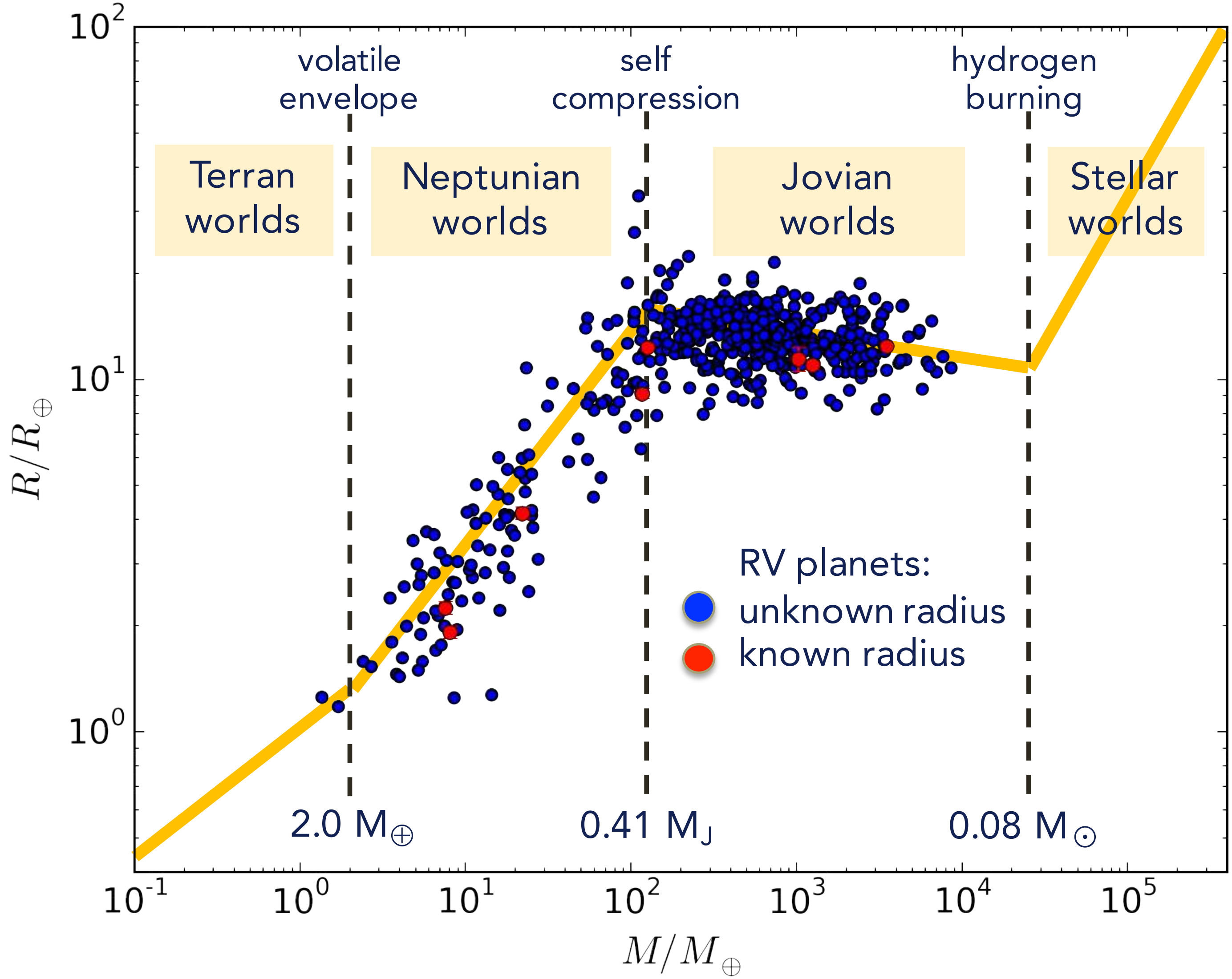
Case 2, there is a planet, H_0 is false.

- if SNR = $z_{obs} > z_{FA}$ --> reject H_0: True Positive (detection)
- if SNR = $z_{obs} < z_{FA}$ --> fail to reject H_0: False Negative (missed detection)



Populate Universe: e.g. known RV planets

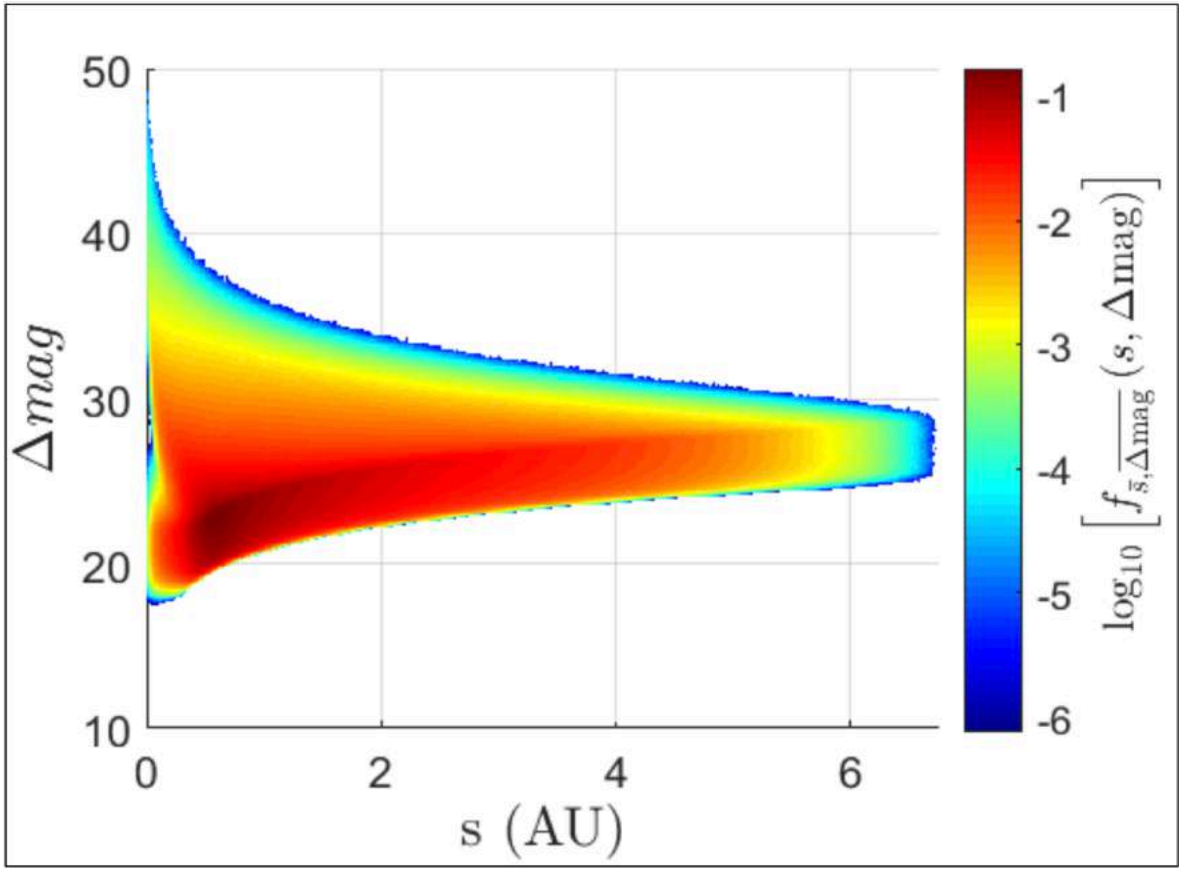
M-R relation from FORECASTER (Chen and Kippling 2016)
available at github.com/chenjj2/forecaster



Example of joint probability density function

Garrett et al. 2016

- PDF of planet orbital and physical properties
- Completeness = CDF (cf. Brown 2005)
- Probability to detect a planet
- Updates completeness values for systems previously observed

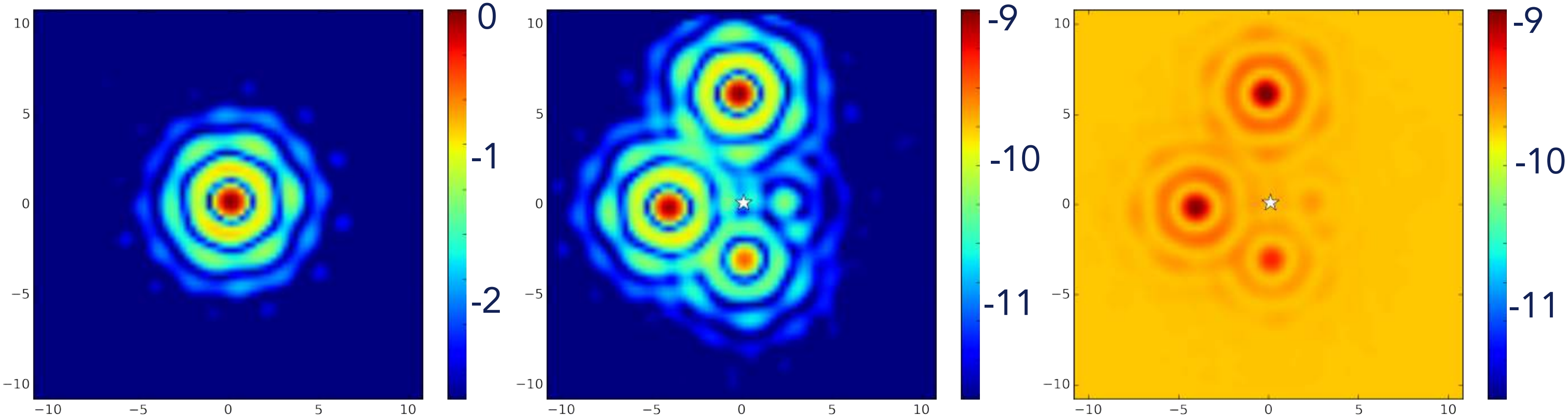


Planet integration time – noise budget (cont'd)

normalized
star PSF

planets
(star cancelled)

+ local zodi
+ exozodi



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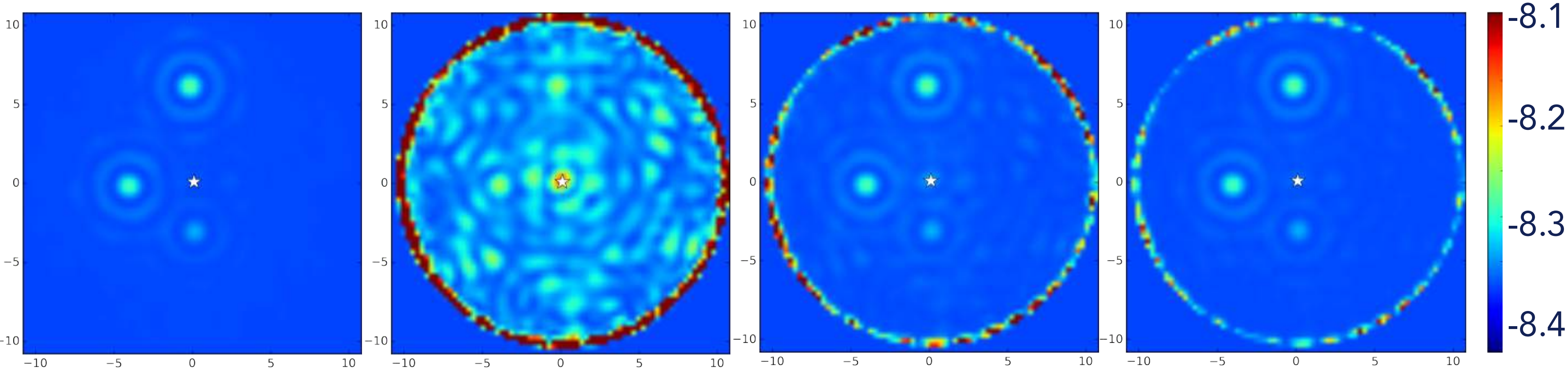
Planet integration time – noise budget (cont'd)

+ detector noise

+ residual speckles

post-processing 10x gain

post-processing 30x gain



e.g. WFIRST contrast/throughput curve