Multi-Mission Modeling for Space-Based Exoplanet Imagers

[10400-54]

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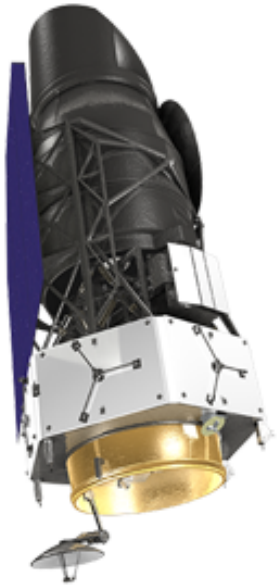
Motivation

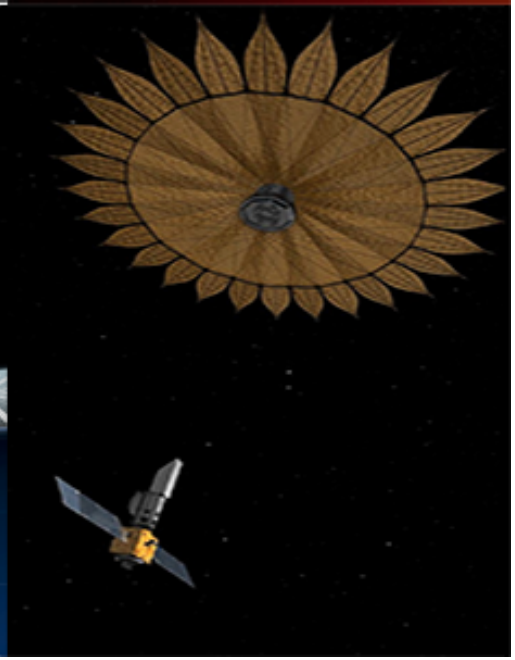



ORIGINS
Space Telescope
Seeing Beyond the Light
Following the rise of dust and metals in galaxies and the path of water across cosmic time to Earth and other habitable planets
Tracing the Signatures of Life and the Ingredients of Habitable Worlds
Unveiling the Growth of Black Holes and Galaxies over Cosmic Time
Charting the Rise of Metals, Dust, and the First Galaxies
Characterizing Small Bodies in the Solar System
The Origins Space Telescope is the mission concept for the Far Infrared Surveyor developed through a community-led study sponsored by NASA in preparation for the 2020 Astronomy and Astrophysics Decadal Survey.


Exo-C
IMAGING NEARBY WORLDS
EXOPLANET DIRECT IMAGING:
CORONAGRAPH PROBE
MISSION STUDY "Exo-C"
FINAL REPORT, MARCH 2015


LUVOIR
Large Ultraviolet / Optical / Infrared Surveyor
LUVOIR is a concept for a highly capable, multi-wavelength observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of astrophysics, from the epoch of reionization, through galaxy formation and evolution, to star and planet formation. Powerful remote sensing observations of Solar System bodies will also be possible. LUVOIR will study a wide range of exoplanets in depth, including those that might be habitable – or even inhabited.
Hubble
LUVOIR


Exo-S
Starshade Probe-Class
Exoplanet Direct Imaging Mission Concept
FINAL REPORT MARCH 2015
CL #15-1155

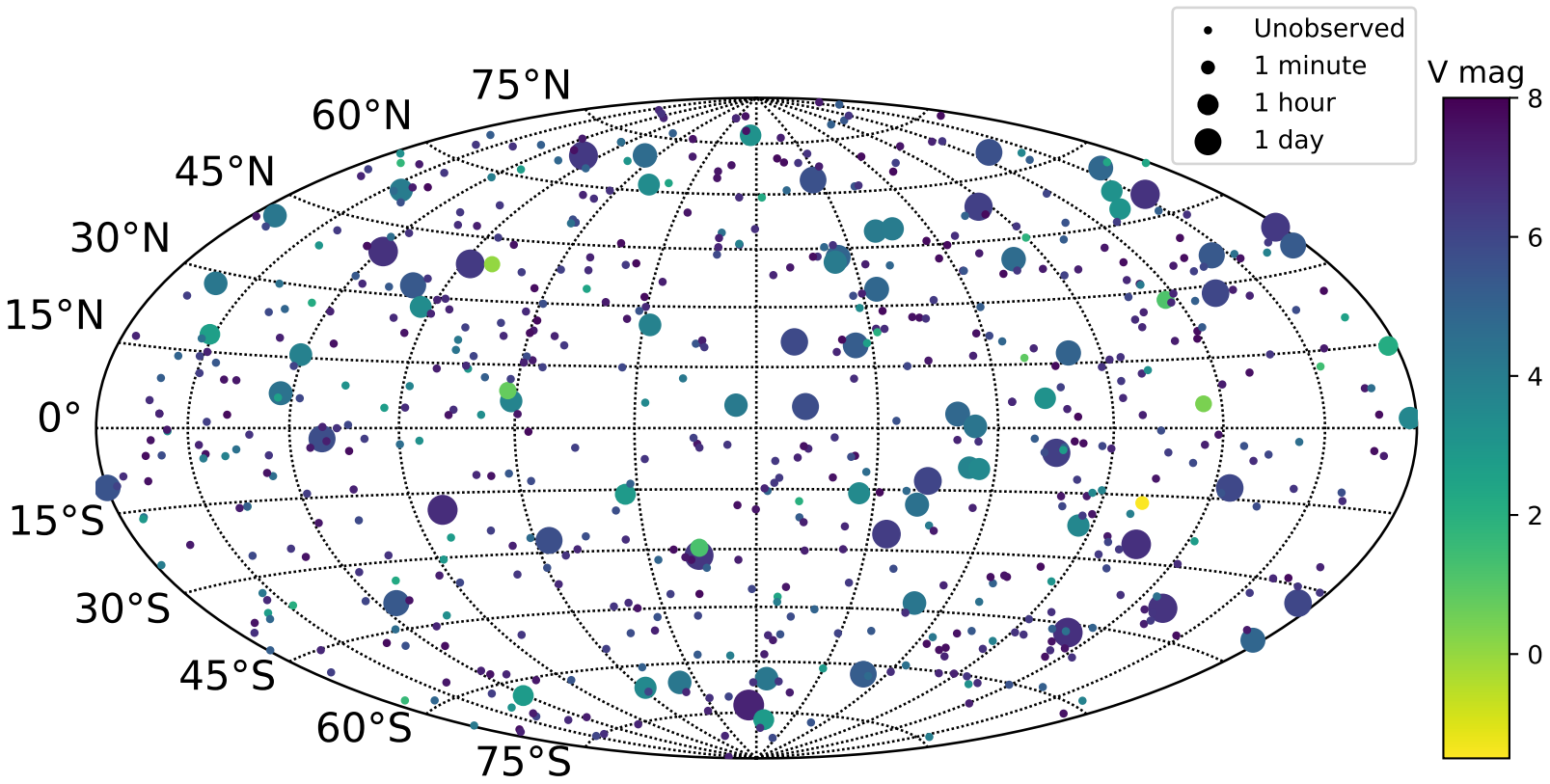


Questions

What do we want to say about all these missions?

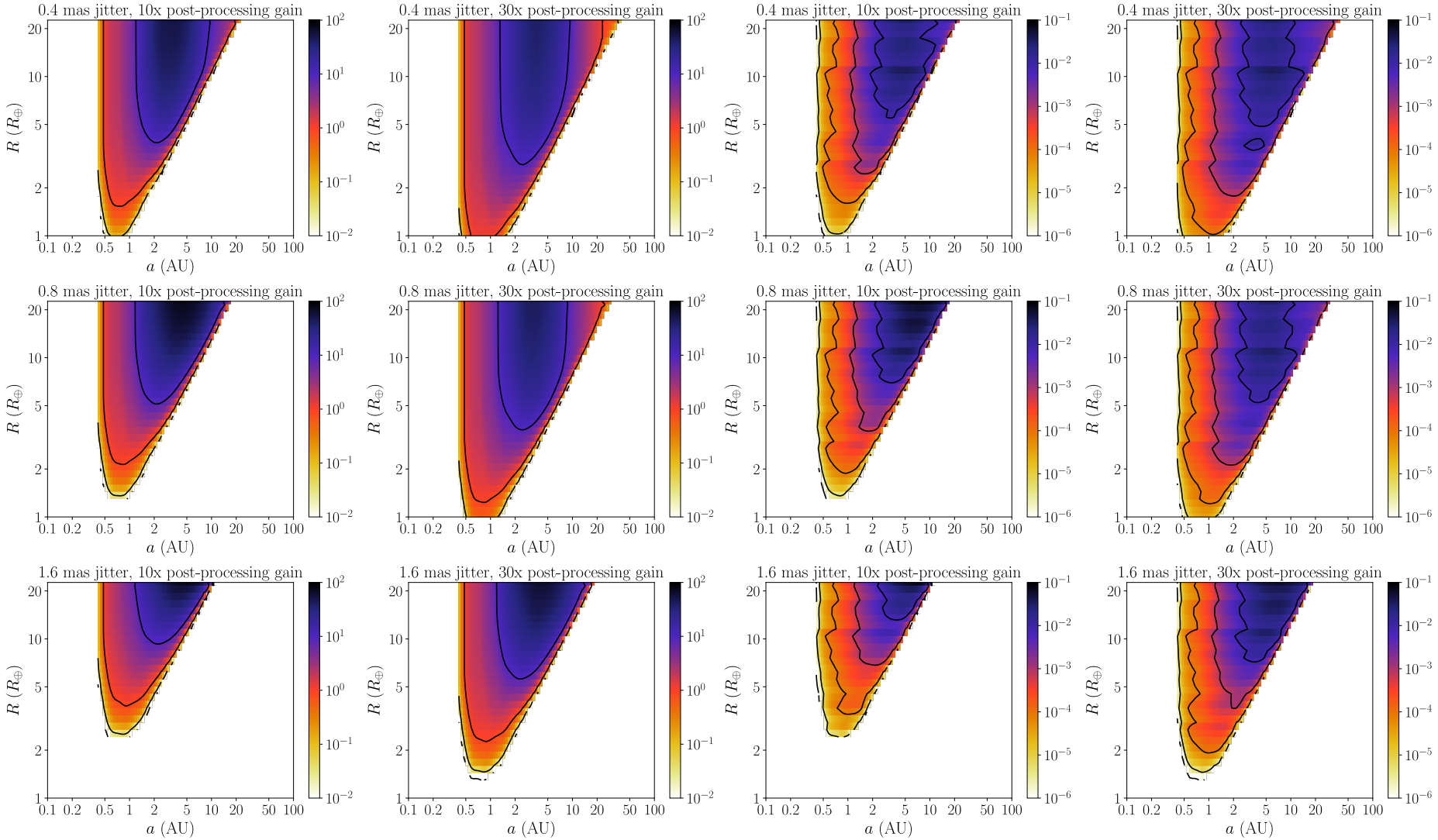
What tools do we have on hand to say it?

Approach 1: Full Mission Simulations



See: Savransky and Garrett (2015), Delacroix et al. (2016)
EXOSIMS: `https://github.com/dsavransky/EXOSIMS`;
`http://ascl.net/1706.010`

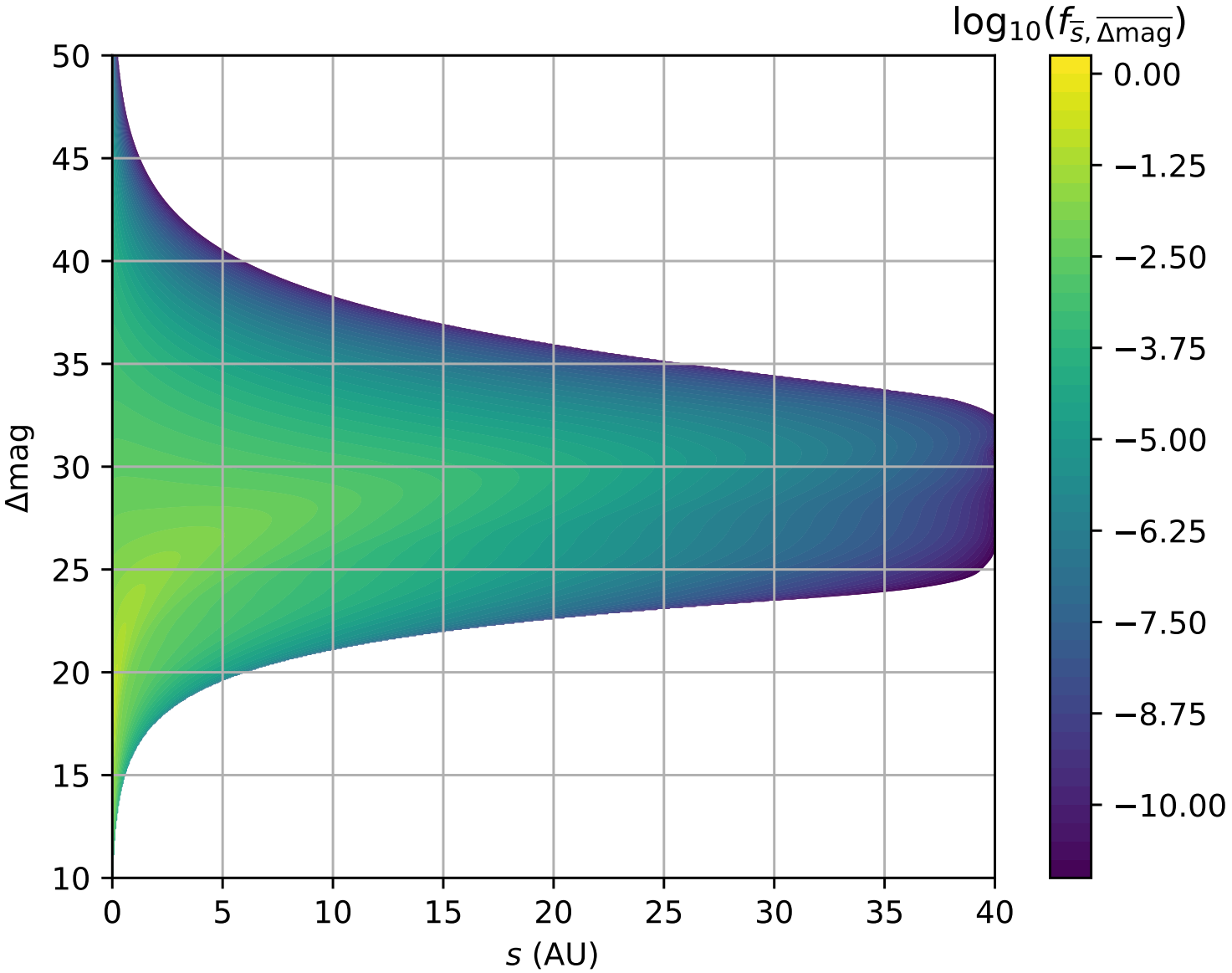
Approach 2: Depth of Search



See: Lunine et al. (2008), Garrett et al. (2017)

DoS: `https://github.com/dgarrett622/DoS`

Completeness



See: Brown (2005), Garrett and Savransky (2016)

Summed Completeness Maximization

$$\arg\min_{\{t_i\}} \left(-\sum_i^n c_i(t_i) \right)$$

subject to:

$$t_{\max} - \sum_i^n t_i - \left(\sum_i^n t_i^{\text{over}}(t_i > 0) \right) \geq 0$$

such that:

$$0 \leq t_i \leq t_{\max} \qquad \forall i\,.$$

See: Hunyadi et al. (2007a,b); Stark et al. (2014)

Tiny Bit of Math

$$c = \int_{\Delta\mathrm{mag}_{\mathrm{min}}(s_{\mathrm{min}})}^{\Delta\mathrm{mag}_u} \int_{s_{\mathrm{min}}}^{s_u(\Delta\mathrm{mag})} f_{\bar{s},\overline{\Delta\mathrm{mag}}}\left(s, \Delta\mathrm{mag}\right)\, \mathrm{d}s\, \mathrm{d}\Delta\mathrm{mag}.$$

(See Garrett and Savransky (2016))

$$\Delta\mathrm{mag}\left(t\right) = -m - 2.5\log_{10}\left(\frac{\mathrm{SNR}}{\mathcal{F}_0 T}\sqrt{\frac{C_b}{t} + C_{sp}^2}\right)$$

(See Nemati (2014) and Nemati (this conference))

$$\frac{\mathrm{d}\Delta\mathrm{mag}}{\mathrm{d}t} = \frac{5C_b}{4\ln(10)}\frac{1}{C_b t + \left(C_{sp} t\right)^2}$$

$$\left.\frac{\mathrm{d}c}{\mathrm{d}t}\right|_{t_{\mathrm{int}}} = \left[\int_{s_{\mathrm{min}}}^{s_u(\Delta\mathrm{mag}(t_{\mathrm{int}}))} f_{\bar{s},\overline{\Delta\mathrm{mag}}}\left(s, \Delta\mathrm{mag}\left(t_{\mathrm{int}}\right)\right)\, \mathrm{d}s\right] \left.\frac{\mathrm{d}\Delta\mathrm{mag}}{\mathrm{d}t}\right|_{t_{\mathrm{int}}}$$

Where to Begin?

This is an unfriendly constraint:

$$t_{\min} - \sum_{i}^{n} t_i - \left(\sum_{i}^{n} t_i^{\text{over}}(t_i > 0) \right) \geq 0$$

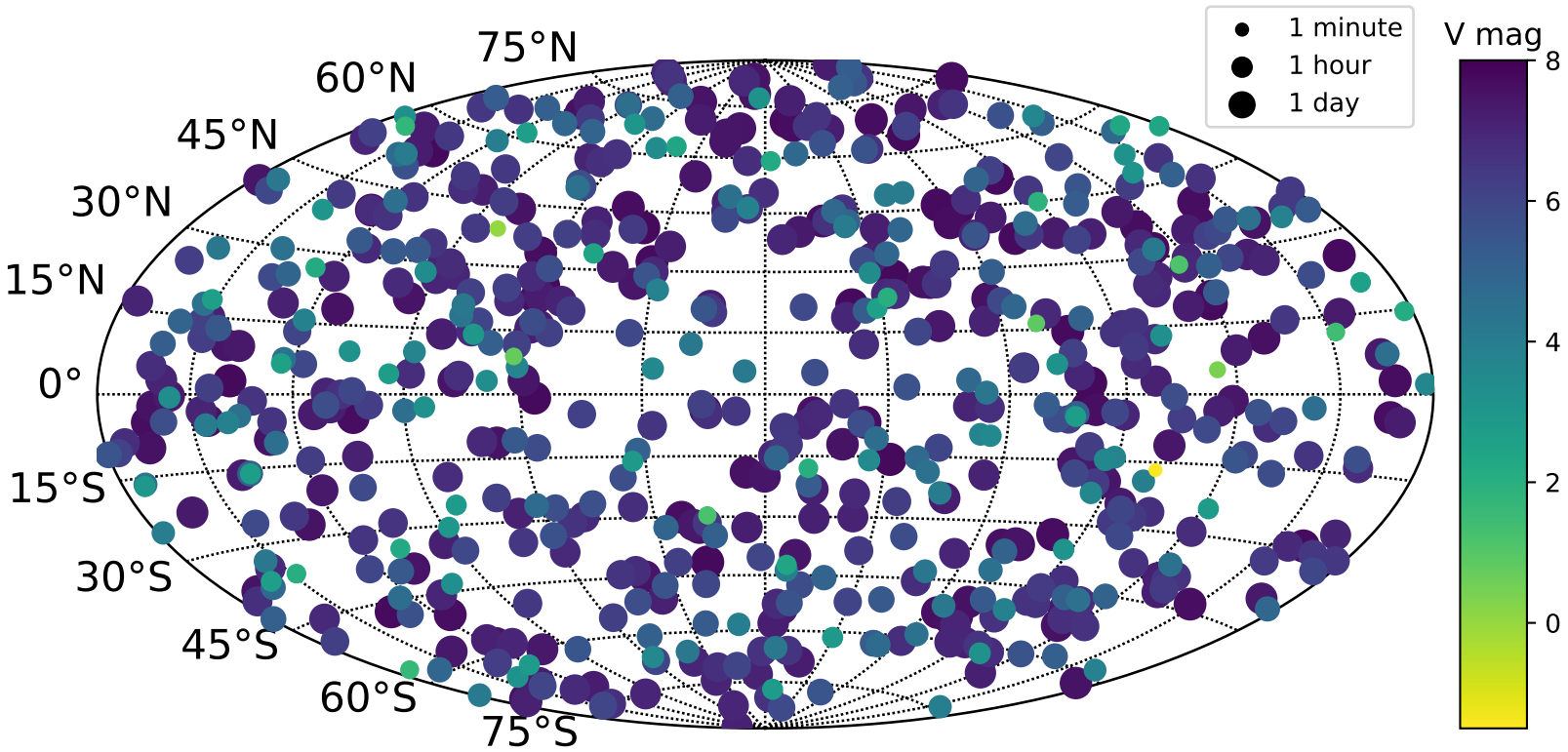
Consider instead:

$$\left.\begin{array}{c} \arg\min_{T} \left(-\sum_{i \in T} c_i \right) \\ \text{subject to:} \\ \sum_{i \in T} (t_i + t_i^{\text{over}}) \leq t_{\max} \end{array}\right\} \begin{array}{c} \arg\min_{\mathbf{x}} \left(-\mathbf{c}^T \mathbf{x} \right) \qquad \mathbf{c}, \mathbf{t} \in \mathbb{R}^N \\ (\mathbf{t} + \mathbf{t}^{\text{over}})^T \mathbf{x} < t_{\max} \\ \mathbf{x} \in \mathbb{Z}^N \\ \mathbf{0} \leq \mathbf{x} \leq \mathbf{1} \\ T = \{ i : x_i = 1, \forall x_i \in \mathbf{x} \} \end{array}$$

Alphabet Soup

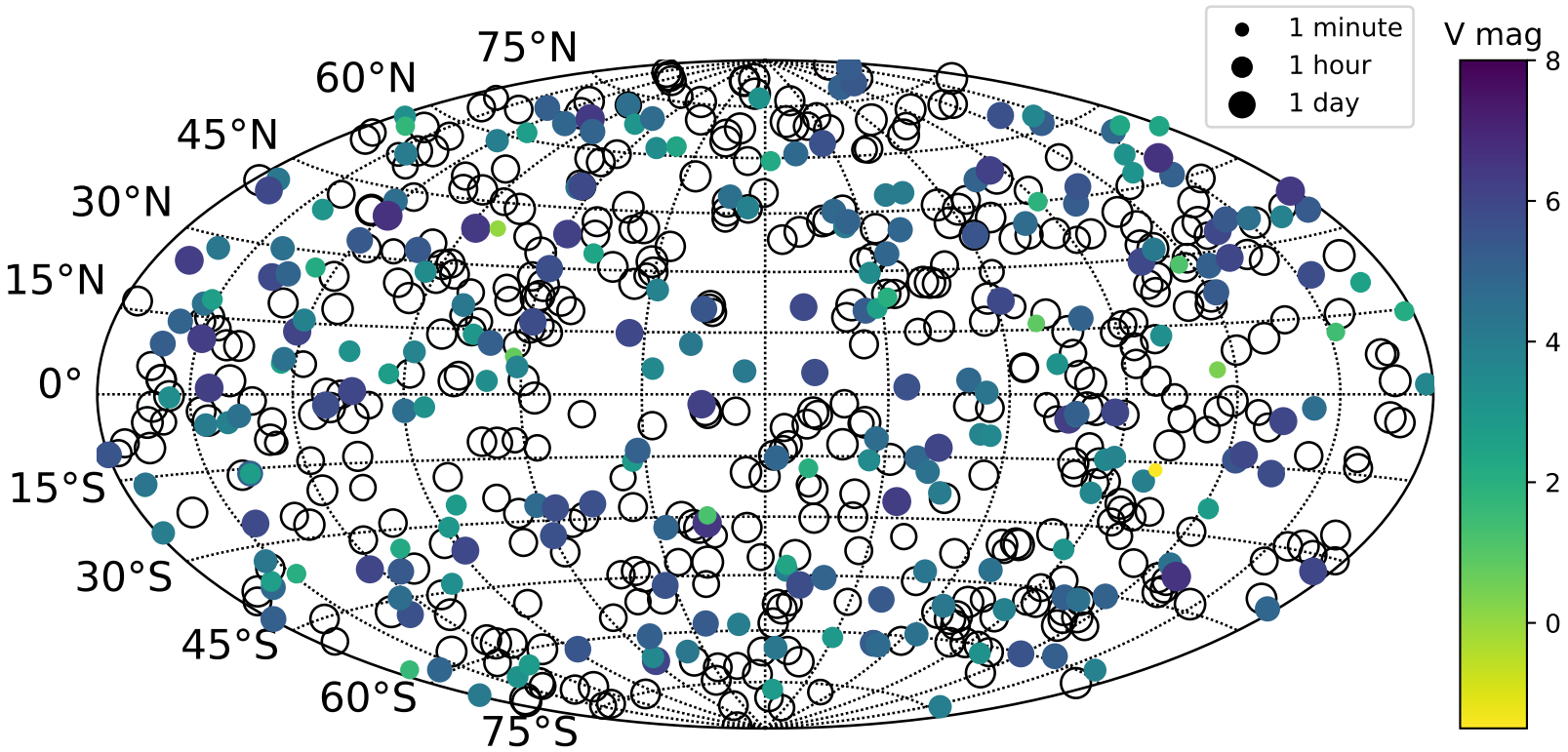
- The original problem is a nonlinear optimization. We would like to solve it using Sequential Least-Squares Quadratic Programming (SLSQP [Kraft, 1994])
  - This is hard and computationally expensive if you don't start near a local extremum
- The fixed integration time problem is a Binary Integer Linear Programming Problem (BILPP [Williams, 2009])
  - Actually NP-complete, but computationally cheap for reasonably sized target lists using branch and cut

Where to Begin (again)?



Option 1: Use an integration time for an assumed limiting planet Δmag

Where to Begin (again)?



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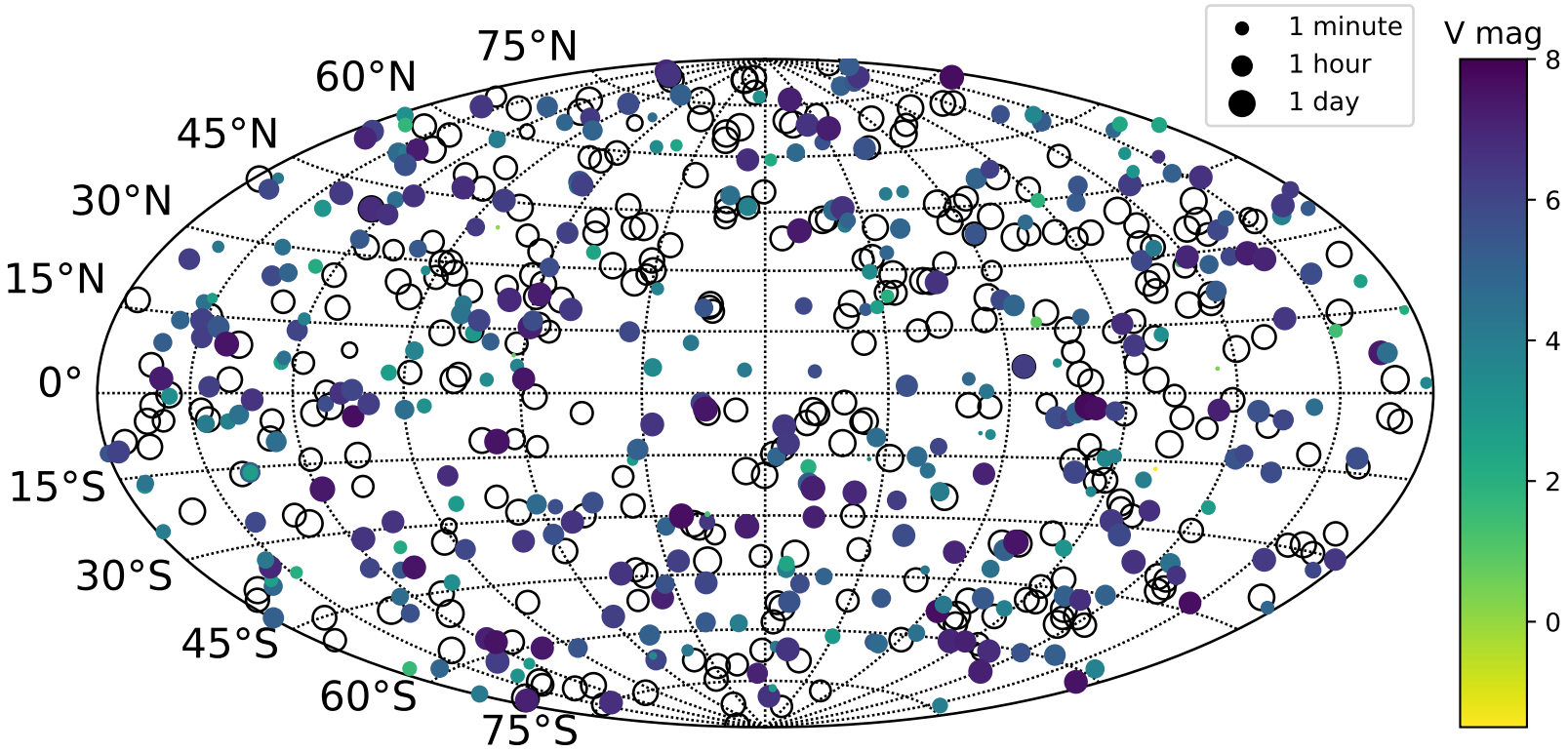
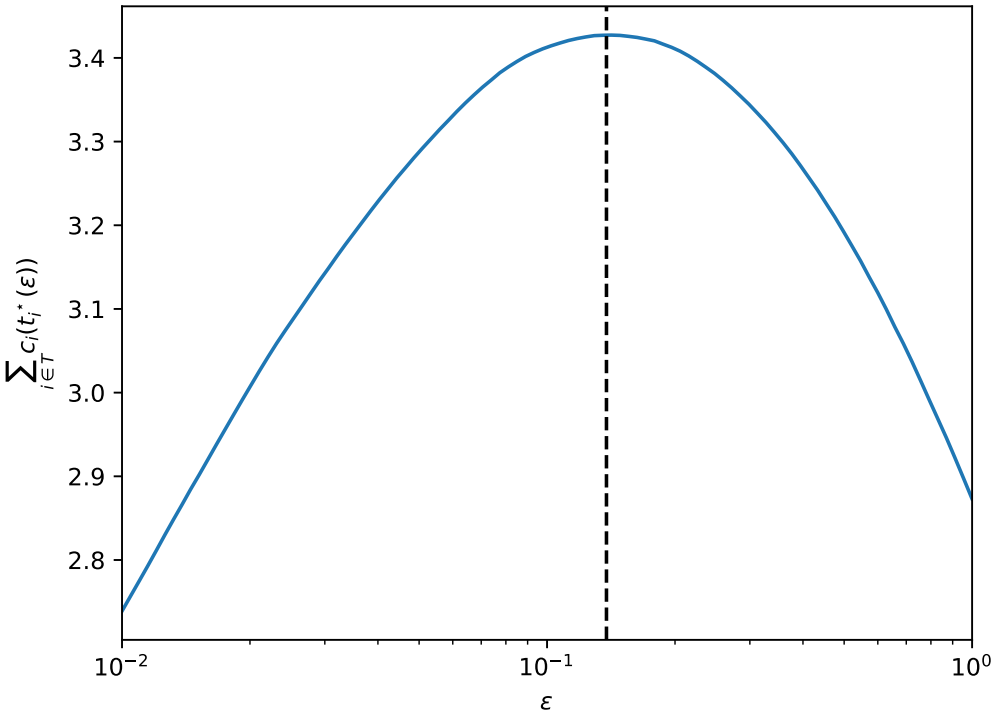


Option 2: Use an integration time to maximize c/t

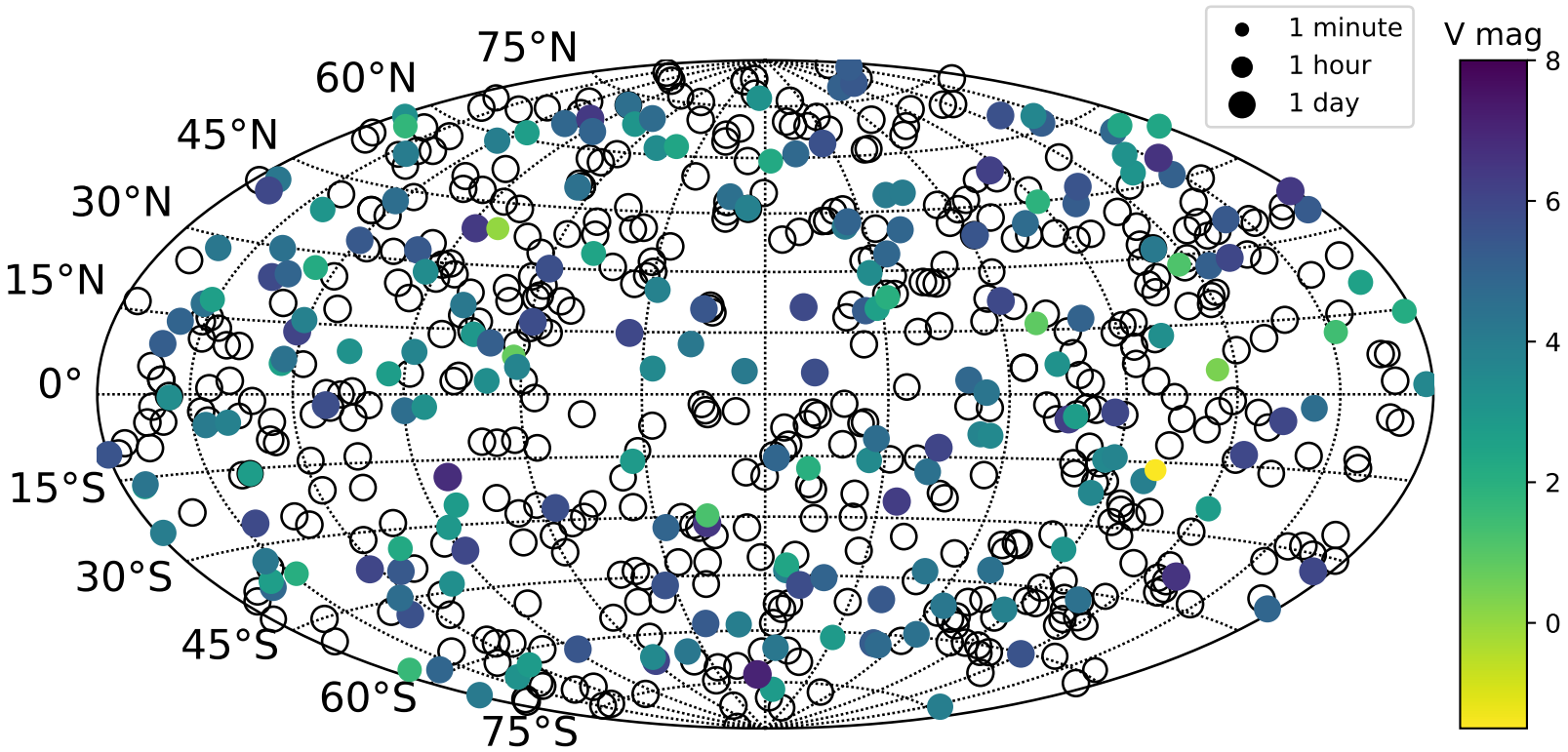
Option 3

$$\left.\frac{\mathrm{d}\Delta\mathrm{mag}}{\mathrm{d}t}\right|_{t^\star} \leq \varepsilon$$

$$t^\star = \frac{1}{2C_{sp}^2\varepsilon\sqrt{\log(10)}} \times \left(-C_b\varepsilon\sqrt{\log(10)} + \sqrt{C_b\varepsilon\left(C_b\varepsilon\log(10) + 5C_{sp}^2\right)}\right)$$

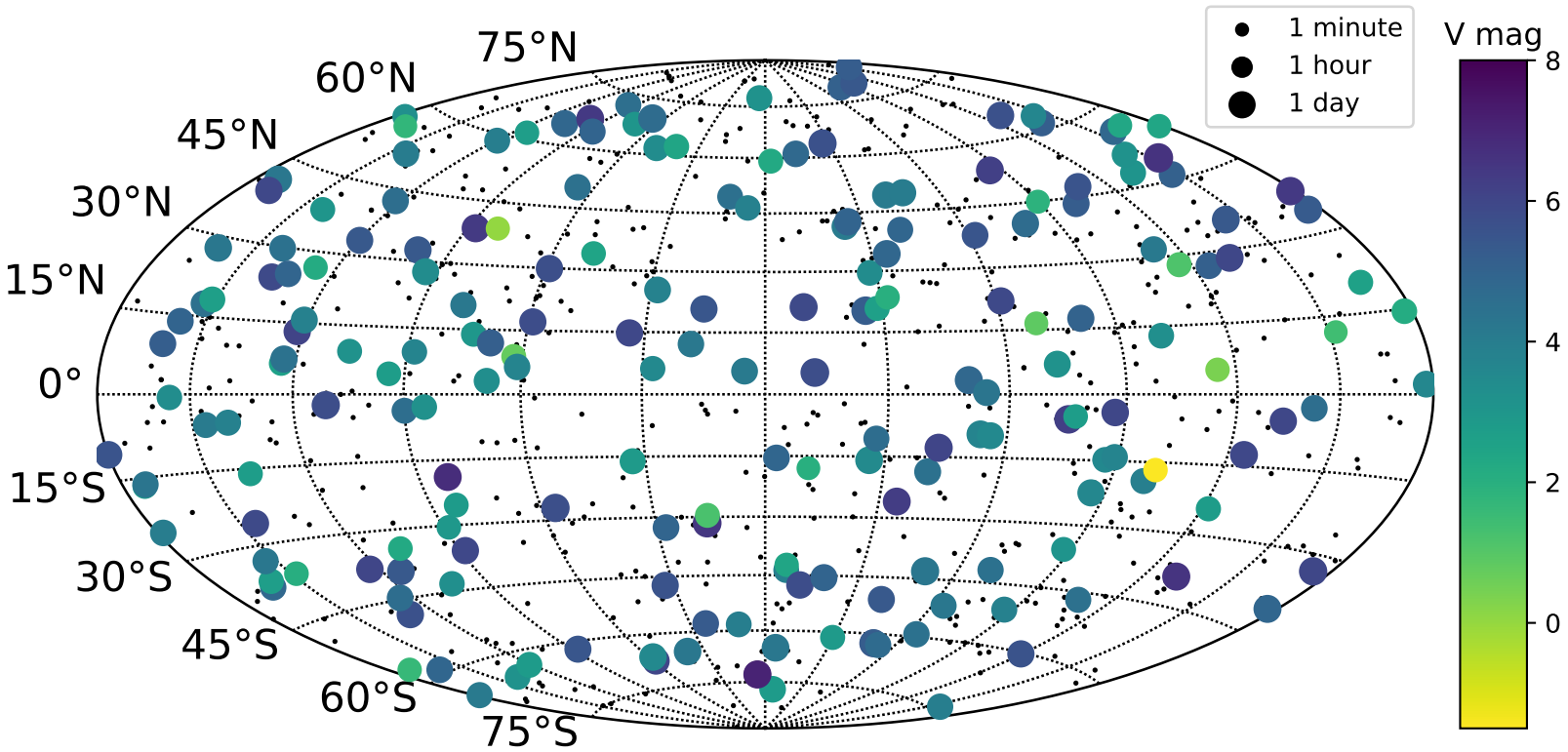


Option 3



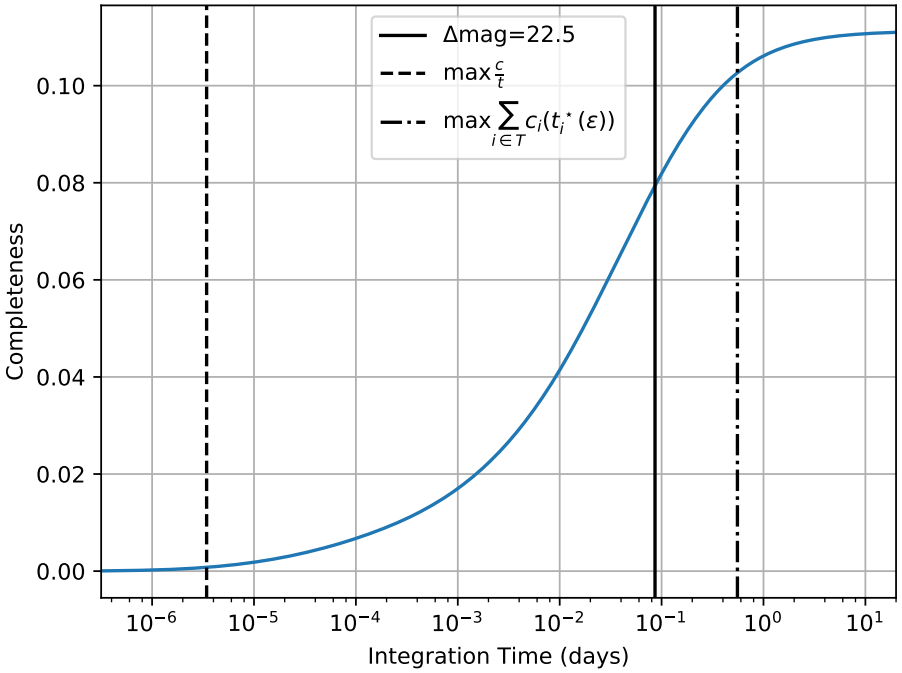
Option 3: BILPP step

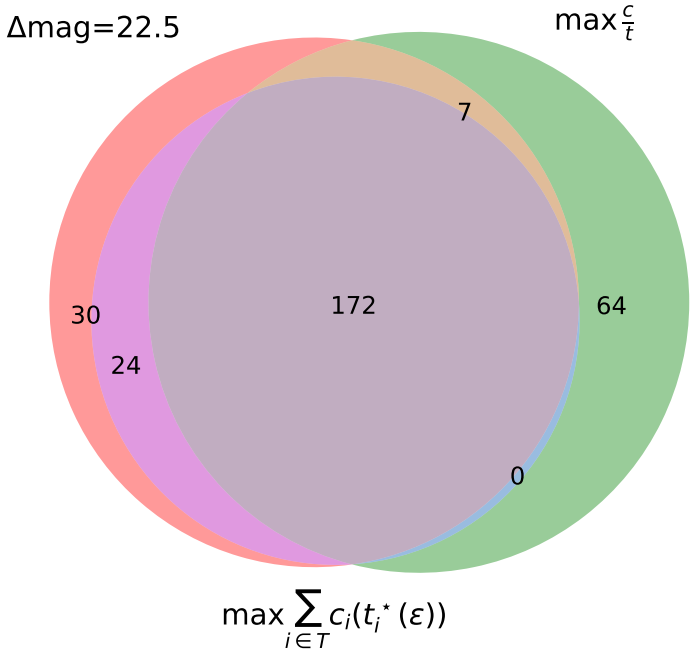
Option 3



Option 3: SLSQP step

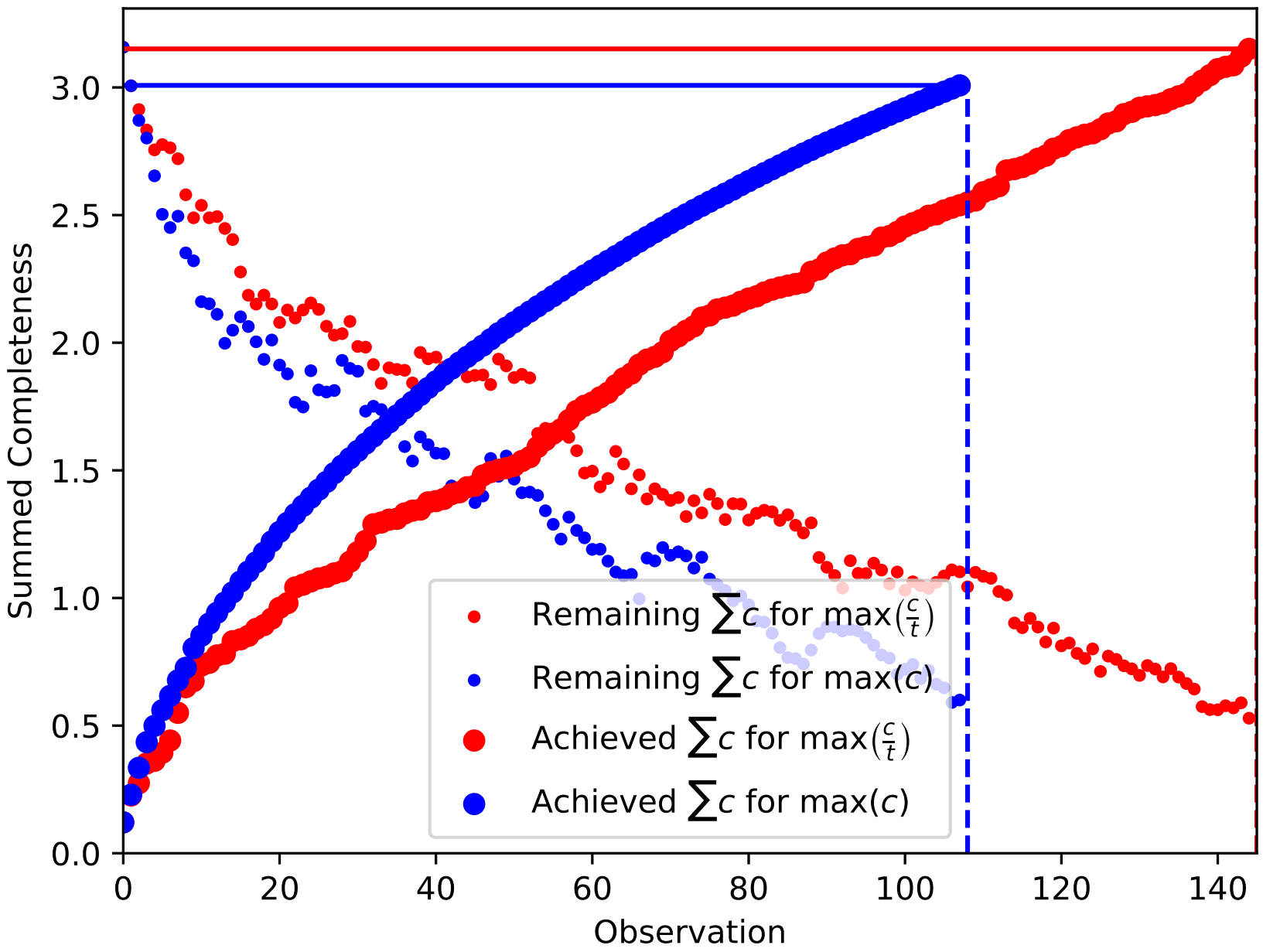
Optimization Summary



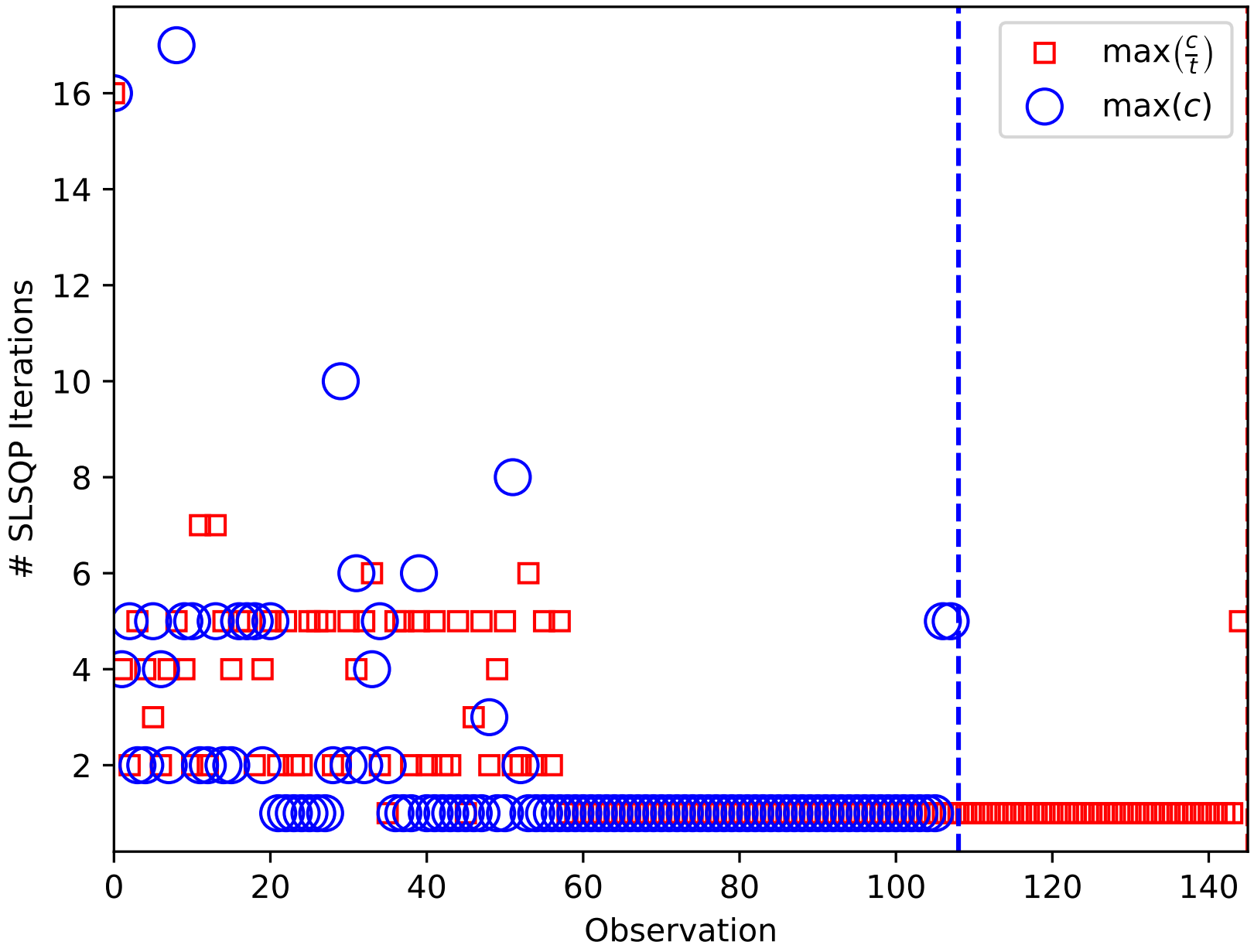


Case	BILPP # Stars	BILPP $\sum c_i$	SLSQP It	SLSQP FC	SLSQP # Stars	SLSQP $\sum c_i$
Δmag=22.5	232	2.77	52	67	232	3.43
$\arg\max_t \frac{c}{t}$	345	0.26	97	305	193	3.45
$t^\star\left(\arg\max_\varepsilon \sum c_i\right)$	196	3.42	28	30	196	3.47

Completeness Maximization in Survey Simulations



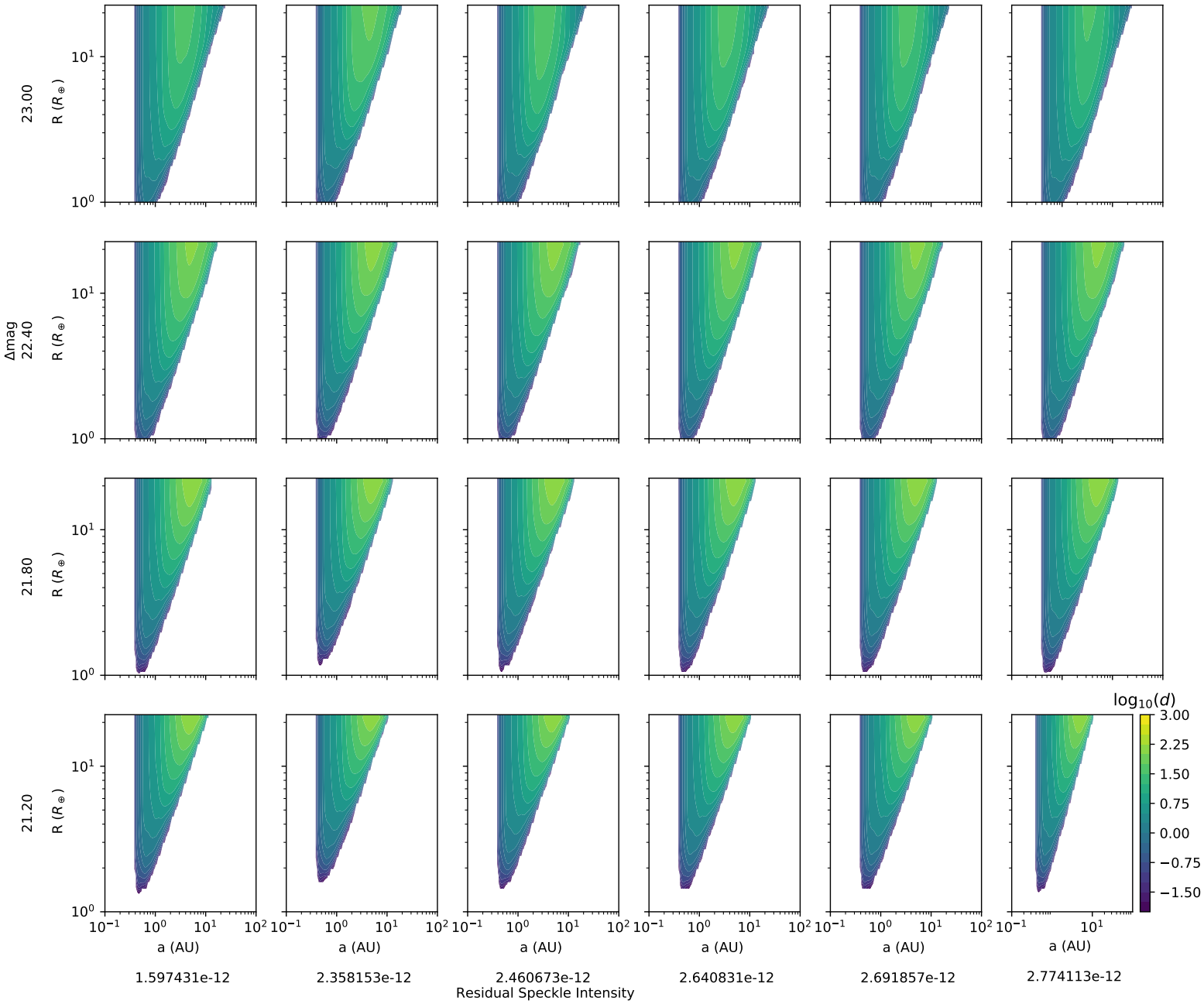
Turns Out to be Quite Feasible



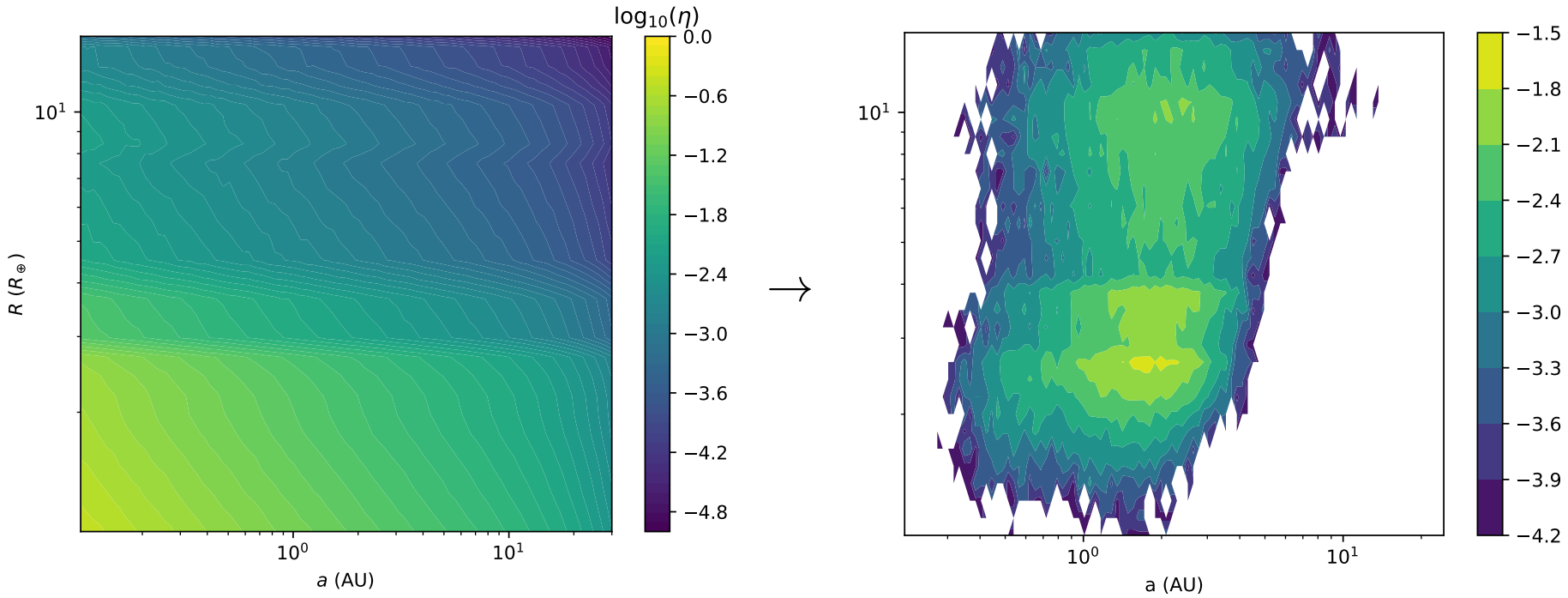
So, What Can We Say?

- Summed completeness gives you a number for how many planets from a given population you should expect to discover
- Mission simulations give you the distribution of this value (and many others)
- Depth of search tells you what kinds of planets your instrument is sensitive to

Phase Space Exploration



We have the tools to evaluate how a mission interacts with the population of exoplanets



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