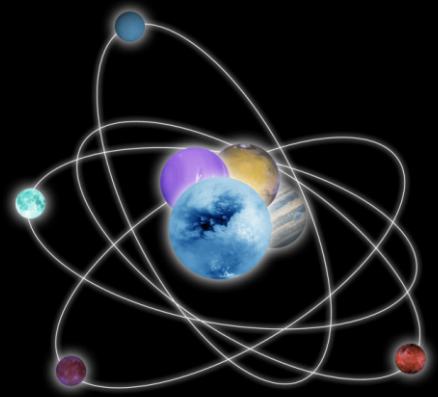
Exoplanet Characterisation Observatory



EChO Long Term Mission Planning Tool

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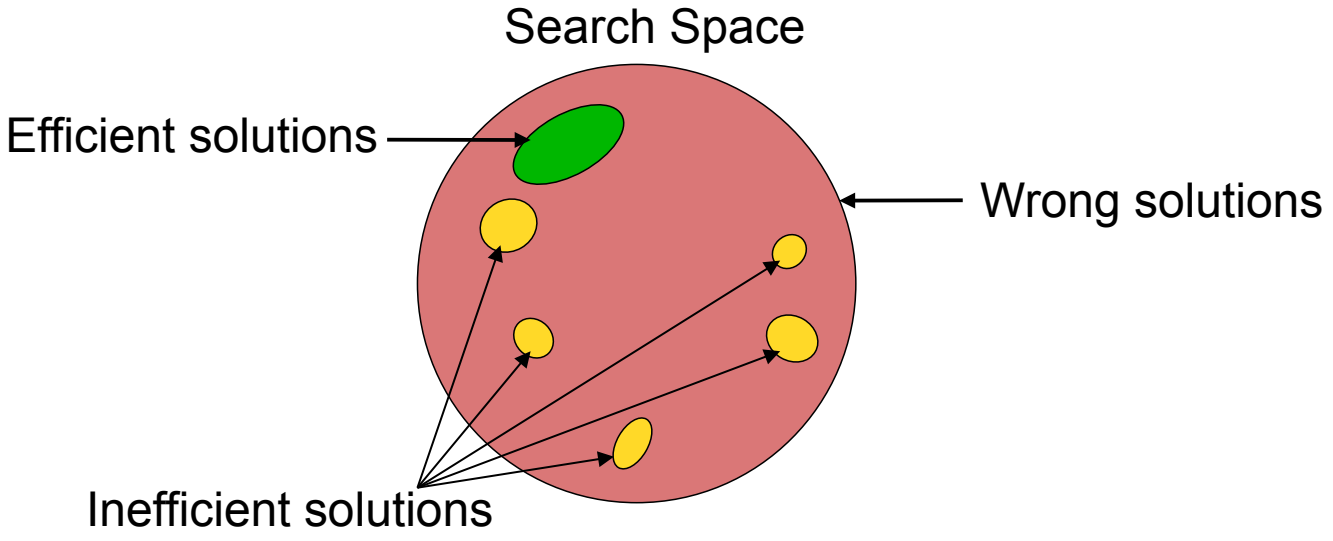
Introduction

- EChO will need a serious long-term planning exercise to make the most of the available time
- Important to size the mission (planning efficiency, slew time) and assess its scientific return
- Collection of time-critical events ⇨ Five years of EChO:
  - 238 targets
  - 25 events per target (average value)
  - Each target can be observed in 550 different windows (average)
  - Number of combinations: $(238 \cdot 25)^{550} \sim 10^{2100}$
- Combinations can be:
  - Wrong (with conflicts) → most of them
  - Inefficient → some of them
  - Efficient → very few of them
- We propose to solve this optimization problem with an Artificial Intelligence technique ⇨ Long Term Mission Planning Tool

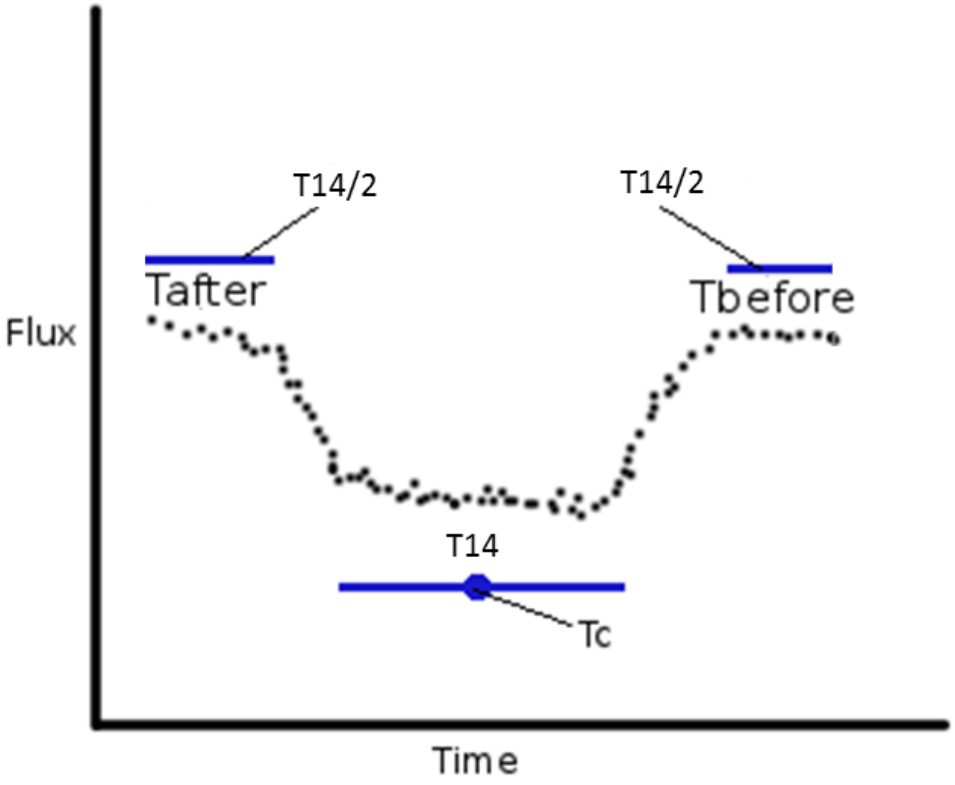
What Is a Genetic Algorithm?

- It is a paradigm that generates solutions to optimization problems by simulating natural evolution: selection, crossover and mutation
- This paradigm makes it possible to explore the search space, which is a vast area with a large amount of potential solutions, including the most efficient ones
- What is an "efficient solution"?
  - A solution that highly optimizes the objectives defined in the problem



Event definition

- Light observed in transit (primary eclipse) and occultation (secondary eclipse)
- Exact occurrence can be calculated in advance (Tc)
  - Total observ. time: 2·T14 = T14 + Tb
  - Tb = Tbefore + Tafter
  - Tbefore = T14/2
  - Tafter = T14/2



LT-MPT Design

- Process:
  - **Step 0.** Calculate the time windows of each target event
  - **Step 1.** Clean up impossible targets
  - **Step 2.** Insert downlinks and station keepings minimizing potential conflicts with priority targets (Genetic Algorithm)
  - **Step 3.** Obtain observation planning avoiding overlaps and optimizing some specific objectives (Genetic Algorithm)
  - **Step 4.** Remove observations of incomplete targets (targets observed less than an 80% of their required number of events)
  - **Step 5.** Fill gaps with new observations

Mock EChO Sample: MRS realizations

- Starting from the MRS, an algorithm calculates realizations by randomizing several parameters:
  - Defined range of periods for each planet class (w/ overlap) and generated random values flat in log P
  - Uniform distribution in RA and dec
  - Random origin of ephemeris
  - No change in M and R (both star and planet)
  - Homogeneous distribution in K from K=3 to K_{mean}+0.2
  - Scaled duration and planet temperature from period
  - Scaled number of events from scaled period and K magnitude
  - Scaled distance from K magnitude

10x

Typ	Ms	Teff	Rs	dist	Ks	Tpl	P	T0	Rpl	Mpl	T14	#ev	RA	Dec
HSE M2	0.37	3580	0.37	27.09	8.53	966	0.71207	2456000.6	7	1.8	2604	334	9.8489	-34.7166
HSE M0	0.54	4060	0.54	25.84	7.24	1322	0.59112	2456000.09	7	1.8	3149	158	9.0651	6.3339
HSE M0	0.54	4060	0.54	26.4	7.29	1397	0.50069	2456000.22	7	1.8	2979	156	1.889	-42.4212
HSE K1	0.76	5000	0.76	25.39	6.09	1040	3.19392	2456001.90	7	1.8	6939	157	14.8059	9.2345
HSE K1	0.76	5000	0.76	19.59	5.53	1867	0.55163	2456000.27	7	1.8	3864	52	18.3377	10.7904
HSE K1	0.76	5000	0.76	27.93	6.3	1733	0.69054	2456000.02	7	1.8	4165	114	17.4275	32.9208
HSE G1	1.02	5850	1.02	30.19	5.63	1613	1.83826	2456000.76	7	1.8	7023	176	5.9944	-50.3452
HSE G1	1.02	5850	1.02	23.48	5.09	1207	4.39179	2456003.77	7	1.8	9388	142	1.7034	57.1714
HSE G1	1.02	5850	1.02	29.03	5.55	1916	1.09668	2456000.33	7	1.8	5912	137	5.2221	16.0264
HSE G1	1.02	5850	1.02	28.37	5.5	1818	1.28503	2456000.47	7	1.8	6233	138	6.1416	-81.9273
HSN M0	0.54	4060	0.54	35.93	7.95	835	2.34306	2456000.14	6	2.6	4983	55	17.0342	-22.1333
HSN K1	0.76	5000	0.76	35.33	6.81	786	7.39729	2456005.84	6	2.6	9180	42	11.9408	52.1627
HSN K1	0.76	5000	0.76	31.08	6.53	1426	1.23799	2456000.83	6	2.6	5059	17	13.23	58.3945
HSN G1	1.02	5850	1.02	40.13	6.25	1285	3.63808	2456001.12	6	2.6	8817	32	0.0855	-29.0563
HSN G1	1.02	5850	1.02	37.4	6.1	2214	0.71092	2456000.66	6	2.6	5117	16	3.9181	5.443
HSN G1	1.02	5850	1.02	40.78	6.29	1364	3.04055	2456000.25	6	2.6	8305	31	19.0908	36.3674
HSN G1	1.02	5850	1.02	39.4	6.21	1412	2.74104	2456001.08	6	2.6	8023	28	4.7885	2.2526
HSN F8	1.14	6200	1.2	38.35	5.72	2104	1.19115	2456000.43	6	2.6	6889	17	13.0977	29.5505
							...							
HJ F8	1.14	6200	1.2	90.74	7.59	940	13.33714	2456006.14	300	10	15413	20	17.066	30.4729
HJ F8	1.14	6200	1.2	90.74	7.59	940	13.33714	2456012.81	300	10	15413	88	17.066	30.4729
HJ F8	1.14	6200	1.2	92.07	7.62	945	13.14597	2456008.40	300	10	15339	21	14.8289	-13.5723
HJ F8	1.14	6200	1.2	92.07	7.62	945	13.14597	2456014.97	300	10	15339	90	14.8289	-13.5723
HJ F8	1.14	6200	1.2	74.72	7.17	1576	2.83469	2456000.42	300	10	9198	8	15.5671	-3.9914
HJ F8	1.14	6200	1.2	74.72	7.17	1576	2.83469	2456001.84	300	10	9198	35	15.5671	-3.9914
HJ F8	1.14	6200	1.2	86.3	7.48	1556	2.94149	2456000.47	300	10	9312	11	19.6859	4.5421
HJ F8	1.14	6200	1.2	86.3	7.48	1556	2.94149	2456001.94	300	10	9312	48	19.6859	4.5421
HJ F8	1.14	6200	1.2	94.76	7.69	1831	1.80559	2456001.15	300	10	7914	11	18.0447	27.3354
HJ F8	1.14	6200	1.2	94.76	7.69	1831	1.80559	2456002.05	300	10	7914	49	18.0447	27.3354
HJ F8	1.14	6200	1.2	86.81	7.5	1477	3.44145	2456000.36	300	10	9812	12	22.3457	-3.0563
HJ F8	1.14	6200	1.2	86.81	7.5	1477	3.44145	2456002.08	300	10	9812	51	22.3457	-3.0563
HJ F8	1.14	6200	1.2	85.11	7.45	2044	1.29966	2456000.06	300	10	7093	8	13.8445	-17.1615
HJ F8	1.14	6200	1.2	85.11	7.45	2044	1.29966	2456000.71	300	10	7093	35	13.8445	-17.1615
HJ F8	1.14	6200	1.2	92.63	7.64	1224	6.04587	2456005.2	300	10	11840	16	1.3202	47.1443
HJ F8	1.14	6200	1.2	92.63	7.64	1224	6.04587	2456008.22	300	10	11840	71	1.3202	47.1443
HJ F8	1.14	6200	1.2	90.74	7.59	1595	2.73347	2456000.81	300	10	9087	12	13.4924	63.7723
HJ F8	1.14	6200	1.2	90.74	7.59	1595	2.73347	2456002.17	300	10	9087	52	13.4924	63.7723

LT-MPT Objectives

- Maximize planning efficiency
- Maximize scientific return (i.e., the number of completed targets)
  - It is computed with the number of completed targets weighted according the target priority
- How is the priority of the targets defined?
  1) Targets of classes with more criticality (difficult classes)
  2) From the targets of the same class, those less critical (easy targets)
  - Criticality of class *C* (the higher the value, the more critical is the class)

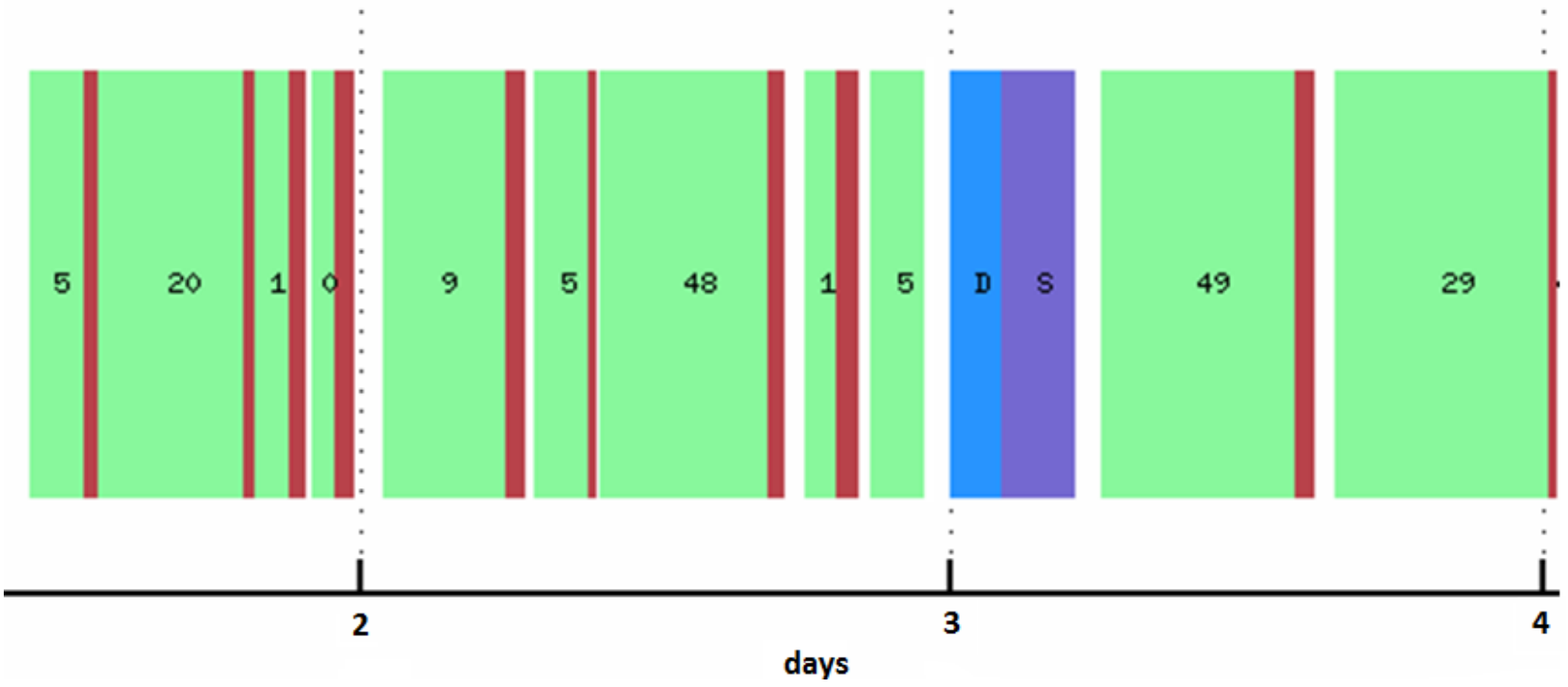
$$\text{ClassCriticality}(C) = \sum t \in C \uparrow \text{TargetCriticality}(t)$$

  - Criticality of target *t* (the higher the value, the more critical is the target)

$$\text{TargetCriticality}(t) = Events\downarrow t \cdot T14\downarrow t \,/\, Visibility\downarrow t$$

- Any target observed less than an 80% of its required number of events is dropped

Long Term Mission Plan (LTMP) of a Few Days



	Observation of a target
	Slew
	Downlink
	Station Keeping
	Gap

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Analysis of the Results

- Problem Conditions
  - 10 MRS scenarios and 1 real sample scenario
    - Executed 100 times with different random seeds
  - Long Term Mission Plan (five years, 2022-2026)
  - 238 targets MRS / 122 targets Real Sample
    - Each one needs a different number of observations (events)
    - Observations with a duration of 2·T14
  - 520 Downlinks (2 hours / 3.5 days)
  - 65 Station Keepings (8 hours / 28 days)
  - Slew time between targets
    - Slew speed of 45 degrees per 10 minutes plus a flat 5-minute overhead
  - No calibrations considered

Quantitative Results (I)

- Mission Reference Sample
  - Average results for 10 different scenarios
  - Usable Science Team: 31671 hours
  - Total Input Time: 26773.03 hours

Downlink Configuration	Planning Efficiency		Slew Time		Events Planned		Targets Completed	
Fixed Downlinks	84.68%	±0.55	9.42%	±0.04	91.14%	±0.68	94.24%	±0.41
Downlinks ± 10%	88.04%	±0.53	9.23%	±0.07	91.79%	±0.57	96.62%	±0.23
No Downlinks	93.29%	±0.63	9.62%	±0.07	95.45%	±0.56	98.32%	±0.16

- Real Sample
  - Usable Science Team: 31671 hours
  - Total Input Time: 17563.80 hours

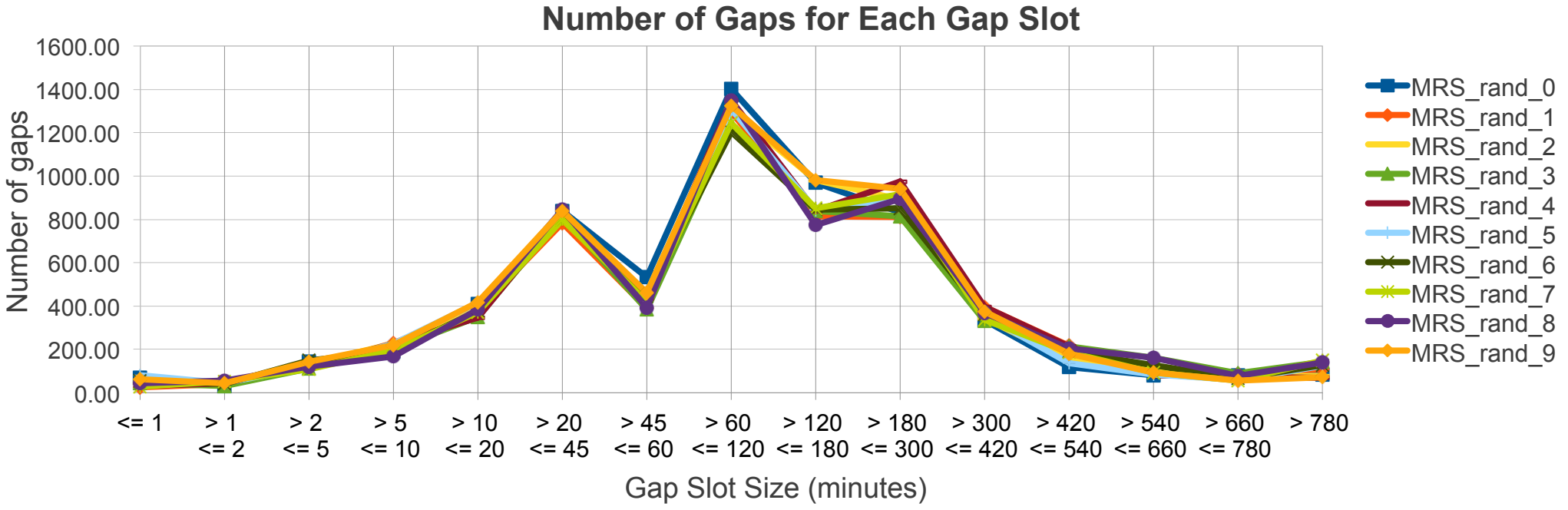
Downlink Configuration	Planning Efficiency		Slew Time		Events Planned		Targets Completed	
Fixed Downlinks	87.72%	±1.79	5.09%	±0.05	89.67%	±1.54	99.21%	±0.17

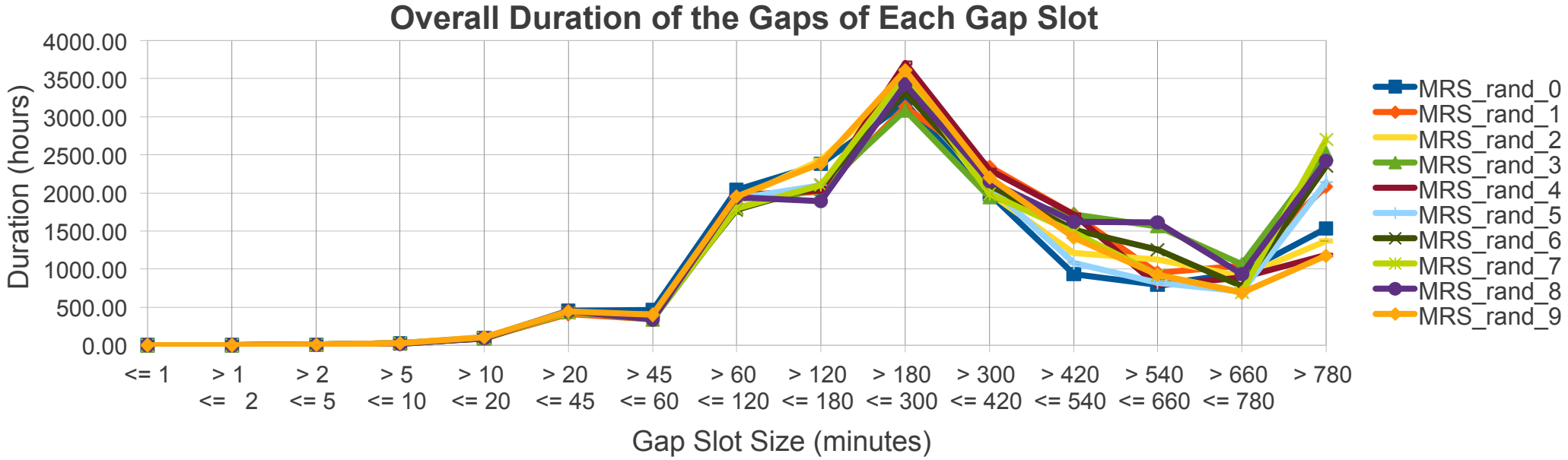
Quantitative Results (II)

- Mission Reference Sample
  - Average Observation Duration: 4.06 hours
  - Average Slew Duration: 22.05 minutes

- Real Sample
  - Average Observation Duration: 4.1 hours
  - Average Slew Duration: 12.94 minutes

Gap Distribution





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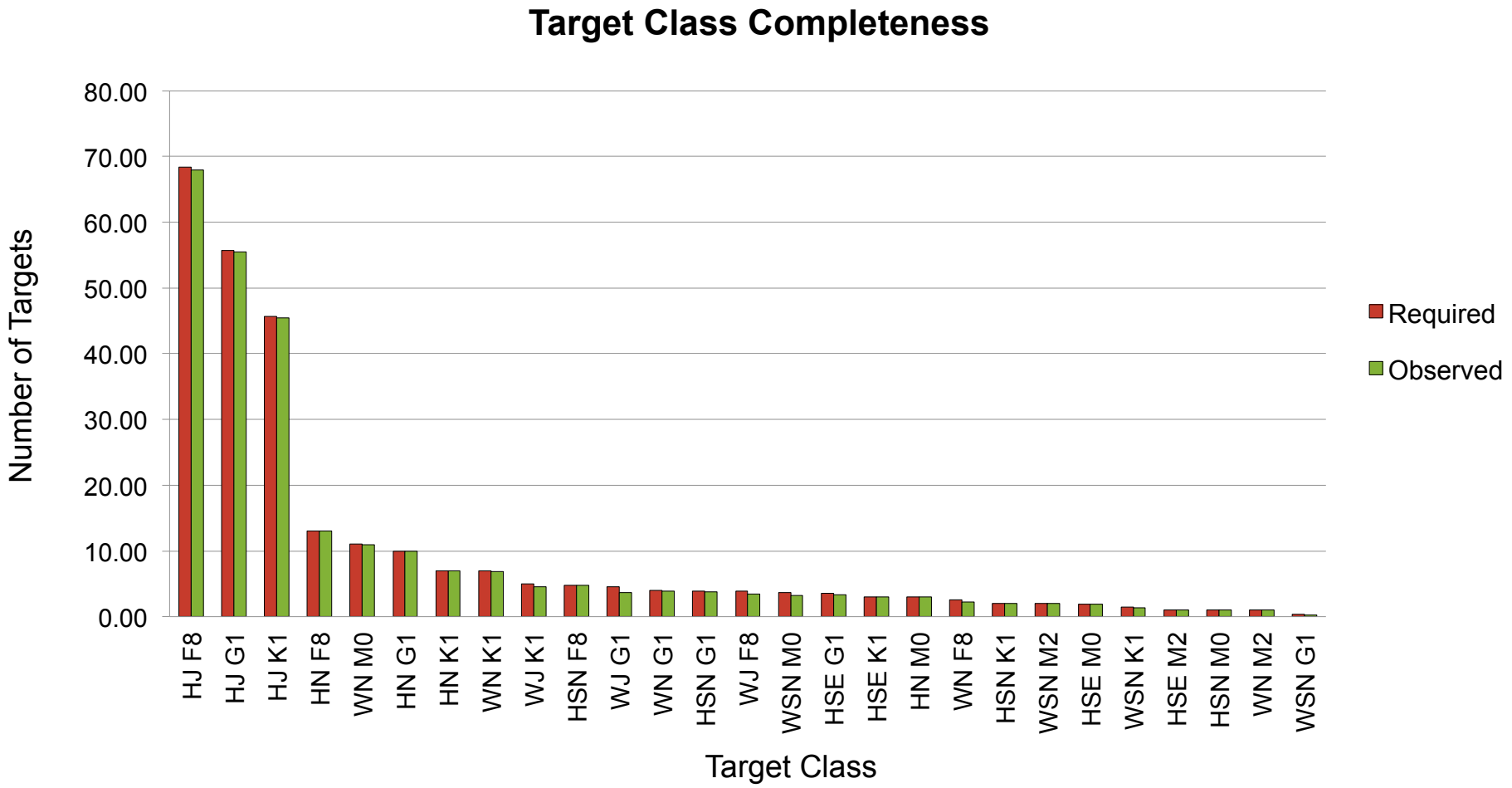
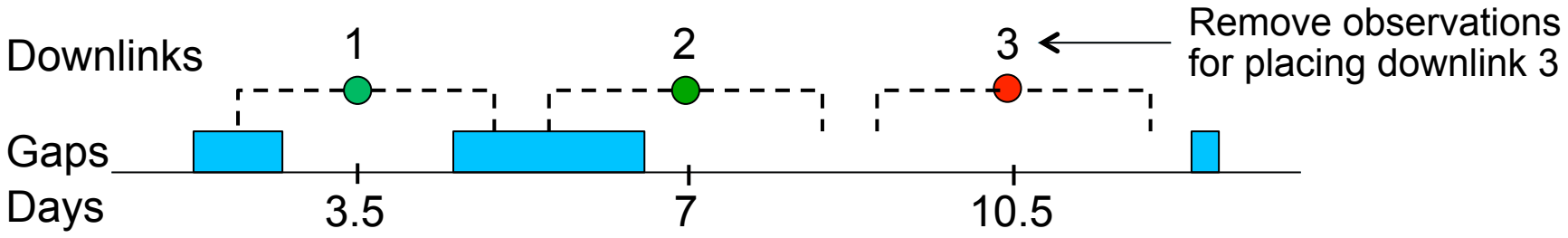
Class Distribution



Downlinks as Gap Fillers



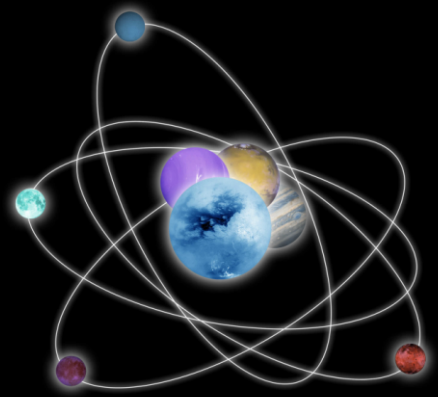
- Percentage of downlinks placed for different flexibilities
  - Percentage according to the 520 downlinks
  - Flexibility according to a percentage of the 3.5 days

Name	3.5days +/- 10%	3.5days +/- 20%
Average	96.44	99.25

LT-MPT Summary

- Similar results on the artificial and the real samples
  - High planning efficiency (around 90%)
  - Almost all the targets can be completed (observed >80% of events)
- Downlinks limit some observations
  - To add some flexibility to them can improve the planning efficiency
- There are around 5000 gaps longer than 20 minutes
  - Additional observations can be planned
- Slew time cannot be reduced without affecting the efficiency (a multiobjective algorithm based on minimizing the slew time has been analyzed with no real gain)
- Room to plan extra constraints (i.e., dependencies between observations)

Exoplanet Characterisation Observatory



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The EChO Mission Reference Sample (MRS)

Typ	Ms	Teff	Rs	dist	Ks	Tpl	P	a	Rpl	Mpl	T14	num	nev1	nev2
HSE M2	0.37	3580.00	0.37	27.94	8.60	1000.00	0.64	1.56	1.80	7.00	2515.82	1.00	344.00	0.00
HSE M0	0.54	4060.00	0.54	27.83	7.40	1200.00	0.79	2.04	1.80	7.00	3470.03	2.00	202.00	0.00
HSE K1	0.76	5000.00	0.76	27.92	6.30	1500.00	1.06	2.79	1.80	7.00	4811.57	3.00	132.00	0.00
HSE G1	1.02	5850.00	1.02	28.38	5.50	1500.00	2.29	5.12	1.80	7.00	7555.43	4.00	168.00	0.00
HSN M0	0.54	4060.00	0.54	36.69	8.00	1200.00	0.79	2.04	2.60	6.00	3470.03	1.00	40.00	0.00
HSN K1	0.76	5000.00	0.76	36.81	6.90	1500.00	1.06	2.79	2.60	6.00	4811.57	2.00	24.00	0.00
HSN G1	1.02	5850.00	1.02	37.41	6.10	1500.00	2.29	5.12	2.60	6.00	7555.43	4.00	24.00	0.00
HSN F8	1.14	6200.00	1.20	36.24	5.60	1500.00	3.29	6.76	2.60	6.00	9665.27	5.00	22.00	0.00
WSN M2	0.37	3580.00	0.37	33.59	9.00	600.00	2.46	3.83	2.60	6.00	3937.69	2.00	90.00	0.00
WSN M0	0.54	4060.00	0.54	36.69	8.00	600.00	5.24	7.19	2.60	6.00	6517.44	4.00	86.00	0.00
WSN K1	0.76	5000.00	0.76	36.81	6.90	600.00	13.78	15.36	2.60	6.00	11296.41	2.00	64.00	0.00
WSN G1	1.02	5850.00	1.02	37.41	6.10	600.00	29.62	28.21	2.60	6.00	17738.34	1.00	63.00	0.00
HN M0	0.54	4060.00	0.54	63.76	9.20	1200.00	0.79	2.04	4.00	15.00	3470.03	3.00	7.00	0.00
HN K1	0.76	5000.00	0.76	63.97	8.10	1500.00	1.06	2.79	4.00	15.00	4811.57	7.00	4.00	0.00
HN G1	1.02	5850.00	1.02	62.09	7.20	1500.00	2.29	5.12	4.00	15.00	7555.43	10.00	3.00	0.00
HN F8	1.14	6200.00	1.20	62.98	6.80	1500.00	3.29	6.76	4.00	15.00	9665.27	13.00	3.00	0.00
WN M2	0.37	3580.00	0.37	33.59	9.00	600.00	2.46	3.83	4.00	15.00	3937.69	1.00	5.00	0.00
WN M0	0.54	4060.00	0.54	63.76	9.20	600.00	5.24	7.19	4.00	15.00	6517.44	11.00	14.00	0.00
WN K1	0.76	5000.00	0.76	63.97	8.10	600.00	13.78	15.36	4.00	15.00	11296.41	7.00	10.00	0.00
WN G1	1.02	5850.00	1.02	62.09	7.20	600.00	29.62	28.21	4.00	15.00	17738.34	4.00	9.00	0.00
WN F8	1.14	6200.00	1.14	65.61	7.00	600.00	39.41	35.42	4.00	15.00	21011.33	3.00	10.00	0.00
HJ K1	0.76	5000.00	0.76	139.95	9.80	1500.00	1.06	2.79	10.00	300.00	4811.57	26.00	11.00	0.00
HJ G1	1.02	5850.00	1.02	135.84	8.90	1500.00	2.29	5.12	10.00	300.00	7555.43	32.00	13.00	0.00
HJ F8	1.14	6200.00	1.20	137.79	8.50	1500.00	3.29	6.76	10.00	300.00	9665.27	39.00	12.00	0.00
WJ K1	0.76	5000.00	0.76	92.46	8.90	600.00	13.78	15.36	10.00	300.00	11296.41	5.00	22.00	0.00
WJ G1	1.02	5850.00	1.02	89.75	8.00	600.00	29.62	28.21	10.00	300.00	17738.34	5.00	18.00	0.00
WJ F8	1.14	6200.00	1.14	86.48	7.60	600.00	39.41	35.42	10.00	300.00	21011.33	5.00	16.00	0.00
HJ K1	0.76	5000.00	0.76	92.46	8.90	1500.00	1.06	2.79	10.00	300.00	4811.57	10.00	17.00	65.00
HJ G1	1.02	5850.00	1.02	89.75	8.00	1500.00	2.29	5.12	10.00	300.00	7555.43	12.00	13.00	55.00
HJ F8	1.14	6200.00	1.20	91.04	7.60	1500.00	3.29	6.76	10.00	300.00	9665.27	15.00	13.00	56.00

These are the main general object classes of EChO

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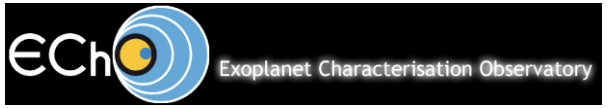

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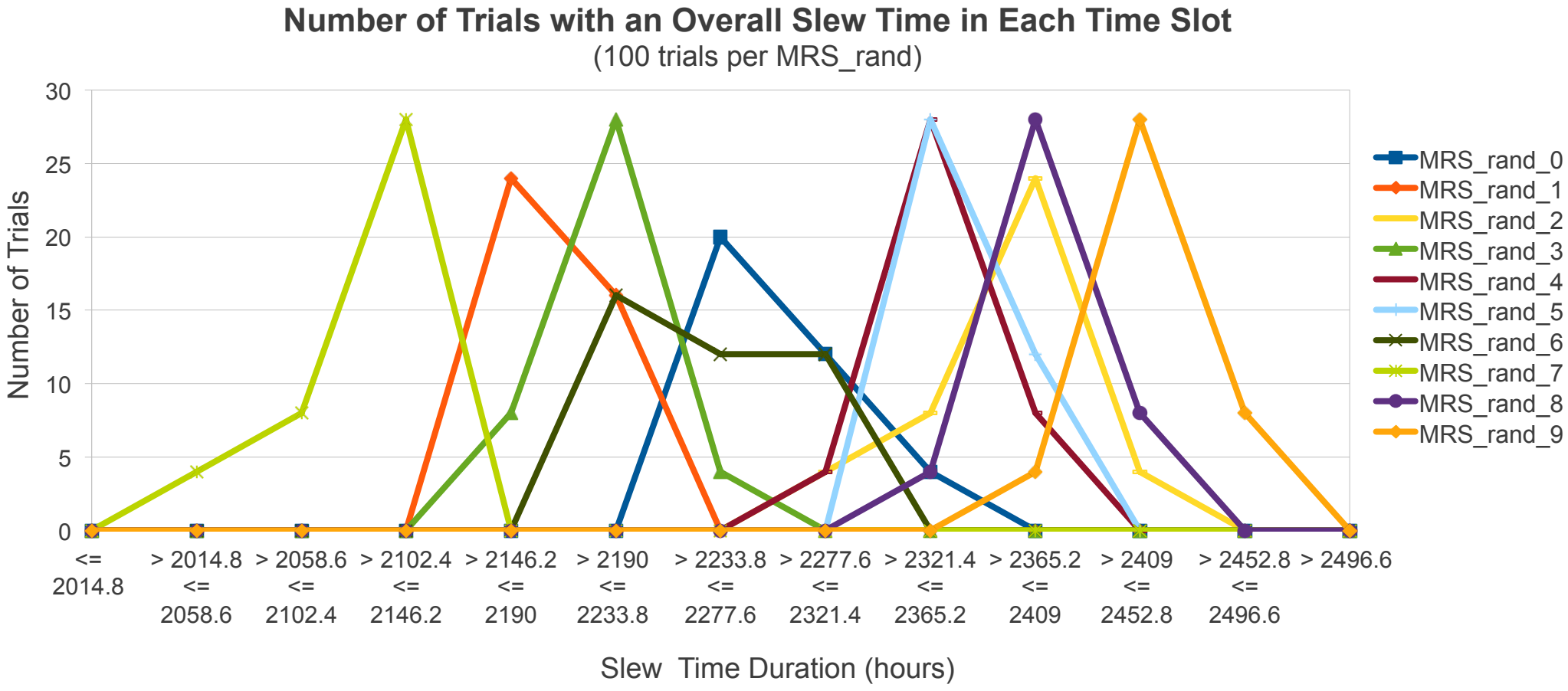
Slew Time Distribution



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