The Extreme Precision Radial Velocity Initiative

Jennifer Burt
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Jet Propulsion Laboratory, California Institute of Technology
(on behalf of the entire EPRV working group)

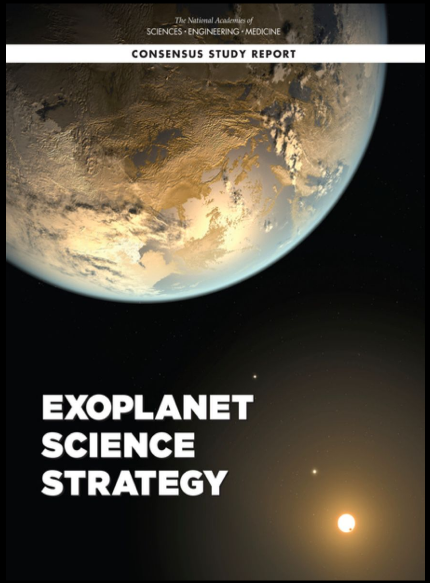
EPRV Working Group Objective

The Extreme Precision Radial Velocity (EPRV) Working Group was chartered by the NASA Astrophysics Division (APD) and NSF Division of Astronomical Sciences (AST) to deliver a report that includes a recommendation for the most promising ground-based program architecture and supporting research efforts necessary to achieve the goal of measuring the masses of temperate, terrestrial planets orbiting nearby, Sun-like stars amenable to direct imaging with future mission concepts such as HabEx, LUVOIR, or Starshade Rendezvous.

https://exoplanets.nasa.gov/exep/NNExplore/EPRV

Based on the 2018 ESS report:

"Radial velocity measurements are currently limited by variations in the stellar photosphere, instrumental stability and calibration, and spectral contamination from telluric lines. Progress will require new instruments installed on large telescopes, substantial allocations of observing time, advanced statistical methods for data analysis informed by theoretical modeling, and collaboration between observers, instrument builders, stellar astrophysicists, heliophysicists, and statisticians."



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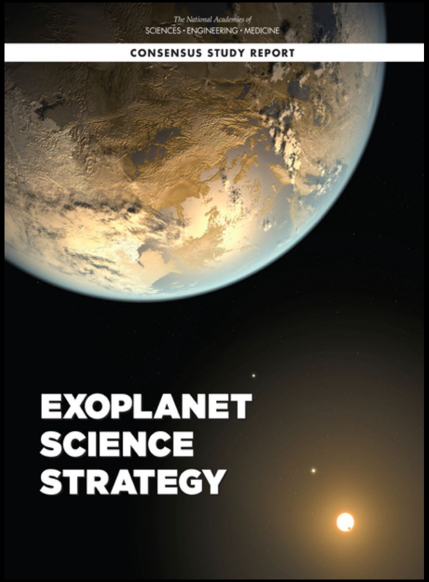

So, what are we doing about all of these challenges?

We identified some experts in those areas

Steering Group

Scott	Gaudi	Co-chair	The Ohio State University
Gary	Blackwood	Co-chair	NASA ExEP / Jet Propulsion Laboratory
Andrew	Howard		Caltech
David	Latham		Harvard-Smithsonian Center for Astrophysics
Debra	Fischer		Yale University
Eric	Ford		Pennsylvania State University
Heather	Cegla		University of Geneva
Peter	Plavchan		George Mason University
Andreas	Quirrenbach		Landessternwarte; University of Heidelberg
Jennifer	Burt		Massachusetts Institute of Technology
Eric	Mamajek	Ex officio	NASA ExEP / Jet Propulsion Laboratory
Chas	Beichman	Ex officio	NASA Exoplanet Science Institute / Caltech

Members

Chad	Bender	University of Arizona
Jonathan	Crass	Notre Dame University
Scott	Diddams	National Institute of Standards and Technology
Xavier	Dumusque	Université de Genève
Jason	Eastman	Harvard-Smithsonian Center for Astrophysics
Benjamin	Fulton	NASA Exoplanet Science Institute / Caltech
Sam	Halverson	Massachusetts Instititute of Technology
Raphaëlle	Haywood	Harvard-Smithsonian Center for Astrophysics
Fred	Hearty	Pennsylvania State University
Stephanie	Leifer	NASA / Jet Propulsion Laboratory
Johannes	Loehner-Boettcher	University Corp. for Atmospheric Research
Annelies	Mortier	Kavli Inst. for Cosmology, Univ. of Cambridge
Ansgar	Reiners	University of Göttingen
Paul	Robertson	University of California, Irvine
Arpita	Roy	Caltech
Christian	Schwab	Macquarie University
Andreas	Seifahrt	University of Chicago
Andrew	Szentgyorgyi	Harvard-Smithsonian Center for Astrophysics
Ryan	Terrien	Carleton University
Johanna	Teske	Carnegie Observatories/DTM
Samantha	Thompson	University of Cambridge
Gautam	Vasisht	NASA / Jet Propulsion Laboratory

Participants

Suzanne	Aigrain		Oxford University
Megan	Bedell		Flatiron Institute
Rebecca	Bernstein		Carnegie Observatories
Ryan	Blackman		Yale University
Cullen	Blake		University of Pennsylvania
Lars	Buchhave		Technical University of Denmark
John	Callas	Ex officio	NASA ExEP / Jet Propulsion Laboratory
David	Ciardi	Ex officio	NASA Exoplanet Science Institute / Caltech
William	Chaplain		University of Birmingham
Jessi	Cisewski-Kehe		Yale University
Andrew	Collier-Cameron		Saint Andrews University
Matthew	Cornachione		University of Utah
Nadege	Meunier		University of Grenoble
Joe	Ninan		Pennsylvania State University
John	O'Meara		W. M. Keck Observatory
Joel	Ong		Yale University
Sharon	Wang		Carnegie Institution for Science
Sven	Wedemeyer-Boehm		University of Oslo
Lily	Zhao		Yale University

ExoTAC (Exoplanet Technical Assessment Committee)

Alan	Boss	Chair	Carnegie Institution for Science
Rebecca	Oppenheimer		American Museum of Natural History
Joe	Pitman		Heliospace Corporation
Lisa	Poyneer		Lawrence Livermore Laboratory
Stephen	Ridgeway		National Optical Astronomy Observatory

F. Approvals and Concurrences

E-SIGNED by Douglas Hudgins on 2019-07-23 17:36:36 GMT

Approve/____________________/ 2019-07-23 17:36:36 UTC .

Dr. Douglas M. Hudgins Date

Exoplanet Exploration Program Scientist, NASA/APD

E-SIGNED by Jeff Neff on 2019-07-24 22:25:37 GMT

Approve/____________________/ 2019-07-24 22:25:37 UTC .

Dr. James E. Neff Date

NN-EXPLORE Program Director, NSF/AST

And then we got to work

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(after they kindly volunteered to help out)

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Science Mission Drivers (leads: Howard & Bender)
Identify science goals for the initiative and determine target star list to guide EPRV survey considerations

Survey Strategy (Burt & Teske)
Evaluate ability of architectures to observe prime target list. Design 2020s PRV survey to characterize stellar variability & multiplicity

Instrument Performance Evaluation (Halverson)
Assess top level system error budgets in the context of community derived science goals and requirements

Pipelines, Analysis & Statistical Inference (Roy & Ford)
Identify research efforts necessary to improve spectral analysis, RV determination & noise modeling

Instrumentation & Calibration (Leifer & Szentgyorgyi)
Identify new EPRV and supporting instrumentation/technology needed before the 2030 survey begins

Realistic Resource Evaluation (Quirrenbach & Diddams)
Evaluate expected costs, risks, and realism of EPRV architectures and supporting research efforts.

Intrinsic Stellar Variability (Cegla & Haywood)
Identify observational and analytical techniques needed to characterize & correct various types of stellar variability

Telluric Mitigation Strategies (Bender)
Identify observational and analytical techniques needed to quantify the impacts of telluric lines in the Earth's atmosphere and mitigate their effects

We defined a potential target list

- **Combined target lists from the HabEx, LUVOIR, and Starshade Rendezvous future mission concepts**
- **Eliminated stars with T_{eff} > 6200K or vsini > 10 km/s due to lack of RV information content**
- **Stars split into a 'green' and 'yellow' list:**
  - **Green stars have vsini < 5 km/s and appear on at least two studies' target lists**
  - **Yellow stars have vsini < 10 km/s or appear on only one study target list**

	Starshade Rendezvous	HabEx (4m)	LUVOIR-B (8m)	LUVOIR-A (15m)	Union Sample
# of stars	32	51	158	287	199
<V mag>	4.34	4.71	5.4	5.76	5.58
<Distance> (pc)	8.2	8.8	12.1	15.36	15.18
F stars	4	12	48	99	112
G stars	14	16	55	98	101
K stars	9	18	39	58	58
M stars	1	4	15	29	31
"Sun-like" stars (Sp Type: F7-K9)	24	40	116	197	206

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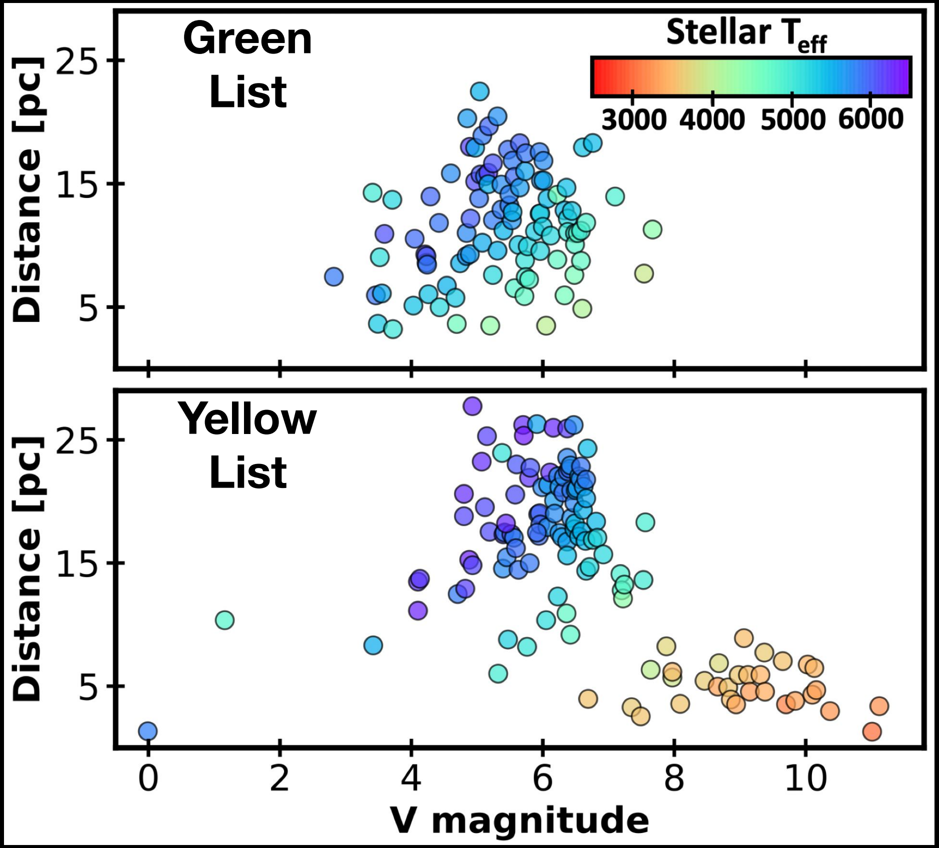


Then defined some musts

MUSTS		Success Criteria
M0a		Determine the feasibility by 2025 to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth
M0b		**Demonstrate the feasibility** to detect (with a well characterized and sufficiently small false discovery rate) and measure the mass (msini with <=10% fractional precision) of <=1earth mass planets that orbit a 1 M_Sun main sequence star and receive insolation within 10% Insolation_Earth prior to 2030 Decadal Survey.
M1a		Design and execute a set of **precursor surveys and analysis activities** on the 'green' and 'yellow' stars on evolving target star list and on the Sun
M1b		**Demonstrate the feasibility to survey** each of the 'green' stars on evolving target list at the level of M0b.
M2		**Meet Intermediate Milestone:** By 2025, demonstrate on-sky feasibility with capabilities in-hand to detect *K* down to 30 cm/s for periods out to few hundred days using a statistical method that has been validated using simulated and/or observed spectra time-series
M4		**Capture Knowledge** from current and near-future generation of instruments, surveys, analysis, and coordination activities to help inform development of future EPRV instruments.

… and some wants

WANTS	Relative Science
W1	Survey as many 'yellow' stars as possible on evolving stellar target list.
W2	Measure masses of temperate terrestrial planets orbiting M stars, not on yellow target list
W3	Use follow-up of transiting temperate terrestrial planets to inform the mass-radius relation from key transit discoveries
W4	Validate methods of stellar variability mitigation, telluric mitigation, and statistical validation, key for the EPRV method, including using follow-up of transiting planets
	Relative Schedule
W5	**Schedule**: Start the precursor M1a surveys **as soon as possible**, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)
W6	**Schedule:** Start the Dream Survey as soon as possible, so as to maximize impact at PDR on design of direct imaging missions (e.g. HabEx, LUVOIR)
	Relative Cost
W10	Least estimated cost

	Relative Difficulty
W7	Prefer the architecture with the greatest relative probability of success to meet stellar variability requirement
W8	Relative difficulty to secure required telescopes/instruments, fraction of time, and observing cadence and coordination between telescopes
W9	Prefer the architecture the greatest probability of success of achieving the survey referenced in M1b
	Other Factors
W11	Take advantage of opportunities for international collaboration and draw from as broad of a pool of relevant expertise and observing facilities as possible
W12	Maximize use of, and knowledge and understanding of, existing facilities (observatories), infrastructure, and hardware (including detectors)
W13	Maximize broader impacts in society
W14	Encourage free exchange of ideas, including data and source codes
W15	Implement as a coordinated and distributed program
W16	Encourage collaboration between the subdisciplines in stellar astrophysics, heliophysics, instrumentation, statistics and earth sciences (mitigating tellurics)

And started thinking about observing approaches

Architecture:	0a : No New Funds but Using Existing Assets and Organization [Scott]	0b : New Funds Requested, using existing assets and organizations [Fred]	I : 2.4m telescopes combined with NEID-esque instruments [Jenn]	II : 4-6m class telescopes [Andrew]	III : 10m class telescopes [O'Meara]	IV : 25m class telescope [Andy]	V : T.H.E-Like - 3m class + SMF Instruments [Chas]	VI : Exotic Telescope Tech [Peter]	VII : Exotic Spectrograph Tech [Peter]	VIII : Hybrid Exclusive [BJ]

- Wavelength coverage
- Spectral resolution
- # of telescopes and assumed time allocation
- Instrument noise floor
- Instrument efficiency
- Wavelength calibration source

- Observing cadence
- Desired RV precision
- Minimum SNR requirement
- Total survey length

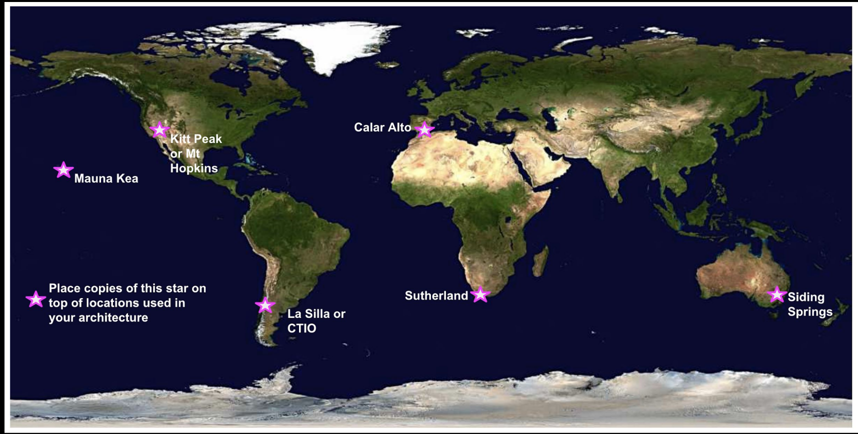
- Site selection for each facility in architecture
- Latitude, longitude and elevation
- Average weather loss
- Median Seeing

- Steps taken to address stellar activity (observing cadence, minimum SNR, FTE investments, etc)

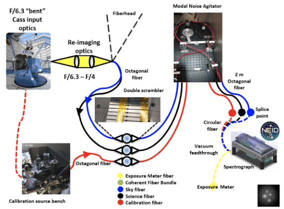
- Plans for survey plan to characterize stellar activity and eliminate problematic stars before EPRV survey

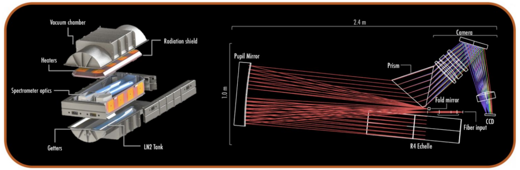
- Improvements to data reduction and analysis pipelines
- Improvements to statistical planet detection efforts
- Investments in instrumentation testbeds

Example architecture layout



At each facility: 2.4m telescope + super Neid + solar feed





Super Neid: same design basics as Neid (wavelength coverage, gain, read noise, etc), but set instrument noise floor at 10 cm/s

Description of observing set up at each facility

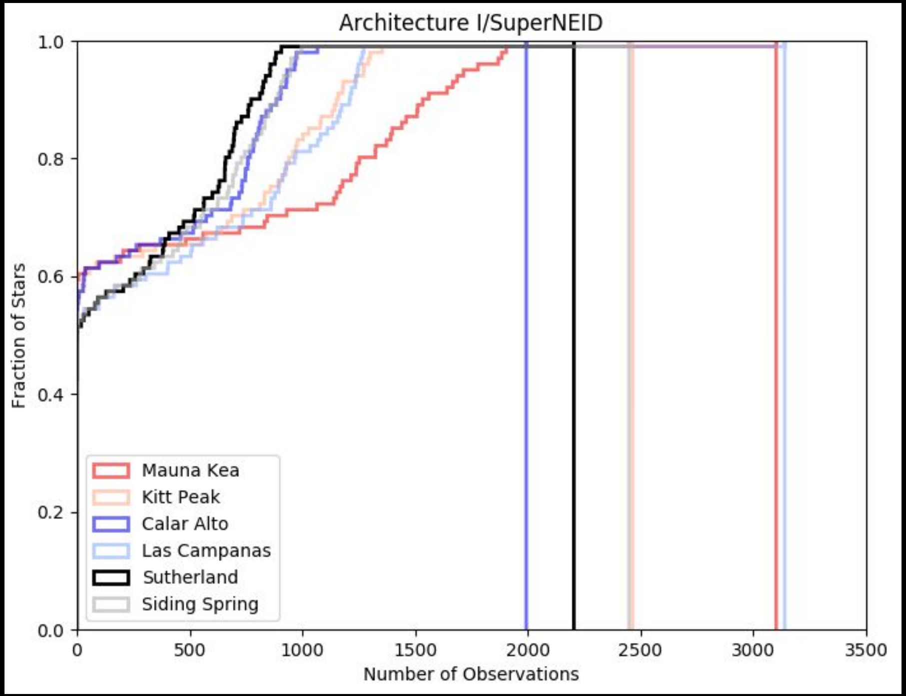
- **Telescope aperture**: 2.4m telescope
- **Basic instrument description**: Super-Neid, same basic instrument parameters as Neid but it has an instrumental noise floor of 10cm/s
- **Is there a solar feed?** Yes
- **Any other key details for understanding the telescope/instrument combo?** The telescopes are dedicated facilities, so they spend 100% of their time on the EPRV survey
- **Details on any driving technologies (e.g. adaptive optics, fiber slicers, etc):**

Fill in these details
Wavelength : 380-930nm
Resolution : 150k
Total efficiency : 7%
Instrument noise floor : 10 cm/s
Telescope allocation : 100%

Description of observing plan:

- **Describe stellar target list**: Include all stars on the green list
- **Describe observing cadence**: Observe each star at least once per night on at least one of the telescopes
- **Describe goal RV precision and SNR**: 10cm/s photon noise and SNR >= 300 during each visit to a given star
- **Any other key details for observing strategy (overlapping standard stars, etc)**: Have 4 standard stars (2N/2S) that are observed on three telescopes in that hemisphere each night to allow for better informed RV data combination

Some things we're able to simulate



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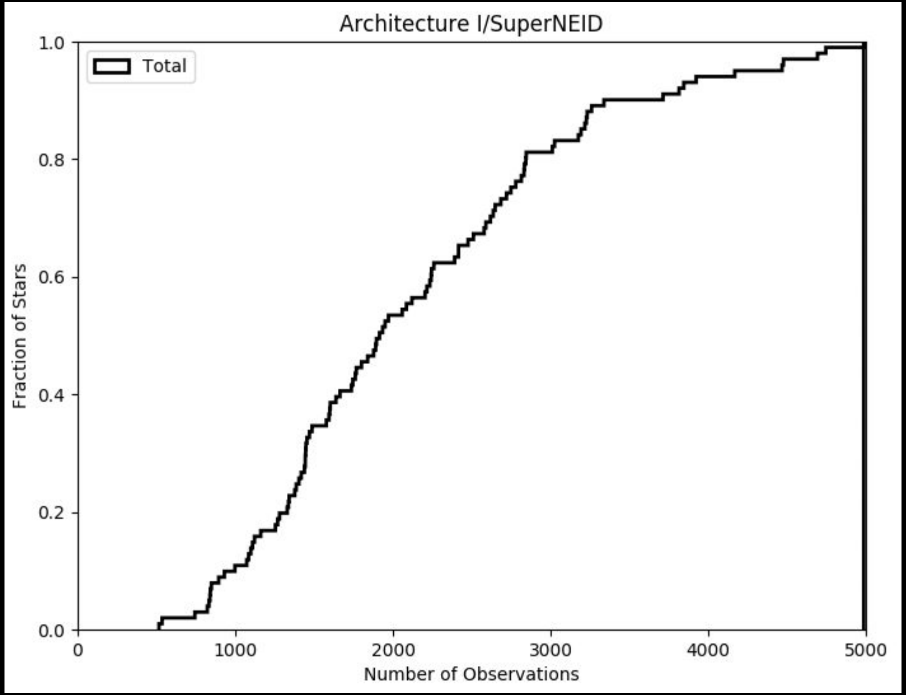

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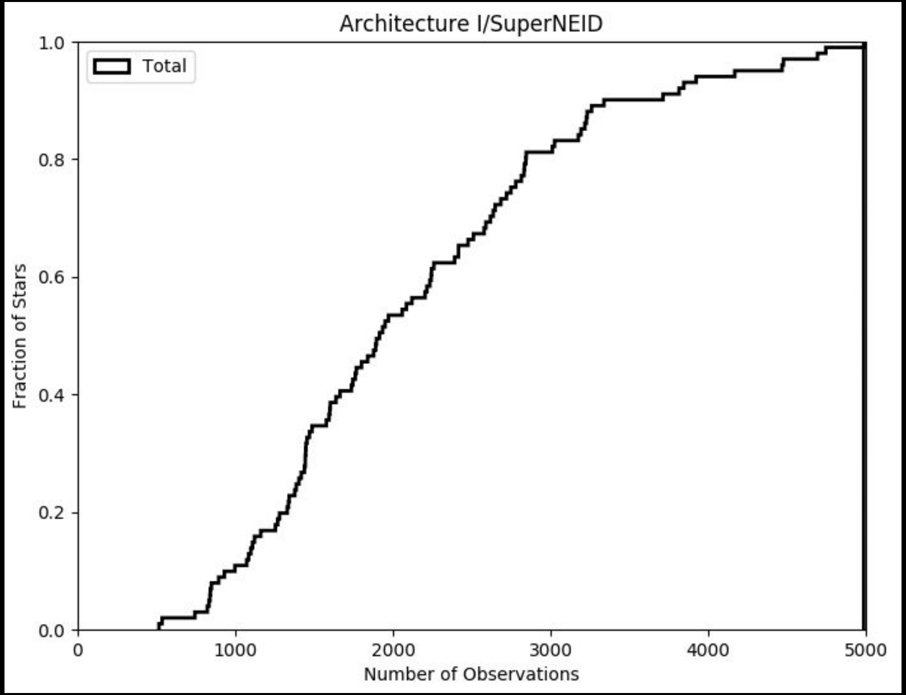

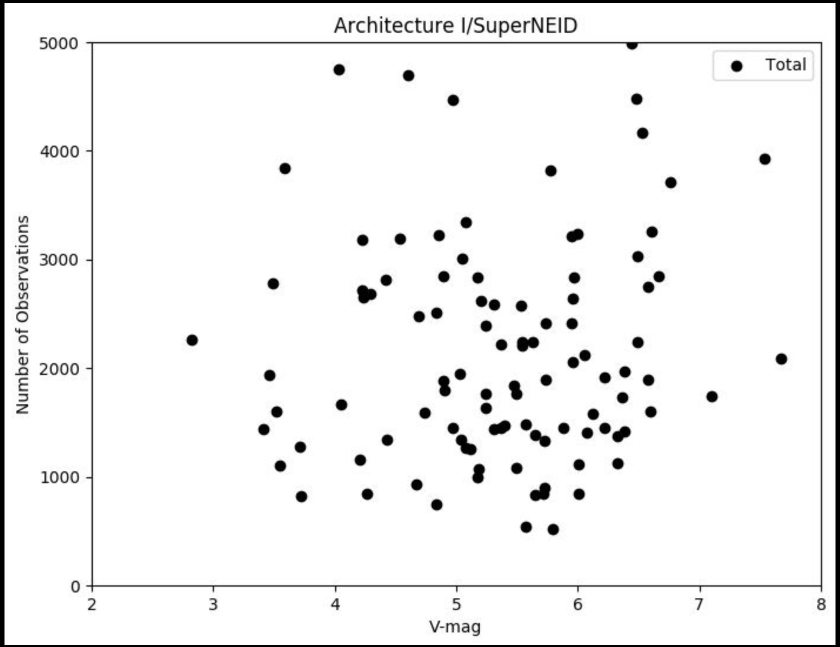

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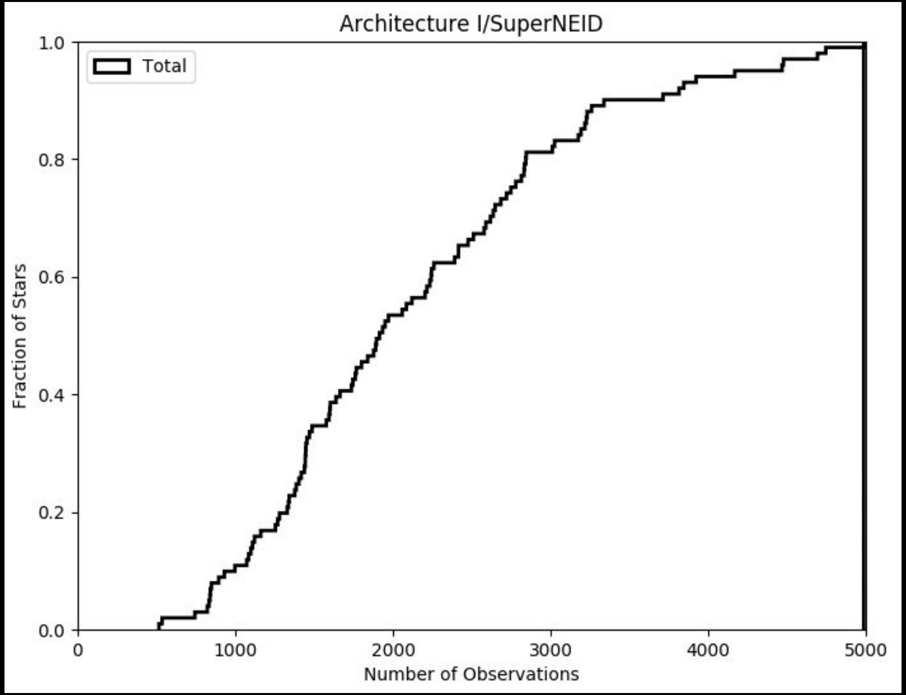

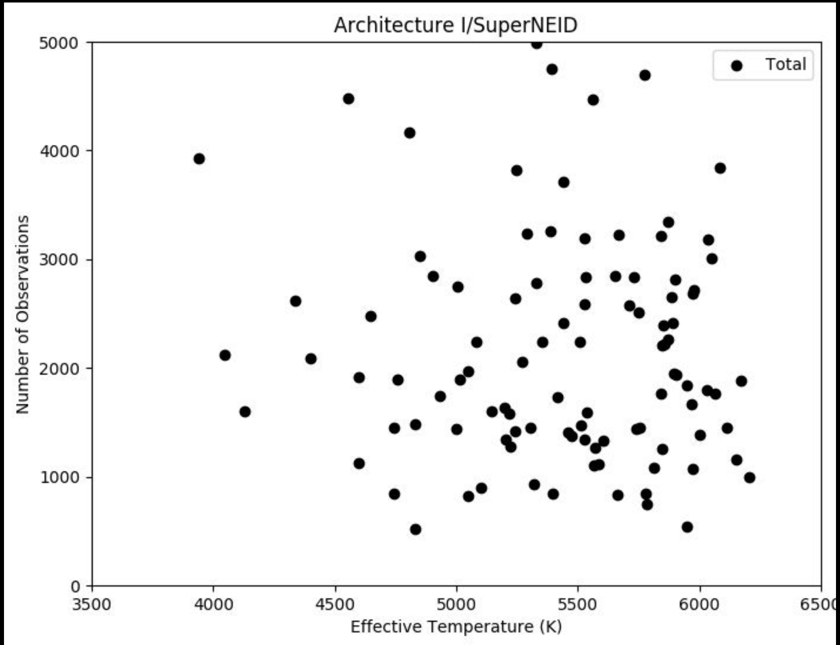

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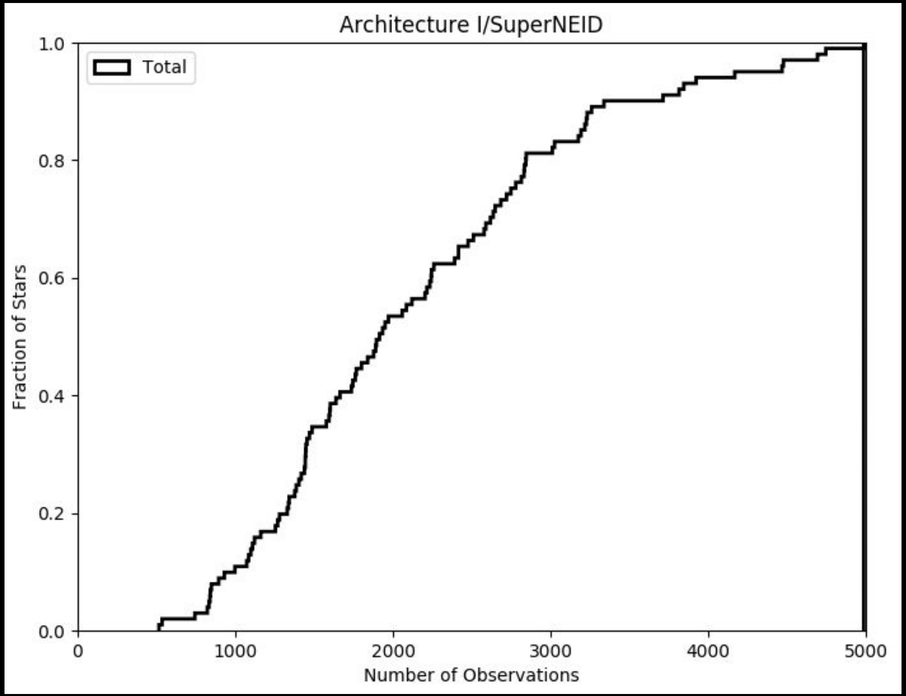
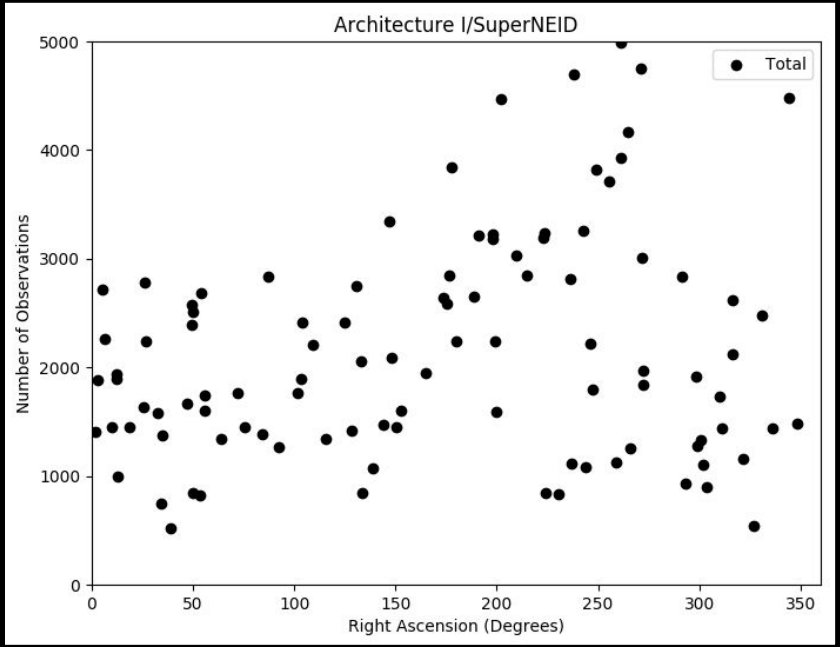
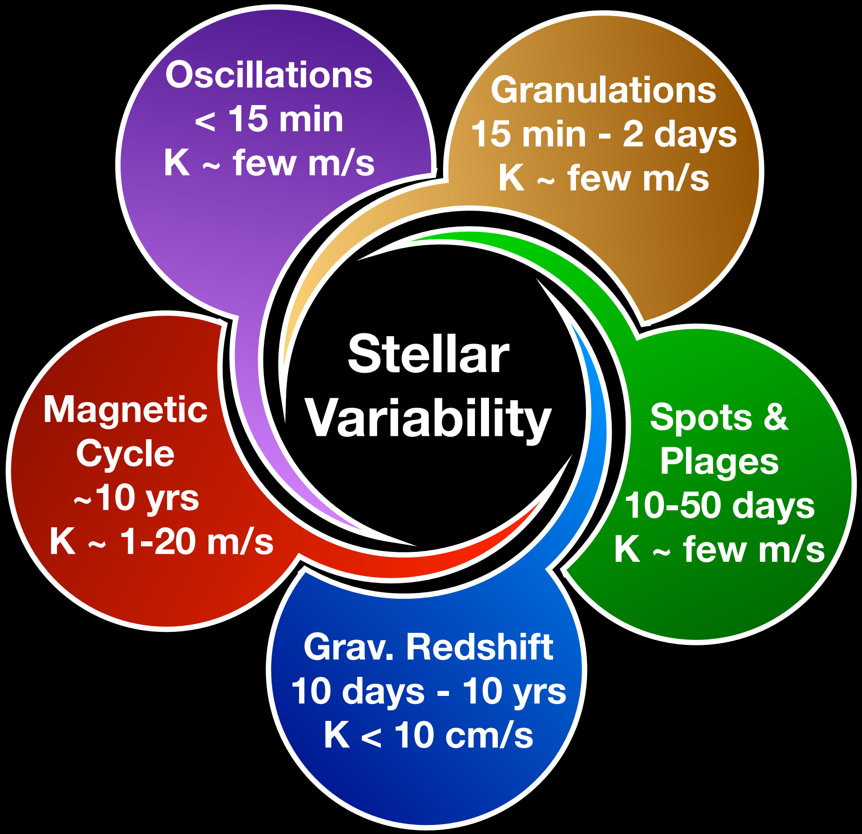




And others we're not



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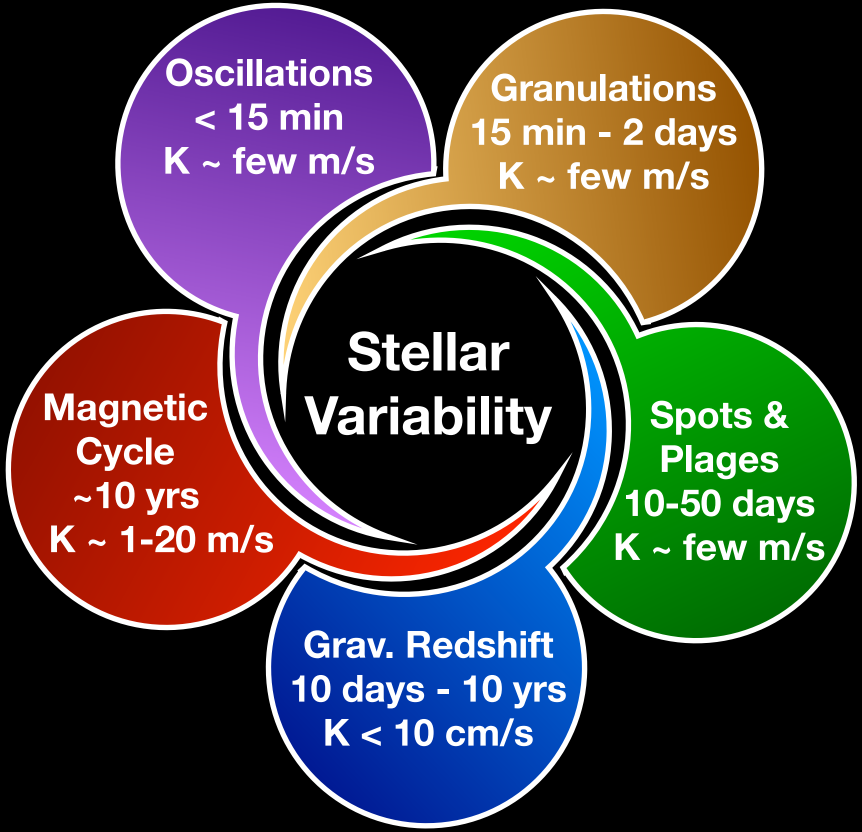

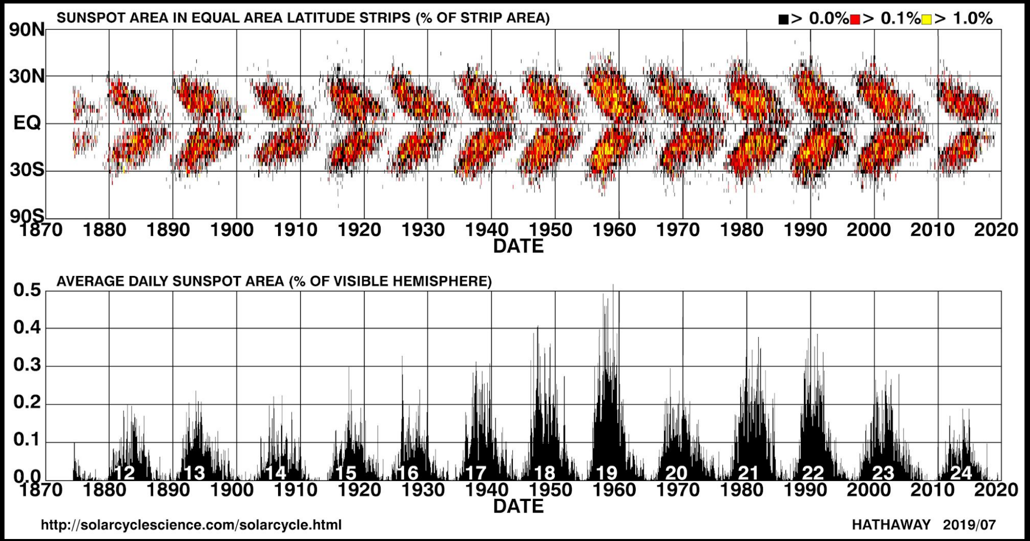

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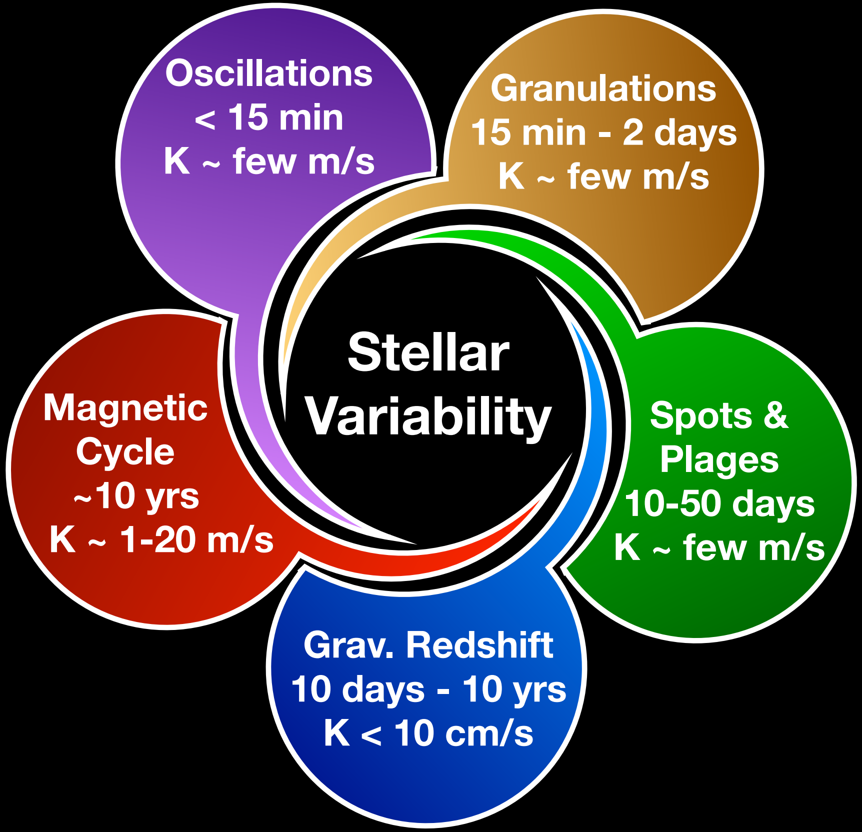

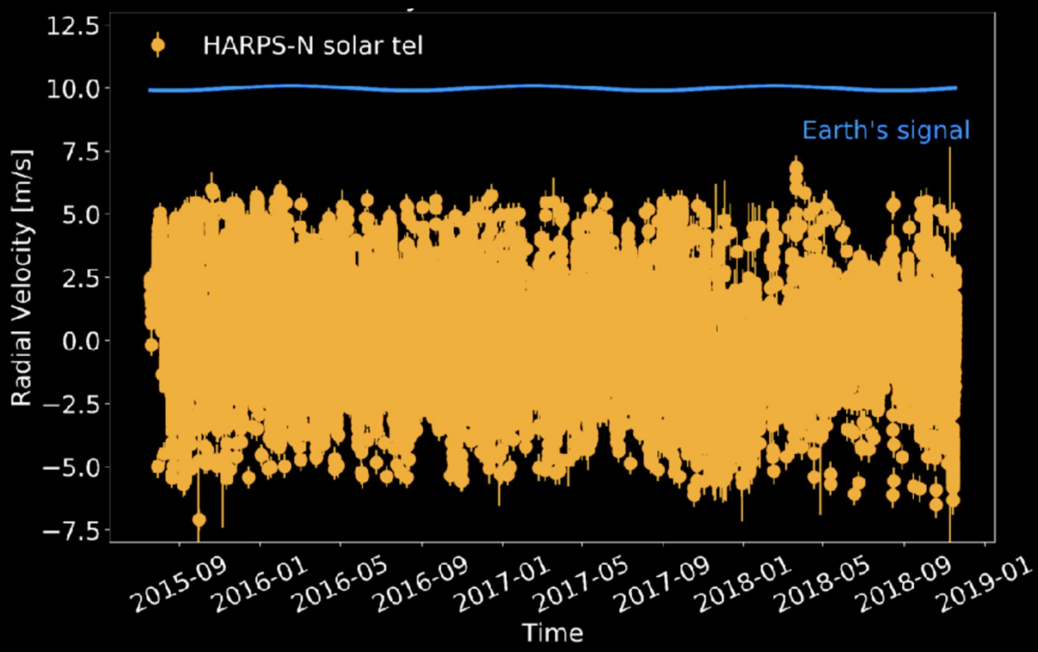

After simulations, each architecture will be assessed by each working group using custom rubrics

Category of information	Good	Better	Best
Stellar activity: rotation periods and long-term magnetic activity cycle	*Medium or high-resolution spectroscopic observations covering Ca H&K, with cadence of ~1/week, lasting ?? years	*High resolution (100,000+), moderate-S/N (100+) spectroscopic observations covering at least Ca H&K and deriving RVs, with cadence of every night for 2 months and ~1/week for the rest of the season, lasting ?? years	*High resolution (100,000+), high-S/N (300+) spectroscopic observations with stabilized spectrograph, covering Ca H&K + more activity indicators, and deriving RVs, with cadence of every night the whole season, lasting ?? years *Space-based photometry of targets deemed to be "quiet" in Ca H&K, cadence of 30 min or better, lasting 2+ months
Stellar multiplicity	*Gaia astronometry to look for companions stars via RUWE and Gaia RV	Good+ *Lower precision (10's to 100's of m/s) RV observations to look for stellar companions, with cadence of ~1/month	Better+ *High-resolution imaging to search for companions within 0.5''
Existence of other planets, particularly longer period	*Observations with any PRV spectrograph, cadence ~1/month, precision ~ 3 m/s, lasting for 5+ years	*Observations with any PRV spectrograph, cadence ~1/week, precision ~ 3 m/s, lasting for ~ 10 years	*Observations with a stabilized PRV spectrograph, cadence ~1/week, precision ~3 m/s, lasting for ~10 years
Sample of stars	all green	all green plus some yellow	all green+yellow

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#	Requirement	Bare Minimum	Strongly Recommended	Bonus
2)	PRV observations of sun	Collect solar data for at least of half days each year for one solar cycle from a least 2 high priority instruments* and place in public archive. (Data collection + ~2 FTEs/year, GS or PD-level for associated analysis)	Collect solar data as many days as practical from three or more high priority instruments* as long as instruments are in operation and place in public archive. (Data collection + ~1 FTE/year/instrument, GS or PD-level for associated analysis)	Fund solar telescopes for additional high-priority instruments.
1)	PRV observations of RV benchmark stars	Collect data on 4 RV benchmark stars from at least 2 high priority instruments* and place in in public archive. For cadence see Group D requirement. (Data collection + ~2 FTEs/year, GS or PD-level for associated analysis)	Collect data on 4-10 benchmark stars from three or more high priority instruments* and place in in public archive. For cadence see Group D requirement. (Data collection + ~1 FTEs/year/instrumnt, GS or PD-level for associated analysis)	Standardize data products and data format in archive.
3)	R&A in Stellar Variability Mitigation	Develop and apply stellar variability for at least one wavelength-domain mitigation strategy and one temporal domain mitigation strategy. Verify, validate and assess utility of mitigation strategies using solar and RV benchmark star observations. (~4 FTEs/year, GS or PD level)	Develop and apply at least three stellar variability mitigation strategies for both wavelength and temporal domains. Verify, validate and assess utility of each mitigation strategy using solar and RV benchmark star observations. (~8 FTEs/year, GS or PD level)	
4)	Cross-comparisons of data from different instruments to evaluate effectiveness of mitigation strategies and to inform future spectrograph/survey designs	Compare precision of RV amplitudes as a function of instrument specifications (e.g., R, SNR, sampling, etc.), temporal instrument characteristics (e.g., absolute and relative drift), observing strategies, and orbital period, for data meeting bare minimum requirements 1 & 2. (~2 FTE/year = 0.5 FTE for each instrument + additional 1 FTE independent of any instrument team)	Compare precision of RV amplitudes as a function of instrument specifications (e.g., R, SNR, sampling, etc.), temporal instrument characteristics (e.g., absolute and relative drift), and observing strategies, orbital period, for all data, including both bare minimum and additional data collected to meet "strongly recommend" for requirements 1 & 2. (~1 FTE/year/instrument + additional 2FTE/year not associated with an instrument team)	Fund teams closely associated with each instrument and at least one team quite distant from each high-priority instrument being compared to gain benefit of each team's experience and independent perspectives
5)	Developing modular, open-source pipeline for EPRV science	Adapt existing proven RV pipeline (eg. ESPRESSO, future KPF public code) to be usable across instruments and open-source. Validate and verify result code on data from at least 2 high priority instruments. (~2FTE/year, 1 Engineer-level, 1 PD-level)	Fund development of community pipeline, based on heritage of best existing codes. Include modular design with multiple algorithms for key modules. Support multiple teams making targeted contributions to improve code. (~6FTE/year, 3 Engineer-level, 3 PD-level)	Gather instrument/testbed data on sub-pixel detector properties, calibration stability etc. for pipeline ingestion.
6)	Series of EPRV Data Challenges	Fund data challenges to compare effectiveness of strategies for: (1) mitigation of rotationally-modulated signals for sun, (2) mitigation of granulation, super-granulation and pulations for sun, (3) mitigation of combined stellar variability for other sun-like stars. (~15-24 FTEs, spread over ~6 years)	Fund a series of planned data challenges to address specific aspects of problem, using both simulated and real data, so as to compare effectiveness of strategies, learn from each exercise and improve the state-of-the-art. This would be limited by human capacity at ~1 data	Strategy for integrating expertse/contributions from international colleagues.

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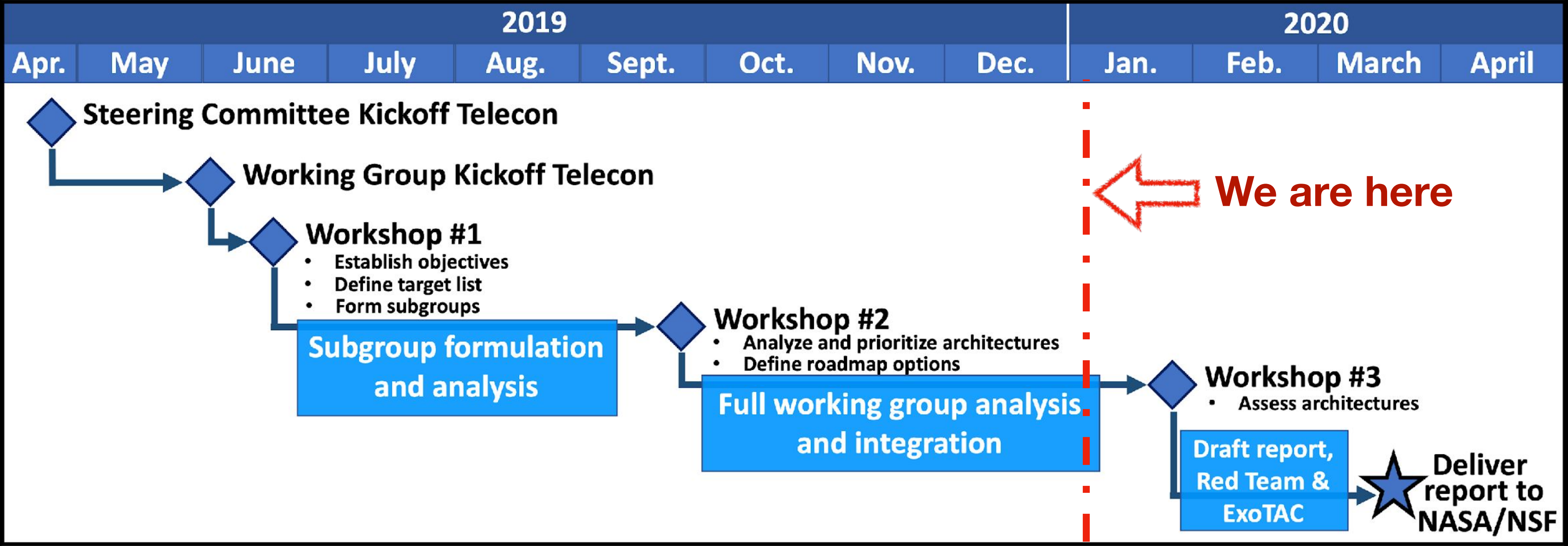
	Minimum requirement	Best	Notes
Cadence	Nightly	3x a night	Higher cadence preferred over larger sample
Resolution	100k	130-180k	
SNR	>300	800-1000	Scaling: A*R^3 + B*R^2 + C*R + D
Activity Indicator	Ca HK (390 nm)	Ca HK + more	Visible range is primary wavelength range requested. Bonus if you push to 700-900nm and beyond.
Supplementary obs.	Solar telescope		
Call to action:			
R&A Effort	https://docs.google.com/spreadsheets/d/1kA_pLMLbbXZ1rUh8WTQeKK0WBI4fxx-Y7e54g3OCuqM/edit#gid=0 Group D Recommendation		https://docs.google.com/spreadsheets/d/1kA_pLMLbbXZ1rUh8WTQeKK0WBI4fxx-Y7e54g3OCuqM/edit#gid=0 Stellar Error Budget
Plan for global coordination	Yes		
Standardised data products	Raw & processed + pipeline		

Time Line


2019
2020
Apr.
May
June
July
Aug.
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
March
April
Steering Committee Kickoff Telecon
Working Group Kickoff Telecon
Workshop #1
• Establish objectives
• Define target list
• Form subgroups
Subgroup formulation and analysis
Workshop #2
• Analyze and prioritize architectures
• Define roadmap options
Full working group analysis and integration
We are here
Workshop #3
• Assess architectures
Draft report, Red Team & ExoTAC
Deliver report to NASA/NSF

Questions?