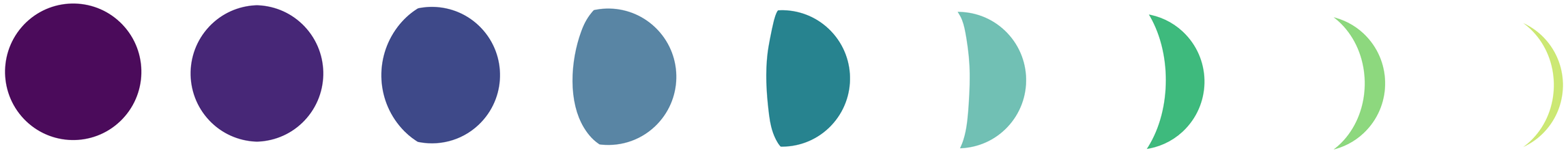
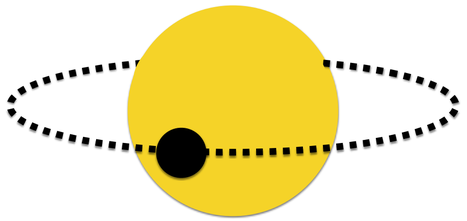
ATMOSPHERIC MODELS AT THE ONSET OF NEXT-GENERATION TELESCOPES

NATASHA E. BATALHA, MARK S. MARLEY, NIKOLE K. LEWIS, JONATHAN FORTNEY



LANDSCAPE OF EXO-ATMOSPHERE CODES



VPL's SMART code

Fortney/Marley Codes

NEMESIS; Barstow, Irwin+

ATMO; Tremblin+

Madhusudhan & Seager

CHIMERA;Line+

Benneke & Seager

MassSpec; De Witt & Seager

TauRex;Waldmann+

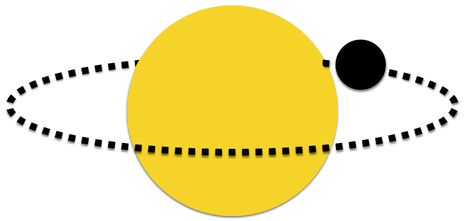
ExoTransmit;Kempton

PLATON;Zhang+

BART; Harrington+

petitRADTRANS;Molliére+

HELIOS;Malik+



VPL's SMART code

Fortney/Marley Codes

NEMESIS; Barstow, Irwin+

CHIMERA;Line+

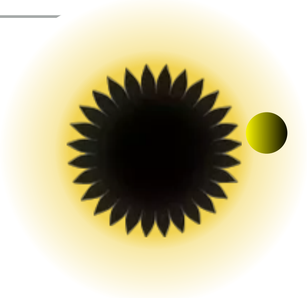
TauRex;Waldmann+

PLATON;Zhang+

petitRADTRANS;Molliére+

HELIOS;Malik+

ATMO; Tremblin+



VPL's SMART code

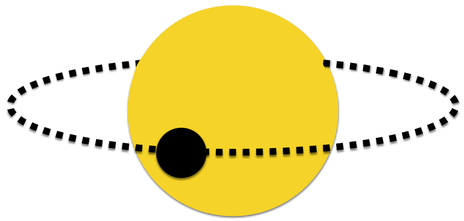
NEMESIS; Irwin+

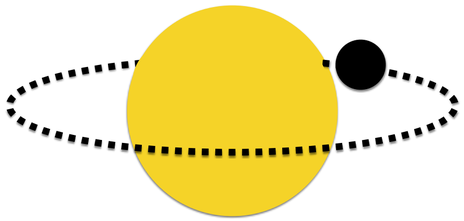
Lacey/Madhusudhan/Burrows

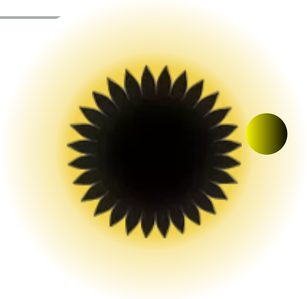
Marley/Cahoy/Lupu/ Feng

Natasha Batalha

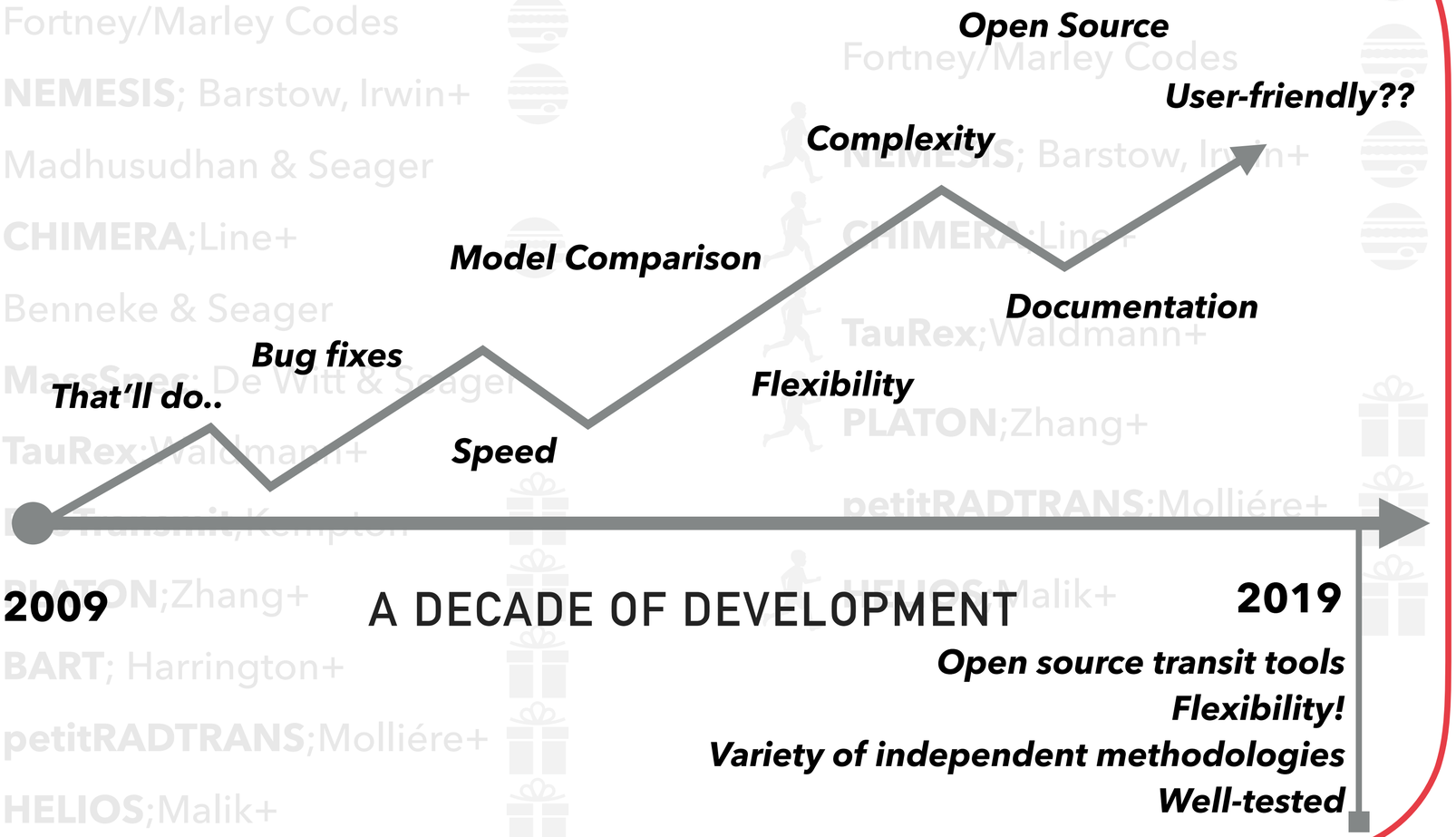
LANDSCAPE OF EXO-ATMOSPHERE CODES







TRANSITS



A DECADE OF DEVELOPMENT

Open source transit tools
Flexibility!
Variety of independent methodologies
Well-tested

VPL's SMART code

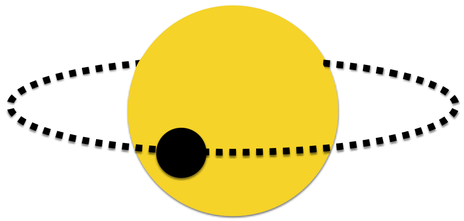
NEMESIS; Irwin+

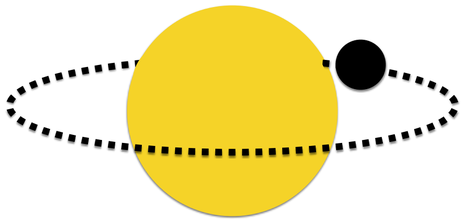
Lacey/Madhusudhan/Burrows

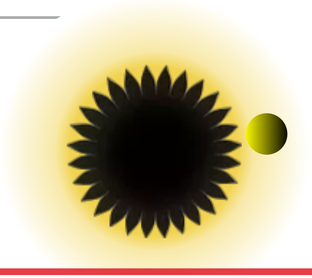
Marley/Cahoy/Lupu/
Feng

Natasha Batalha

LANDSCAPE OF EXO-ATMOSPHERE CODES







TRANSITS

REFLECTED LIGHT

That'll do..

Bug fixes

Speed

Model Comparison

Flexibility

Complexity

Documentation

Open Source

User-friendly??

- ***WFIRST design***
- ***Future mission concepts***
- ***Ground based obs.***
- ***Increase in complexity !***

2009

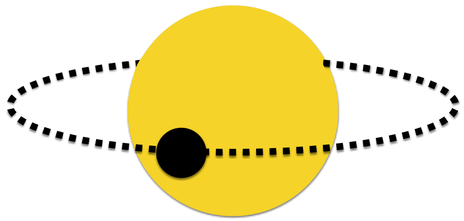
2019

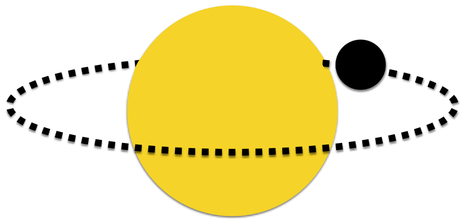
2025

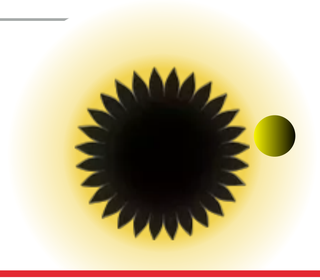
A DECADE OF DEVELOPMENT

Open source transit tools
Flexibility!
Variety of independent methodologies
Well-tested

SCATTERING IN REFLECTED LIGHT IS HARD

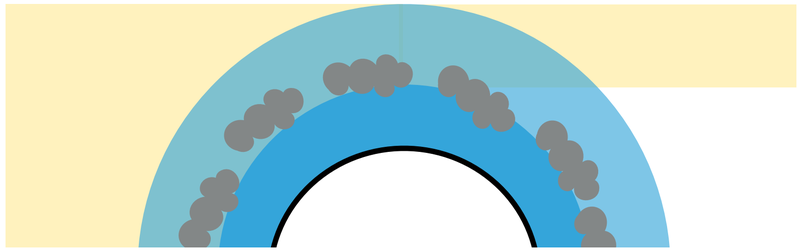






Clouds are sources of extinction (1 param)

P_{cld}

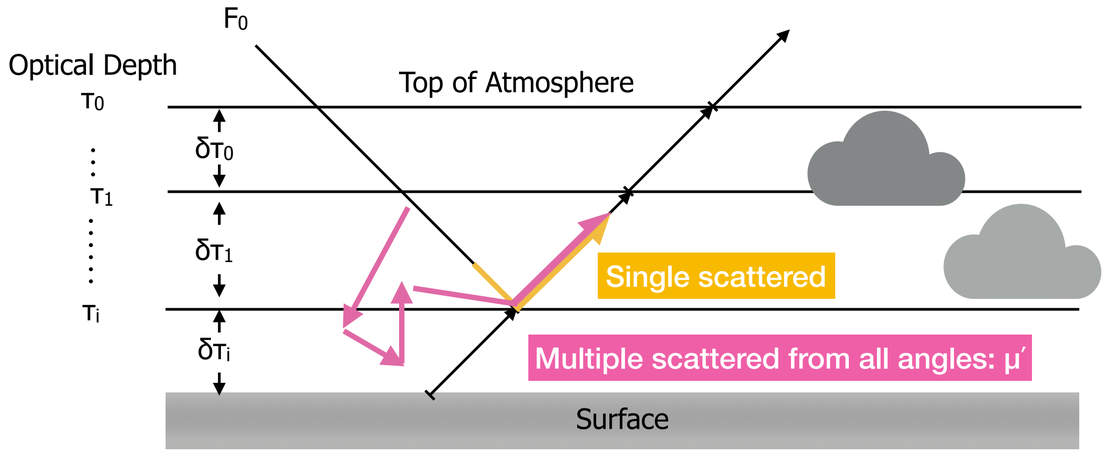


Scattering treated as cross section (2 param)

$\propto \sigma_r \lambda^{-a}$

Clouds scatter ! (7+ params)

$ncld, g, f, \omega, \tau, P_{cld}, dP_{cld}$



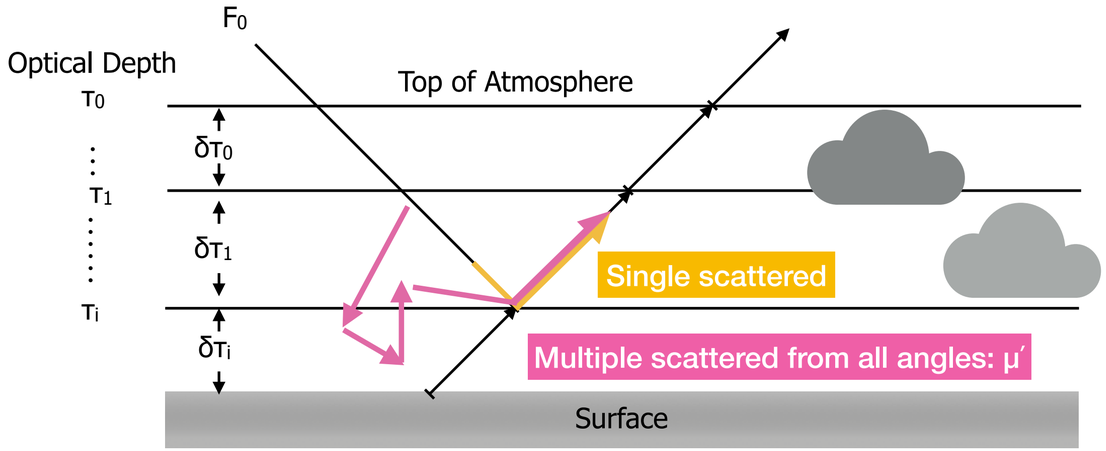
# of approximations begins to increase...

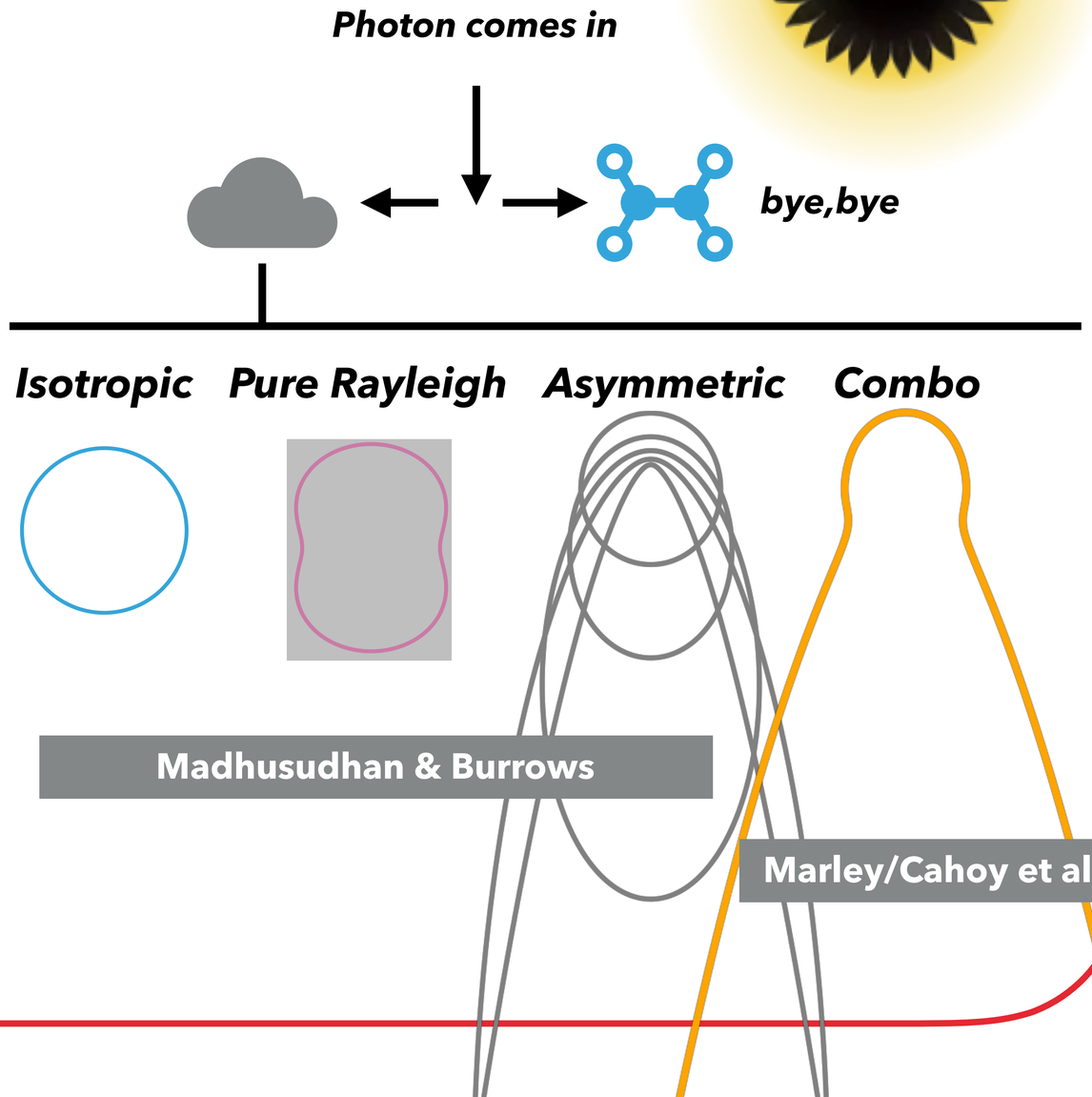
AXIS OF COMPLEXITY

SCATTERING IN REFLECTED LIGHT IS HARD

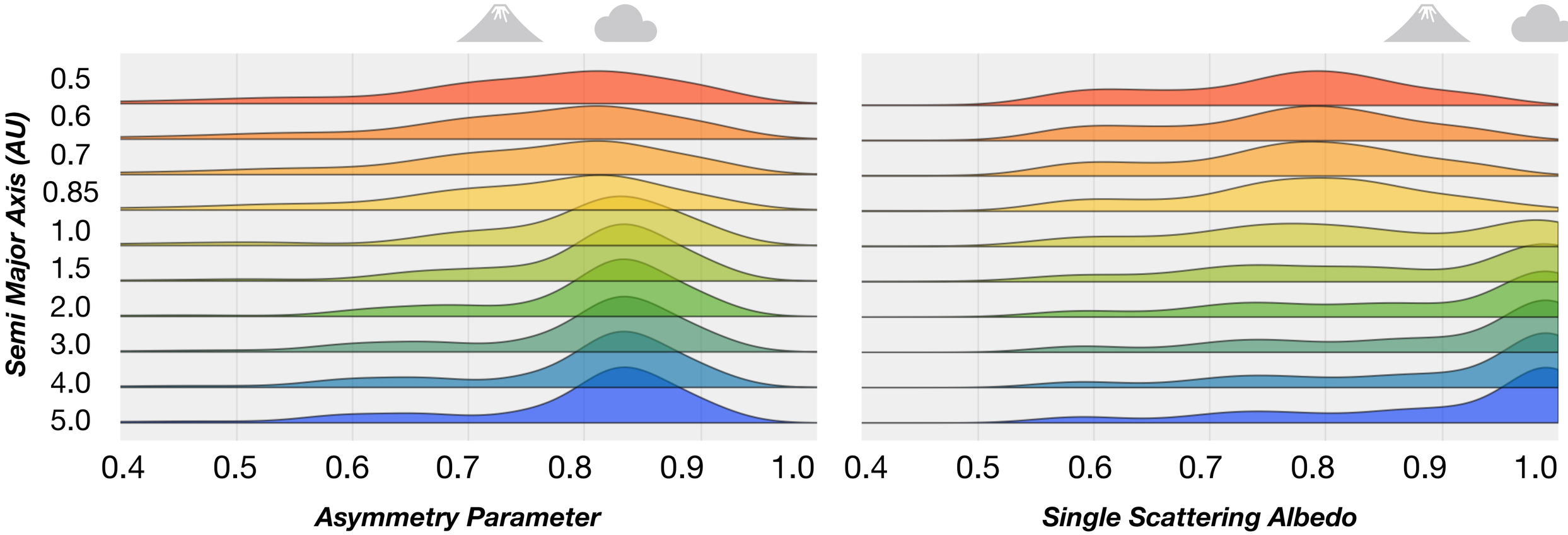
Clouds scatter ! (7+ params)

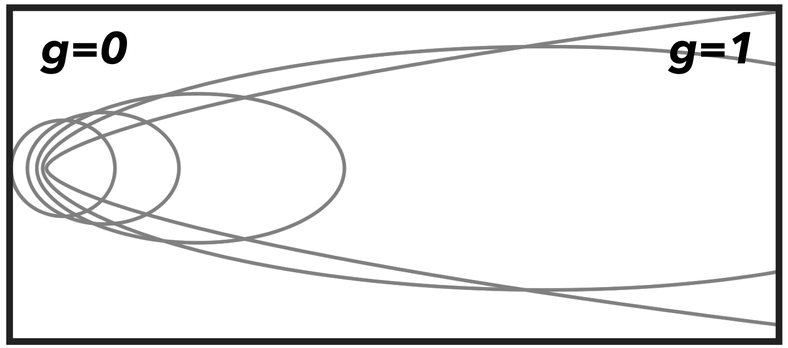
ncld, g, f, ω, τ, P_{cld}, dP_{cld}

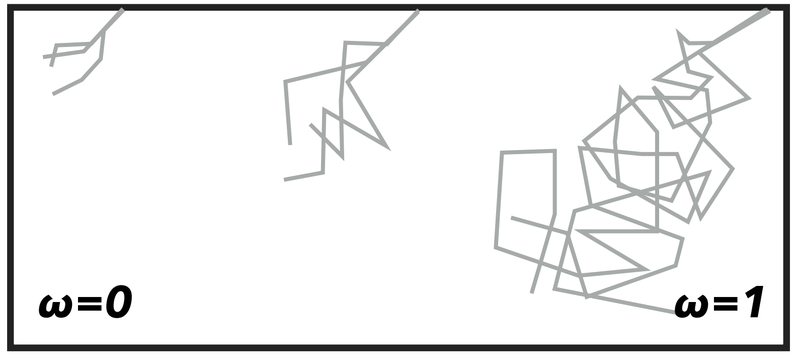




SCATTERING PROPERTIES IN EXOPLANETS WILL BE DIVERSE

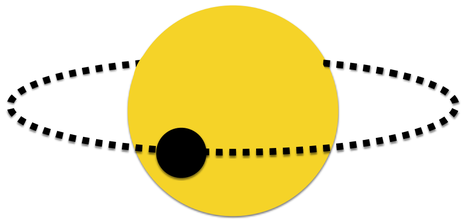


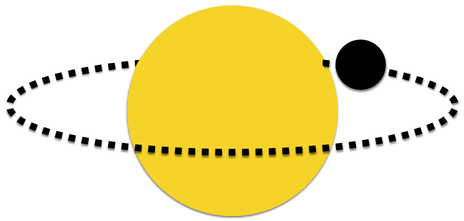


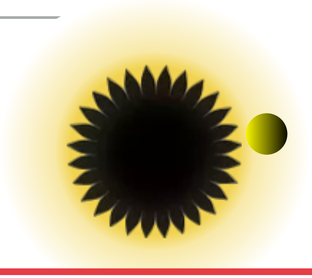


Natasha Batalha

LANDSCAPE OF EXO-ATMOSPHERE CODES







TRANSITS

REFLECTED LIGHT

That'll do..

Bug fixes

Speed

Model Comparison

Flexibility

Complexity

Documentation

Open Source

User-friendly??

- ***We need versatility!***
- ***WFIRST design***
- ***Future mission concepts***
- ***Ground based obs.***

2009

A DECADE OF DEVELOPMENT

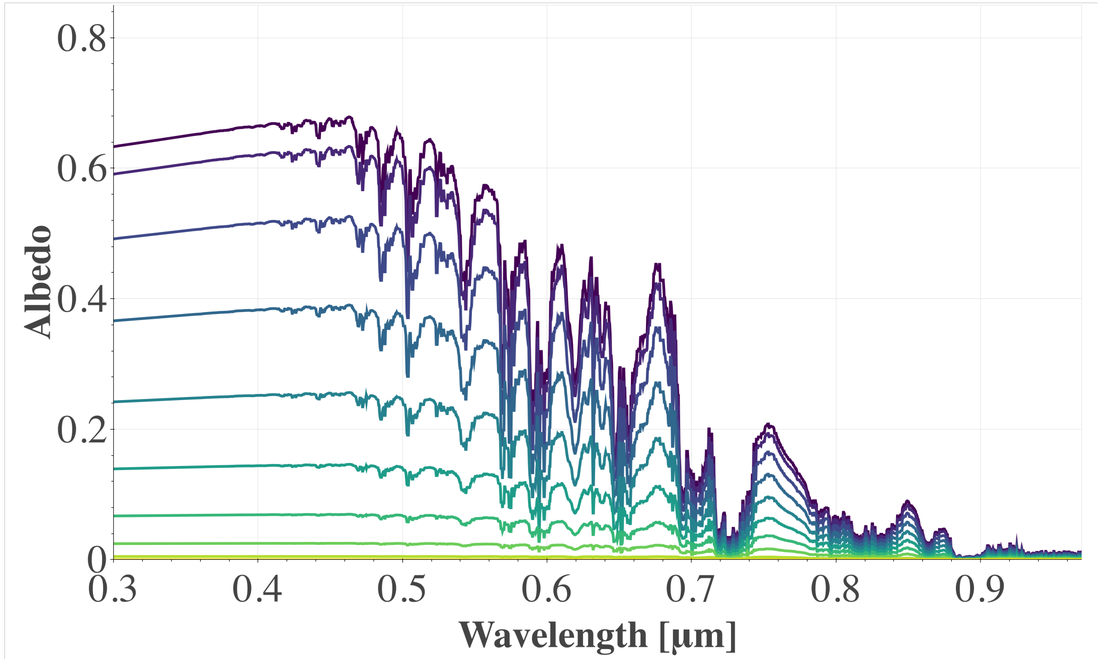
2019

Open source transit tools
Flexibility!
Variety of independent methodologies
Well-tested

2025

COMPUTATION OF PHASE-DEPENDENT REFLECTED LIGHT SPECTROSCOPY WITH…

- Written in python but has retained the speed of the fortran
- Original Marley methodology with several updates
- Docs: https://natashabatalha.GitHub.io/picaso
- Math: https://natashabatalha.Github.io/picaso_dev
- Front end in development



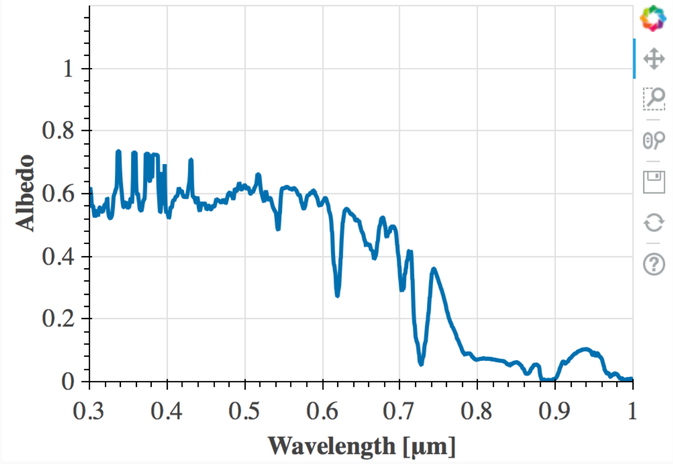
5-ISH LINES TO A SPECTRUM

```
#phase angle
start_case.phase_angle(0) #radians

#define gravity
start_case.gravity(gravity=25, gravity_unit=u.Unit('m/(s**2)')) #any astropy units avai
lable

#define star
start_case.star(5000,0,4.0) #pysynphot database, temp, metallicity, logg
```

```
start_case.atmosphere( df = pd.DataFrame({'pressure':np.logspace(-6,2,60),
                                          'temperature':np.logspace(-6,2,60)*0+2
00,
                                          "H2":np.logspace(-6,2,60)*0+0.837,
                                          "He":np.logspace(-6,2,60)*0+0.163,
                                          "CH4":np.logspace(-6,2,60)*0+0.000466}
)
                      )
```

```
wno_ch4, alb_ch4 = start_case.spectrum()
```

```
show(jpi.spectrum(wno_ch4, alb_ch4, plot_width=500))
```

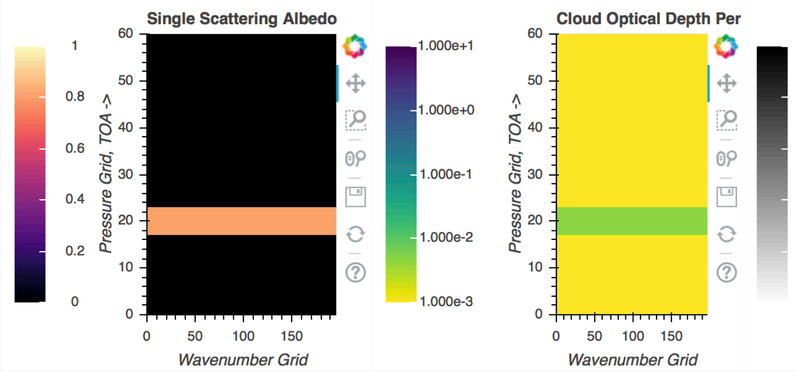


Handles everything from "***simple***" or ***parameterized*** inputs to full ***modeled*** atmospheric profiles that can be read in as dictionaries, arrays, files, etc.

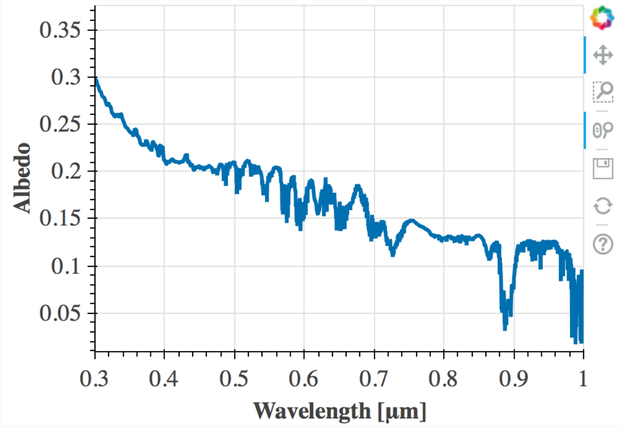
```
In [10]:
#set model clouds, note these are lists since you can specify multiple cloud layers
case1.clouds( g0=[0.9], w0=[0.8], opd=[0.5], p = [1], dp=[5])
```

Plotting simple cloud profile

```
In [11]:
nwno = 196 #this is the default number for A&M cloud code (see below if your wave grid i
s different)
nlayer = 60 #one less than the number of PT points in your input
show(jpi.plot_cld_input(nwno, nlayer,df=case1.inputs['clouds']['profile']))
```




```
In [12]:
wno, alb = case1.spectrum()
show(jpi.spectrum(wno, alb, plot_width=500))
```



Ditto for clouds. "Simple" to fully modeled.

The Radiative Transfer in PICASO

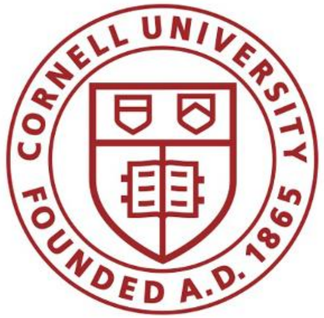
An explanation of the code.

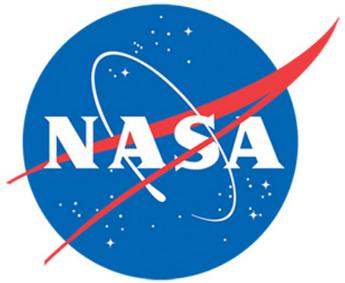
Scroll Down

Truly user-friendly atmosphere codes ***must solve*** inaccessible opacity problem.

Downloadable tar file? But what about updates? I don't want 100s Gigs of opacities! What about availability of disk space?

"A COMMUNITY TOOL FOR COMPUTING, VISUALIZING, AND MANIPULATING MOLECULAR & ATOMIC OPACITIES"





ExoMol

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

Natasha Batalha

Science PI

Nikole Lewis

PI

Mark Marley

Richard Freedman

Iouli Gordon

Jonathan Tennyson

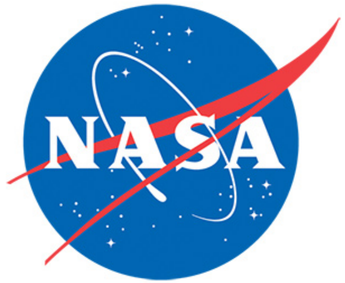
Sergey Yurchenko

Clara Sousa-Silva

Jeff Valenti

Acronym pending. Suggestions encouraged...

"A COMMUNITY TOOL FOR COMPUTING, VISUALIZING, AND MANIPULATING MOLECULAR & ATOMIC OPACITIES"



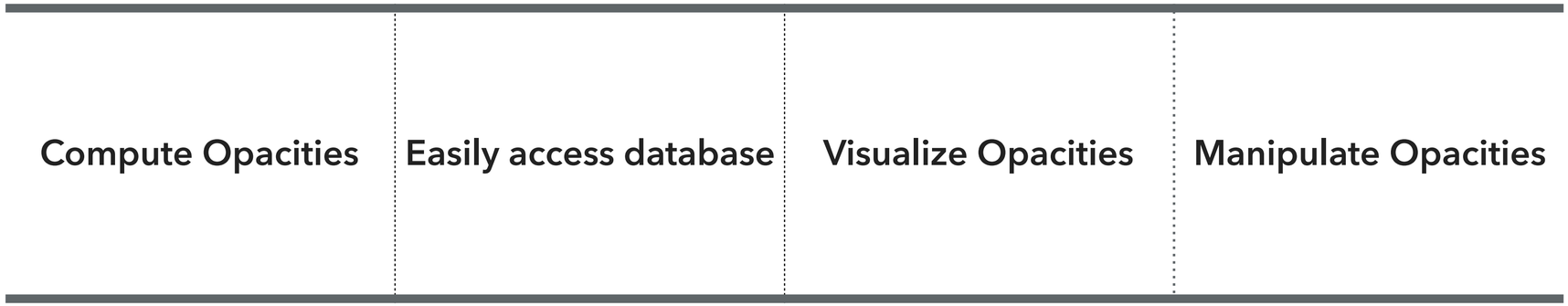
ExoMol

Richard Freedman

HAPI

ExoCross

STEPPING STONE TO INCREASING ACCESSIBILITY OF OPACITIES



Novice

"Where does water absorb?"

Theorist

"I need opacities for my model"

Retrievals

"Do changes in opacity sources change retrieved abundances?"

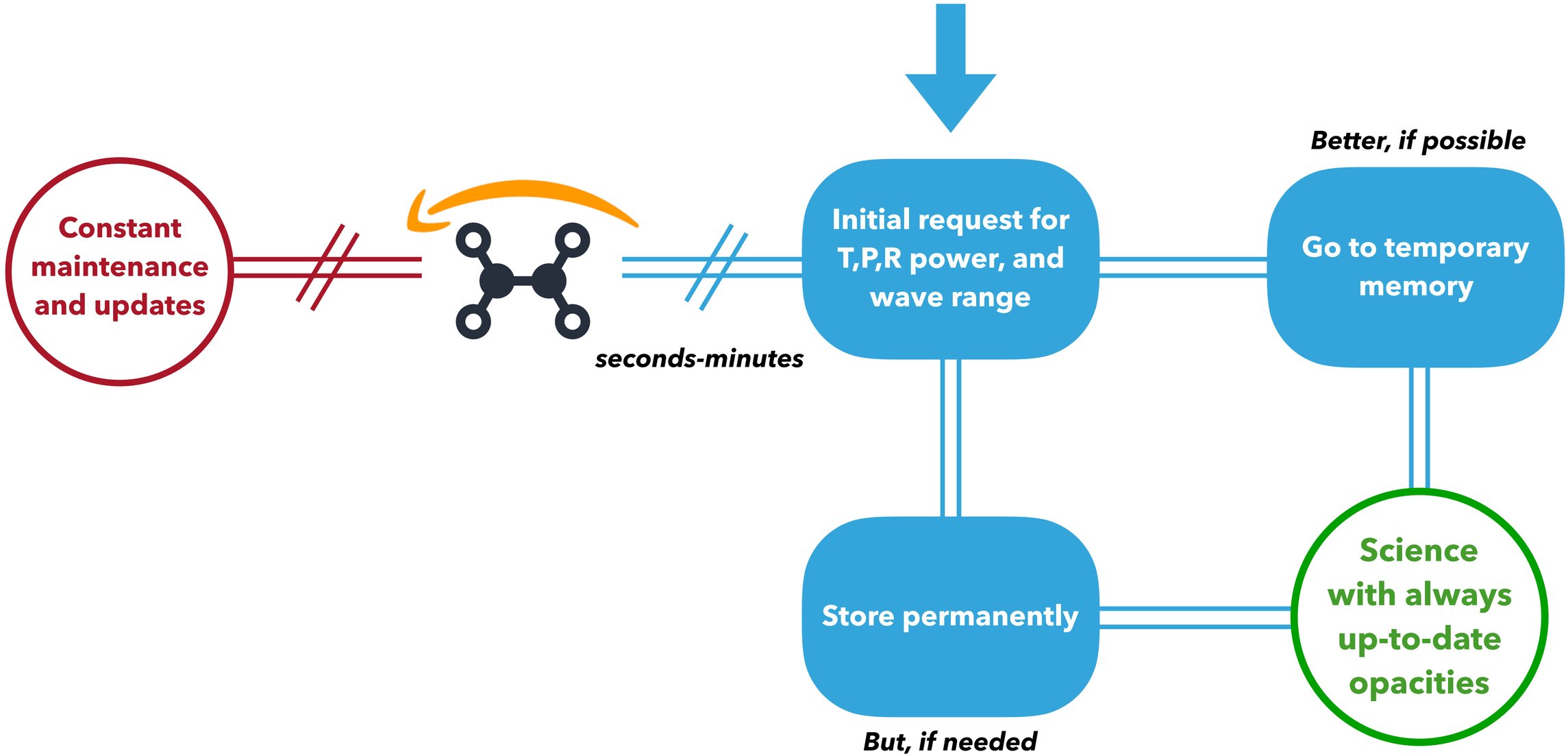
Observer

"What JWST mode do I use for detecting C_2H_2?"

Expert in Opacities

"I want to create my own line profile and contribute a pipeline module"

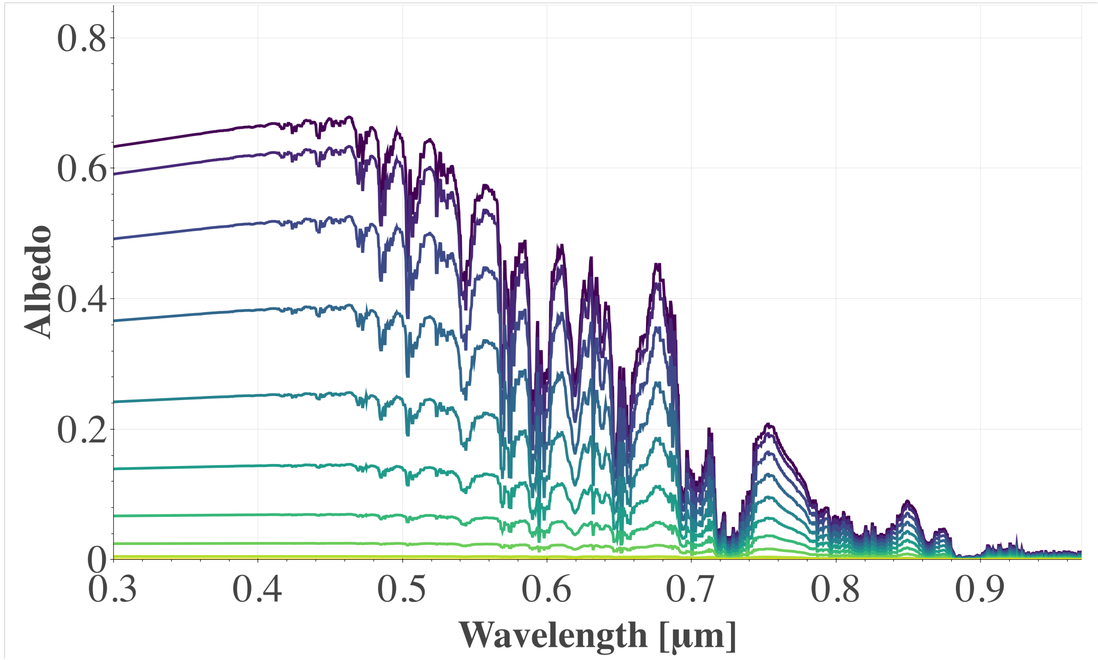
USER STARTS HERE



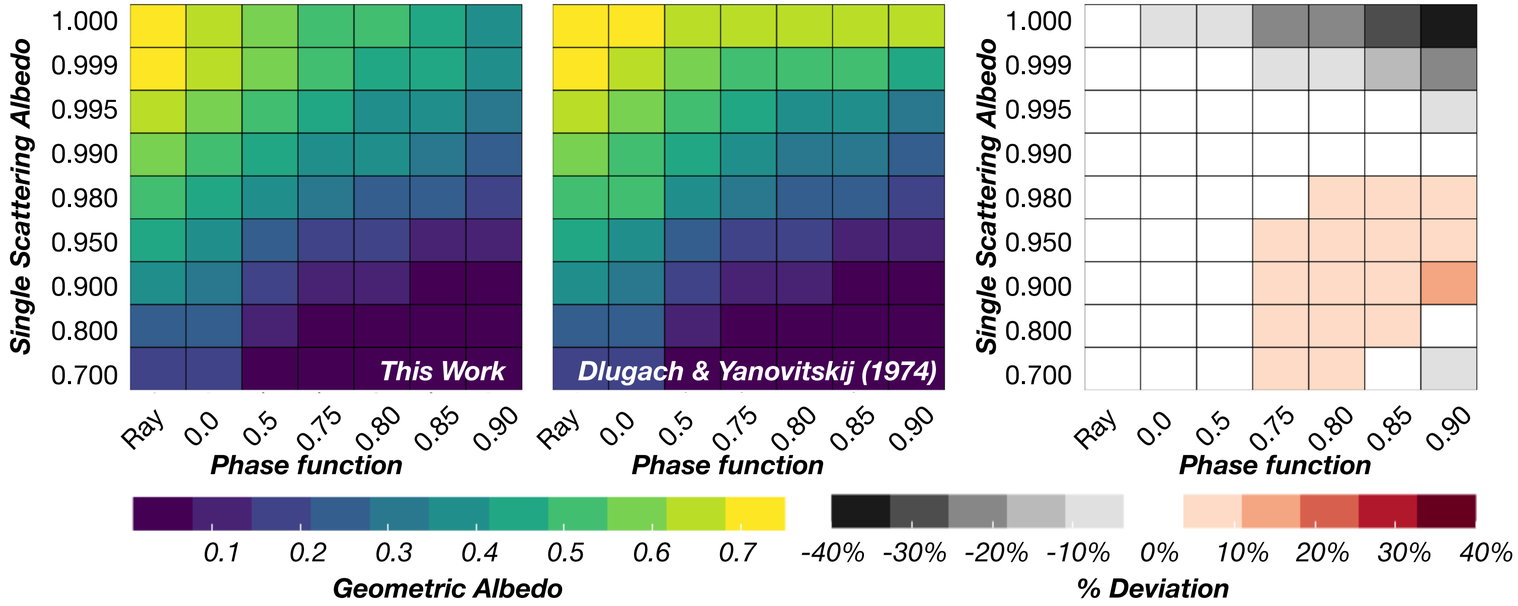
Other ideas for increased productivity?

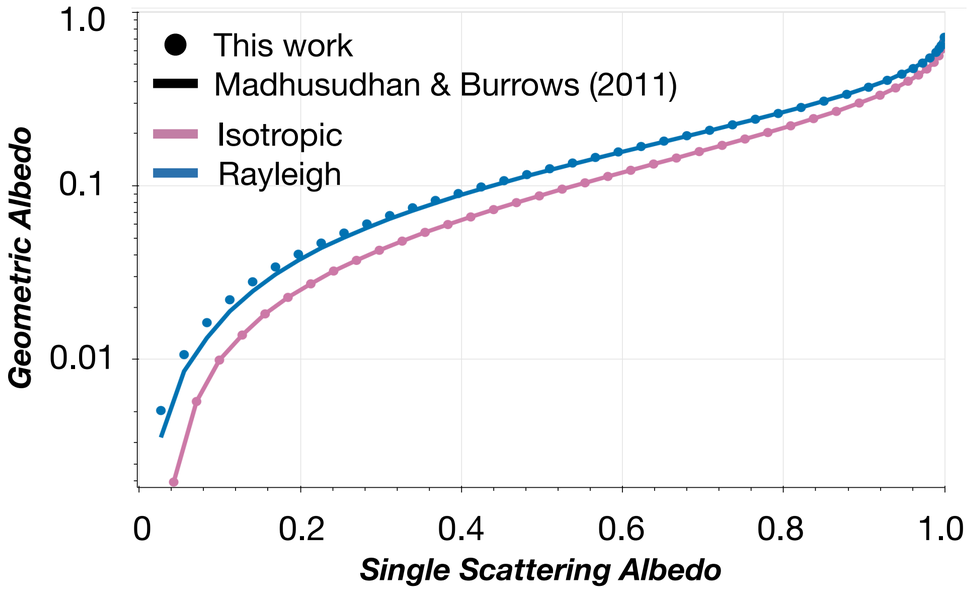
COMPUTATION OF PHASE-DEPENDENT REFLECTED LIGHT SPECTROSCOPY WITH…

- ***Highly accessible ! Yay!***
- But we also want something that is robust, reliable.



TEST MODULES TO PROPERLY BASELINE WITH OLDER AND NEWER CODES





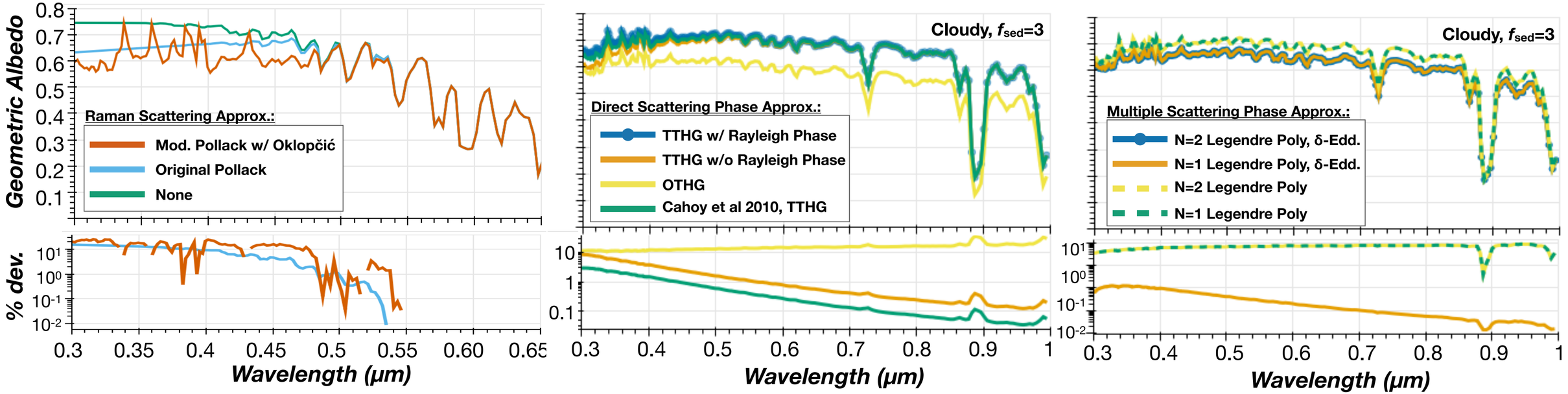
CODES AGREE MOSTLY WITHIN 10% EXCEPT AT HIGH ASYMMETRY OR LOWER SSA

CAN'T BASELINE TO OTHER CODES IF YOU CAN'T COMPARE APPLES TO APPLES

COMBATING COMPLEXITY WITH TRANSPARENT ASSUMPTIONS

```
In [3]: print('Options for Direct Scattring Phase: ', jdi.single_phase_options())

        print('Options for Multiple Scattring Phase: ', jdi.multi_phase_options())

        print('Options for Raman Scattring: ', jdi.raman_options())
```

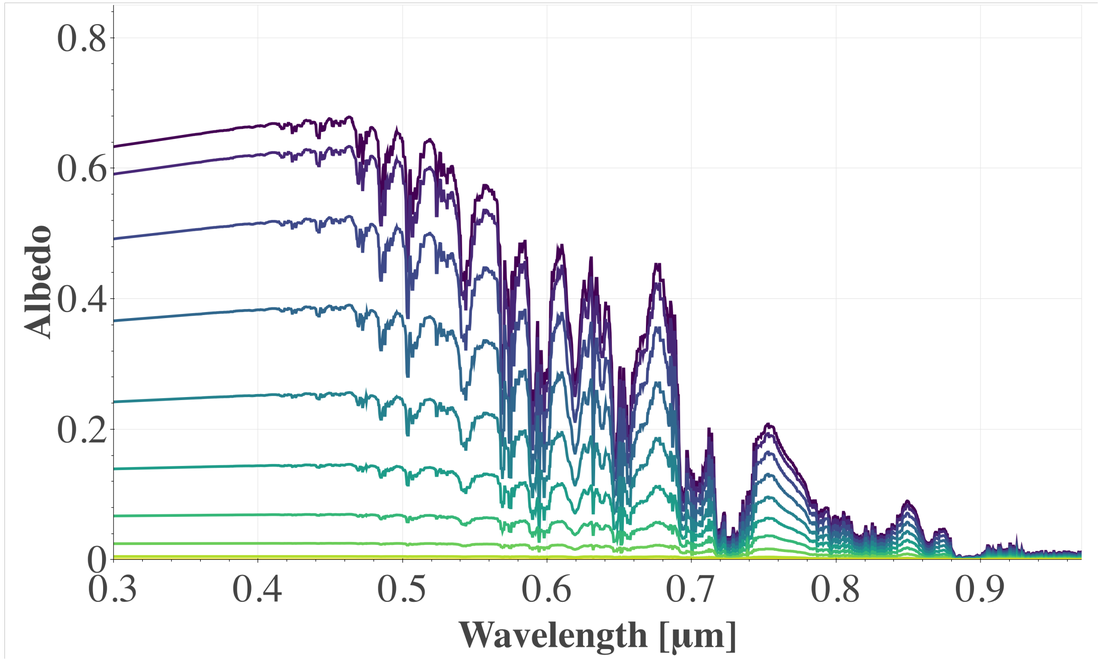
```
Can also set functional form of forward/back scattering in approx['TTHG_params']
Options for Direct Scattring Phase:  ['cahoy', 'OTHG', 'TTHG', 'TTHG_ray']
Can also set delta_eddington=True/False in approx['delta_eddington']
Options for Multiple Scattring Phase:  ['N=2', 'N=1']
Options for Raman Scattring:  ['oklopcic', 'pollack', 'none']
```



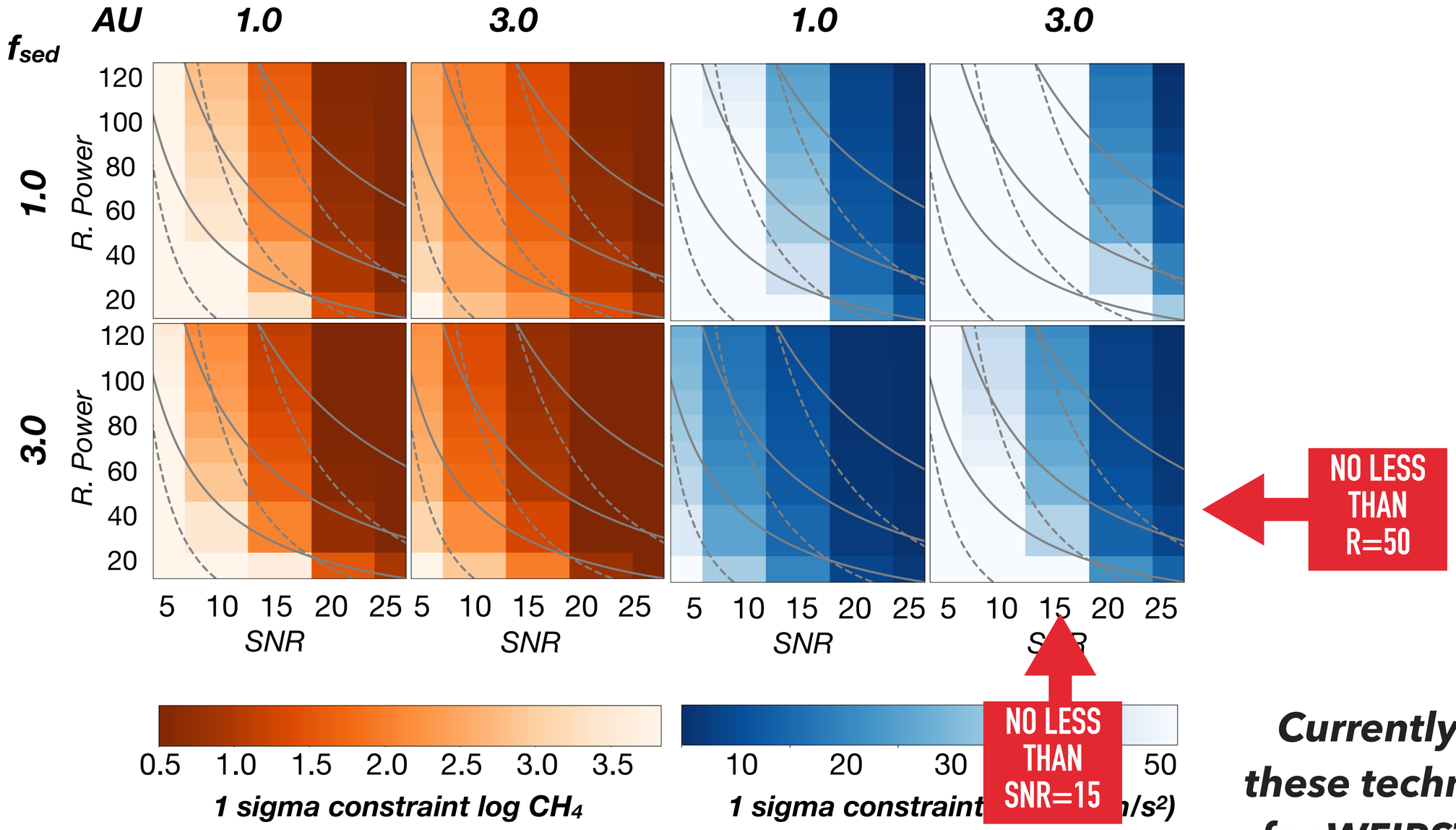
COMPUTATION OF PHASE-DEPENDENT REFLECTED LIGHT SPECTROSCOPY WITH…

PICASO

- ***Highly accessible! Yay!***
- ***Robust and Testable! Yay!***
- ***Clearly defined assumptions! Yay!***

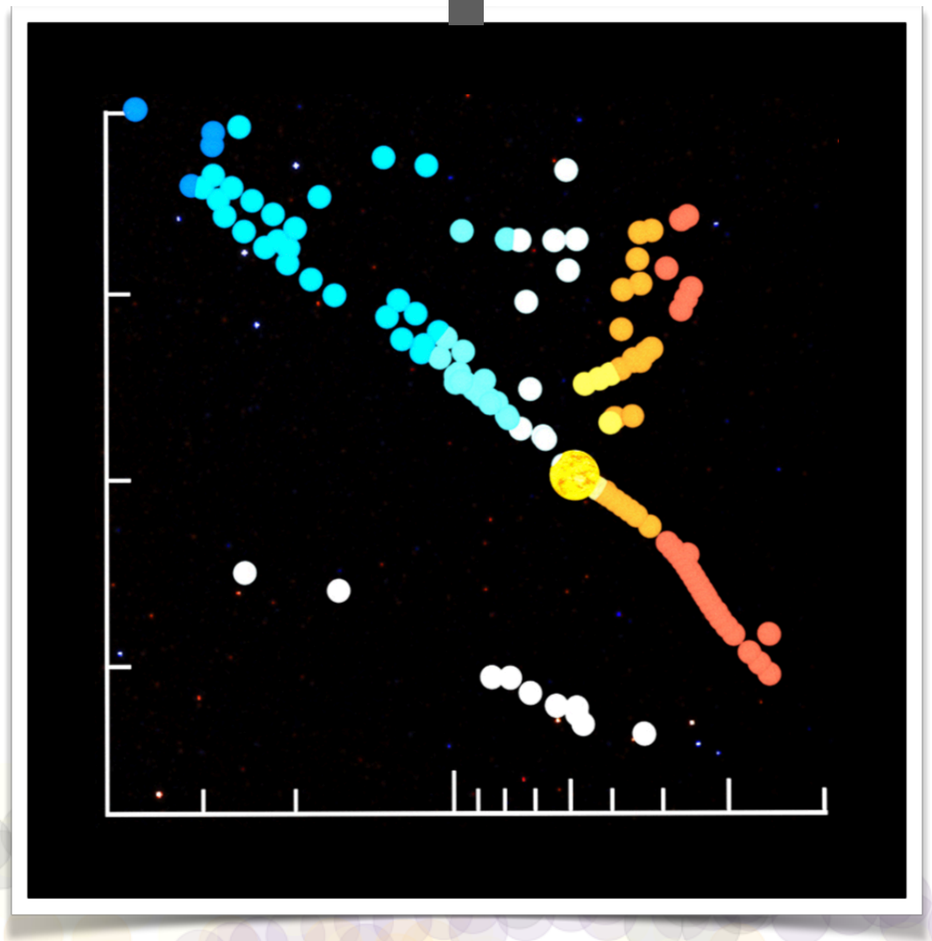


PICASO + INFORMATION CONTENT THEORY TO ASSESS MISSION DESIGN OBJECTIVES



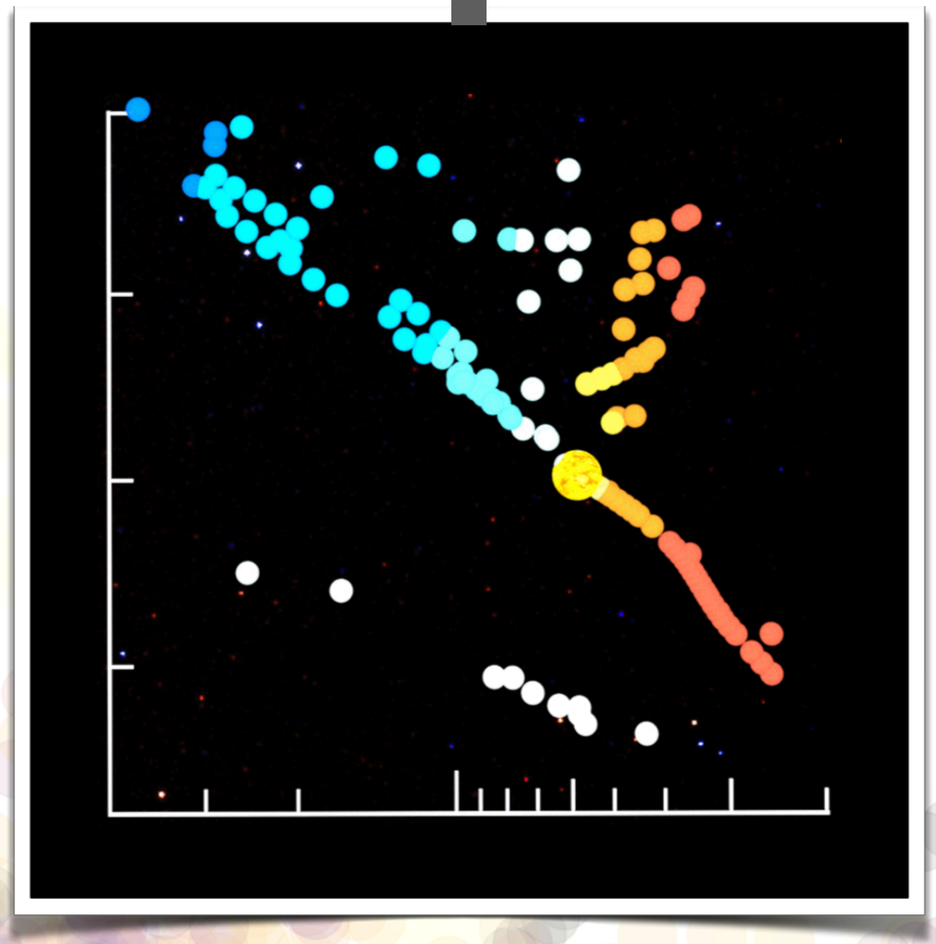
Currently using these techniques for WFIRST filter assessment.

HR Diagram

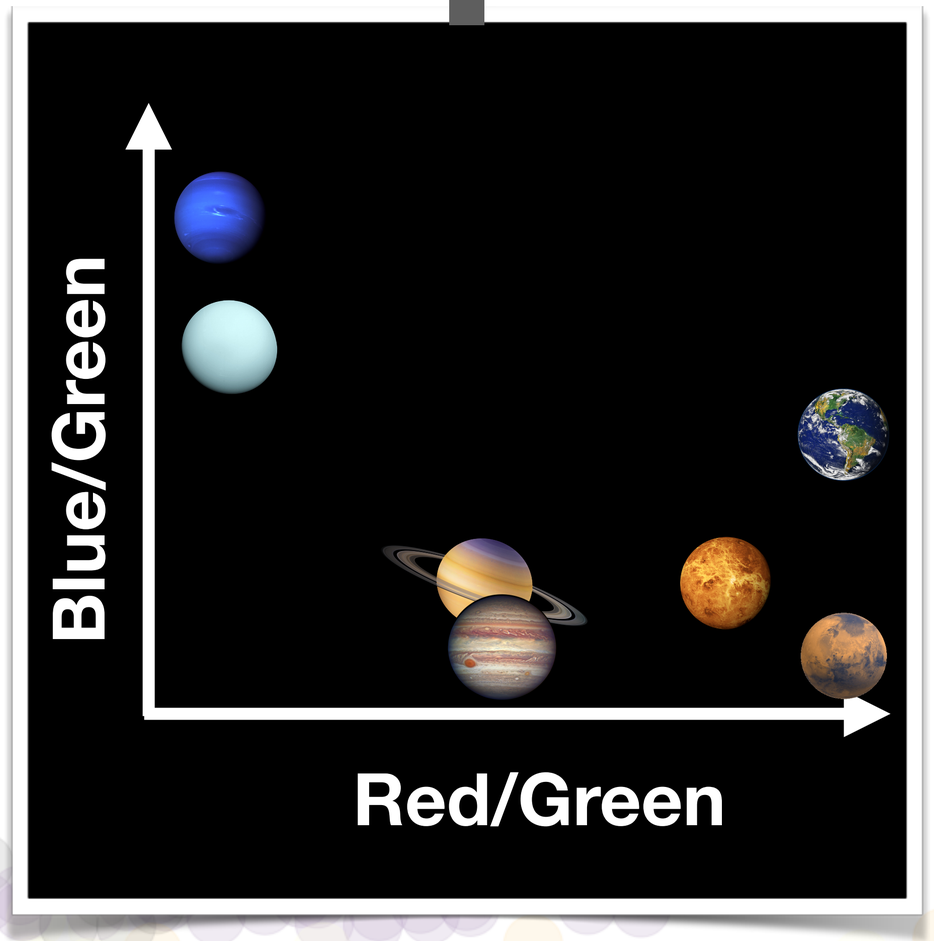


Natasha Batalha

HR Diagram

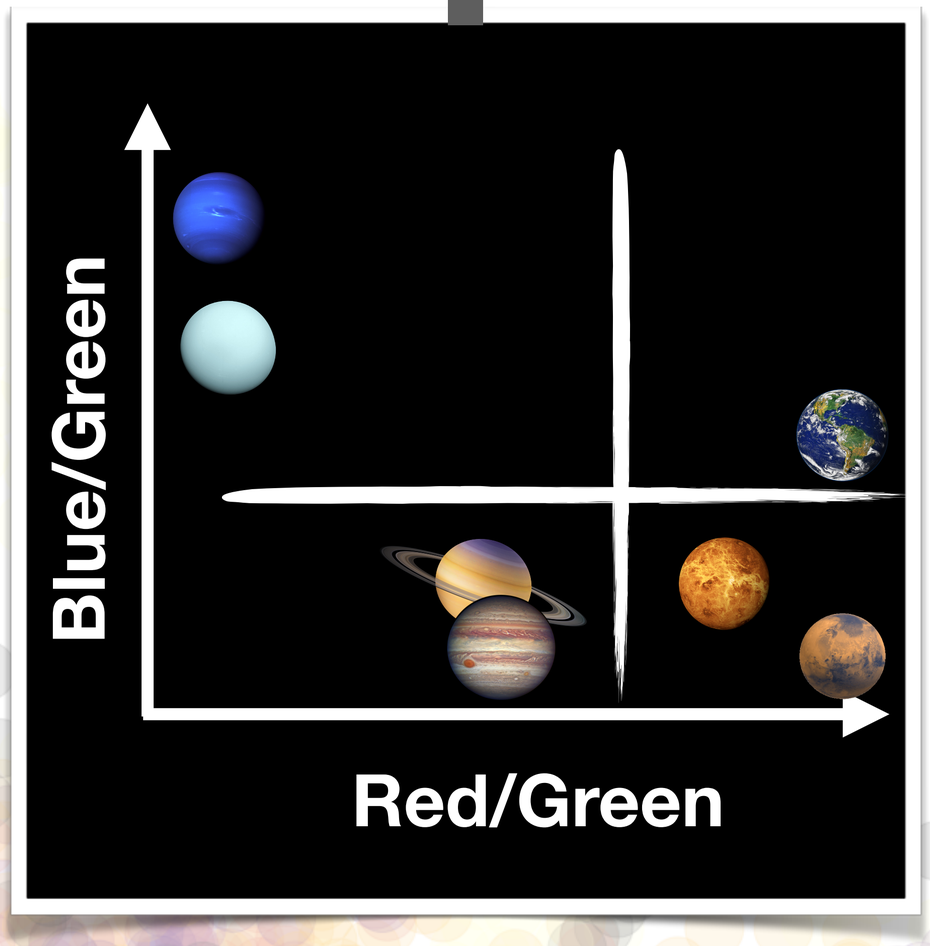


Solar System

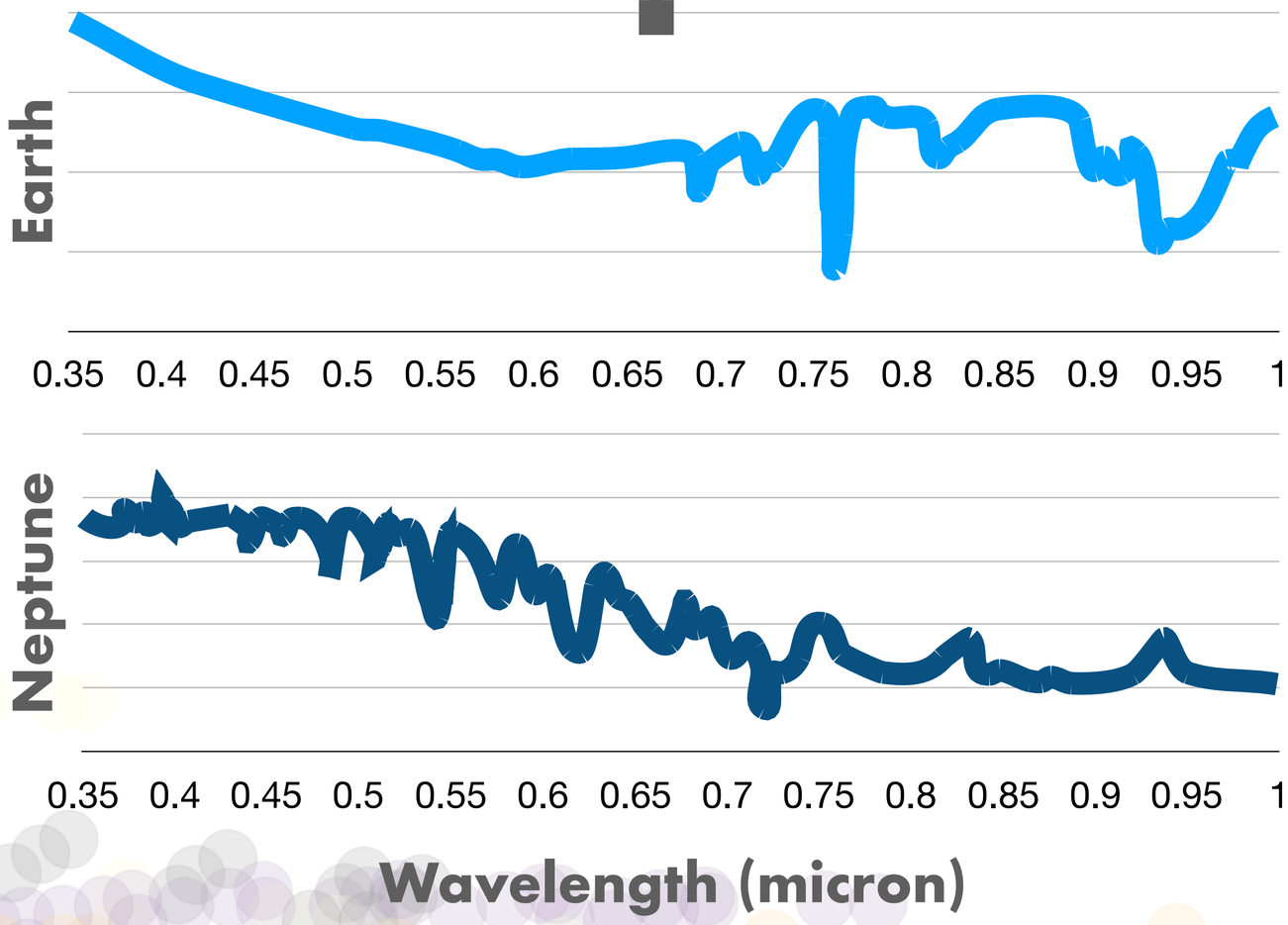


Natasha Batalha

Solar System



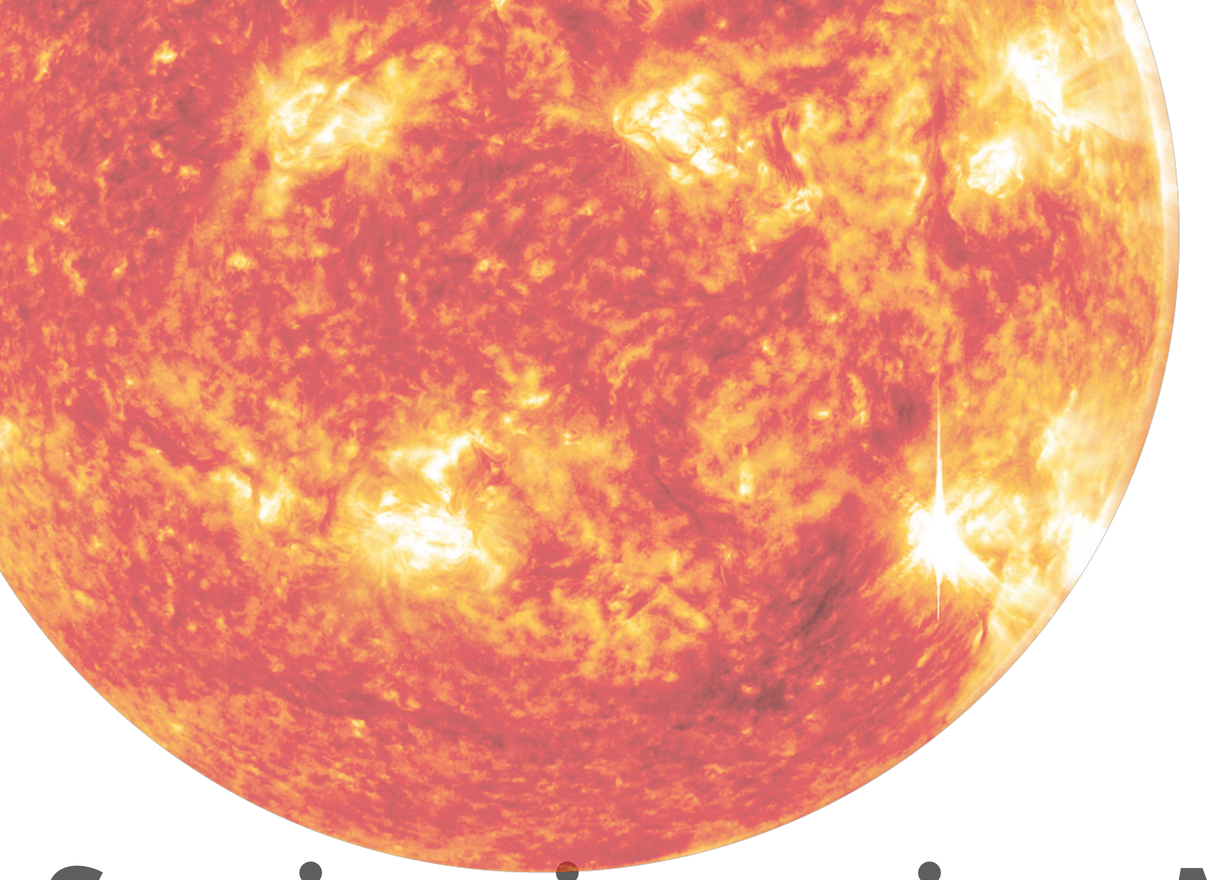
Pale Blue Dot



Goals:

- Are there any correlations between physical planet properties and WFIRST-like photometric filters
- If so, can we leverage those to create color-color plot that separate planets into physically motivated groups
- If not color-color plot, can lots of statistics do the trick?

Natasha Batalha



Semi-major axis x M/H x clouds x phase=

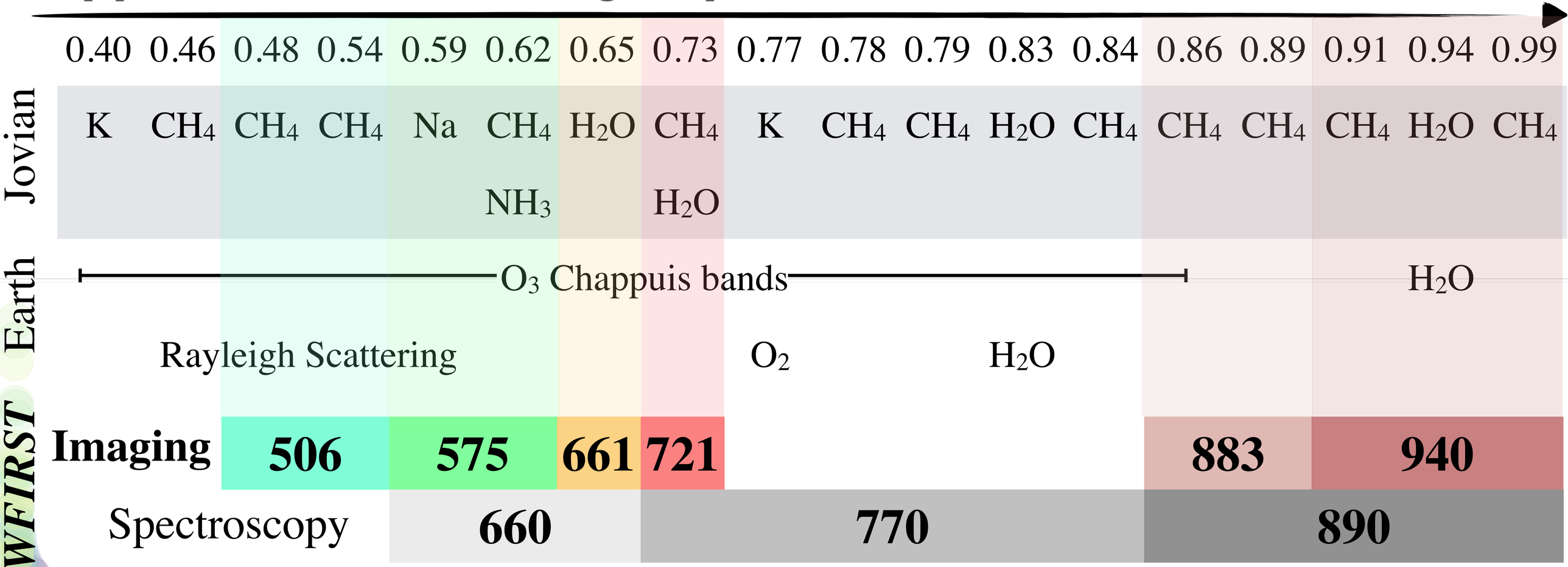
*(*temperature*)

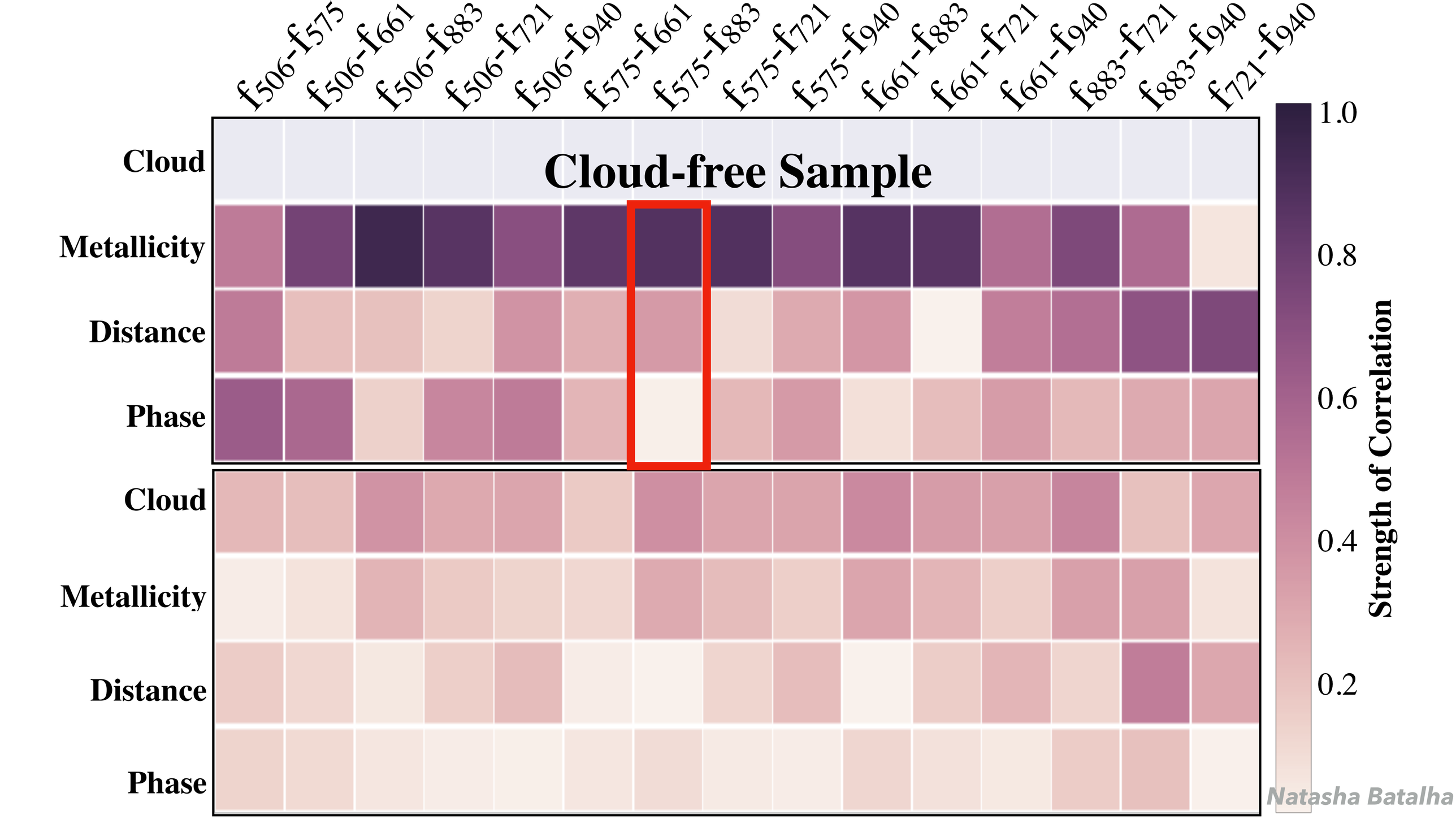
10,000 reflected light spectra

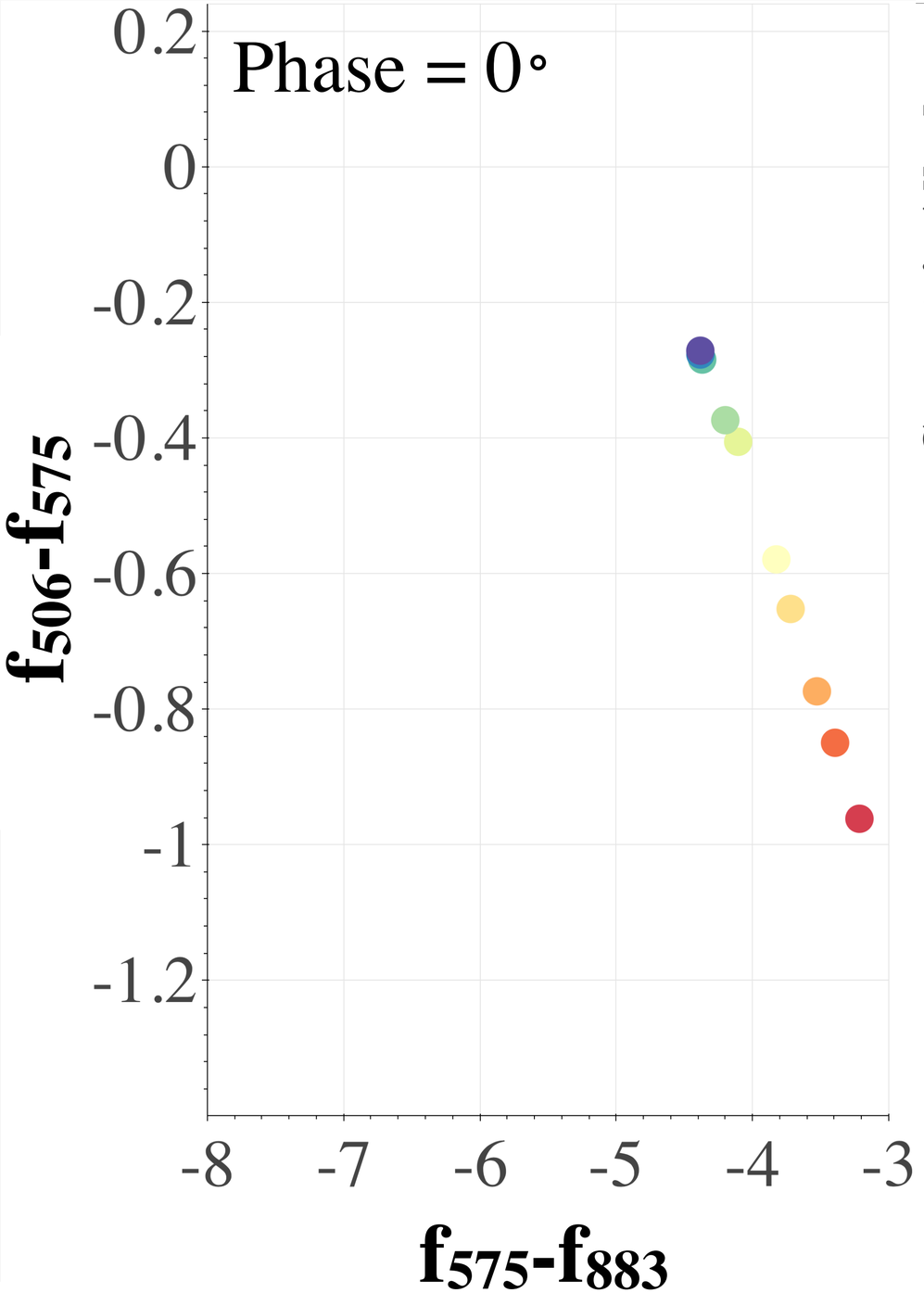
Models all on Zenodo!

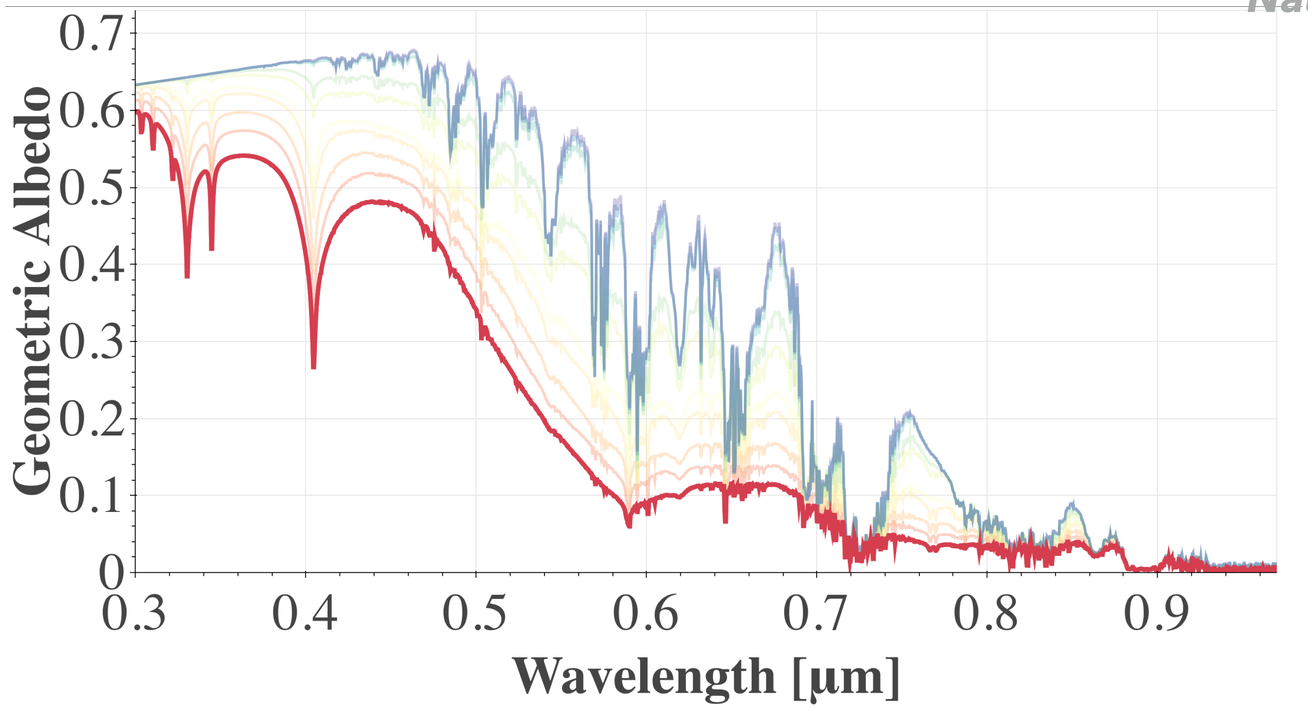
Natasha Batalha

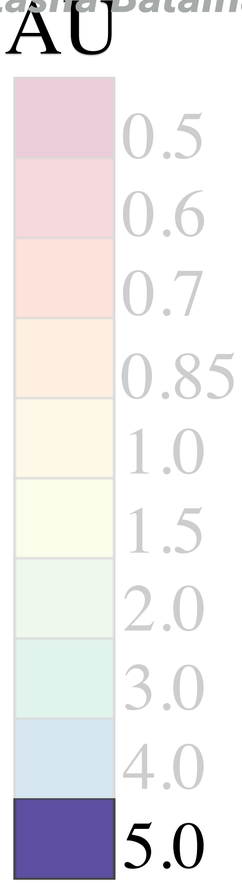
Approximate Wavelength (μm)



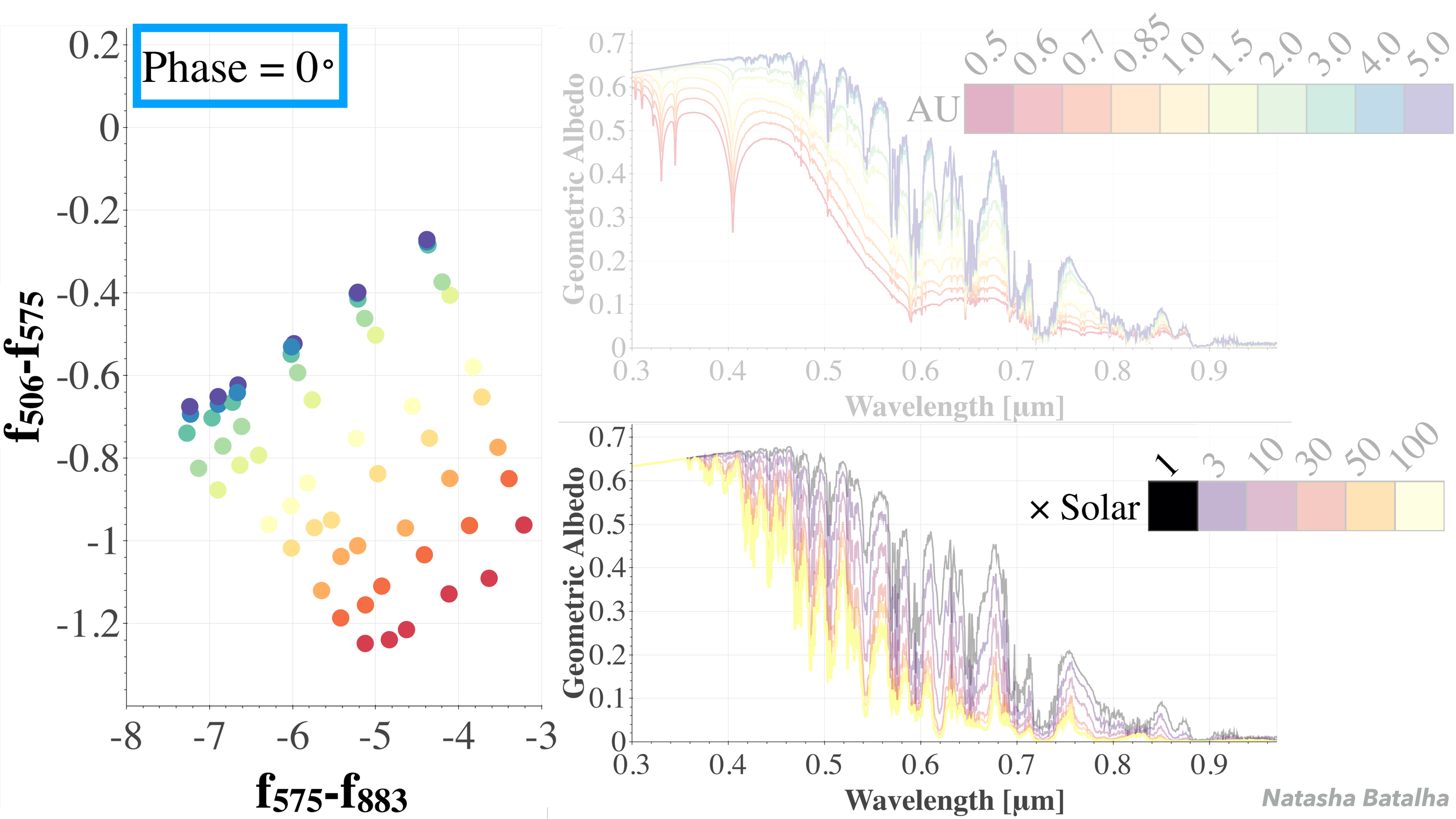

f506-f575
f506-f661
f506-f883
f506-f721
f506-f940
f575-f661
f575-f883
f575-f721
f575-f940
f661-f883
f661-f721
f661-f940
f883-f721
f883-f940
f721-f940
Cloud-free Sample
Cloud
Metallicity
Distance
Phase
Cloud
Metallicity
Distance
Phase
1.0
0.8
0.6
0.4
0.2
Strength of Correlation
Natasha Batalha



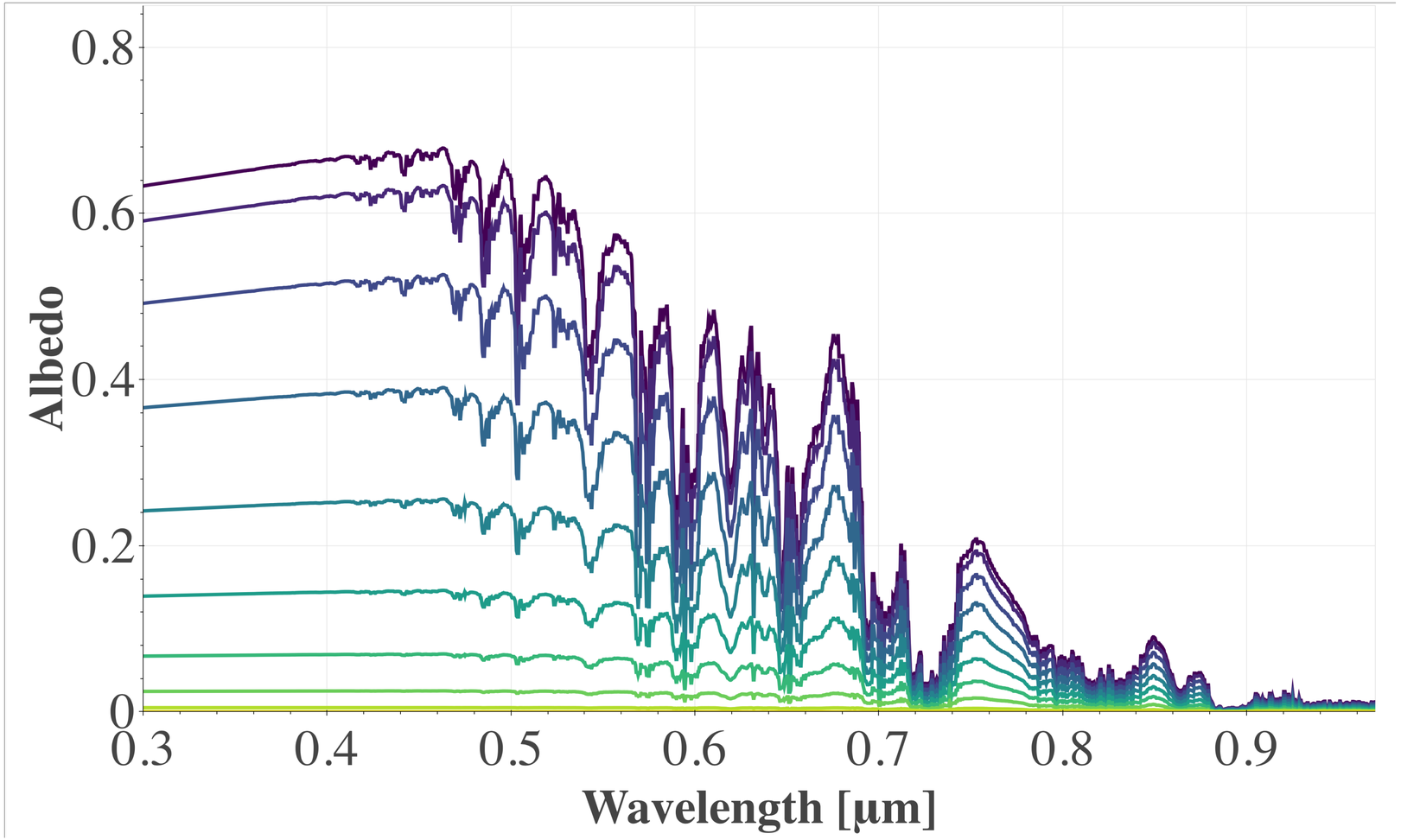


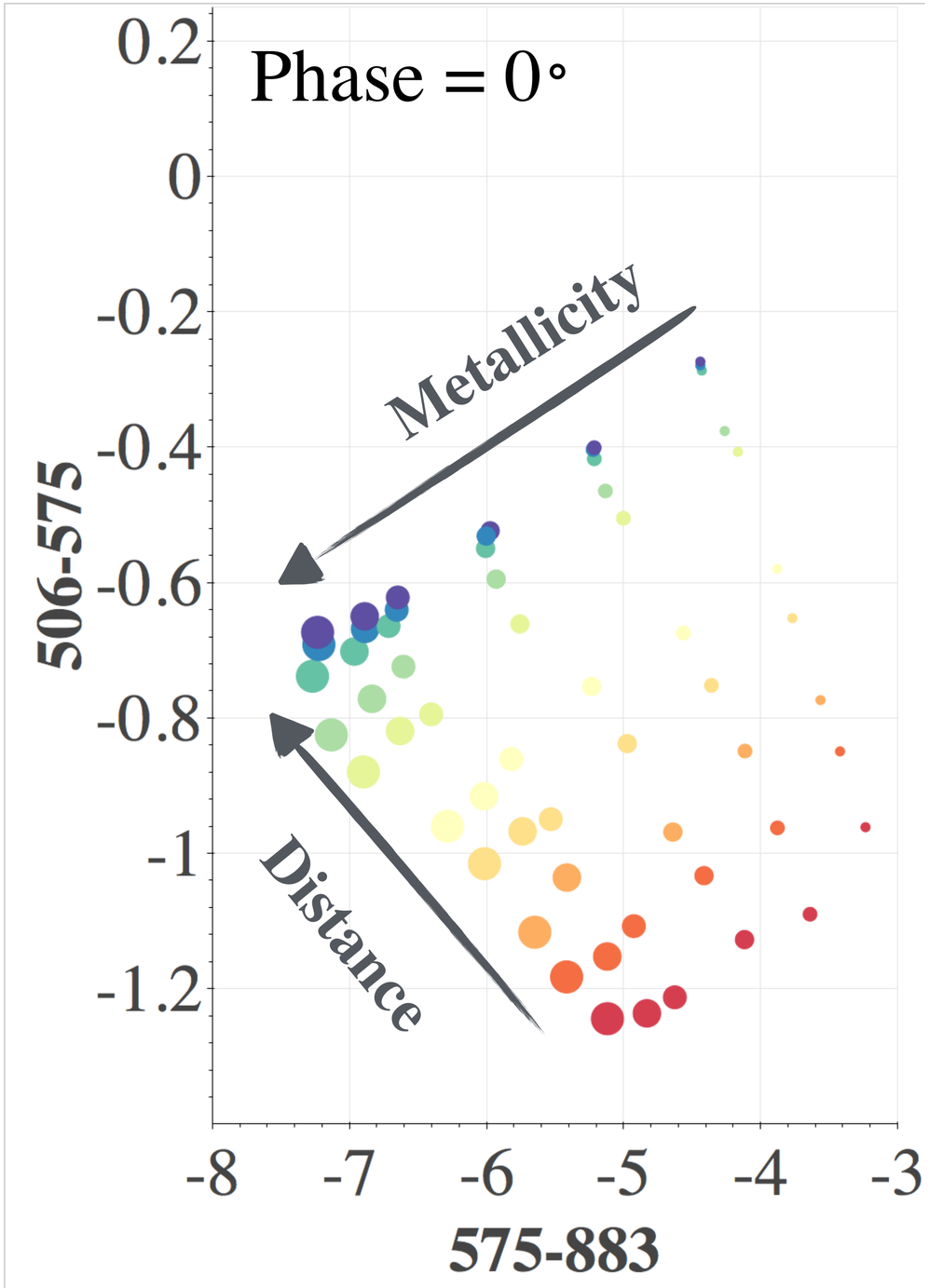


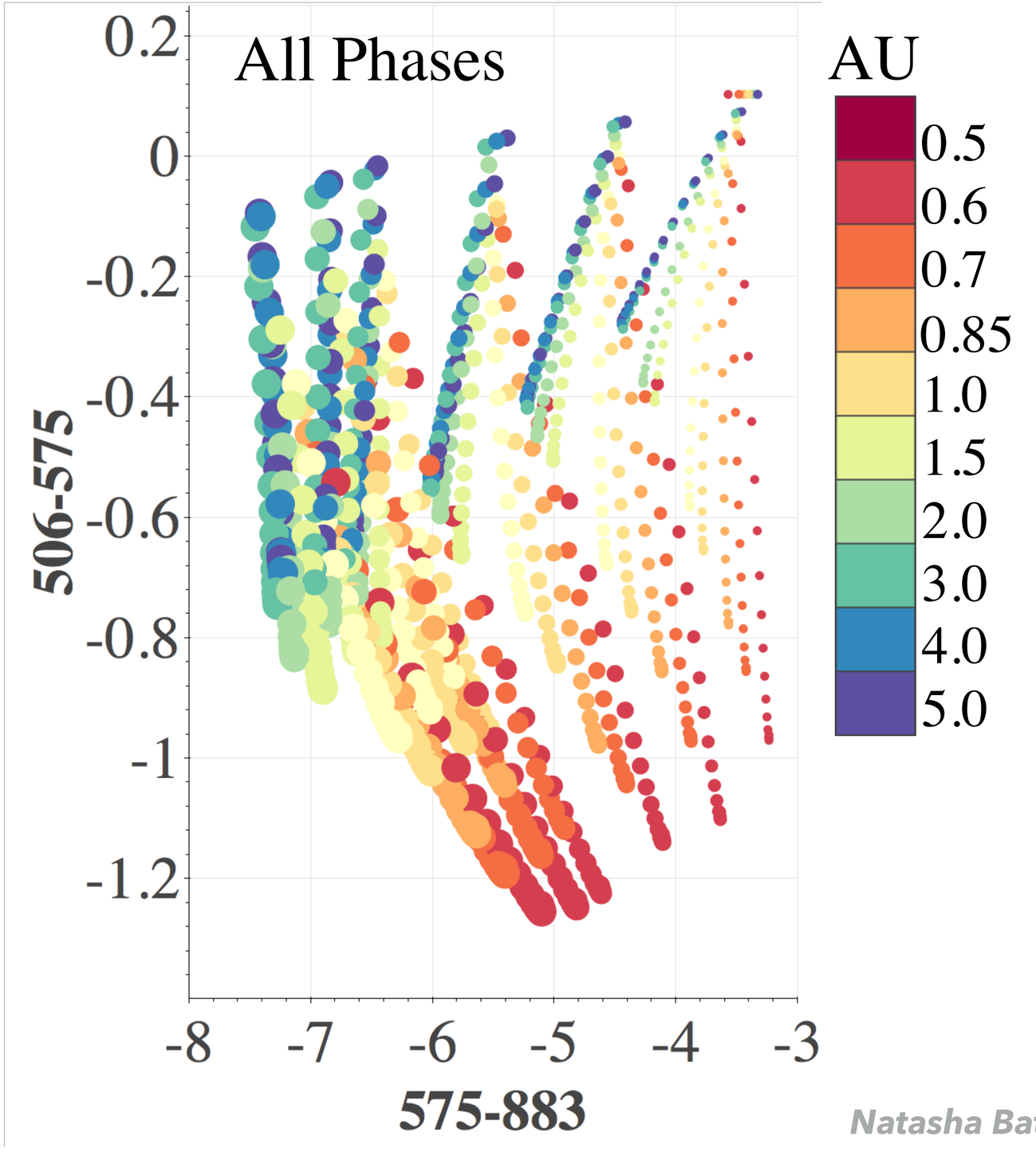
Natasha Batalha

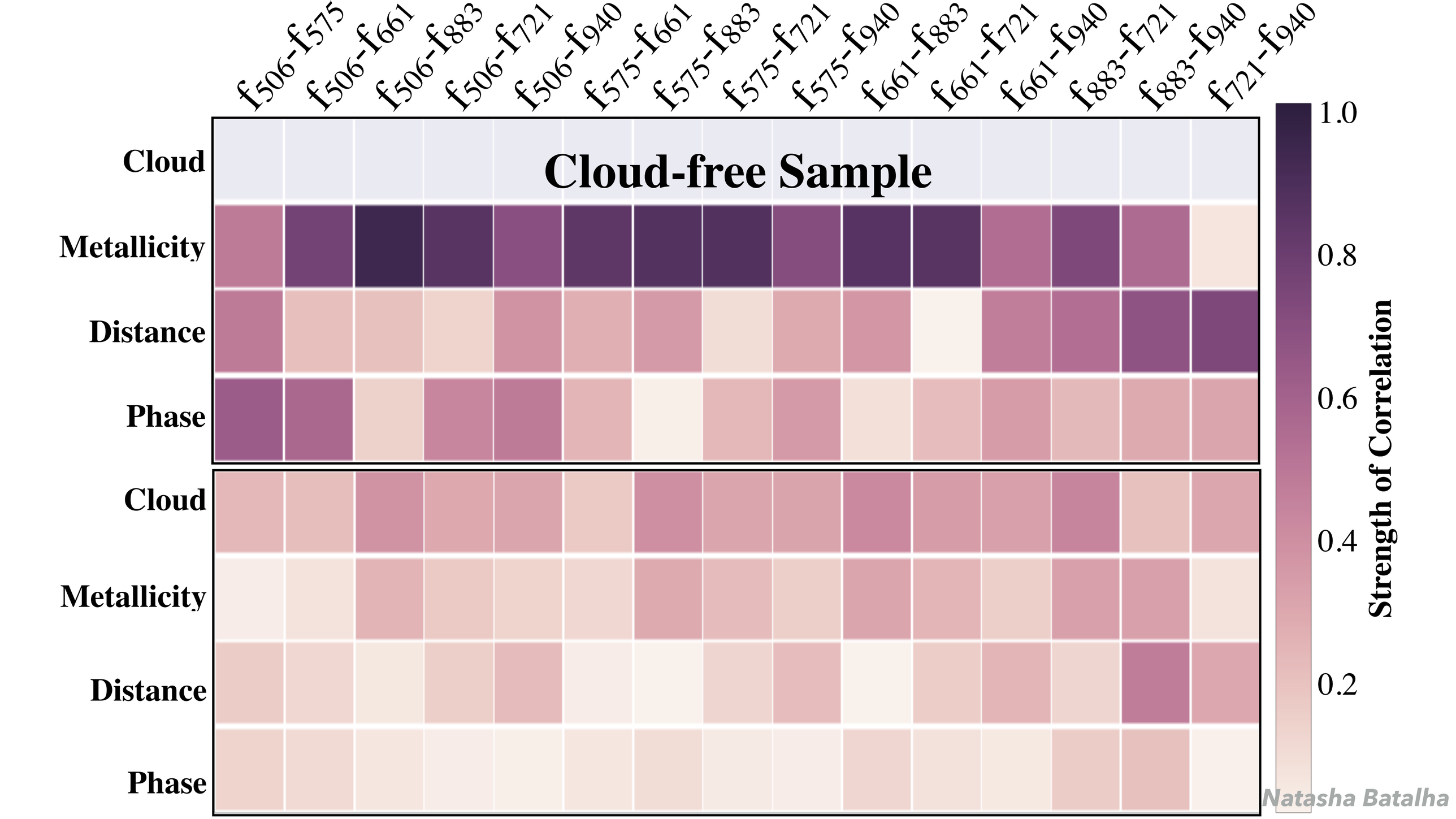

Phase = 0°
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-8
-7
-6
-5
-4
-3
f506-f575
f575-f883
Geometric Albedo
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Wavelength [μm]
0.5
0.6
0.7
0.85
1.0
1.5
2.0
3.0
4.0
5.0
AU
Geometric Albedo
Wavelength [μm]
1
3
10
30
50
100
× Solar
Natasha Batalha

Full Phase



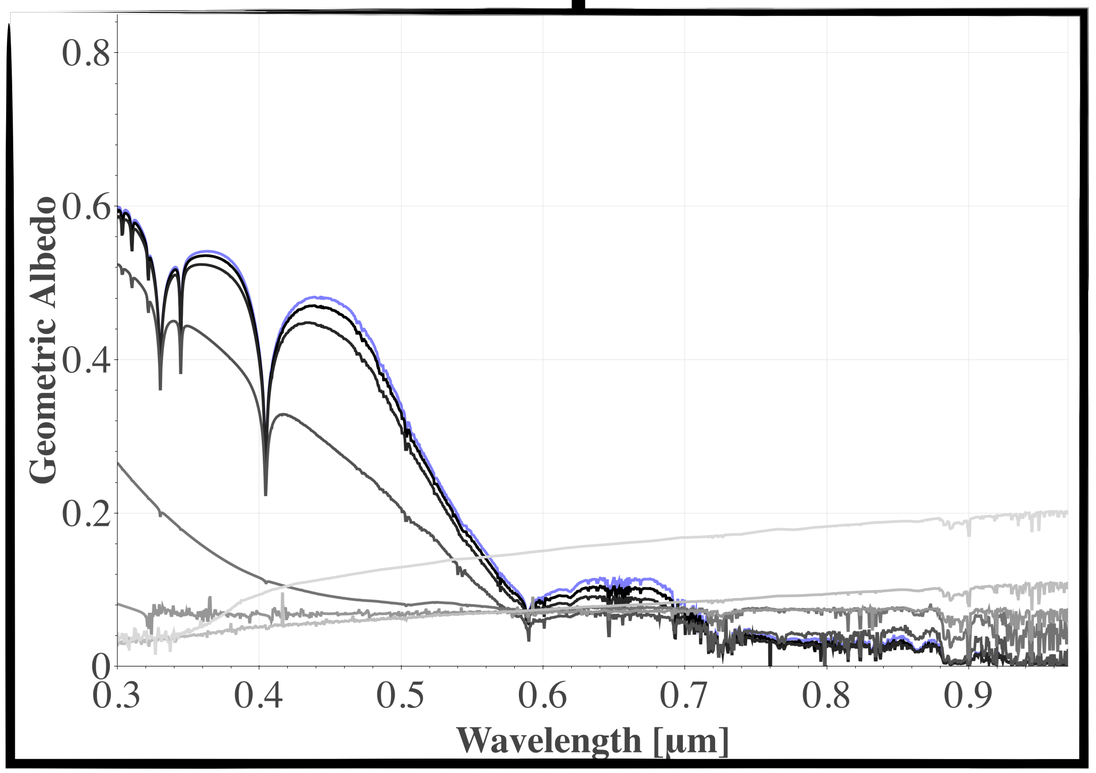





f506-f575
f506-f661
f506-f883
f506-f721
f506-f940
f575-f661
f575-f883
f575-f721
f575-f940
f661-f883
f661-f721
f661-f940
f883-f721
f883-f940
f721-f940
Cloud-free Sample
Cloud
Metallicity
Distance
Phase
Cloud
Metallicity
Distance
Phase
1.0
0.8
0.6
0.4
0.2
Strength of Correlation
Natasha Batalha

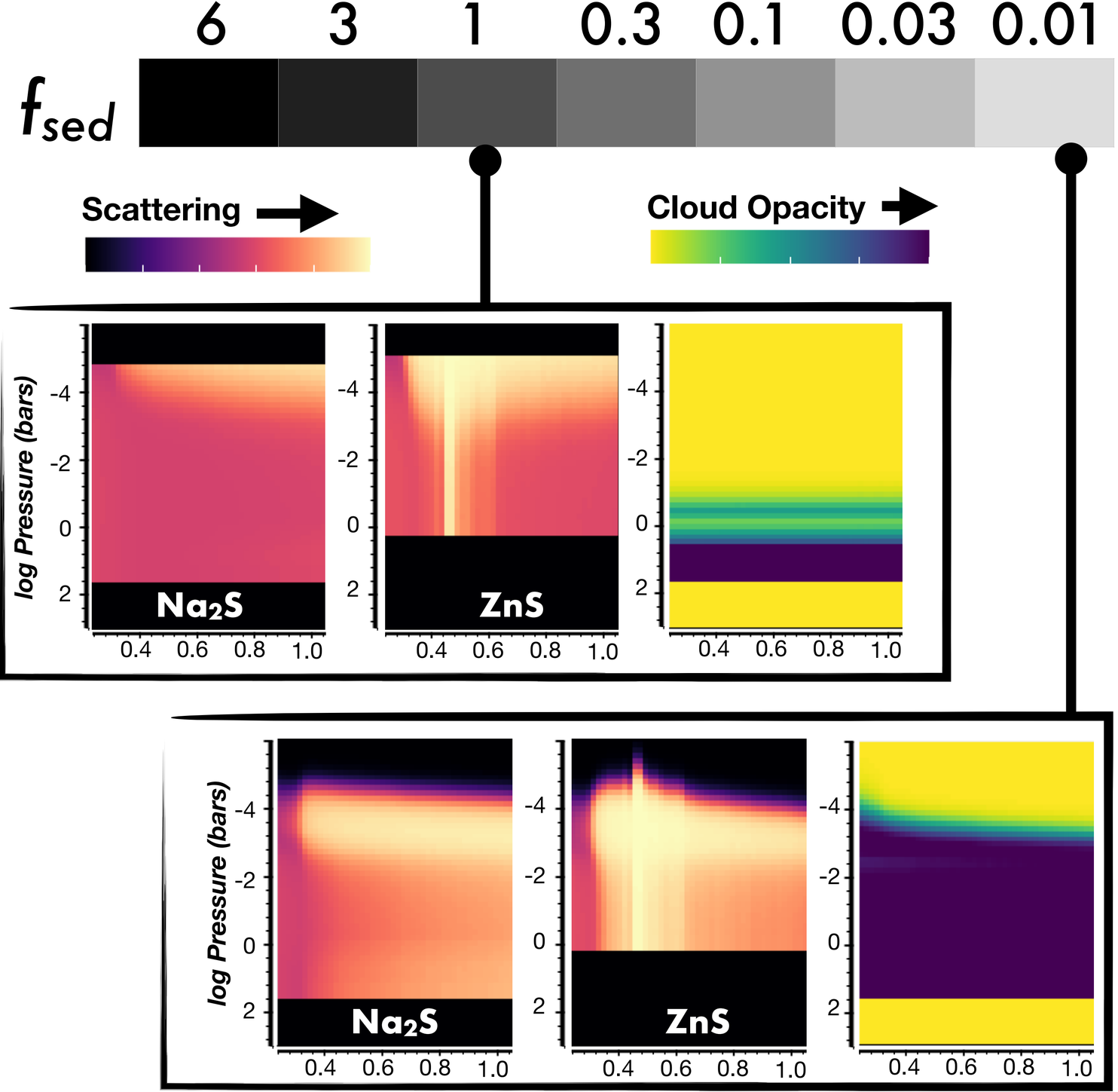
Clouds drive structure of reflected light spectra

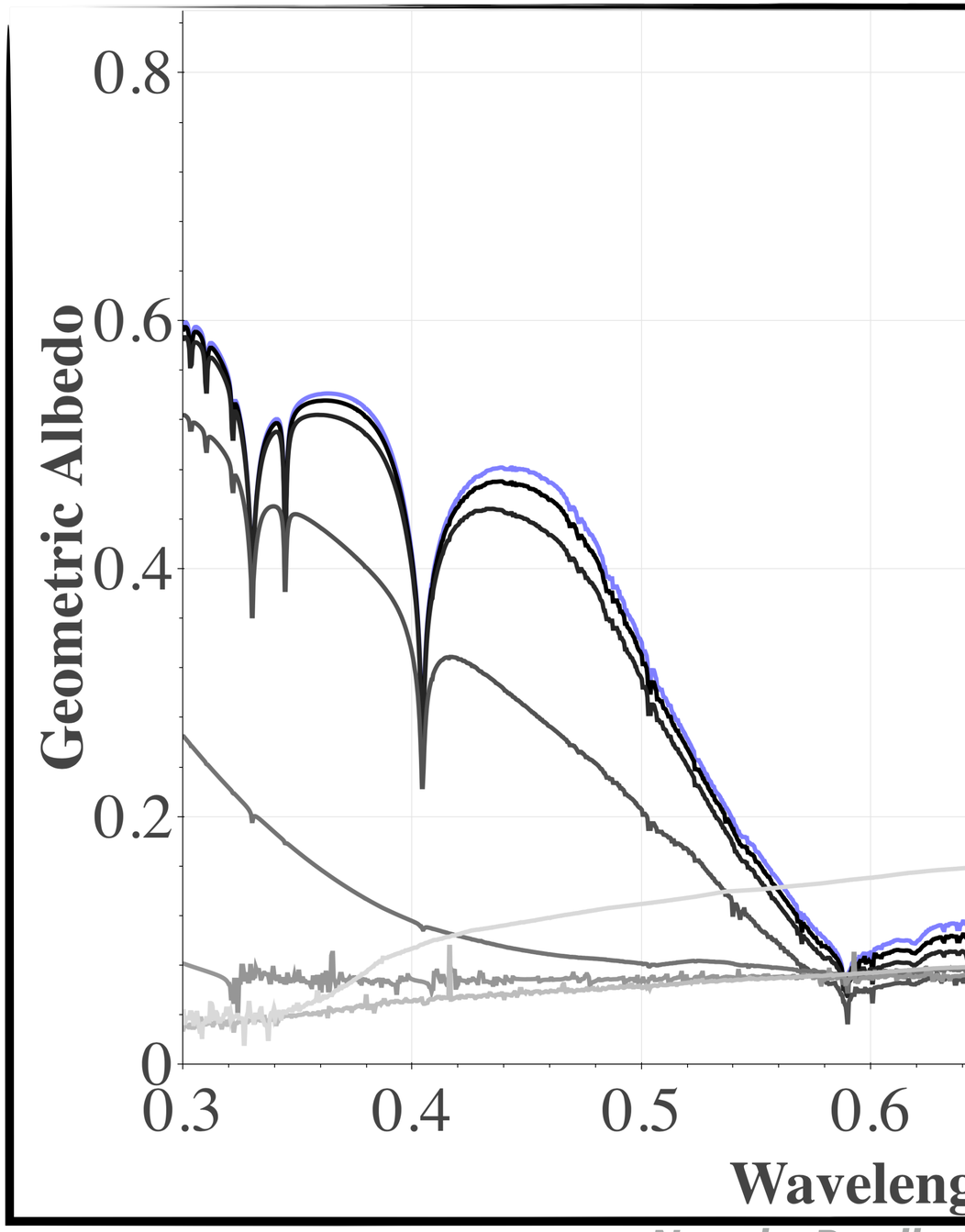
AU



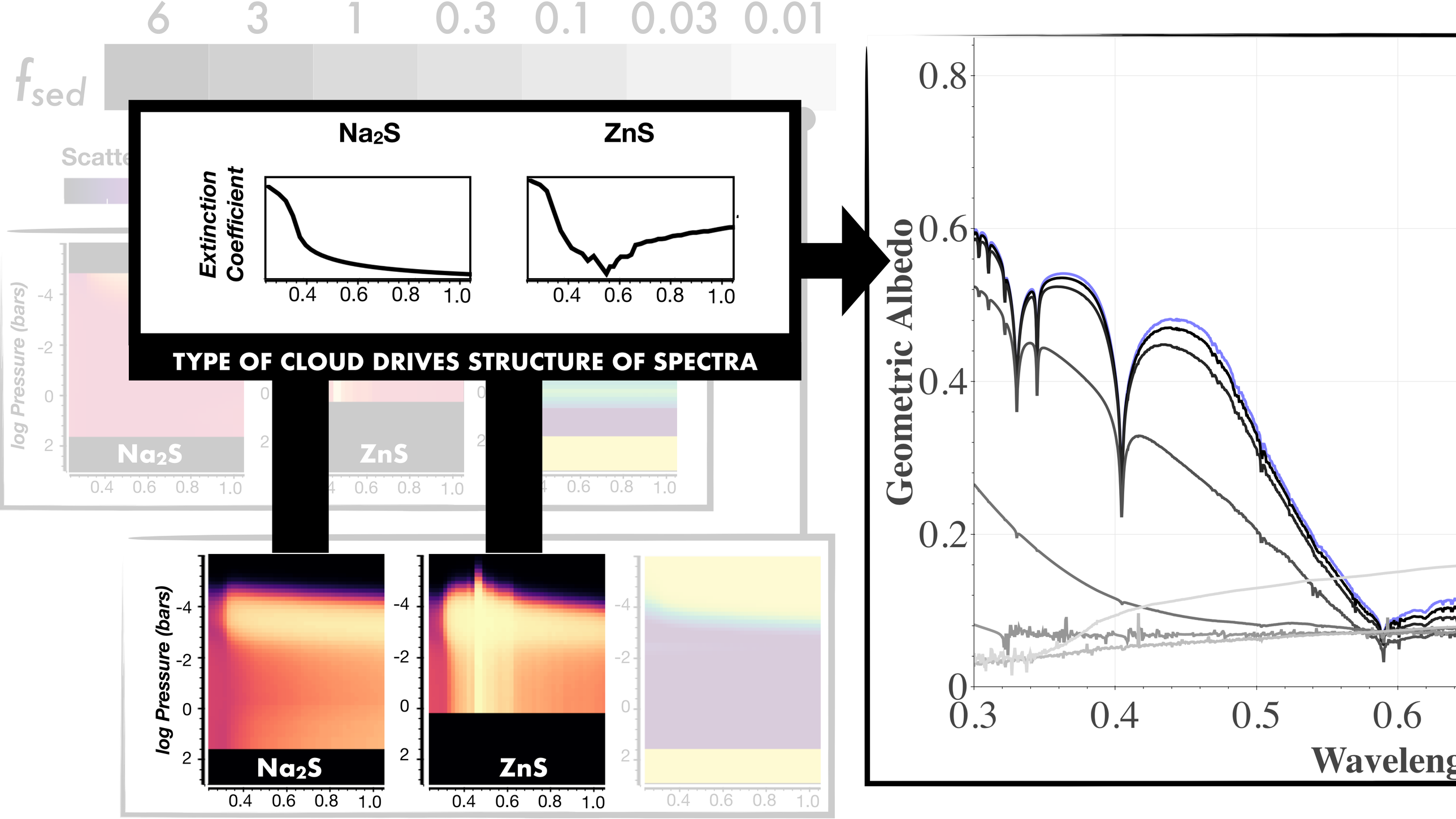
f_{sed} 6 3 1 0.3 0.1 0.03 0.01

Natasha Batalha



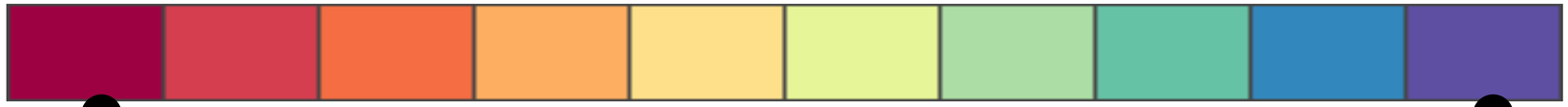


Natasha Batalha

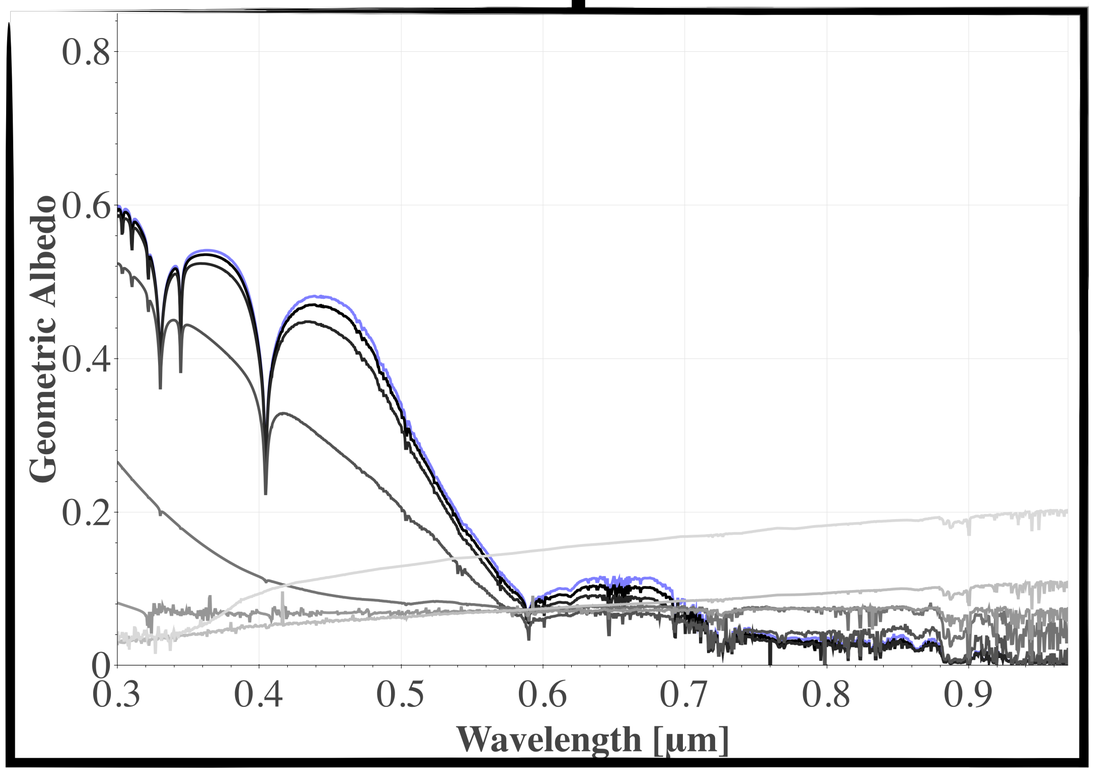

6 3 1 0.3 0.1 0.03 0.01
f_{sed}
Scatte
log Pressure (bars)
-4
-2
0
2
Na2S
ZnS
0.4 0.6 0.8 1.0
Na2S
ZnS
Extinction Coefficient
0.4 0.6 0.8 1.0
0.4 0.6 0.8 1.0
TYPE OF CLOUD DRIVES STRUCTURE OF SPECTRA
log Pressure (bars)
-4
-2
0
2
Na2S
ZnS
0.4 0.6 0.8 1.0
0.4 0.6 0.8 1.0
0.4 0.6 0.8 1.0
Geometric Albedo
0.8
0.6
0.4
0.2
0
0.3 0.4 0.5 0.6
Waveleng

Clouds drive structure of reflected light spectra

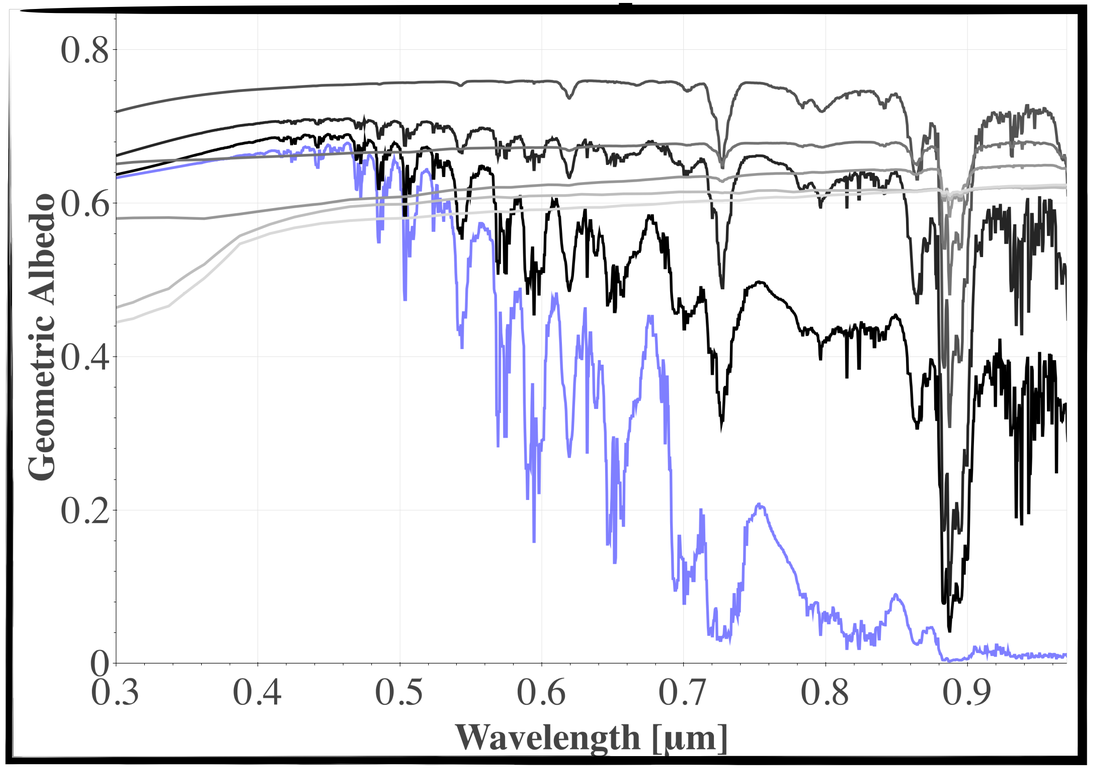
AU



Alkali Clouds



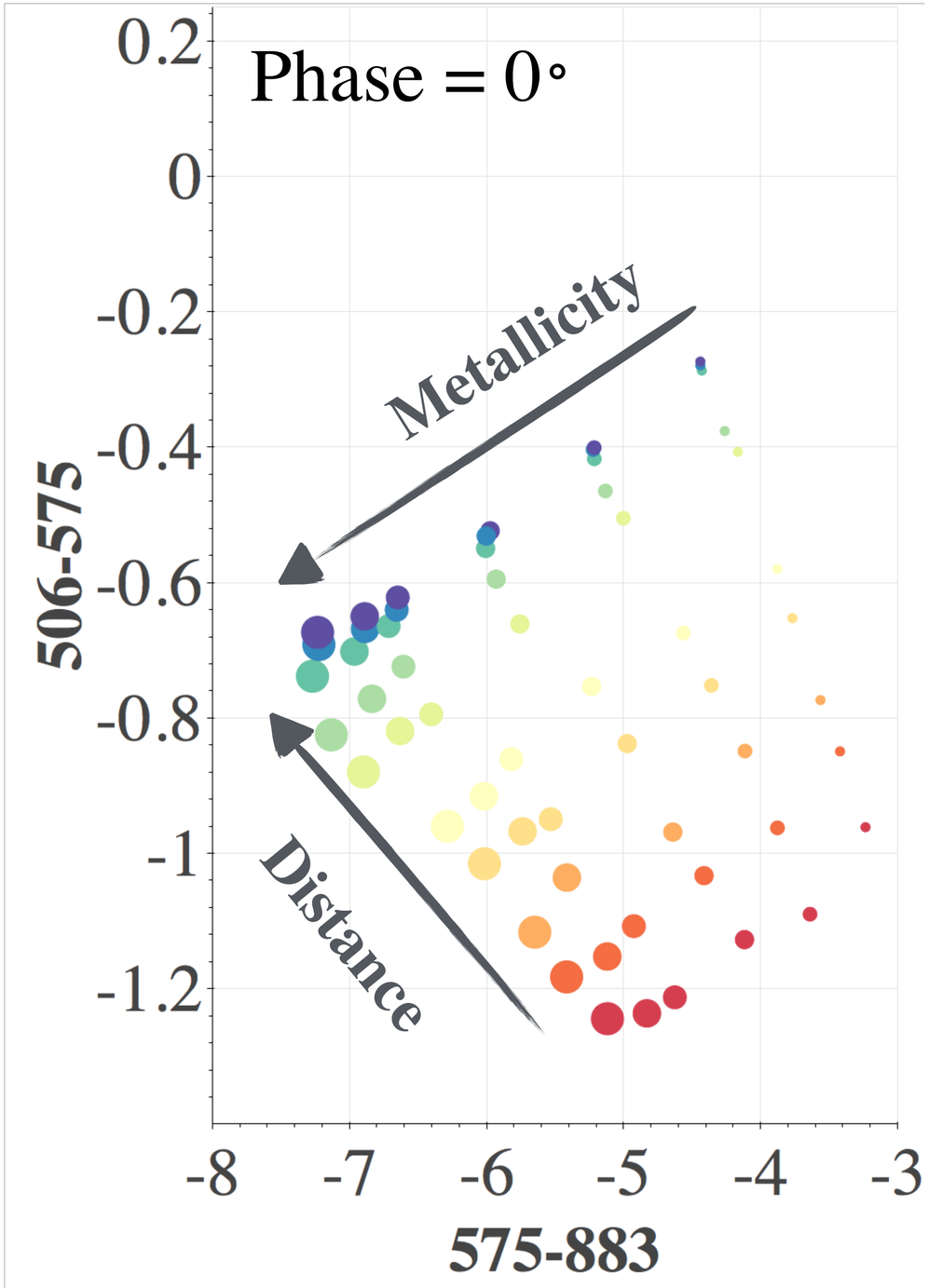
Water Clouds (MacDonald+2018)

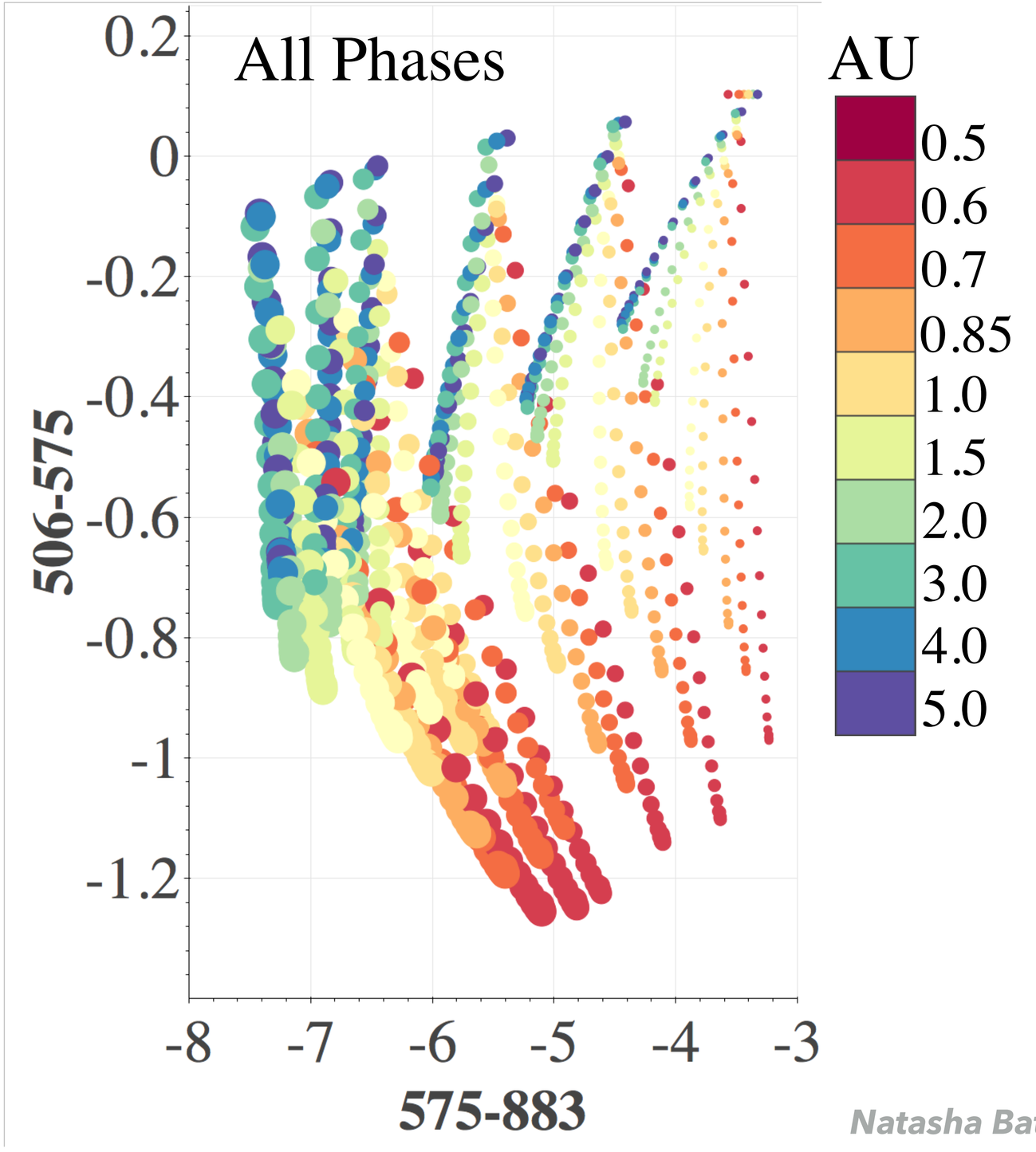


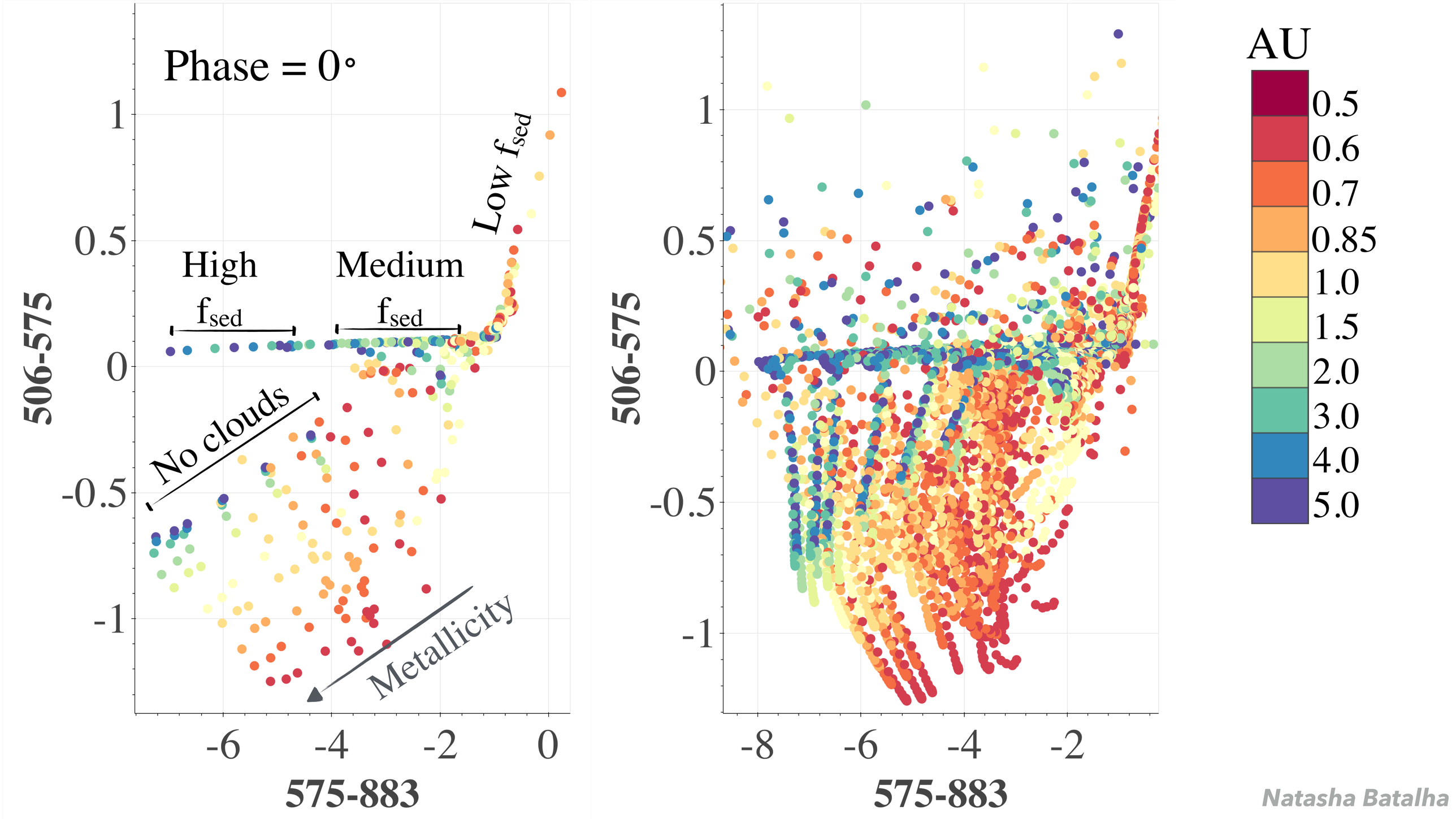
6 3 1 0.3 0.1 0.03 0.01

f_{sed}

Natasha Batalha







Natasha Batalha

scikit-learn for planet classification

Naive Bayes

Linear Discriminant Analysis

Classification and Regression Trees

K Neighbor Classifier

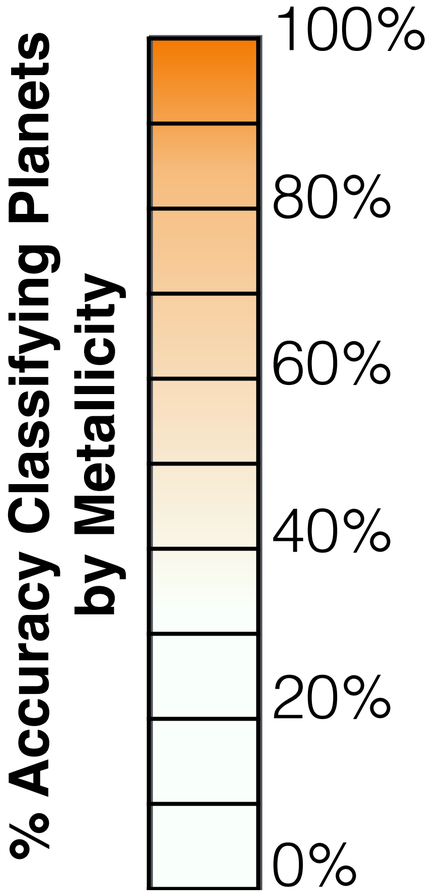
Support Vector Machine

Logistic Regression

Tutorials available at github.com/natashabatalha/colorcolor

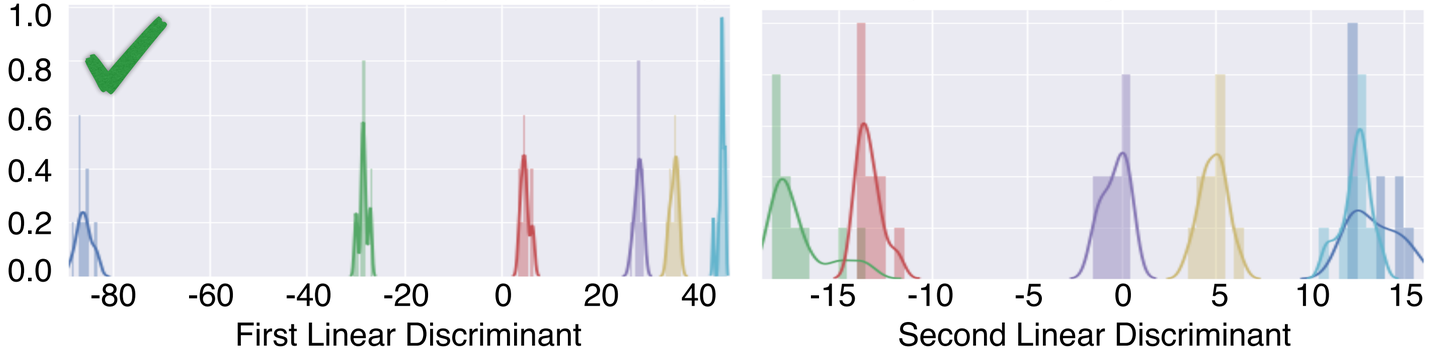
Bored? Go to natashabatalha.github.io/color-color.html

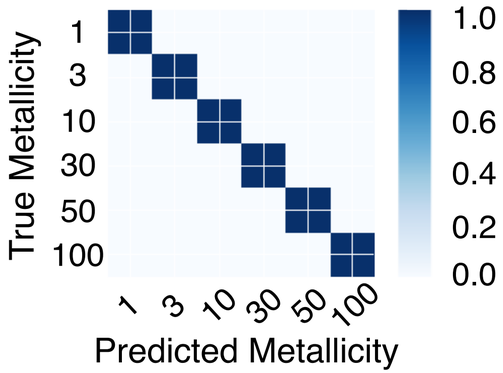
Classification and Regression Trees | Linear Discriminant Analysis



Sample Used	Algorithm Used	2 Filters (nm)	3 Filters (nm)	4 Filters (nm)	5 Filters (nm)	All Filters
Cloud-free Sample	**LDA**	506,883	506,575,883	All but 721,940	All but 721	
	CART	506,883	506,661,883	All but 721,949	All but 940	

Ability to Classifying Planets by Metallicity for Cloud-free Sample w/ Phase=90

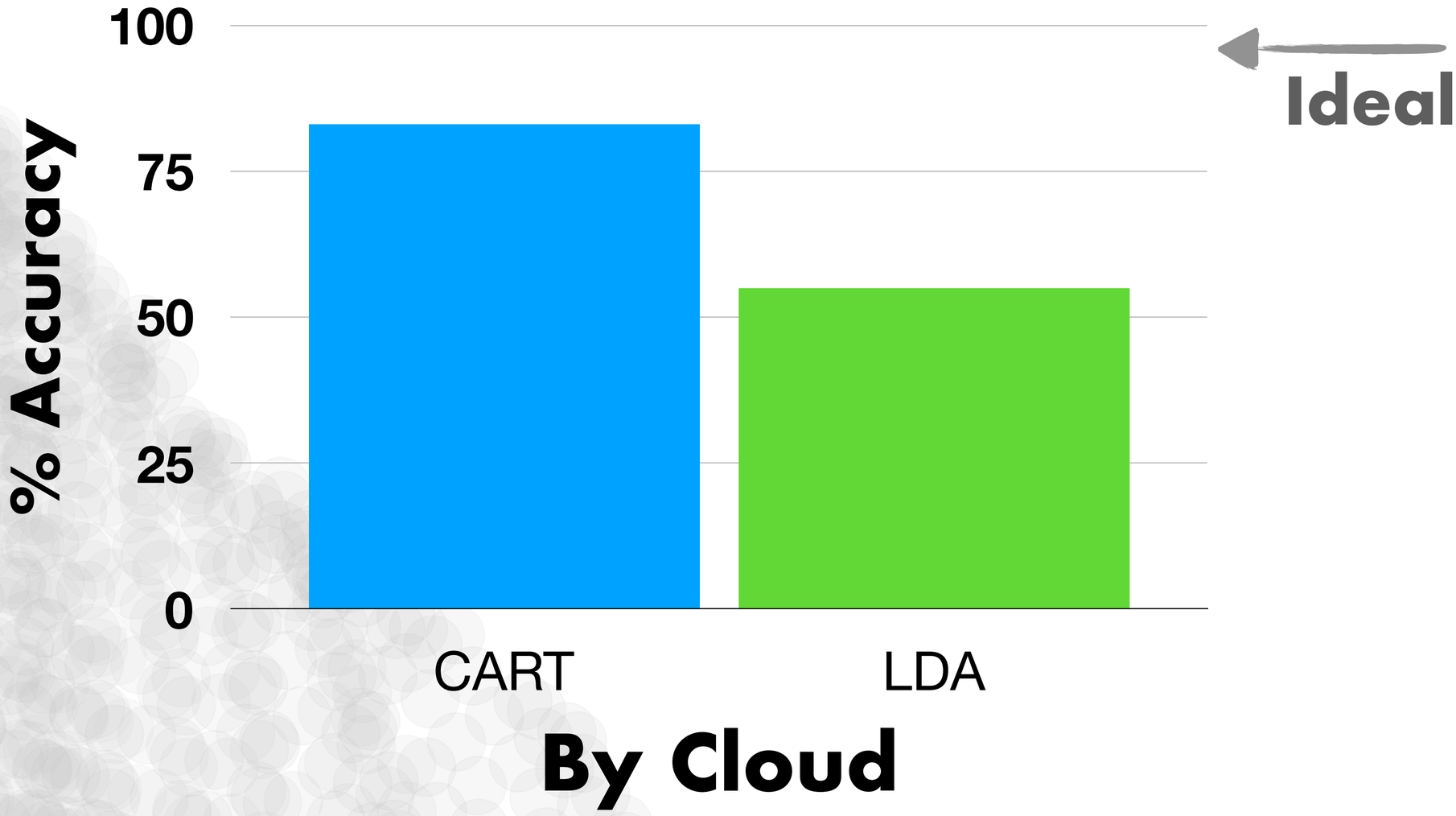


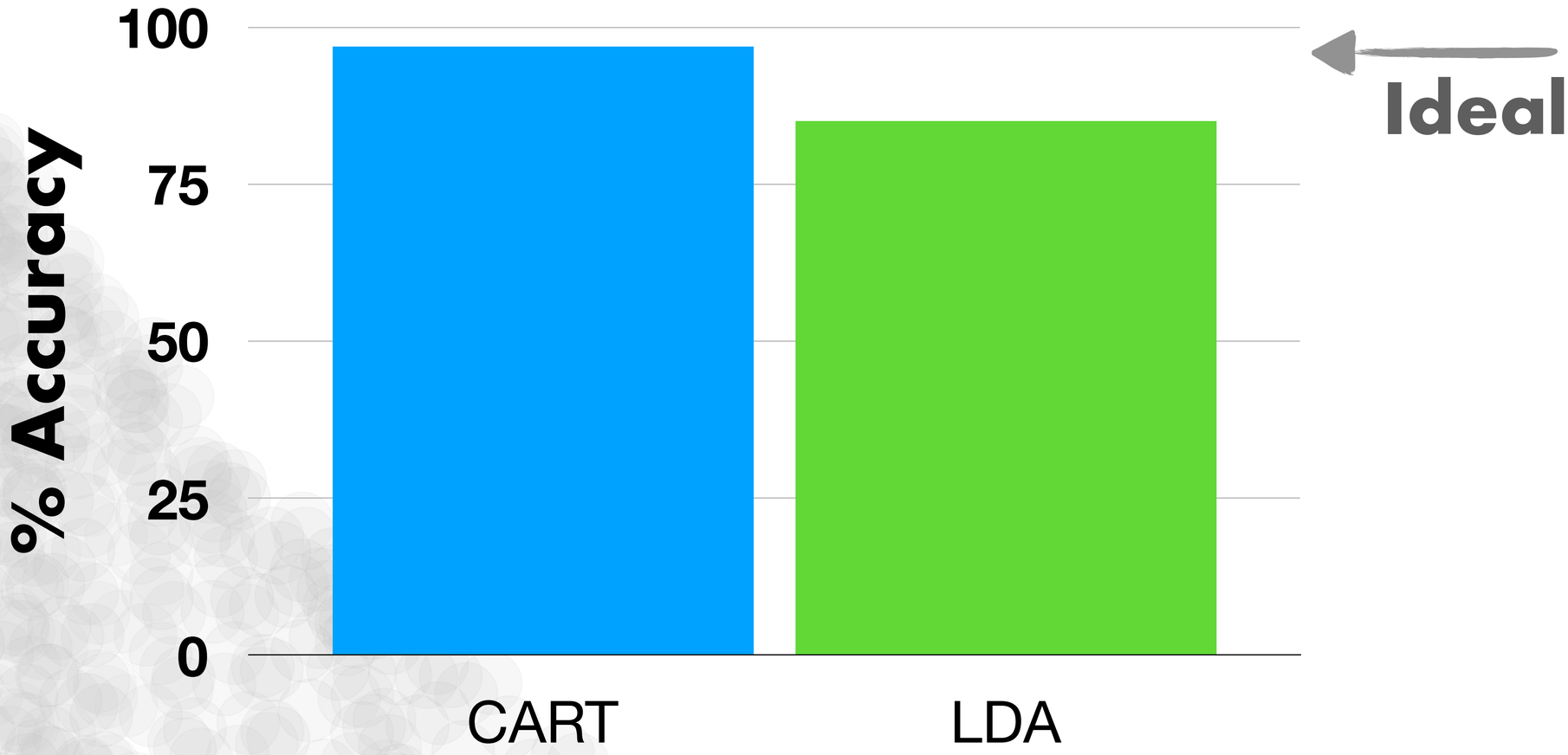


Metallicity:

- 1×Solar
- 3×Solar
- 10×Solar
- 30×Solar
- 50×Solar
- 100×Solar

Natasha Batalha


100
75
50
25
0
% Accuracy
Ideal
CART
LDA
By Cloud

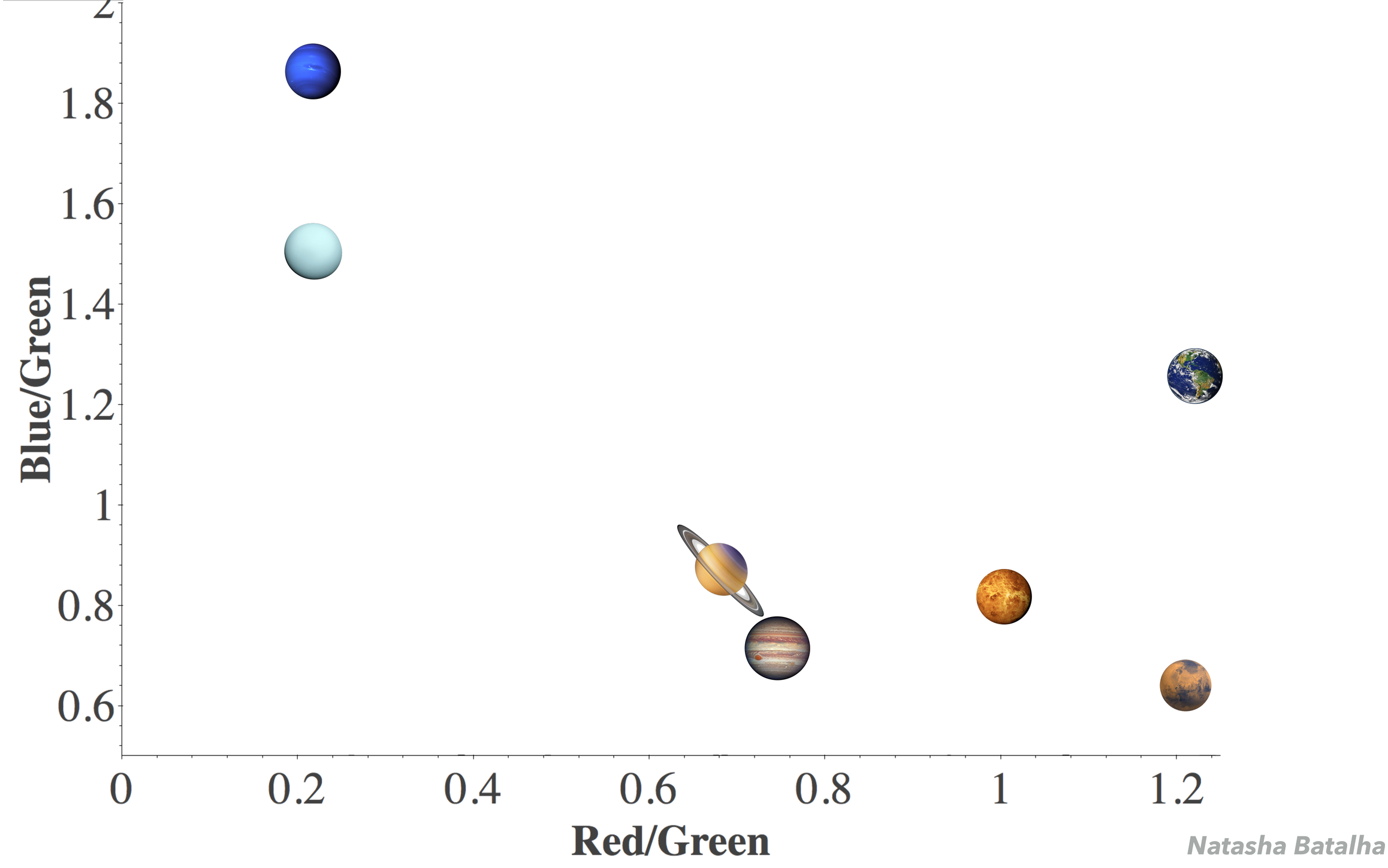


Cloudy or Not?

Color Classification of Extrasolar Giant Planets

Not great for high fidelity atmospheric studies

3 carefully selected filters is great for identifying potential targets for more time intensive follow-up



Goals:

- Are there any correlations between physical planet property and WFIRST-like filters
- If so, can we leverage those to create meaningful color-color diagrams
- If not color-color plot, can lots of statistics do the trick?

✓Yes, but clouds will largely drive photometry of directly imaged planets

✓Yes if it is known a-priori that the planet is clear

✓ML techniques help especially in teasing out very cloudy cases

Goals:

- Are there any correlations between physical planet property and WFIRST-like filters

✓Yes, but clouds will largely drive photometry of directly imaged planets

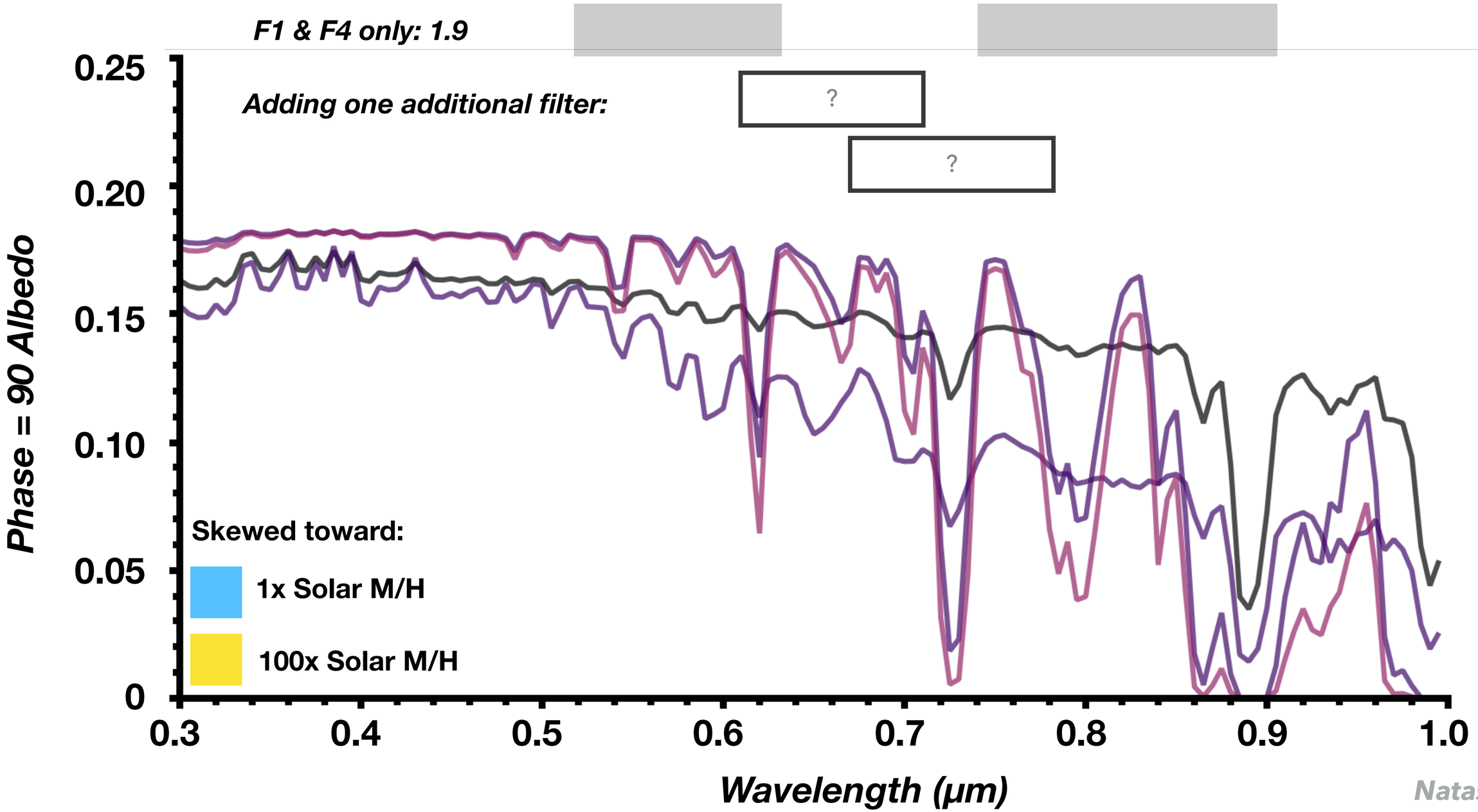
- If so, ca… hat the create n… diagram…

What about for current WFIRST??

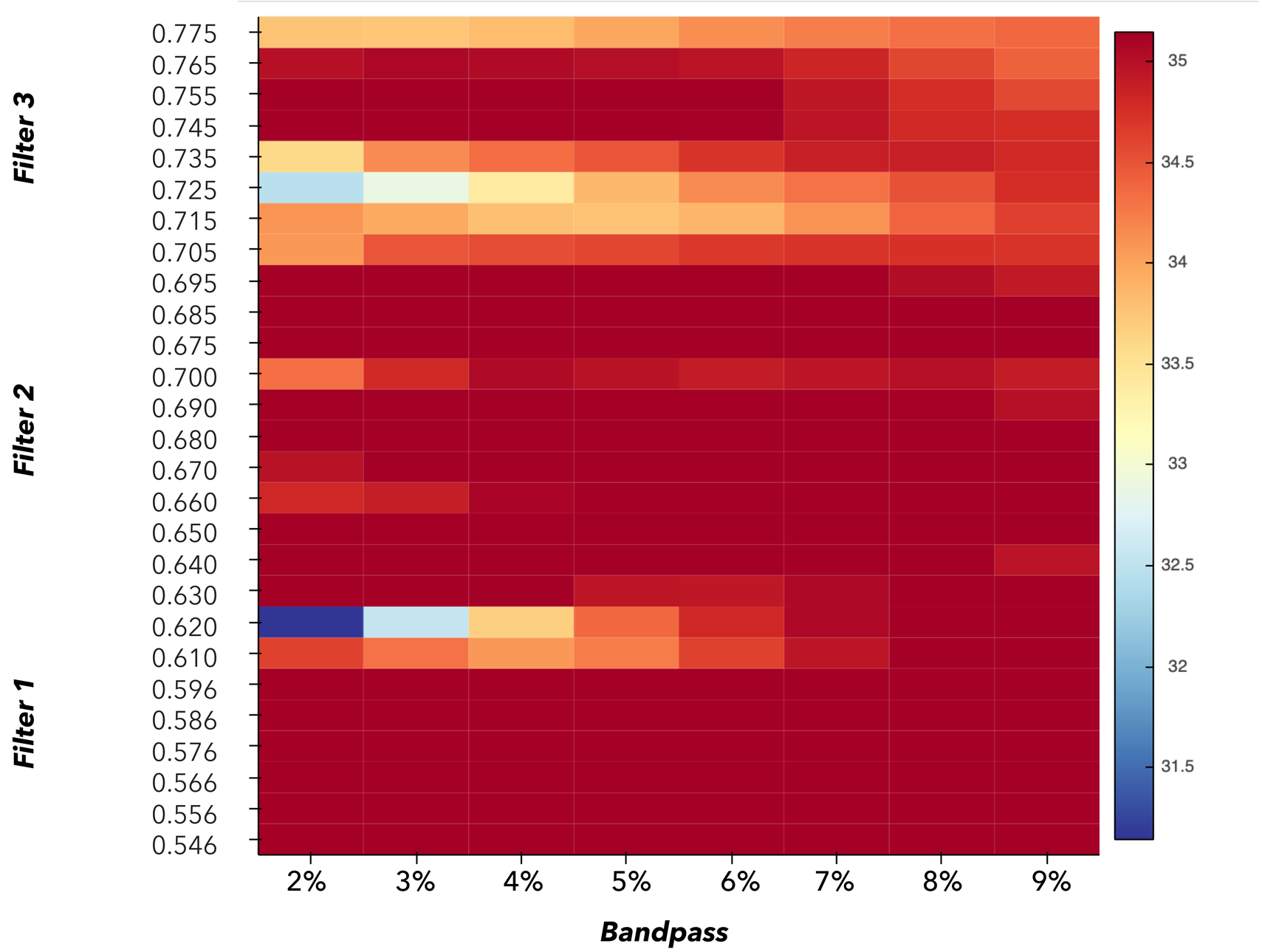
- If not color-color plot, can lots of statistics do the trick?

✓ML techniques help especially in teasing out very cloudy cases

CURRENT WFIRST FILTER ANALYSIS



Natasha Batalha



- Docs: https://natashabatalha.GitHub.io/picaso
- Math: https://natashabatalha.Github.io/picaso_dev
- PICASO Code: https://github.com/natashabatalha/picaso
- Color Color Code: https://github.com/natashabatalha/colorcolor

Reflected light hard

We hope this tool helps a lot

Let's do cool science