Phase curves and the taxonomy of asteroids

Max Mahlke

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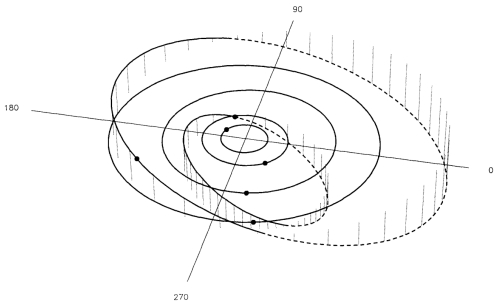
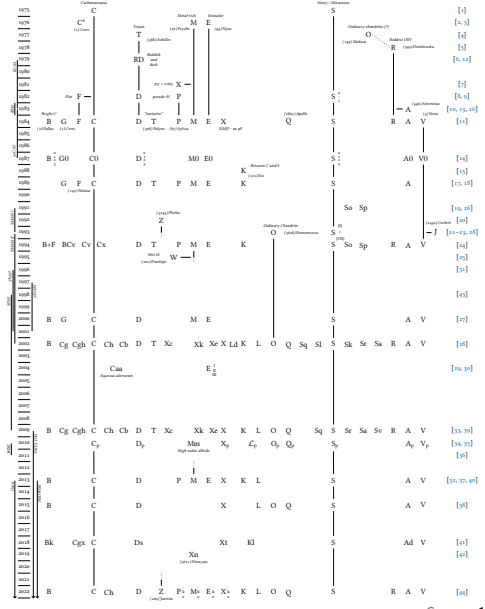
With contributions from Jerome Berthier, Benoit Carry, Larry Denneau, Roman Le Montagner, Pierre-Alexandre Mattei, and Julien Peloton



Taxonomies: Spoilt for choice

- Many observables, many systems
  - Spectroscopy, photometry, albedo
  - UV, visible, near-infrared, $>3\,\mu m$
- Practice Choice depends on your data
  - Gaia spectra → ?
- Theory What makes a good taxonomy?



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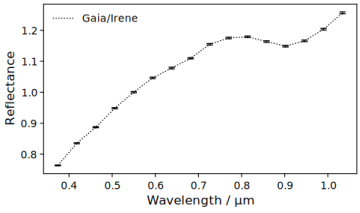

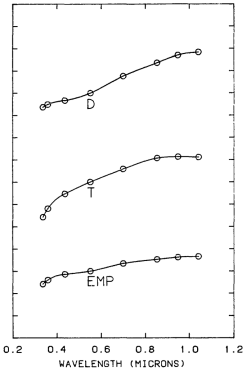

Figure: Tholen 1984 · Data: Gaia DR3

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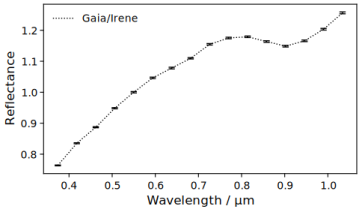
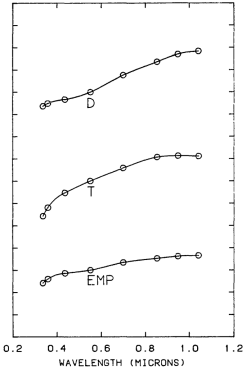
- Theory What makes a good taxonomy?
  - Observational accessibility → describe many asteroids
  - Observational variability → large vocabulary





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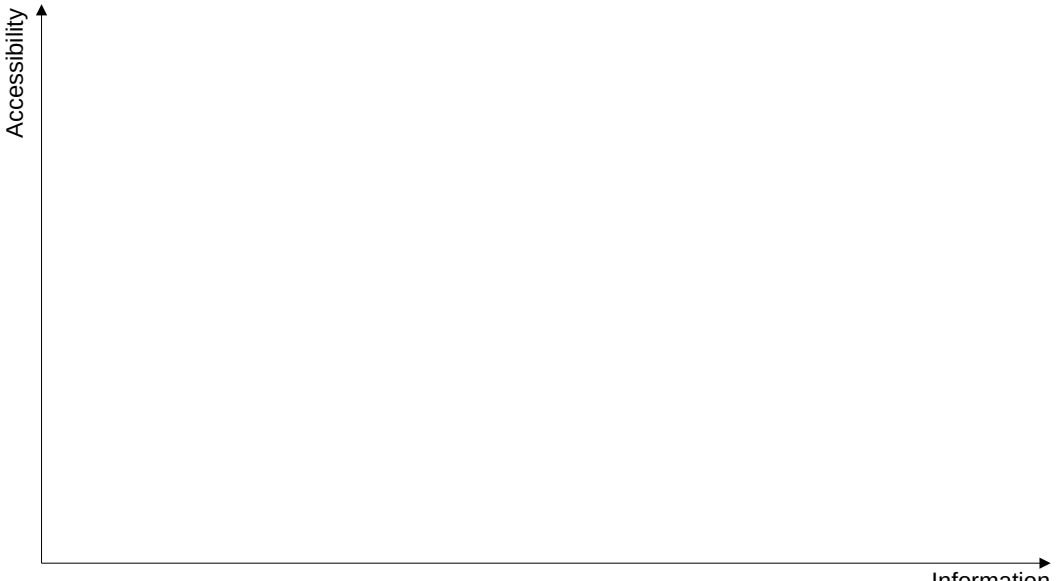
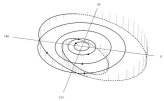

Accessibility
Information

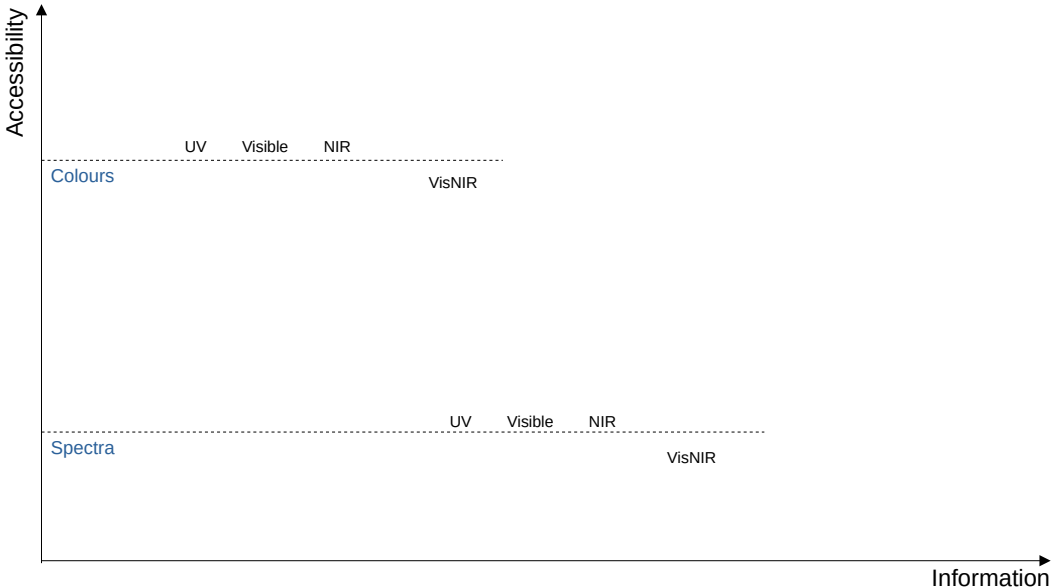
Accessibility

Astrometry



Sample-Return

Information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UV
Visible
NIR
Colours
VisNIR
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Visible
NIR
Spectra
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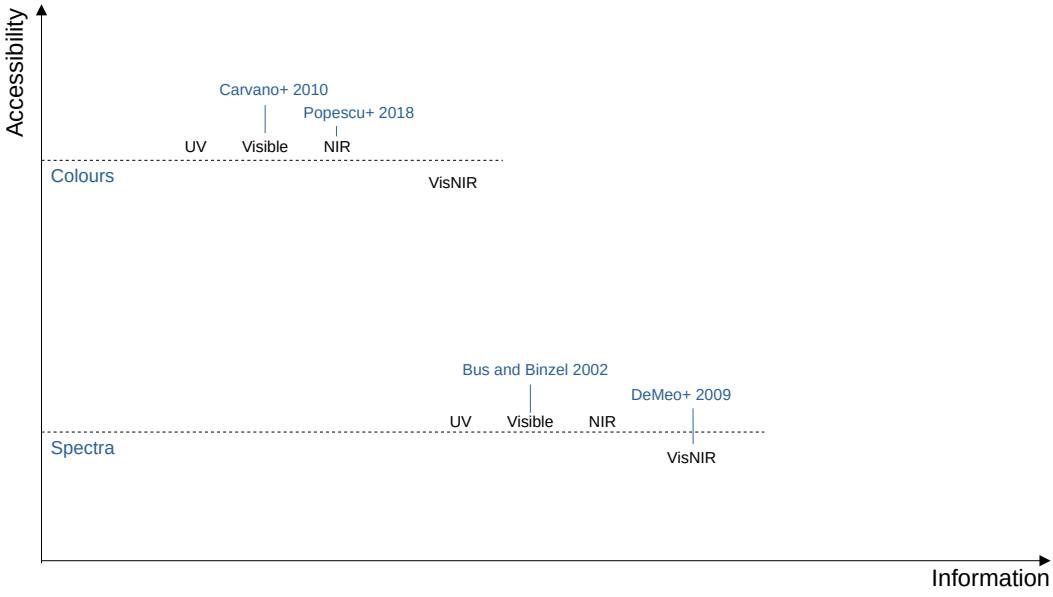
Accessibility
Carvano+ 2010
Popescu+ 2018
UV
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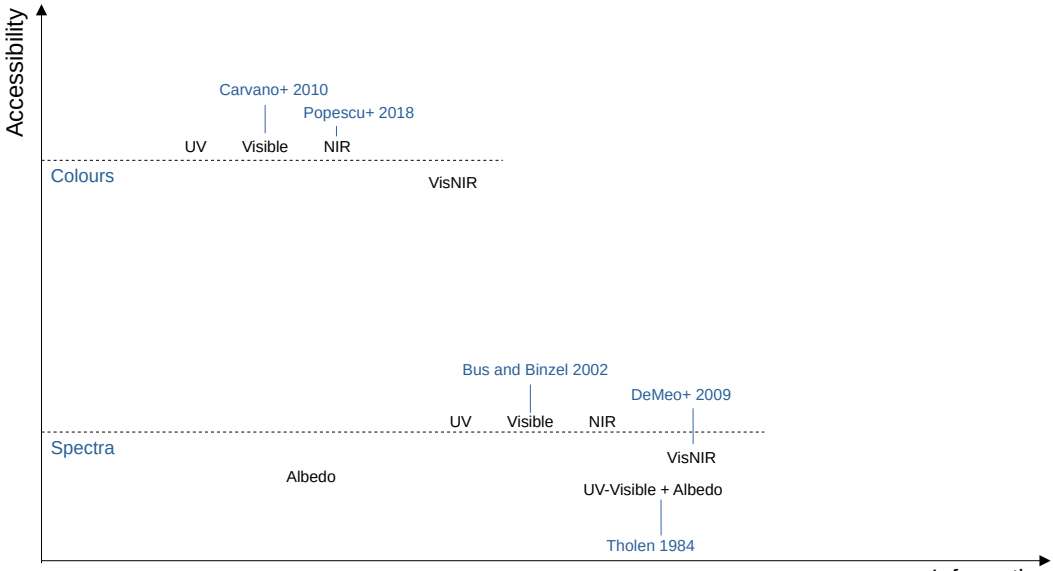
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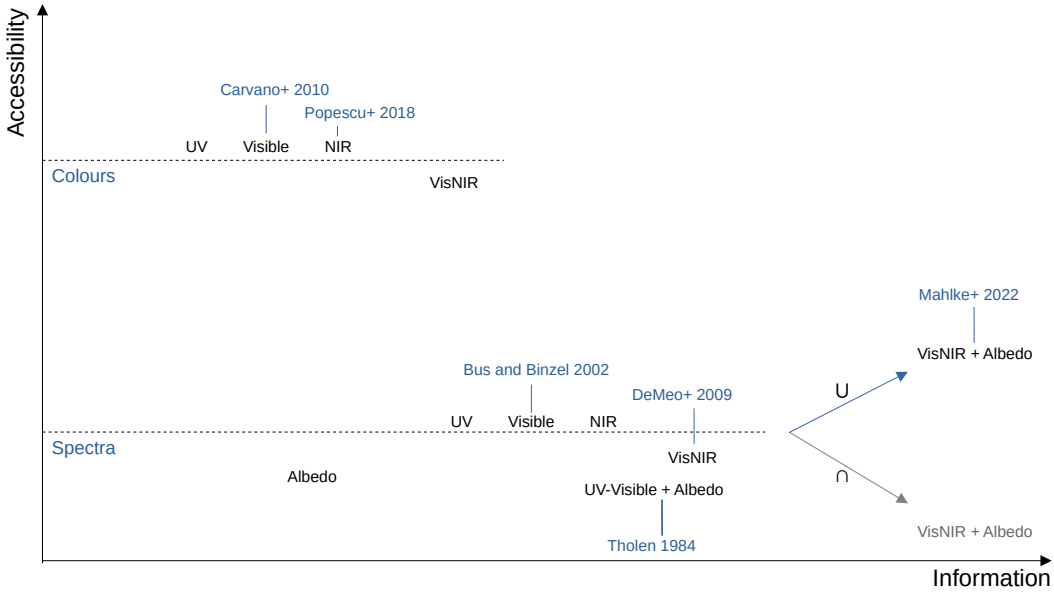
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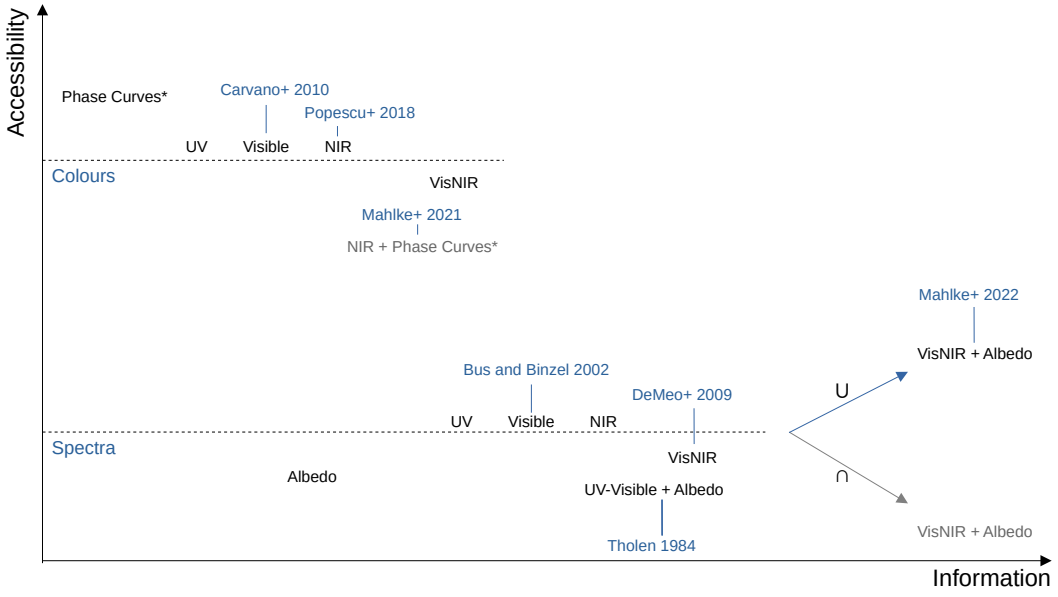
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Carvano+ 2010
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UV
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Mahlke+ 2021
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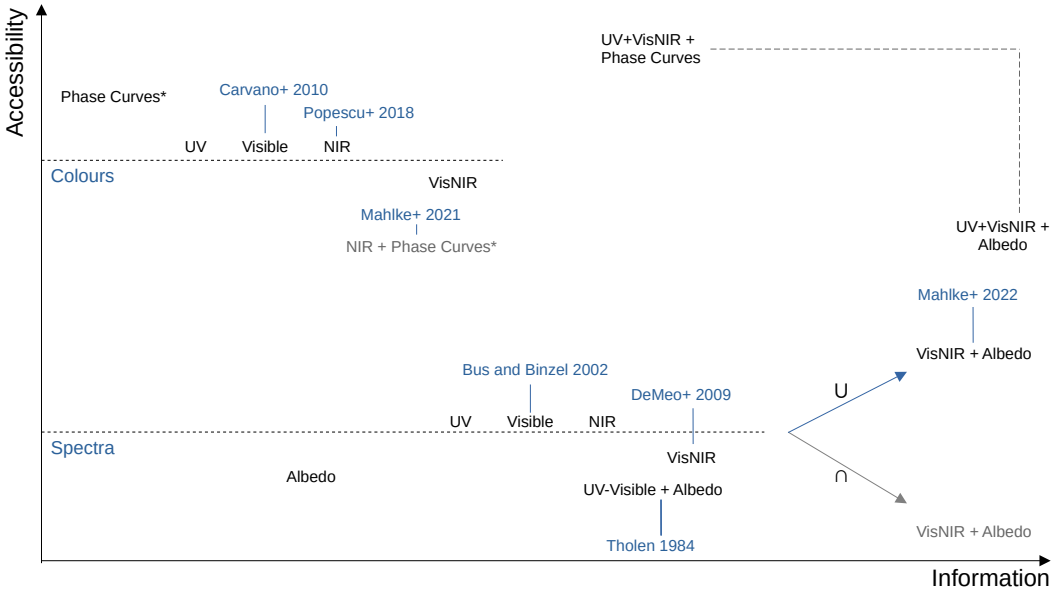
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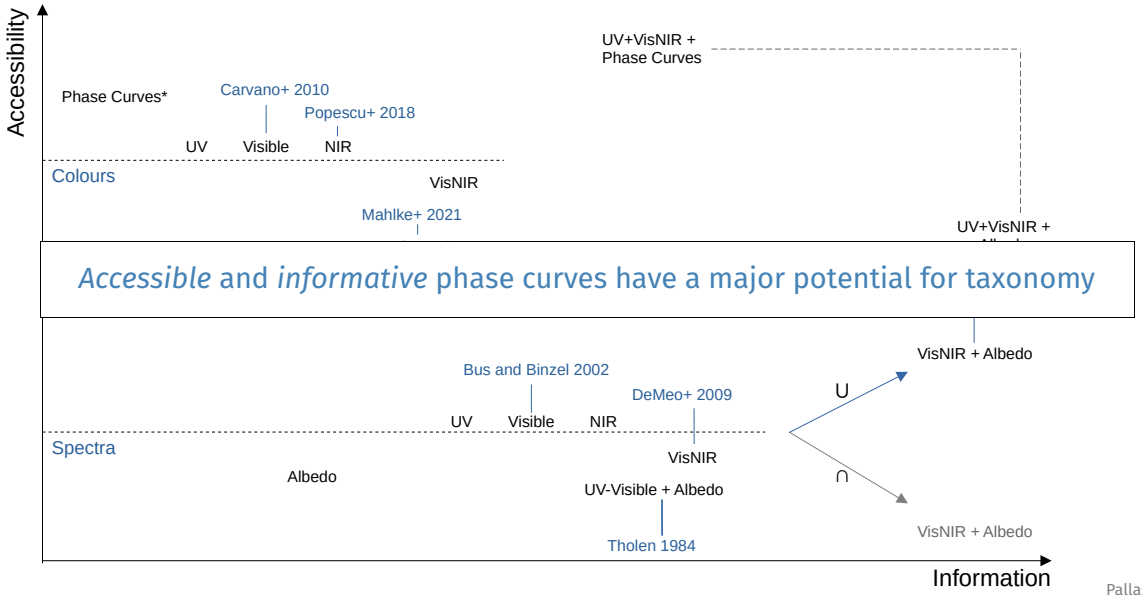
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Phase Curves
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Accessible and informative phase curves have a major potential for taxonomy
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Compositional information in phase curves

- Absolute colours $[H_i - H_k]$ Multi-band
- Shape $[G_1 G_2]$ Single-band
  - Slope → indicator of taxonomy
  - Opposition effect → indicator of taxonomy

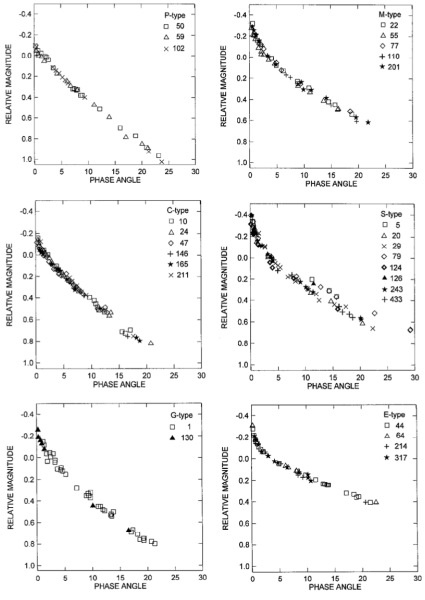

Figure: Belskaya and Shevchenko 2000

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- Absolute colours $[H_i - H_k]$ Multi-band
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- In first order, $G_1 G_2$ correlate with albedo

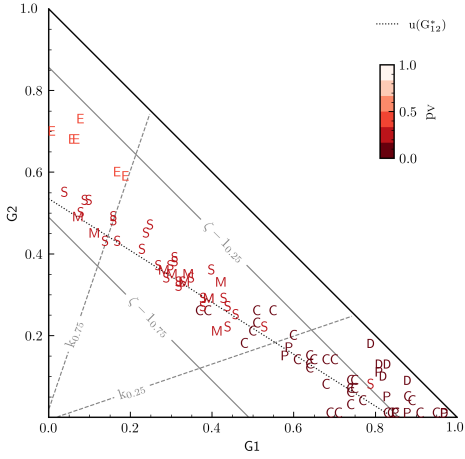
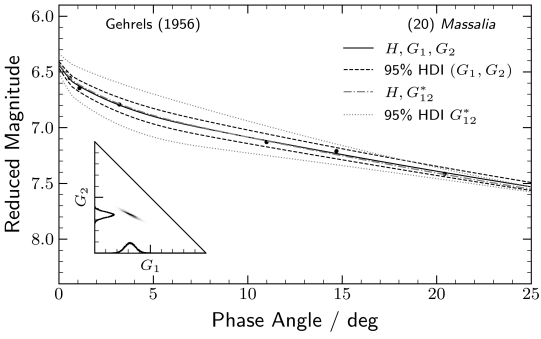


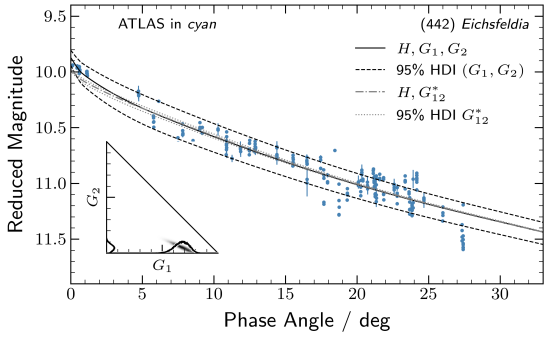
Figure: Mahlke 2022 · Data: Shevchenko+ 2016

Targeted



High observational effort → Low accessibility
Full target characterisation → High accuracy
Surface structure?

Non-Targeted



Large-scale surveys → High accessibility
Sparse photometry → Low accuracy

Figures: Mahlke+ 2021 · Data: Gehrels 1956 · ATLAS

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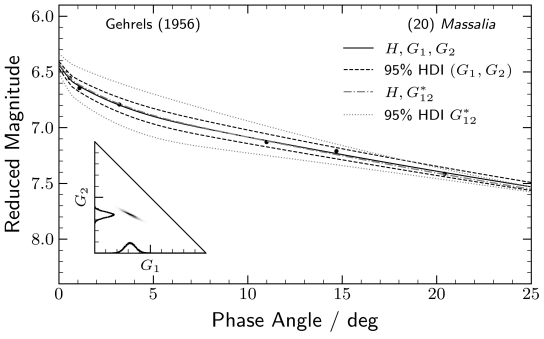

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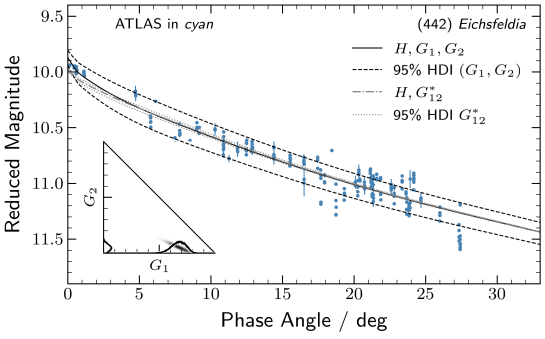

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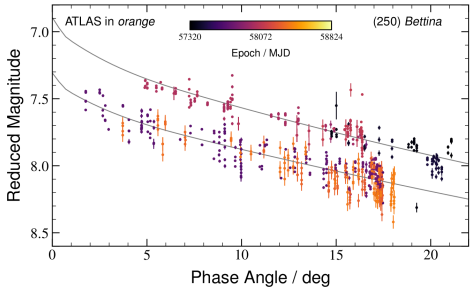
Can we determine taxonomy from non-targeted phase curves?

Figures: Mahlke+ 2021 · Data: Gehrels 1956 · ATLAS

Systematics in non-targeted phase curves

- Sampling
  - We need large N
  - We need low $\alpha_{\min}$
  - We need large $\Delta\alpha$



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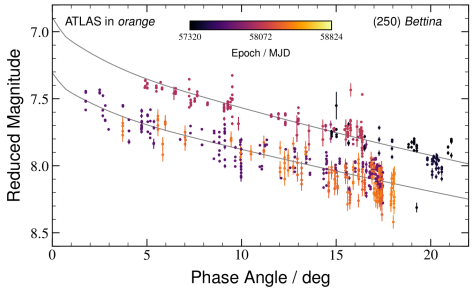
II Apparitions

- Manageable if large number of observations

→ sHG1G2 Talk by Benoit



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III Rotations

- Larger effect than apparitions
- Difficult to treat automatically

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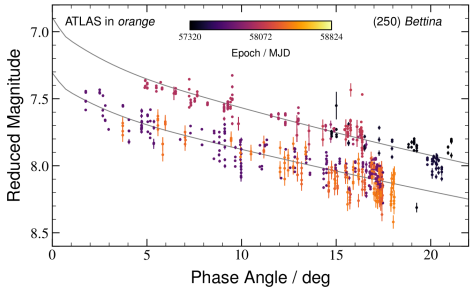
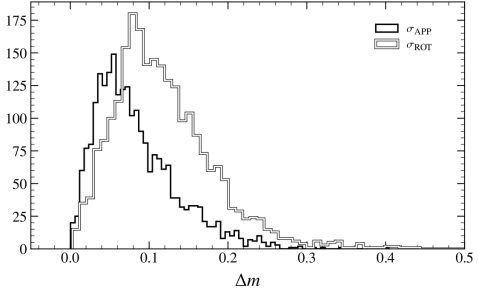
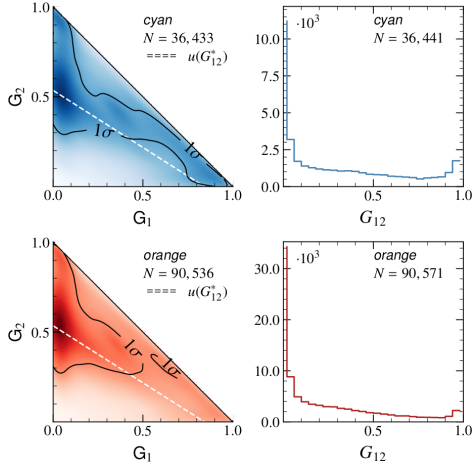




A proof-of-concept with ATLAS photometry

- 34,800,000 observations
- Dual band: *orange* and *cyan*
- 180,025 objects
  - 94,777 after requiring N⩾50 and $\alpha_{\min} \leqslant 3$
- G_1G_2 show biased distribution towards (0, 0.5)



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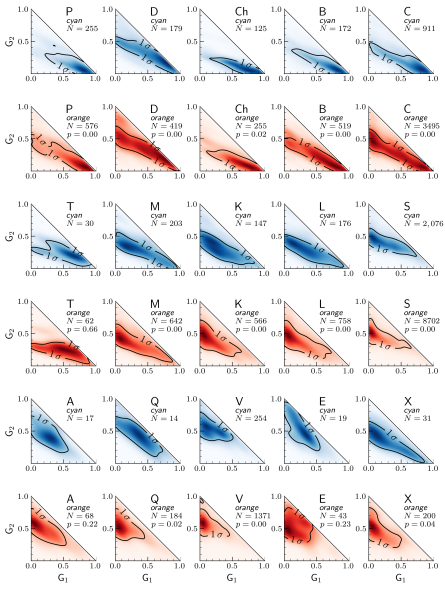
Stricter sampling constraints reveal taxonomic signature!

- High number of observations (N>125)
- Low minimum observed phase angle (⩽2 deg)



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Yes, we can determine taxonomy from non-targeted phase curves!

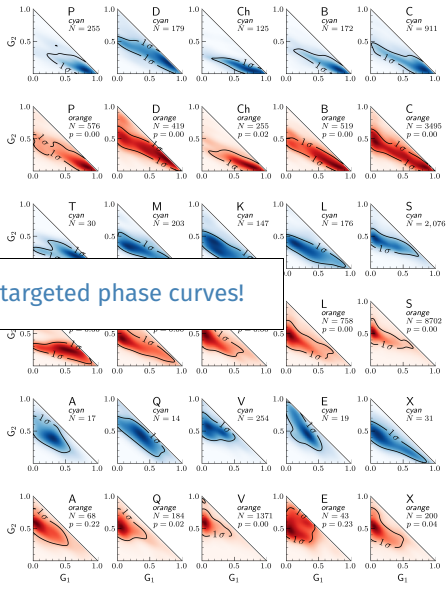
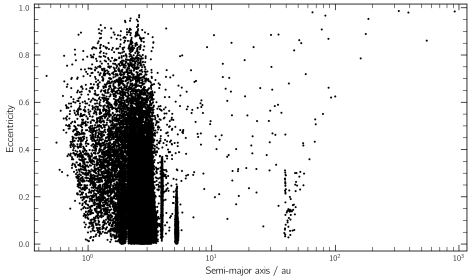


Figure: Mahlke+ 2021

A treasure trove: ATLAS SSCAT V2[1]

- 188,000,000 observations
- 702,061 objects
  - Inner SolSys + Trojans → 579,000 objects
- Dual band: *orange* and *cyan*



[1] http://astroportal.ifa.hawaii.edu/atlas/sscat

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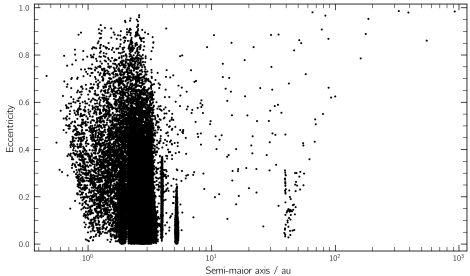
Revisiting ATLAS phase curves [Preliminary results]

- From 4[1] to 9 years worth of observations
  - Average N in *orange*: ∼300
  - Average N in *cyan*: ∼100
- Fitting >1,000,000 phase curves
  - About 80% done
  - Fit with HG1G2, sHG1G2



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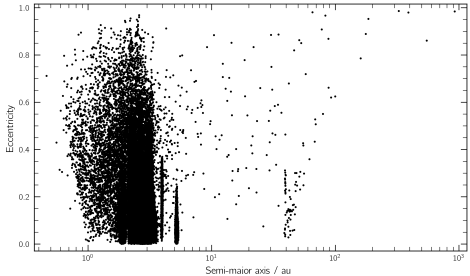

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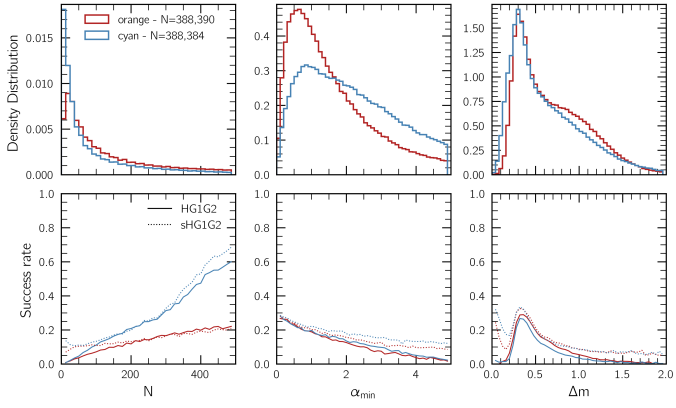
Success rates - when do we get physical solutions?

- N is important but not decisive
- $\alpha_{min} \geqslant 5deg \rightarrow$ no solution
- Δm is decisive!
- HG_1G_2 21%|26%, sHG_1G_2 26%|41%



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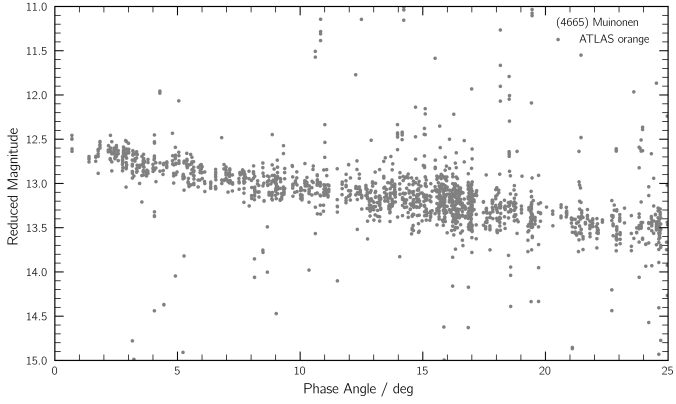

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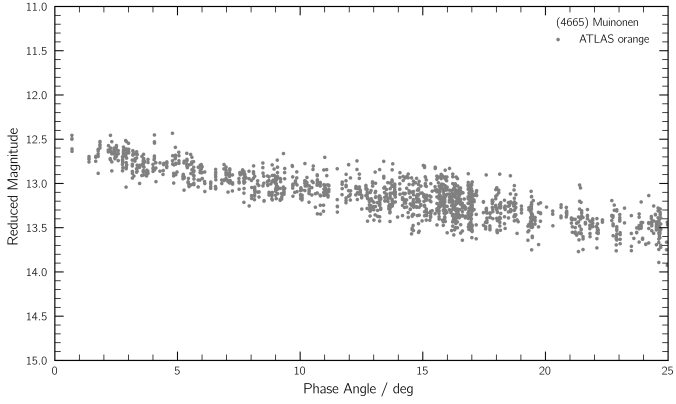

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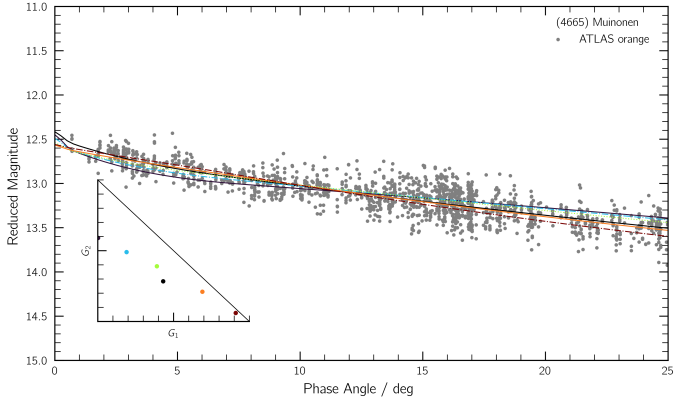

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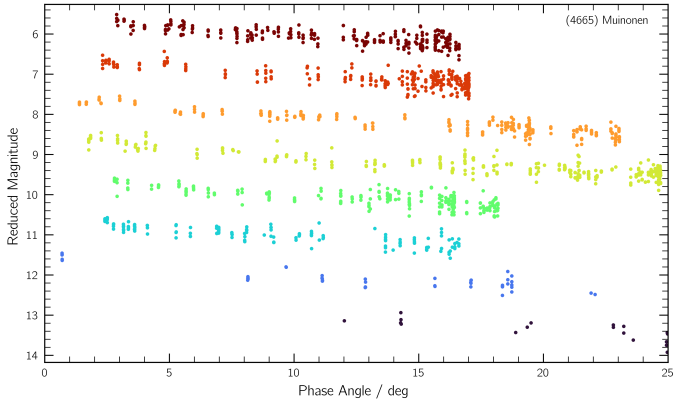

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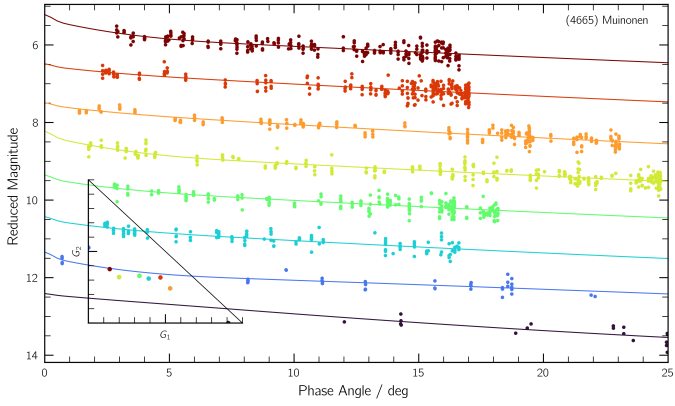

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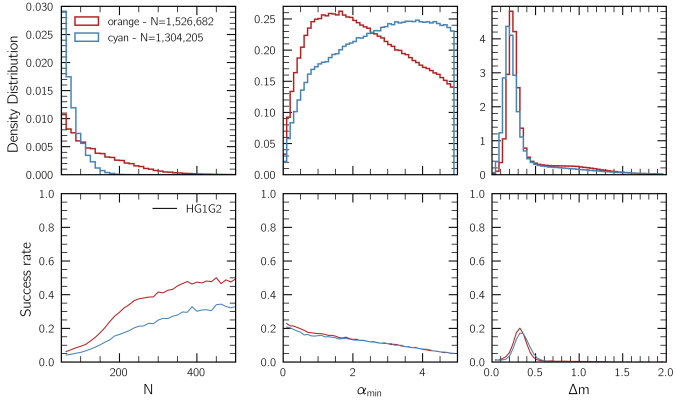
Addressing apparitions with data volume

- Almost 3,000,000 phase curves fit!
- N stagnates
- α_{min} less impactful
- Δm approaches δ-function
- HG_1G_2 24%|33%



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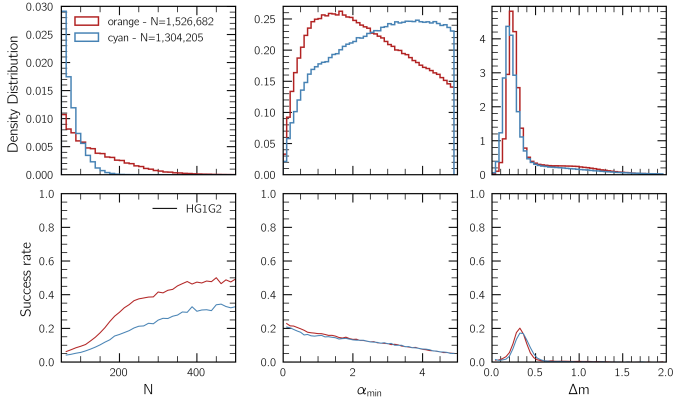
- Almost 3,000,000 phase curves fit!
- N stagnates
- α_{min} less impactful
- Δm approaches δ-function
- HG_1G_2 24%|33%



→ We can address apparitions with high sampling (better: sHG_1G_2)

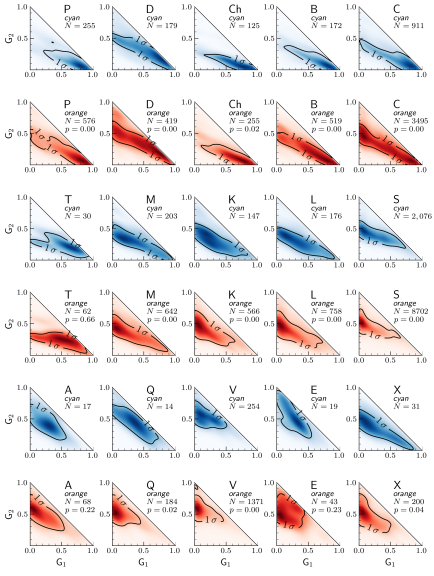
→ Rotation strongly affects the solutions

Looking at the taxonomic signature again

1. Factor 5 in sample size since 2021
2. Apparition-separated phase curves
3. sHG1G2 reduces spread in G_1G_2

Remaining blur-factors are

- Rotation
- Misclassifications
- Separation of *spectral* classes → never 100%



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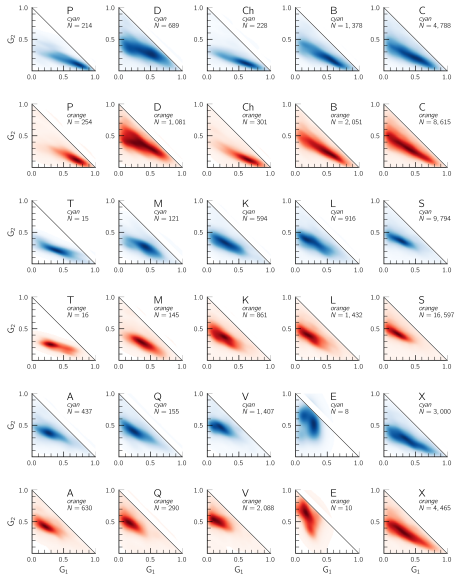

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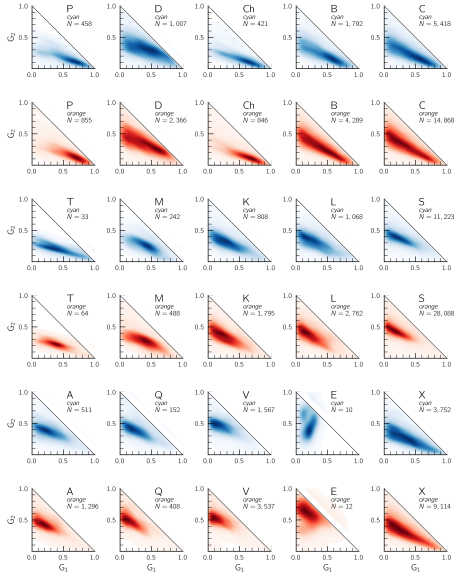

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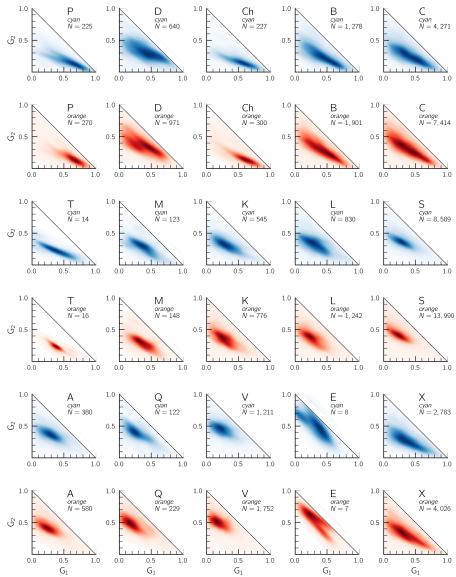


- Accessible and informative phase curves have major potential for taxonomy
- We can determine taxonomy from non-targeted phase curves via G_1G_2
- The better we address systematics, the stronger the taxonomic signal
  - Sampling → LSST
  - Apparitions → Sampling or sHG_1G_2
  - Rotation → $ssHG_1G_2$?

→ In the near future, the majority of taxonomic classifications will be done single-band phase curves

Introducing `phunk` Beta

- `python` package for phase curve fitting
- Many models, including sHG_1G_2
- Open-source

`https://github.com/maxmahlke/phunk`

phunk

Features - Install - Documentation

Features

Observe the phase curve of an asteroid, ...

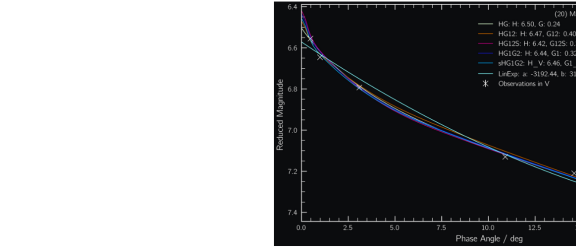
```
>>> from phunk import PhaseCurve
>>> # Observations of (20) Massalia from Gehrels 1956
>>> phase = [0.57, 1.09, 3.20, 10.99, 14.69, 20.42]  # in degrees
>>> mag = [6.555, 6.646, 6.793, 7.130, 7.210, 7.414]
>>> epoch = [35193, 35194, 35198, 35214, 35223, 35242]  # in MJD
>>> pc = PhaseCurve(phase=phase, mag=mag, epoch=epoch, target='massalia')
```

..., fit it in one of multiple photometric models, ...

```
>>> pc.fit(["HG", "HG12", "HG12S", "HG1G2", "sHG1G2", "LinExp"])
```

..., and plot / process the results.

```
>>> pc.HG1G2.H
>>> pc.HG12.H
>>> pc.plot()
```



Also check out `rocks` and `classy`!