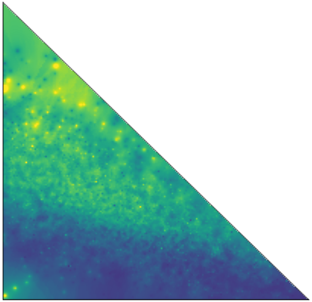
Size-determination of NEOs
Absolute magnitude from sky surveys



B. Carry[1], J. Peloton[2], M. Mahlke[3], J. Berthier[4], R. Le Montagner[2]

[1]Lagrange, OCA, Nice
[2]IJCLab, Orsay
[3]IAS, Orsay
[4]IMCCE, Paris Observatory

Size Determination of Potentially Hazardous Near-Earth Objects

$$D = \frac{1329}{\sqrt{p_V}} 10^{-0.2H}$$

Size Determination of Potentially Hazardous Near-Earth Objects

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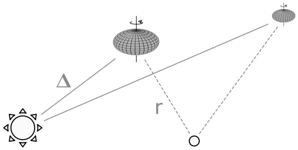
Size Determination of Potentially Hazardous Near-Earth Objects

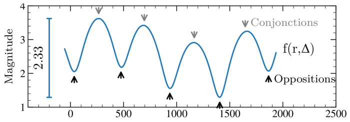
$$D = \frac{1329}{\sqrt{p_V}} 10^{-0.2 H_V}$$

$$H := H_V(r = 1, \Delta = 1, \gamma = 0^\circ)$$

Computing the absolute magnitude

- **Distance**



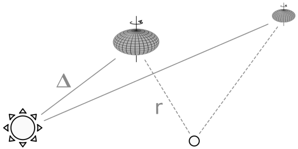


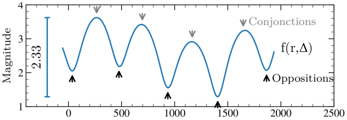
- HG Bowell1989

$$H = m - f(r, \Delta)$$

Computing the absolute magnitude

- **Distance**

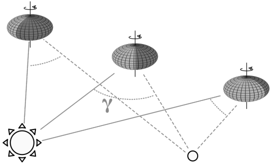


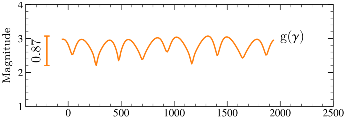


  - HG Bowell1989

$$H = m - f(r, \Delta)$$

- **Phase**



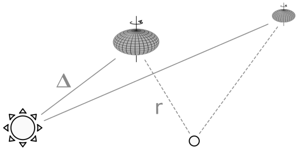


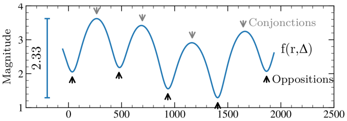
  - HG Bowell1989
  - HG$_1$G$_2$ Muinonen+2010
  - HG$^\star_{12}$ Pentillä+2016 (previous talk)

$$H = m - f(r, \Delta) - g(\gamma)$$

Computing the absolute magnitude

- **Distance**

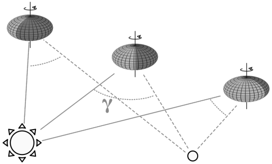


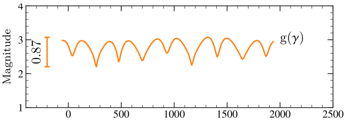


- HG Bowell1989

$H = m - f(r, \Delta)$

- **Phase**





- HG Bowell1989
- HG_1G_2 Muinonen+2010
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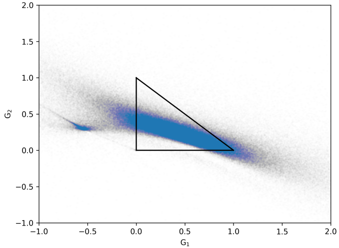
$H = m - f(r, \Delta) - g(\gamma)$



Data from Oszkiewicz+2011

(48% success rate)

Computing the absolute magnitude - Issues

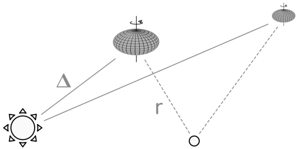
- **Many fits to phase function fail**
  - Model is simple: 2 (HG, $\mathtt{HG}^{\star}_{12}$) or 3 ($\mathtt{HG_1G_2}$) parameters only
  - Generally $N_{obs} \gg N_{params}$
  - ▷ Why fit fails?

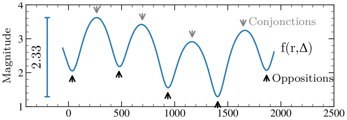
- **Potential sources of failure**
  - Observations close-enough to opposition? 3–5°, Mahlke+2021
  - Photometric uncertainties? Central limit theorem for $N_{obs} \gg 1$
  - Photometric systematics? See Hoffman+2024 and talk tomorrow
  - ▷ Why fit fails in some targeted studies? Devogèle+2020, Jackson+2022

- **The issue is the geometry!**
  - $H := H_V(r = 1, \Delta = 1, \gamma = 0°)$
  - H is defined for **spheres**

Computing the absolute magnitude - Solution?

- **Distance**

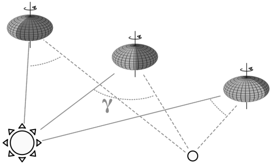


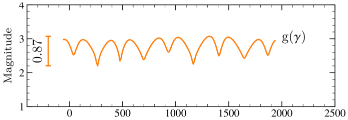


  - HG Bowell1989

$$H = m - f(r,\Delta)$$

- **Phase**





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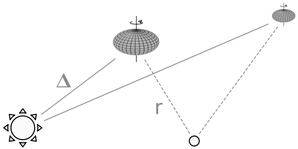
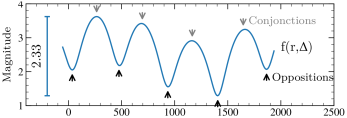
$$H = m - f(r,\Delta) - g(\gamma)$$

Computing the absolute magnitude - Solution?

- **Distance**





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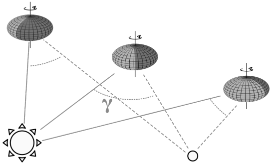
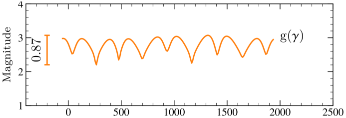
$$H = m - f(r, \Delta)$$

- **Phase**





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  - HG_1G_2 Muinonen+2010
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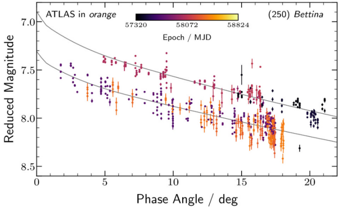
$$H = m - f(r, \Delta) - g(\gamma)$$

- **Aspect!**

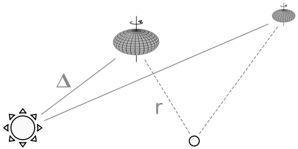


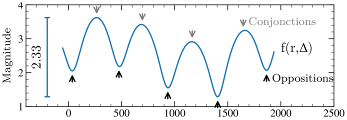
Mahlke+2021

See also Jackson+2022

Computing the absolute magnitude - Solution?

- **Distance**

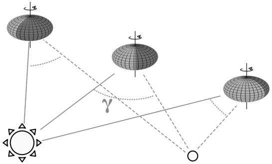


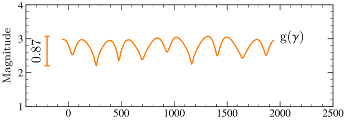


  - HG Bowell1989

H=m -$f(r,\Delta)$

- **Phase**





  - HG Bowell1989
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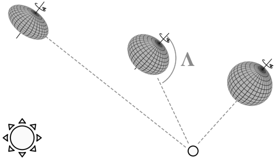
  - HG$^{\star}_{12}$ Pentillä+2016 (previous talk)

H=m -$f(r,\Delta)$-$g(\gamma)$

- **Aspect**



H=m -$f(r,\Delta)$-$g(\gamma)$-$s(\alpha,\delta)$

Taking the geometry into account

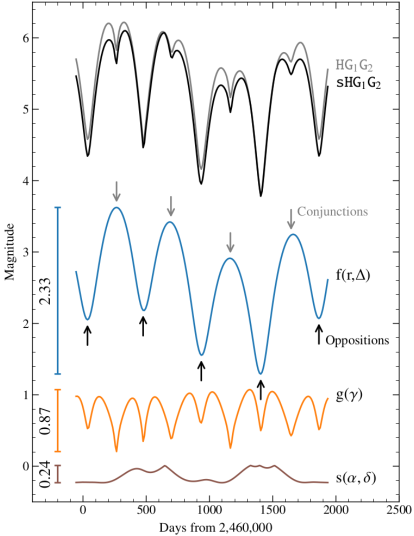
- **Let's assume asteroids are oblate spheres**
  - Dimensions $a = b \geq c$
  - (α_0, δ_0) the spin-axis coordinates $\rightarrow \Lambda =$ aspect angle
  - R the oblateness (a/c)

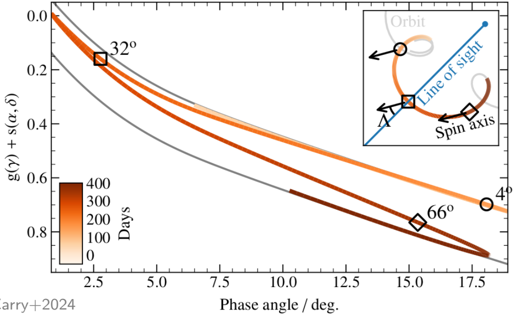
- **Introducing the $\mathtt{sHG_1G_2}$ model** Carry+2024
  - $H = m - f(r, \Delta) - g(\gamma) - s(\alpha, \delta)$
  - $s(\alpha, \delta) = 2.5 \log_{10} [1 - (1 - R) |\cos \Lambda|]$
  - Model with $3N_{filter} + 3$ parameters: $(\mathtt{H}, \mathtt{G_1}, \mathtt{G_2})_{\times N} + (\alpha_0, \delta_0, R)$

  ▷ Avoid opposition-to-opposition issues Jackson+2022 – Single-apparition for NEOs
  ▷ Wavelength dependance of the phase function Sanchez+2012, Binzel+2019, Cellino+2020, Mahlke+2021

- **This changes the definition of absolute magnitude**
  - $H := H_{filter}(r = 1, \Delta = 1, \gamma = 0°, \Lambda = 90°)$
  - H is defined in the **equator**

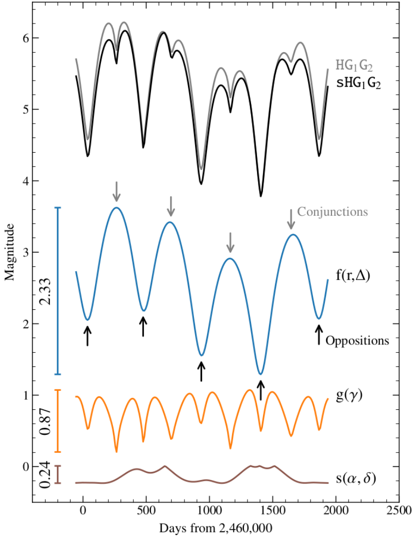
Illustration of sHG$_1$G$_2$ model

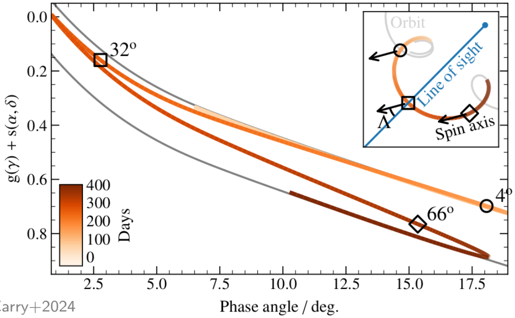




Carry+2024

Illustration of sHG_1G_2 model



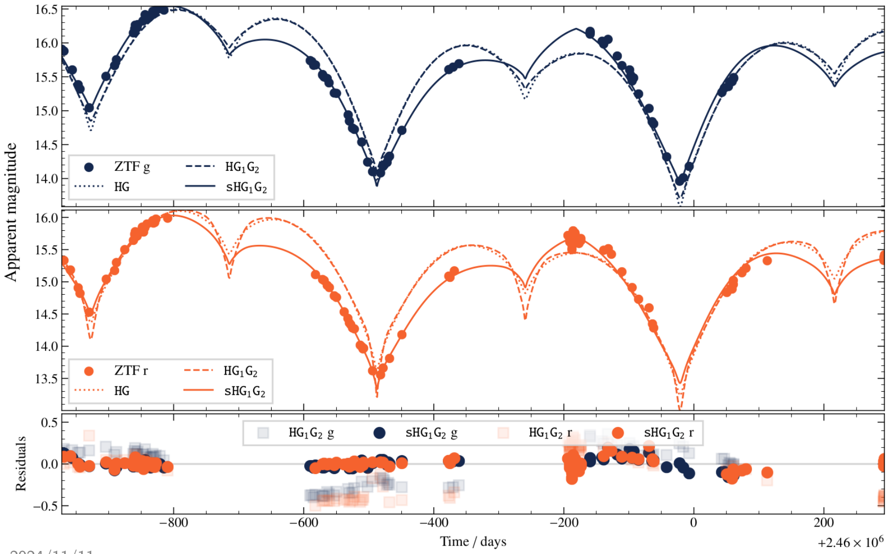


Carry+2024

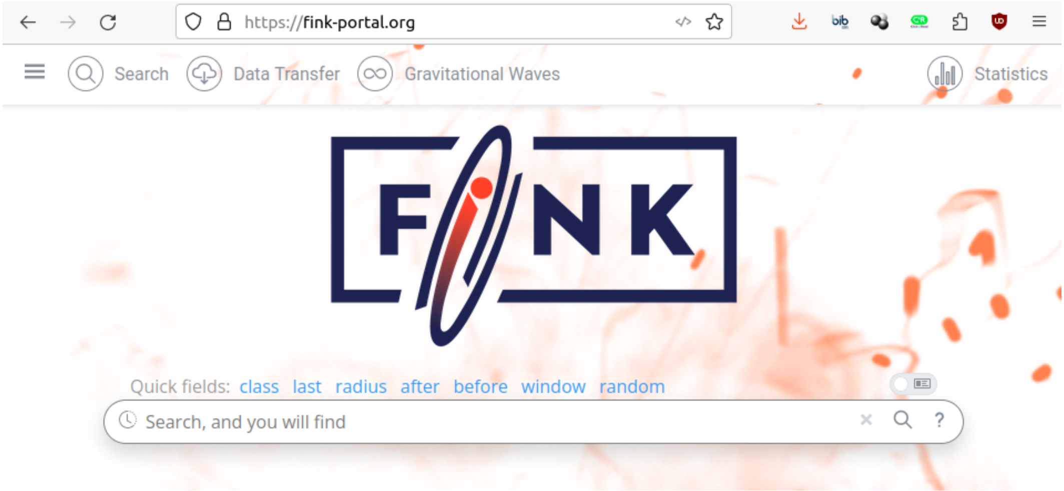
(H, G_1, G_2) are biased by geometry!

Particularly true for NEOs

Illustration of sHG$_1$G$_2$ model

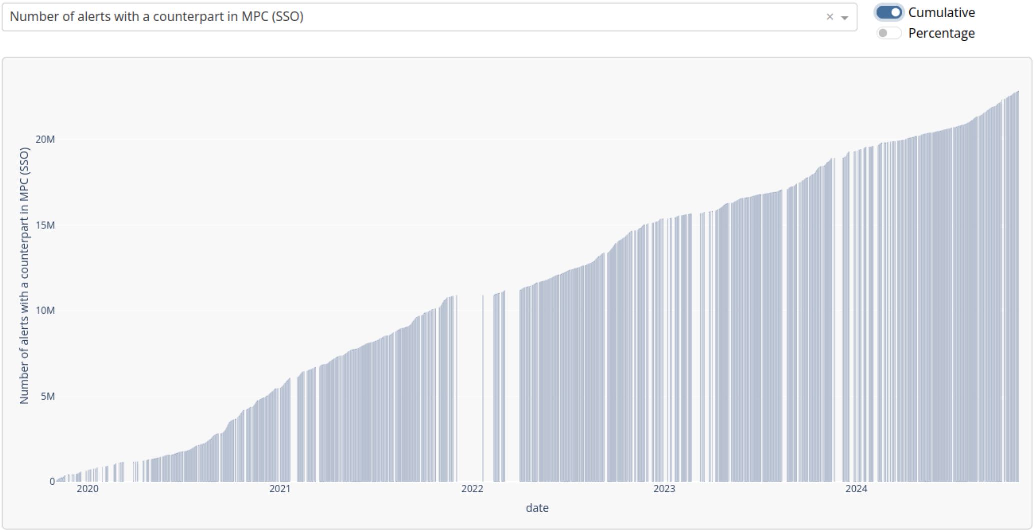


Data: FINK!

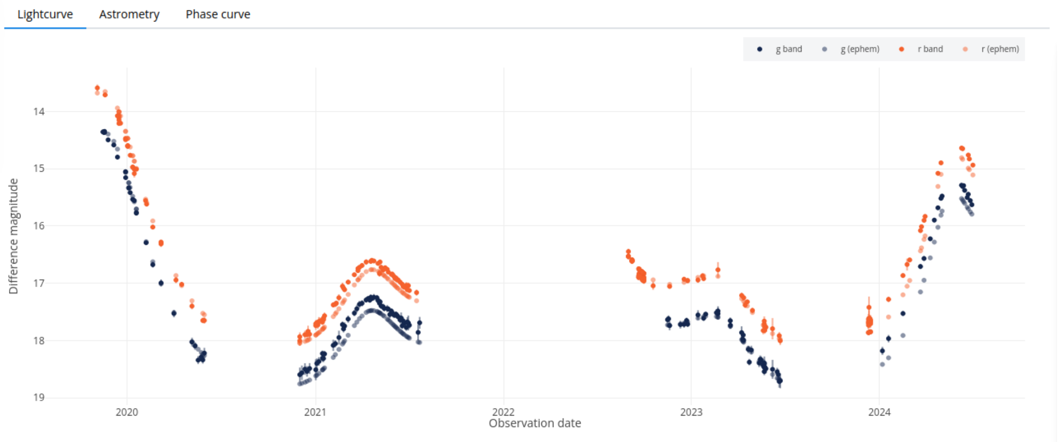


Moller+2021 – `https://fink-portal.org/`

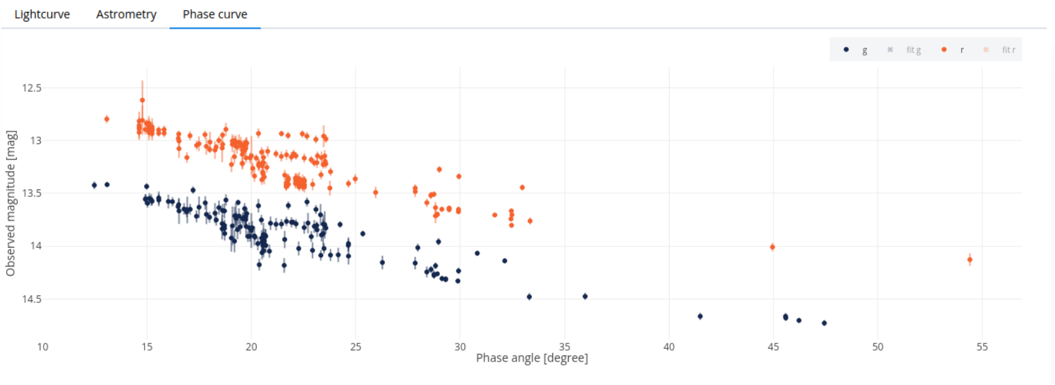
Data: FINK!


Number of alerts with a counterpart in MPC (SSO)
Cumulative
Percentage
Number of alerts with a counterpart in MPC (SSO)
0
5M
10M
15M
20M
2020
2021
2022
2023
2024
date

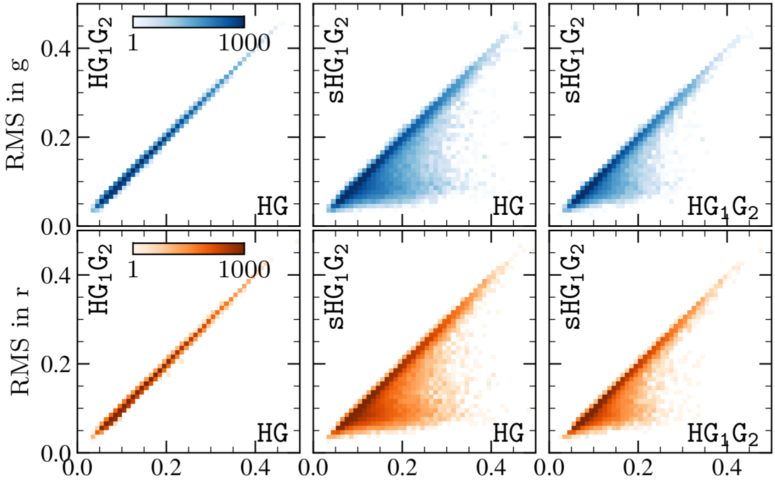
Data: FINK!


Lightcurve
Astrometry
Phase curve
g band
g (ephem)
r band
r (ephem)
Difference magnitude
14
15
16
17
18
19
2020
2021
2022
2023
2024
Observation date

Data: FINK!


Lightcurve
Astrometry
Phase curve
g
fit g
r
fit r
12.5
13
13.5
14
14.5
Observed magnitude [mag]
10
15
20
25
30
35
40
45
50
55
Phase angle [degree]

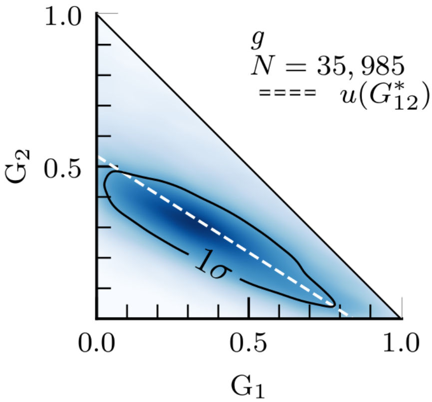
Validation: Quality of fit

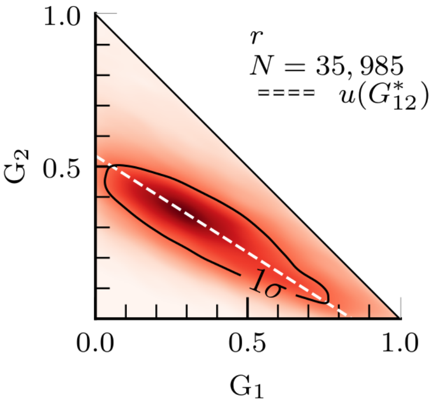


Successful fits: 41% with HG$_1$G$_2$ → **55**% with sHG$_1$G$_2$

72% → 81% with at least one filter

Validation: Phase parameters $\Leftrightarrow g(\gamma)$





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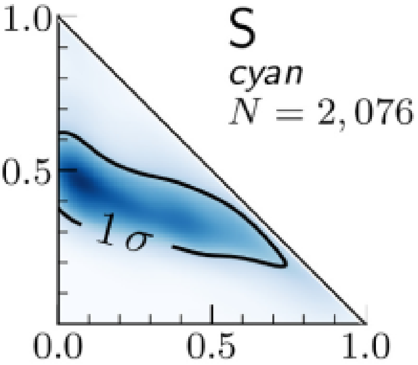
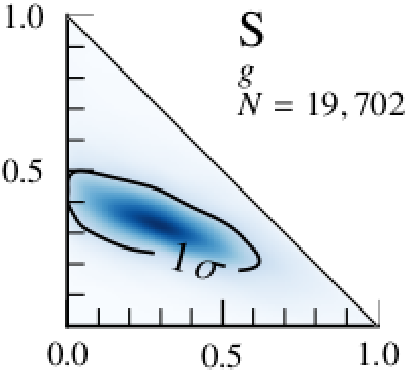
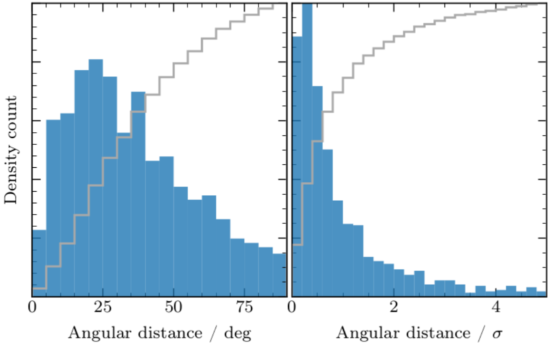


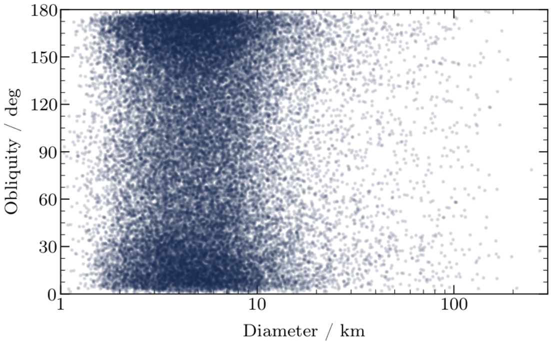
ATLAS, Mahlke+2021 (next talk)



ZTF, Carry+2024

Bonus: Spin parameters $\Leftrightarrow s(\alpha, \delta)$



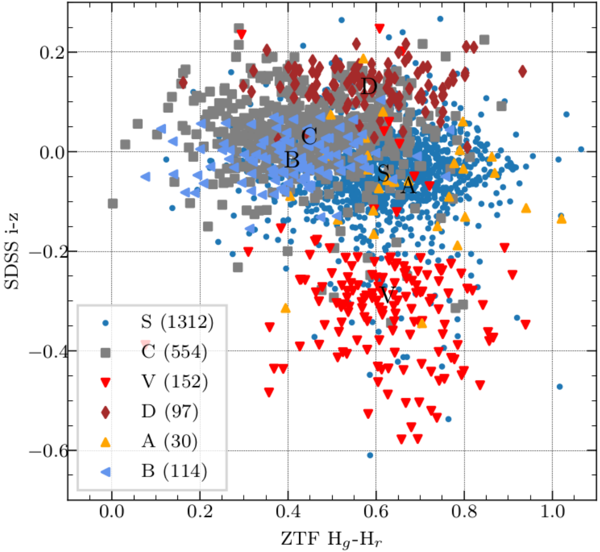


Data from SsODNet via rocks (Berthier+2023), see:

https://ssp.imcce.fr/forms/ssocard

https://rocks.readthedocs.io/en/latest/

Validation: Colors ⇔ H



Disc.1: Taking the **full** geometry into account

- **Let's assume asteroids are tri-axial ellipsoid**
  - Dimensions $a \geq b \geq c$
  - (α_0, δ_0) the spin-axis coordinates $\rightarrow \Lambda =$ aspect angle
  - P_s sidereal rotation period
  - a/b and a/c the axes ratio

- **Introducing the $\mathtt{ssHG_1G_2}$ model** Preliminary!
  - $H = m - f(r, \Delta) - g(\gamma) - ss(\alpha, \delta, t)$
  - $ss(\alpha, \delta, t) =$ [*projected area of a spinning ellipsoid on the sky*] Surdej & Surdej (1978)
  - **Frugal** model with $3N_{filter} + 5$ parameters: $(\mathtt{H},\mathtt{G_1},\mathtt{G_2})_{\times N} + (\alpha_0,\delta_0,P_s,a/b,a/c)$
  - Critical aspect : initial estimates & local minima

- **This changes (again) the definition of absolute magnitude**
  - $H := H_{filter}(r = 1, \Delta = 1, \gamma = 0°, \Lambda = 90°, \varphi = 0°)$
  - H is defined in the **equator**, facing the **prime meridian**
  - ▷ Capacity to compute the **surface area** during mid-infrared observations WISE, NEOMIR

Illustration of ssHG$_1$G$_2$ model

Illustration of $\mathtt{ssHG_1G_2}$ model

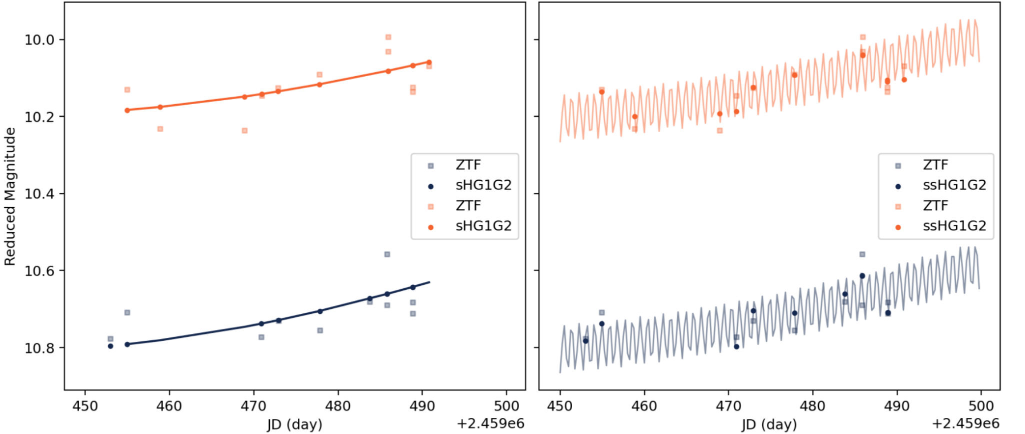
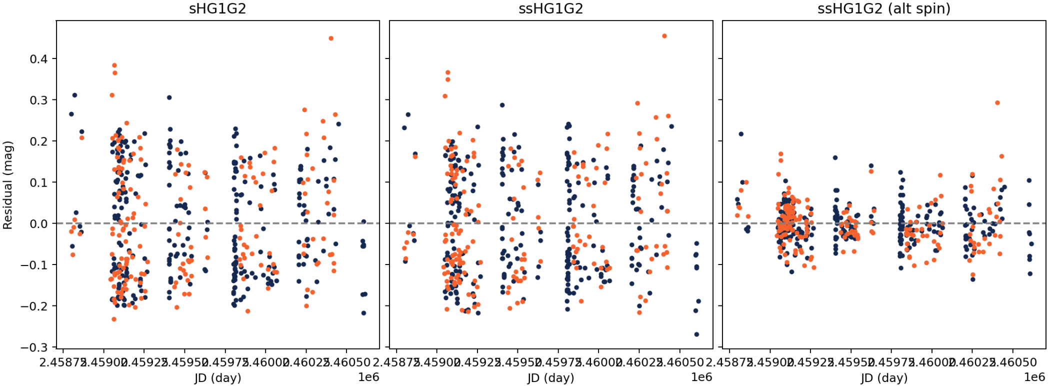


Illustration of $ssHG_1G_2$ model



$HG \rightarrow HG_1G_2 \rightarrow sHG_1G_2 \rightarrow ssHG_1G_2$

Improve residuals, H, G_1, G_2 & **determine** spin and shape

Disc.2: Size Determination

$$D = \frac{1329}{\sqrt{p_V}} 10^{-0.2H}$$

Disc.2: Size Determination

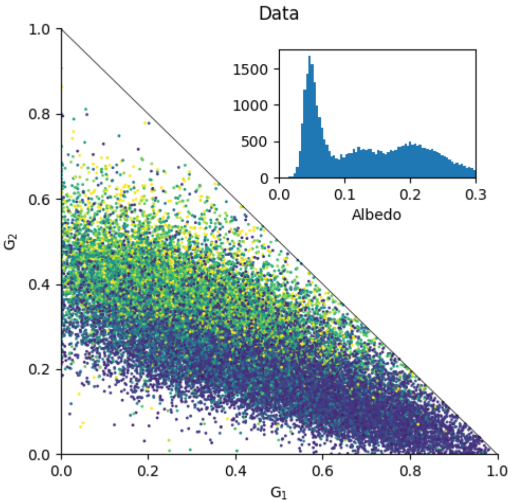
$$D = \frac{1329}{\sqrt{p_F}} 10^{-0.2 H_F}$$

Disc.2: Size Determination

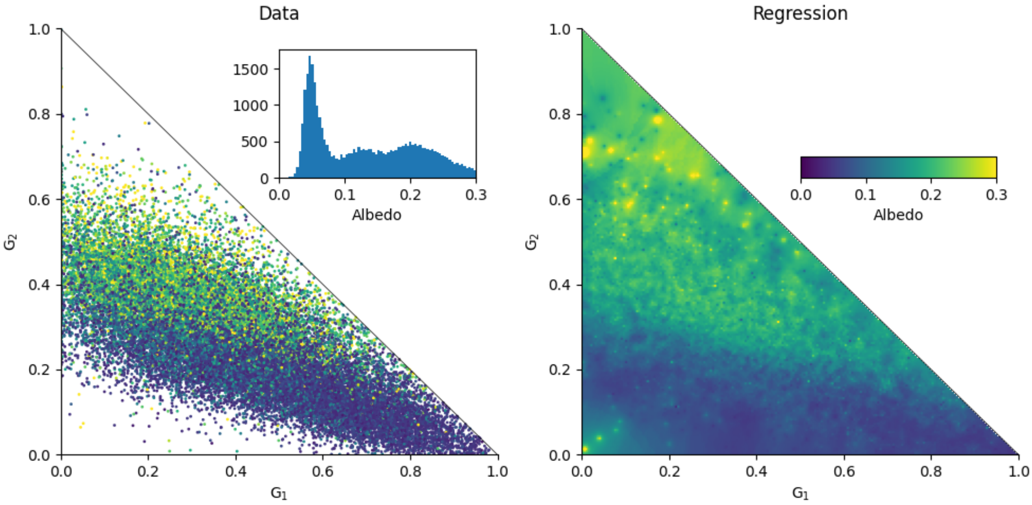
$$D = \frac{1329}{\sqrt{p_F}} 10^{-0.2 H_F}$$

$$p_F = f\left(G_{1,F}, G_{2,F}\right)$$

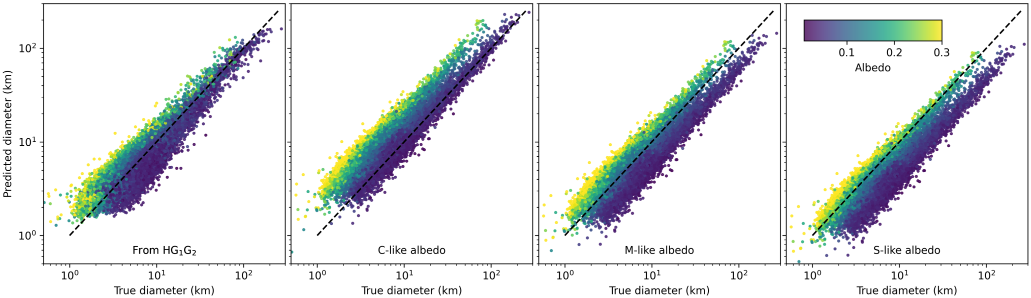
Disc.2: Size Determination from phase curves



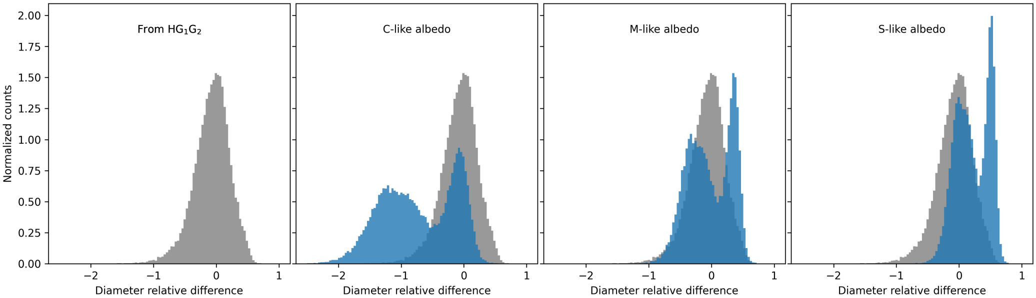
Disc.2: Size Determination from phase curves



Disc.2: Size Determination from phase curves



Disc.2: Size Determination from phase curves



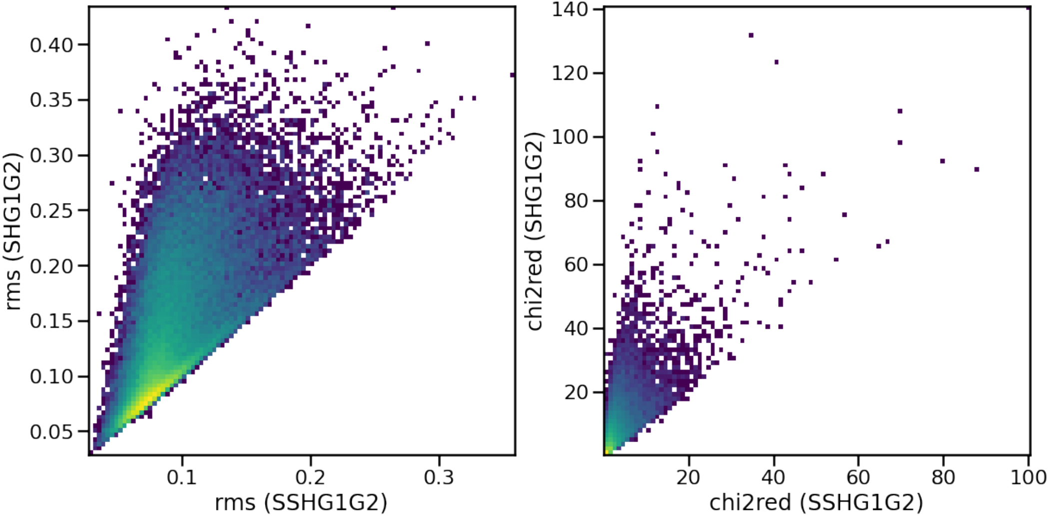
Summary and discussions

- **Phase curves from sparse photometry**
  - Required for H → diameter
  - $HG < HG^{\star}_{12} < HG_1G_2 < sHG_1G_2 < ssHG_1G_2$
  - Occam's razor **vs** sparsity of data F-test...

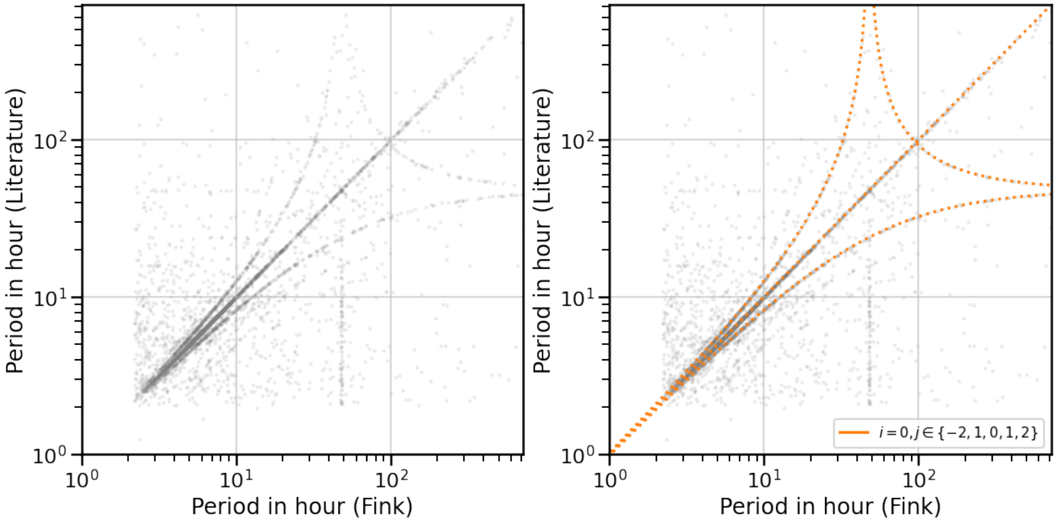
- **Size determination of potentially hazardeous near-Earth objects**
  - Geometry must be taken into account **vs** biases on (H, G_1, G_2)
  - Promising new approach to estimate size from phase curves **only**
  - Higher fidelity model → diameter estimate with mid-infrared WISE, NEOSurveyor, NEOMIR
  - ▷ Low-phase angle observations required for G_1G_2 LSST, FlyEye

- **Era of large sky surveys & alert streams**
  - Currently: ATLAS, ZTF, Gaia 10^5 SSOs, inc. 30k NEOs
  - Soon: LSST, FlyEye 10^6 SSOs, inc. 10^5 NEOs
  - ▷ Need robust & fast, multi-model & multi-sources fits

Preliminary results on $\mathtt{ssHG_1G_2}$



Preliminary results on ssHG$_1$G$_2$



Preliminary results on $ssHG_1G_2$