The distance of the Magellanic clouds

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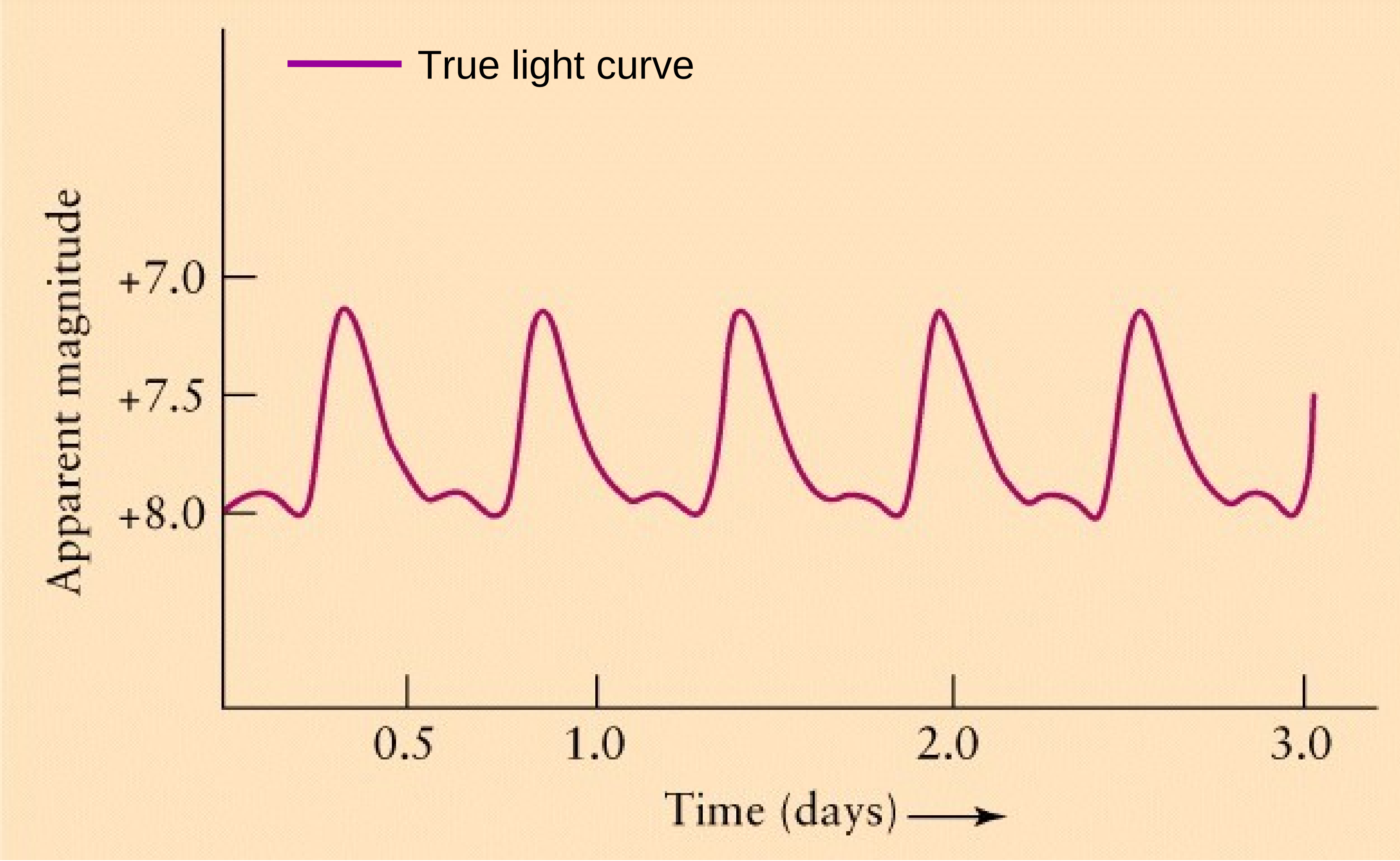
- Time series of variable stars
- Fit of the light curves
- Mean magnitudes
- Period Wesenheit relations for distance estimate

What is a time series?



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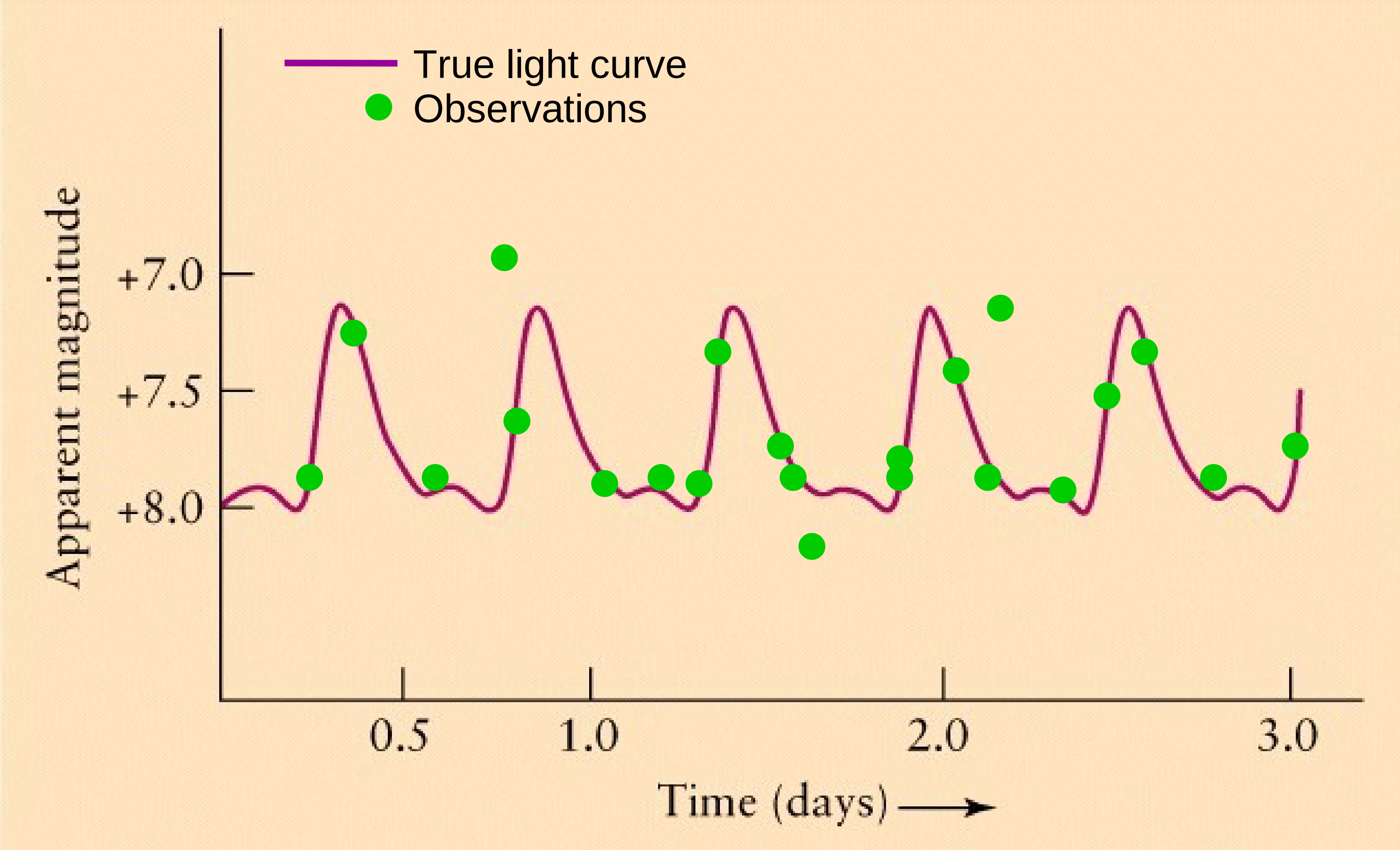

What is a time series?

mag	error	filter		JD			Dataset
13.242	0.0146	1	1	2450601.7136	2.38	0.052	bond5:obj5105.als
13.238	0.0147	1	1	2450601.7144	2.44	0.083	bond5:obj5106.als
13.358	0.0148	1	1	2450601.7336	2.25	0.054	bond5:obj5204.als
13.378	0.0155	1	1	2450601.7547	2.44	0.078	bond5:obj5403.als
13.387	0.0169	1	1	2450601.7641	2.69	0.177	bond5:obj5503.als
13.086	0.0202	1	1	2451996.8152	3.54	0.006	bond7:obj5203.als
13.077	0.0240	1	1	2451996.8334	5.70	0.031	bond7:obj5207.als
13.265	0.0080	1	1	2452013.6910	3.70	1.338	danish:dfsc0086.als
13.296	0.0083	1	1	2452013.6921	3.19	1.252	danish:dfsc0087.als
13.337	0.0120	1	1	2452013.7073	4.98	1.385	danish:dfsc0099.als
13.330	0.0078	1	1	2452013.7081	3.52	1.304	danish:dfsc0100.als
13.330	0.0151	1	1	2452013.7090	5.85	0.894	danish:dfsc0101.als
13.336	0.0126	1	1	2452013.7098	5.12	1.135	danish:dfsc0102.als
13.343	0.0097	1	1	2452013.7107	3.96	0.851	danish:dfsc0103.als
13.344	0.0141	1	1	2452013.7115	5.38	0.699	danish:dfsc0104.als
13.345	0.0133	1	1	2452013.7124	5.30	1.063	danish:dfsc0105.als
13.364	0.0155	1	1	2452013.7131	4.32	1.149	danish:dfsc0106.als
13.389	0.0181	1	1	2452013.7393	5.89	0.429	danish:dfsc0115.als
13.408	0.0135	1	1	2452013.7427	3.00	0.693	danish:dfsc0116.als
13.389	0.0103	1	1	2452013.7456	3.15	0.863	danish:dfsc0117.als
13.374	0.0186	1	1	2452013.7490	7.57	0.645	danish:dfsc0118.als
13.376	0.0235	1	1	2452013.7510	8.52	0.479	danish:dfsc0119.als
13.379	0.0213	1	1	2452013.7529	8.32	0.618	danish:dfsc0120.als
13.382	0.0221	1	1	2452013.7548	8.29	0.518	danish:dfsc0121.als
13.379	0.0144	1	1	2452013.7567	6.49	0.770	danish:dfsc0122.als
13.309	0.0115	1	1	2452013.7977	3.22	0.633	danish:dfsc0140.als
13.219	0.0140	1	1	2452013.8094	3.91	0.546	danish:dfsc0150.als
13.176	0.0167	1	1	2452013.8113	6.98	0.523	danish:dfsc0151.als
13.162	0.0174	1	1	2452013.8133	7.27	0.611	danish:dfsc0152.als
13.143	0.0207	1	1	2452013.8152	8.02	0.575	danish:dfsc0153.als
13.128	0.0182	1	1	2452013.8171	7.45	0.601	danish:dfsc0154.als
13.114	0.0152	1	1	2452013.8190	6.78	0.708	danish:dfsc0155.als
13.028	0.0292	1	1	2452013.8642	6.13	0.594	danish:dfsc0174.als
12.979	0.0090	1	1	2452013.8776	2.71	0.254	danish:dfsc0185.als
12.957	0.0158	1	1	2452013.8792	6.33	0.430	danish:dfsc0186.als
12.960	0.0143	1	1	2452013.8809	5.89	0.433	danish:dfsc0187.als
12.960	0.0129	1	1	2452013.8826	5.46	0.402	danish:dfsc0188.als
12.961	0.0137	1	1	2452013.8843	5.47	0.325	danish:dfsc0189.als

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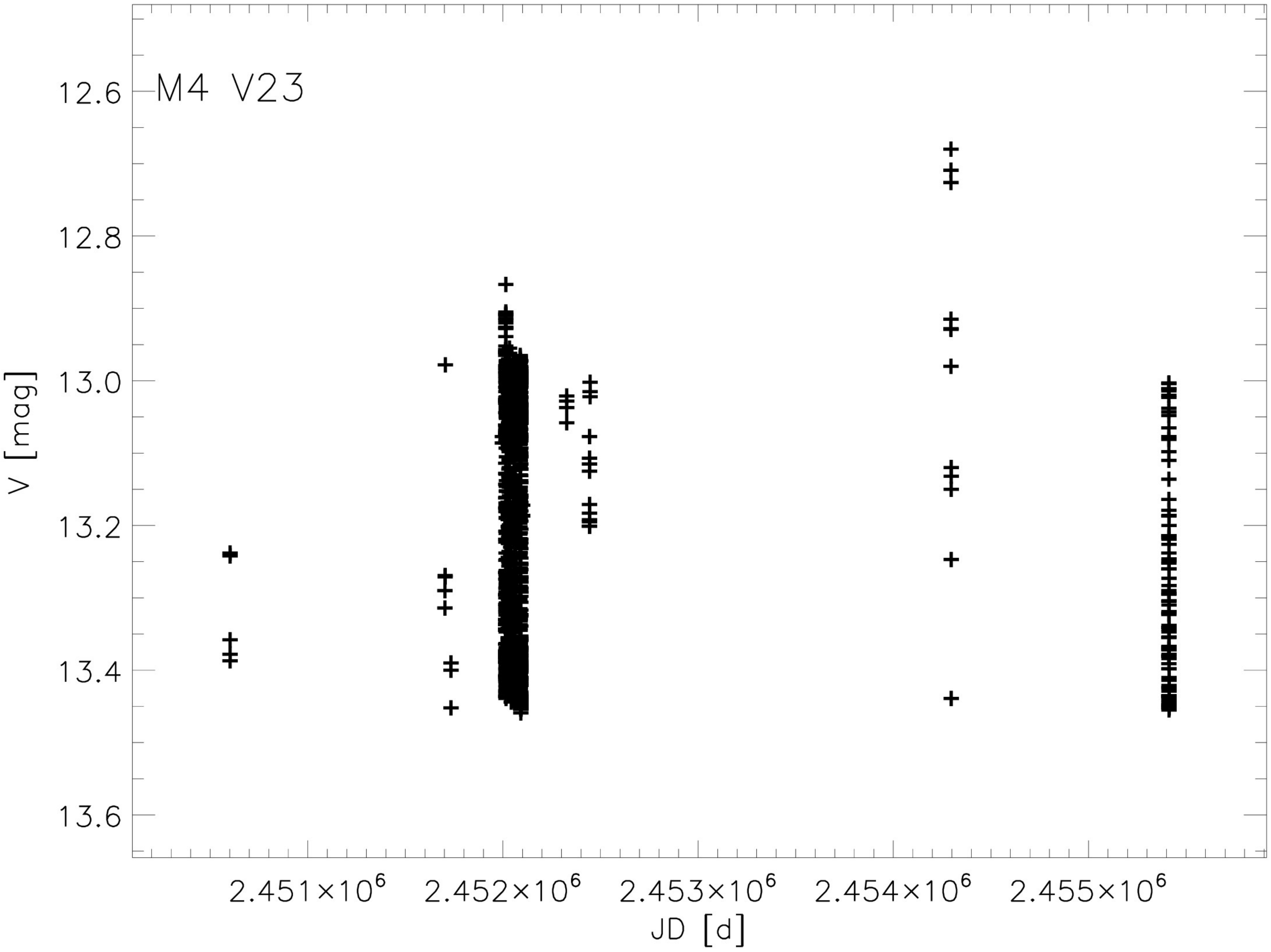

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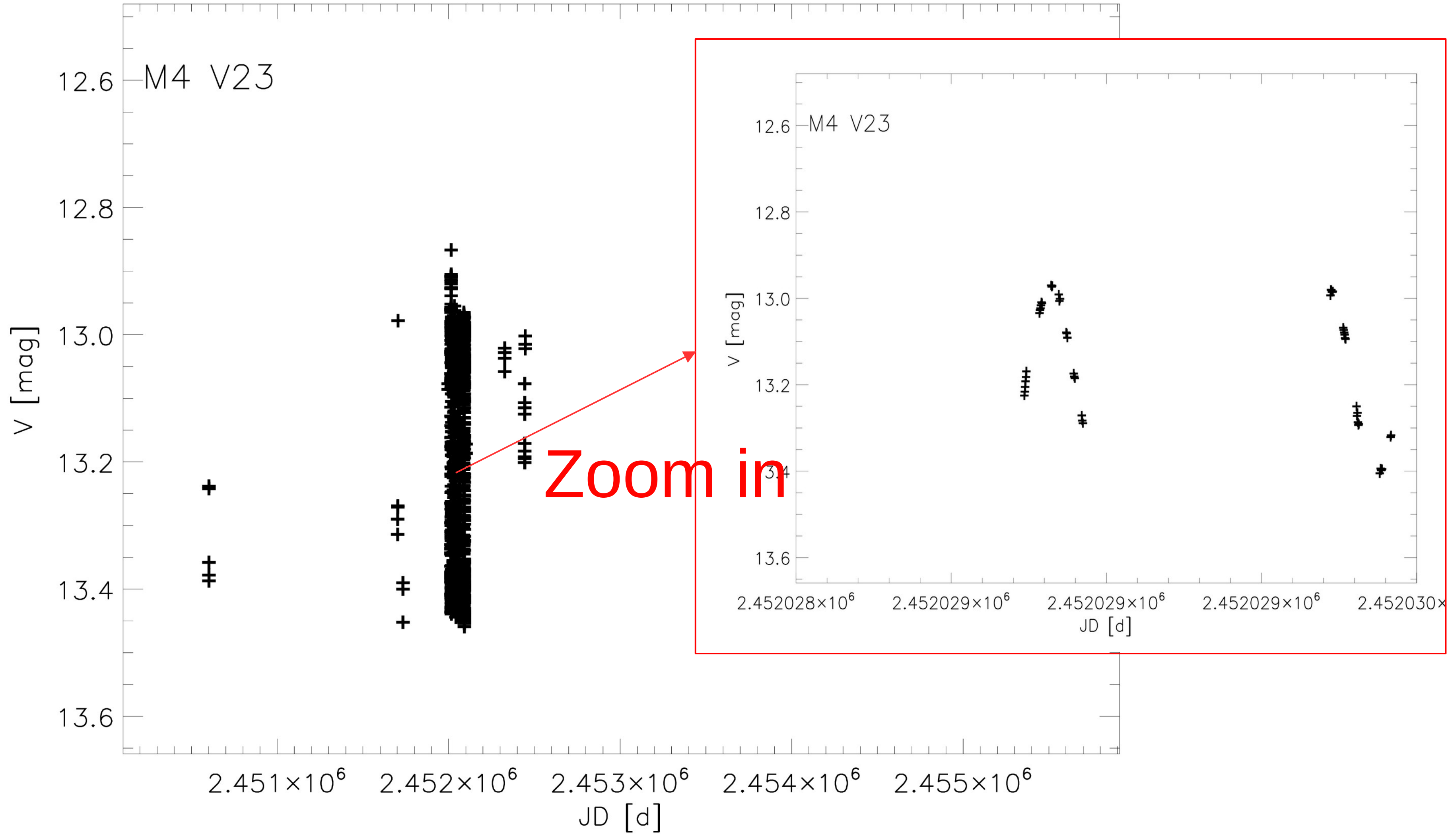

How to get time series

Depends on what you want...

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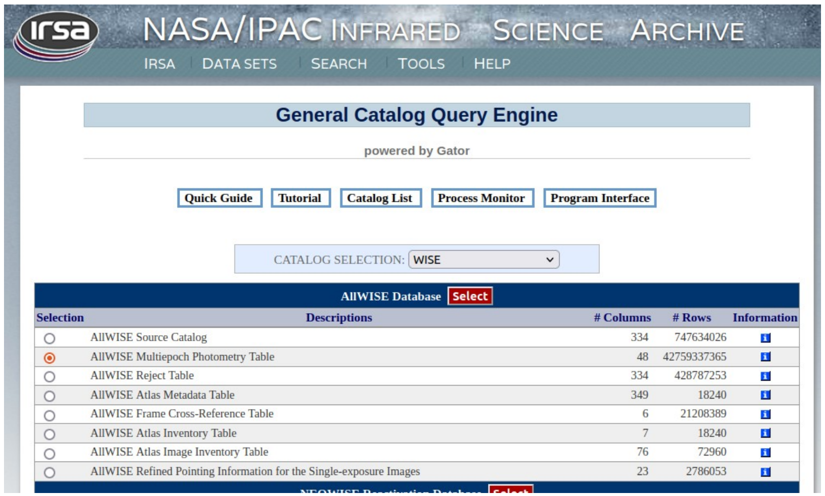
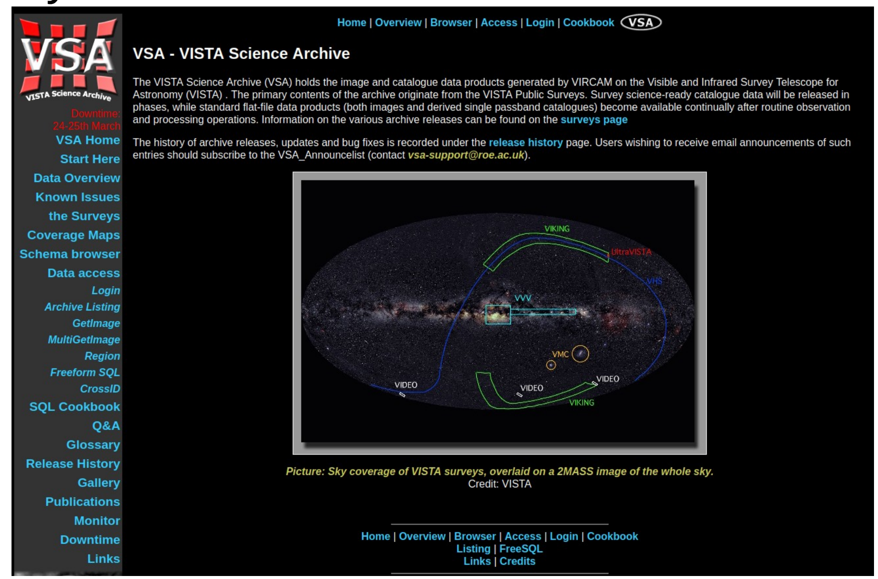
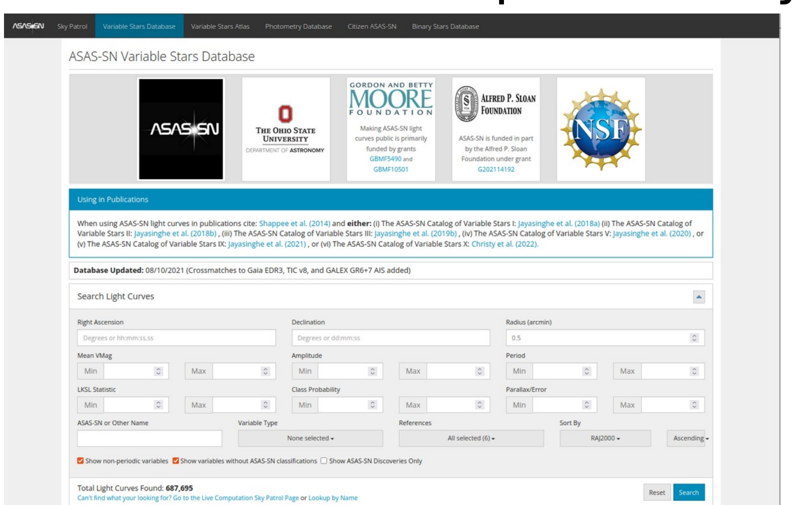


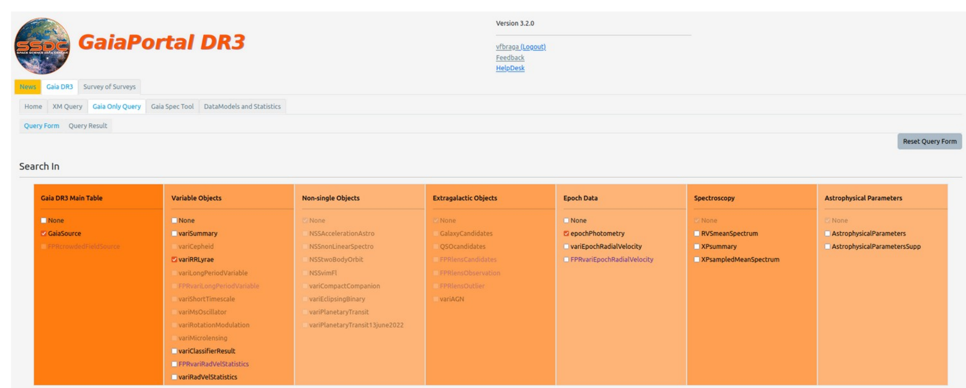
WISE Mid-Infrared photometry



VISTA Near-Infrared photometry



ASAS-SN optical photometry

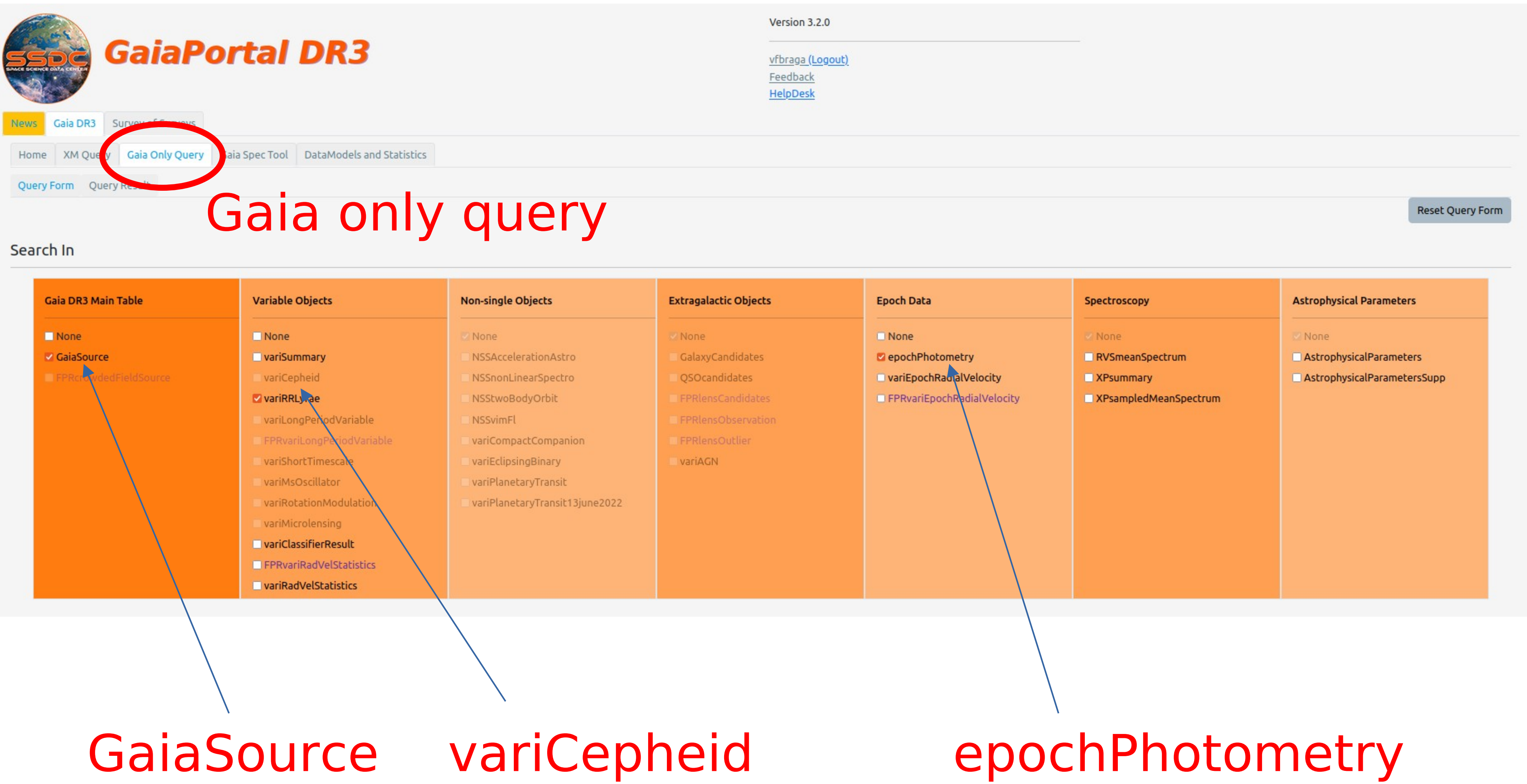


Gaia Optical photometry

Gaia time series

Gaia portal at ASI:

http://gaiaportal.asdc.asi.it/DR3/GODR3/query/form



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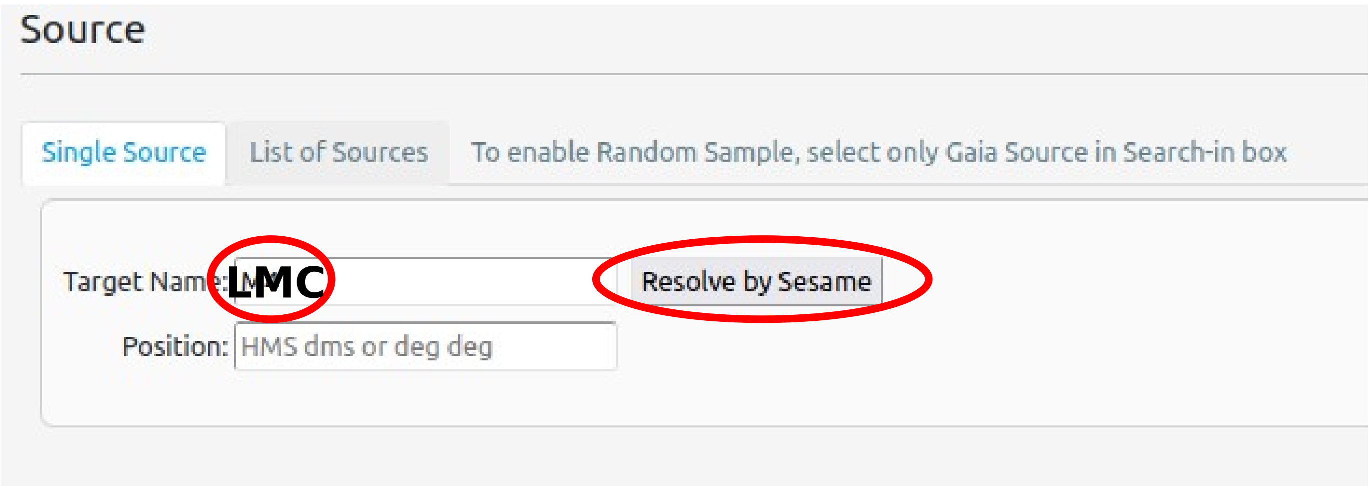
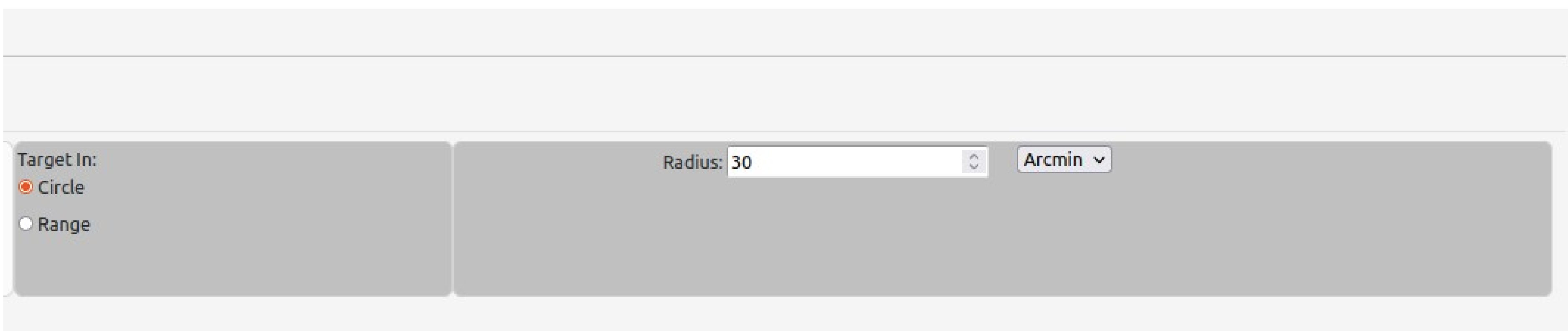


Globular cluster M4: has some RRLs, all at the same distance



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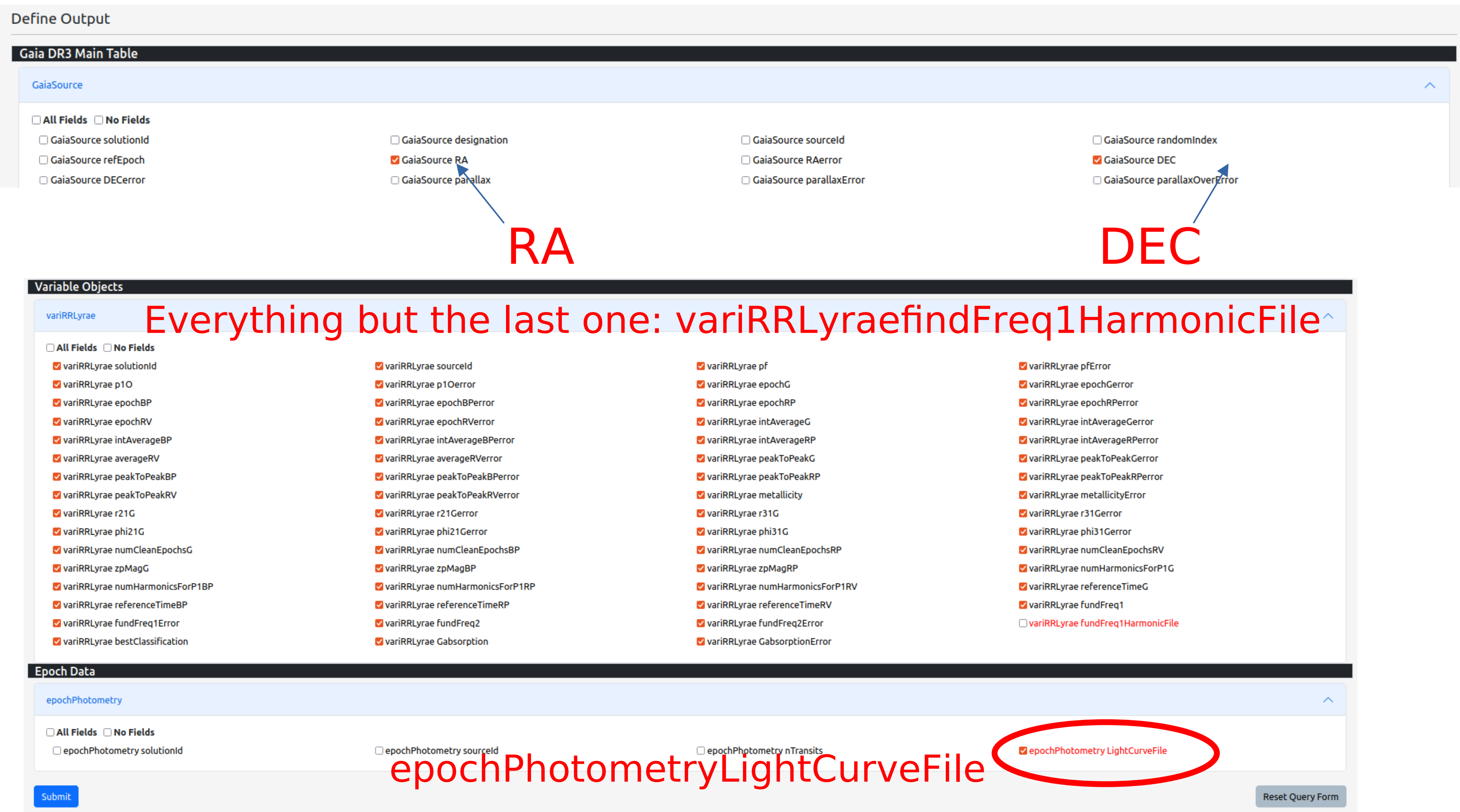


Gaia time series

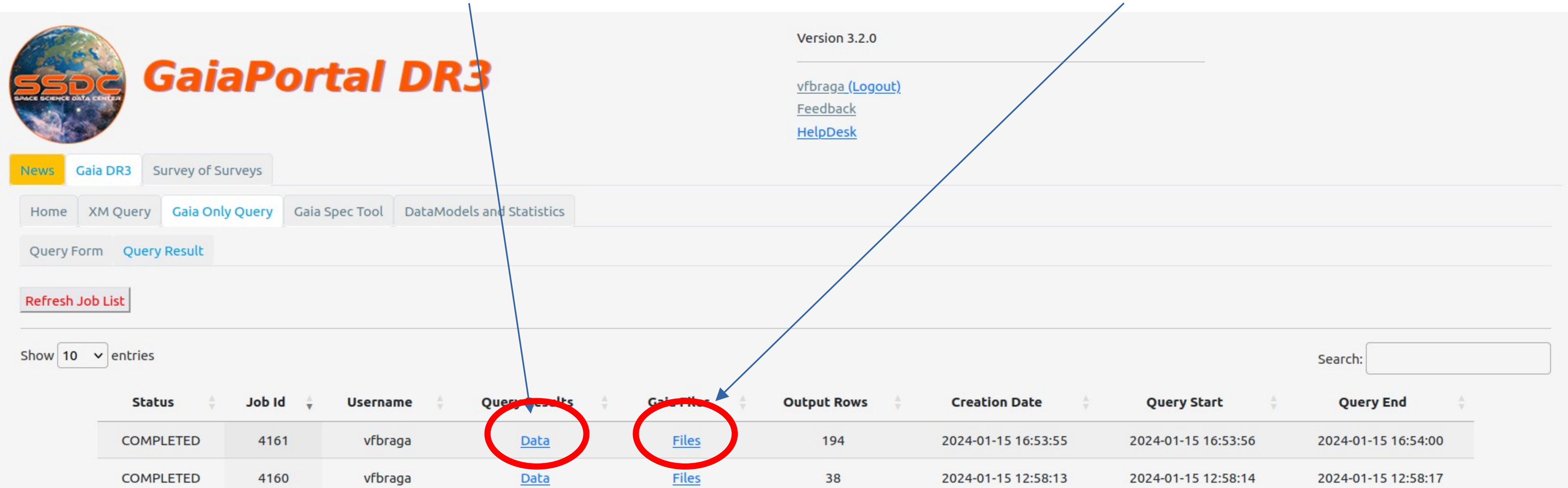
Gaia portal at ASI:

http://gaiaportal.asdc.asi.it/DR3/GODR3/query/form

Table of properties

You will get two files

Time series tar file



The time series archive has a complicated structure: to unzip it, follow these steps from command line:

```
> tar --strip-components=7 -xvf result_*.list.tar
> ls *zip | awk '{print "unzip "$1}' > unzip_files
> source unzip_files
```

Gaia time series

Structure of a light curve file:

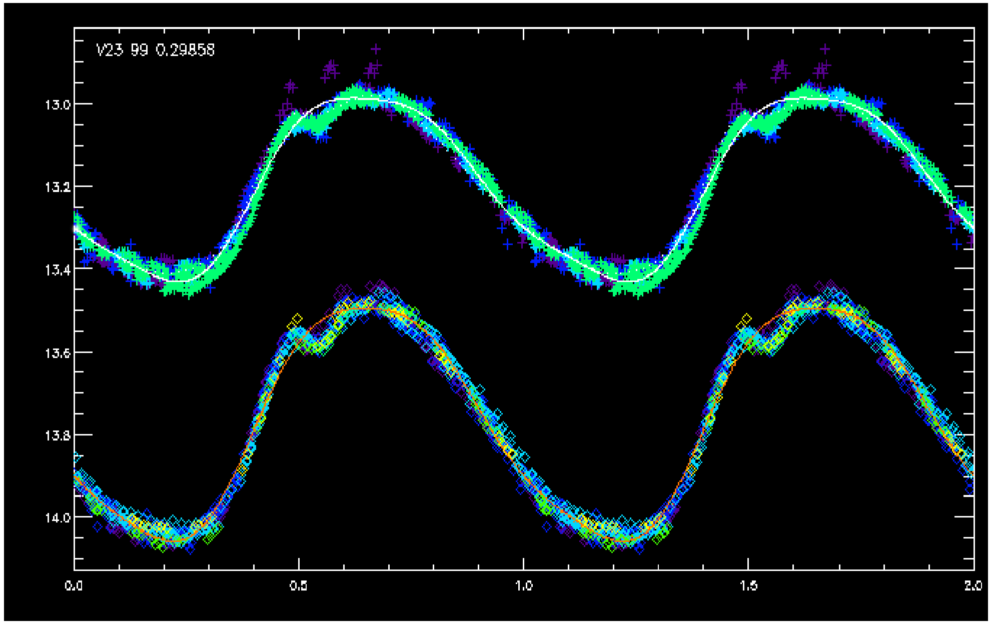
rpObsTime rpFluxOverError rpMag

FluxError	bpFluxOverError	bpMag	rpObsTime	rpFlux	rpFluxError	rpFluxOverError	rpMag	photometryFlagNoisyData	variabilityFlagGReject	variabilityFlagBpReject	v
4.27118290784531	473.34903	13.252639482755896	1710.4715044[illegible]17257	94208.75491764495	152.97383553647464	615.8488	12.312[illegible]7340888328	1	0	0	
1.8965240828027	388.9086	13.483993949145619	1710.5455032302223	84968.99263554292	151.81718707639055	559.6797	12.424744327577358	1	0	0	
.02125982247544	372.0365	14.05060935690214	1742.849102633857	58948.59294189628	118.16969869845126	498.84695	12.821711892965464	0	0	0	
.06155658796604	361.9702	14.055511467603507	1742.9231036183241	56694.01760267621	117.21226109191105	483.68674	12.864052415616348	0	0	0	
								0	0	1	
9.83116593450933	563.2906	13.097701018903198	1913.626801013107	100162.66673230626	151.53473234613668	660.98816	12.246130804447318	1	0	0	
6.33087158751565	471.93658	13.317347565881704	1913.7008153018307	91675.52197574612	145.20492890259604	631.35266	12.34226202266573	0	0	0	
3.70414404379845	381.69977	13.844747177571048	1913.8769853517638	69771.27627769508	131.63974923768976	530.0168	12.638703832903754	0	0	0	
								1	0	1	
.56997426437657	343.3843	14.05970796422756	1926.8833673571673	56648.93156298144	119.55706401925225	473.82336	12.864916193179363	0	1	0	
1.20051238006457	540.5431	12.80274380891083	1926.9573811232815	122718.44867010706	178.12688643214437	688.93835	12.025620859753817	1	1	0	
2.8276379111259	841.20337	12.108703361099835	1927.13355348338	258469.6006326943	249.3578714121709	1036.5408	11.216871821688274	0	1	0	
.31493468796963	379.01465	14.039180866527252	2022.4422393771292	64748.56204629118	121.1050504792458	534.6479	12.719820181329151	1	0	0	
9.85449594101064	582.26904	13.142090488772451	2022.6923894413603	100926.00301195565	150.1164233735486	672.3182	12.237887815748286	0	0	0	
.47802635547022	351.6433	14.058189907654729	2022.9425382135582	60261.8112992995	117.42236055353128	513.20557	12.797790048166888	1	0	0	
.91922553146262	390.29147	14.024843644508083	2023.0165410218485	59935.780855085104	115.81529657577288	517.5118	12.803680081717953	0	0	0	
1.73831480684558	552535	13.18336253759433	2023.192685953697	99222.60705624733	152.25655283320057	651.68036	12.256368916504918	0	0	0	
4.46929337081541	468.77997	13.613647937806741	2023.2666885903955	79463.88101180292	133.40973530831076	595.6378	12.497471070761714	0	0	0	
.0287155561006	370.96732	14.053642224619944	2023.442832964355	60146.66395113605	119.18951811514235	504.6305	12.799866640908952	1	0	0	
.31107912941555	382.12338	14.00576982858021	2023.5168354464304	60704.27917123931 5	118.79859912970163	510.9848	12.789847234959375	1	0	0	
8.6108563953472	547.65155	13.219087370488662	2023.6929794606167	97144.48237093657	151.12876616111643	642.7928	12.279350154896097	0	0	0	
4.93306859985911	454.76627	13.64179069591178	2023.766981860596	78253.55166275585	134.07381979489168	583.6602	12.514135356613782	1	0	0	
								0	0	1	
.73303282365319	383.3389	14.009371703575601	2024.0171280524937	60256.84097855194	117.87598121859807	511.18845	12.797879602058938	0	0	0	
6.7512070963698	535.5391	13.259183950042438	2024.1932718730952	95580.43505519928	150.2756050087872	636.0343	12.296972993716281	1	0	0	
3.69191071917733	447.46866	13.672273465119613	2024.2672743059456	77317.98237574169	133.3817380377334	579.67444	12.527194219841553	1	0	0	
.83524417857808	369.55765	14.060164695741742	2024.4434183021929	59500.41412859127	119.3588880474468	498.50006	12.811595529978806	1	0	0	
5.63735286135437	523.5123	13.293428041248527	2024.6935652159866	93453.15839498705	150.09089157045284	622.6438	12.321410542101985	0	0	0	
0.64909183620694	450.26697	13.697842317724522	2024.7675678672204	76252.68755351467	130.65953693126528	583.5983	12.542257613268497	0	0	0	
.02061078303798	367.82407	14.075386584878853	2024.9437127988938	58784.07676509749	117.51433670962506	500.22897	12.8247462467455 1	1	0	0	
0.03432436629463	526.2426	13.33731359915072	2025.1938613098973	91207.29020971549	143.30937716478442	636.4363	12.347821618839225	0	0	0	
.42655967994689	382.3869	14.053302445920044	2025.4440109633463	59131.226516425195	115.65975073837812	511.25156	12.818353282779526	0	0	0	
7.5436828539764	522.56104	13.367701451353138	2025.694161964266	89668.71203698614	141.40766438151365	634.1149	12.36629317169558	0	0	0	
								1	0	1	

These are the Rp band data, there are also G and Bp!

Uncertainty on magnitude for each point: 2.5 / (ln(10) * rpFluxOverError)

Mean magnitude estimate

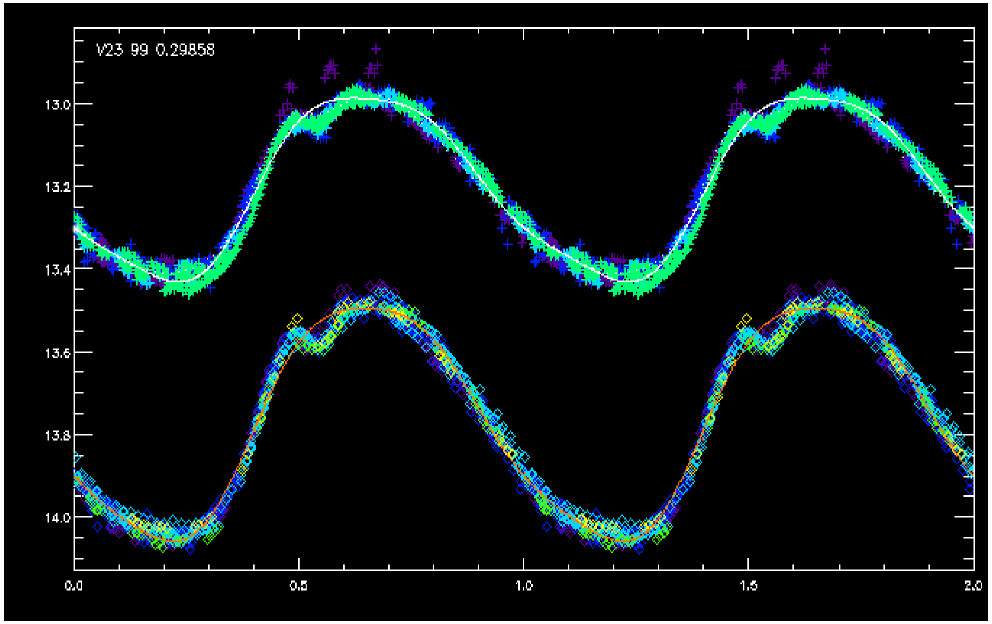


Phasing: fold the lightcurve with the period that minimizes the χ^2

$$\phi_i = ((t_i - t_0)/P) \% 1$$

Remainder of the division by 1: just pick the decimal figures

Mean magnitude estimate



Phasing: fold the lightcurve with the period that minimizes the χ^2

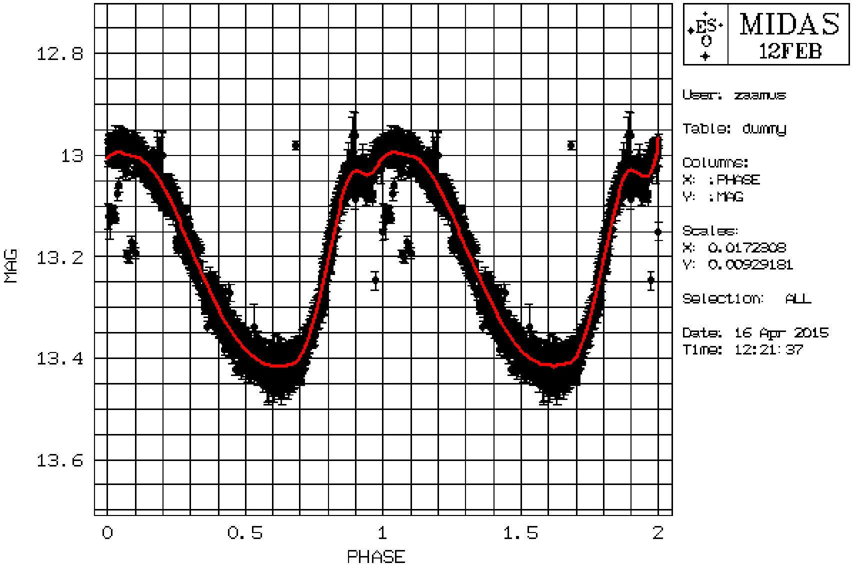
$$\phi_i = ((t_i - t_0)/P) \% 1$$

Remainder of the division by 1: just pick the decimal figures

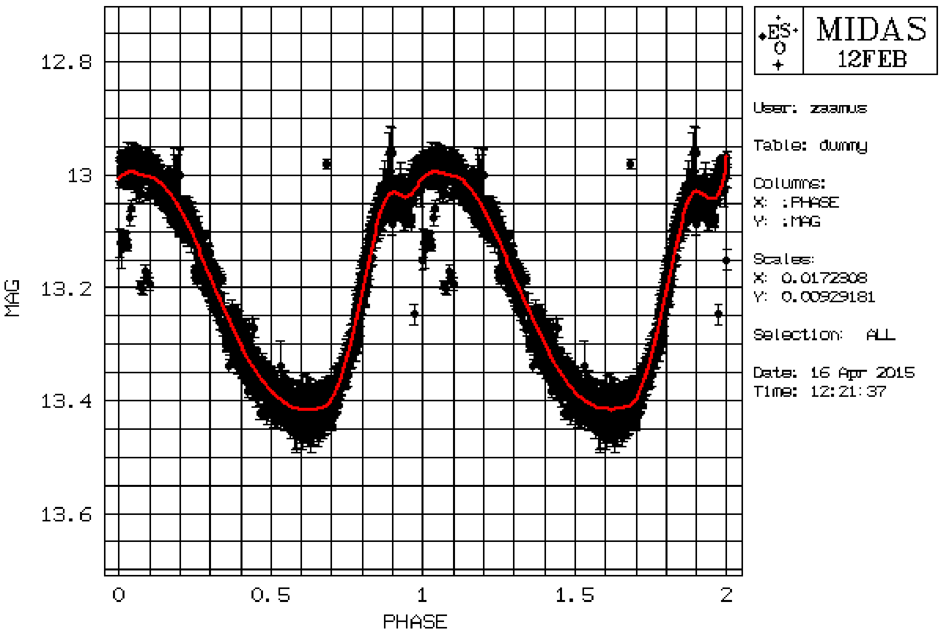
On the folded light curve, fit with a Fourier series

Code for Fourier series fit

https://drive.google.com/file/d/1ysZTlVAUuzP0NrTh95rvatcyk1gZNqdo/view?usp=sharing



Mean magnitude estimate



Mean magnitude is a logarithmic quantity --> intensity average over the cycle

One cannot calculate <mag> integrating the fit as it is: all the points of the fit must be converted to intensity

$I_i = 10^{\wedge}(-0.4*mag_i)$

for each phase point of the fit (i)

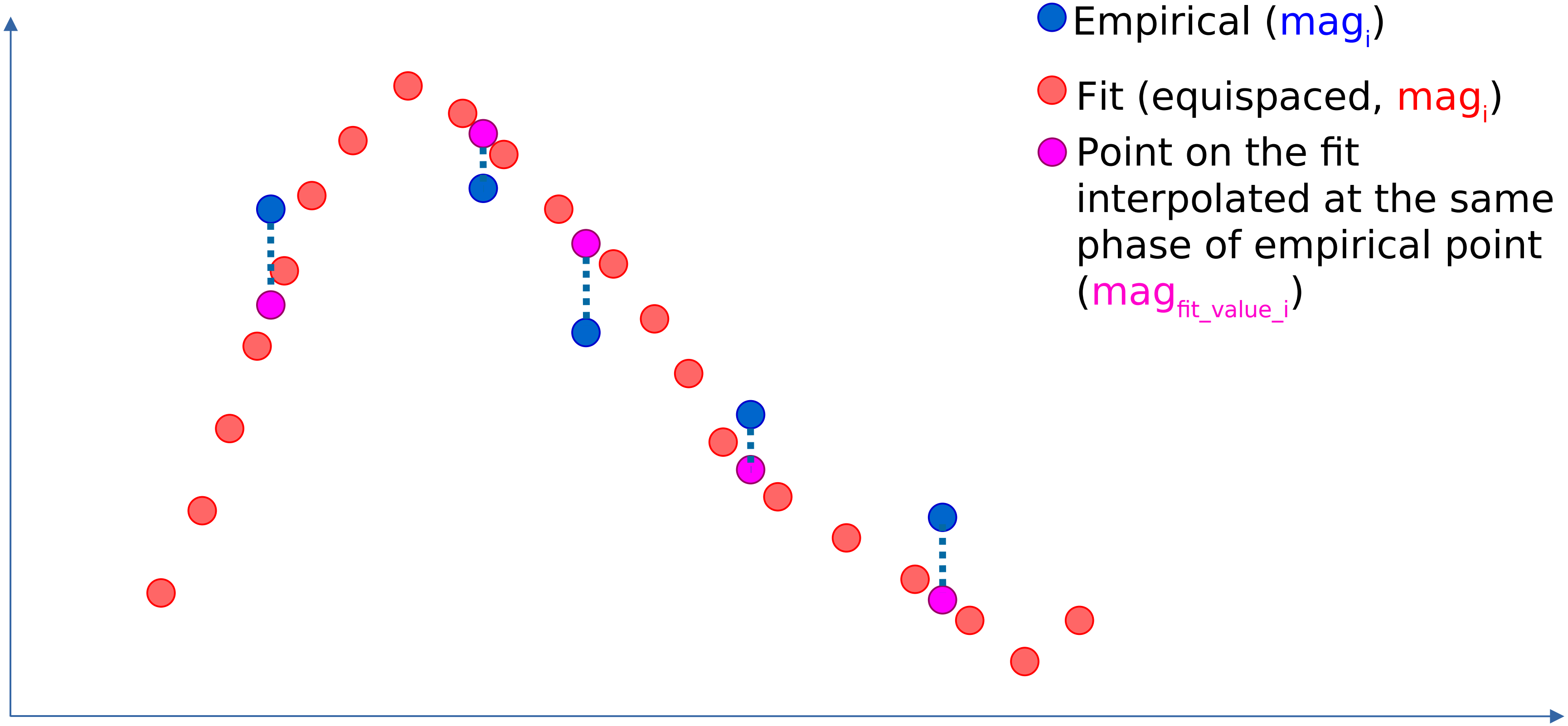
Now you can calculate the mean intensity <I>...

... and estimate <mag>

$\langle I \rangle = ((I_1+I_n)/2 + \Sigma_{i=2,n-1} (I_i)) / n$

$\langle mag \rangle = -2.5 \log10(\langle I \rangle)$

Mean magnitude estimate



$$err\langle mag\rangle = \left(\Sigma_i \, (mag_i - mag_{fit\_value\_i})^2/(n-1)\right)^{1/2}$$

n: number of phase points

Period Wesenheit relation

PL relations should be corrected by extinction… but this can be a complicated task

Period Wesenheit relation

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So, we define the Wesenheit magnitude (or pseudo-magnitude)

$$W^{X}_{YZ} = X - \left(\frac{A_Y}{A_X} - \frac{A_Z}{A_X} \right)^{-1} (Y - Z)$$

Ratios of extinction between different passbands

e.g. (X=G=Bp ; Y=Rp)

$$W^{G}_{BR} = G - 1.90\,(Bp - Rp)$$

Ripepi+2023

Period Wesenheit relation

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So, we define the Wesenheit magnitude (or pseudo-magnitude)

$$W_{YZ}^{X} = X - \left(\frac{A_Y}{A_X} - \frac{A_Z}{A_X} \right)^{-1} (Y - Z)$$

Ratios of extinction between different passbands

e.g. (X=G=*Bp* ; Y=*Rp*)

$$W_{BR}^{G} = G - 1.90 \left(Bp - Rp \right)$$

Ripepi+2023

- Independent of reddening by construction assuming an universal reddening law
- Mimics a PLC relation (σ ~ 0.03)
- Some combinations of bands (*VBV, VBI*) give metal-independent PW relations.

$$W_{YZ}^{X} = a + b * logP$$

Period Wesenheit relation

Type	Mode	α	β	σ_{ABL}	Band
			All sky		
DCEP	F	-2.744 ± 0.045	-3.391 ± 0.052	0.015	$W(G, G_{\mathrm{BP}} - G_{\mathrm{RP}})$
DCEP	1O	-3.224 ± 0.028	-3.588 ± 0.065	0.021	$W(G, G_{\mathrm{BP}} - G_{\mathrm{RP}})$
T2CEP	–	-1.224 ± 0.039	-2.542 ± 0.088	0.041	$W(G, G_{\mathrm{BP}} - G_{\mathrm{RP}})$

Ripepi+(2023) Table 3

Different pulsation modes follow different PL/PW relations

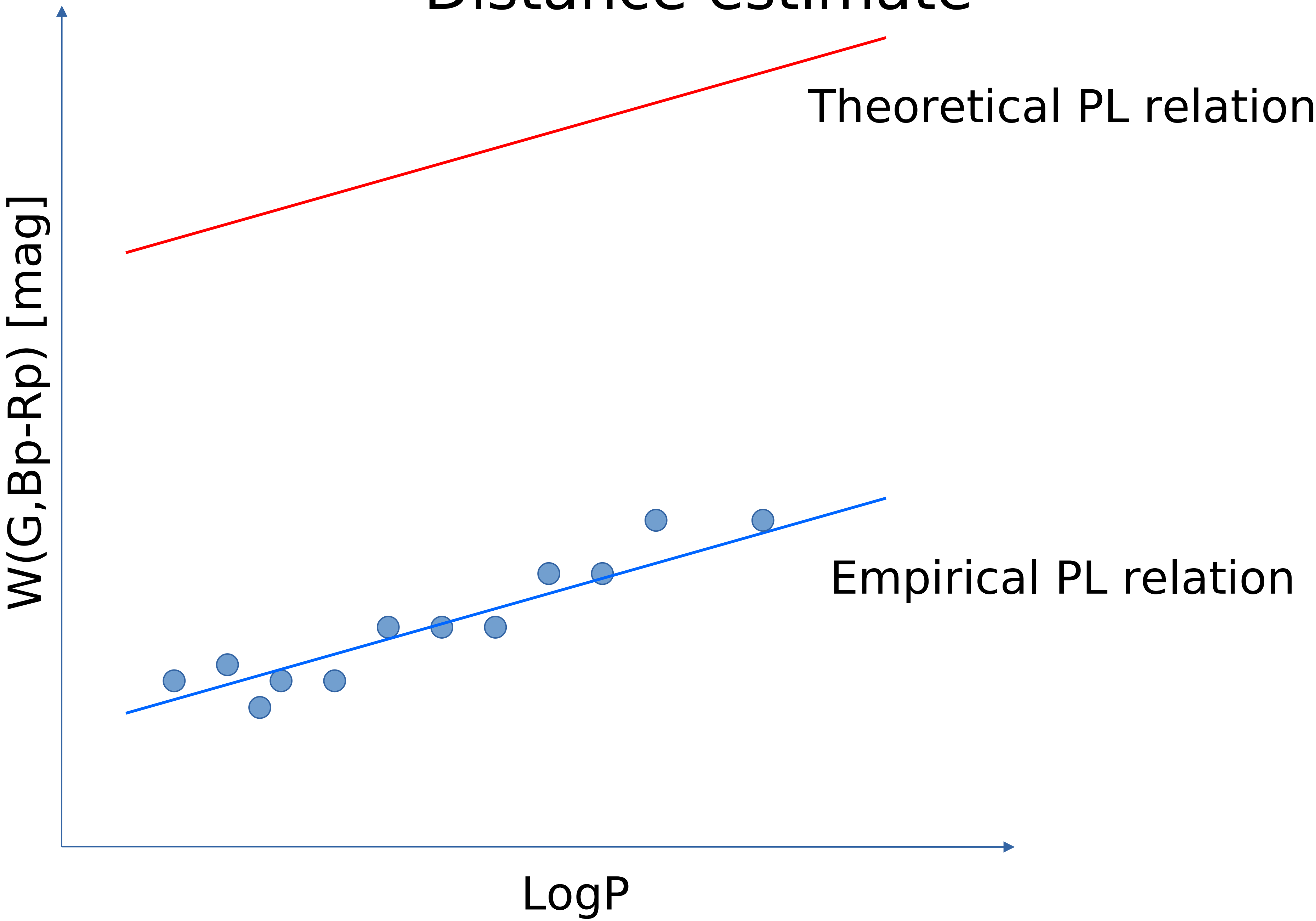
Each of you can decide to use either DCEP-F, DCEP-1O or T2CEP

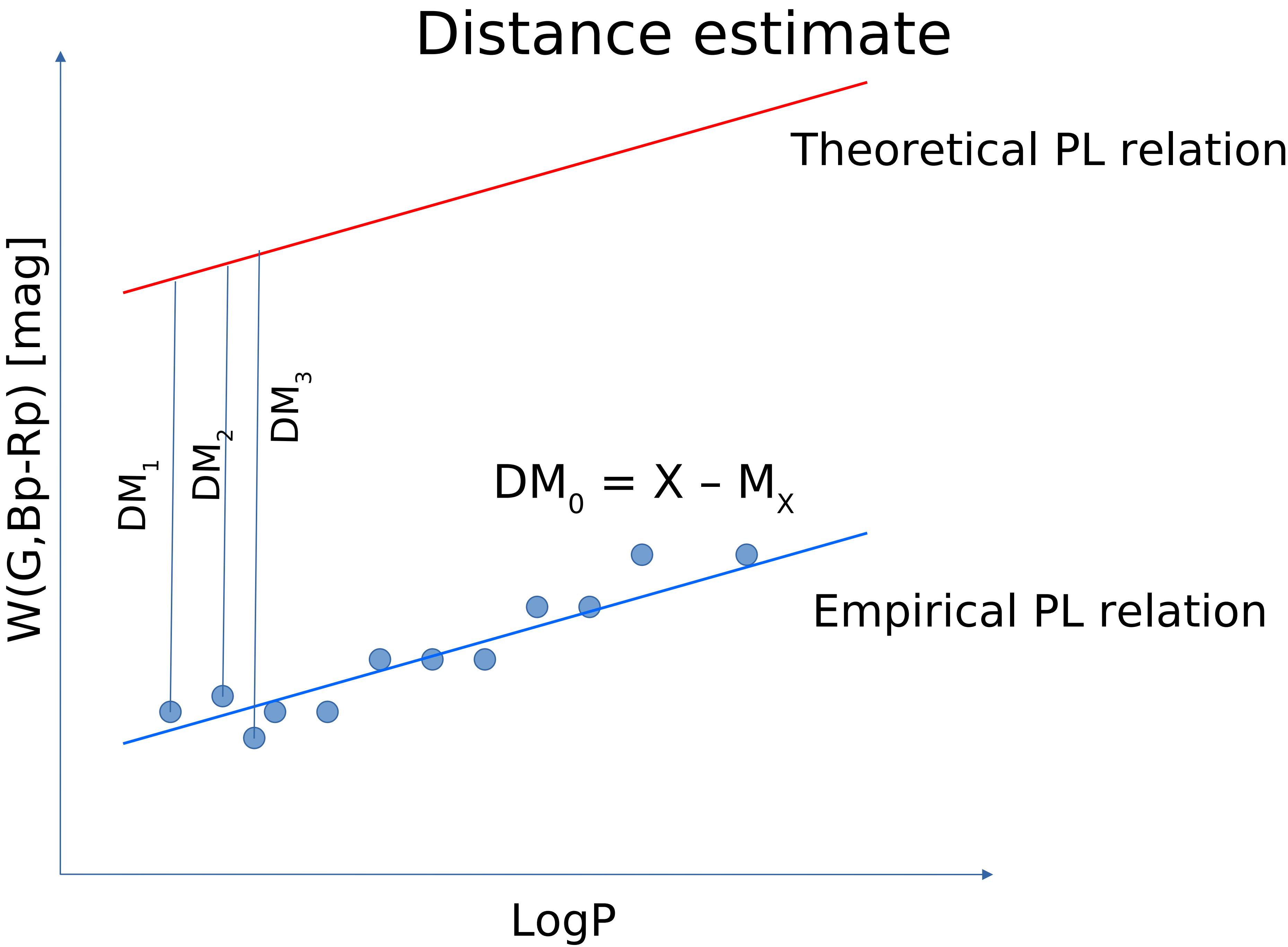
Select the type of variable from the result table (columns variCepheid_typeBestClassification and variCepheid_modeBestClassification)

Table Browser for 36: result_JOB05208_v5gf794r4pv7r5i5r9v6s5rjrv.csv

..	variCepheid_...	variCepheid_...	variCe...	variCeph...	variCepheid_...	variCeph...	variCepheid_...	variCeph...	variCepheid_...	variCepheid_typeBestClassification	variCep...	variCepheid_mod...	variCe...
29	1737,8672	1695,99519		0,69294	4,49433E-6					DCEP		FIRST_OVERTONE	
30	1695,99505	1695,99513		1,27651	3,50297E-5	1,58466	8,07895E-6	0,63105	3,21725E-6	DCEP		MULTI	1O/2O
31	1695,99503	1695,99512		0,48073	1,15992E-5					DCEP		FIRST_OVERTONE	
32	1695,99502	1695,99511		0,02727	5,12221E-5					T2CEP	RV_TAU	NOT_APPLICABLE	
33	1737,79316	1737,79325		0,15079	3,38863E-6					DCEP		FUNDAMENTAL	
34	1695,99502	1695,99511		1,05581	1,68696E-5					DCEP		FIRST_OVERTONE	

Distance estimate





Distance estimate
Theoretical PL relation
DM_1
DM_2
DM_3
$DM_0 = X – M_X$
Empirical PL relation
W(G,Bp-Rp) [mag]
LogP

Distance estimate

$\langle X \rangle$: mean value of X; δX: error on X; n: number of variables

1) Convert DM to distance for each variable

$$d = 10\^{}(DM_0+5)/5 \qquad \sigma d/d = \ln(10)*\sigma DM_0/5$$

2) Calculate (weighted) average distance and error on the mean [Bevington, Data reduction and error analysis, eq. 4.23]

$$\langle d \rangle = \Sigma_i(d_i*w_i)/\Sigma_i\, w_i \qquad \sigma\langle d \rangle = (1/(n-1)*\Sigma_i\, w_i(d_i-\langle d \rangle)^2/\Sigma_i\, w_i)^{1/2}$$

Where w_i are the weights: $w_i = 1/\sigma d_i^2$

3) Convert average distance to average DM (and error)

$$\langle DM_0 \rangle = 5*\log_{10}(\langle d \rangle) - 5$$

$$\delta\langle DM_0 \rangle = 5*\log_{10}(e)*\sigma\langle d \rangle/\langle d \rangle$$