The amateur astronomer's pursuit of the widest field of view

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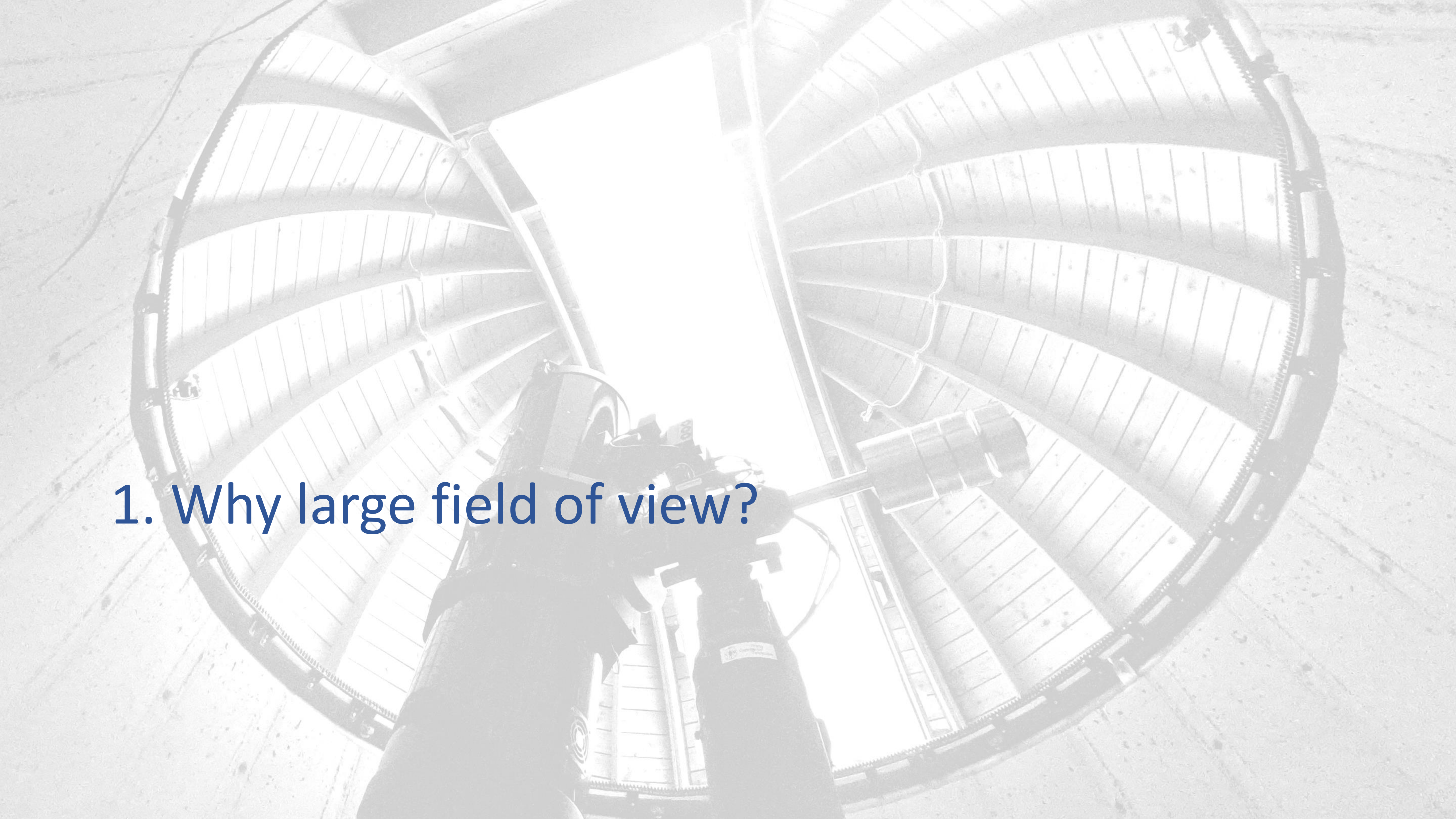
Agenda

1. Why large field of view?
2. Field of view vs. resolution dilemma
3. Professional and amateur wide-field telescopes
4. Wide-field observation data processing implications
5. A few results from an amateur wide-field setup



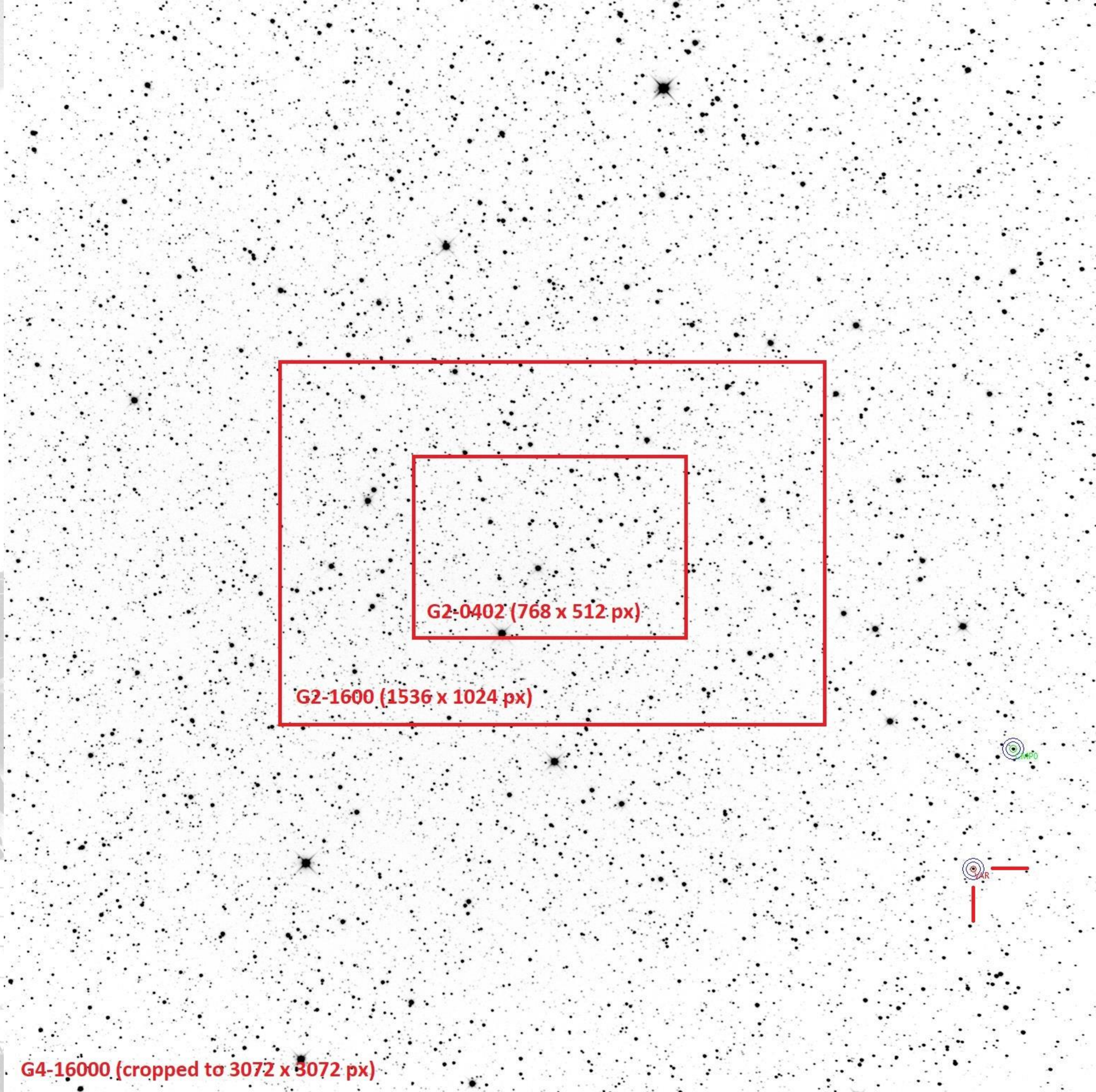
1. Why large field of view?

Astronomical observations are demanding and expensive activities

- A certain **minimal level of instrumentation** with substantial input cost is needed to acquire data usable for meaningful astronomical research.
  - Wide-field setup is more expensive than the standard one – typically a camera with bigger sensor and a better field corrector is needed. But majority of equipment remains the same.
- Time-domain observations take **a lot of time**.
  - The observing time is even more precise for amateurs, who do astronomy as a hobby in a free time, in addition to regular employment.
- When money is invested and time is spent, it is highly desirable to **maximize the scientific output** of each observing run.
- Wider field of view **proportionally increases** a number objects, acquired through single observing run.
  - Some of these objects may be possibly scientifically interesting.

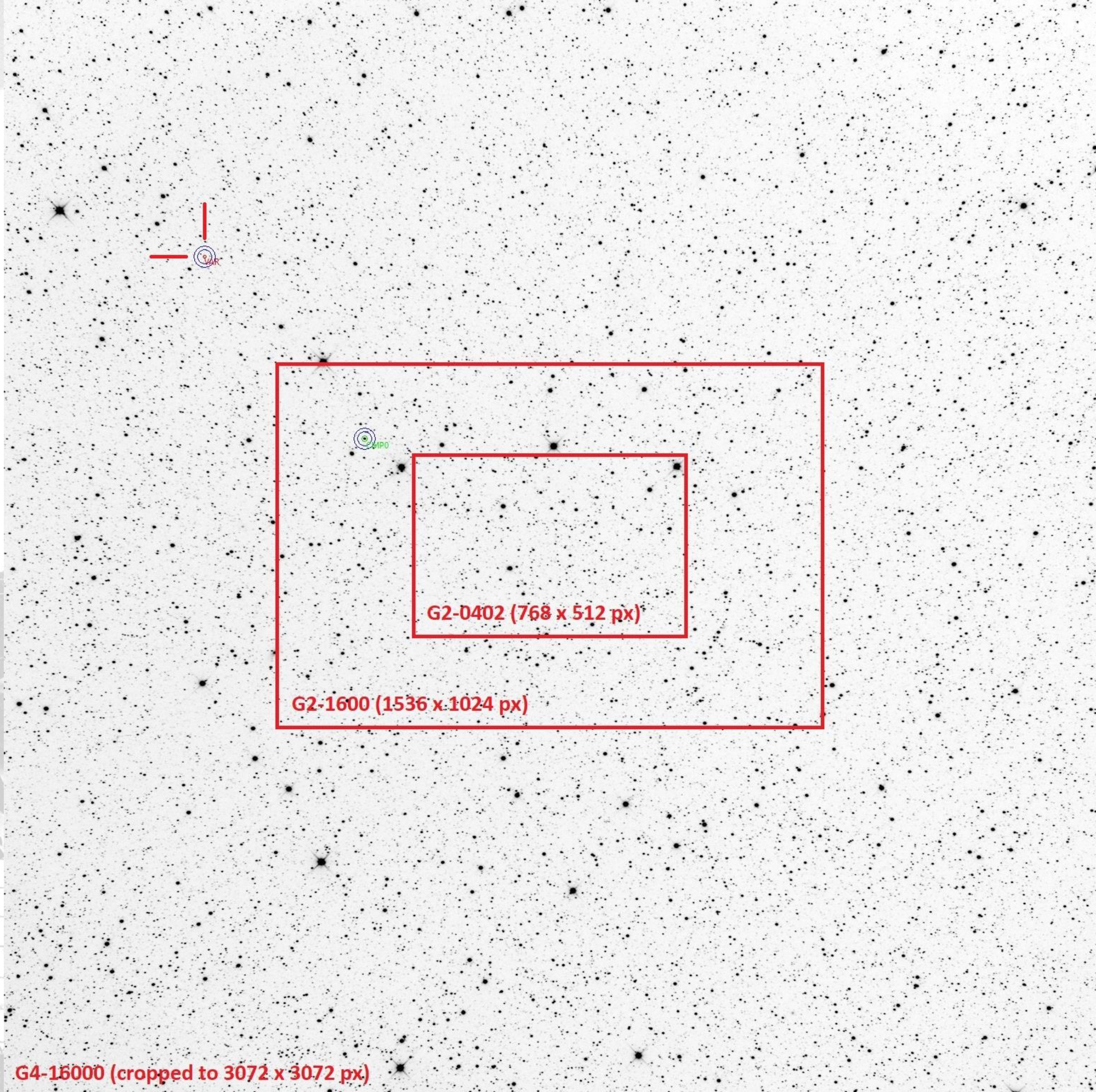
So, what is wide-field good for?

- A discovery image of CzeV343 **doubly-eclipsing quadruple star**, acquired in 2012.
  - A wide-field setup (for its time), with 70 × 70 minutes field of view, was used.
- The star would remain undetected if the target was observed with then-standard setups.



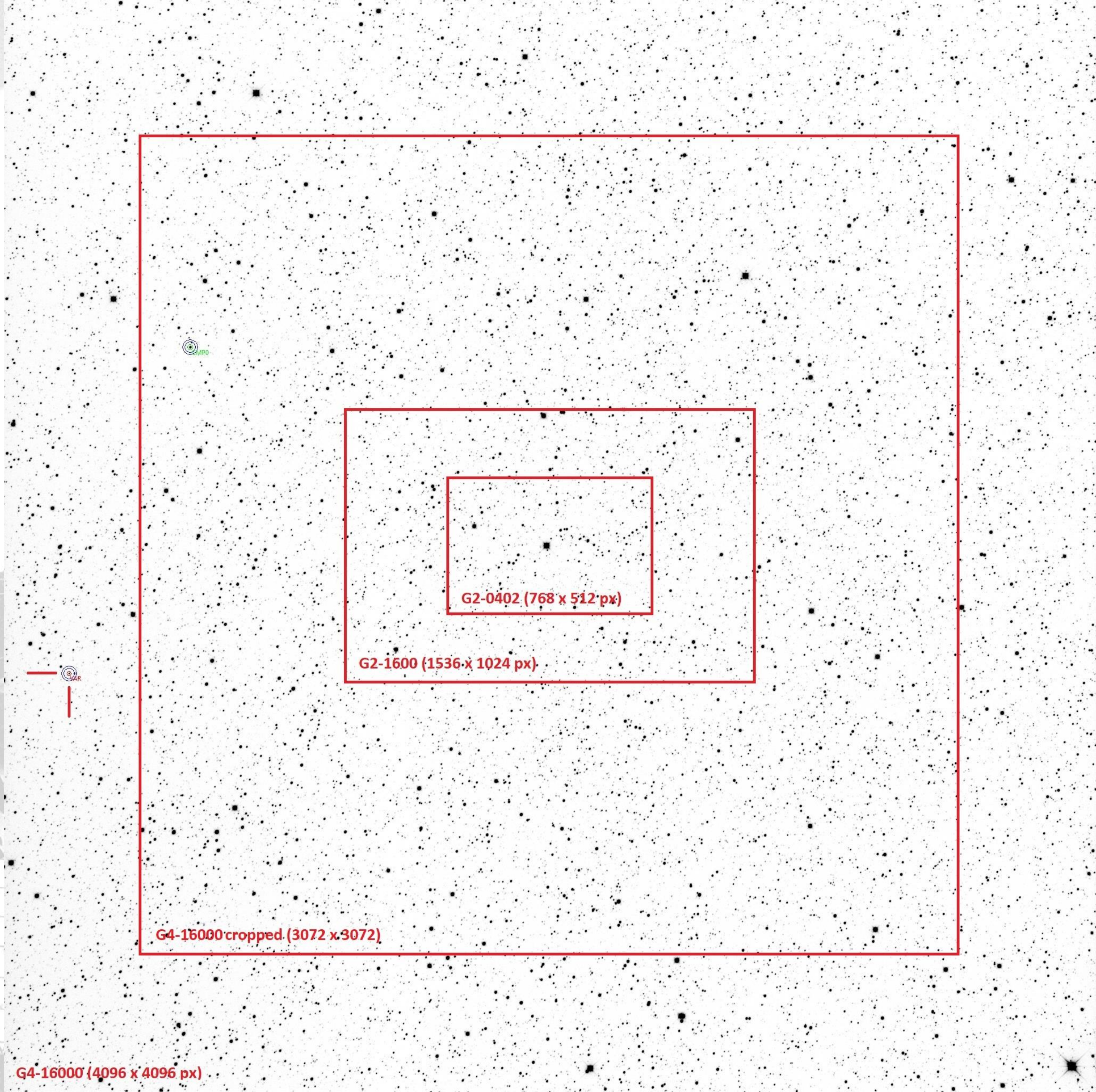
CzeV404 dwarf nova

- Discovery image of the CzeV404 SU UMa-type **cataclysmic variable** with period in the CV period gap, acquired in 2012.
  - The CzeV404 is more a link between SU UMa-type and SW Sex-type (Kára J. et al., A&A, Vol 652, A49).
- Also this star was discovered outside of the typical field of view of amateur telescopes.
  - The same telescope with 70 × 70 minutes field of view was used.



Discoveries
close to the edge

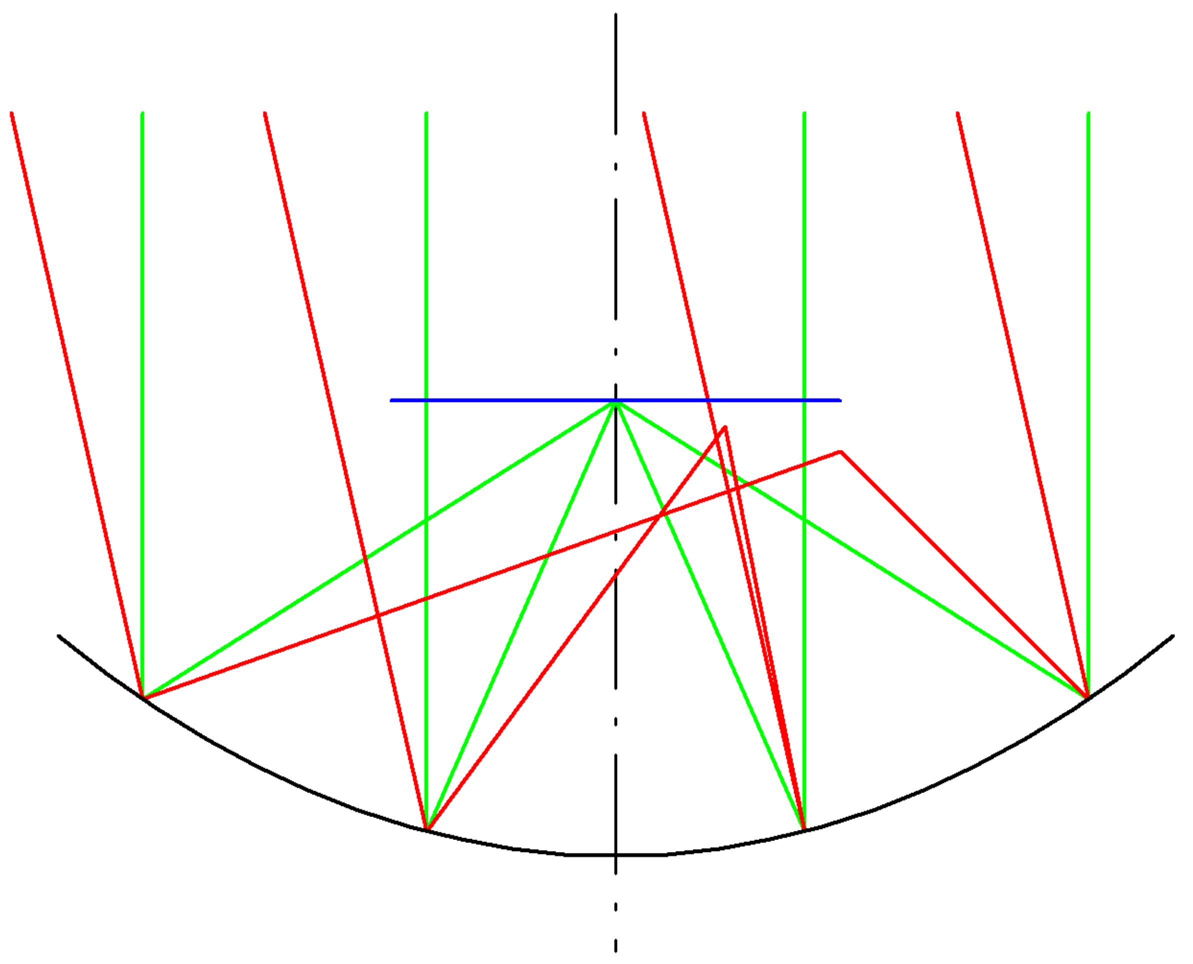
- **5 out of 6** doubly-eclipsing quadruple stars discovered at TCMT.org are located outside of the typical amateur telescope field of view.
  - First, respective stars were discovered as eclipsing variables.
  - Then the quadruple star nature was identified from the long-term observations.
- The upgraded telescope, offering 90 × 90 minutes field of view and 4096 × 4096 pixels resolution camera was used.



2. Field of view vs. resolution dilemma

Achieving wide field – a race against nature

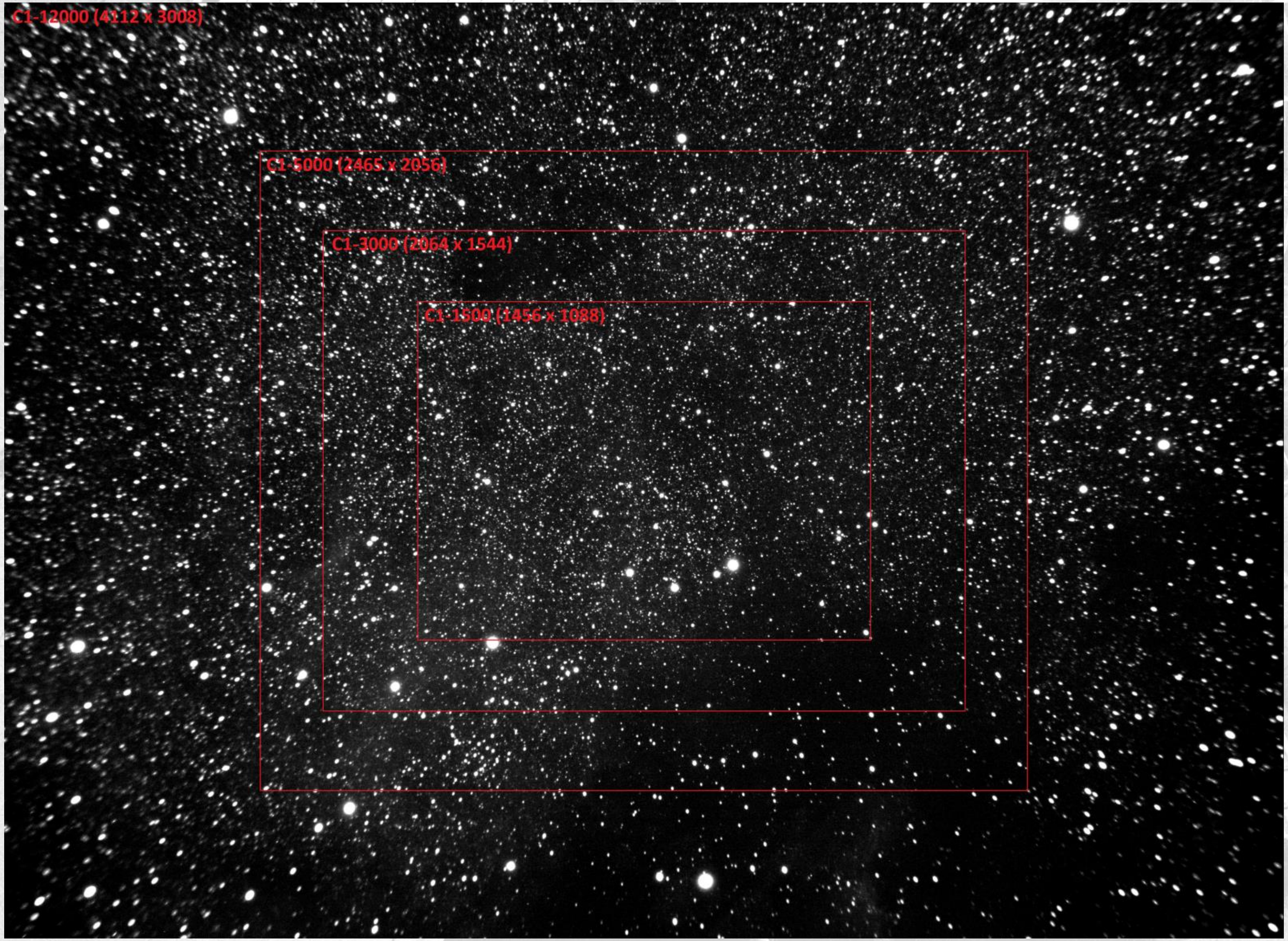
- Unfortunately, image quality degradation with the increased angular distance from optical axis is a natural feature of virtually every optical system.
  - Parabolic mirror creates perfect image on axis, but images suffer from coma aberration further from optical axis.
- Even worse, many optical system cannot produce perfect image even on optical axis.
  - Refracting telescopes (lenses) require multiple optical elements to create image with aberrations below acceptable levels.



Parabolic mirrors suffer from “coma” aberration and only modern “coma-correctors” can fix it

- Images of the NGC 2244 “Rosette” and M16 “Eagle” nebulae, published in the famous book Vesmír (Universe) by Grygar, Horský and Majer, perfectly illustrate the „coma“ aberration of parabolic mirrors.

Example of a small ED refractor aberrations

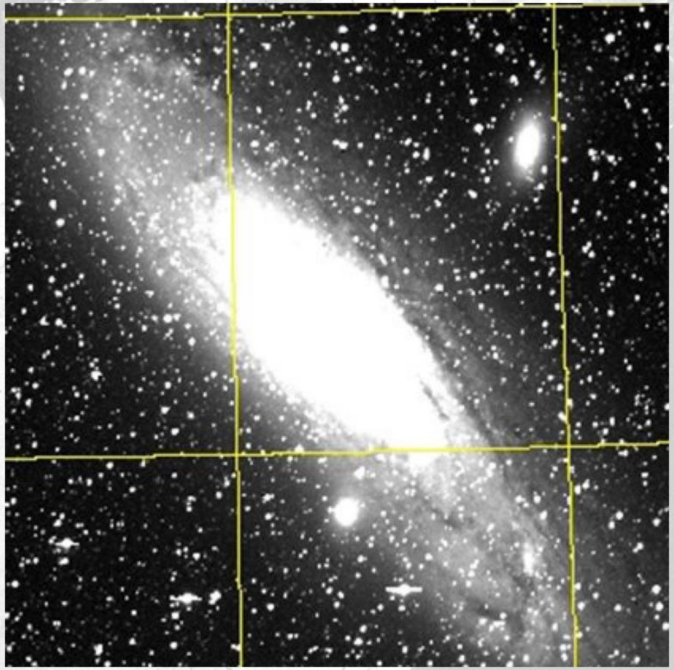


Photographic lenses

- Truly wide-field optics is commonly available in the form of **photographic lenses**.
  - Many individual lenses working together offer more degrees of freedom to correct aberrations.
  - Sometimes, lenses are made of low-dispersion glasses and/or aspherical lenses are used.
  - Lenses are typically designed to cover either APS or Full-Frame (24 × 36 mm) sensor formats.
  - Still, image quality of photographic lenses close to the sensor border is often surprisingly bad.
- Photographic lens focal length typically varies from centimeters to a few tens of centimeters.
  - Such short focal length produces **under-sampled images** with very **low angular resolution**, typically an order of magnitude worse compared to even moderate seeing limit.
- Also, photographic lens diameter typically spans only centimeters.
  - Light gathering area of such lens is only a fraction of typical reflecting telescope, which **limits the minimum brightness** of observed objects.

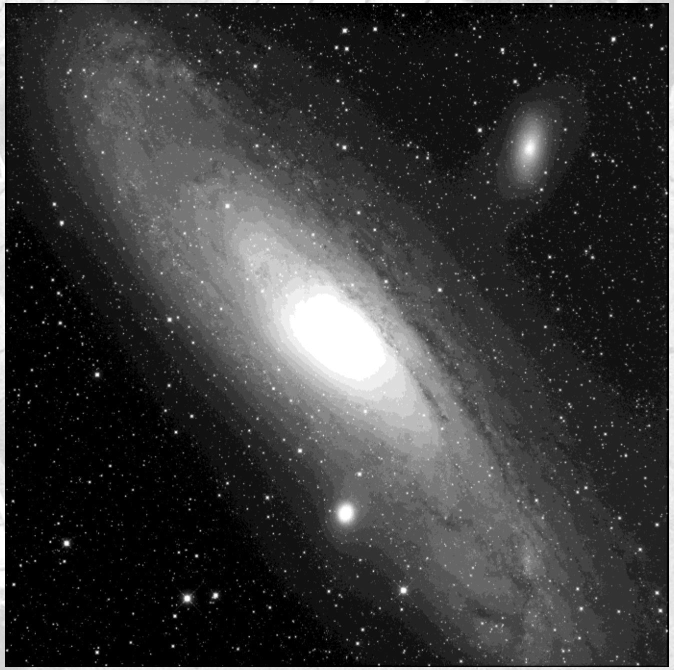
Research projects using photographic lenses

- Many wide-field, all-sky survey projects (WASP, ASAS-SN, …) use commercial off-the-shelf photographic lenses, despite of the very high-end design.
- Cameras used on the **TESS space telescope** are custom made, but share many characteristics of the photographic lenses.



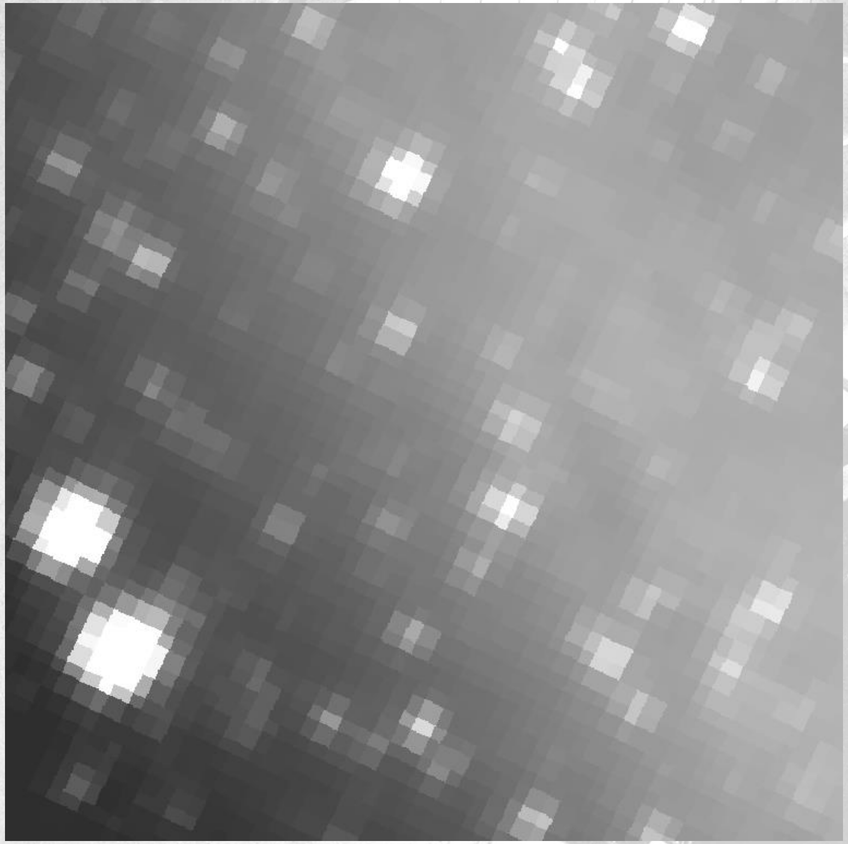
ASAS-SN

TESS

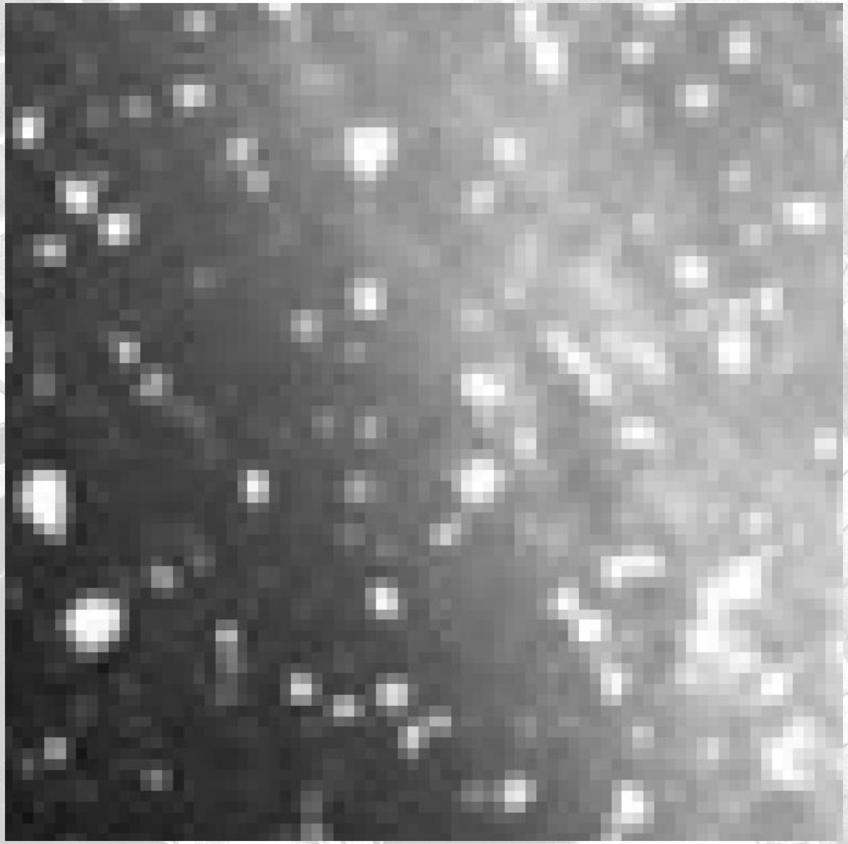


TCMT

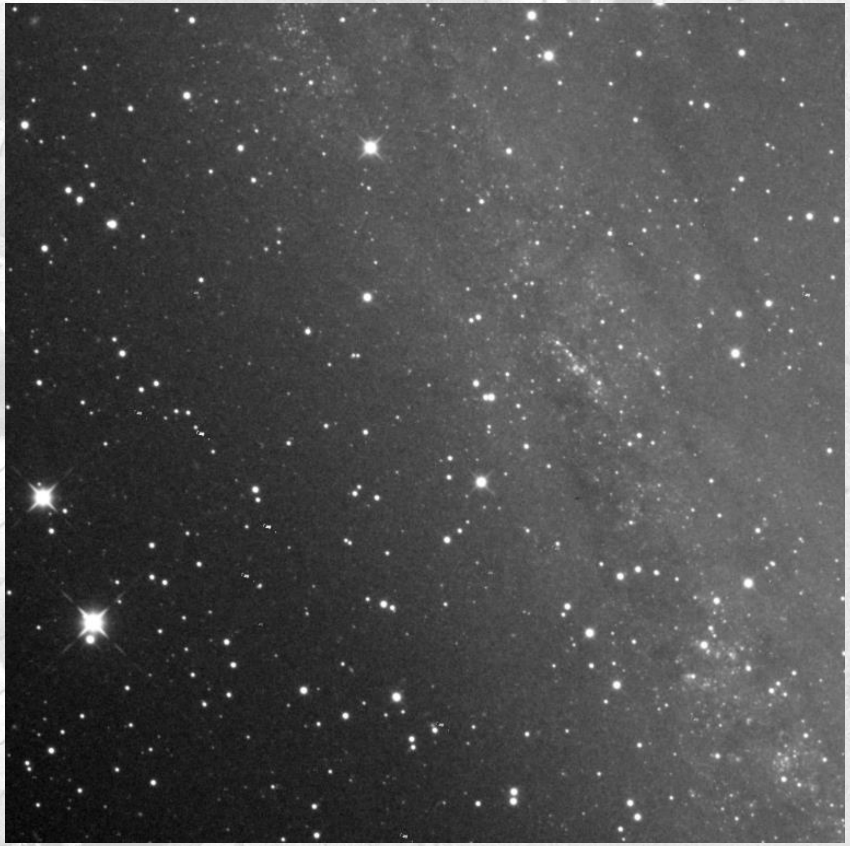
Zoom into M31 image, showing the balance between angular resolution and field of view



TESS



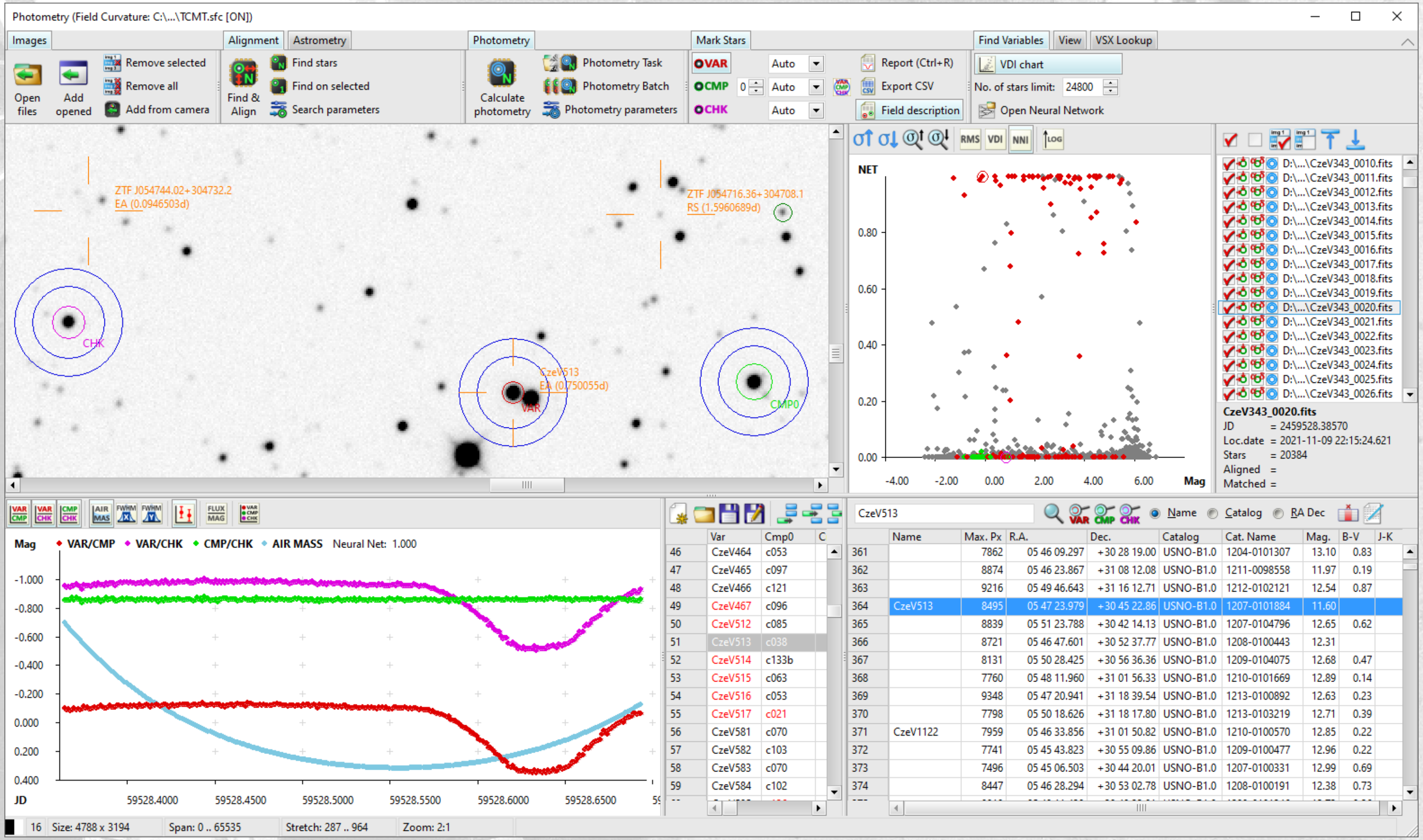
ASAS-SN



TCMT

The aim is to achieve wide field of view without compromising the angular resolution

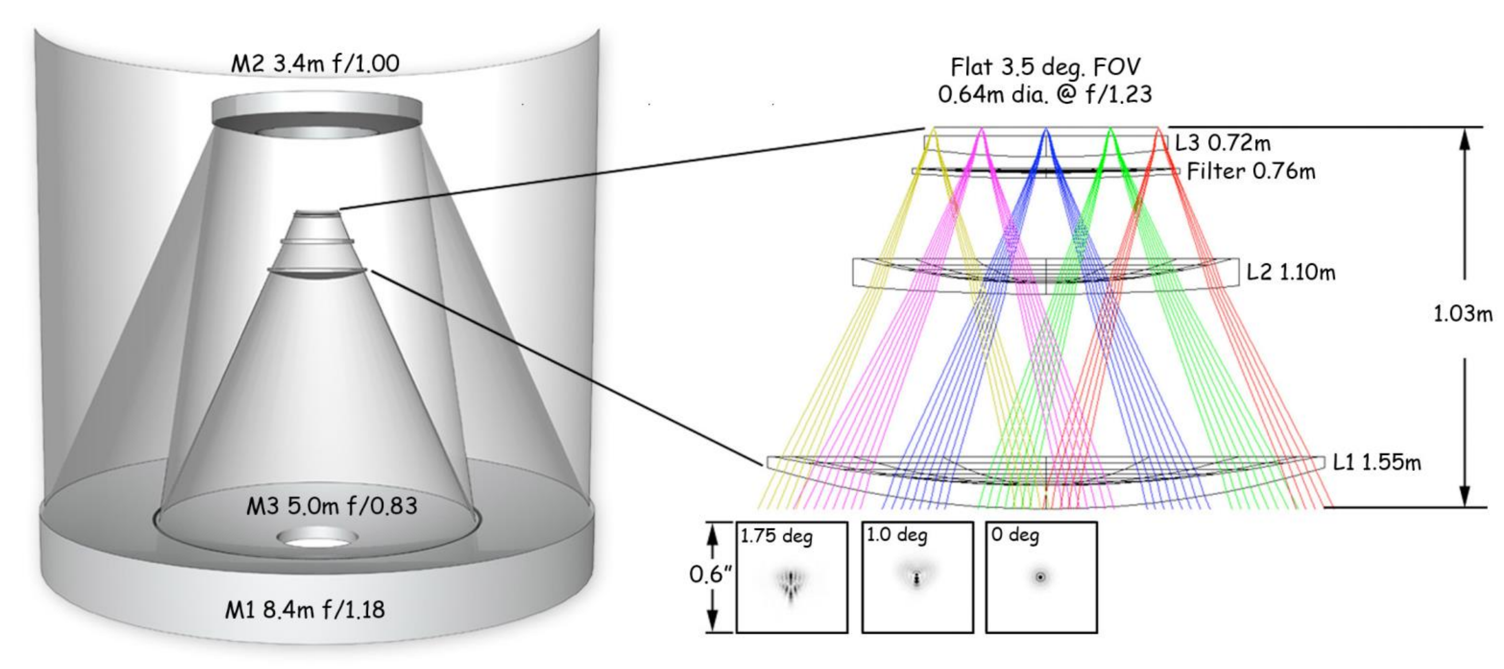
- High angular resolution limits contamination of light sources by nearby stars (blending).
    - Blending could even disable observing of weak sources close to bright stars in dense fields.
- Image sampling between 1 and 2 arc-sec/pixel well corresponds to typical 3 to 6 arc-sec seeing in urban and sub-urban areas.



3. Professional and amateur wide-field telescopes

Wide field with "unlimited" resources

- The current paramount of wide field telescopes will be the **Vera Rubin observatory**.
    - 8.4 m diameter primary mirror.
    - Complex optical design, incorporating three mirrors and three lenses (four if we count the filter).
    - Mirrors M1 and M3 are manufactured on single substrate.
    - 3-element refracting corrector in front of the camera with 1.55m front lens diameter.
    - 3.5° field of view.
    - 3.2 GPx CCD camera.

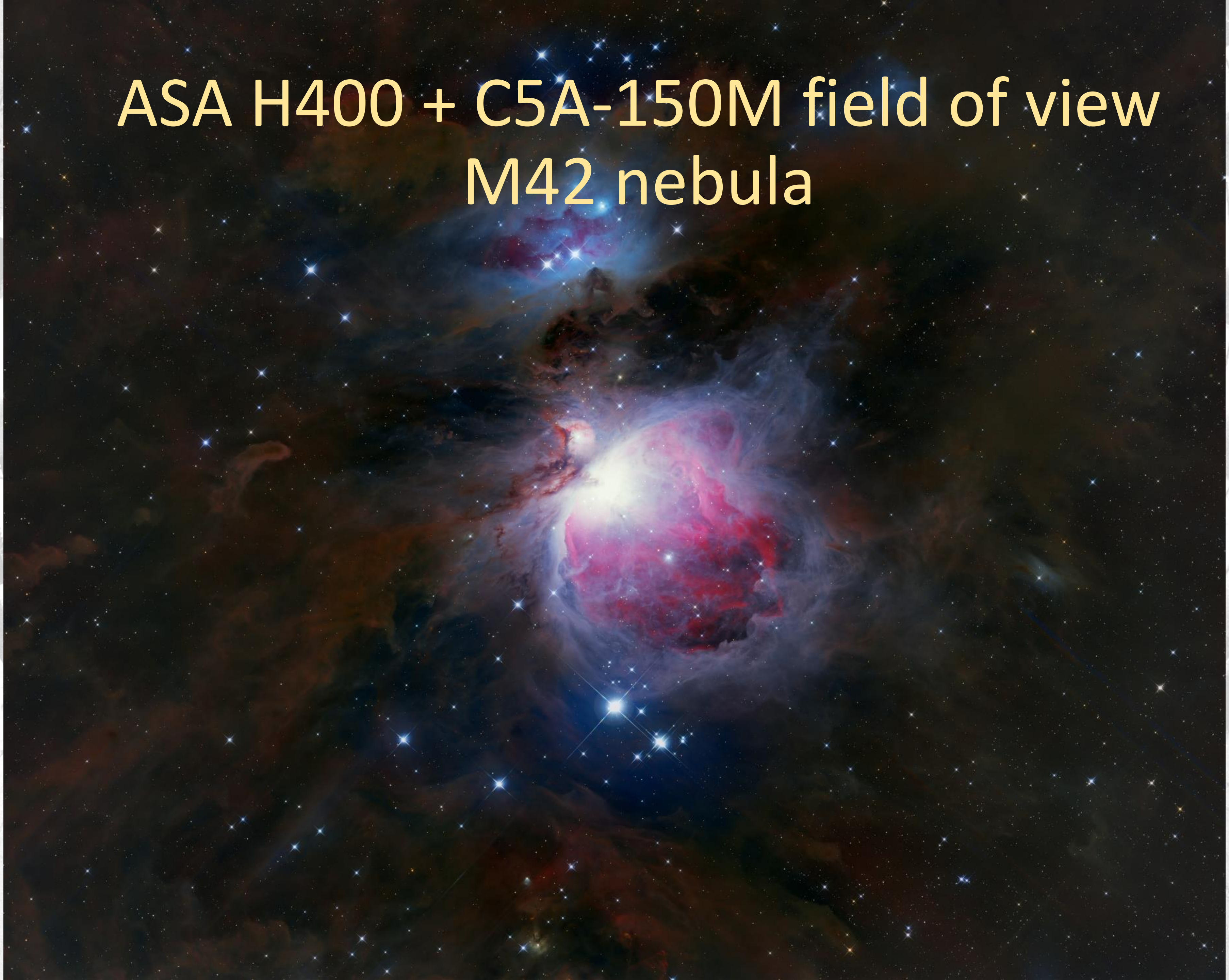


Down-to-Earth wide field telescope, still a bit out of reach for amateurs

- ASA H400 f/2.4 hyperbolic astrograph.
- 400 mm mirror diameter, 960mm focal length.
- 5-inch corrector for hyperbolic primary, which easily corrects field of view of current very-large sensors.
- Field of view with the C5A-150M camera is 191′ × 143′.
- Sampling with 3.76 µm pixels is 0.81″/pixel.
- Each 14,208 × 10,656 pixels image occupies ~300 MB of memory or drive space.
- OTA cost starts just below 50,000 EUR.

ASA H400 + C5A-150M field of view
M7 cluster

ASA H400 + C5A-150M field of view
M42 nebula



Wide-field refractors

- **Apochromatic** refractors with 3-element objective lenses, equipped with **field-flattener correctors**, are capable to cover middle-format sensors with good quality image.
- The **focal length** of majority of refractors spans the range of **tens centimeters**.
  - Angular resolution is limited.
- The light-gathering area is rather small, the typical refractor **diameter** varies around **10 cm**.
  - Refractors are limited to relatively bright stars.
- Because good-quality refractor consists of **many optical elements**, some of them possibly manufactured from **rare low-dispersion glass**, they are prohibitively expensive.
  - High cost of refractors, low light gathering power and low angular resolution lead to particularly **bad price/performance ratio**.

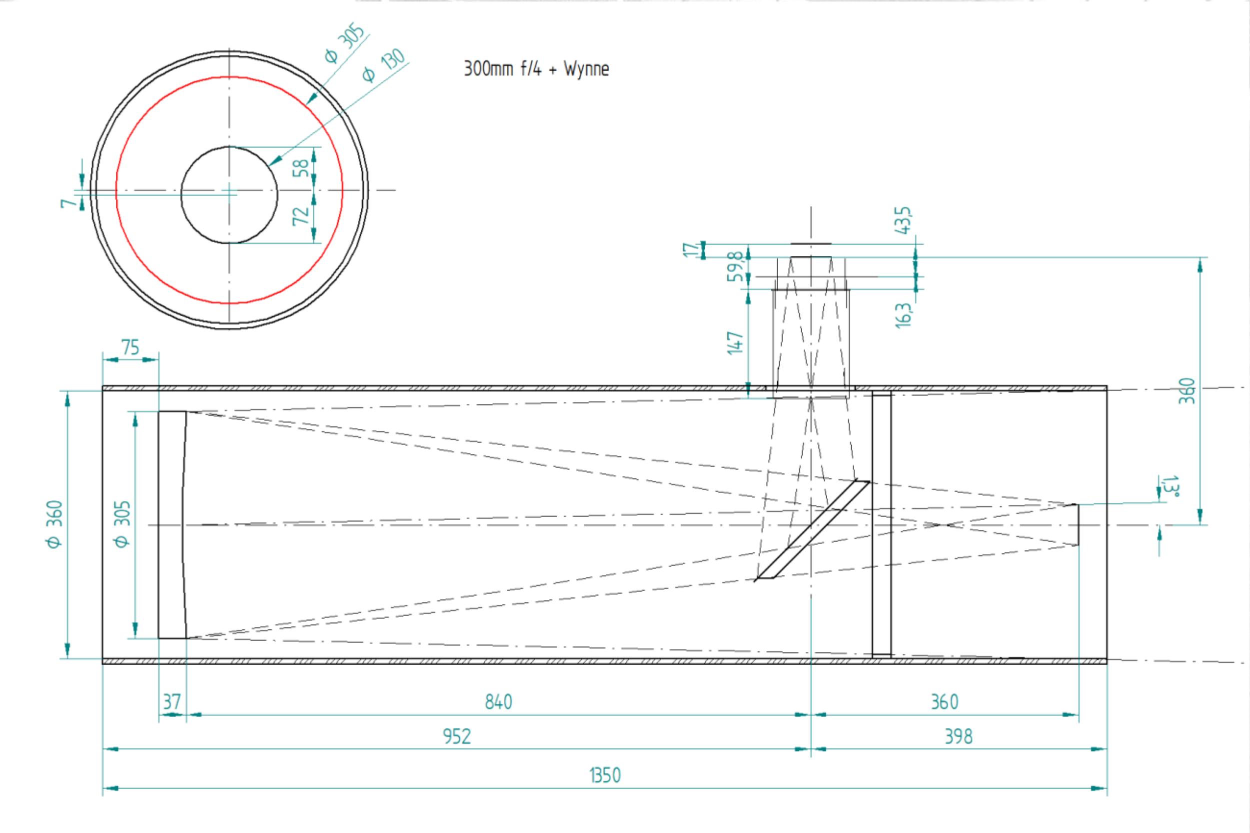
Corrected Newtonian reflector – a perfect "poor-man" wide-field instrument

- **Parabolic mirror** aberrations are **more difficult** to compensate using the refracting element (coma-corrector), compared to mutually mated hyperbolic mirror a corrector.
- But parabolic mirrors are **mass-manufactured** and thus available, much cheaper, very high-quality and often made from Pyrex or other thermally stable material.
- Also, companies may design, manufacture and sell **coma-correctors** working with parabolic mirrors of various diameters and f/ratios, manufactured by various companies.
  - It is not necessary to design and manufacture mirror and corrector together.
- Naturally, there are limits to both mirror f/ratio and its physical dimensions:
  - F-ratio can be typically from f/3.5 to f/5.
  - Minimal focal length typically starts around 75 cm.

A wide-field Newtonian telescope is not just the primary mirror and corrector

Optical aberrations are not the only obstacle, field of view can be also limited by telescope design and component selection:

1. OTA input aperture.
2. Secondary mirror.
3. Focuser and corrector.
4. Filters and/or filter wheel.
5. Camera and its sensor.



Focuser and corrector diameter

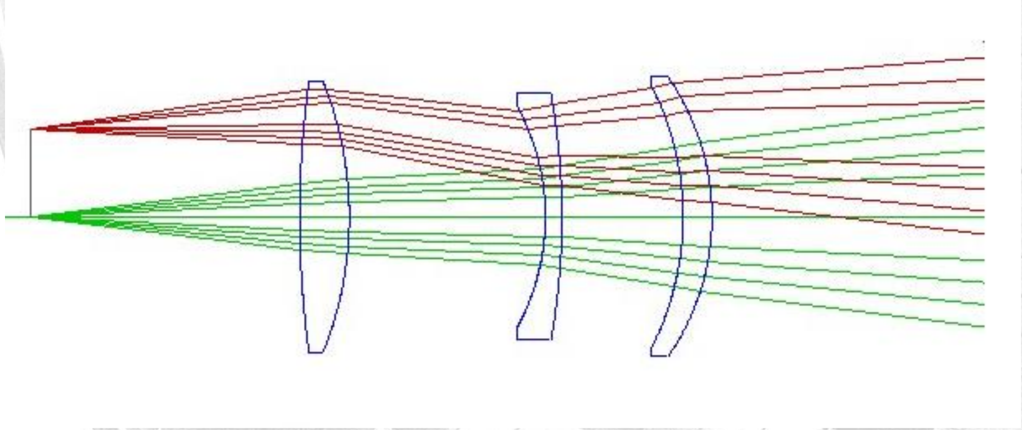
- Prevailing focuser standard is designed for **2” diameter** eyepiece barrels.
- Still, correctors for 2” standard can offer different illuminated circle in the field of view, based on the output element size and corrector mechanical interface design.
  - The M42 × 0.75 output thread significantly limits the illuminated circle.
  - The M48 × 0.75 output thread Uses the 2” diameter to the maximum extend.
  - Special designs can use even greater correctors output diameters.

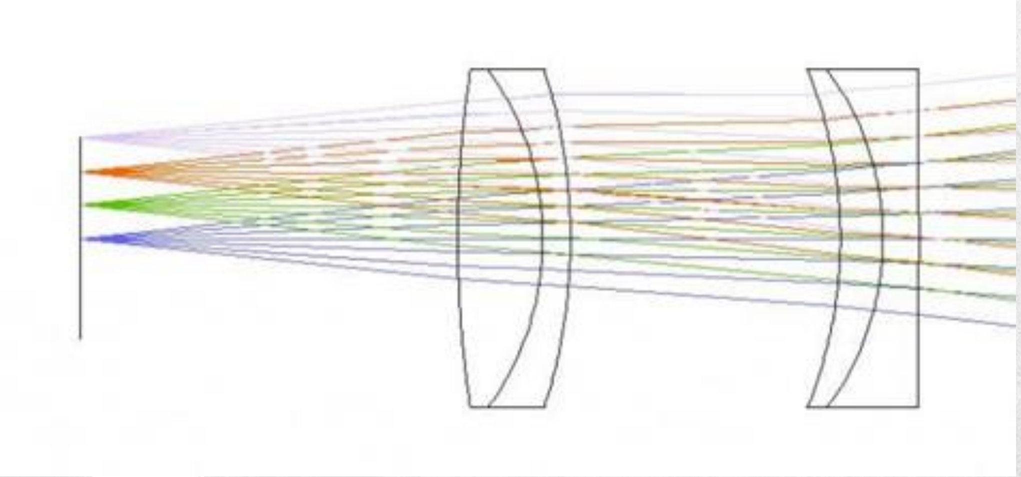
Focuser and corrector diameter

- New **3” diameter** focusers slowly become more common.
  - High-end Newtonian telescopes as well as refractors are equipped with 3” focusers.
- The **4” diameter** focusers and correctors are rare, expensive, and available from only a few companies (ASA).
- The unfortunate trend is discontinuing of mass-manufactured coma-correctors (and optics in general) by European and American companies.

Coma-corrector optical design

- Majority of Newtonian telescope coma-corrector use the **Wynne** design with 3 refracting elements in 3 groups (6 surfaces).
  - Sometimes, Wynne correctors are named after opticians, who designed (calculated) particular corrector (Keller, Riccardi, …).
- The exception is the TeleVue **Paracorr** design, consisting of 4 refracting elements in 2 groups (6 surfaces).
- Important corrector feature is **preserving**, **shrinking,** or **prolonging** of the resulting **focal length**.





Three generations of the wide-field telescopes used at BSObservatory

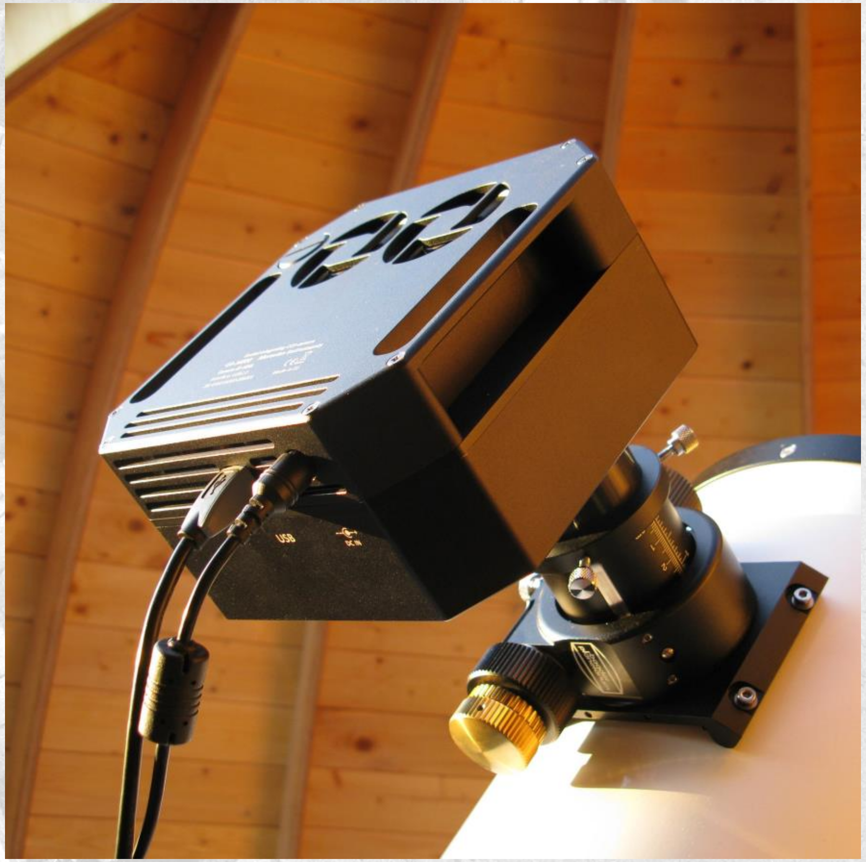
SPX250 (2011)

TCMT version 1 (2015)

TCMT version 2 (2024)

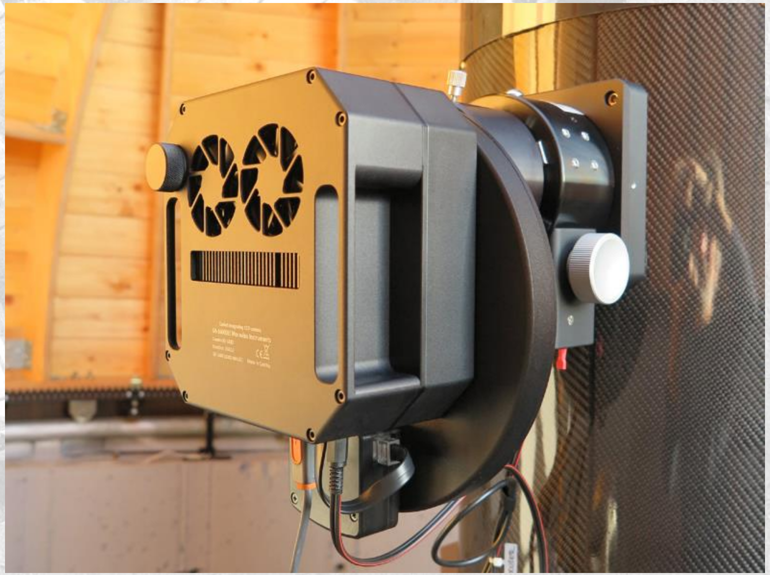
Orion SPX250 – first experiments with wide field at BSObservatory

- Only slightly modified off-the-shelf Newtonian telescope with 25 cm (10”) f/4.7 primary mirror.
  - The 63 mm secondary mirror replaced with 75 mm one.
  - More robust Baader SteelTrack focuser used for rigidity.
  - Numerous mechanical enhancements (e.g. new OTA rings).
  - TeleVue Paracorr STL 2” corrector used.
- Results from this telescope were encouraging.
  - Number of previously unknown variable stars appeared in the field of view, some of them very interesting.
  - Observation methodology changed form ad hoc observation of single star minimum to long-term monitoring of one field of view, which lead to interesting results.
  - **70’ × 70’ field of view** highlighted deficiencies in the used software stack and lead to completely new software development.



TCMT (Thirty CentiMeter Telescope) version 1

- Custom telescope with 30 cm (12”) f/4 primary mirror, purposely designed to cover G4-16000 camera KAF-16803 CCD sensor (37 × 37 mm).
- 110 mm secondary mirror.
- 3” focuser with 3” coma-corrector TeleVue BIG Paracorr.
- Filter wheel for 50 × 50 mm square filters.
- **90’ × 90’ field of view** with only ~30% vignetting and acceptable PSF distortions in the image corners.

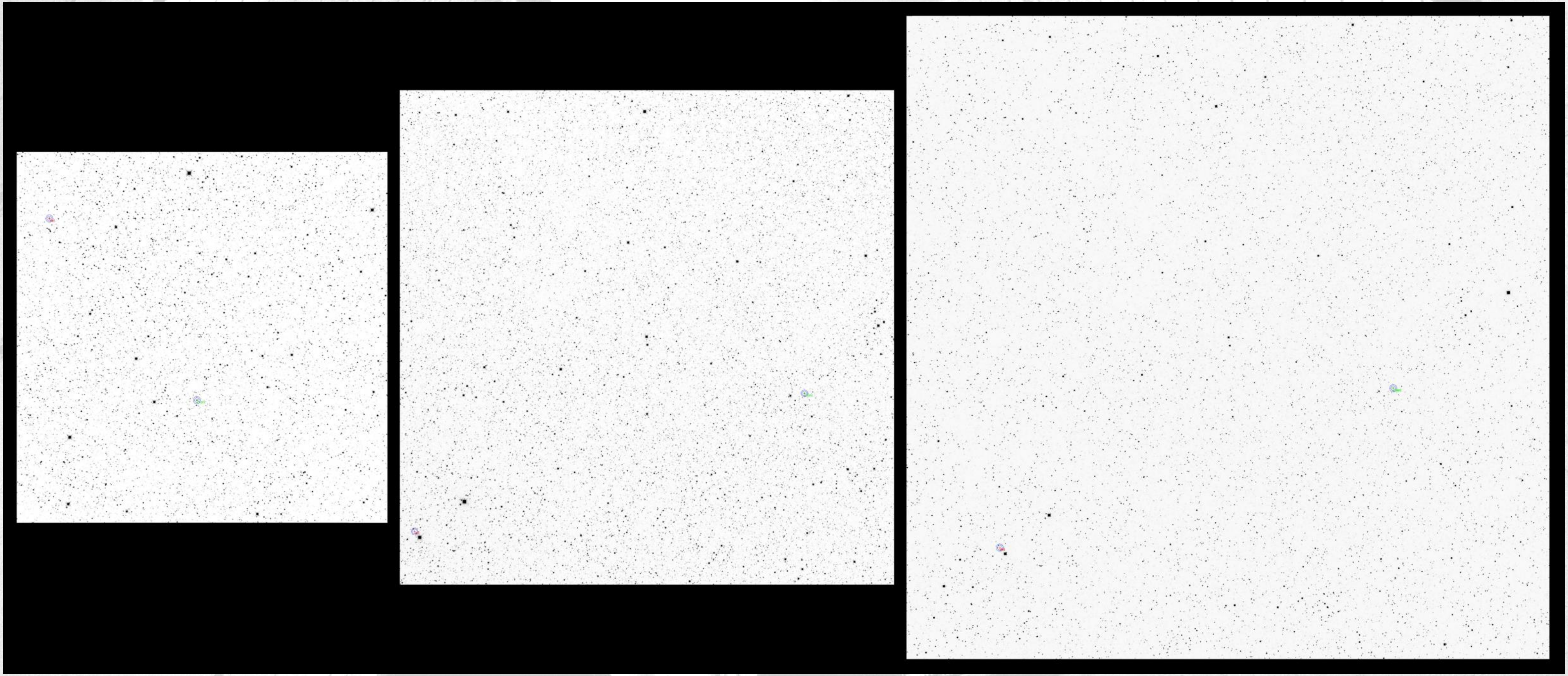


TCMT version 2

- New telescope design intended to overcome the limitations of the version 1, caused by 3” focuser and corrector.
- The same 30 cm (12”) f/4 primary mirror used.
- New OTA internal diameter increased from 344 mm to 360 mm to avoid input aperture vignetting.
- 110 mm secondary mirror replaced with a 130 mm one, again to avoid vignetting.
- 3” focuser replaced with a custom 4” one.
- 3” BIG Paracorr replaced with 4” ASA Wynne.
- G4/C4 camera replaced with C5A-150M camera.
- Field of view increased from 90′ × 90′ to 116′ × 116′ with the same image sampling ~1.3”/px.

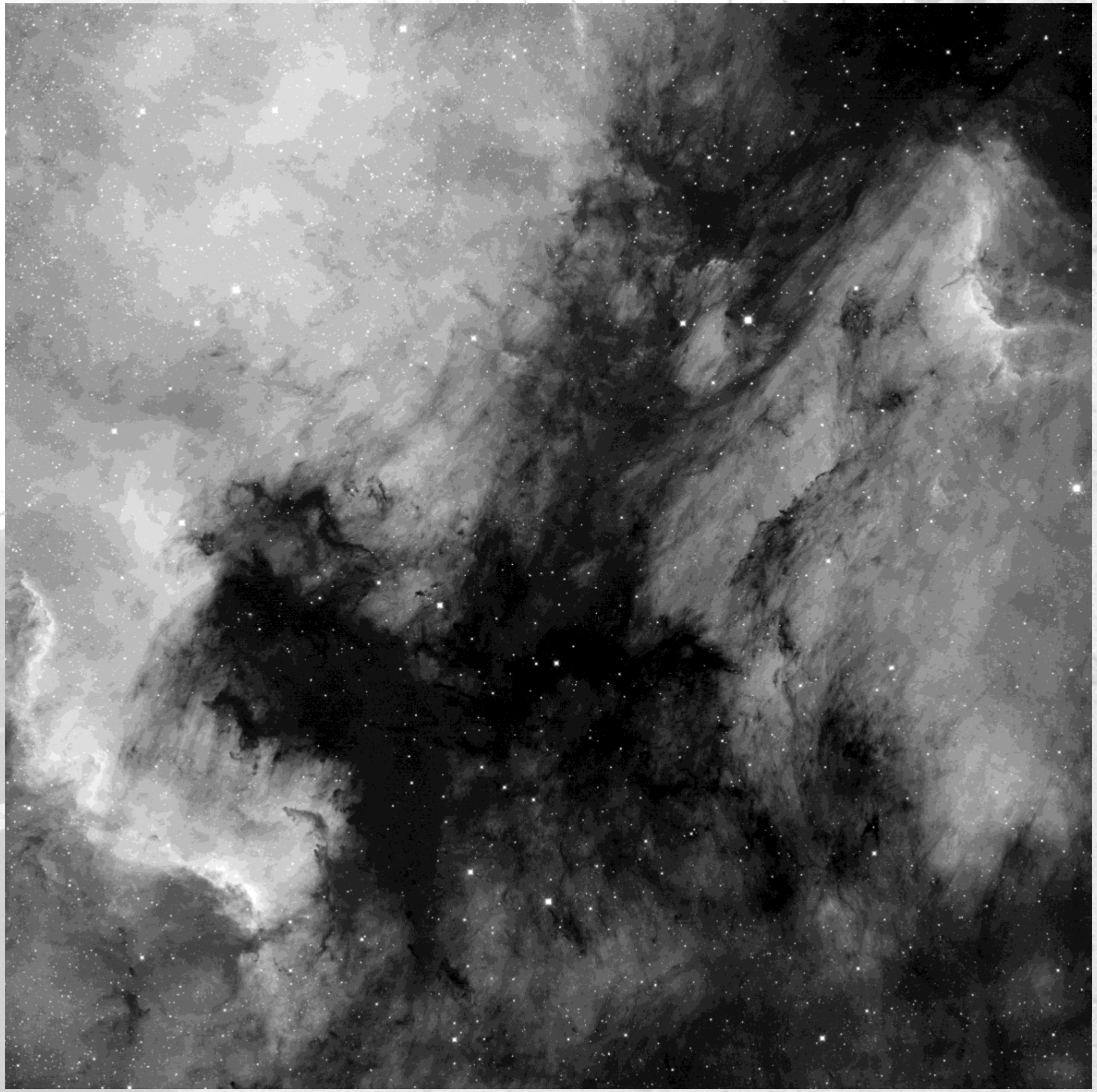
TCMT v2 camera, focuser, and coma-corrector

BSObservatory telescopes field of view comparison

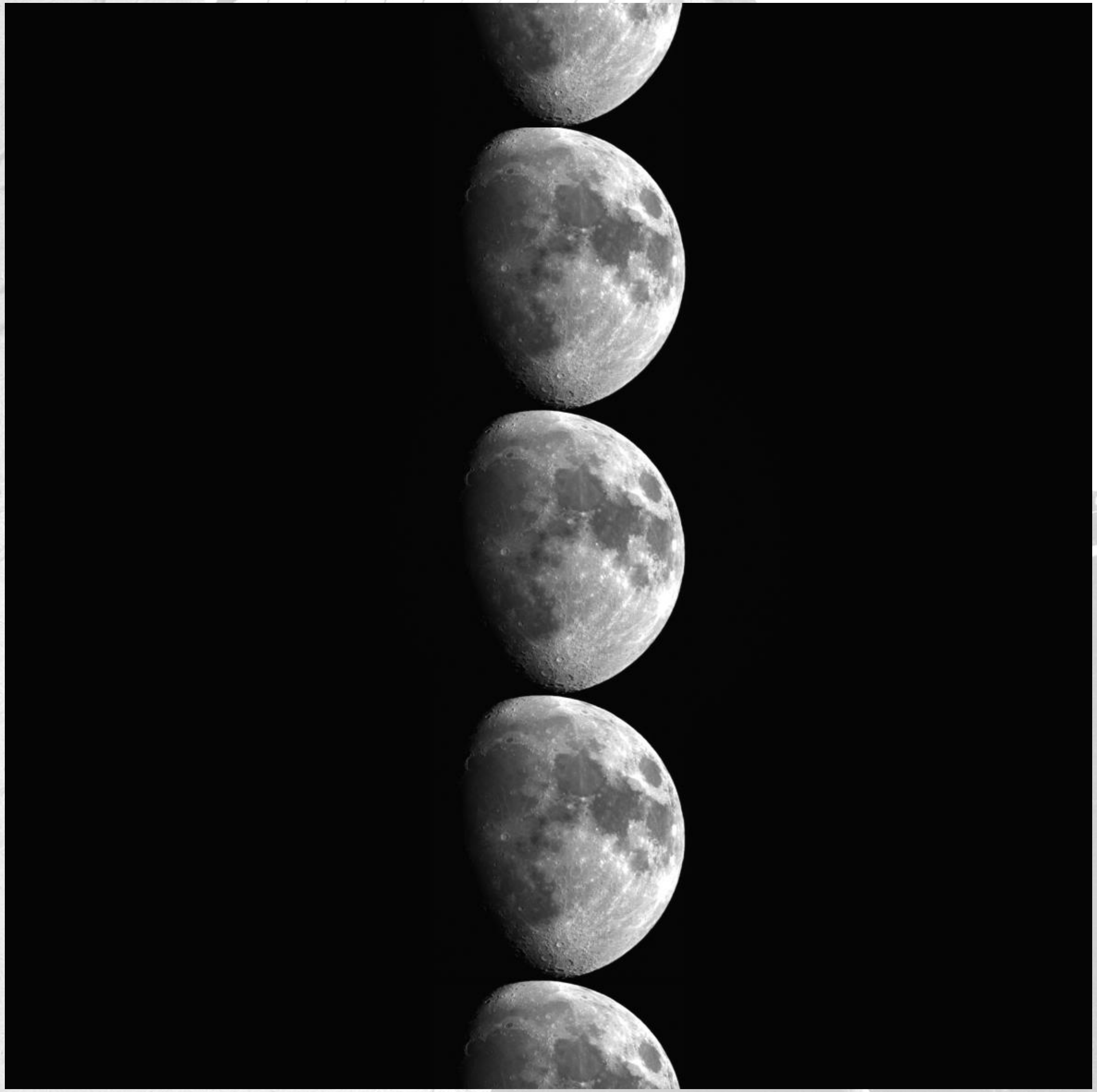


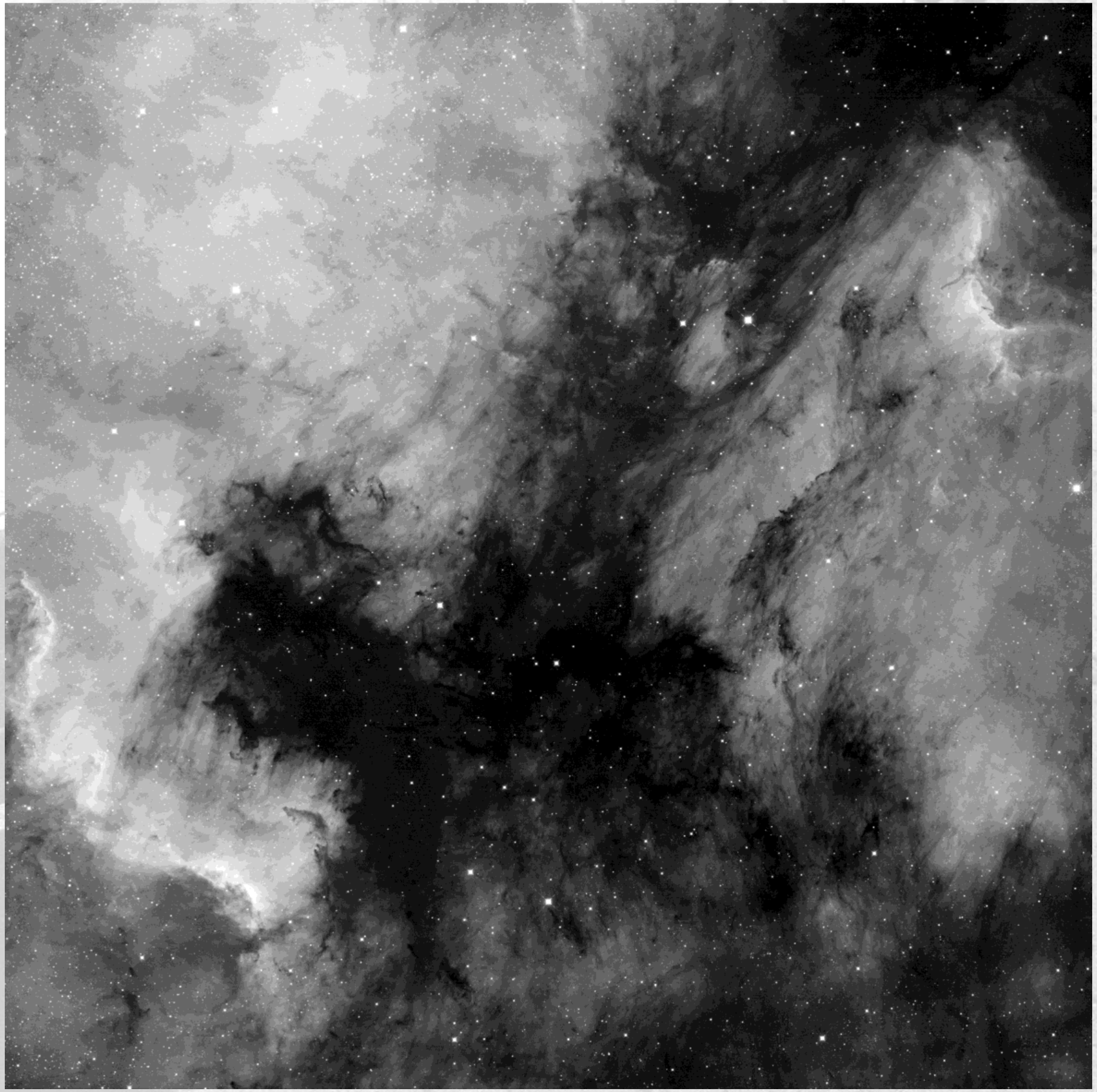
SPX250 TCMT version 1 TCMT version 2

TCMT v2 field of view example



TCMT v2 field of view example





TCMT field of view is achieved without compromising angular resolution

TCMT v2

DSS Red 2 (Palomar Survey)

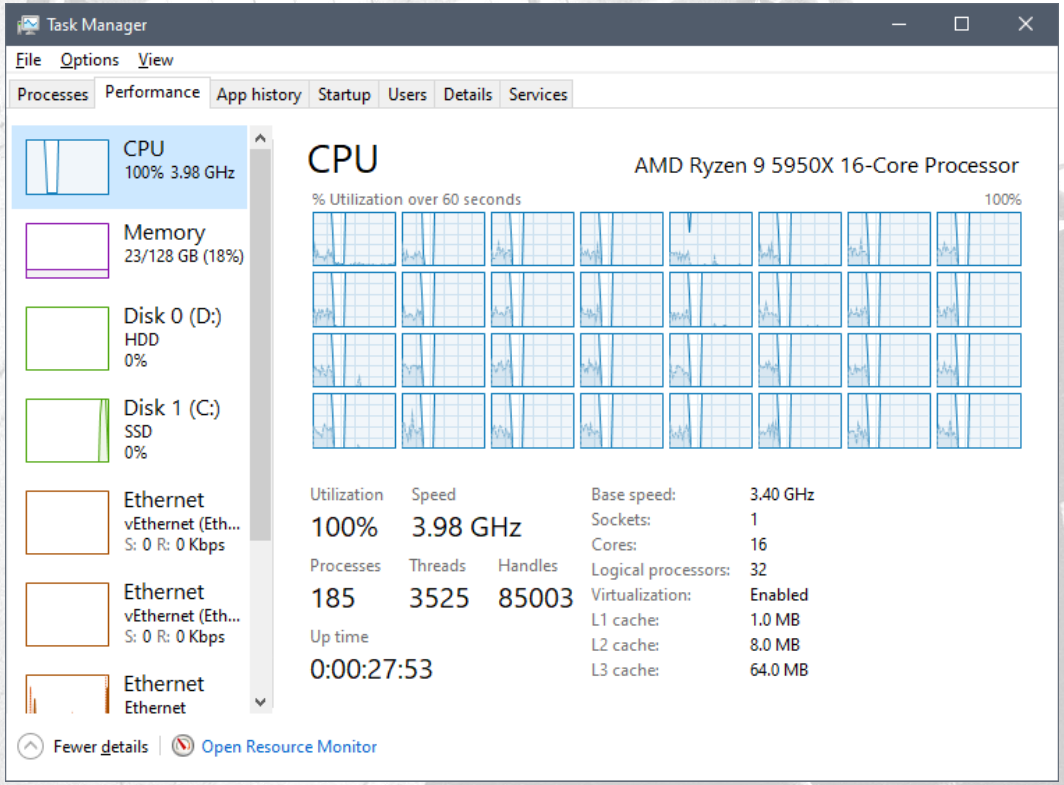
4. Wide-field observation data processing implications

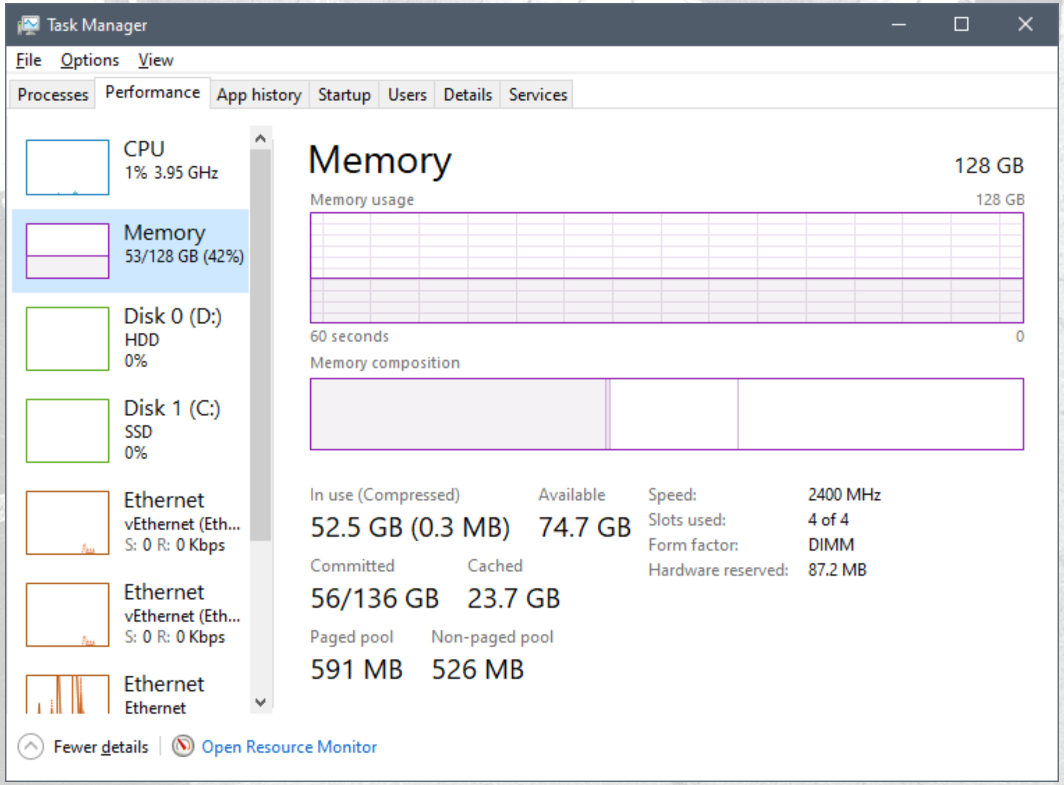
Computer memory requirements

- The software, used to process photometry series from TCMT telescopes, uses **in-memory processing** for performance reasons.
- Single image occupies Width × Depth × 2 Byte of memory (from 32 to 225 MB).
- In the fields with dense stars, the amount of memory needed to hold additional information almost equals to the size of the pixel matric itself.
  - Tens or hundreds thousand stars detected per image with coordinates, fluxes etc.
  - Corresponding catalog stars from one or two catalogs.
- Typical observing run generates from 10 to 20+ GB of raw FITS images, depending on the season and star position (the time for which the star can be observed).
- Computer memory consumption can achieve upper tens of gigabytes.
  - 64 GB is a lower limit, 96 GB is enough in majority of cases, 128 GB is needed for high-cadence, long-lasting series or for unbinned images from the C5 camera.

Computer processing requirements

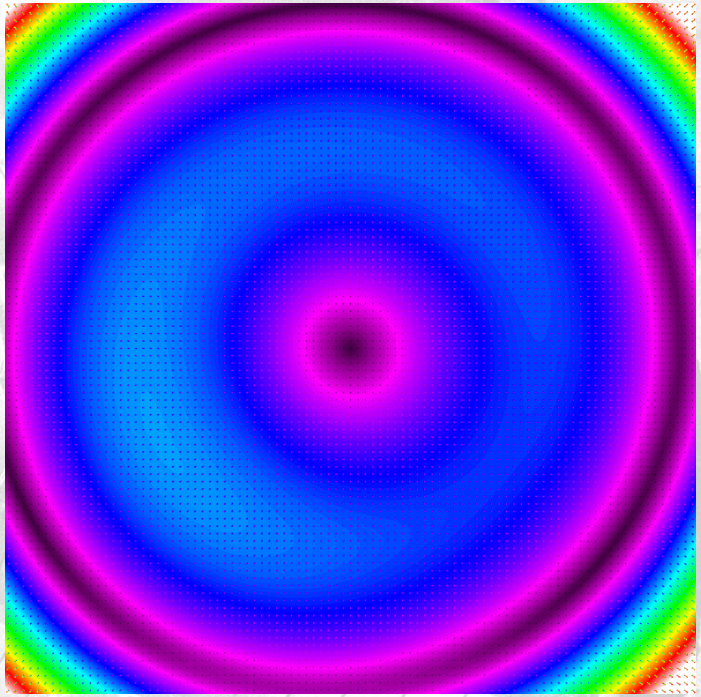
- The software is designed to **utilize every CPU core available** to speed up processing.
- Luckily, tremendously powerful modern PCs, offering **many computing cores** and **large and fast memory**, are more affordable than ever.

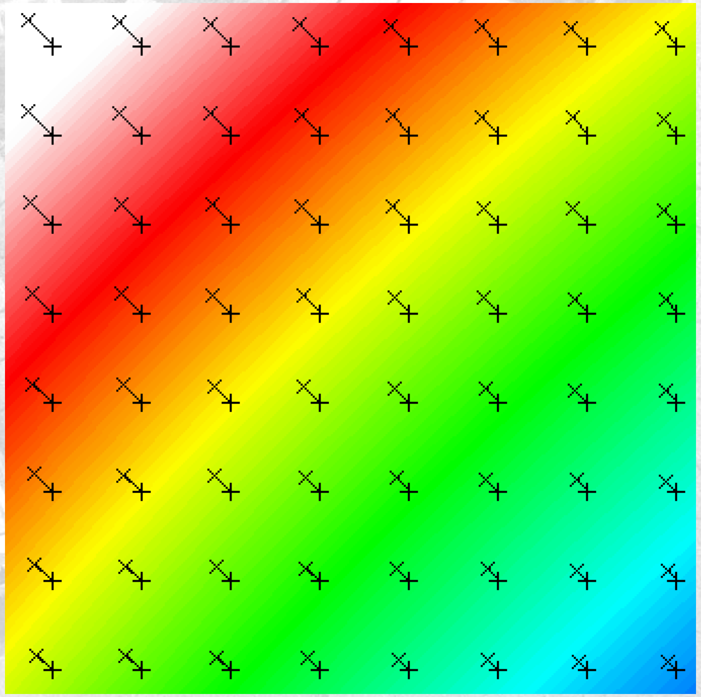




Field curvature

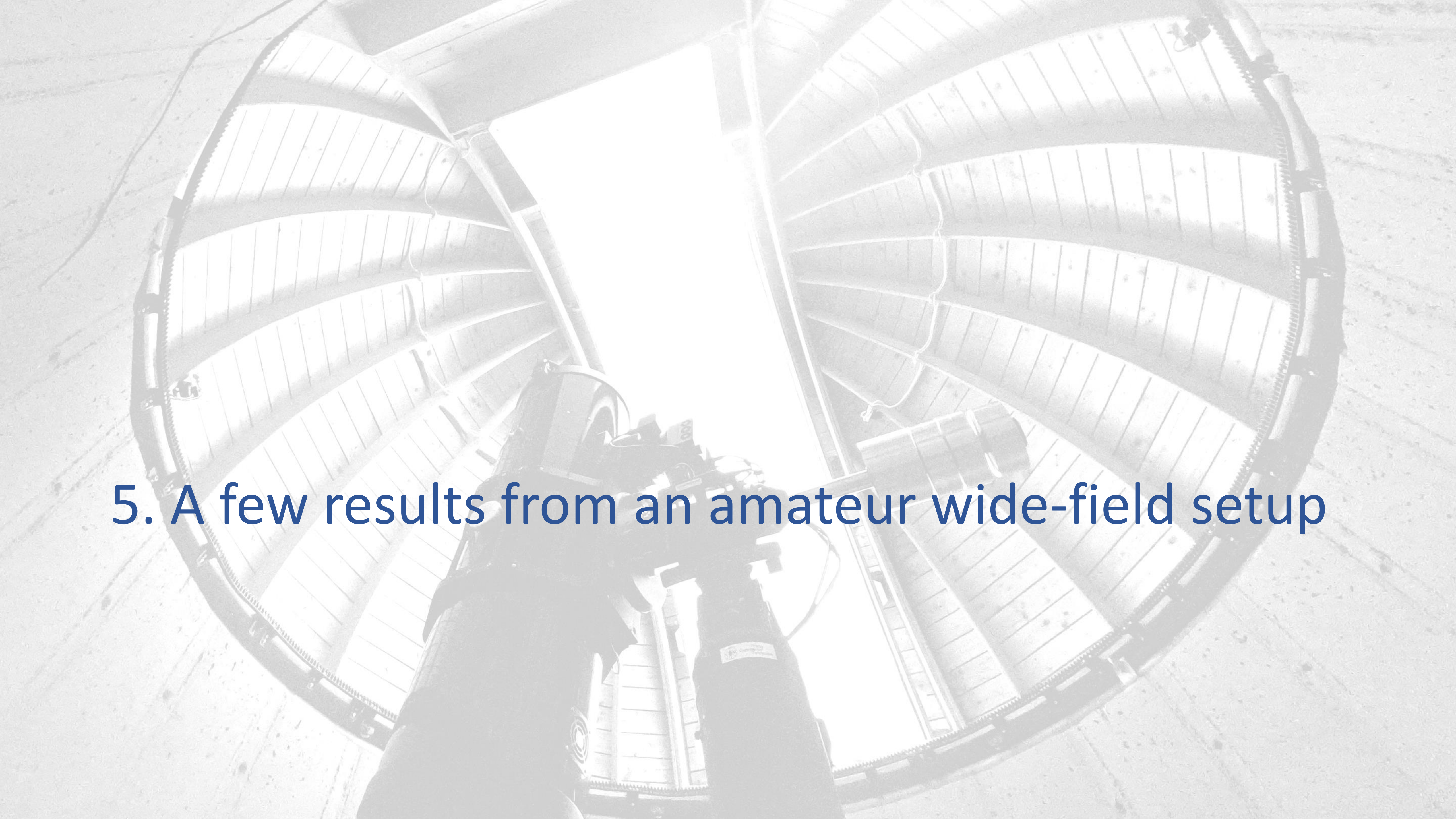
- Coma-correctors ensure to focus star images into as narrow spot as possible, but at the cost of diverting the star images from ideal tangential projection positions.
    - Differences from tangential projections are called “field curvature”.
- The differences between tangential projection and real star position on TCMT images are **more than 15”**, which prohibits matching of image and catalog stars.
- It is necessary to create field curvature model and use it later during image processing.





Field curvature modeling

- The used software can model the field curvature independently in the X and Y axes using two 3rd order 2-dimension polynomials.
- Two types of polynomials are available:
  - Monomial polynomials.
  - Legendre polynomials.
  - Despite Legendre polynomials should be easier to fit, experience shows no or negligible difference between both polynomial types when modeling field curvature.
- Fitting is performed using numerical least squares method applied on the selected pairs of corresponding stars in the image and astrometric catalog.
- Fitted field curvature is stored and later used in subsequent photometric series processing.

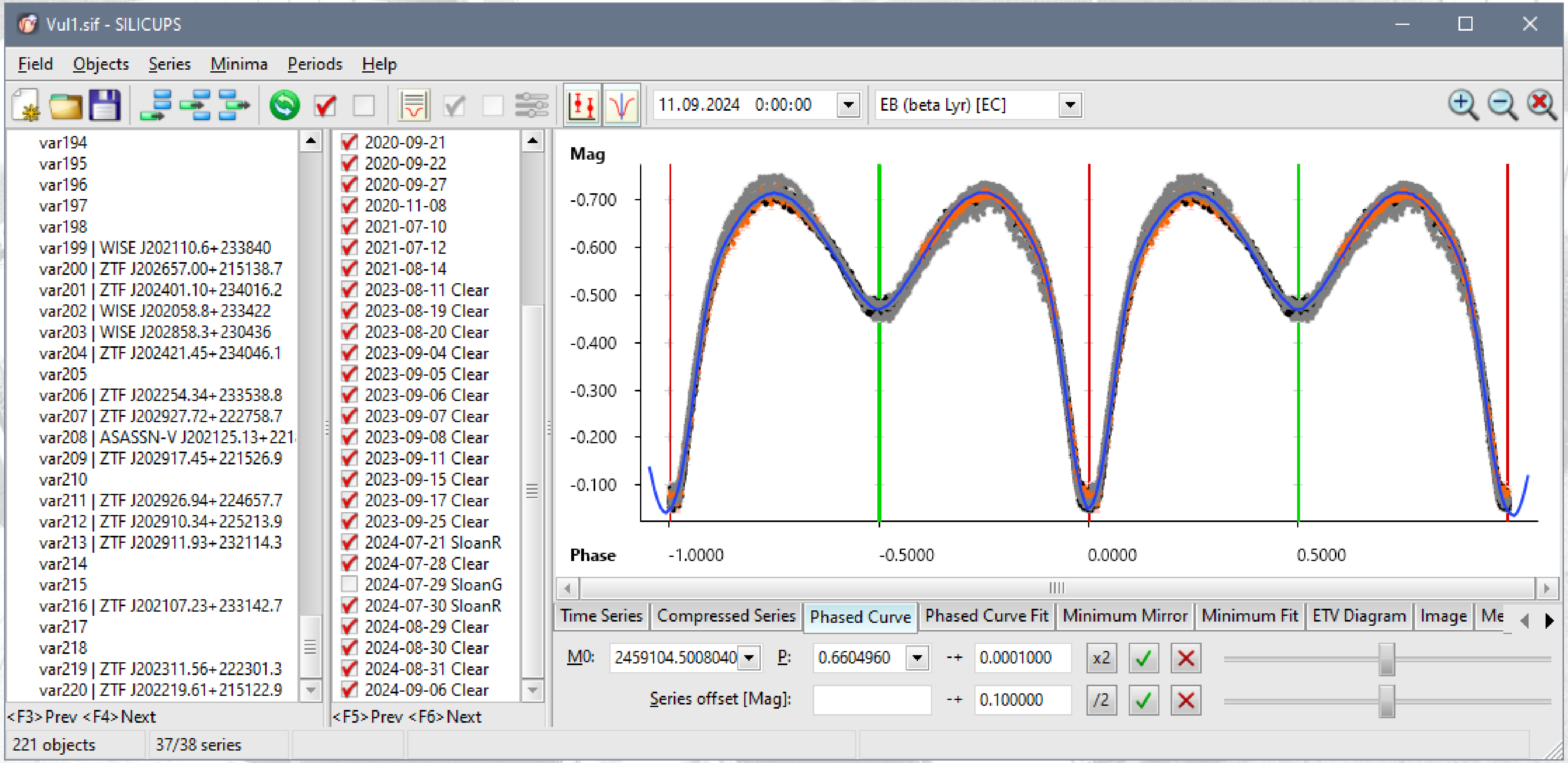


5. A few results from an amateur wide-field setup

BSObservatory observing methodology

- Observing is focused to long-term monitoring of the selected field of view.
  - Here comes the motivation for the widest possible field of view.
- Around one hundred variable stars within the field of view are recorded and characterized.
  - Around ten years ago, only around 5 or 10 variable stars within the field of view were known, remaining ~100 variables were new.
  - With the introduction of massive surveys like ZTF and GAIA, the ratio inverted – only around 10 or 20 variables are previously unknown, others are already included in some catalog.
  - Still, very often the catalogized parameters (M0, Period, sometimes variability type) are way off the observed values.
- Fields with stars exhibiting some interesting feature and worth further research are monitored over many years.
- Long term monitoring of interesting stars may result in high-impact publications.

The first field monitored with TCMT version 2 contains 220 variable stars

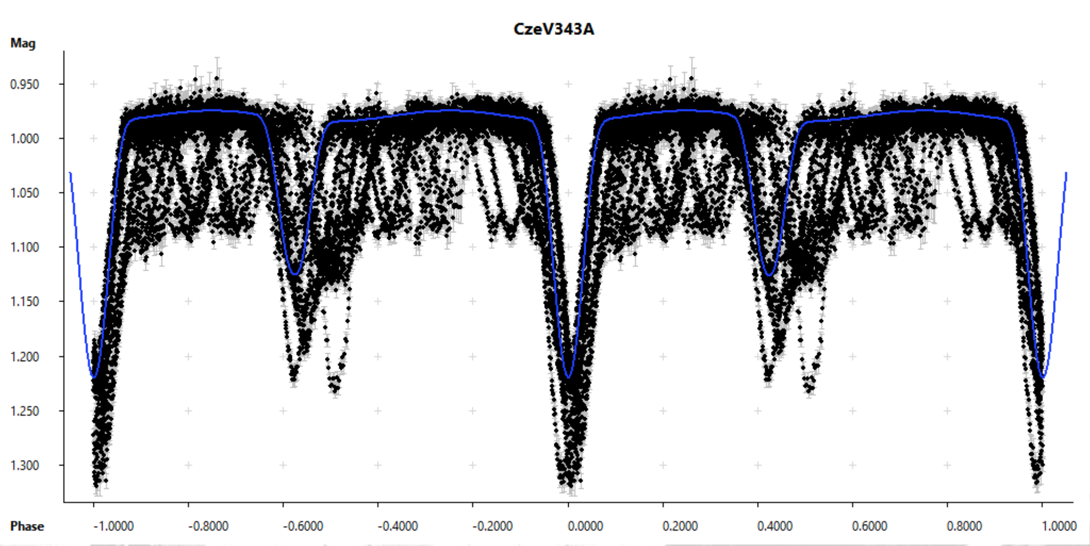


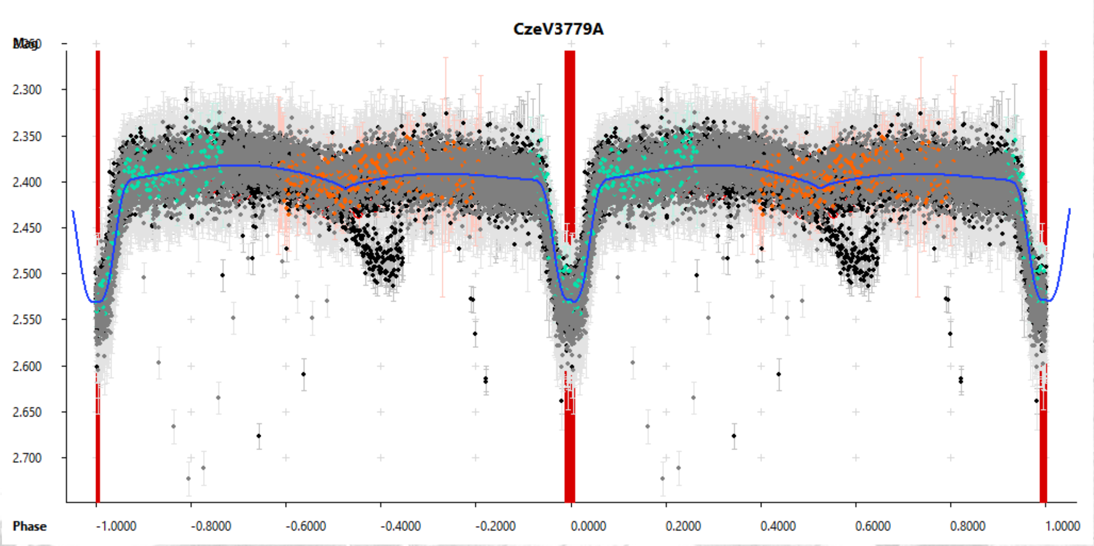
Doubly-eclipsing quadruple star systems

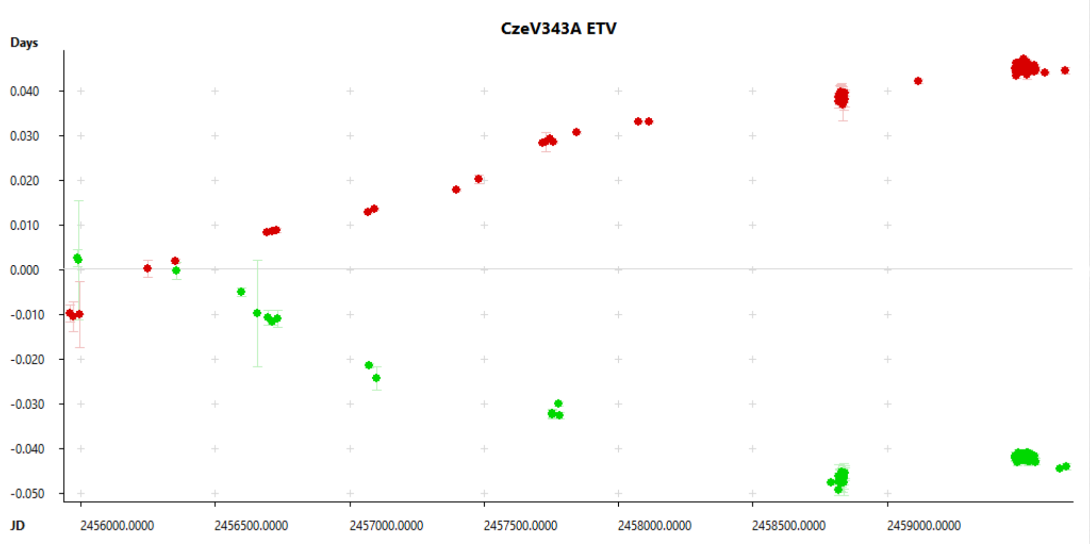
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV343	Aur1	UCAC4 605-025126	05 48 24.012	+30 57 03.59	13.71
CzeV1640	Aur2	UCAC4 591-028146	06 07 18.389	+28 07 25.12	14.56
CzeV1927	Aur2	UCAC4 592-026283	06 03 56.539	+28 17 39.49	14.49
CzeV3836*	Aur2	UCAC4 594-026748	06 06 18.483	+28 40 15.73	12.36
CzeV3758	Cep1	UCAC4 741-074319	21 33 13.380	+58 03 03.91	14.72
CzeV3779	Vul1	UCAC4 561-116505	20 23 29.841	+22 03 13.60	15.15

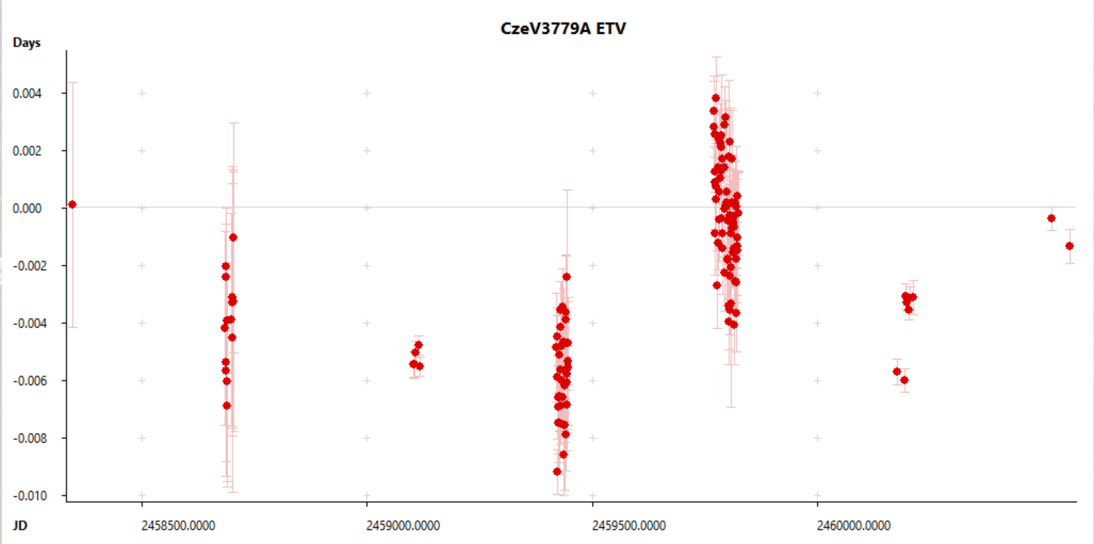
* Apparently also Flare star

Doubly-eclipsing quadruple star systems





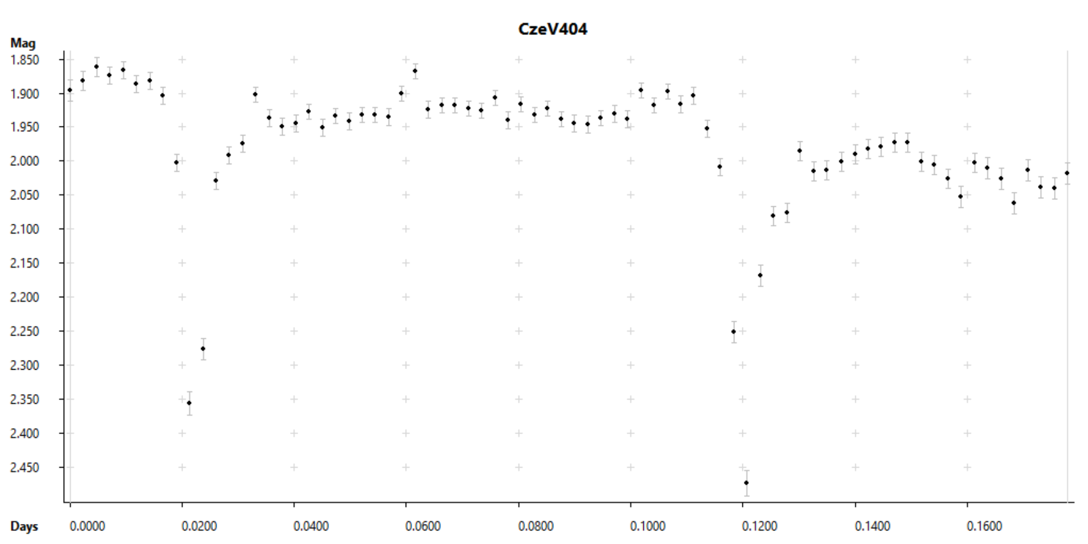


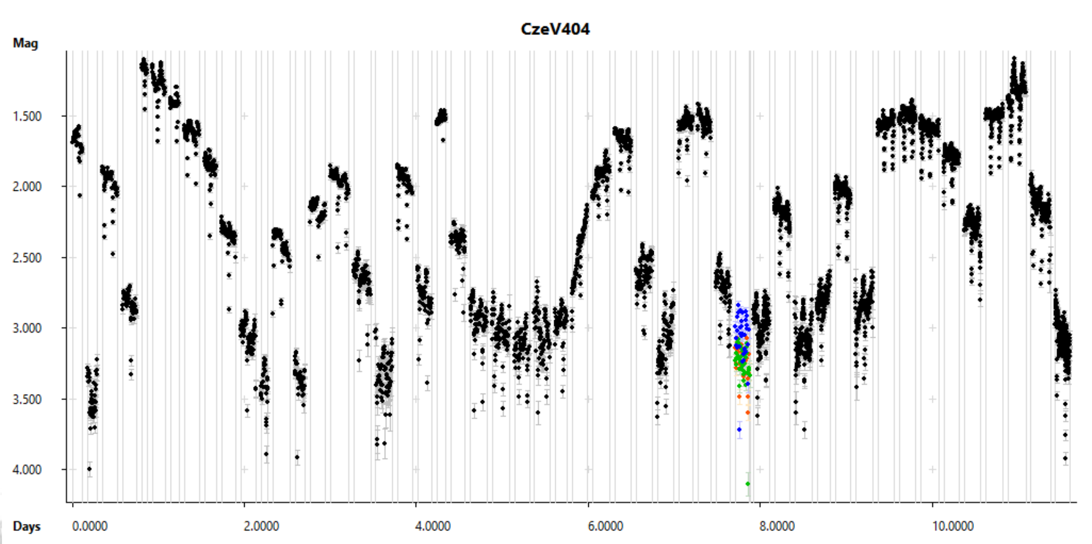


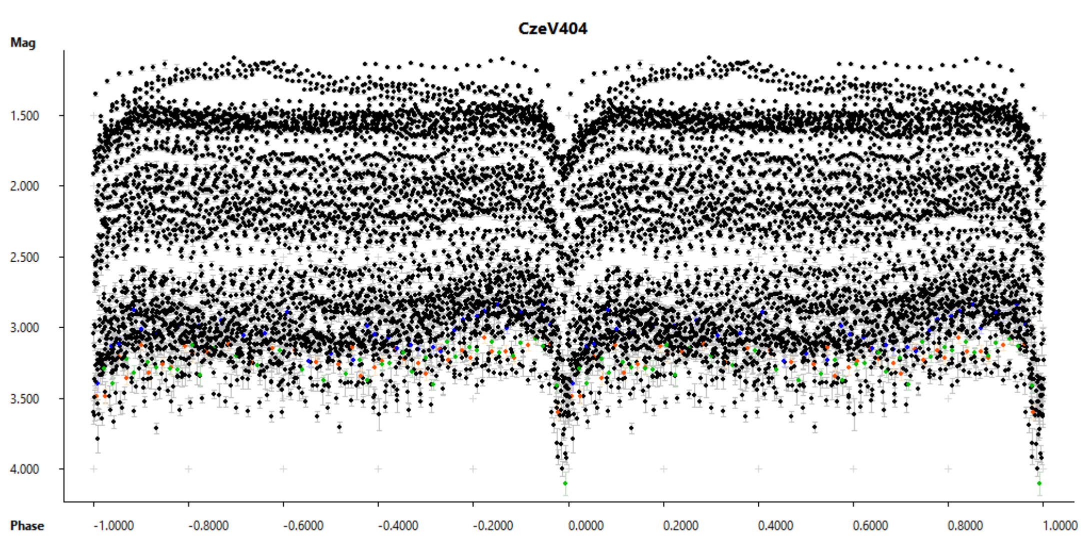
Eclipsing cataclysmic variable

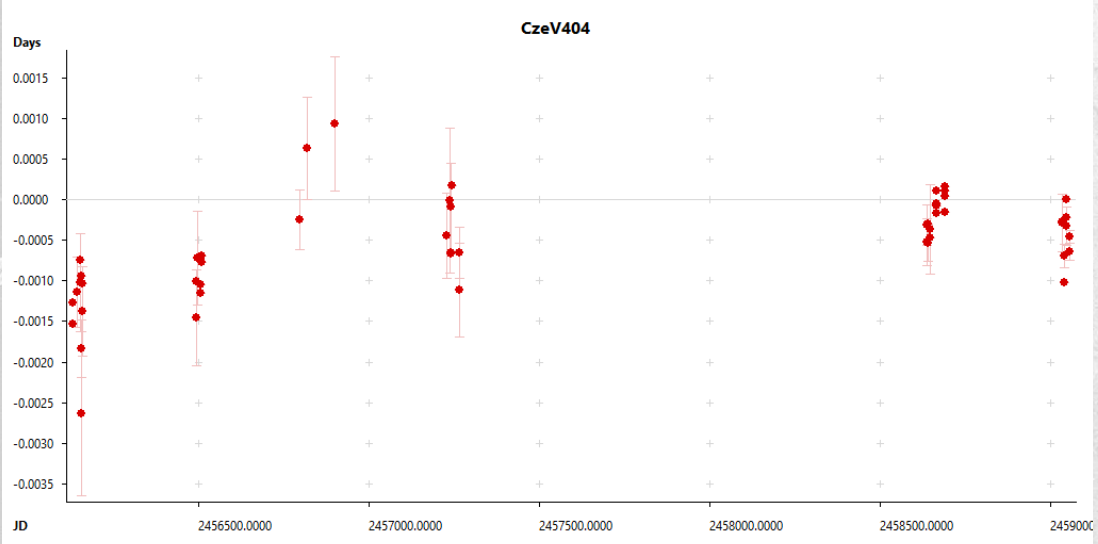
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV404	Her1	UCAC4 513-078584	18 30 01.756	+12 33 46.09	15.64

Eclipsing cataclysmic variable







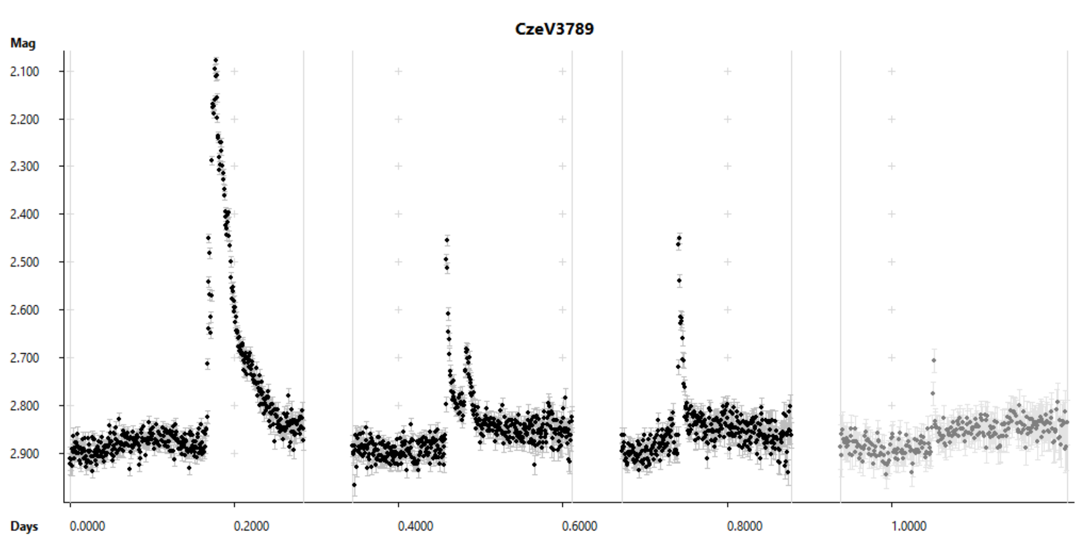


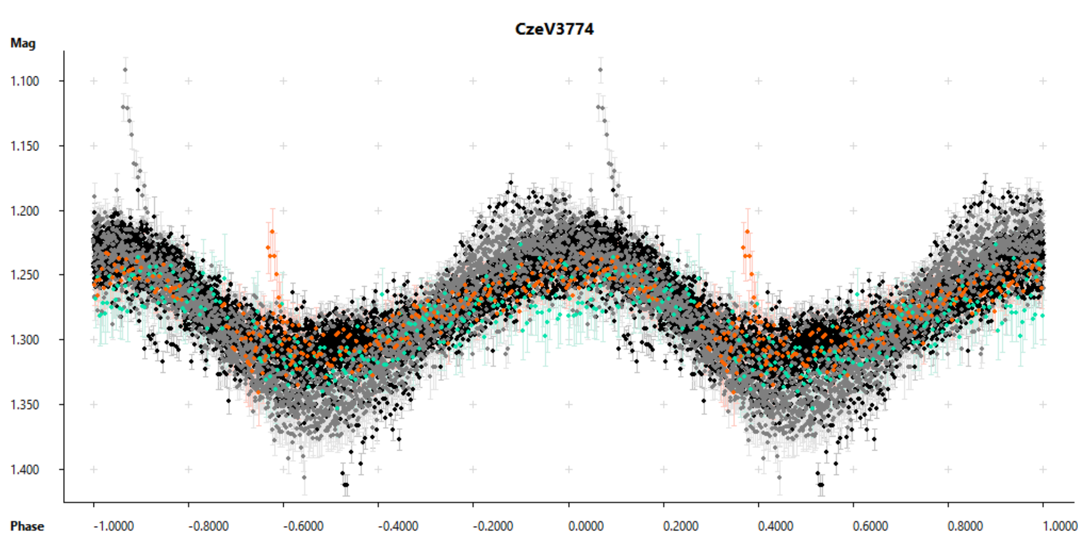
Flare stars

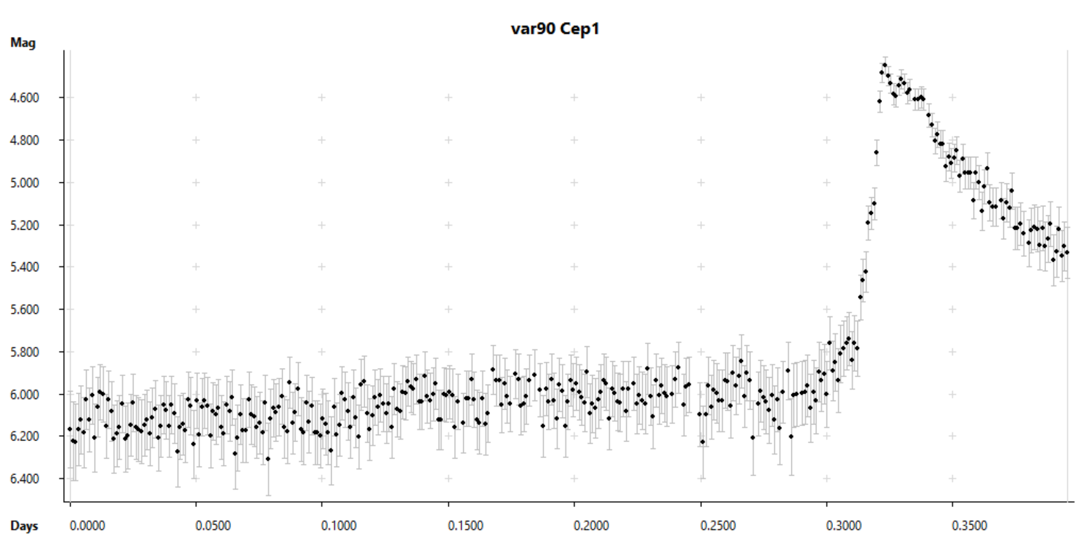
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV812	Cep1	USNO-B1.0 1477-0446775	21 40 22.508	+57 46 24.40	15.32
	Cep1	UCAC4 739-073956	21 38 46.357	+57 38 49.27	13.79
ZTF J214009.25+572739.2	Cep1	UCAC4 738-077736	21 40 09.258	+57 27 39.26	16.19
ZTF J213825.96+573409.3	Cep1	UCAC4 738-077332	21 38 25.977	+57 34 09.46	15.74
	Cep1	USNO-B1.0 1476-0440166	21 37 28.927	+57 36 04.65	18.35
ZTF J214018.00+573801.4	Cep1	USNO-B1.0 1476-0443091	21 40 18.093	+57 38 02.58	16.19
CzeV325	Aql1	UCAC4 516-117958	19 53 31.835	+13 10 18.43	14.85
CzeV3774	Vul1	UCAC4 561-117827	20 26 11.274	+22 06 50.22	14.21
CzeV3789	Vul1	UCAC4 566-107767	20 25 49.762	+23 08 23.11	14.93
CzeV3836*	Aur2	UCAC4 594-026748	06 06 18.483	+28 40 15.73	12.36

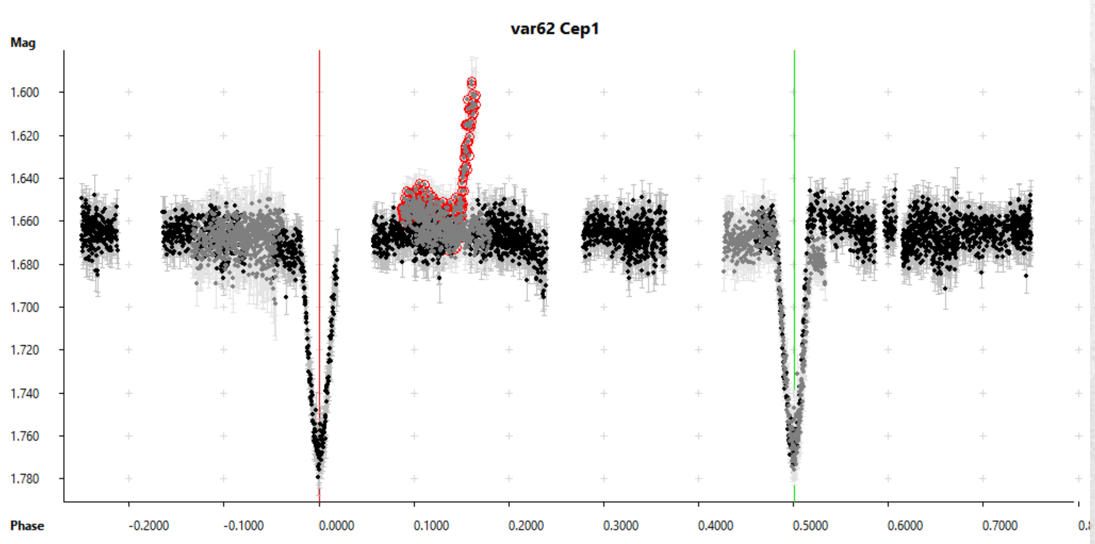
* Doubly eclipsing quadruple star

Flare stars


CzeV3789
Mag
Days


CzeV3774
Mag
Phase


var90 Cep1
Mag
Days

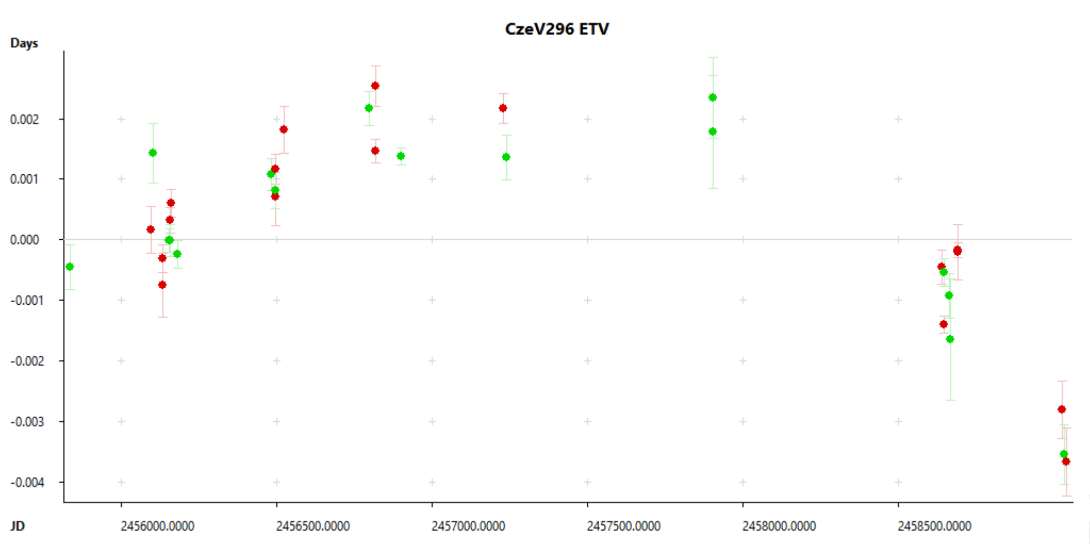

var62 Cep1
Mag
Phase

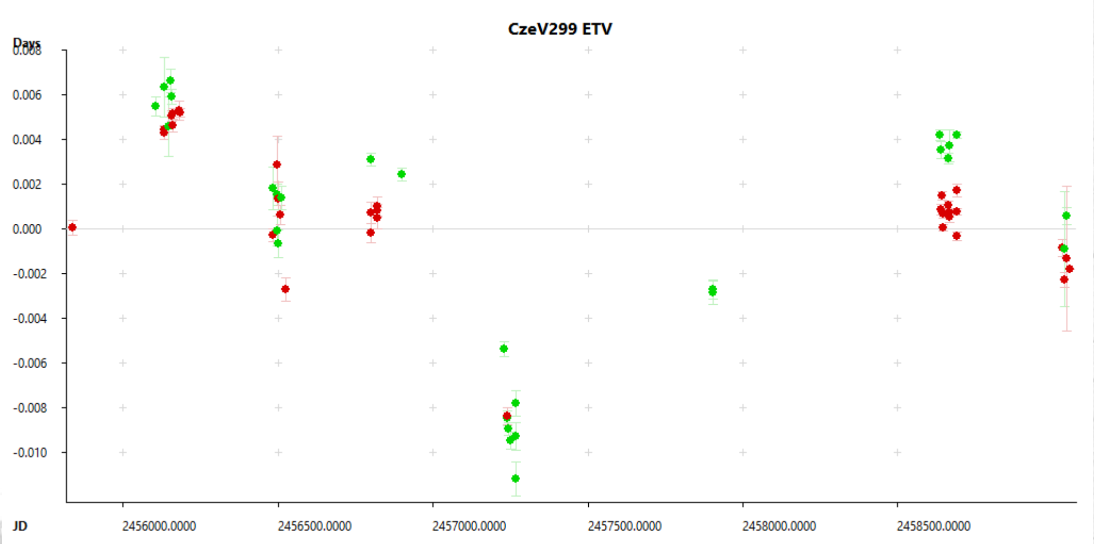
Eclipsing binaries exhibiting ETV changes

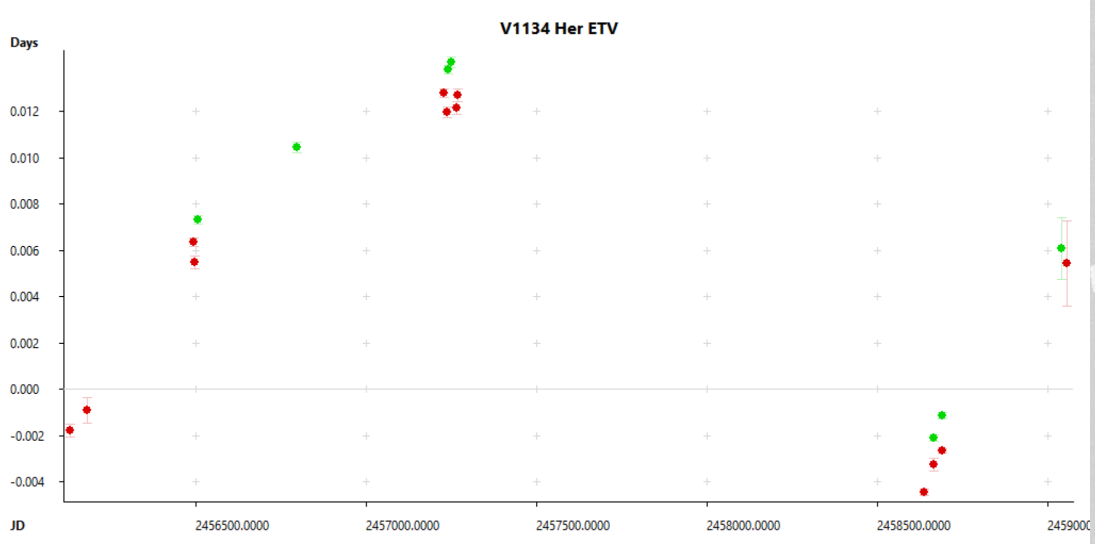
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV1920	Aur2	UCAC4 592-026019	06 03 04.197	+28 20 44.59	16.04
CzeV1950	Aur2	UCAC4 593-026585	06 02 20.250	+28 33 26.42	15.23
CzeV1982	Aur2	UCAC4 593-028061	06 06 50.171	+28 25 22.12	15.23
CzeV2008	Aur2	UCAC4 596-028420	06 04 56.573	+29 00 34.33	13.89
CzeV3102	Aur2	UCAC4 595-027580	06 04 05.970	+28 57 59.92	14.41
ASAS J202345+2234.5	Vul1	UCAC4 563-113316	20 23 45.133	+22 34 19.31	12.22
	Vul1	UCAC4 565-111303	20 23 02.428	+22 59 59.48	15.71
WISE J202257.0+231349	Vul1	UCAC4 567-104371	20 22 57.067	+23 13 49.76	14.26
WISE J202352.9+232248	Vul1	UCAC4 567-104779	20 23 52.926	+23 22 48.63	14.86
CzeV346	Aur1	UCAC4 605-025202	05 48 41.277	+30 51 57.97	15.54
CzeV347	Aur1	UCAC4 606-024400	05 49 11.674	+31 00 23.43	13.32
CzeV353	Aur1	UCAC4 606-025058	05 51 19.766	+31 05 57.98	15.26

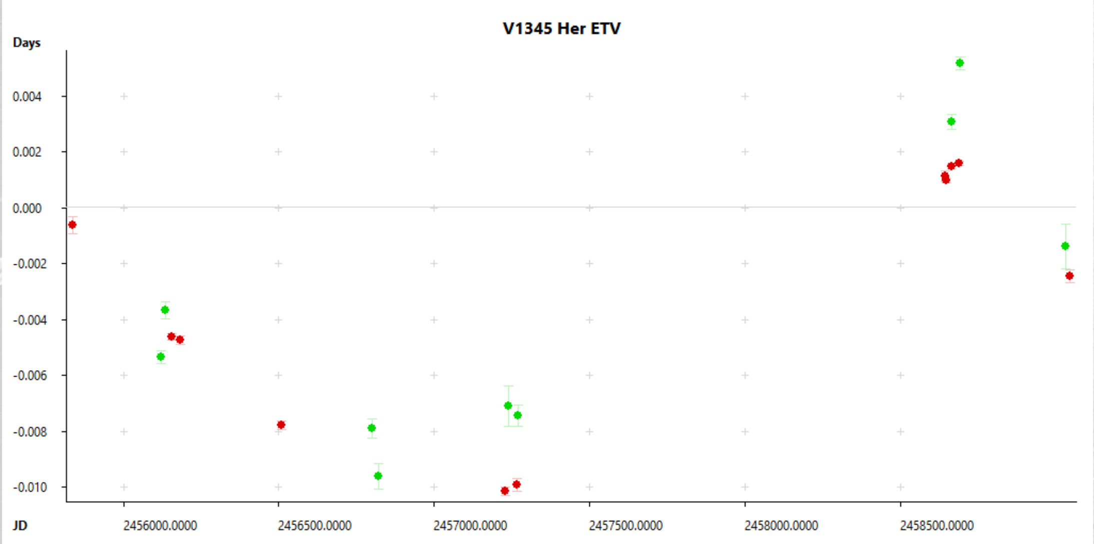
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV589	Aur1	UCAC4 603-025982	05 48 53.879	+30 34 07.38	14.69
FV Aur	Aur1	UCAC4 606-024571	05 49 42.040	+31 07 06.84	14.61
CzeV1153	Aur1	UCAC4 606-024156	05 48 14.766	+31 11 49.73	15.64
FV Aur	Aur1	UCAC4 606-024571	05 49 42.040	+31 07 06.84	14.61
V0772 Aur	Aur2	UCAC4 595-026684	06 01 06.785	+28 58 21.02	12.16
V0784 Aur	Aur2	UCAC4 593-026801	06 02 52.844	+28 25 13.37	14.61
ASAS J182745+1230.5	Her1	UCAC4 513-077958	18 27 45.399	+12 30 28.00	12.02
CzeV299	Her1	UCAC4 512-074575	18 27 41.076	+12 13 20.48	14.99
V1134 Her	Her1	UCAC4 512-074778	18 28 14.494	+12 19 51.06	12.55
V1345 Her	Her1	UCAC4 513-077912	18 27 36.663	+12 32 07.19	14.39
CzeV273	Aql1	UCAC4 517-114737	19 55 50.670	+13 12 45.49	15.62
CzeV275	Aql1	UCAC4 520-116229	19 53 58.291	+13 56 54.92	15.53
CzeV281	Aql1	UCAC4 517-114618	19 55 36.744	+13 12 46.24	15.5
CzeV286	Aql1	UCAC4 518-118829	19 56 31.993	+13 27 55.52	16.12
CzeV896	Aql1	USNO-B1.0 1030-0613324	19 54 31.671	+13 05 07.50	17.52
CzeV904	Aql1	UCAC4 516-119284	19 55 52.824	+13 07 49.98	16.32
CzeV909	Aql1	UCAC4 517-115014	19 56 16.216	+13 23 33.16	16.39

Eclipsing binaries exhibiting ETV changes







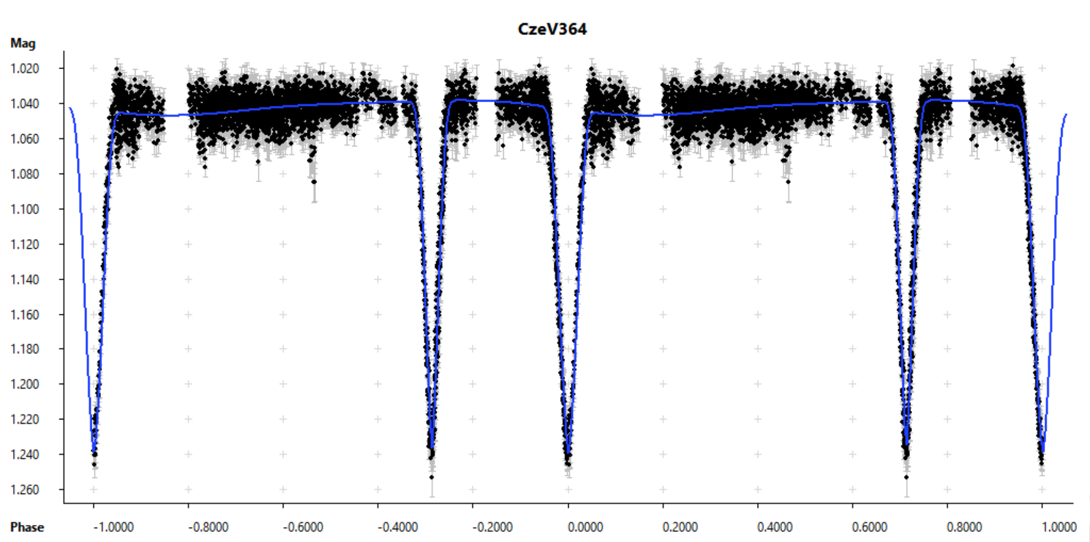


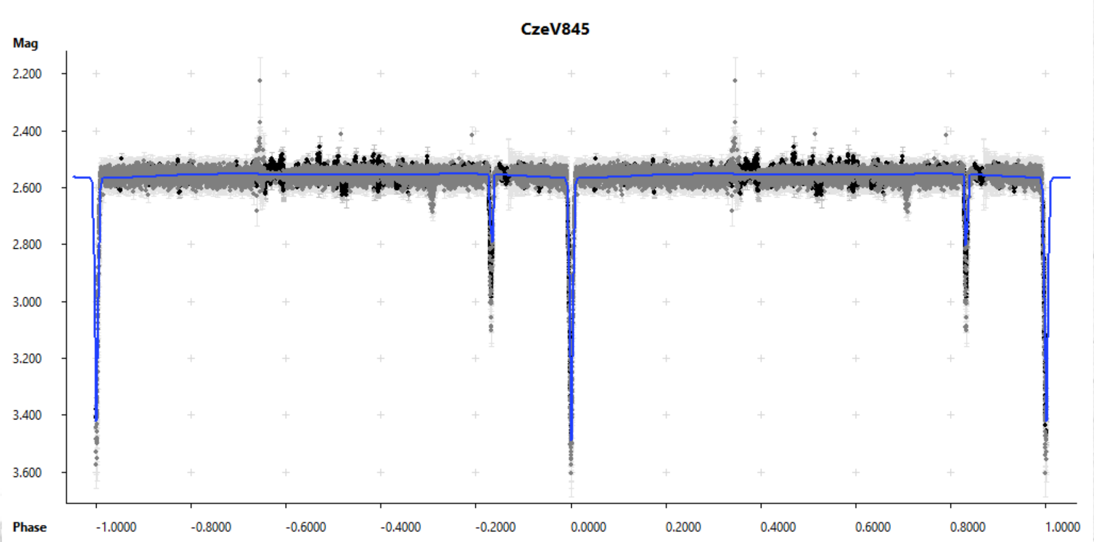
Eccentric detached eclipsing binaries

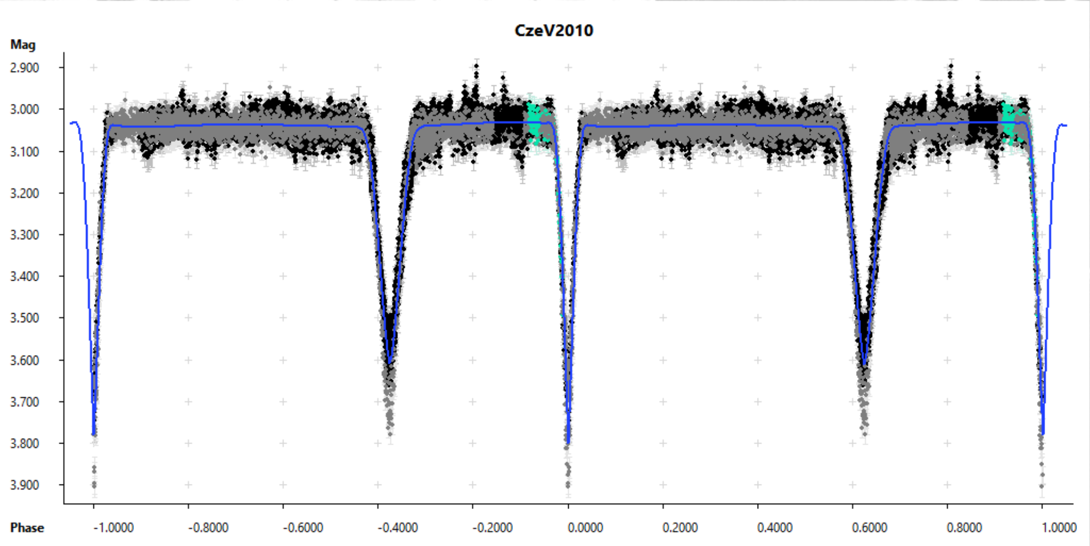
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV347	Aur1	UCAC4 606-024400	05 49 11.674	+31 00 23.43	13.32
CzeV364	Aur1	UCAC4 603-026208	05 49 40.709	+30 25 00.76	13.77
CzeV377	Aur1				
CzeV589	Aur1	UCAC4 603-025982	05 48 53.879	+30 34 07.38	14.69
CzeV609	Aur1	UCAC4 604-024570	05 47 23.197	+30 45 18.21	12.23
CzeV661	Aur1	UCAC4 607-023806	05 48 34.775	+31 19 10.09	15.69
CzeV845	Aur1	UCAC4 604-024193	05 45 26.771	+30 40 35.72	15.17
CzeV1107	Aur1	USNO-B1.0 1215-0101885	05 46 58.126	+31 32 38.72	17.24
CzeV1153	Aur1	UCAC4 606-024156	05 48 14.766	+31 11 49.73	15.64
CzeV1850	Aur1	UCAC4 603-025761	05 47 52.200	+30 30 45.16	12.69
UCAC4 609-022916	Aur1	UCAC4 609-022916	05 45 52.250	+31 42 20.00	14.51
CzeV1918	Aur2	UCAC4 590-027480	06 06 28.407	+27 54 42.65	15.74

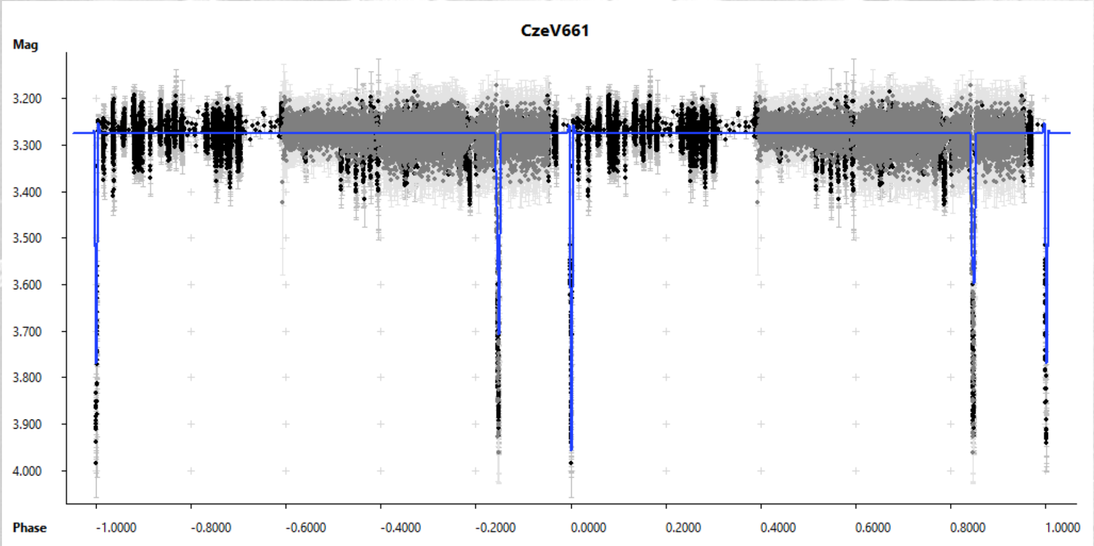
Star	Field	Catalog Id	R.A.	Dec.	Mag.
CzeV1991	Aur2	UCAC4 591-027628	06 05 38.045	+28 11 56.35	11.94
CzeV2008	Aur2	UCAC4 596-028420	06 04 56.573	+29 00 34.33	13.89
CzeV2010	Aur2	UCAC4 593-027142	06 03 47.016	+28 35 31.06	15.24
CzeV2016	Aur2	UCAC4 592-025849	06 02 35.595	+28 17 53.19	15.15
CzeV3098	Aur2	UCAC4 593-027246	06 04 07.885	+28 31 59.36	14.84
CzeV3108	Aur2	UCAC4 592-026155	06 03 33.364	+28 15 10.85	14.46
CzeV3748	Aur2	UCAC4 591-027187	06 04 16.524	+28 07 57.16	13.17
CzeV3119	Aur2	UCAC4 590-026557	06 03 51.499	+27 53 50.49	14.35
CzeV3808	Vul1	UCAC4 562-113162	20 22 35.331	+22 18 19.72	16.27

Eccentric detached eclipsing binaries










Thank you for your attention