The 10th International Conference on
Fuzzy Systems and Data Mining
(FSDM 2024)
Nov. 5-8, 2024
(Matsue, Japan)

FSDM
4562

Satellite Telescope Self-Calibration through Precise Stellar Data Mining

Presented by: **Konstantin Ryabinin**, Gerasimos Sarras, Wolfgang Löffler, Olga Erokhina, Michael Biermann

Affiliation: Astronomisches Rechen-Institut, Center for Astronomy of Heidelberg University

ZENTRUM FÜR ASTRONOMIE

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

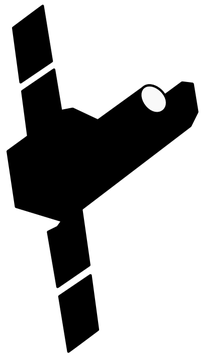
Japan
Astrometry
Satellite
Mission for
INfrared
Exploration

proposed by

国立天文台 NAOJ
National Astronomical Observatory of Japan

to

JAXA



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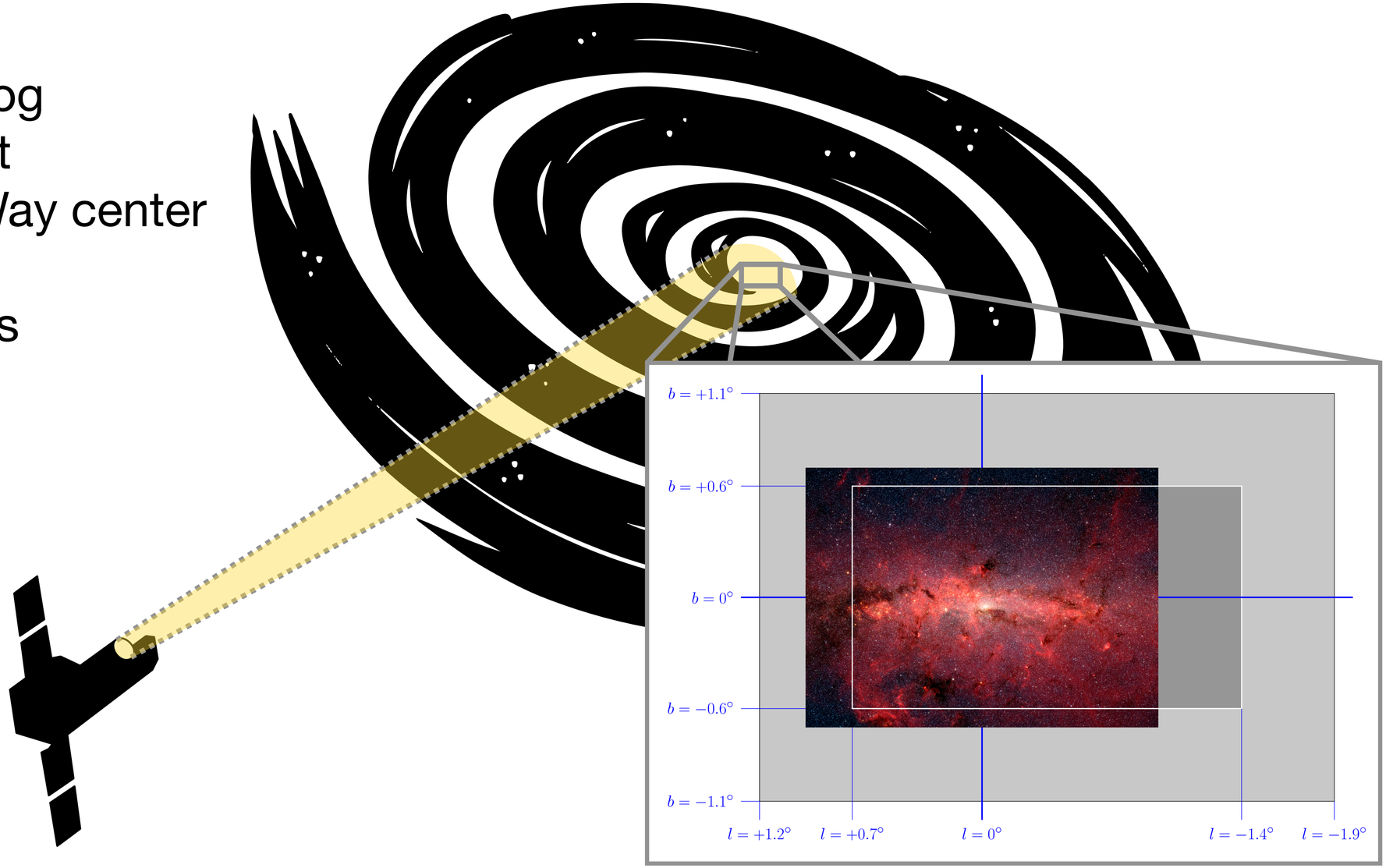
2. Earth-like exoplanets discovery



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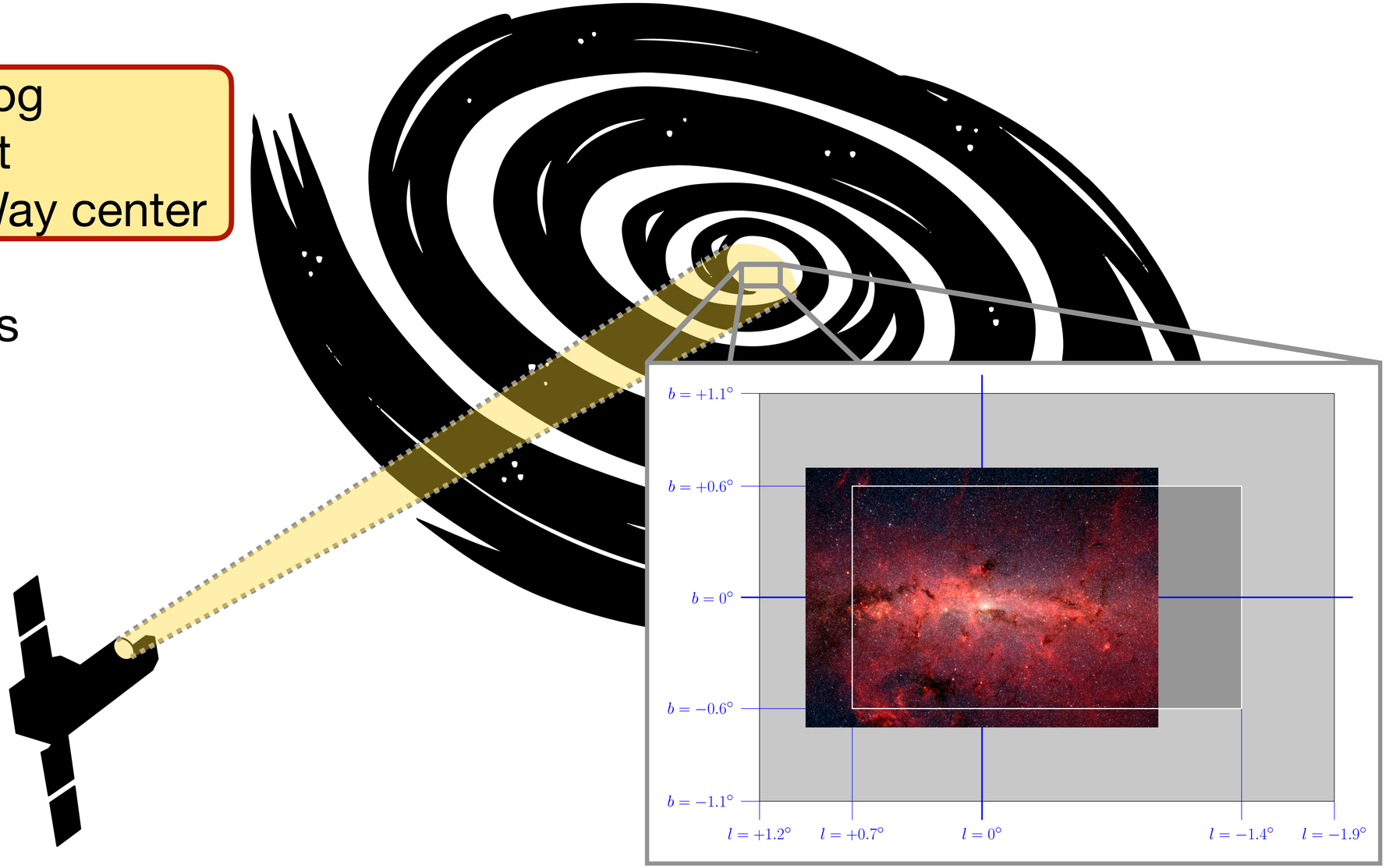
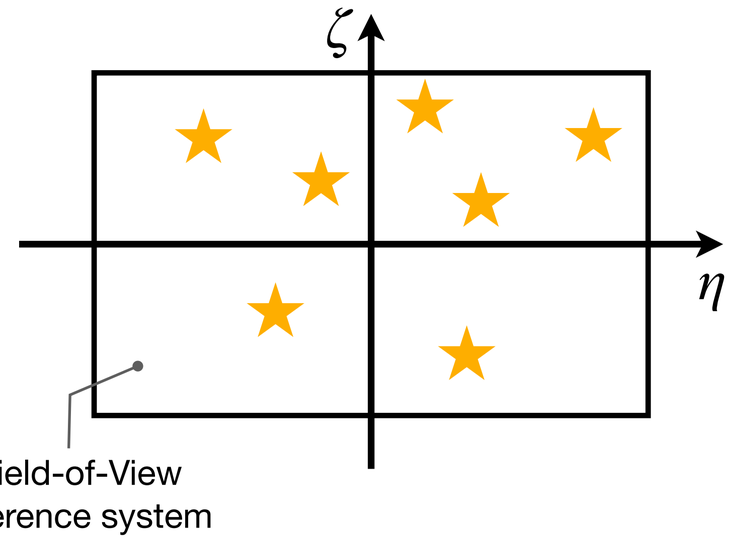


Astrometric Problem



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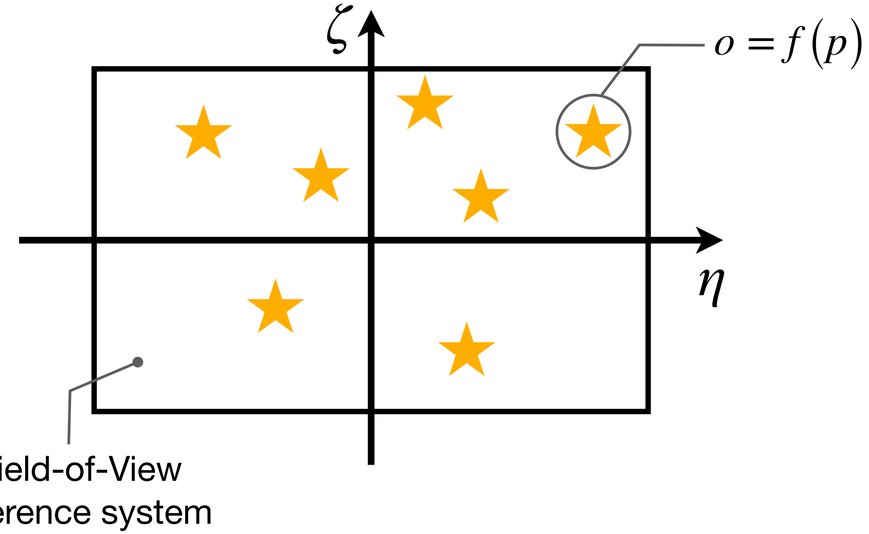

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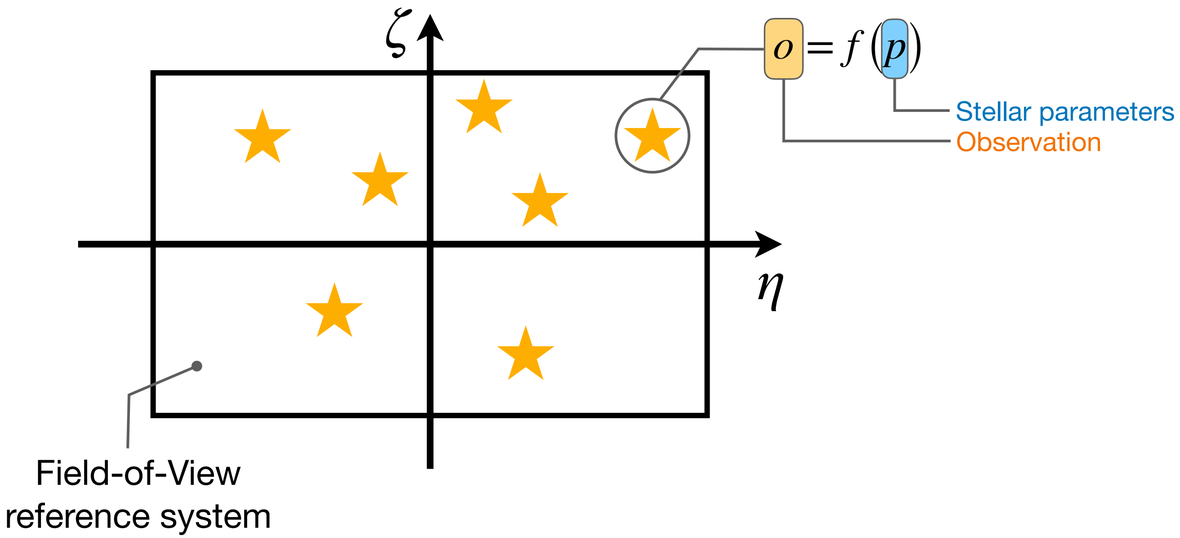

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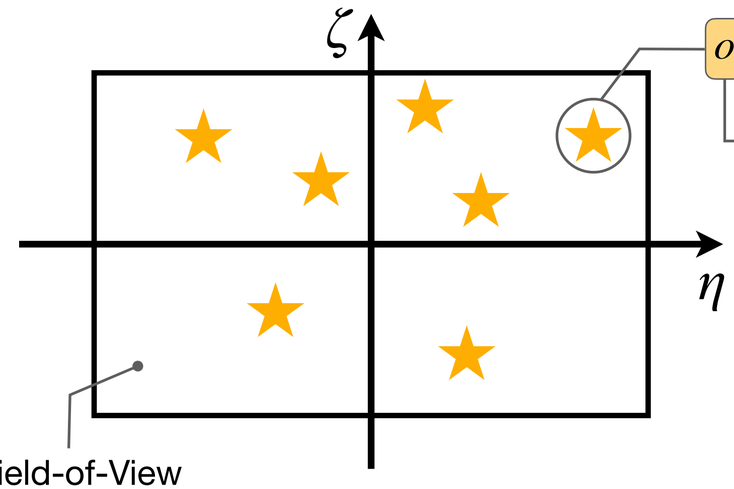


Field-of-View
reference system

$o = f(p)$

Stellar parameters

Observation

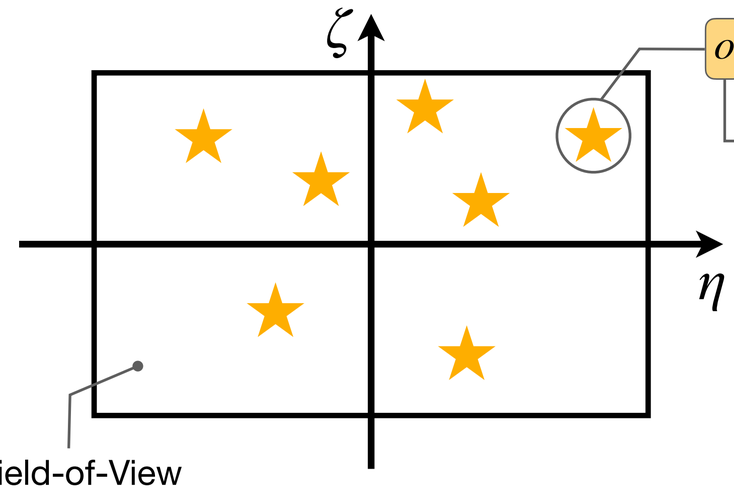
Taylor expansion

$$o = f(\hat{p}) + \frac{\mathrm{d}}{\mathrm{d}p} f(p)\Big|_{\hat{p}} \cdot \Delta\hat{p} + O(\Delta\hat{p}^2)$$

Updates of the stellar parameters
(refinement of the existing star catalog)

Initial guess of the stellar parameters
(data from the existing star catalog)

Astrometric Problem



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Linearization

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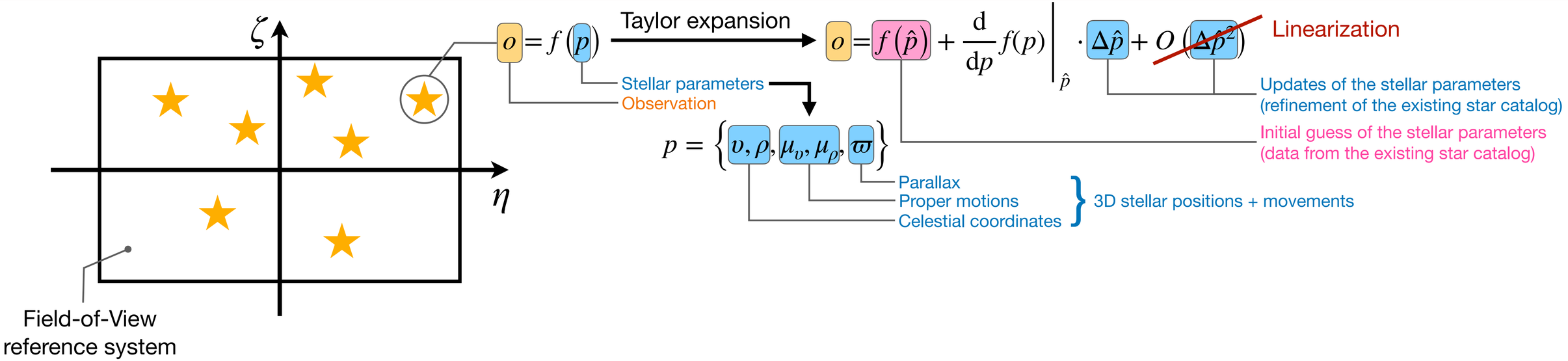
Astrometric Problem



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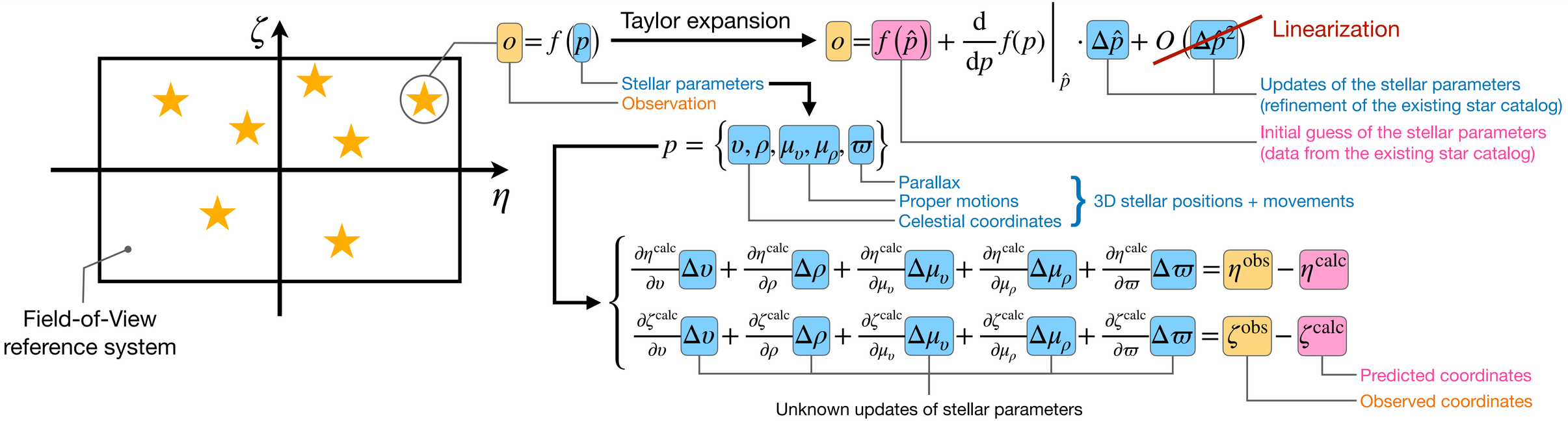

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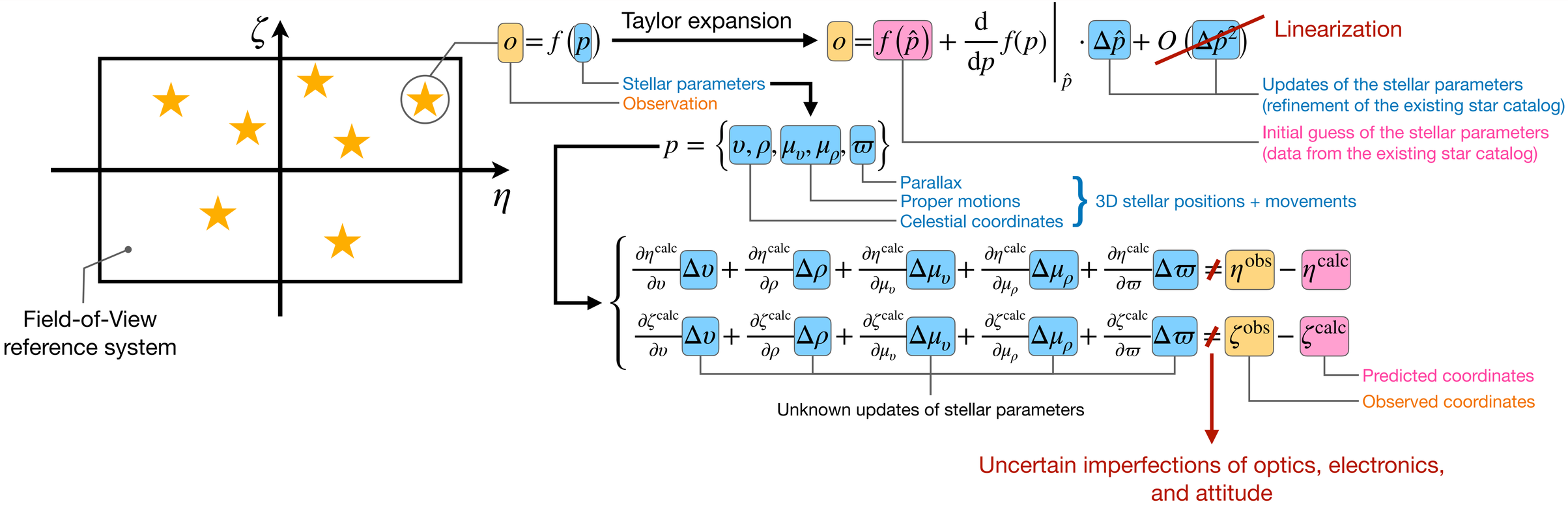

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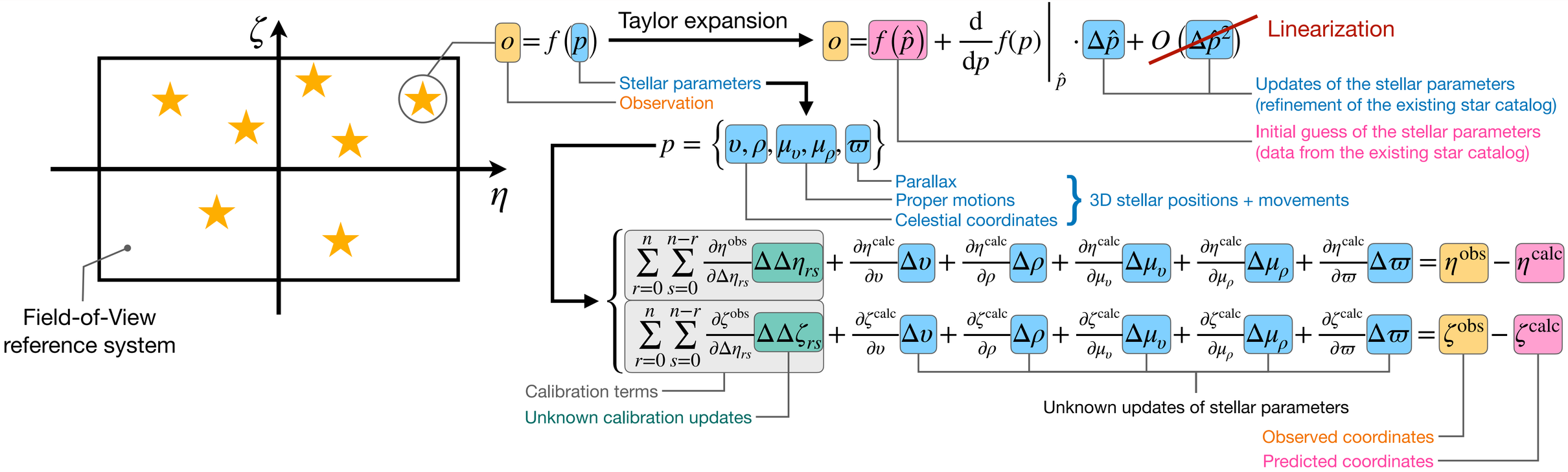

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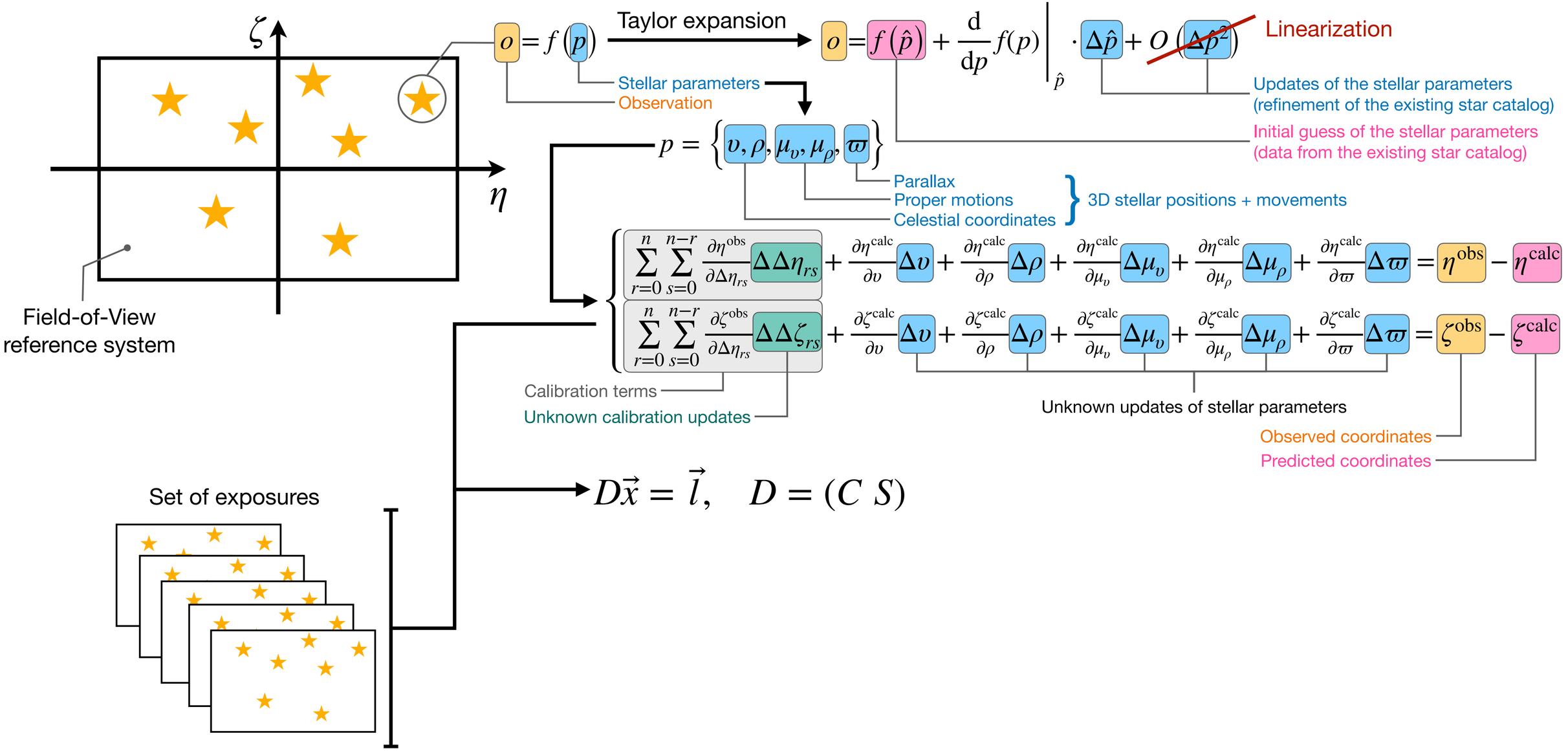

$$o = f(p) \rightarrow o = f(\hat{p}) + \frac{\mathrm{d}}{\mathrm{d}p} f(p)\Big|_{\hat{p}} \cdot \Delta\hat{p} + O(\Delta\hat{p}^2)$$

$$p = \{\upsilon, \rho, \mu_\upsilon, \mu_\rho, \varpi\}$$

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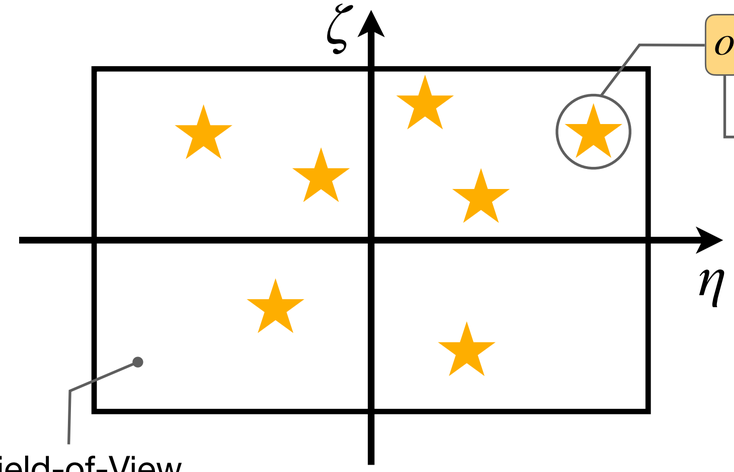
$$D\vec{x} = \vec{l}, \quad D = (C\ S)$$

Astrometric Problem

FSDM 4562



Field-of-View reference system

$o = f(p)$ — Taylor expansion → $o = f(\hat{p}) + \frac{\mathrm{d}}{\mathrm{d}p} f(p)\Big|_{\hat{p}} \cdot \Delta\hat{p} + O(\Delta\hat{p}^2)$ — Linearization

- o: Observation
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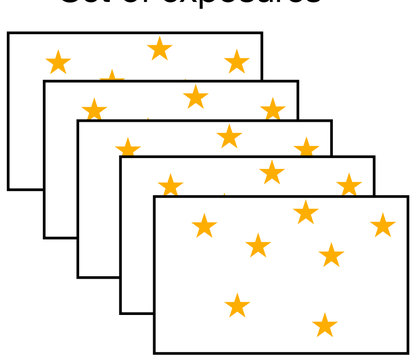
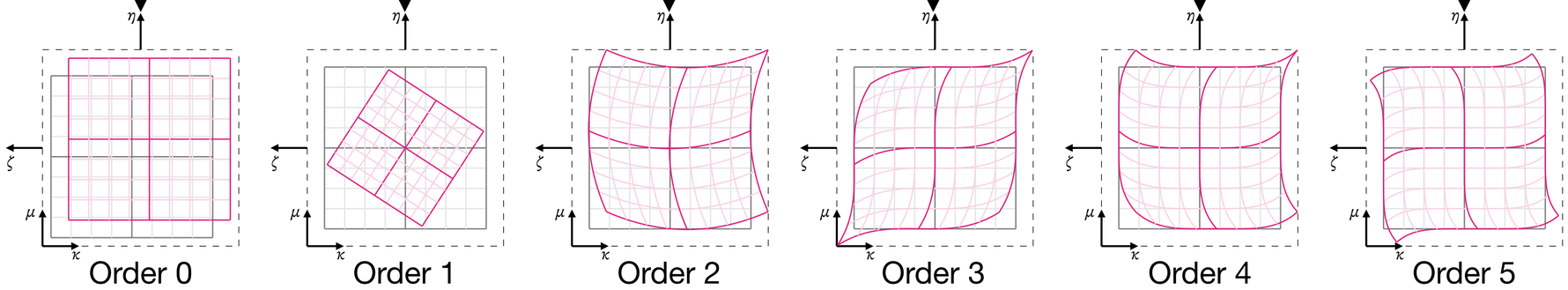
Set of exposures

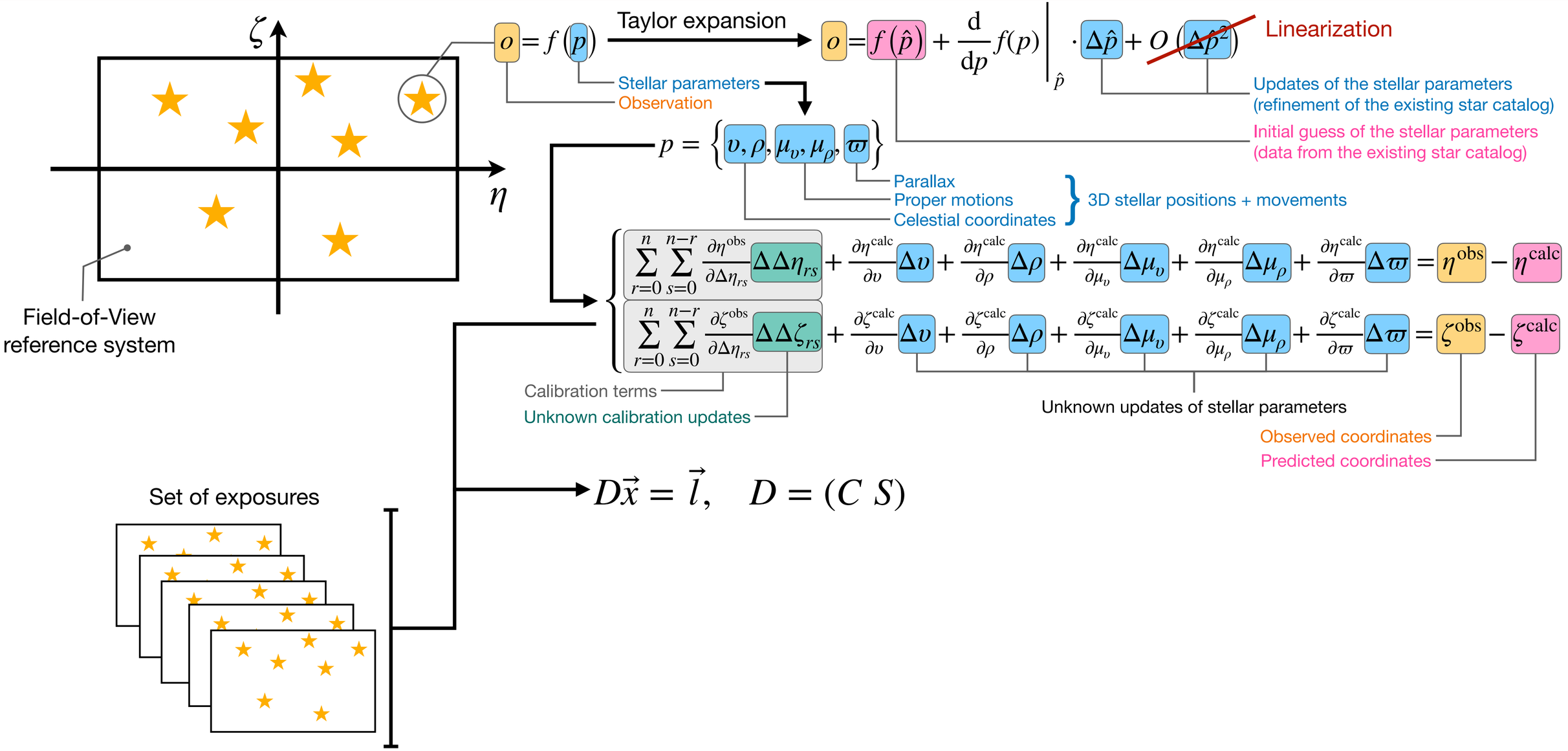


$$D\vec{x} = \vec{l}, \quad D = (C \; S)$$

Legendre polynomials up to 5th order



Astrometric Problem



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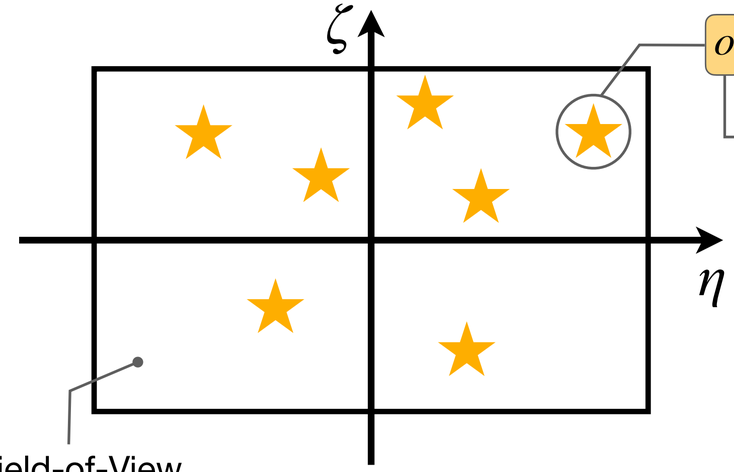

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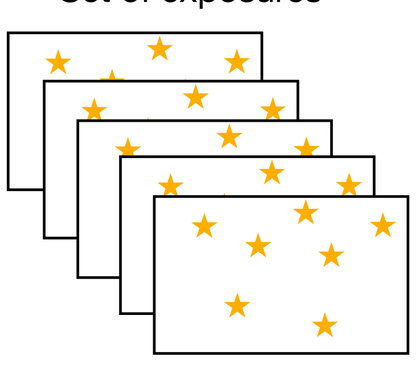

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Overdetermined system

Contains inconsistencies => no unique solution

Best fit [Gauss; Legendre, 1805]

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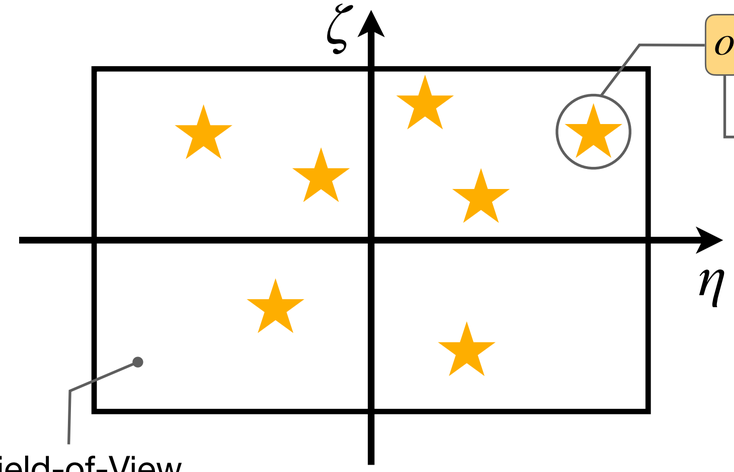
Astrometric Problem



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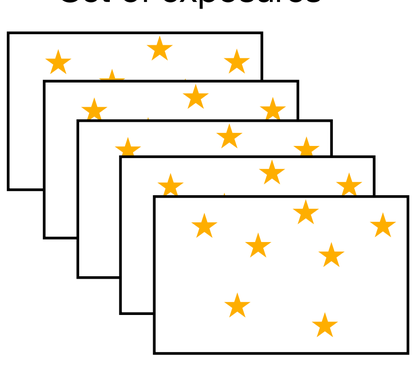

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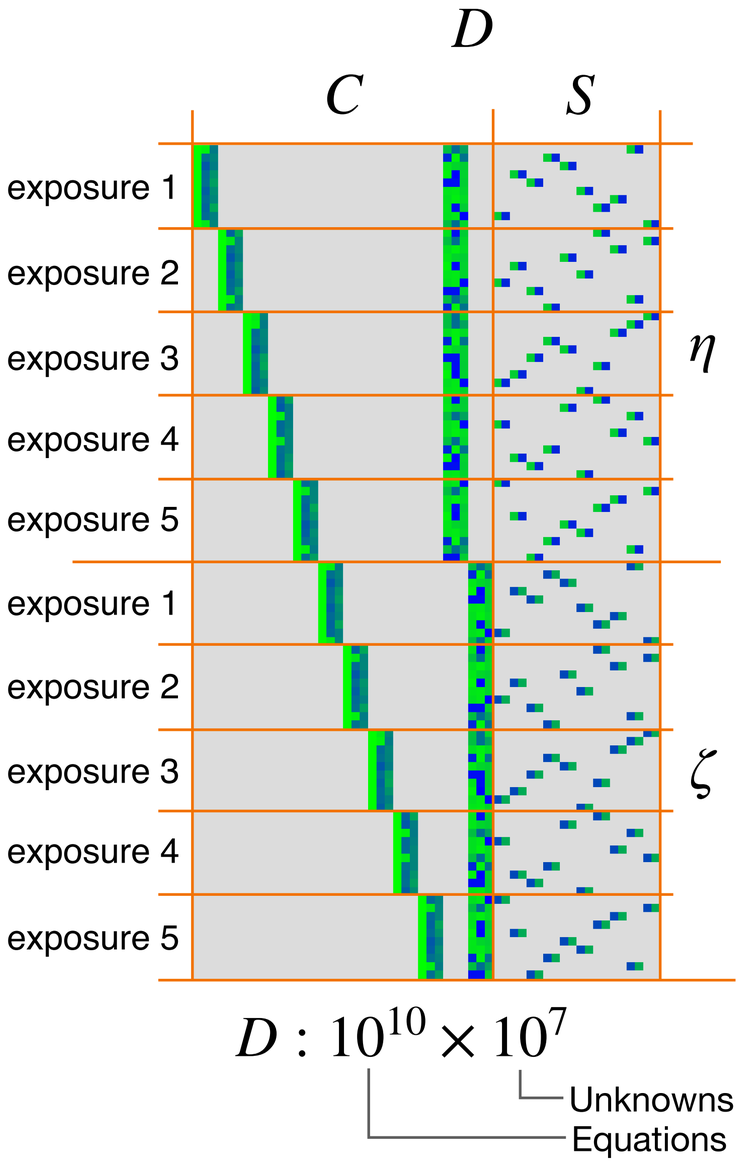
Rank-deficient => pseudo-inverse is needed

Approach to Solution

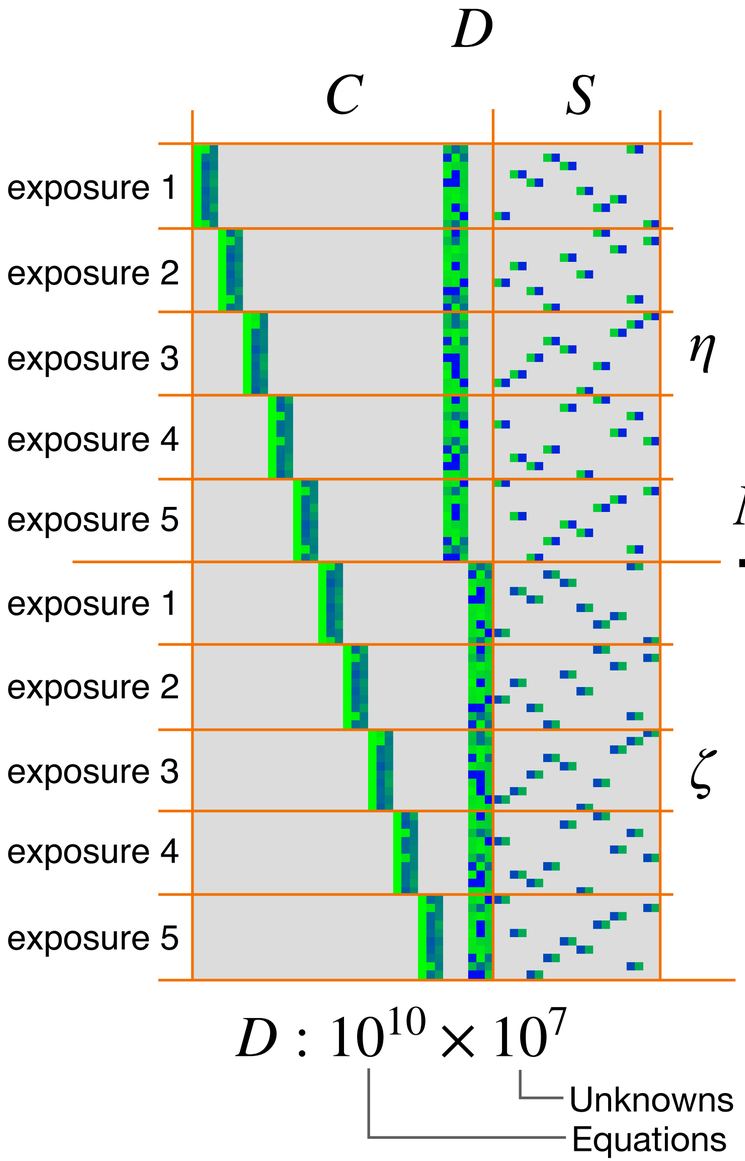
$$\boxed{\vec{x} = N^{+} D^{\top} \vec{l}}$$

Approach to Solution



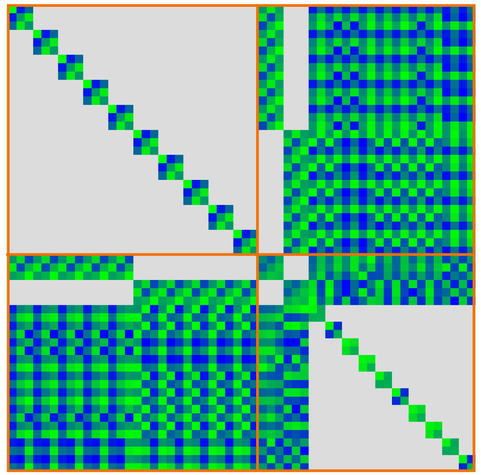
$$\vec{x} = N^{+} D^{\top} \vec{l}$$

Approach to Solution



$$N = D^{\top} D$$

$$\vec{x} = N^{+} D^{\top} \vec{l}$$



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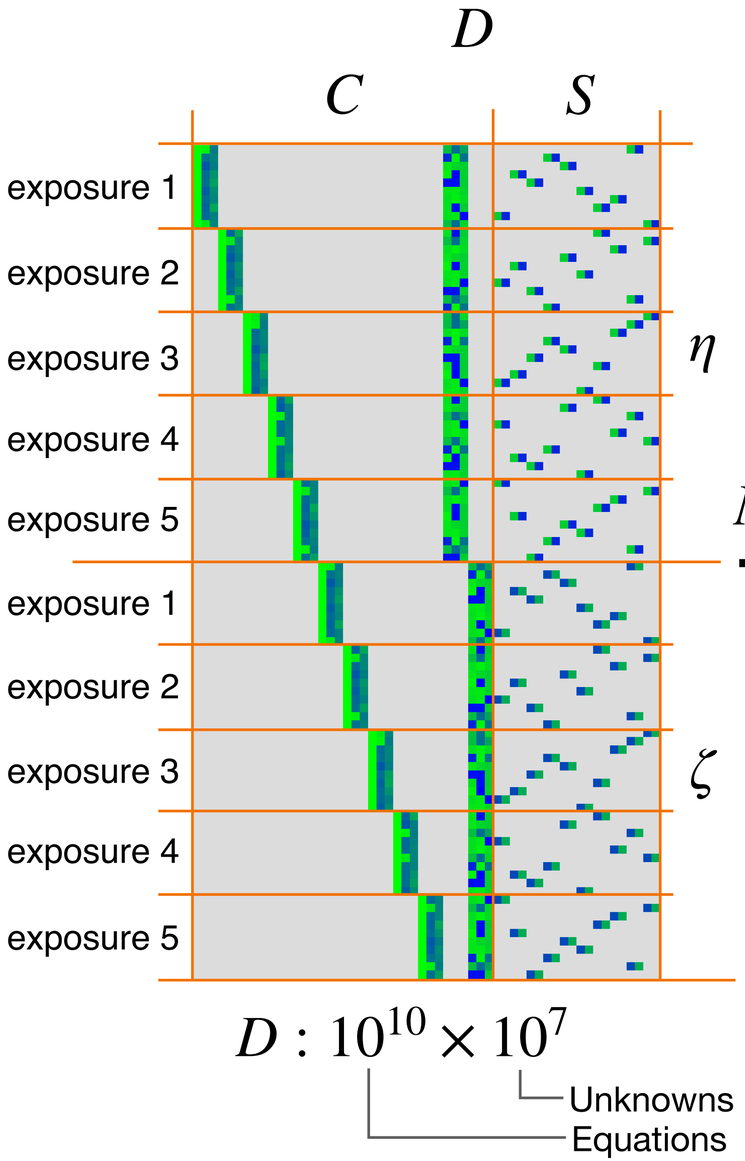
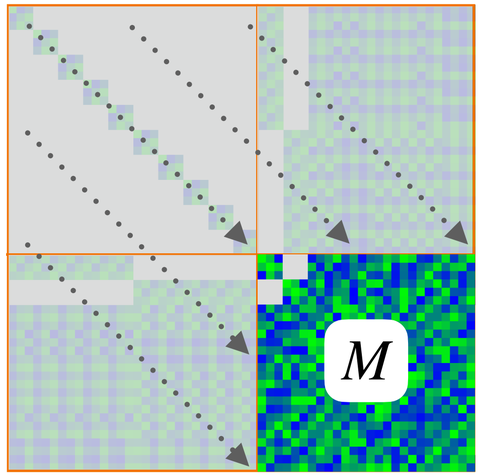


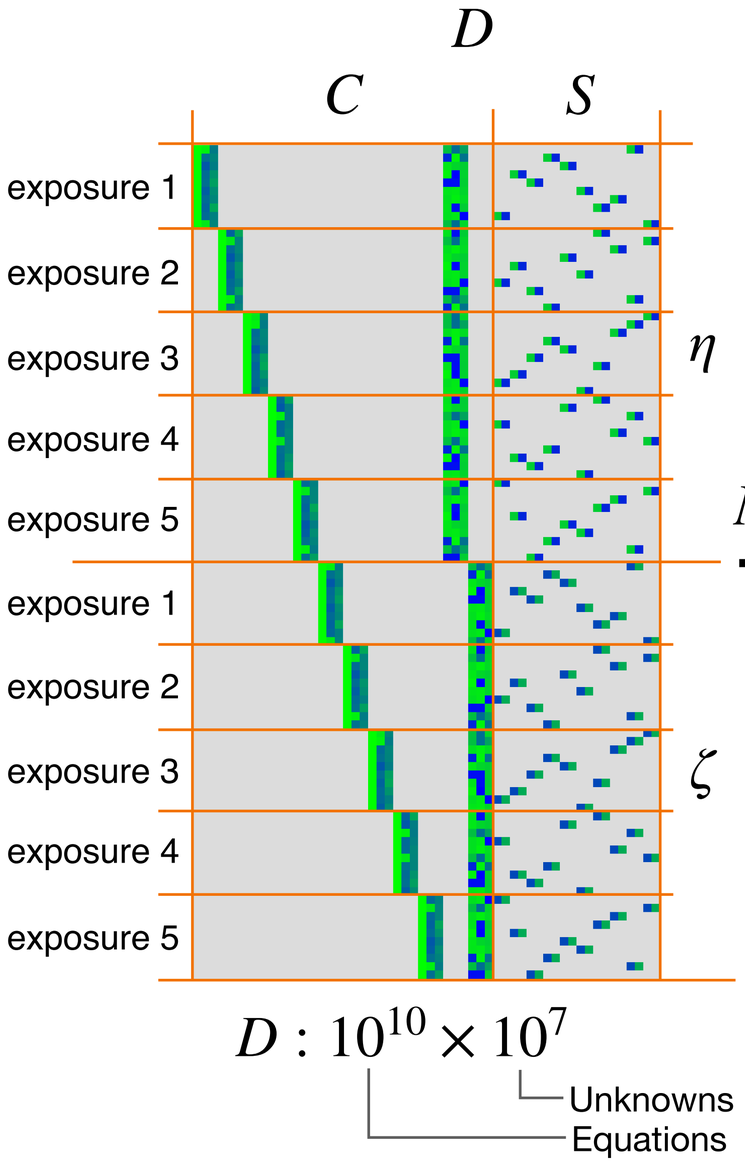
$N = D^{\top} D$

$$\vec{x} = N^{+} D^{\top} \vec{l}$$

Forward elimination



Approach to Solution



$$\vec{x} = N^{+} D^{\top} \vec{l}$$

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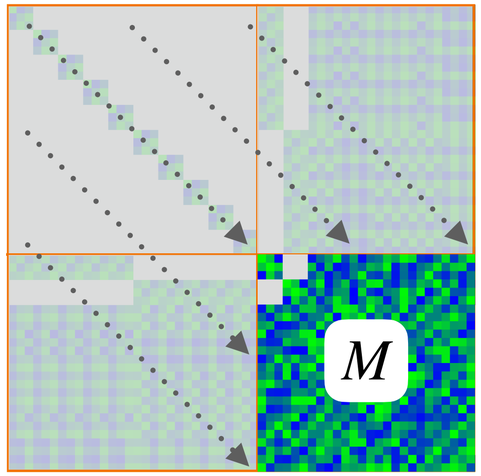
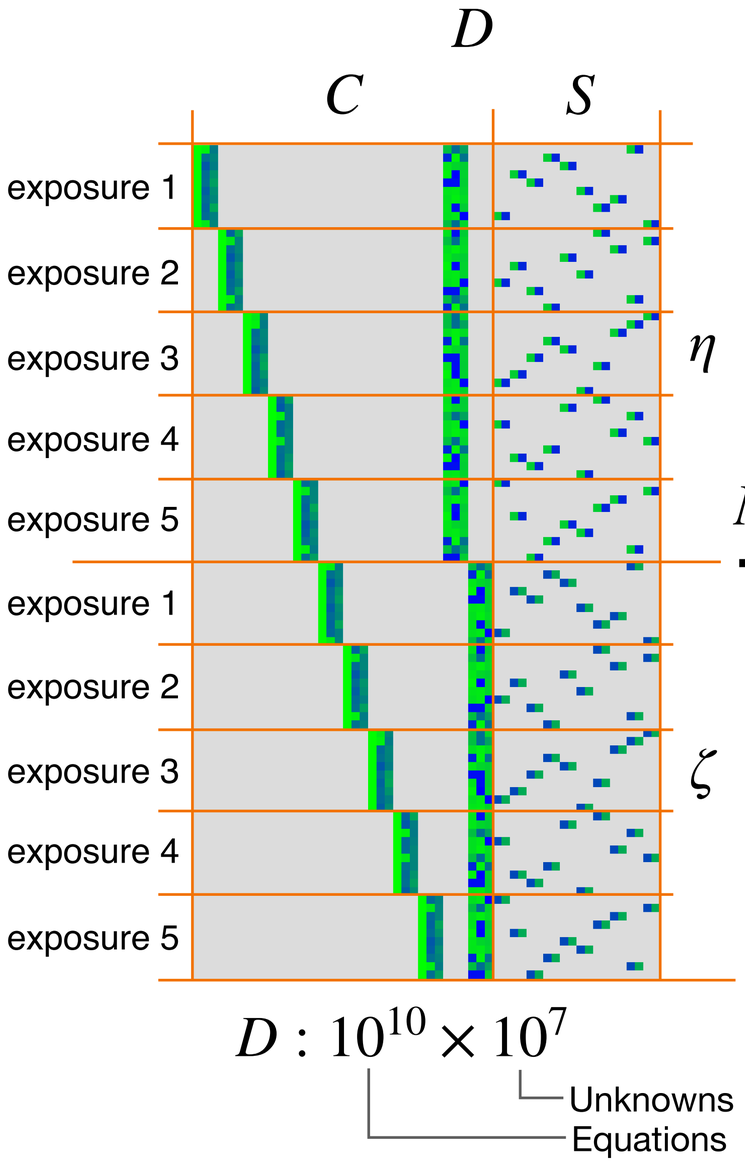
Forward elimination



→ Direct solution

Approach to Solution



$$\vec{x} = N^{+} D^{\top} \vec{l}$$

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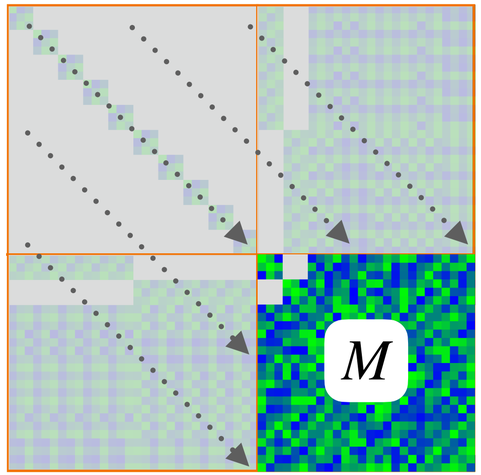
Forward elimination



→ Direct solution

- No convergency issues: optimal solution is guaranteed
- Estimation of uncertainties

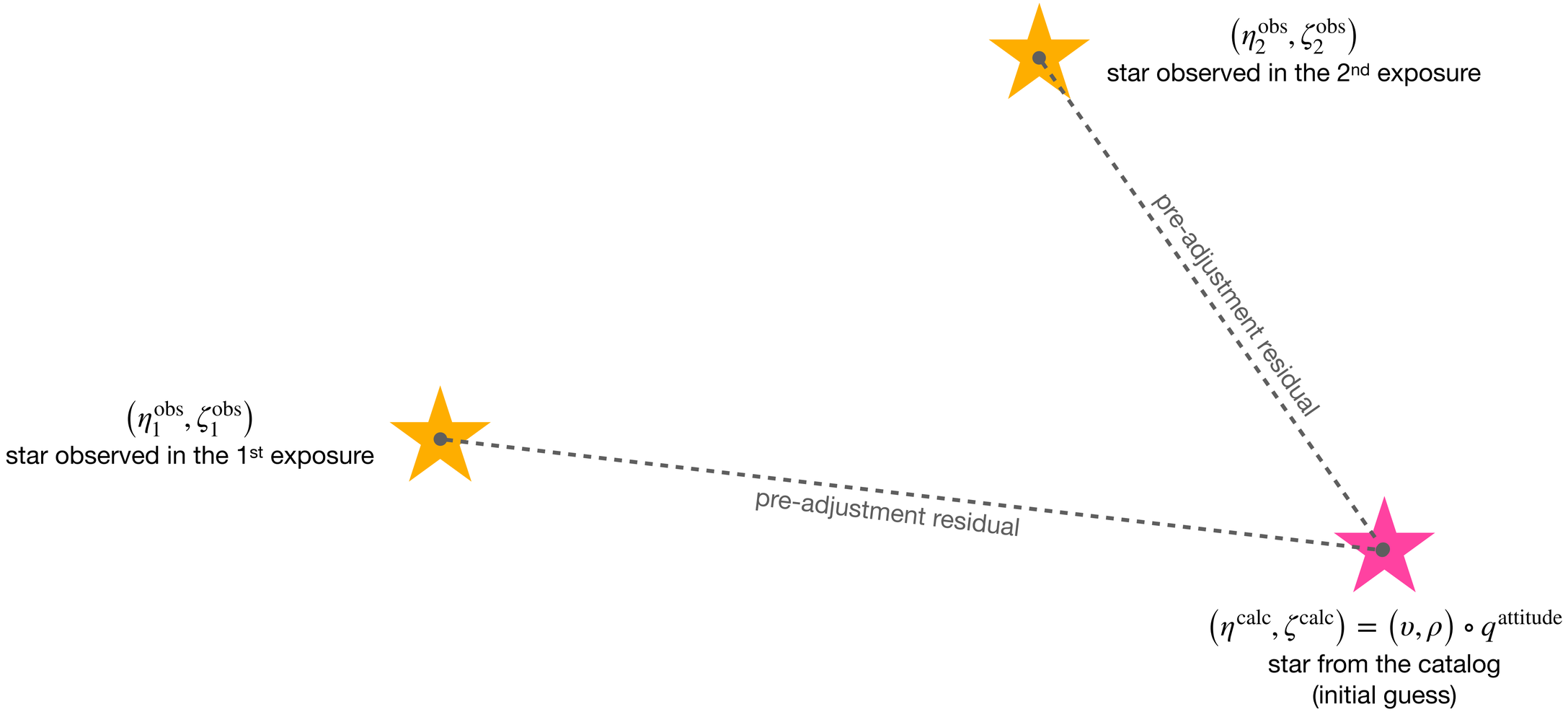
Solution Example

$\left(\eta_2^{\text{obs}}, \zeta_2^{\text{obs}}\right)$
star observed in the 2nd exposure

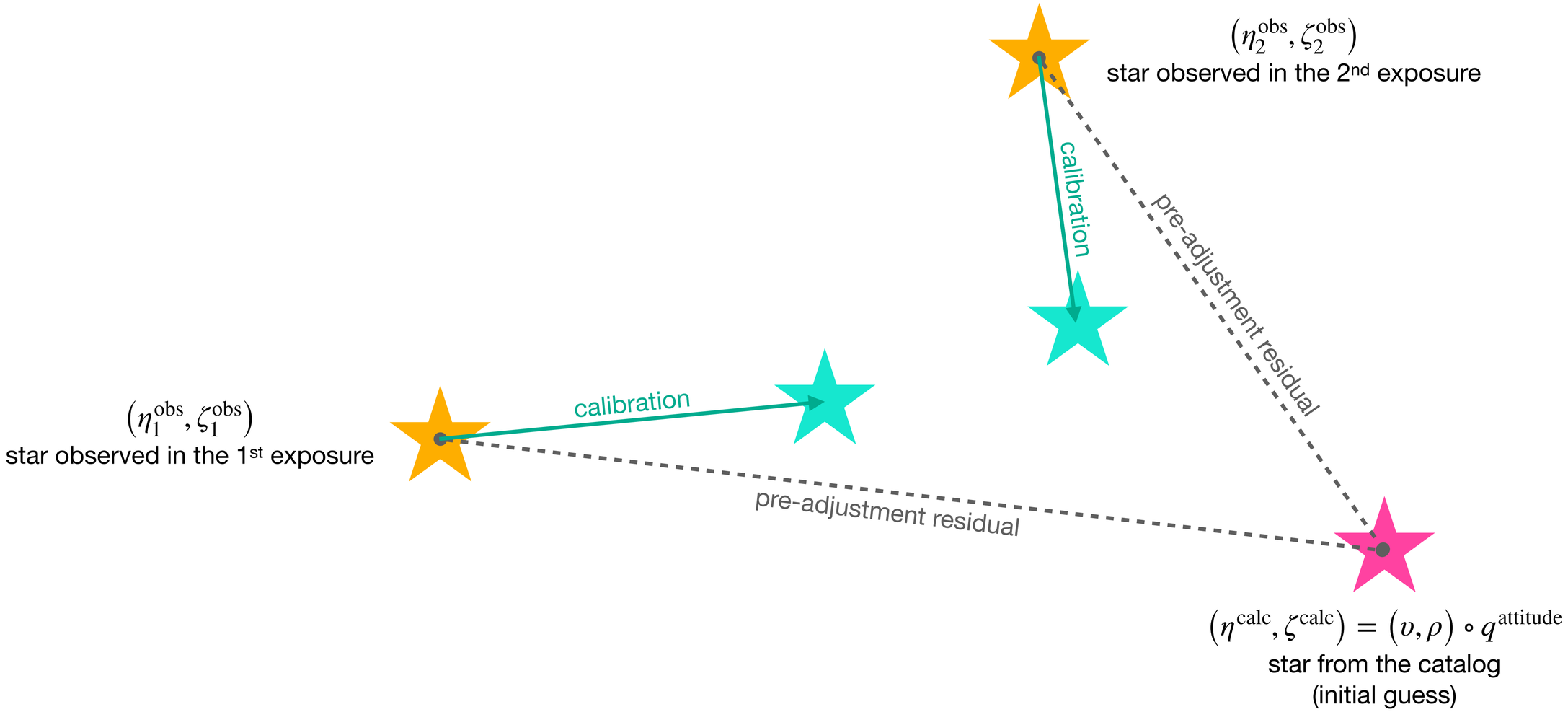
$\left(\eta_1^{\text{obs}}, \zeta_1^{\text{obs}}\right)$
star observed in the 1st exposure

$\left(\eta^{\text{calc}}, \zeta^{\text{calc}}\right) = \left(\upsilon, \rho\right) \circ q^{\text{attitude}}$
star from the catalog
(initial guess)

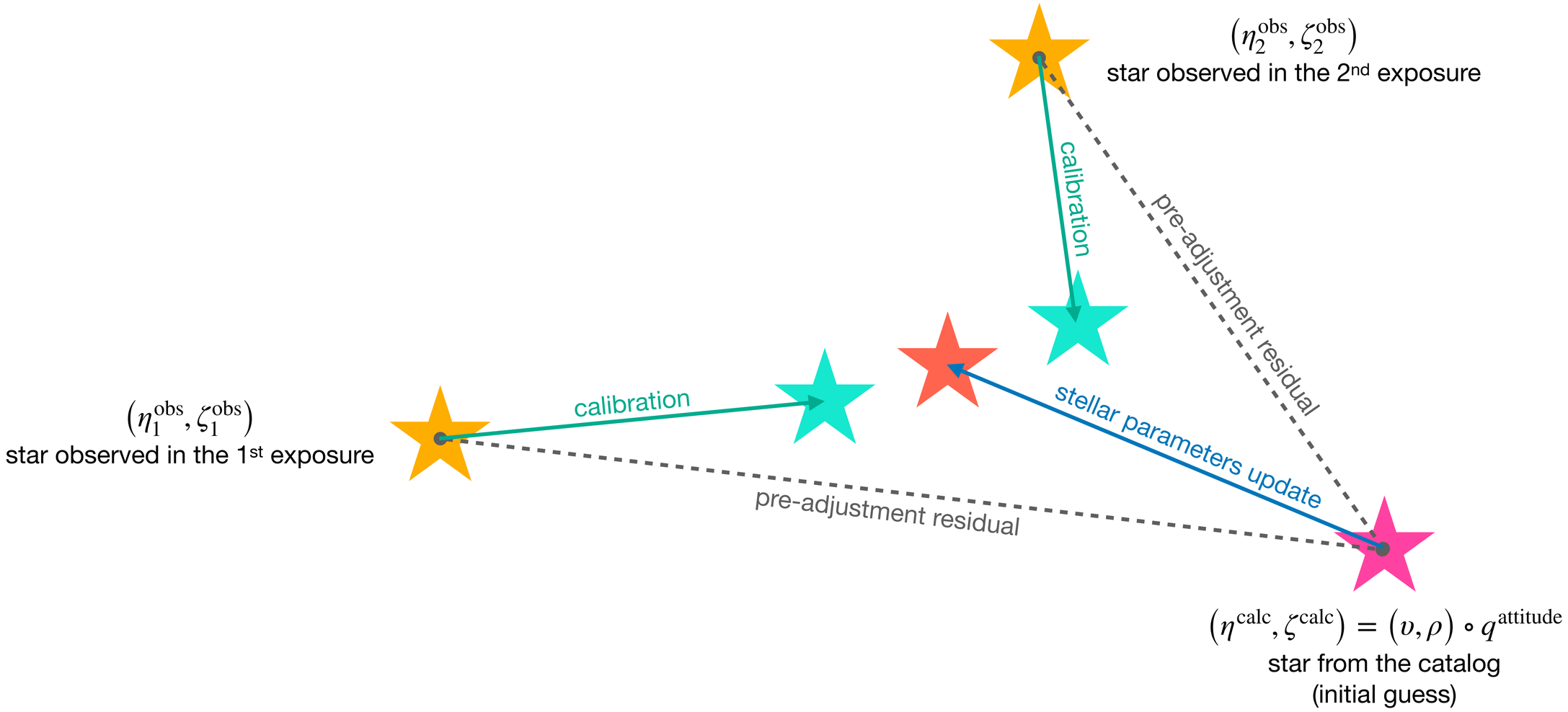
Solution Example



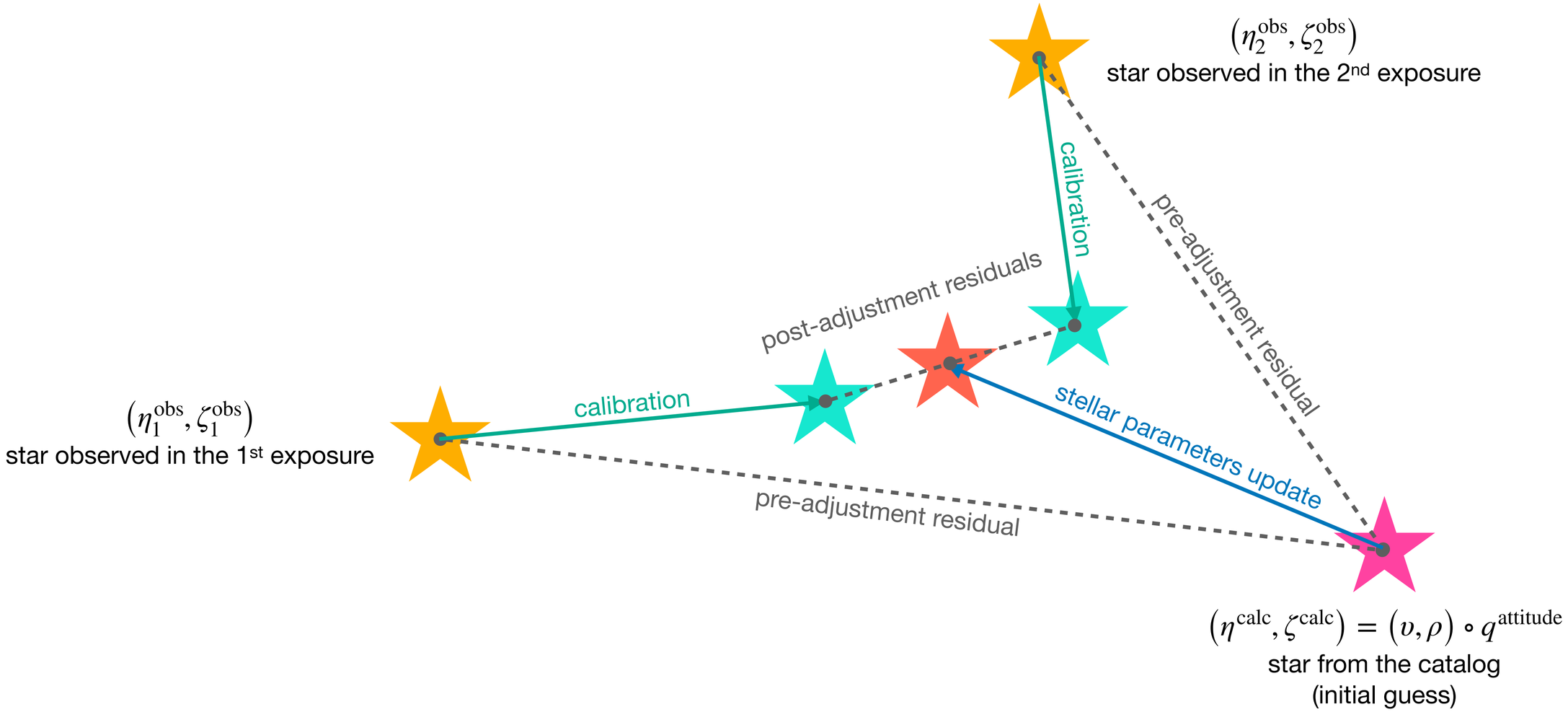
Solution Example



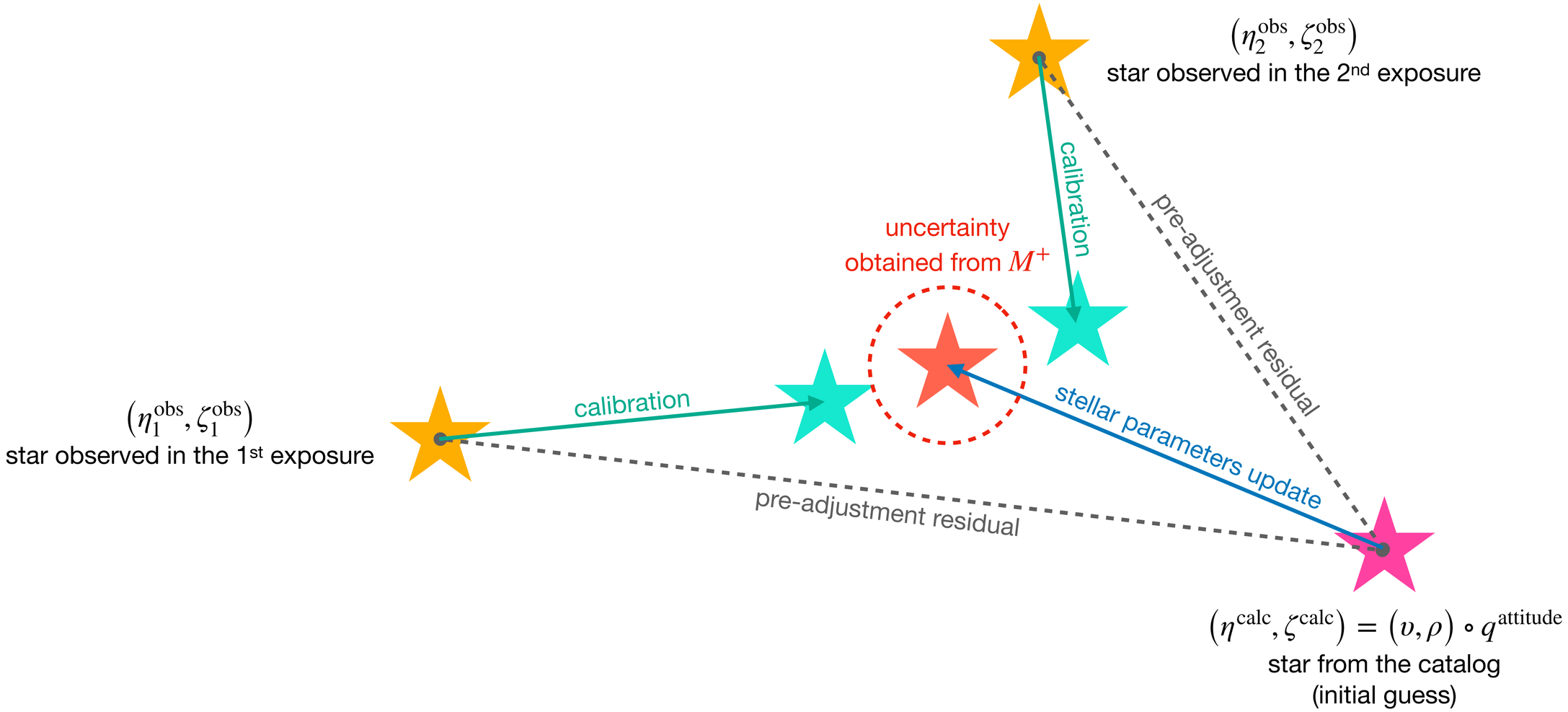
Solution Example



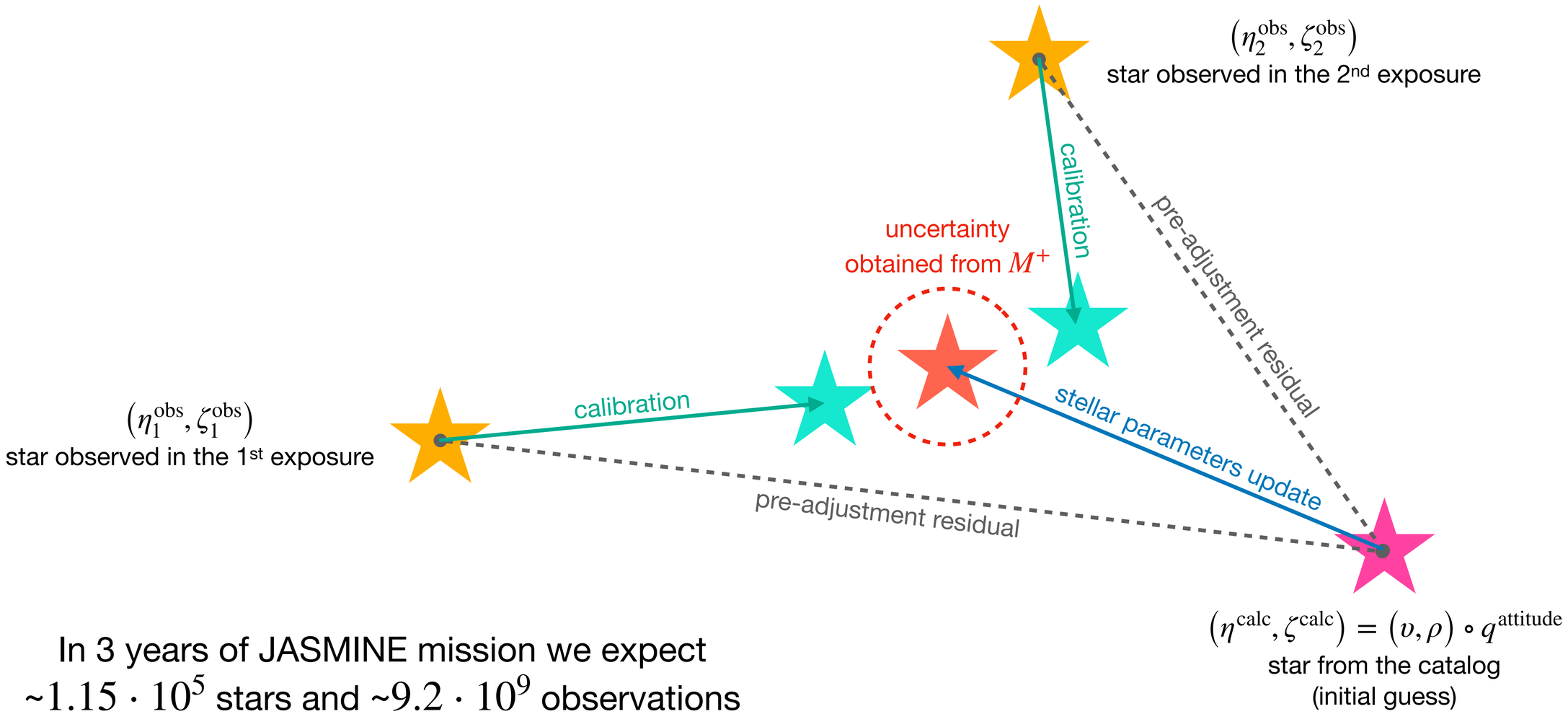
Solution Example



Solution Example



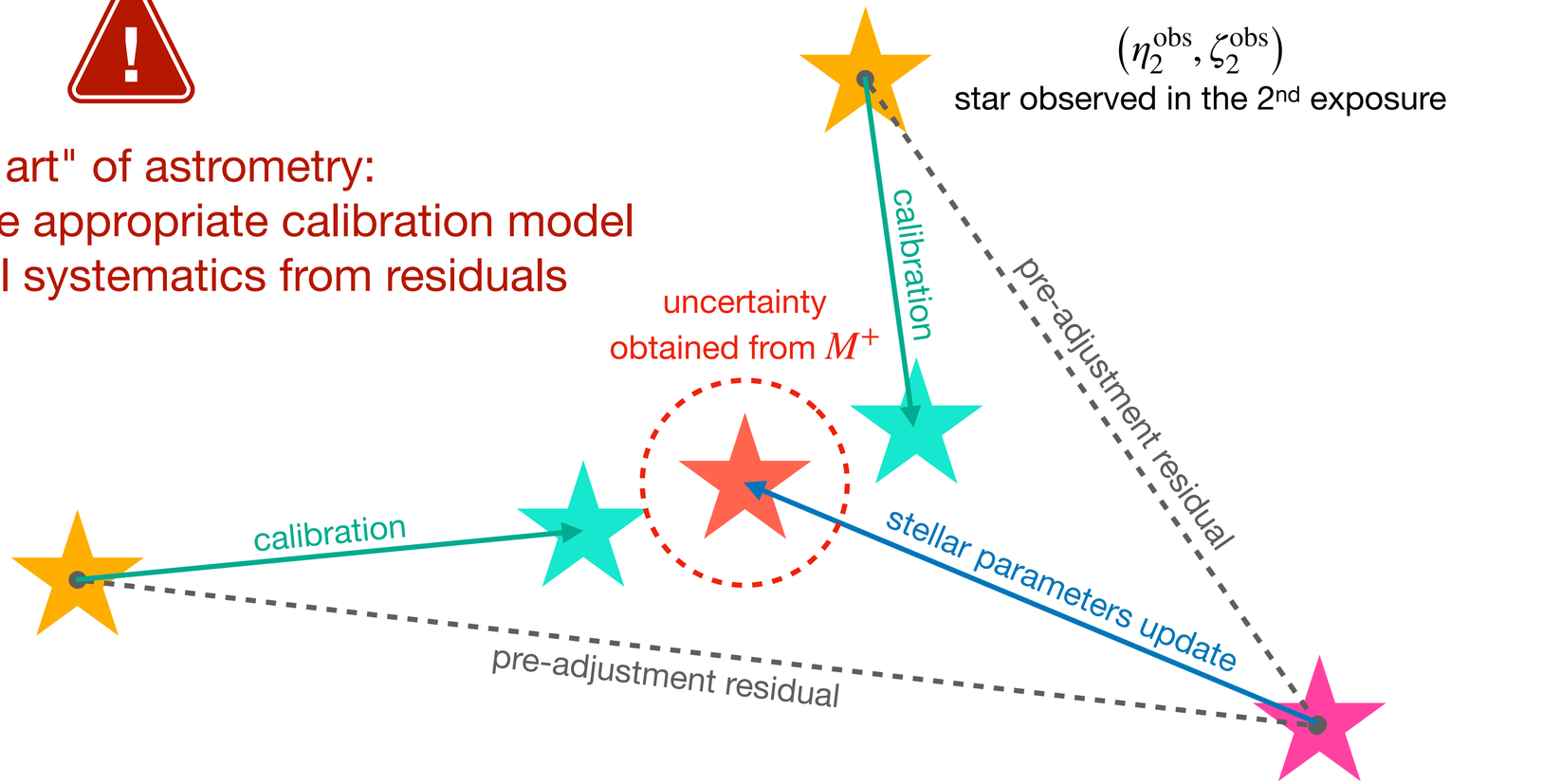
Solution Example



In 3 years of JASMINE mission we expect
~$1.15 \cdot 10^5$ stars and ~$9.2 \cdot 10^9$ observations

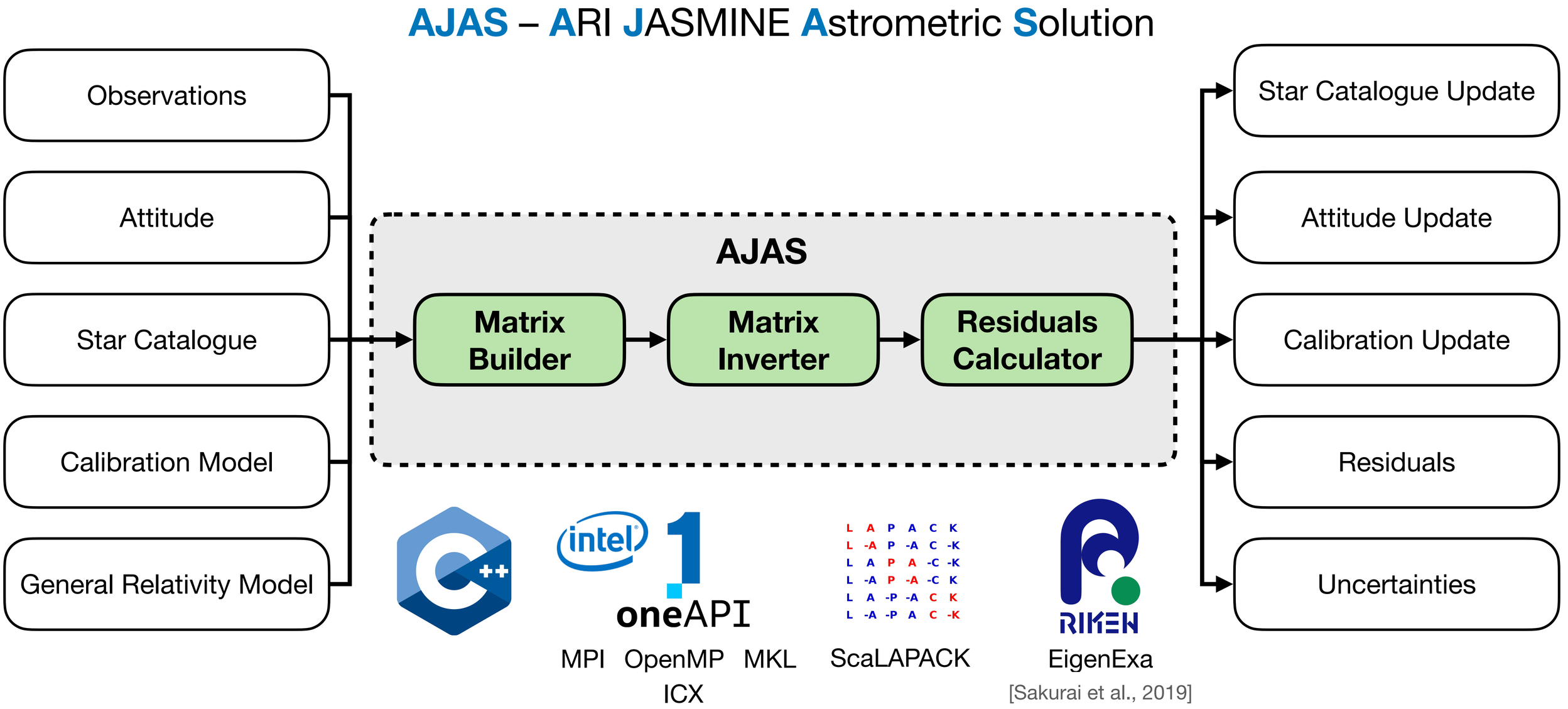
Solution Example

"Fine art" of astrometry:
coming up with the appropriate calibration model
that absorbs all systematics from residuals



In 3 years of JASMINE mission we expect
~$1.15 \cdot 10^5$ stars and ~$9.2 \cdot 10^9$ observations

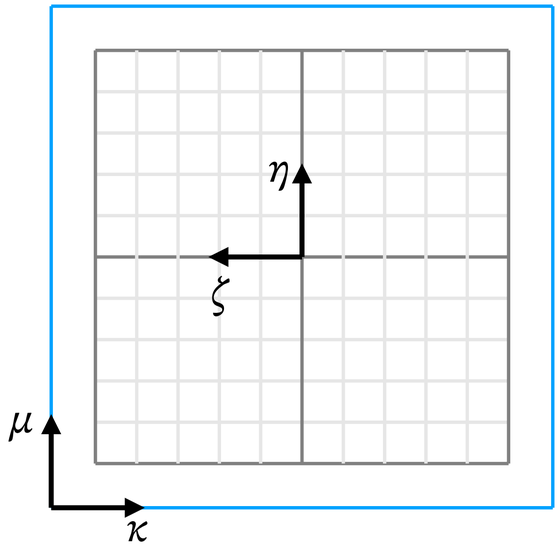
AJAS Pipeline



Calibration Model Validation: Synthetic Distortion

FSDM 4562

Synthetic Pattern: 2196 Stars

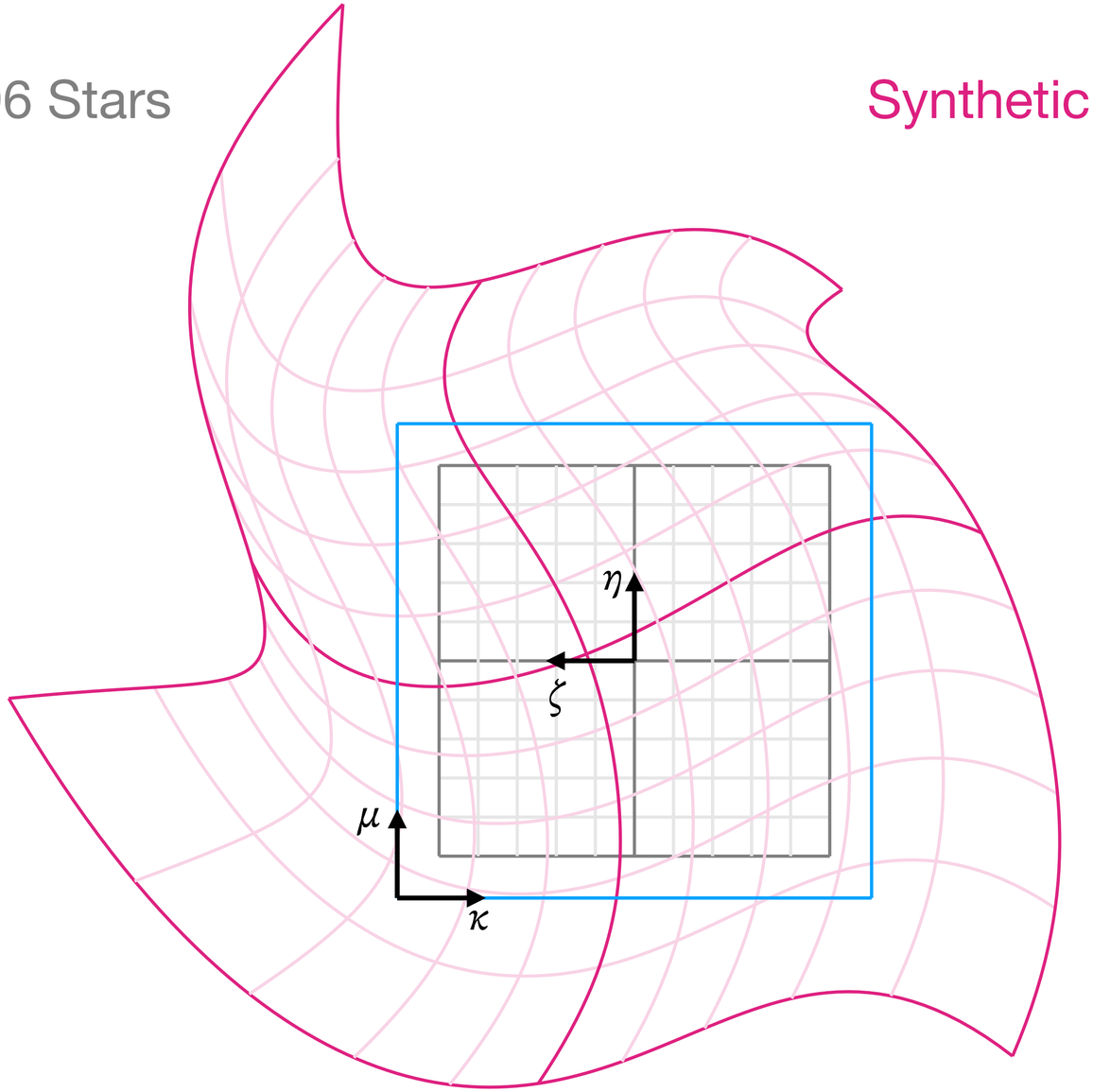


Calibration Model Validation: Synthetic Distortion

FSDM 4562

Synthetic Pattern: 2196 Stars

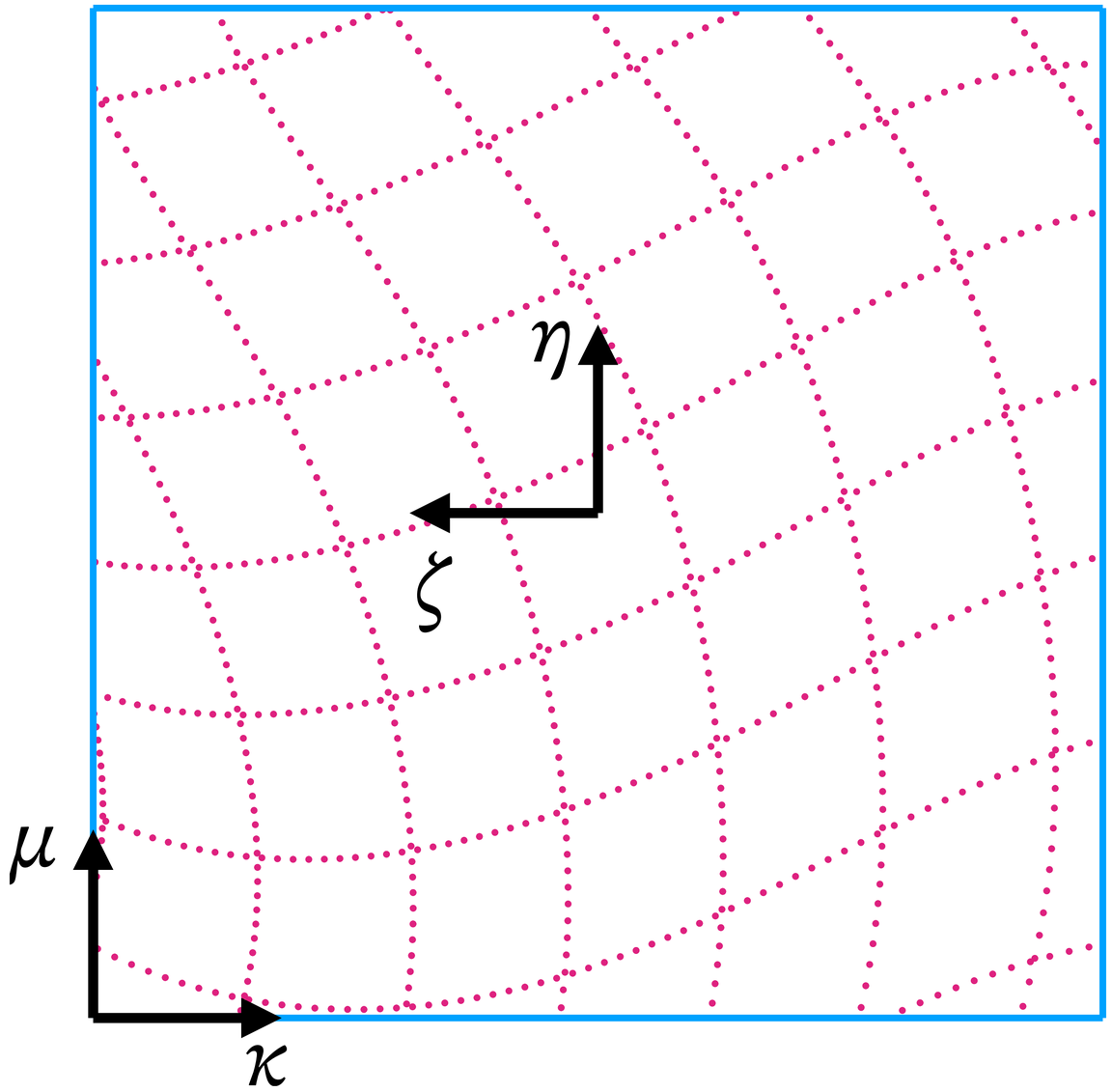
Synthetic Distortion: 775 Stars Visible



Calibration Model Validation: Naïve Solution

FSDM 4562

2 Exposures
1150 Observations

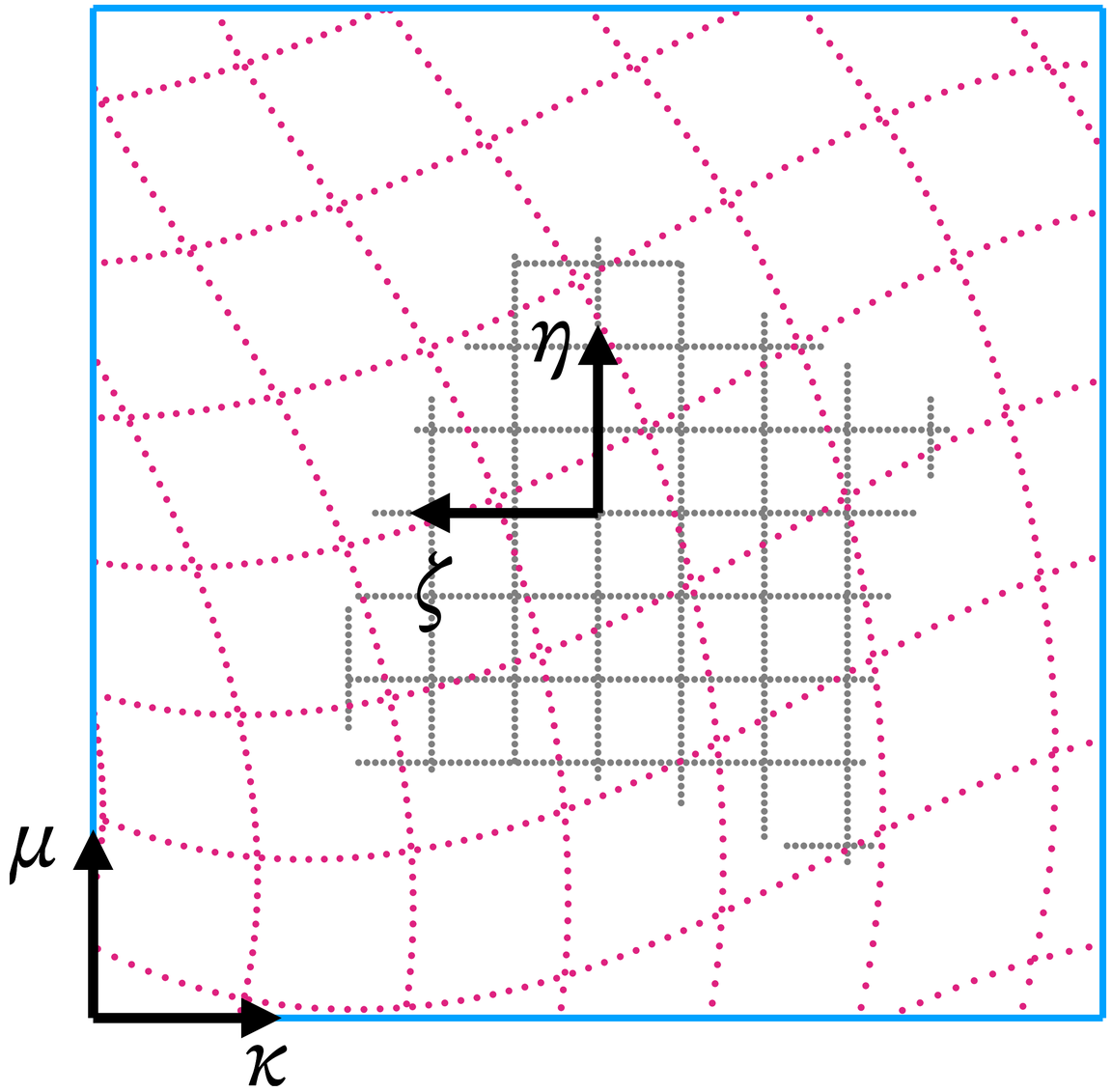


Calibration Model Validation: Naïve Solution

FSDM 4562

2 Exposures
1150 Observations

775 Stars in Catalogue



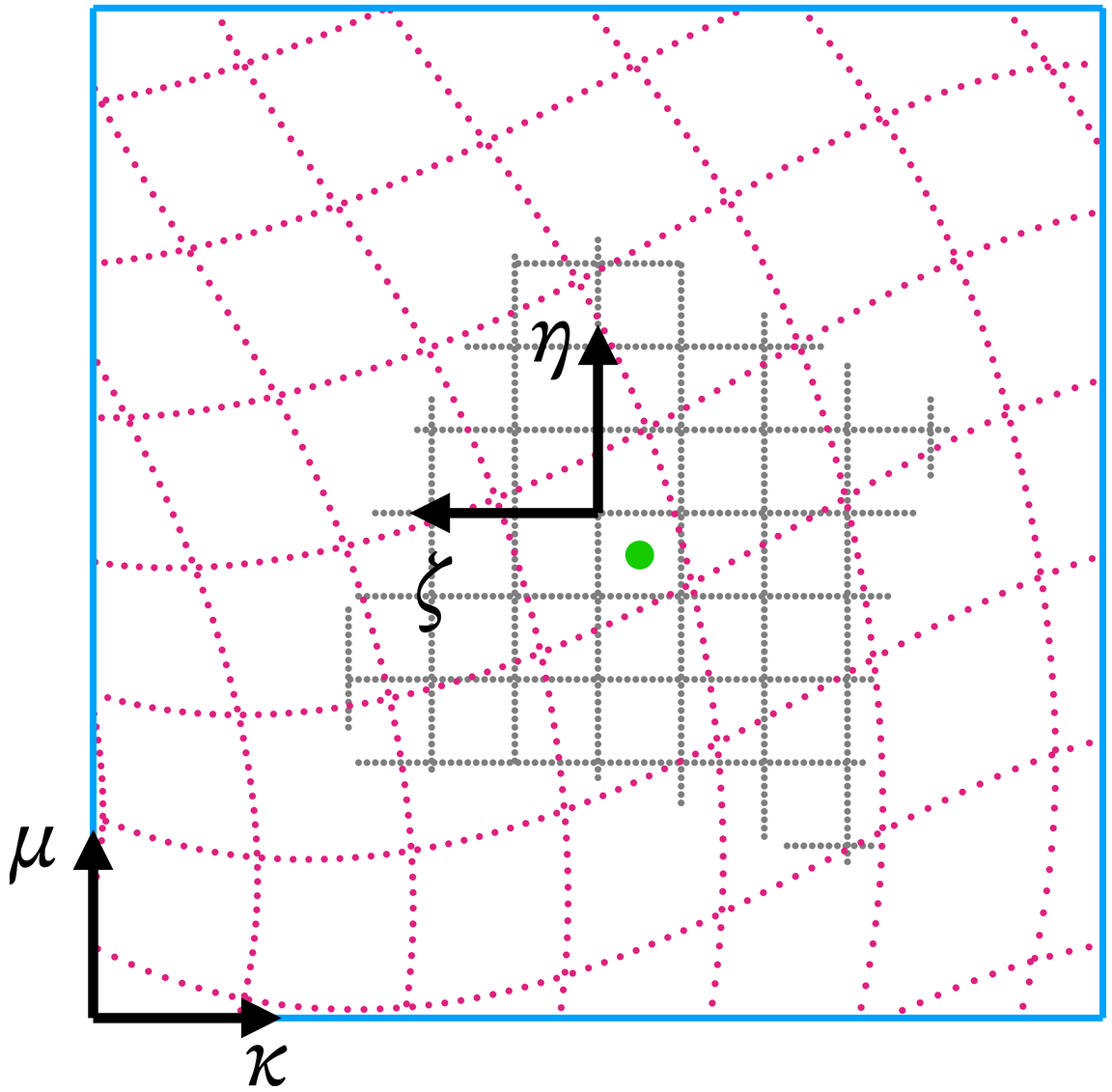
Calibration Model Validation: Naïve Solution

FSDM 4562

2 Exposures
1150 Observations

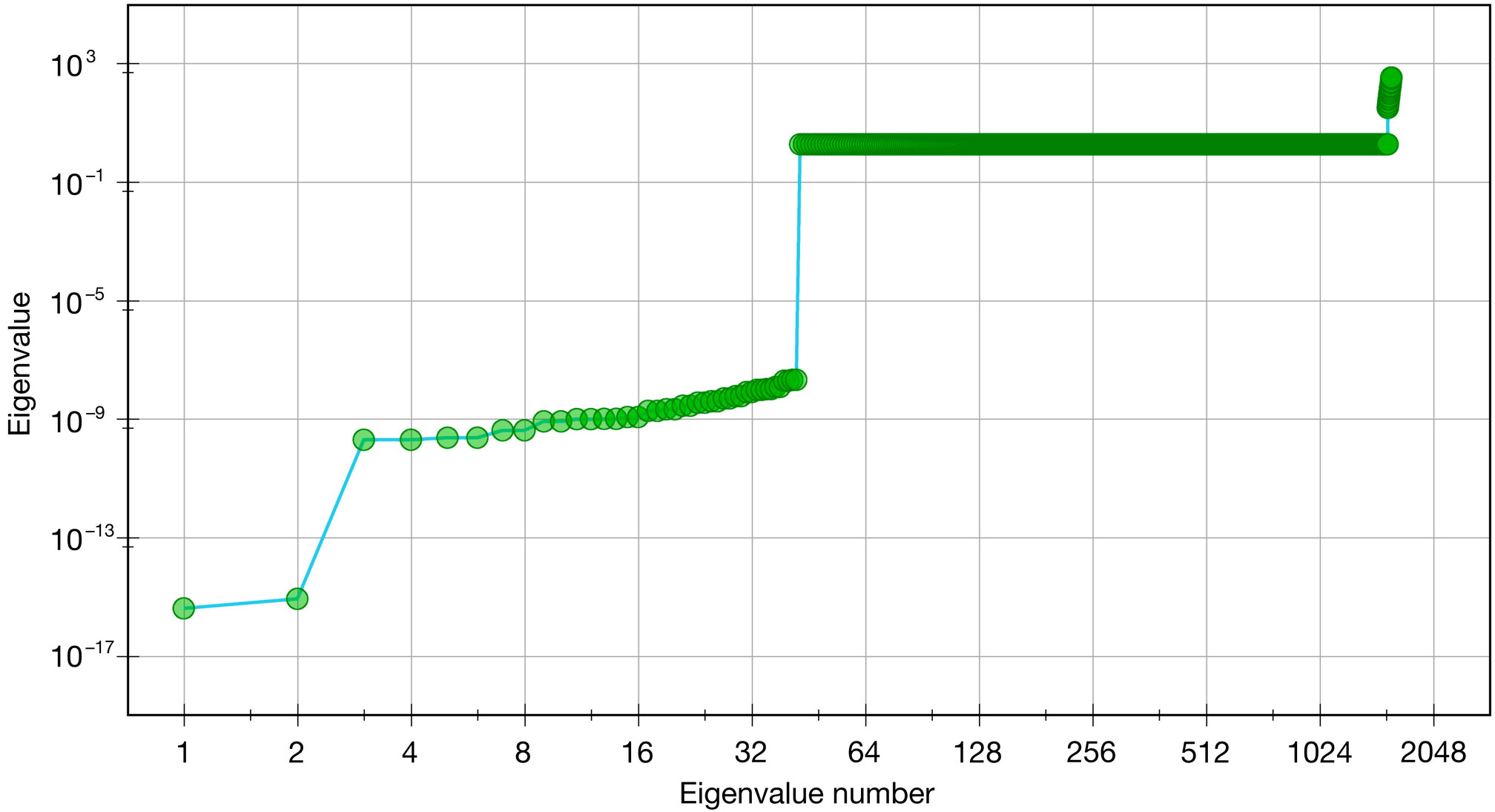
775 Stars in Catalogue

775 Stars Updated



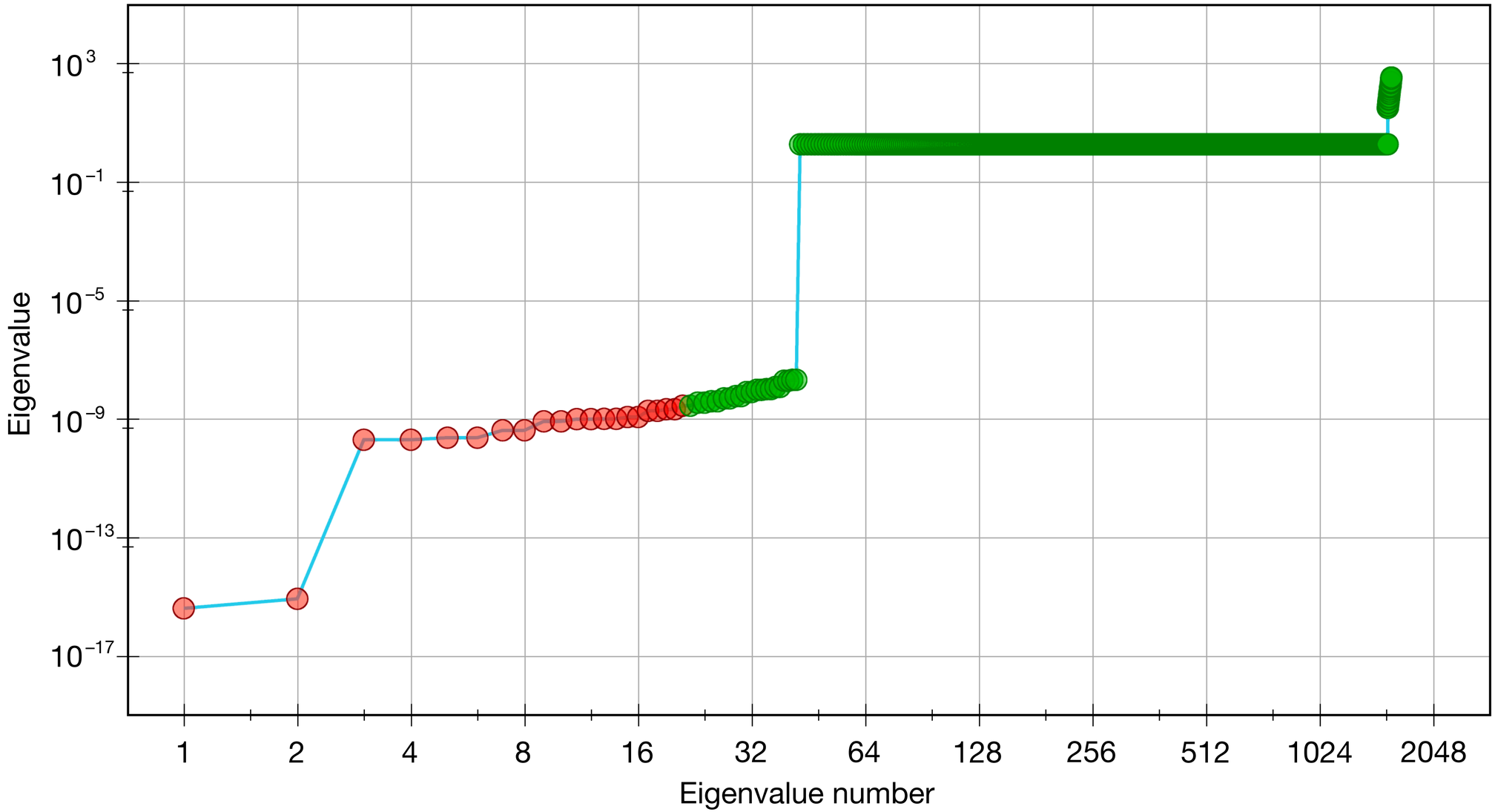
Calibration Model Validation: Spectrum

FSDM 4562



Calibration Model Validation: Spectrum

FSDM 4562



Calibration Model Validation: Wrong Solution

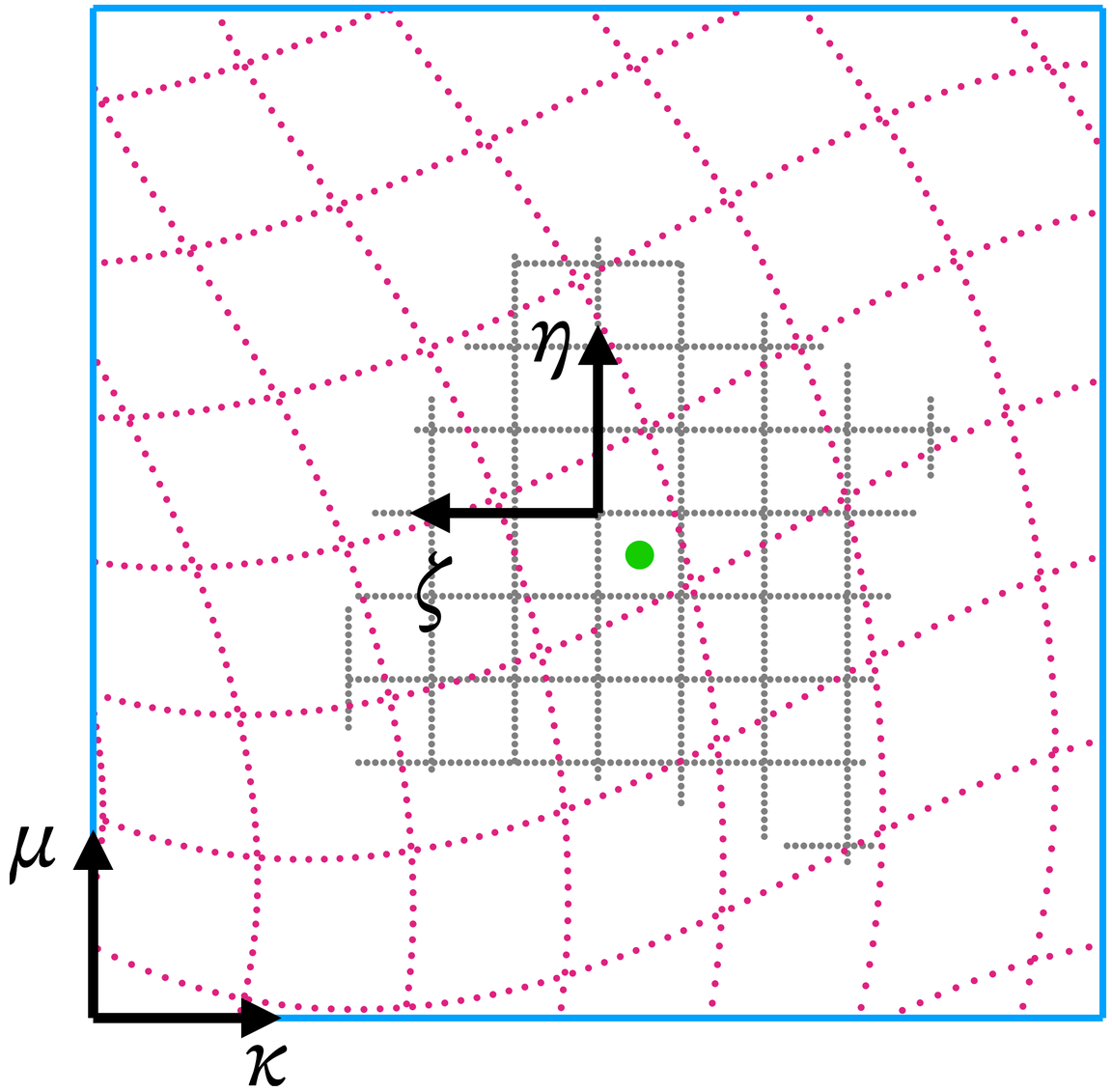
FSDM 4562

2 Exposures
1150 Observations

775 Stars in Catalogue

775 Stars Updated

0 Eigenvalues Cut



Calibration Model Validation: Wrong Solution

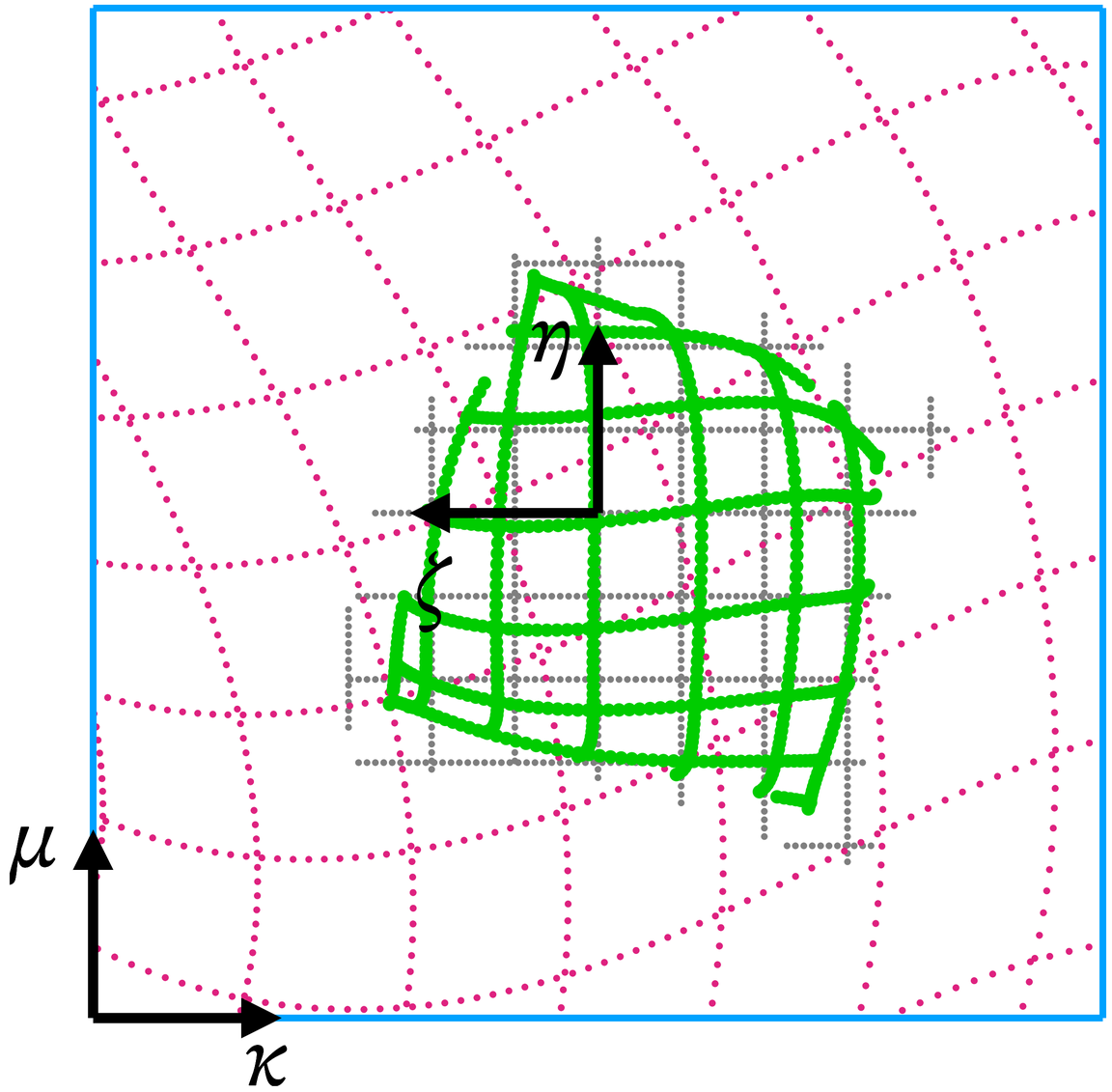
FSDM 4562

2 Exposures
1150 Observations

775 Stars in Catalogue

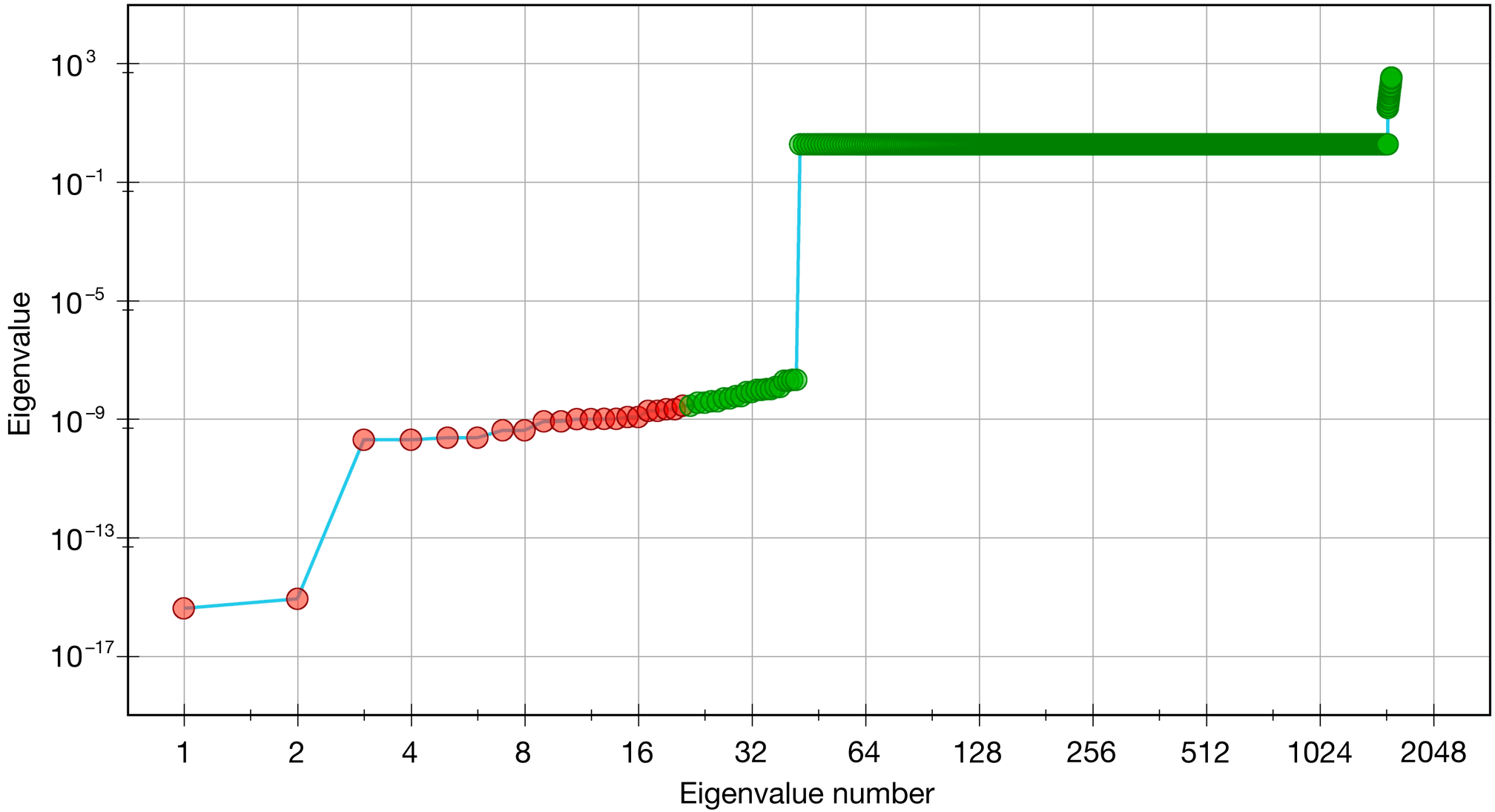
775 Stars Updated

21 Eigenvalues Cut



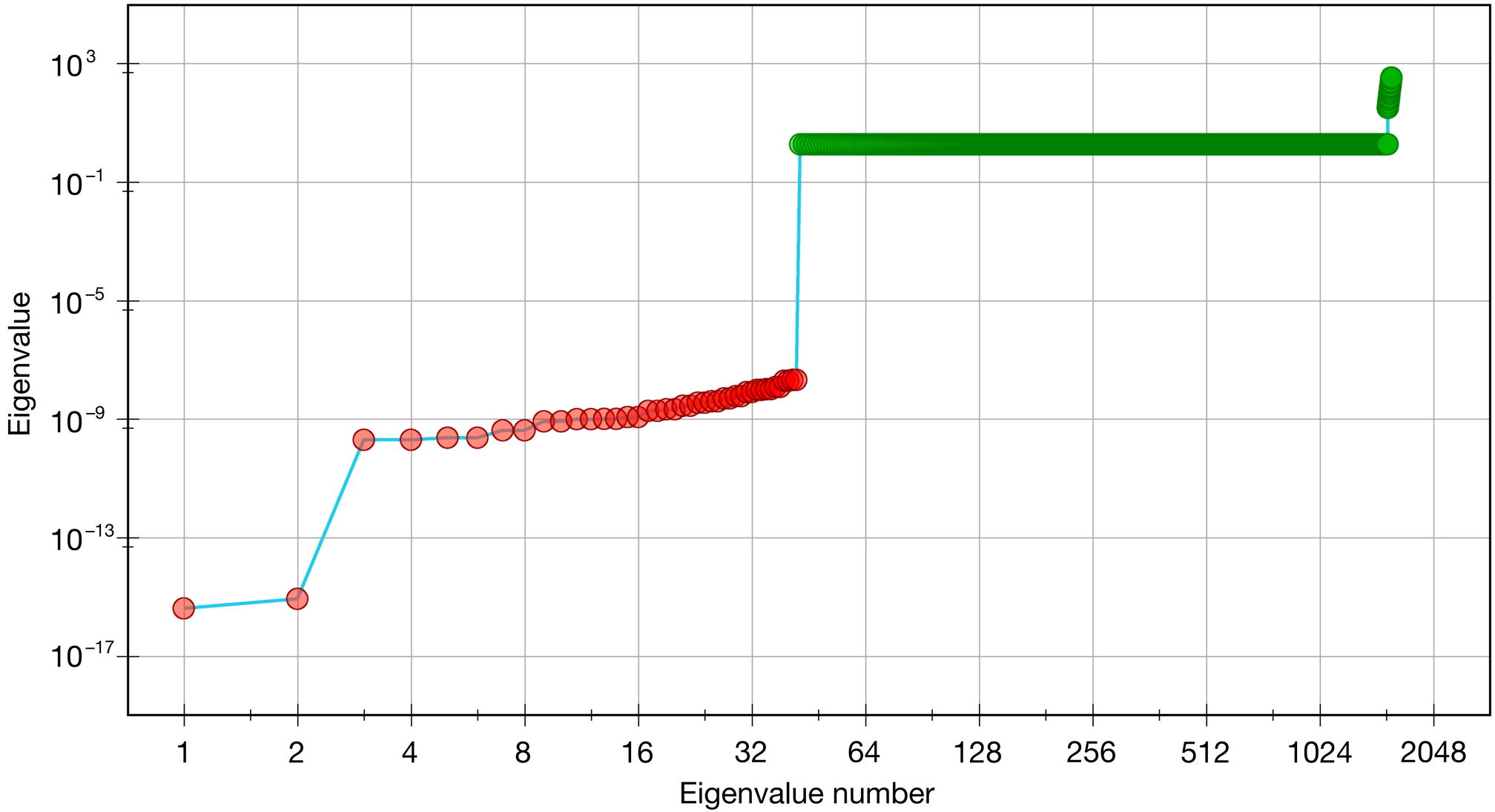
Calibration Model Validation: Spectrum

FSDM 4562



Calibration Model Validation: Spectrum

FSDM 4562



Calibration Model Validation: Correct Solution

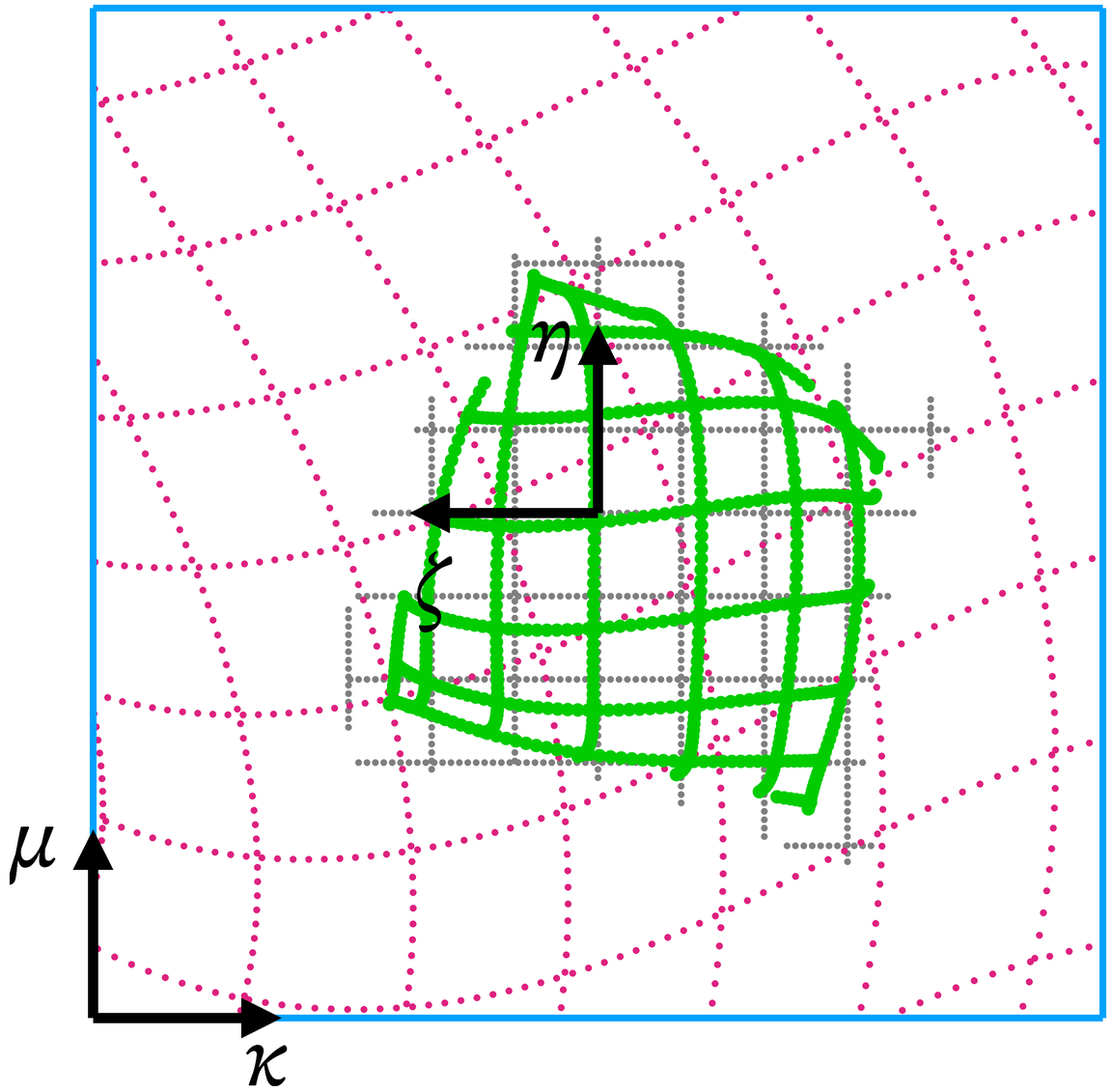
FSDM 4562

2 Exposures
1150 Observations

775 Stars in Catalogue

775 Stars Updated

21 Eigenvalues Cut



Calibration Model Validation: Correct Solution

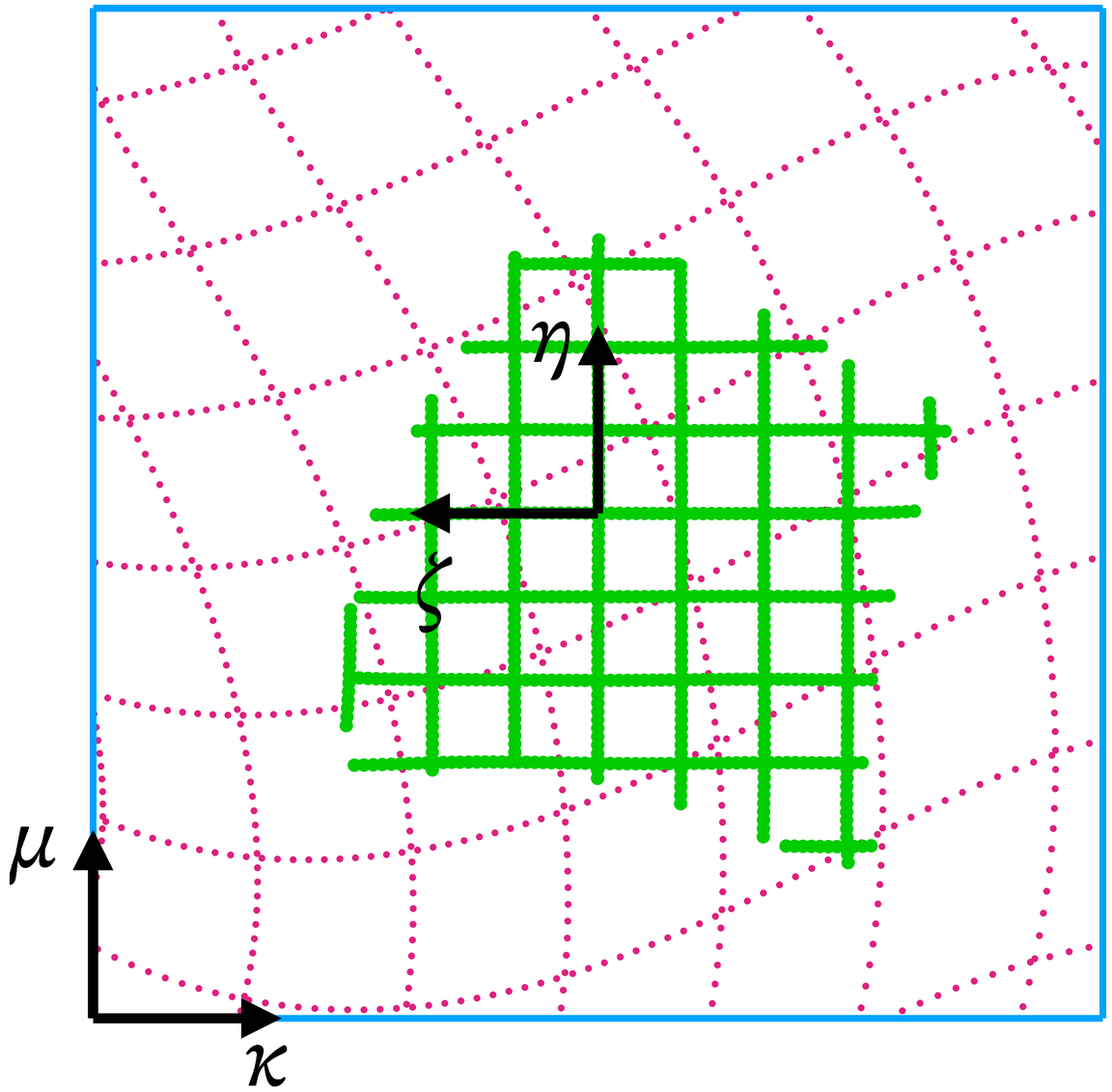
FSDM 4562

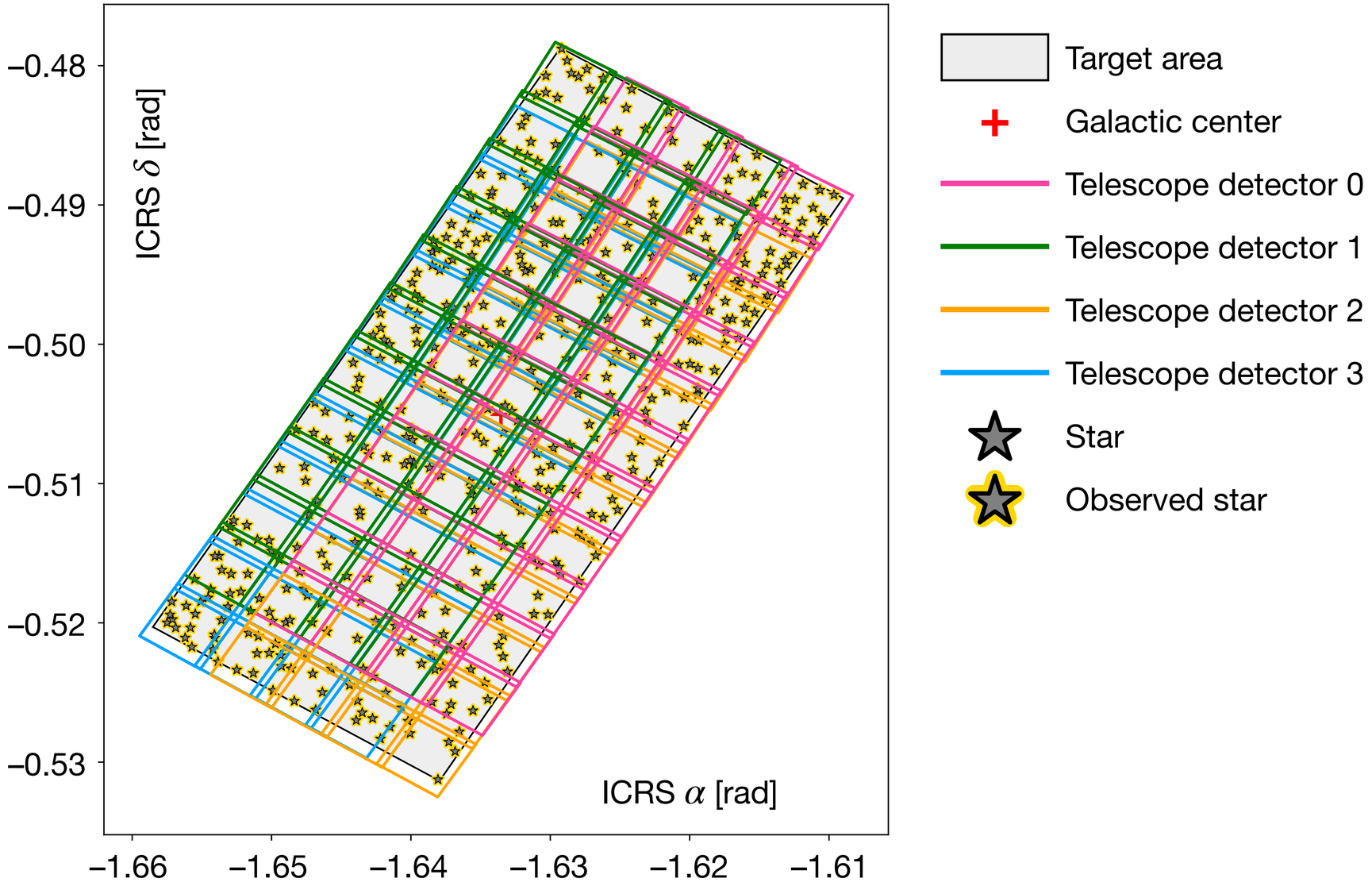
2 Exposures
1150 Observations

775 Stars in Catalogue

775 Stars Updated

42 Eigenvalues Cut



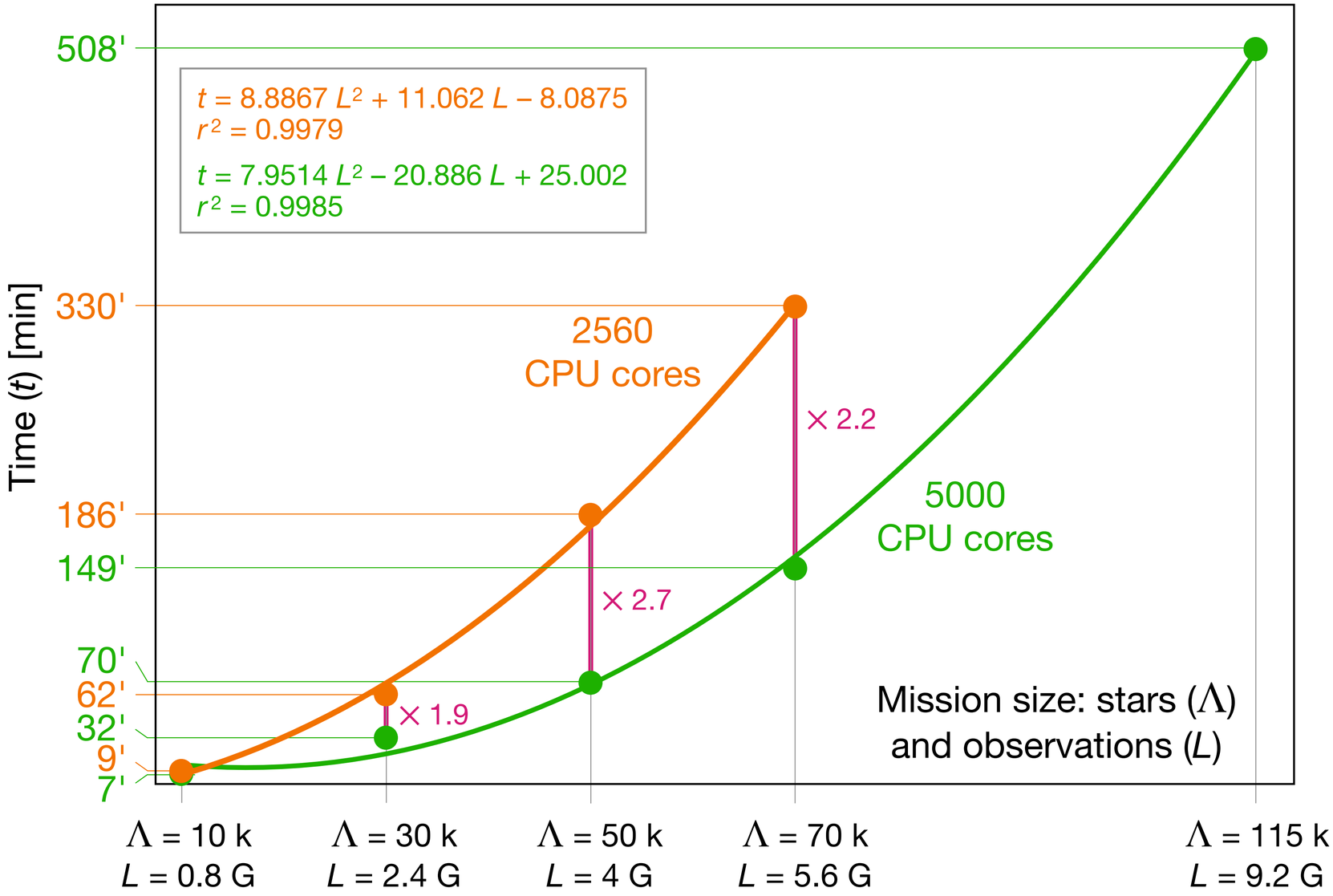

−0.48
−0.49
−0.50
−0.51
−0.52
−0.53
ICRS δ [rad]
−1.66
−1.65
−1.64
−1.63
−1.62
−1.61
ICRS α [rad]
Target area
Galactic center
Telescope detector 0
Telescope detector 1
Telescope detector 2
Telescope detector 3
Star
Observed star

AJAS Performance on a Cluster

bw|HPC

High-Performance Computing services of the state Baden-Württemberg, Germany

CPU: Intel® Xeon Gold 6230, 2.1 GHz, 40 cores
RAM: 90 GB
CPU: Intel® Xeon Platinum 8385, 2.6 GHz, 64 cores
RAM: 256 Gb
Network: InfiniBand
Shared Disk: 40 Tb



AJAS Performance on a Cluster

FSDM 4562

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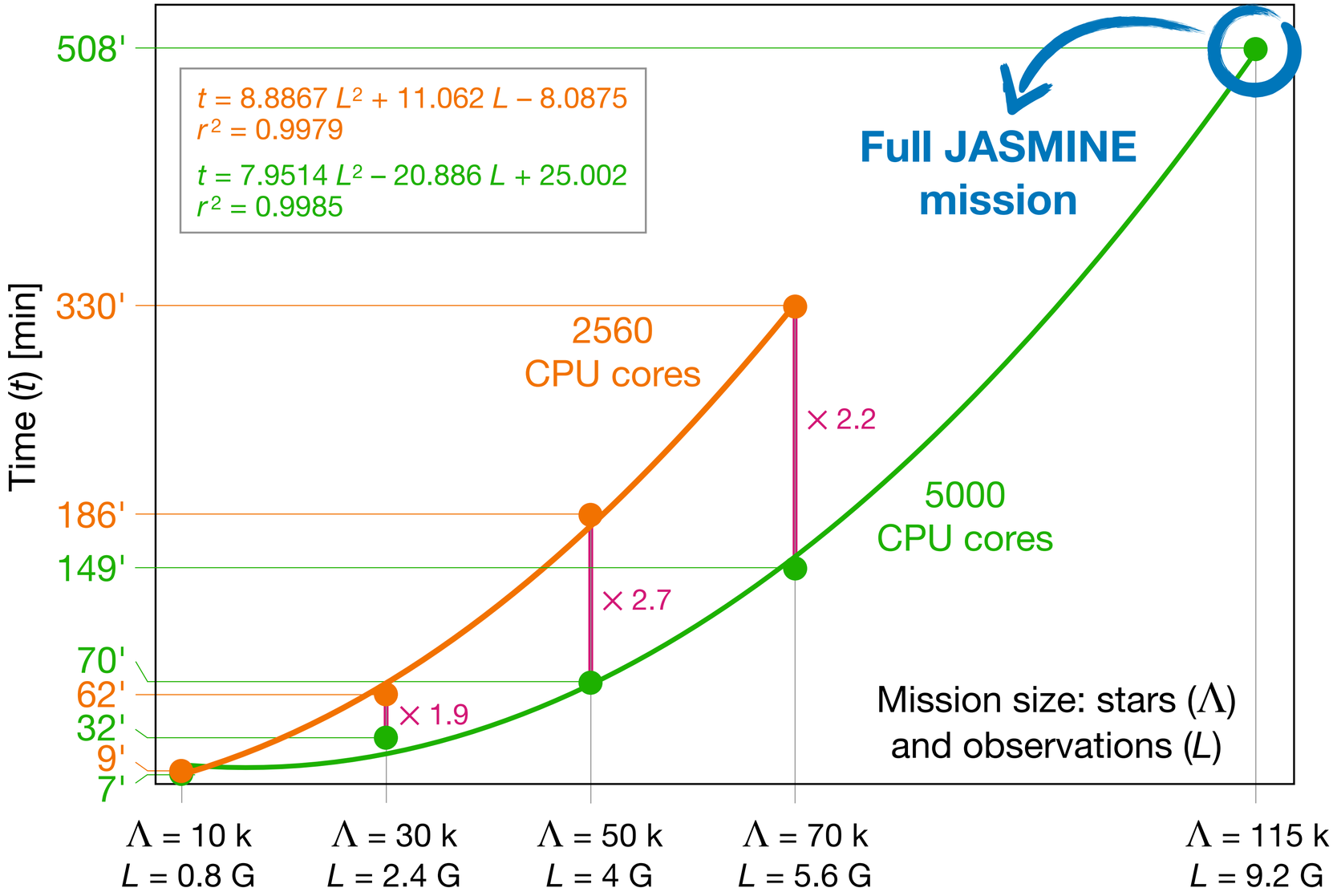

Conclusion

Key Contributions:

1. Direct solver AJAS handles JASMINE problem in 8.5 hours on 5000 CPU cores
2. Calibration model based on the Legendre polynomials can recover significant distortions

Future Work:

1. More complex distortions should be tested
2. Data mining on residuals – extracting systematics and moving it to calibration, so the residuals have random Gaussian distribution

Acknowledgments:

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Nov. 5-8, 2024

(Matsue, Japan)

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Thank you for your attention!

Presented by: **Konstantin Ryabinin**, Gerasimos Sarras, Wolfgang Löffler, Olga Erokhina, Michael Biermann

Affiliation: Astronomisches Rechen-Institut, Center for Astronomy of Heidelberg University

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386