Università
degli Studi
di Ferrara

JMU
Liverpool John Moores University

Optimising the observation strategy of optical counterparts to short GRBs with robotic Liverpool Telescope

Anna Elisa Camisasca
on behalf of a collaboration

Iain Steele

Liverpool
John Moores
University

Manisha Shrestha

Liverpool
John Moores
University

Mattia Bulla

University
of Ferrara

Goal: to optimise the observation strategy with the Liverpool Telescope instruments to constrain kilonovae properties using light curves simulated with POSSIS code.

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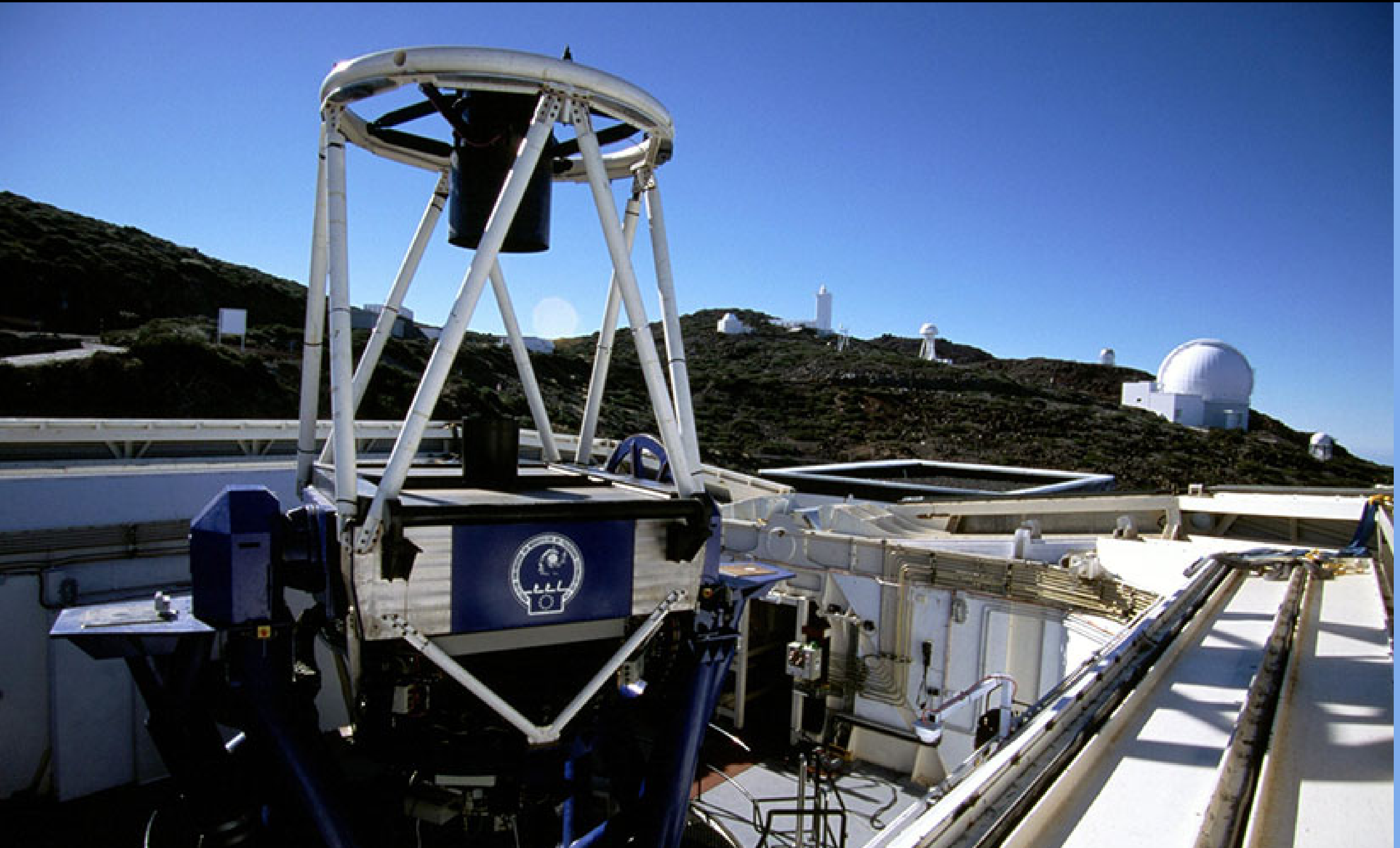
MOPTOP



MOPTOP (Multicolour OPTimised Optical Polarimeter) is a dual-beam polarimeter, currently deployed at the 2-m **Liverpool Telescope**, at the Observatorio del Roque de Los Muchachos on the Canary island of **La Palma**, Spain.

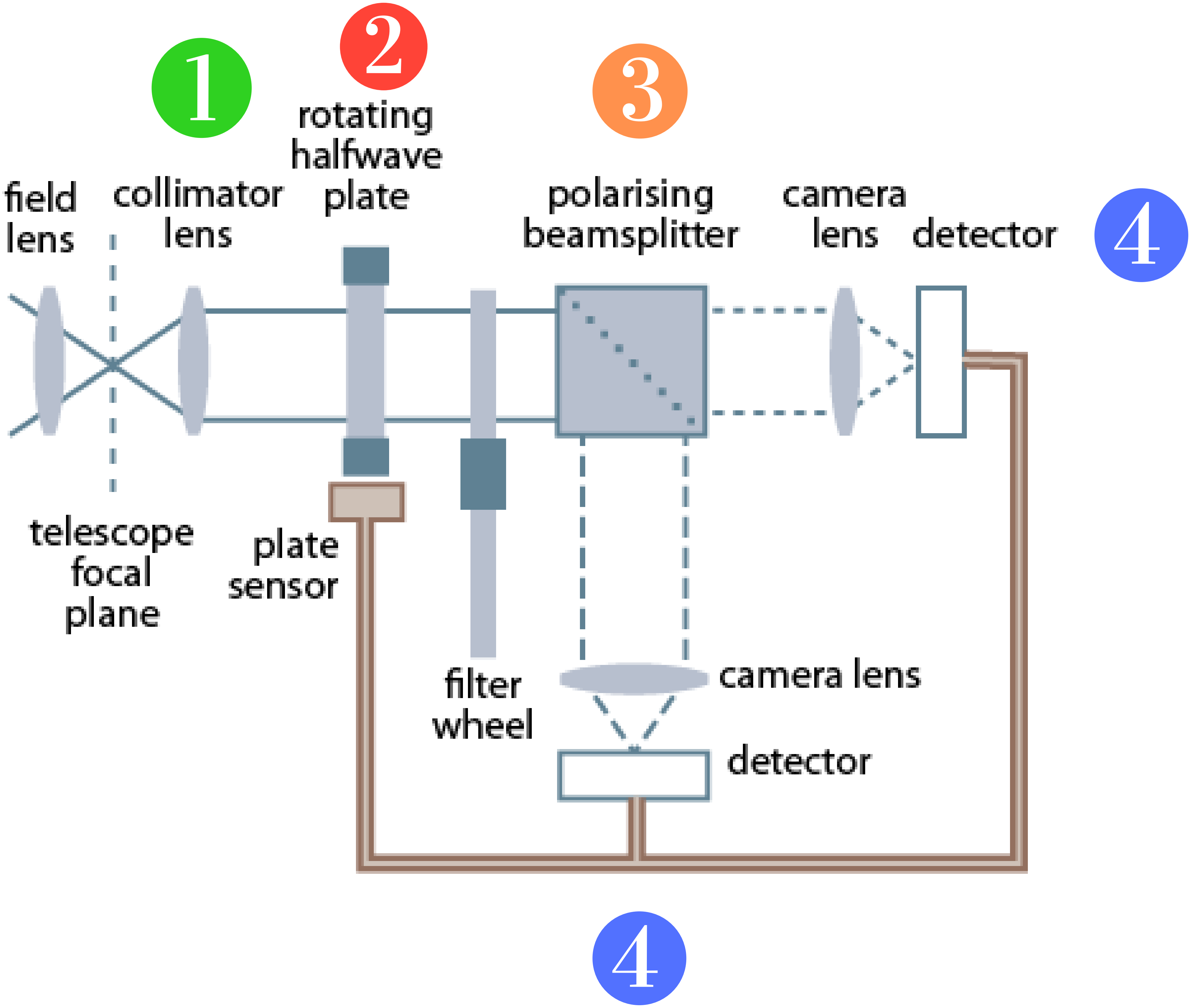
How MOPTOP works

① Light is collimated

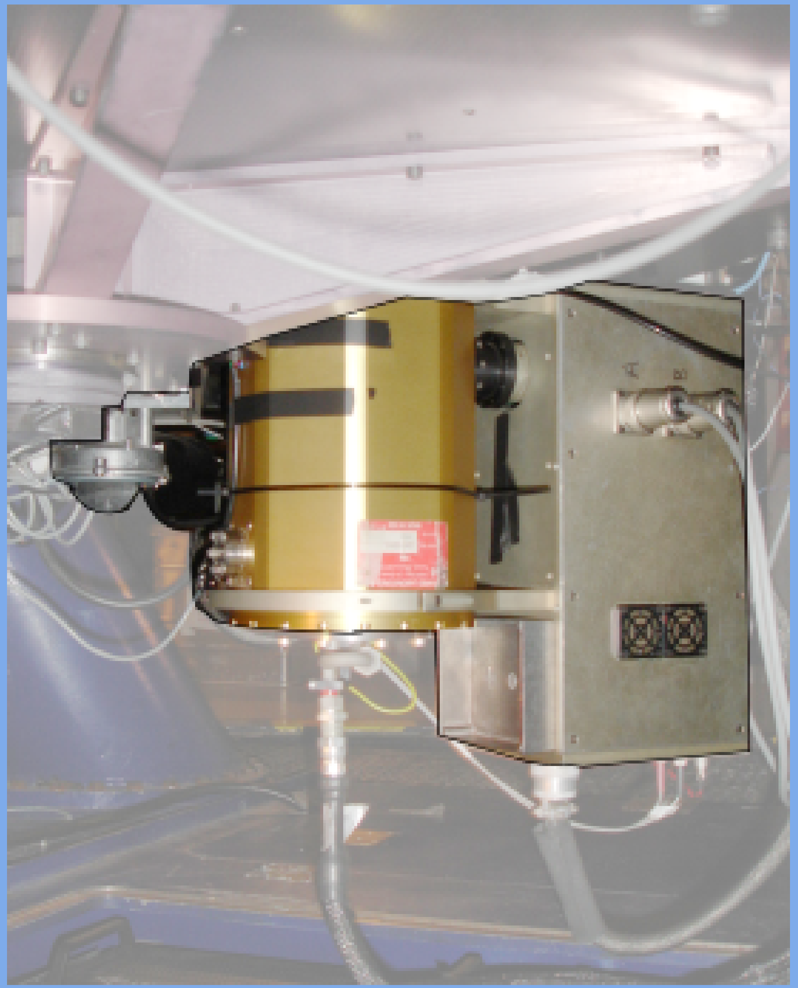
② The beam's polarisation angle is modulated

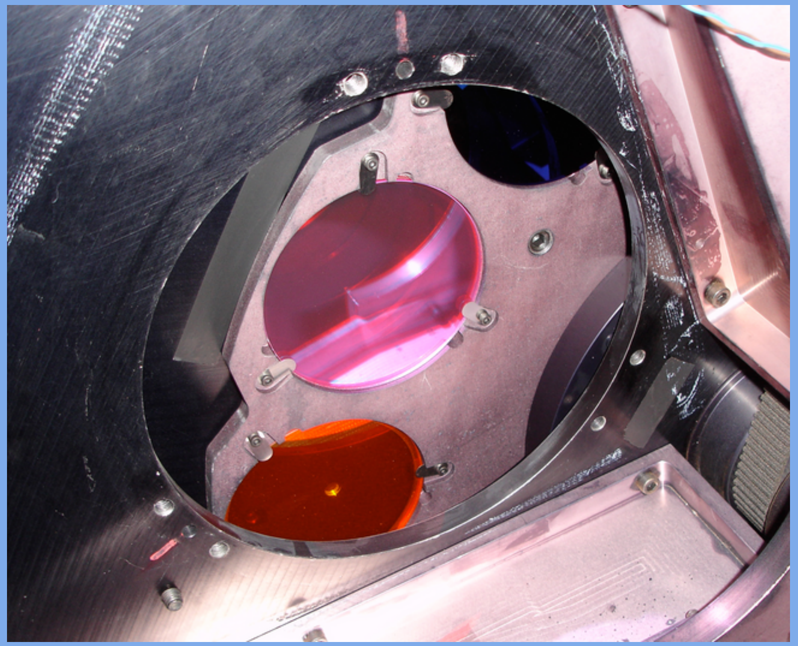
③ The light is split into the p and s polarised states

④ Image is collected by a pair of low-noise fast-readout imaging cameras.

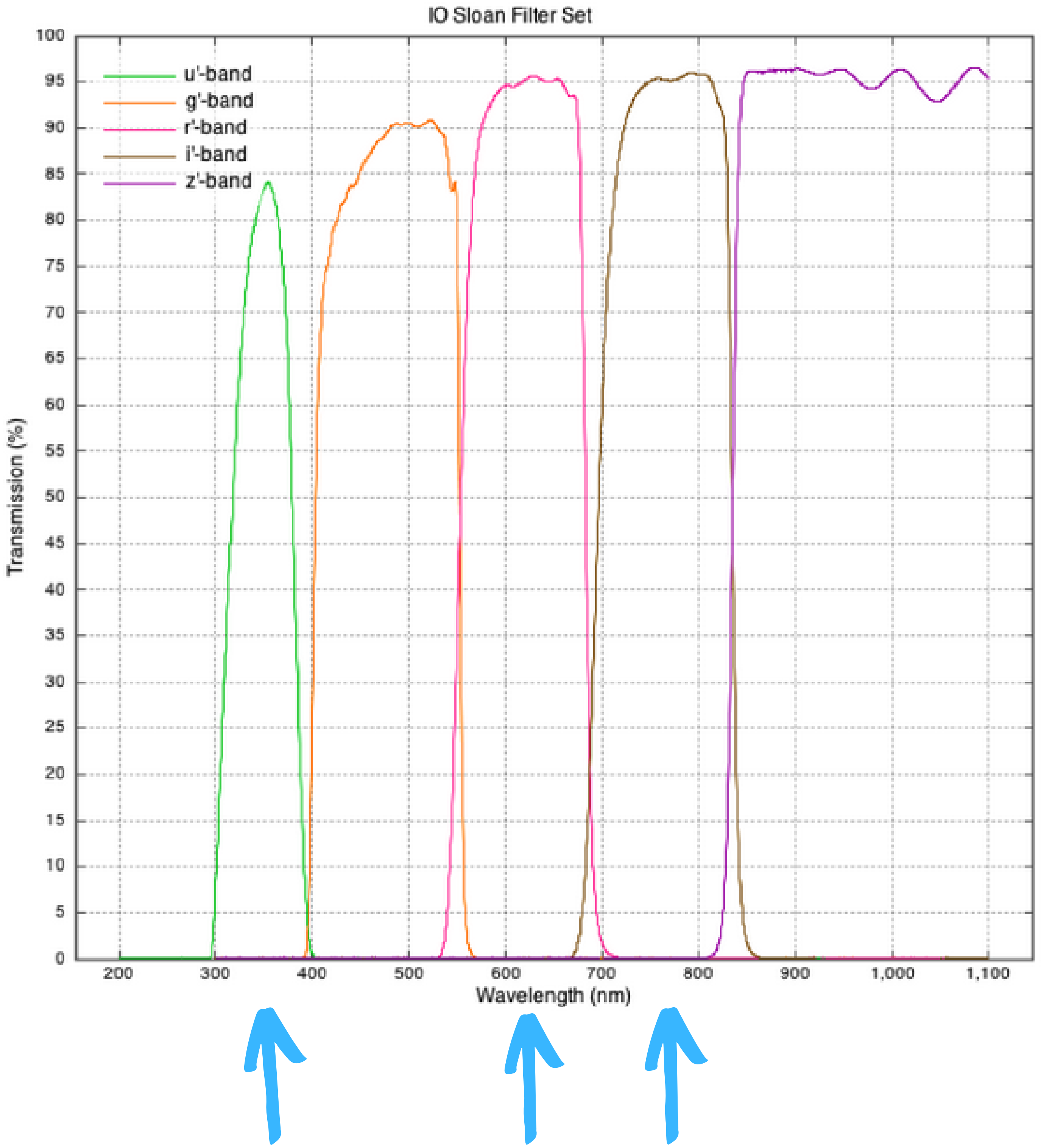


IO:O camera





IO:O is the optical imaging component of the IO (Infrared-Optical) suite of instruments



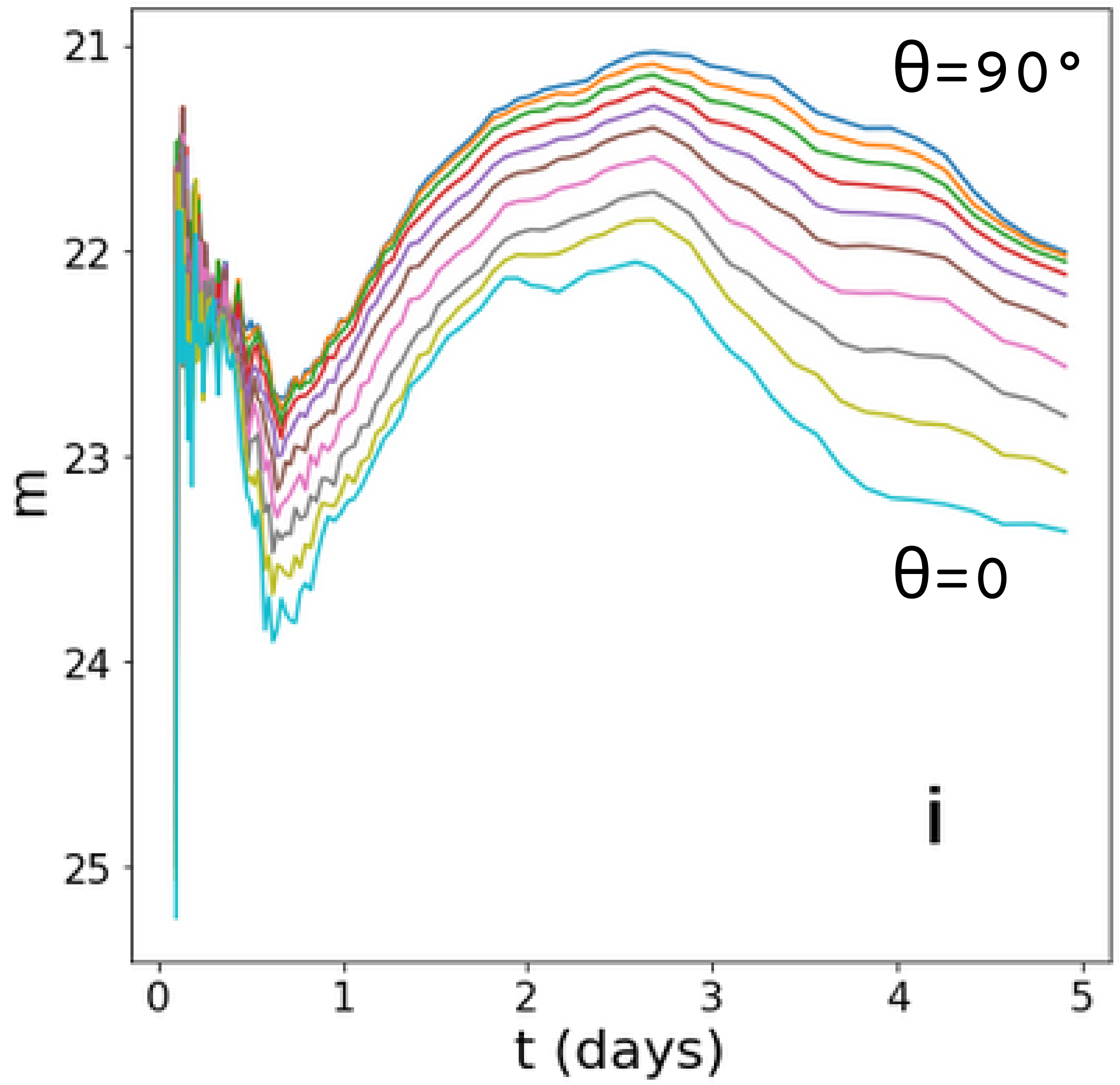
Filter	⟨ZP⟩
u'	24.53
g'	25.80
r'	25.70
i'	25.44
z'	24.84
B	25.16
V	25.24

R. Smith and I. A. Steele, "Liverpool Telescope Technical Note 1: Telescope and IO:O Throughput", (2017)

What is POSSIS?

POSSIS (POlarization Spectral Synthesis In Supernovae) is a time-dependent 3D Monte Carlo **code for modelling radiation transport in supernovae and kilonovae** written by Mattia Bulla. It **predicts** viewing-angle dependent **spectra, light curves and polarization** for both idealized and hydrodynamical explosion models.

M. Bulla, "Possis: predicting spectra, light curves, and polarization for multidimensional models of supernovae and kilonovae", Monthly Notices of the Royal Astronomical Society 489, 5037-5045 (2019)



Model #2, d=250 Mpc, filter = i, $0^\circ \leq \vartheta \leq 90^\circ$

Goal:

we optimise the time exposure sequence necessary in the observation with Liverpool Telescope to study kilonovae (KNe); we used the results obtained simulating the multi-filter light curves (LCs) of KNe with POSSIS.

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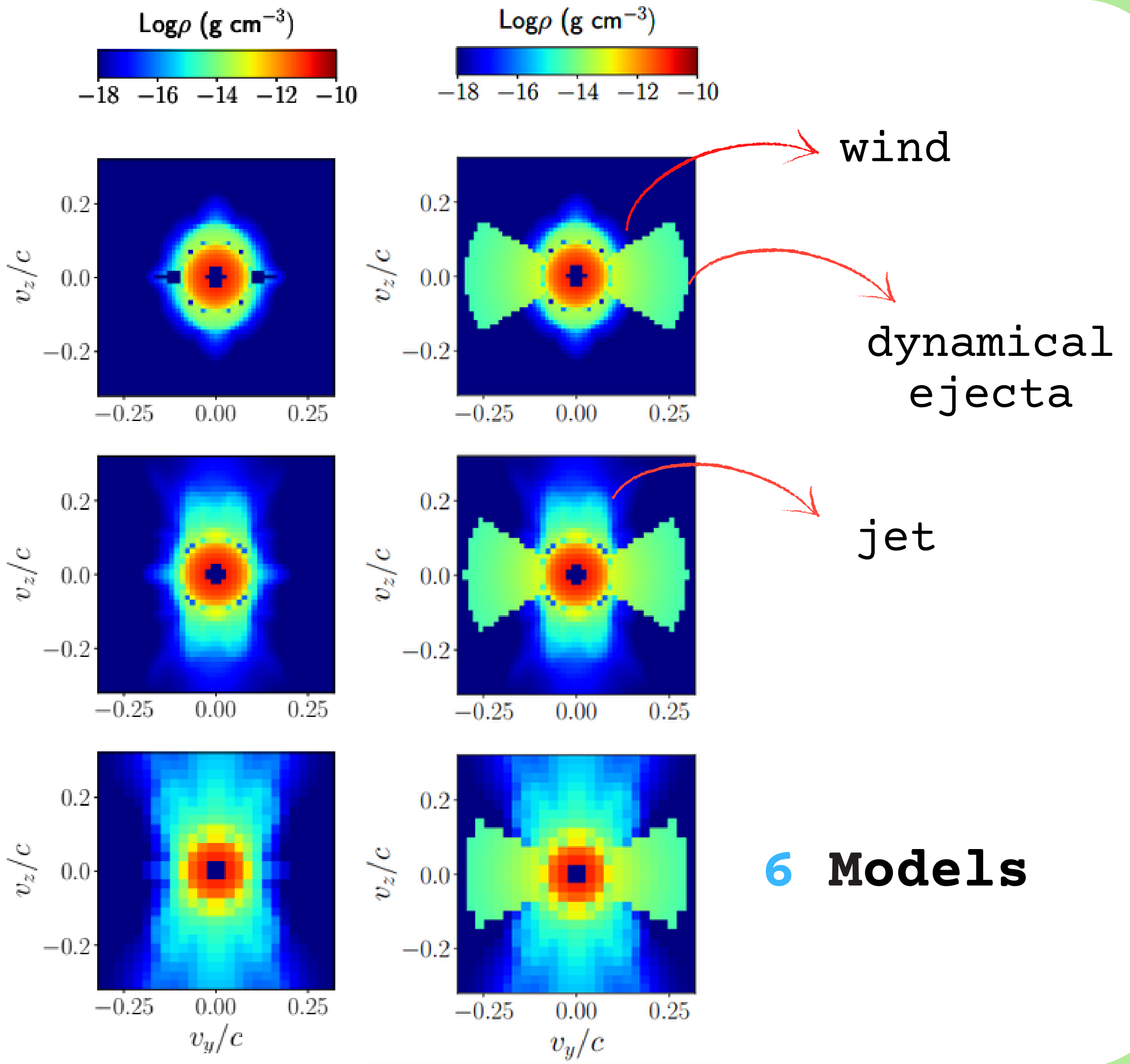
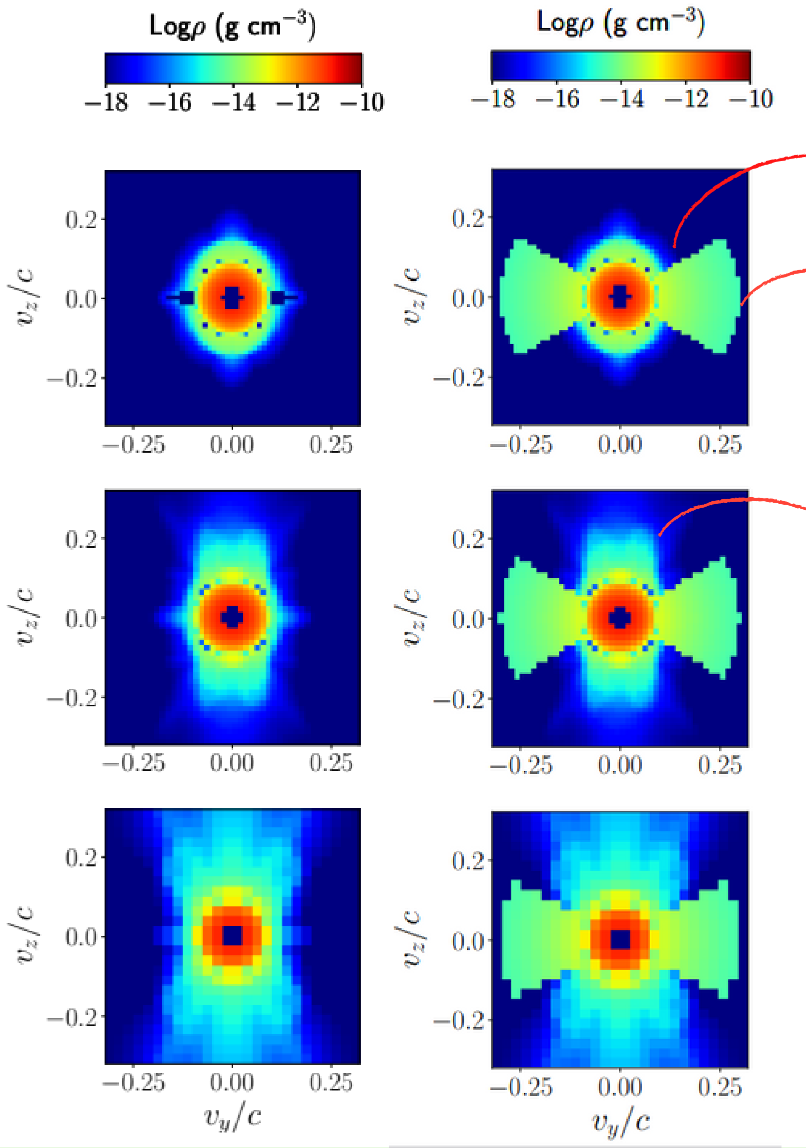
Models, angles, distances and filters



6 Models

Goal: we optimise the time exposure sequence necessary in the observation with Liverpool Telescope to study kilonovae (KNe); we used the results obtained simulating the multi-filter light curves (LCs) of KNe with POSSIS.

Models, angles, distances and filters



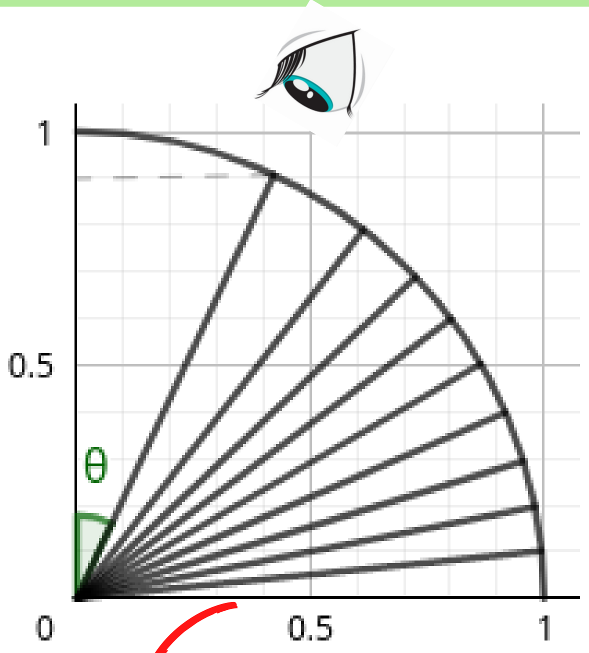
wind

dynamical ejecta

jet

6 Models

θ is the inclination angle.
11 values for θ:
cos θ = 0, 0.1, 0.2, . . . , 1.



merging plane

6 x 11 = 66 configurations for a fixed distance and filter

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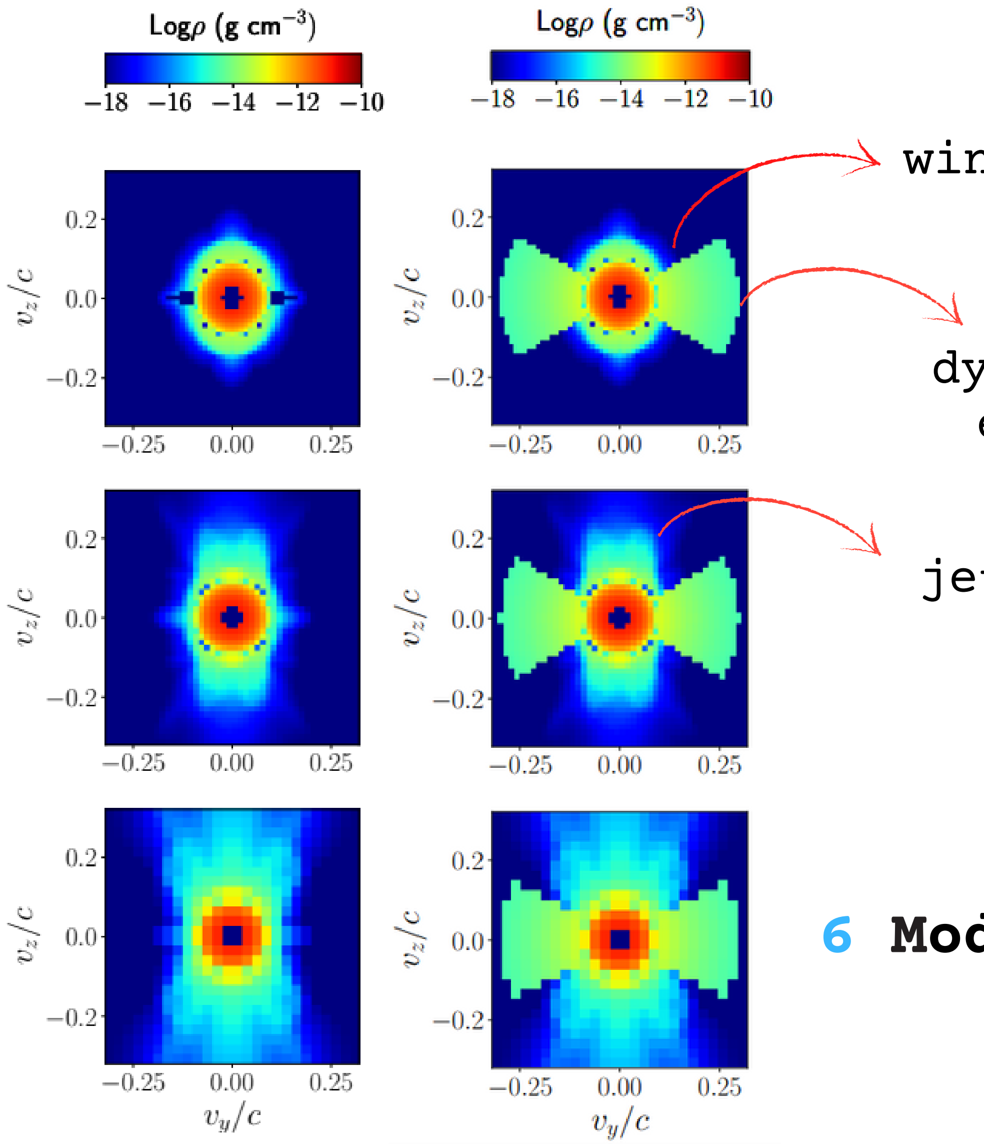
Models, angles, distances and filters



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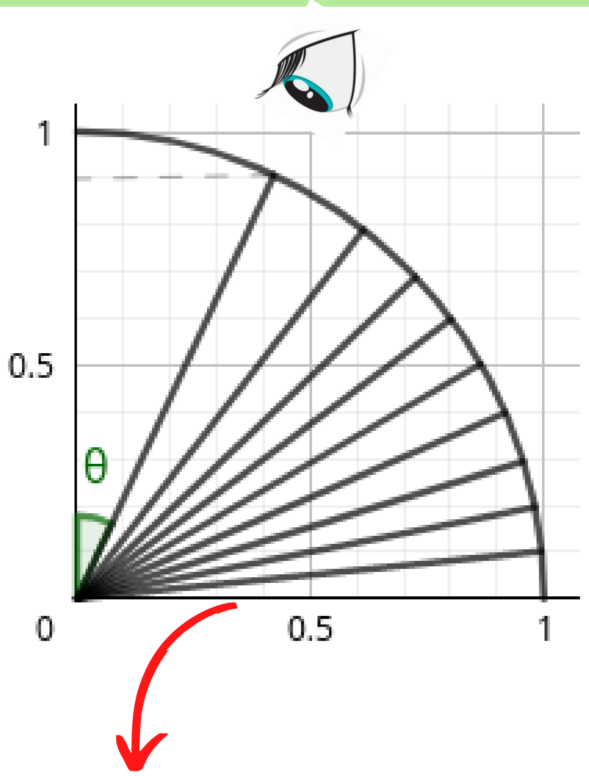

merging plane

d= 20, 40, 80, 160, 250, 350 Mpc.

filters: i, r, u.

6 x 11 = 66 configurations for a fixed distance and filter

3 different procedures

A. Individual filter

B. Colours procedure,
same time exposure for different filters

C. Colours procedure,
different time exposure for different filters

Colours do not depend on the source's distance

For each procedure:
- **2 different binning time (1h or 5h),**
- **time exposure constant or variable**

Procedure A. : individual filter (I)

Individual filter procedure

1. Start with a set of possible time exposure sequences.

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Constant exposure times:

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Constant exposure times:

a. texp = 1h with 1 hour bins;
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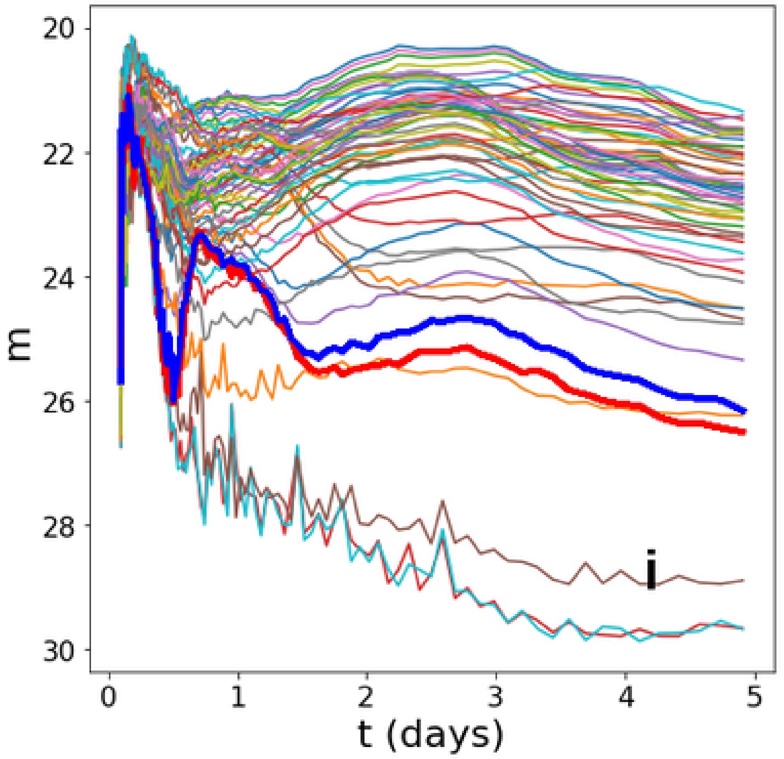
Variable exposure times:

a. for each distance, for each filter, for each LC, we find the most similar LC among all the others



b. For each of the 66 LCs, we find the time exposure tΔ necessary to distinguish it from its most similar one:

$$t_\Delta = \left(\frac{1}{m-m'}\right)^2 \frac{\bar{F}+F_{\mathrm{sky}}}{\bar{F}^2}$$

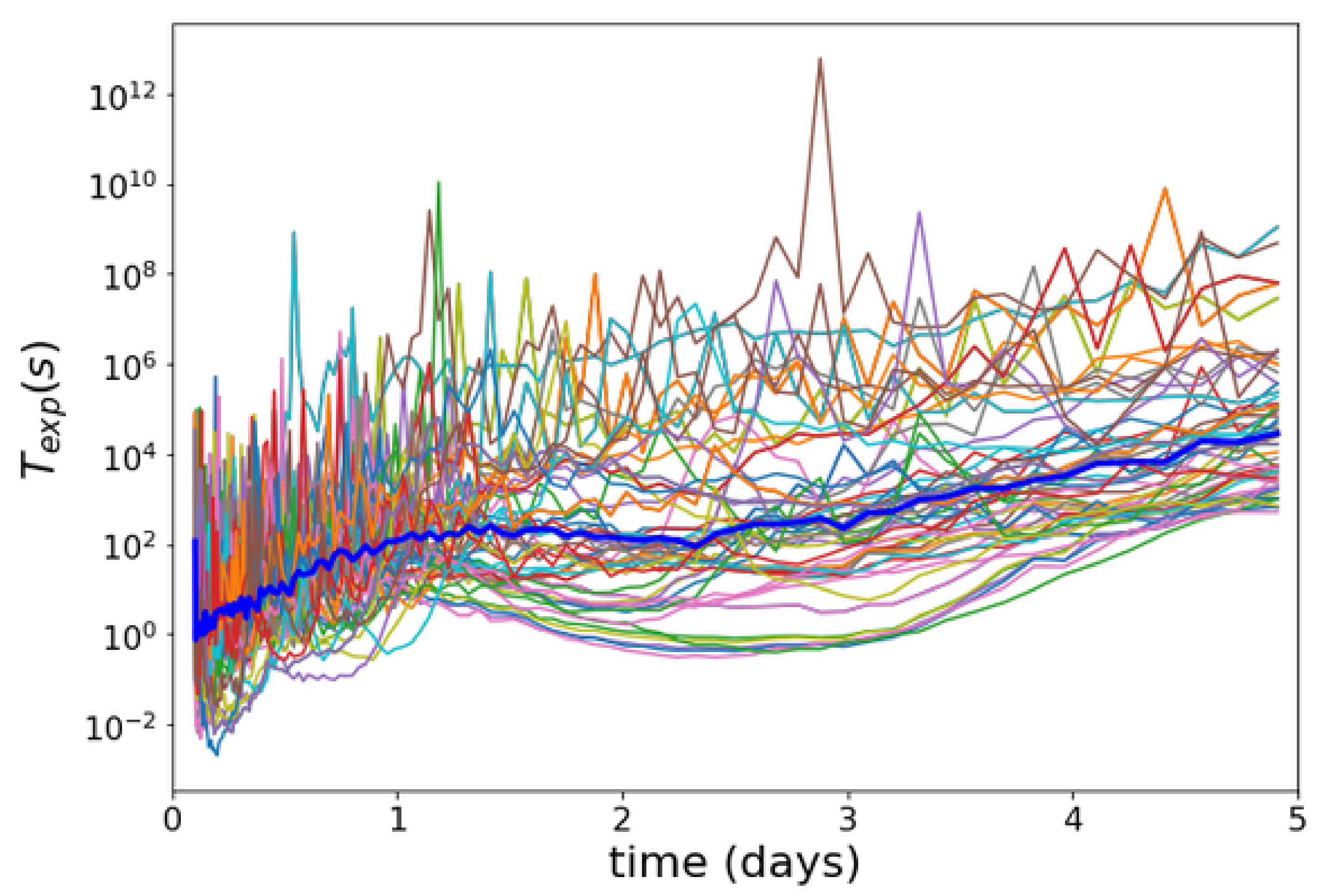
mean photo-electron/s between the 2 LCs

photo-electron/s due to the sky

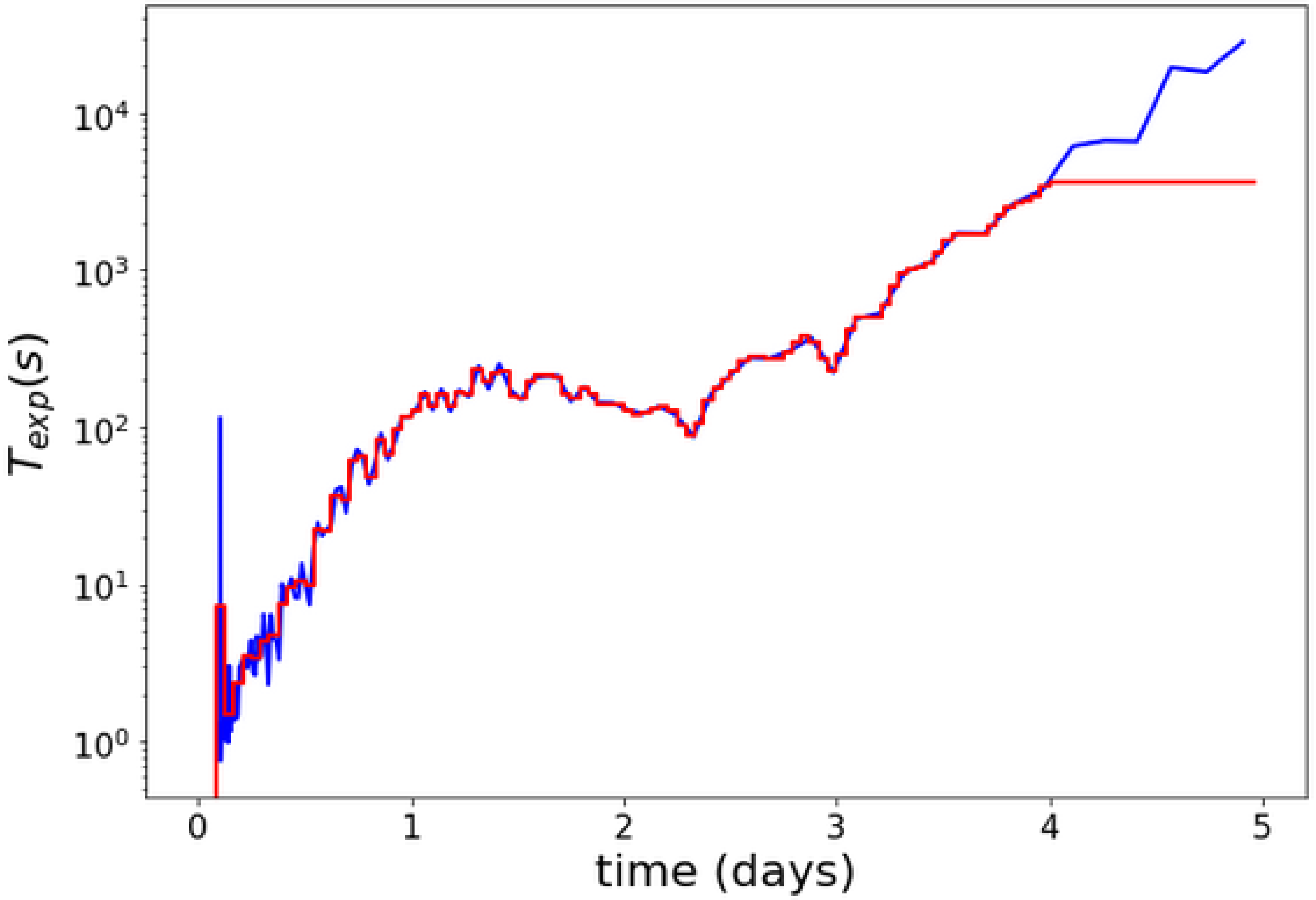
difference between a LC magnitude and the magnitude of the most similar LC

Procedure A. individual filter(II)

c. For each time point, we find the median between all the 66 t∆ obtained in the previous step;

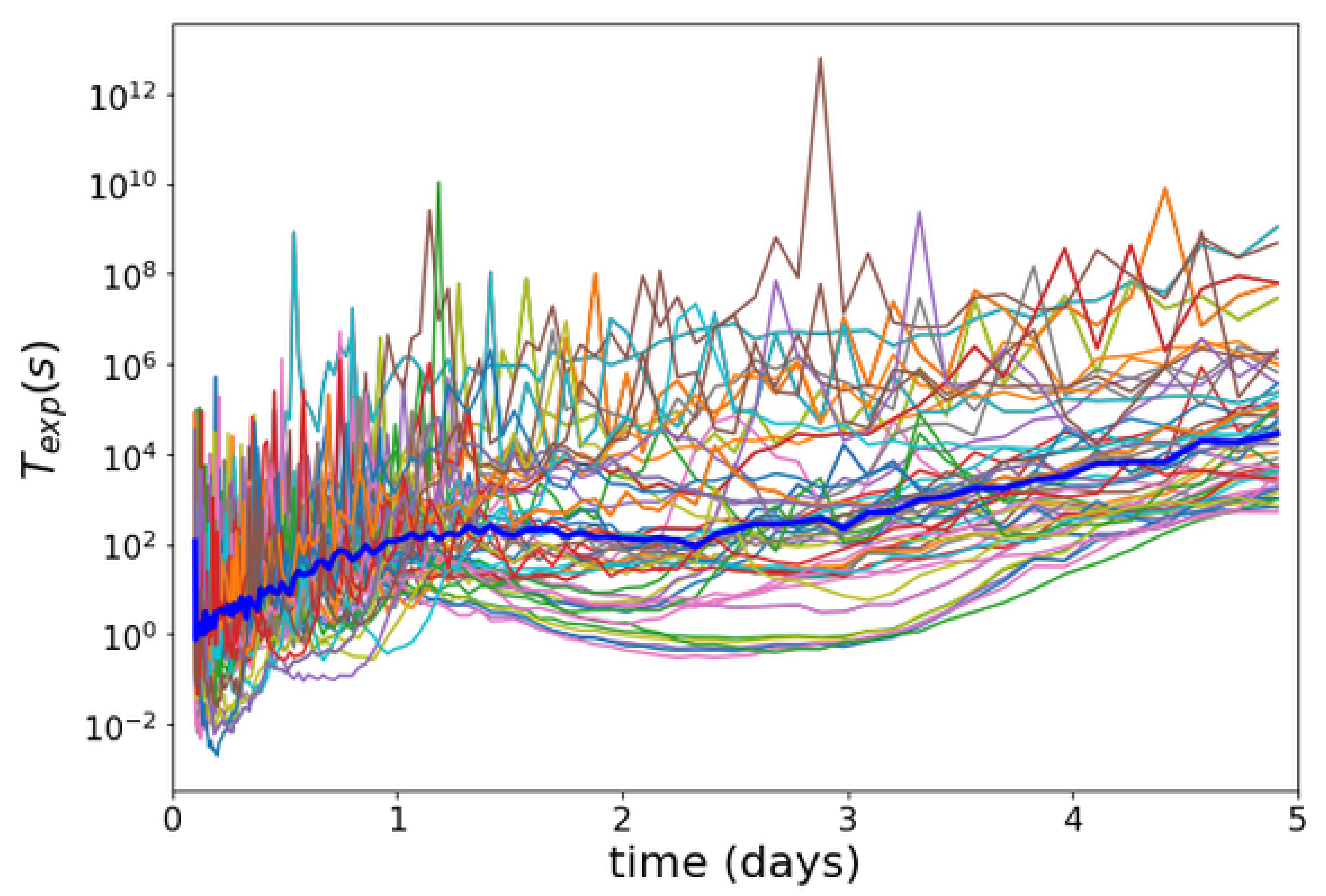


d. We find, for each 1 hour (5 hours) intervals, the mean of t median t*. When t* > 1 hr (t* > 5 hr) for 1 hour (5 hours) intervals, we set the exposure to the whole temporal bin duration (1 or 5 hours).



Procedure A. individual filter(II)

c. For each time point, we find the median between all the 66 tΔ obtained in the previous step;



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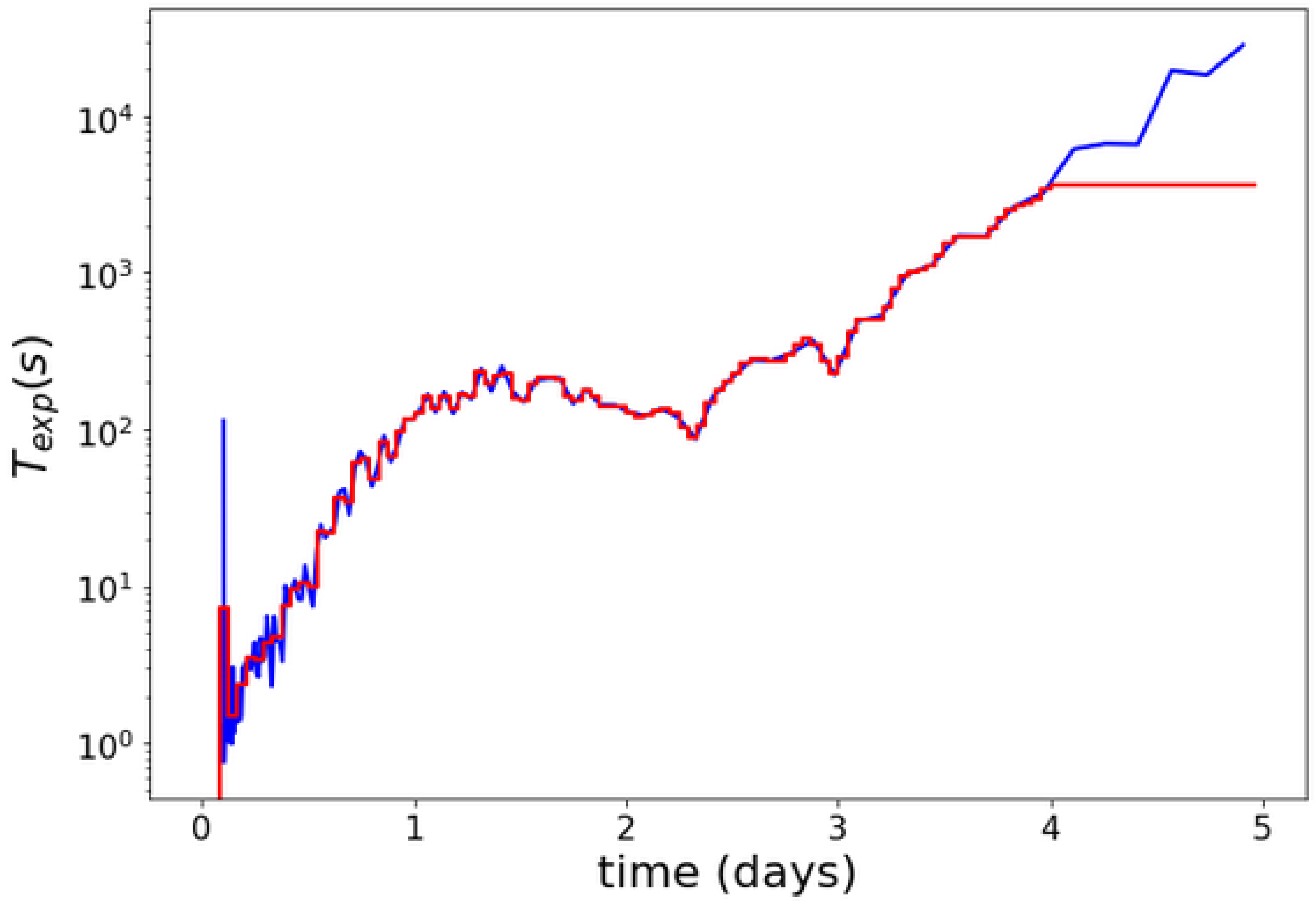


4 different time exposure series:

- texp = constant = 1h with 1 hour intervals;
- texp = constant = 1h · 5 with 5 hours intervals;
- texp = variable with 1 hour intervals;
- texp = variable with 5 hours intervals.

Procedure A. individual filter(III)

Individual filter procedure

1. Start with a set of possible time exposure sequences. ✓
2. For a fixed distance and filter, **we add statistical noise** to the LC.

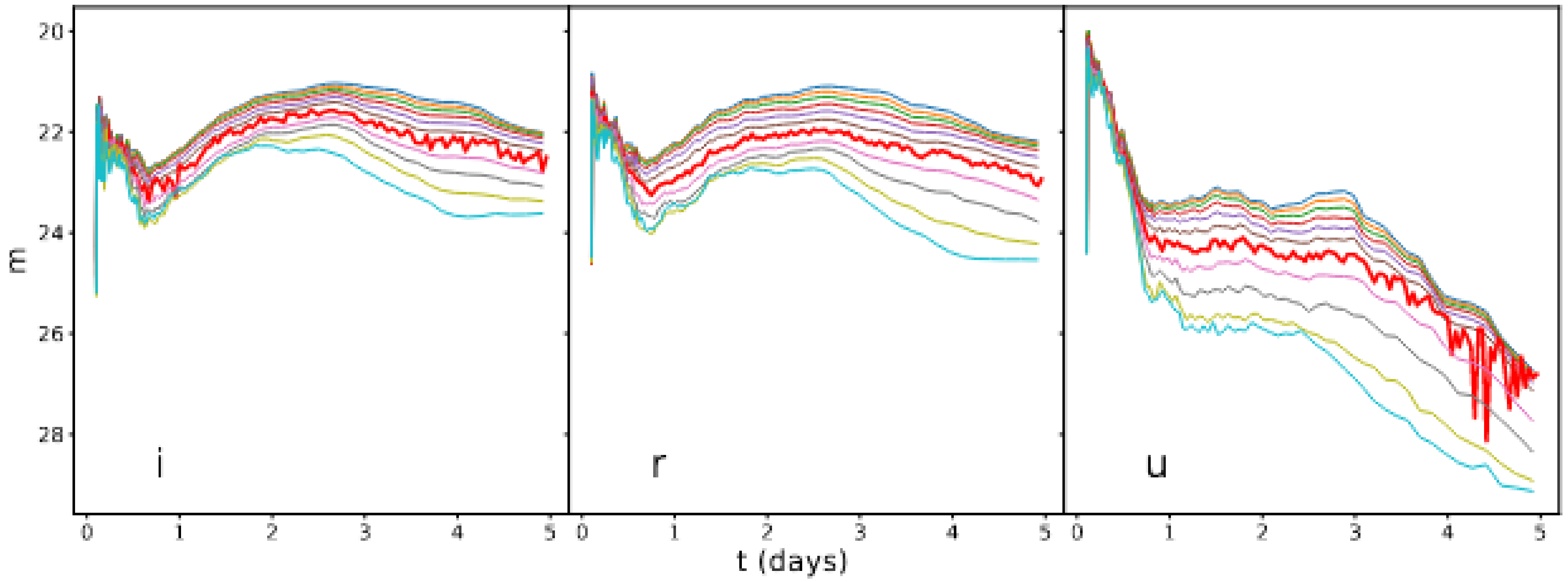
$$F_{\text{noise}} = \frac{C_P}{t_{\text{exp}}} - F_{\text{sky}}$$

$t_{\text{exp}}(F + F_{\text{sky}})$ + Statistical noise

counts/s due to the sky

$$m_{\text{noise}} = z_P - \frac{\log_{10}(F_{\text{noise}})}{0.4}$$

Instrument Zero Point referred to a particular filter



Procedure A. individual filter (IV)

Individual filter procedure

1. Start with a set of possible time exposure sequences. ✓
2. For a fixed distance and filter, we add noise to the LC. ✓
3. We **compare LCN with the others LCs without noise** and we analyse how often we are able to recognize the right LC among the others.

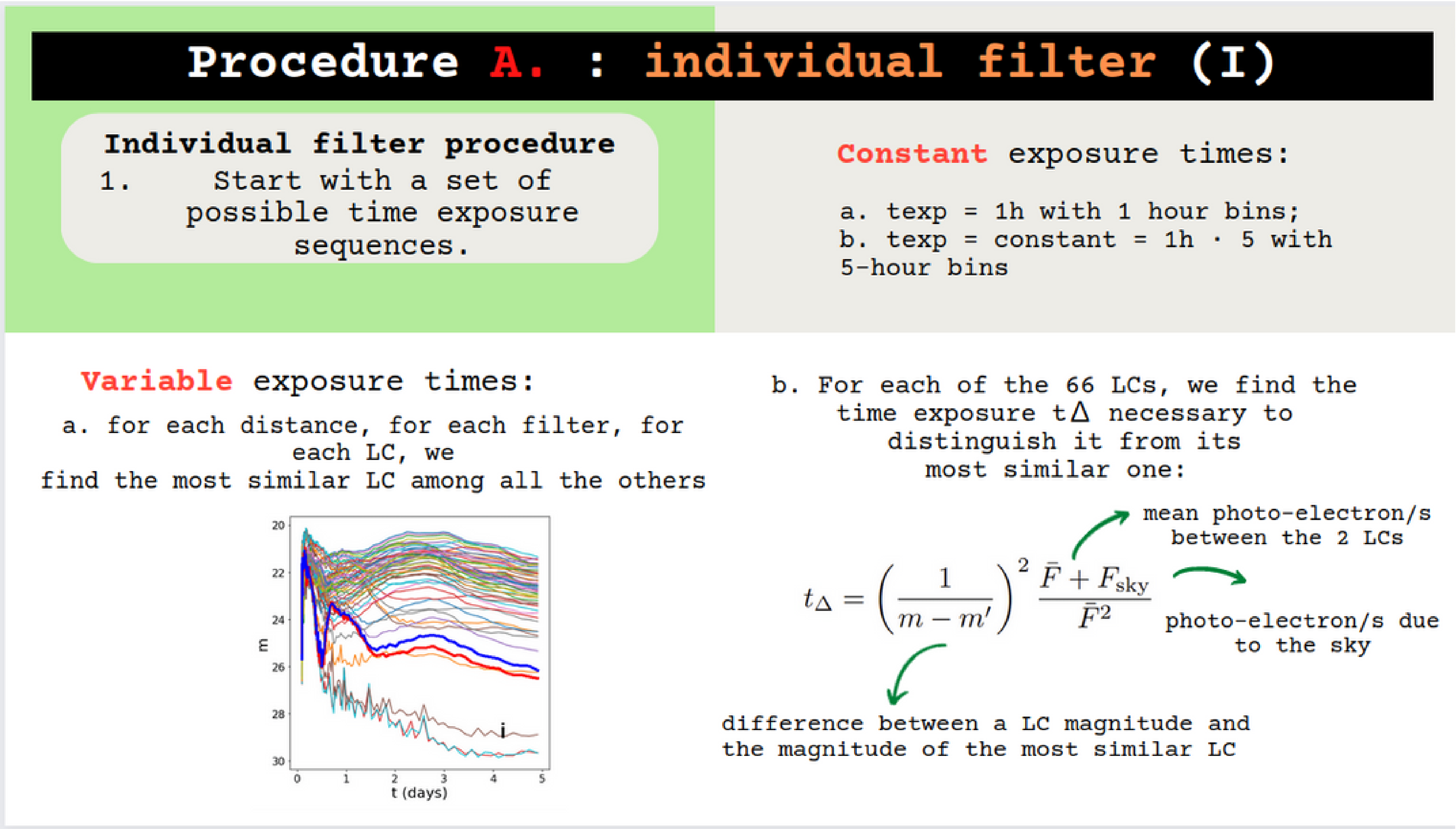
We select the model which minimize:

$$\chi^2 = \sum \left(\frac{m_{\text{model}} - m_{\text{noise}}}{\sigma_{m_{\text{noise}}}} \right)^2 \cdot \frac{1}{N}$$

$$\sigma_{m_{\text{noise}}} = \frac{\sqrt{C_P}}{-0.4 \cdot F_{\text{noise}} \cdot \ln(10) \cdot t_{\text{exp}}}$$

Procedure B. Colours, same texp for different filters (I)

1. Start with a set of possible time exposure sequences.



Procedure A. : individual filter (I)

Individual filter procedure

1. Start with a set of possible time exposure sequences.

Constant exposure times:

a. texp = 1h with 1 hour bins;
b. texp = constant = 1h · 5 with 5-hour bins

Variable exposure times:

a. for each distance, for each filter, for each LC, we find the most similar LC among all the others

b. For each of the 66 LCs, we find the time exposure tΔ necessary to distinguish it from its most similar one:

$$t_\Delta = \left(\frac{1}{m-m'}\right)^2 \frac{\bar{F} + F_{\text{sky}}}{\bar{F}^2}$$

mean photo-electron/s between the 2 LCs

photo-electron/s due to the sky

difference between a LC magnitude and the magnitude of the most similar LC

Procedure B. Colours, same texp for different filters (I)

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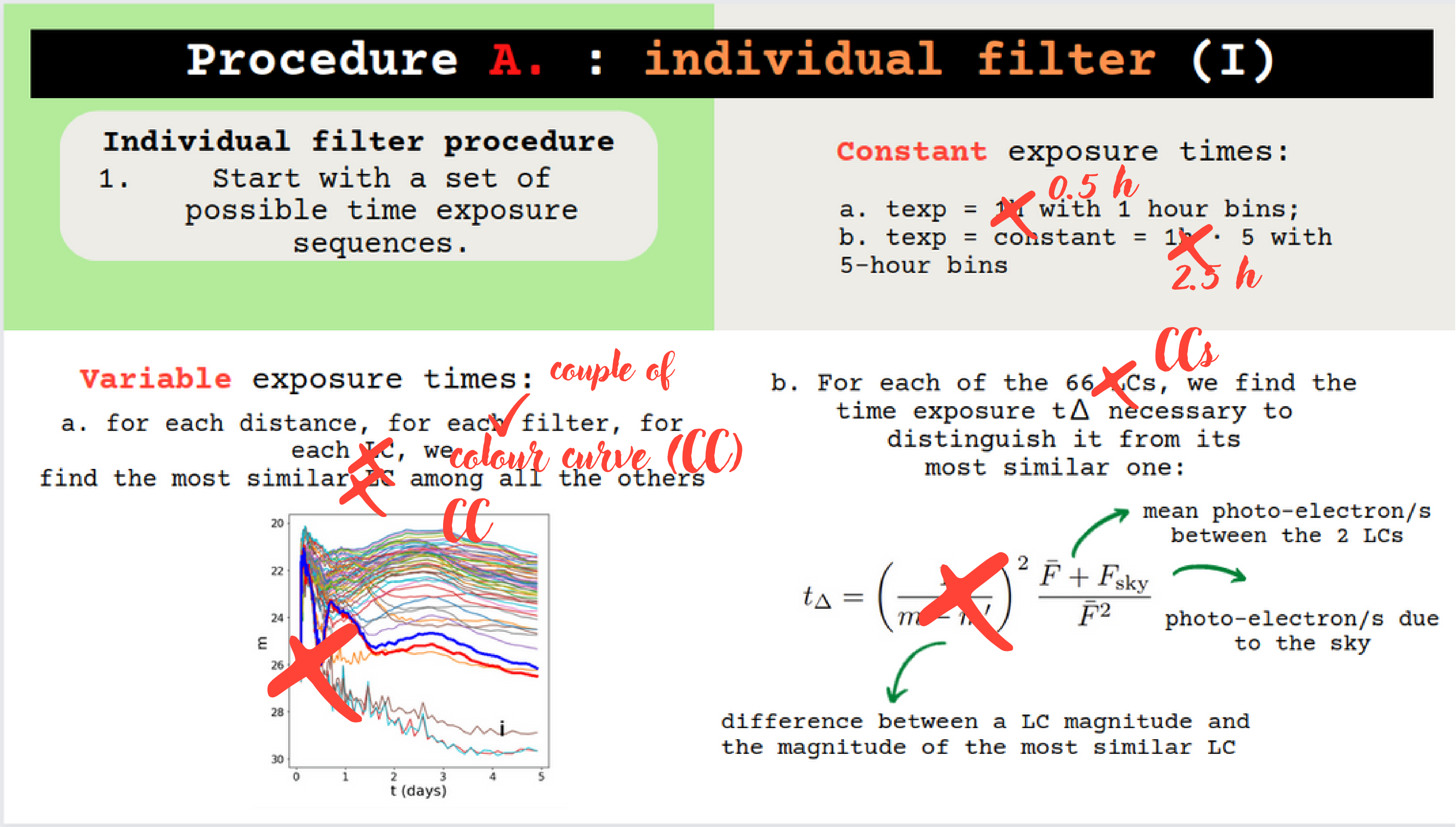


Procedure A. : individual filter (I)

Individual filter procedure

1. Start with a set of possible time exposure sequences.

Constant exposure times:

a. texp = ~~1h~~ 0.5 h with 1 hour bins;
b. texp = constant = ~~1h~~ 2.5 h · 5 with 5-hour bins

Variable exposure times: couple of

a. for each distance, for each ✓ filter, for each ~~LC~~, we colour curve (CC) find the most similar ~~LC~~ CC among all the others

b. For each of the 66 ~~LCs~~ CCs, we find the time exposure tΔ necessary to distinguish it from its most similar one:

$$t_\Delta = \left(\cancel{\frac{1}{m-m'}}\right)^2 \frac{\bar{F}+F_{\rm sky}}{\bar{F}^2}$$

mean photo-electron/s between the 2 LCs

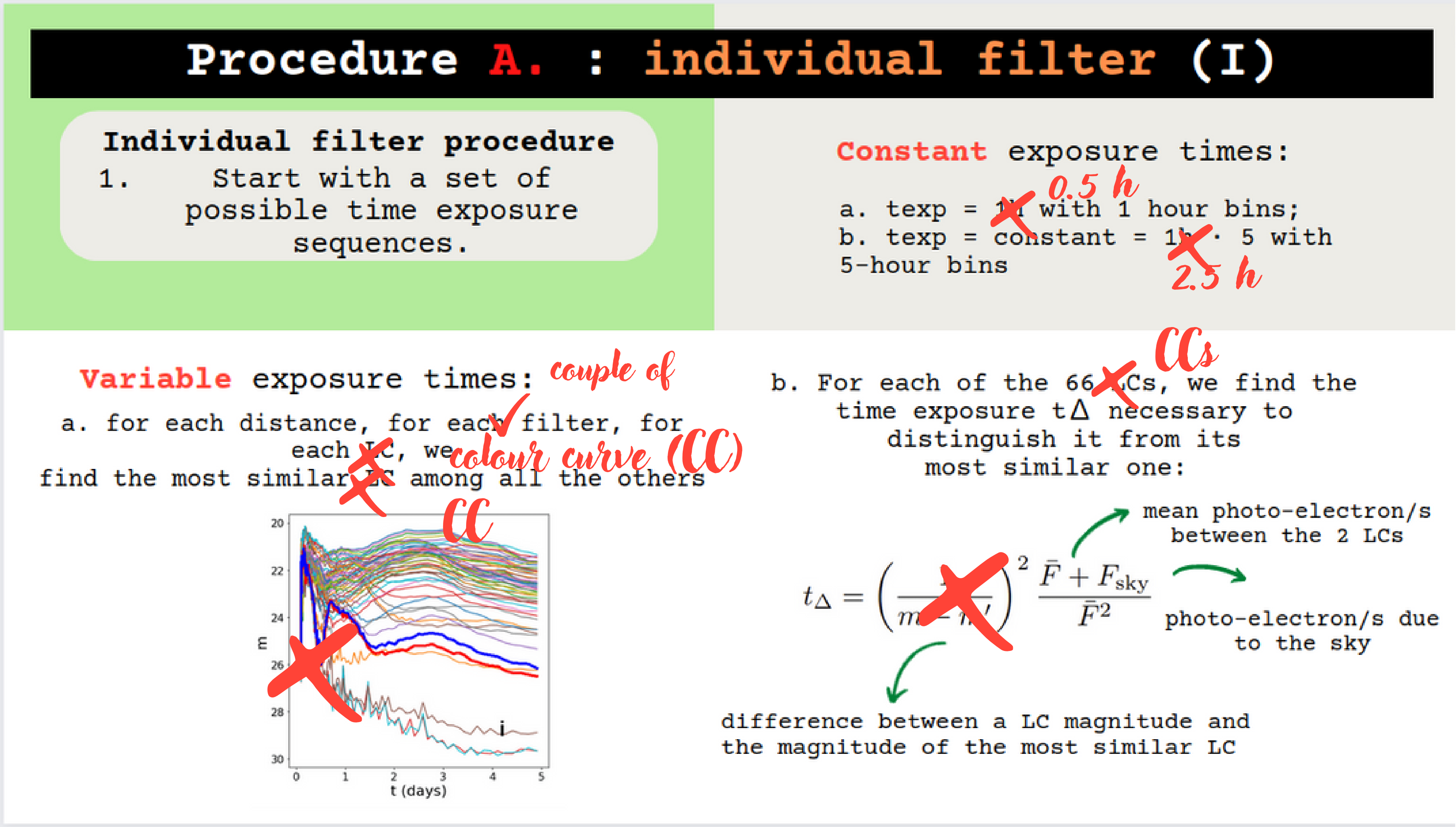
photo-electron/s due to the sky

difference between a LC magnitude and the magnitude of the most similar LC

$$t_\Delta = \left(\frac{1}{\Delta(m_A - m_B)}\right)^2 \cdot \left(\frac{F_A + F_{\rm sky}}{F_A^2} + \frac{F_B + F_{\rm sky}}{F_B^2}\right)$$

Procedure B. Colours, same texp for different filters (I)

1. Start with a set of possible time exposure sequences.



Procedure A. : individual filter (I)

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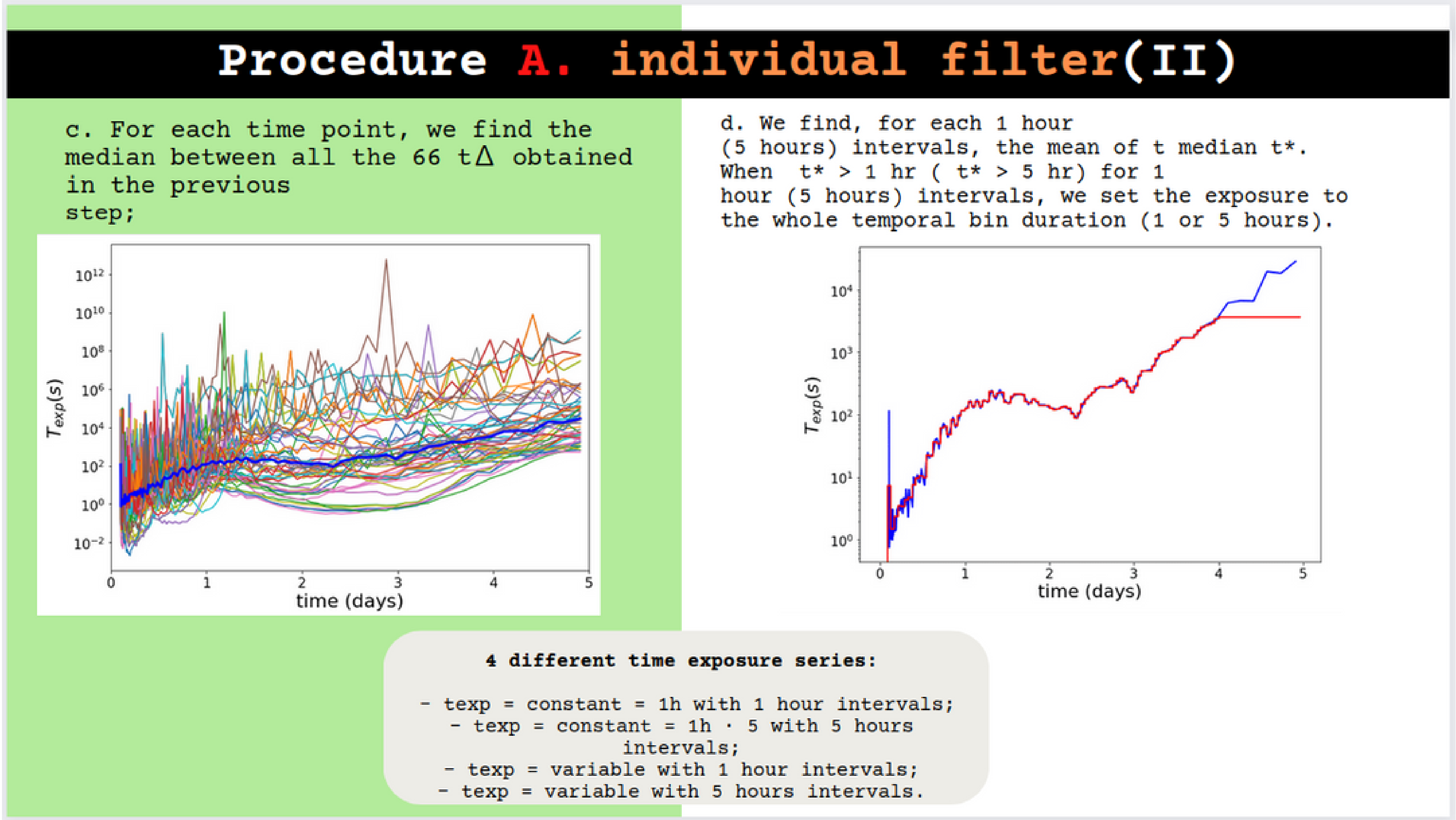
mean photo-electron/s between the 2 LCs

photo-electron/s due to the sky

difference between a LC magnitude and the magnitude of the most similar LC



Procedure A. individual filter(II)

c. For each time point, we find the median between all the 66 tΔ obtained in the previous step;

d. We find, for each 1 hour (5 hours) intervals, the mean of t median t*. When t* > 1 hr (t* > 5 hr) for 1 hour (5 hours) intervals, we set the exposure to the whole temporal bin duration (1 or 5 hours).

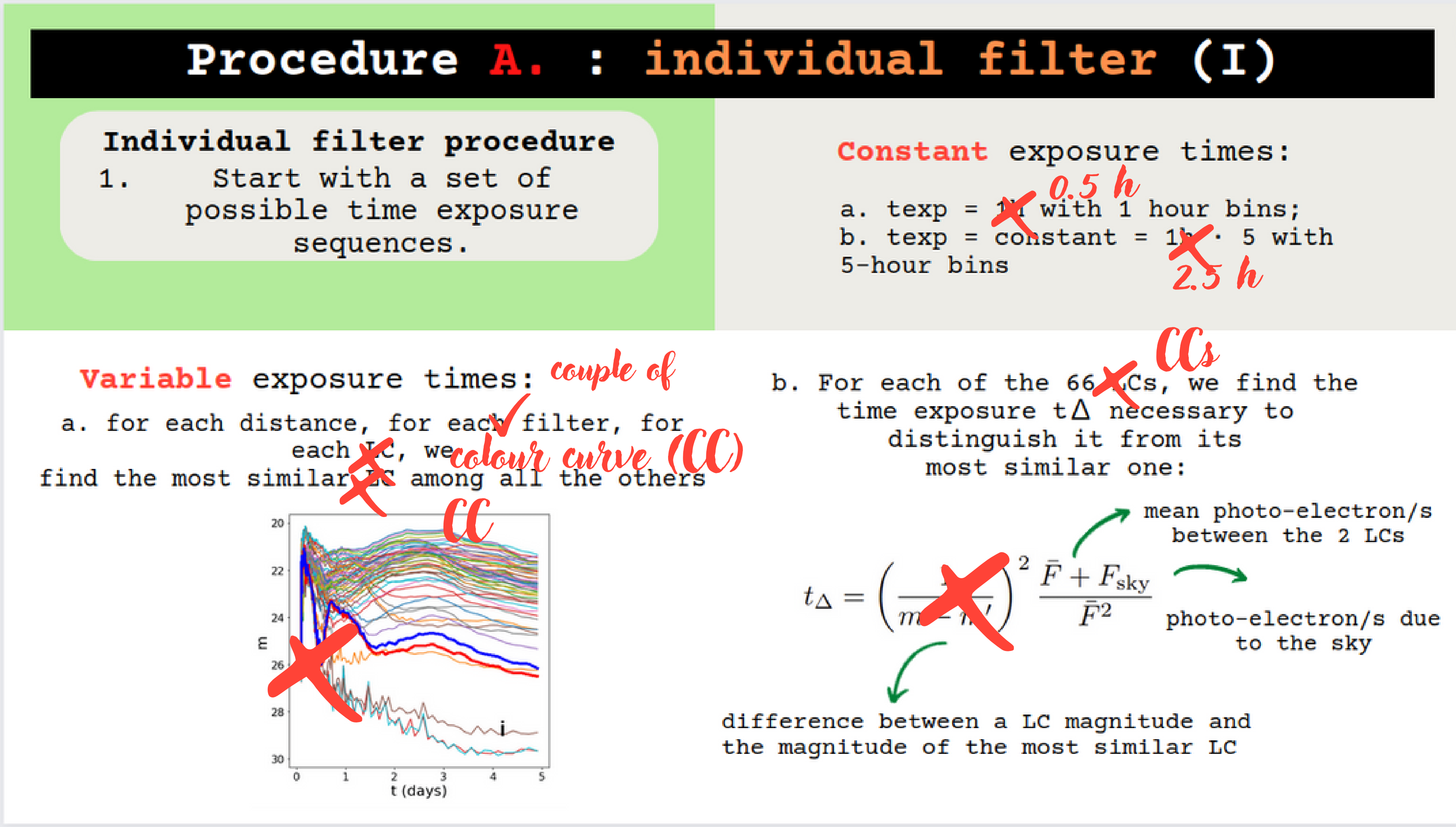
4 different time exposure series:

- texp = constant = 1h with 1 hour intervals;
- texp = constant = 1h · 5 with 5 hours intervals;
- texp = variable with 1 hour intervals;
- texp = variable with 5 hours intervals.

$$t_\Delta = \left(\frac{1}{\Delta(m_A - m_B)}\right)^2 \cdot \left(\frac{F_A + F_{\rm sky}}{F_A^2} + \frac{F_B + F_{\rm sky}}{F_B^2}\right)$$

Procedure B. Colours, same texp for different filters (I)

1. Start with a set of possible time exposure sequences.



Procedure A. : individual filter (I)

Individual filter procedure

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Constant exposure times:

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Variable exposure times: couple of

a. for each distance, for each ✓ filter, for each ~~LC~~ colour curve (CC), we find the most similar ~~LC~~ CC among all the others

b. For each of the 66 ~~LCs~~ CCs, we find the time exposure tΔ necessary to distinguish it from its most similar one:

$$t_\Delta = \left(\cancel{\frac{1}{m - m'}}\right)^2 \frac{\bar{F} + F_{\rm sky}}{\bar{F}^2}$$

mean photo-electron/s between the 2 LCs

photo-electron/s due to the sky

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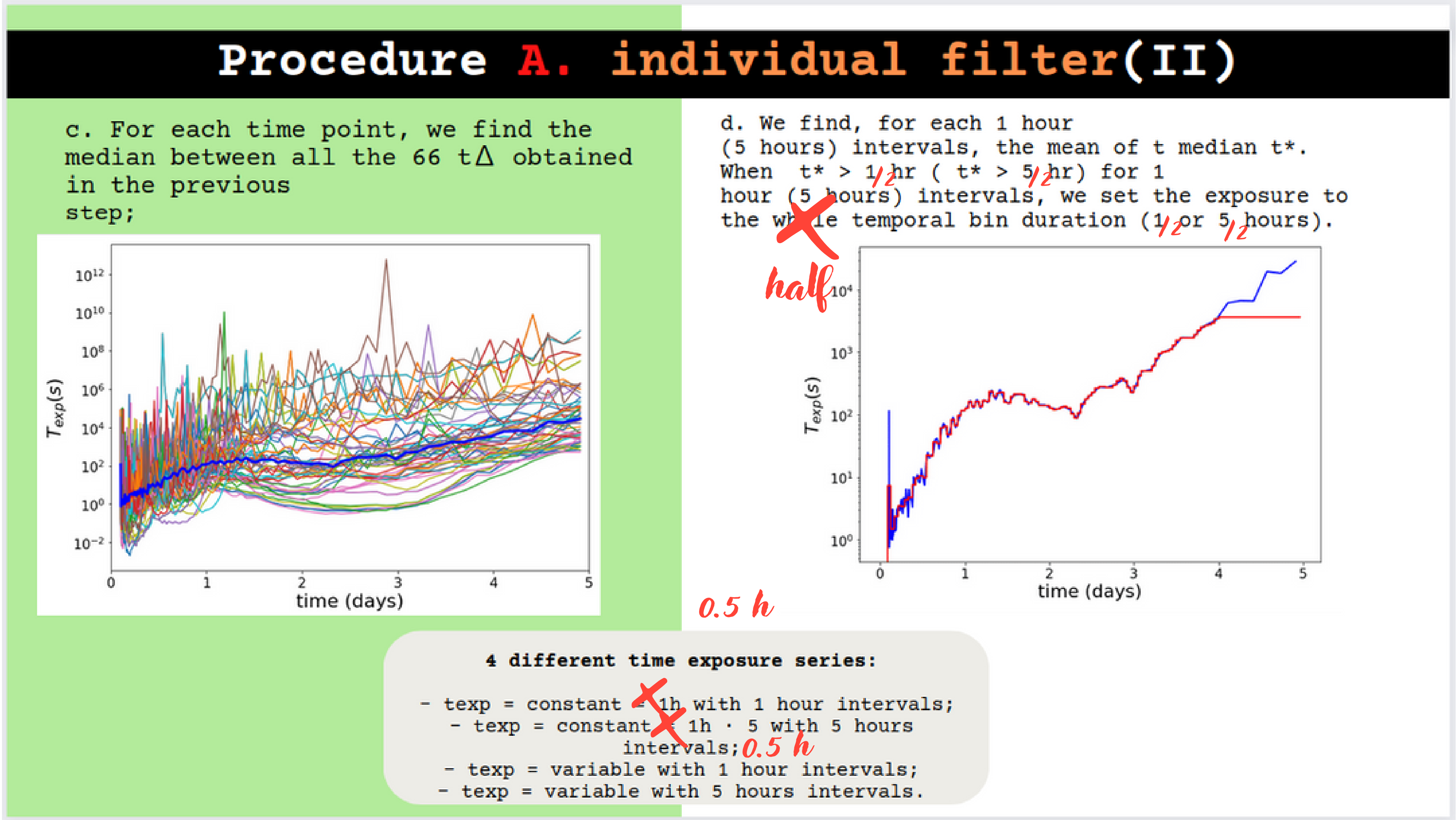


Procedure A. individual filter(II)

c. For each time point, we find the median between all the 66 tΔ obtained in the previous step;

d. We find, for each 1 hour (5 hours) intervals, the mean of t median t*. When t* > 1/2 hr (t* > 5/2 hr) for 1 hour (5 hours) intervals, we set the exposure to the ~~whole~~ half temporal bin duration (1/2 or 5/2 hours).

0.5 h

4 different time exposure series:

- texp = constant ~~= 1h~~ with 1 hour intervals;
- texp = constant ~~= 1h~~ · 5 with 5 hours intervals; 0.5 h
- texp = variable with 1 hour intervals;
- texp = variable with 5 hours intervals.

$$t_\Delta = \left(\frac{1}{\Delta(m_A - m_B)}\right)^2 \cdot \left(\frac{F_A + F_{\rm sky}}{F_A^2} + \frac{F_B + F_{\rm sky}}{F_B^2}\right)$$

Procedure B. Colours, same texp for different filters (II)

1. We find a reasonable time exposure sequence. ✓

2. We **add noise to the LC**. We then **find the colour curves affected with noise** (CCN).

3. We **compare CCN with the colour curves without noise** (CC) and we count how often we recognise the right original model among the others.

Same as with individual filter procedure, than we subtract LCNs to have Colour Curve with Noise (CCNs)

We select the model which minimize:

$$\chi^2 = \sum \frac{(\Delta m_{\text{model}} - \Delta m_{\text{noise}})^2}{\sigma^2_{m_{A,\text{noise}}} + \sigma^2_{m_{B,\text{noise}}}} \cdot \frac{1}{N}$$

$$\Delta m_{\text{model}} = m_{A,\text{model}} - m_{B,\text{model}},$$

$$\Delta m_{\text{noise}} = m_{A,\text{noise}} - m_{B,\text{noise}}.$$

$$\sigma_{m_{\text{noise}}} = \frac{\sqrt{C_P}}{-0.4 \cdot F_{\text{noise}} \cdot \ln(10) \cdot t_{\text{exp}}}.$$

Procedure C. Colours, different texp for different filters

1. We find a reasonable **time exposure sequence.**

we use
for each filter the texp we found in the individual
filter procedure

2. We **add noise to the LC.** We then **find the colour curves affected with noise** (CCN).

same procedure of Colours procedure, same texp for different filters

3. We **compare CCN with the colour curves without noise** (CC) and we count how often we recognise the right original model among the others.

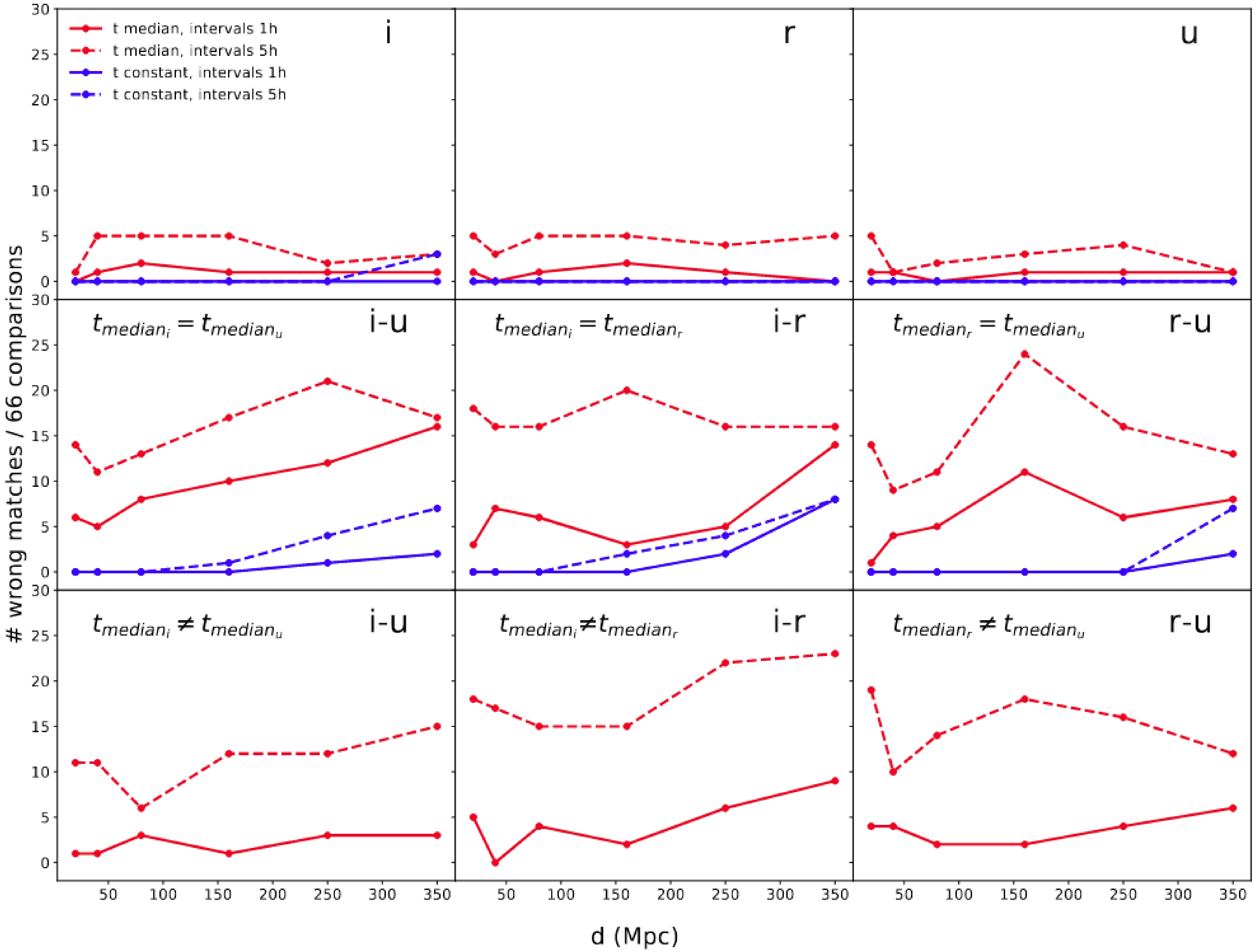
same procedure of Colours procedure, same texp for different filters

Results, general analysis

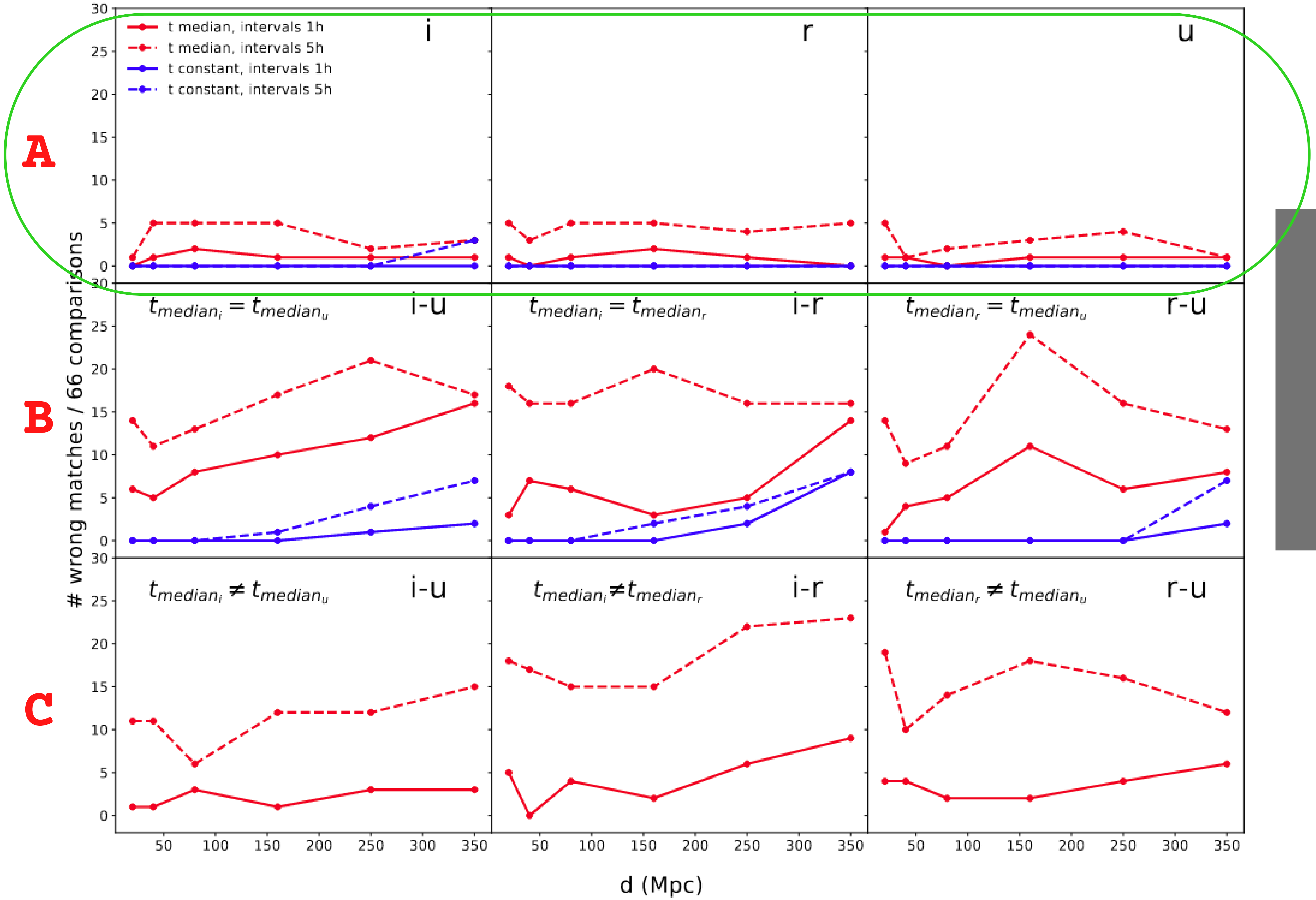
A

B

C



Results, general analysis



The best results are obtained using
constant 1-hour time exposure;
the individual filter procedure seems to work better

Results, texp = constant and 1 hour bins (I)

- ERROR on DISTANCE

1. We consider mistake of **1%** and **2%** on the estimation of the source distance.

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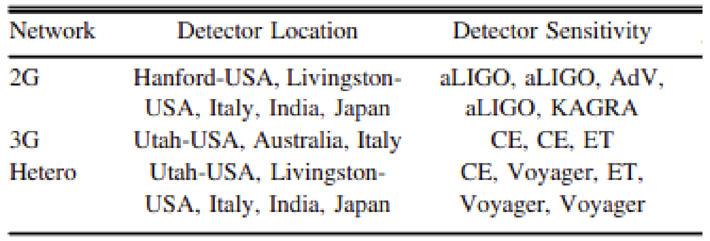
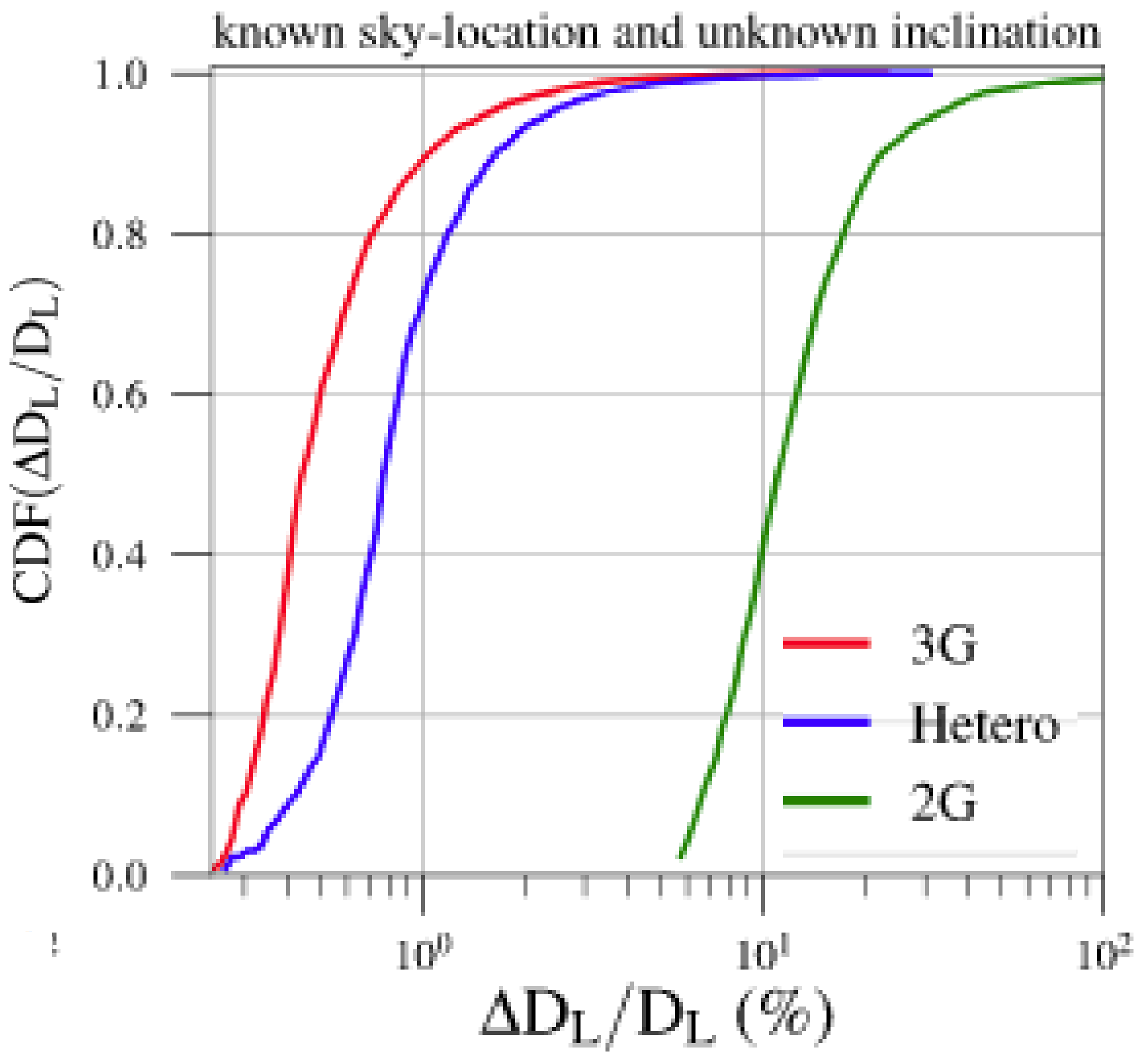


Network	Detector Location	Detector Sensitivity
2G	Hanford-USA, Livingston-USA, Italy, India, Japan	aLIGO, aLIGO, AdV, aLIGO, KAGRA
3G	Utah-USA, Australia, Italy	CE, CE, ET
Hetero	Utah-USA, Livingston-USA, Italy, India, Japan	CE, Voyager, ET, Voyager, Voyager

ERROR on DISTANCE from Gravitational waves Simulations



A. Gupta et al., 2019

Results, texp = constant and 1 hour bins (I)

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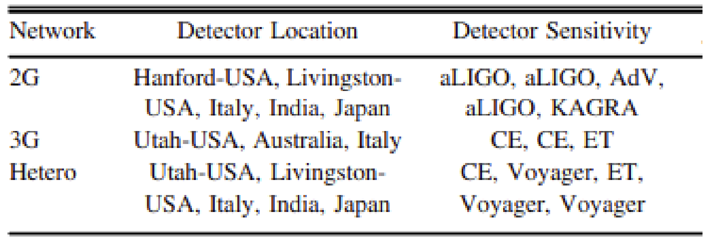

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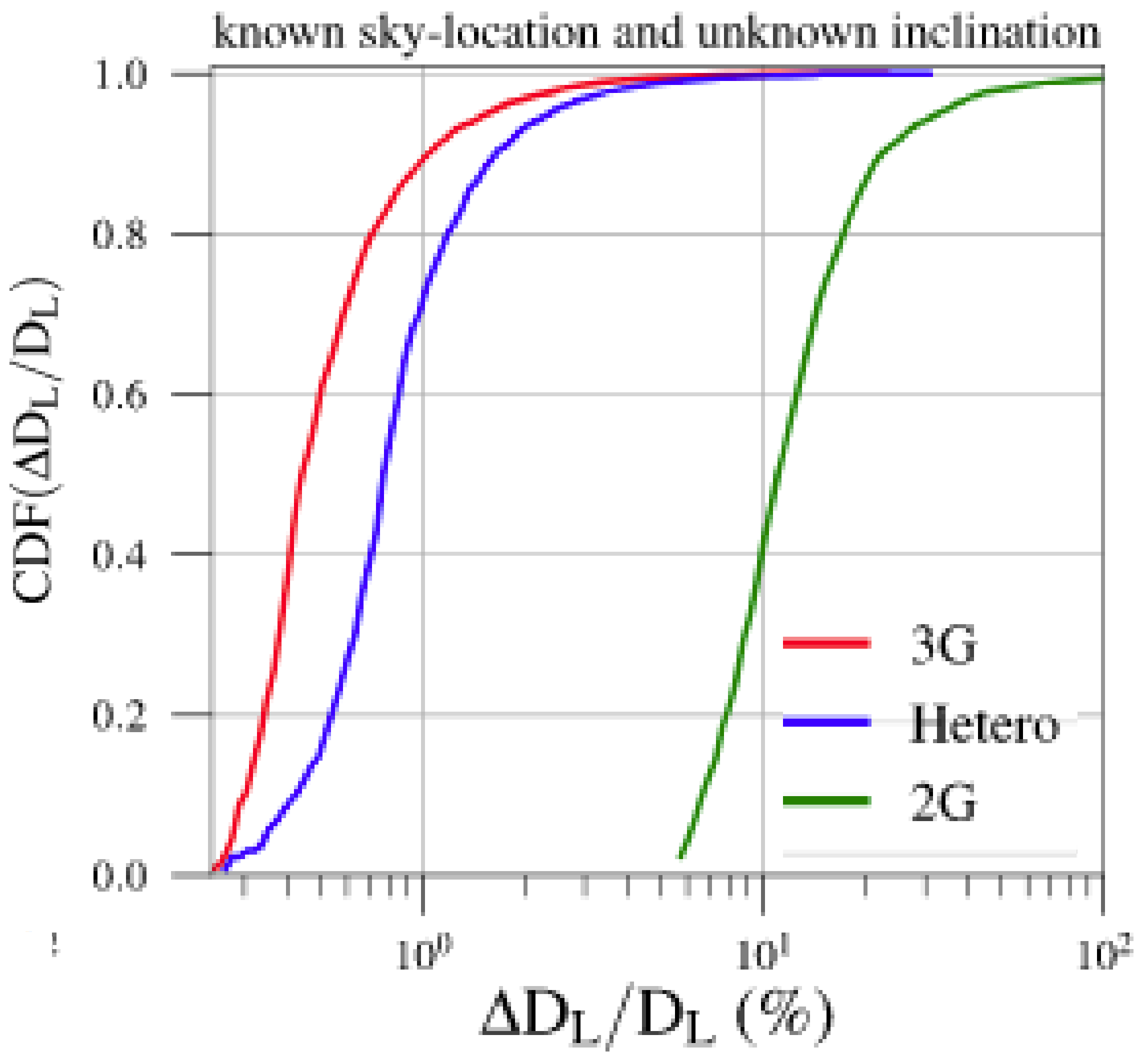
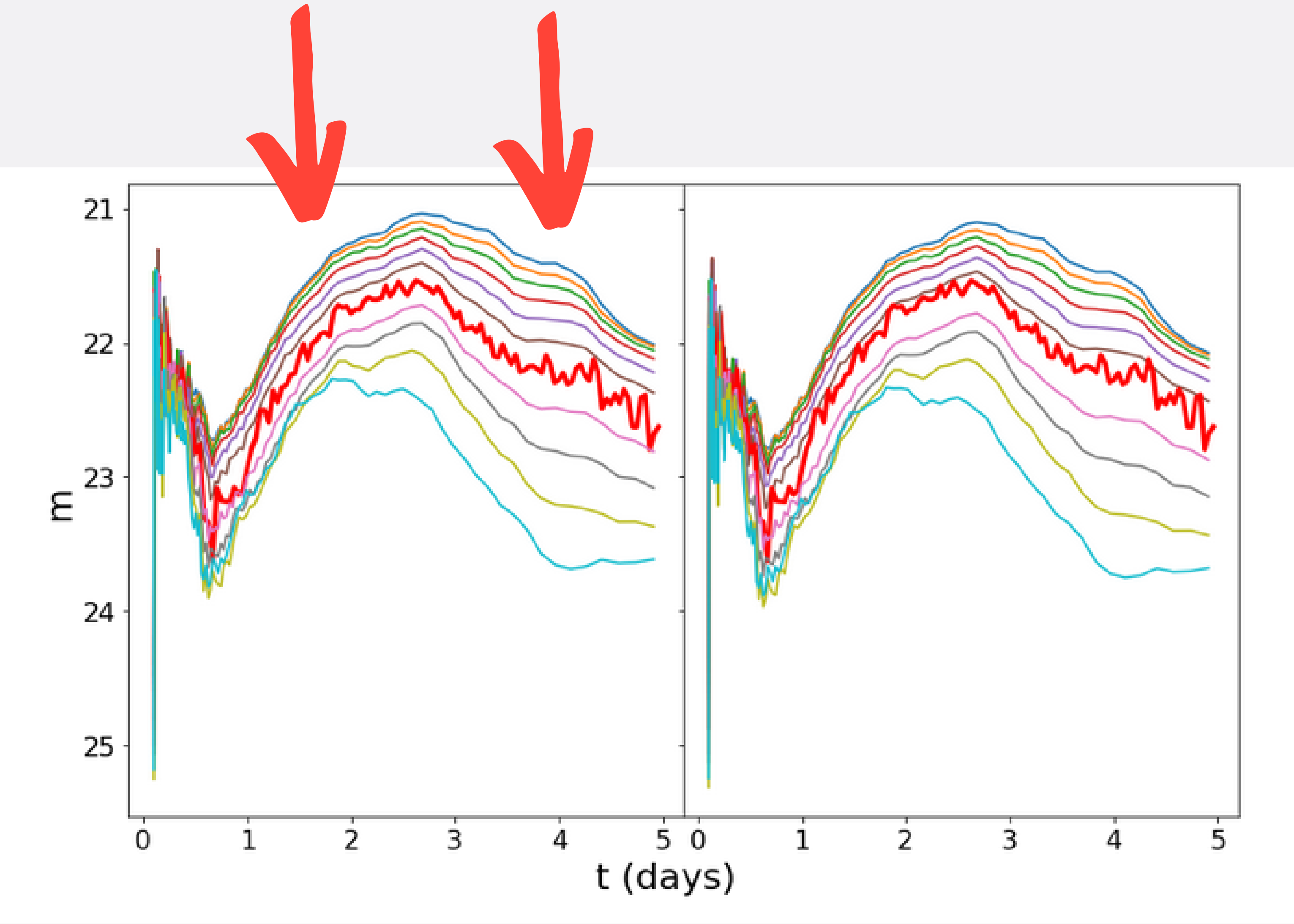


A. Gupta et al., 2019

Shift models LC due to +2% error on distance.

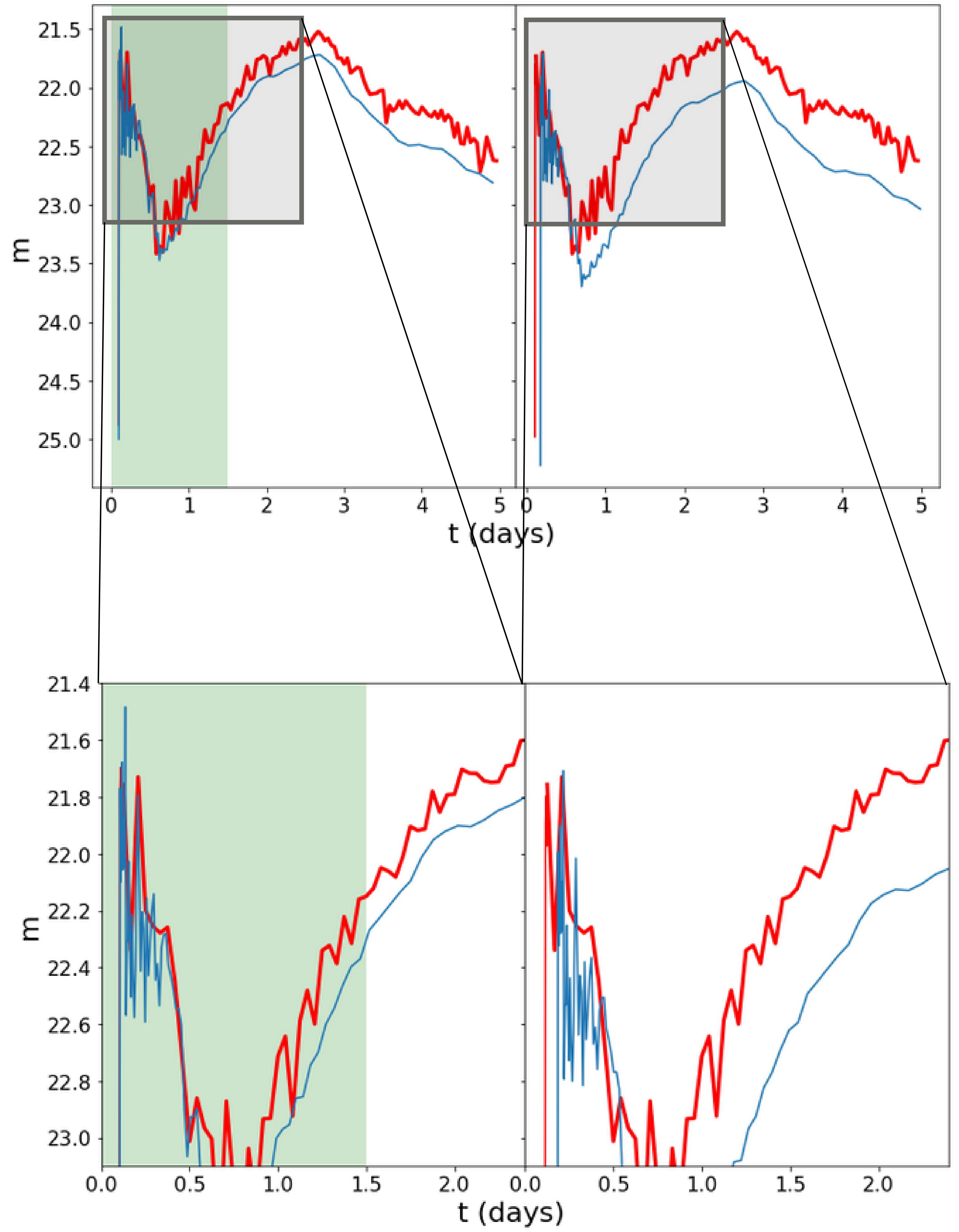


- NO KNOWLEDGE on DISTANCE and MERGER TIME

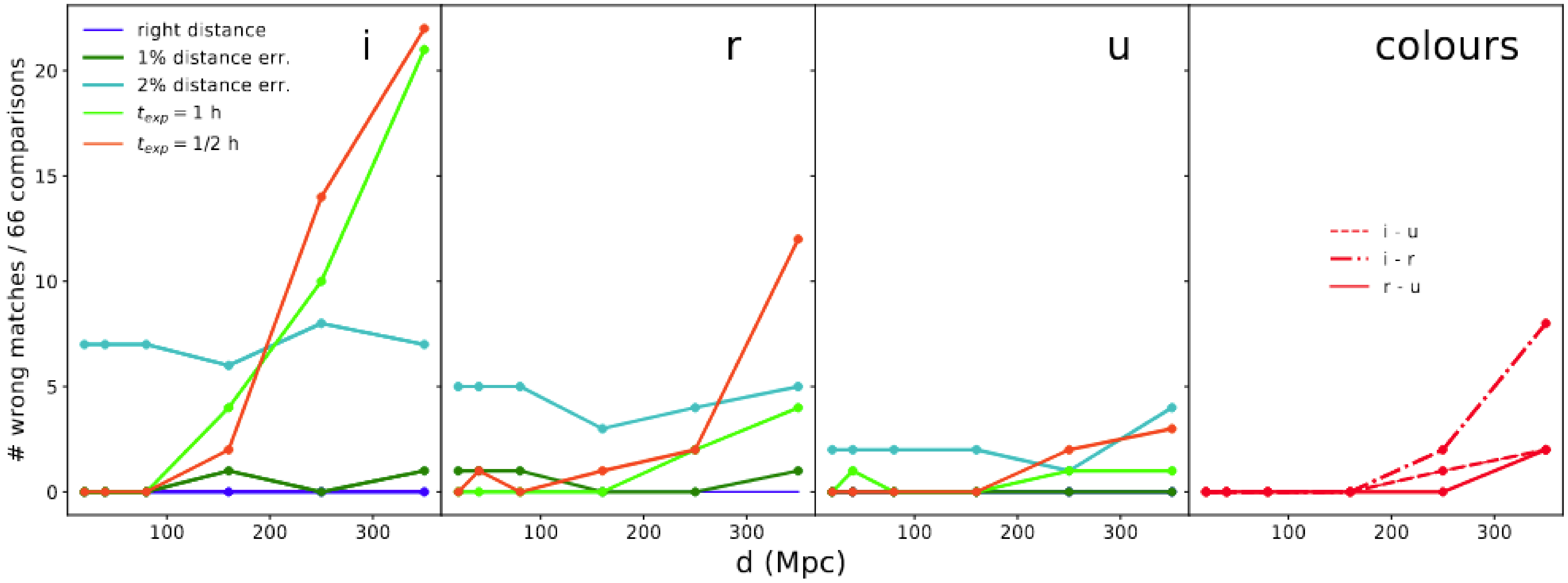
NO KNOWLEDGE on DISTANCE and MERGER TIME

2. We compare LCN with LCs shifted so that the peak flux of LCN in the first 1.5 days coincides in time and intensity with that of LC in the first 1.5 days.

We use this procedure both with constant time exposure of **1 hour** and **1/2 hour**



Results, texp = constant and 1 hour bins (II)



Conclusions

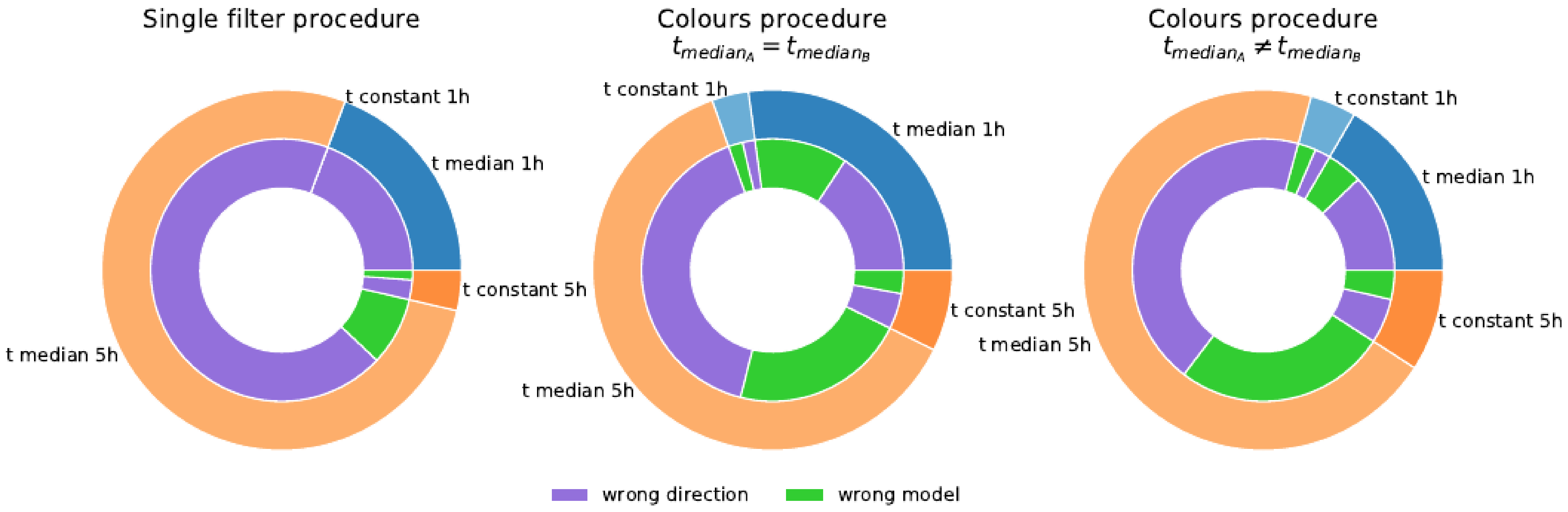
- We considered 6 models, both with and without dynamical ejecta, and 11 different inclination angles;

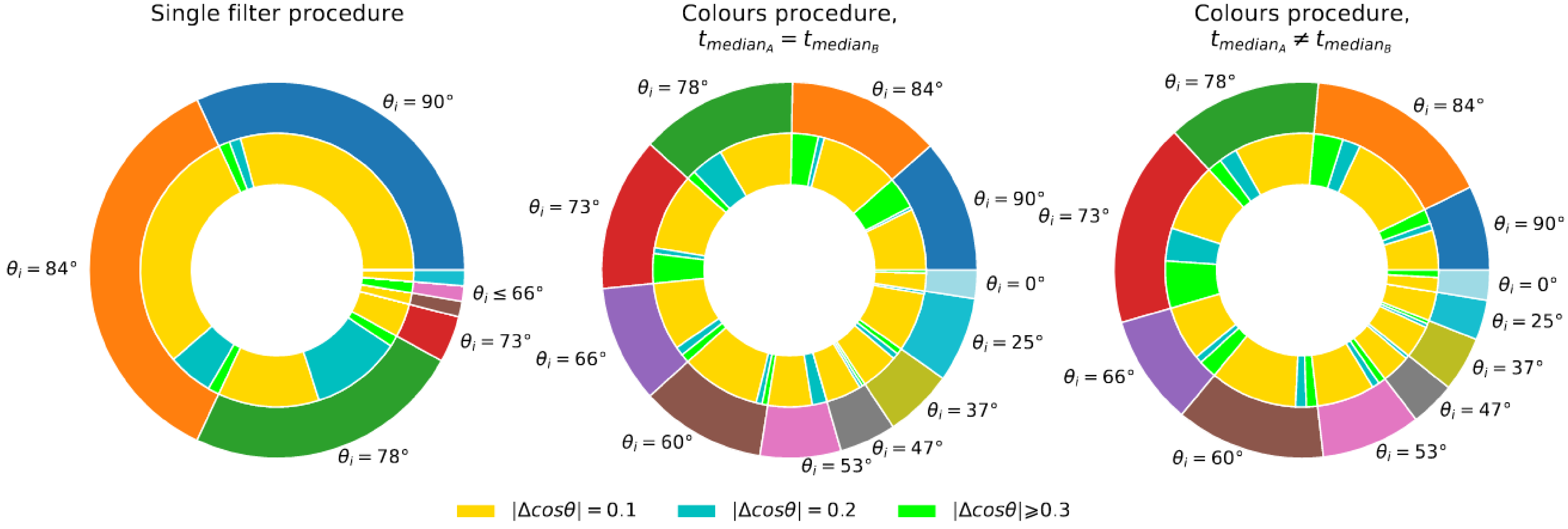
- Best strategy: texp = constant with 1 hour bins. Using this strategy:

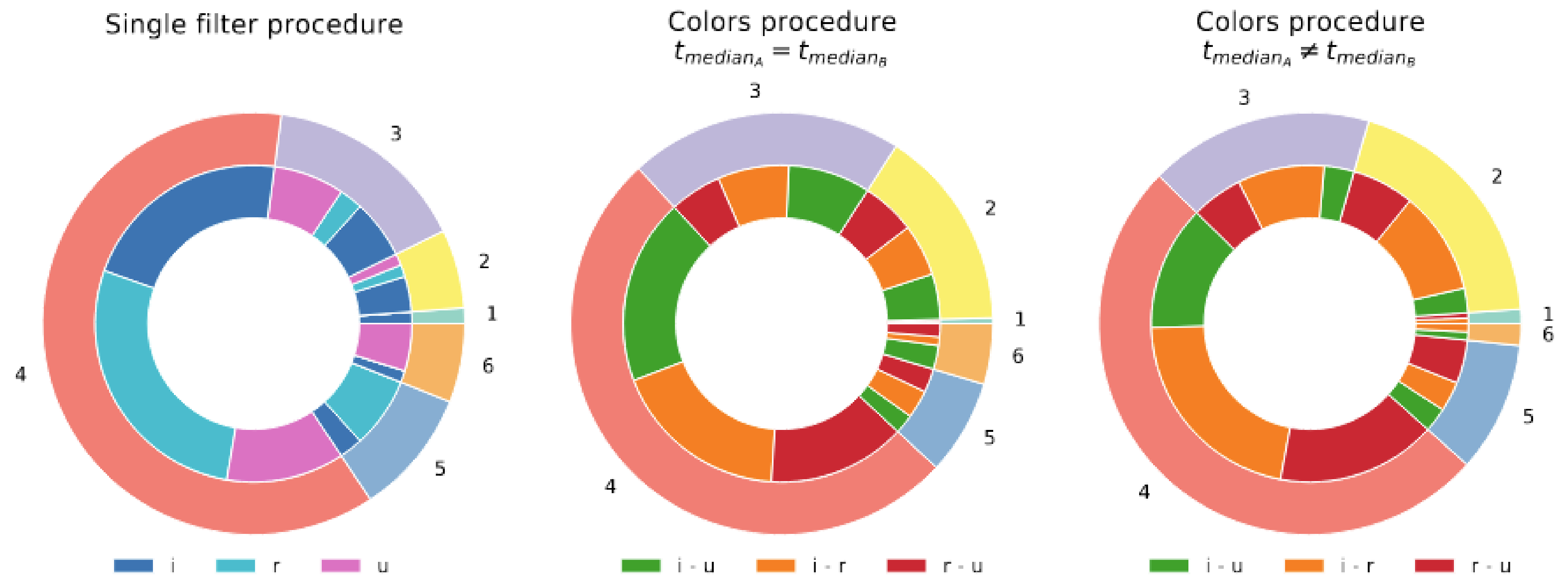
  - when the error on distance is ≤ 1 %, the results are really excellent both with filters and using colours, slightly better with u filter.

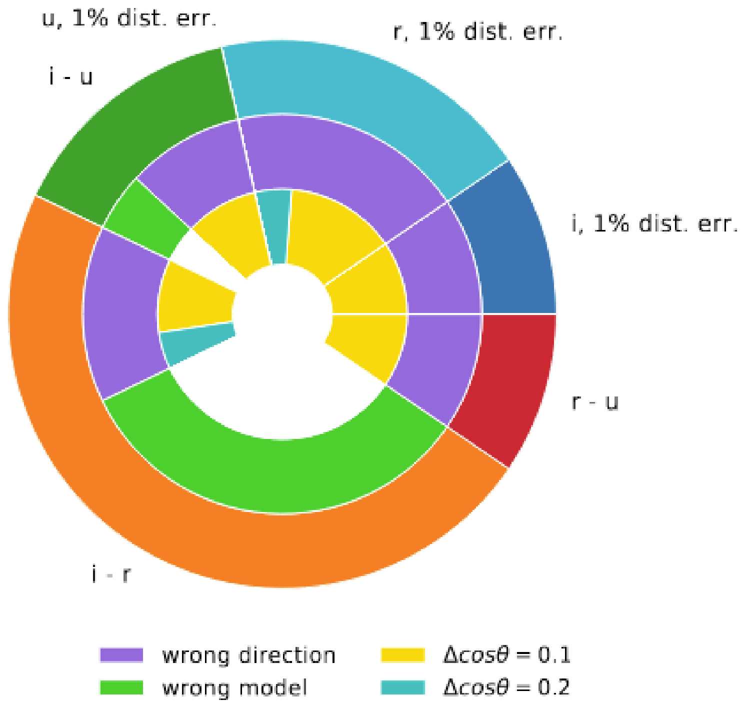
  - when either the error is > 1 % or the distance is unknown, using the i individual filter procedure should be avoided

Thank you!


Single filter procedure
t constant 1h
t median 1h
t constant 5h
t median 5h
Colours procedure
$t_{median_A} = t_{median_B}$
t constant 1h
t median 1h
t constant 5h
t median 5h
Colours procedure
$t_{median_A} \neq t_{median_B}$
t constant 1h
t median 1h
t constant 5h
t median 5h
wrong direction
wrong model


Single filter procedure
$\theta_i = 90°$
$\theta_i = 84°$
$\theta_i \leq 66°$
$\theta_i = 73°$
$\theta_i = 78°$
Colours procedure,
$t_{median_A} = t_{median_B}$
$\theta_i = 78°$
$\theta_i = 84°$
$\theta_i = 90°$
$\theta_i = 73°$
$\theta_i = 0°$
$\theta_i = 25°$
$\theta_i = 66°$
$\theta_i = 37°$
$\theta_i = 60°$
$\theta_i = 47°$
$\theta_i = 53°$
Colours procedure,
$t_{median_A} \neq t_{median_B}$
$\theta_i = 78°$
$\theta_i = 84°$
$\theta_i = 73°$
$\theta_i = 90°$
$\theta_i = 0°$
$\theta_i = 25°$
$\theta_i = 66°$
$\theta_i = 37°$
$\theta_i = 47°$
$\theta_i = 60°$
$\theta_i = 53°$
$|\Delta cos\theta| = 0.1$
$|\Delta cos\theta| = 0.2$
$|\Delta cos\theta| \geqslant 0.3$


Single filter procedure
3
2
1
6
5
4
i
r
u
Colors procedure
$t_{median_A} = t_{median_B}$
3
2
1
6
5
4
i - u
i - r
r - u
Colors procedure
$t_{median_A} \neq t_{median_B}$
3
2
1
6
5
4
i - u
i - r
r - u


u, 1% dist. err.
i - u
r, 1% dist. err.
i, 1% dist. err.
r - u
i - r
wrong direction
wrong model
$\Delta cos\theta = 0.1$
$\Delta cos\theta = 0.2$

We find the most similar LC among all the others minimizing:

$$\sum \left(\frac{m - m'}{m + m'} \right)^2 \cdot \frac{1}{N}$$

Individual procedure

$$\sum \left(\frac{\Delta m - \Delta m'}{\Delta m + \Delta m'} \right)^2 \cdot \frac{1}{N}$$

Color procedures

Possis starts when the expansion reaches the homologous phase (possibly inaccurate with active internal engine, like magnetar)

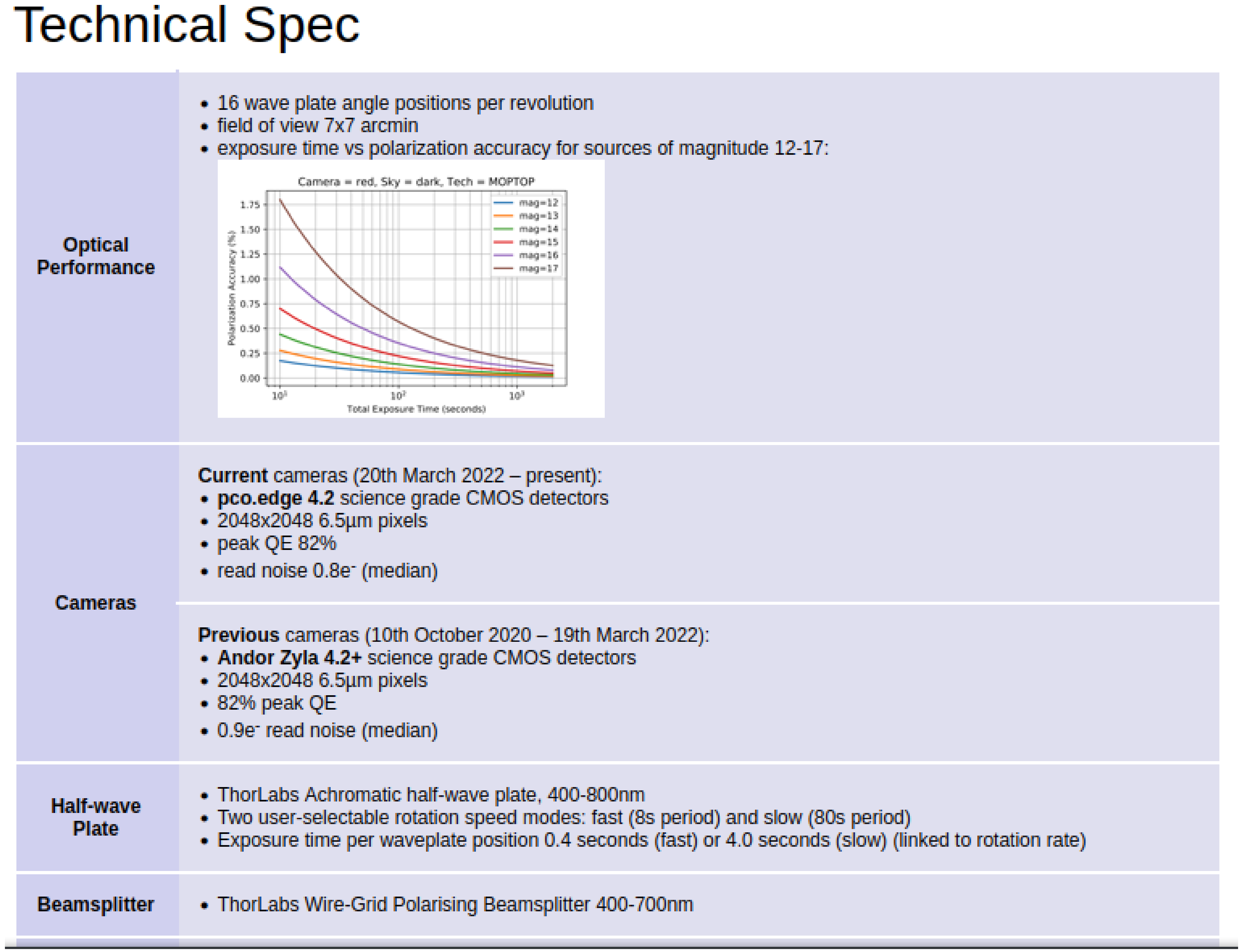
Possis can handle line opacity from bound-bound transitions (κbb) and continuum opacity from either electron scattering (κes), bound-free (κbf) or free-free (κff) absorption.

First days opacity are underextimated so luminosity overestimated (high ionization first days)

with dynamical ejecta higher opacity on merger plane

M disk wind = 0.072 Msun (Nativi)
M dynamical ejecta = 0.005 Msun (da kilonova 2017)

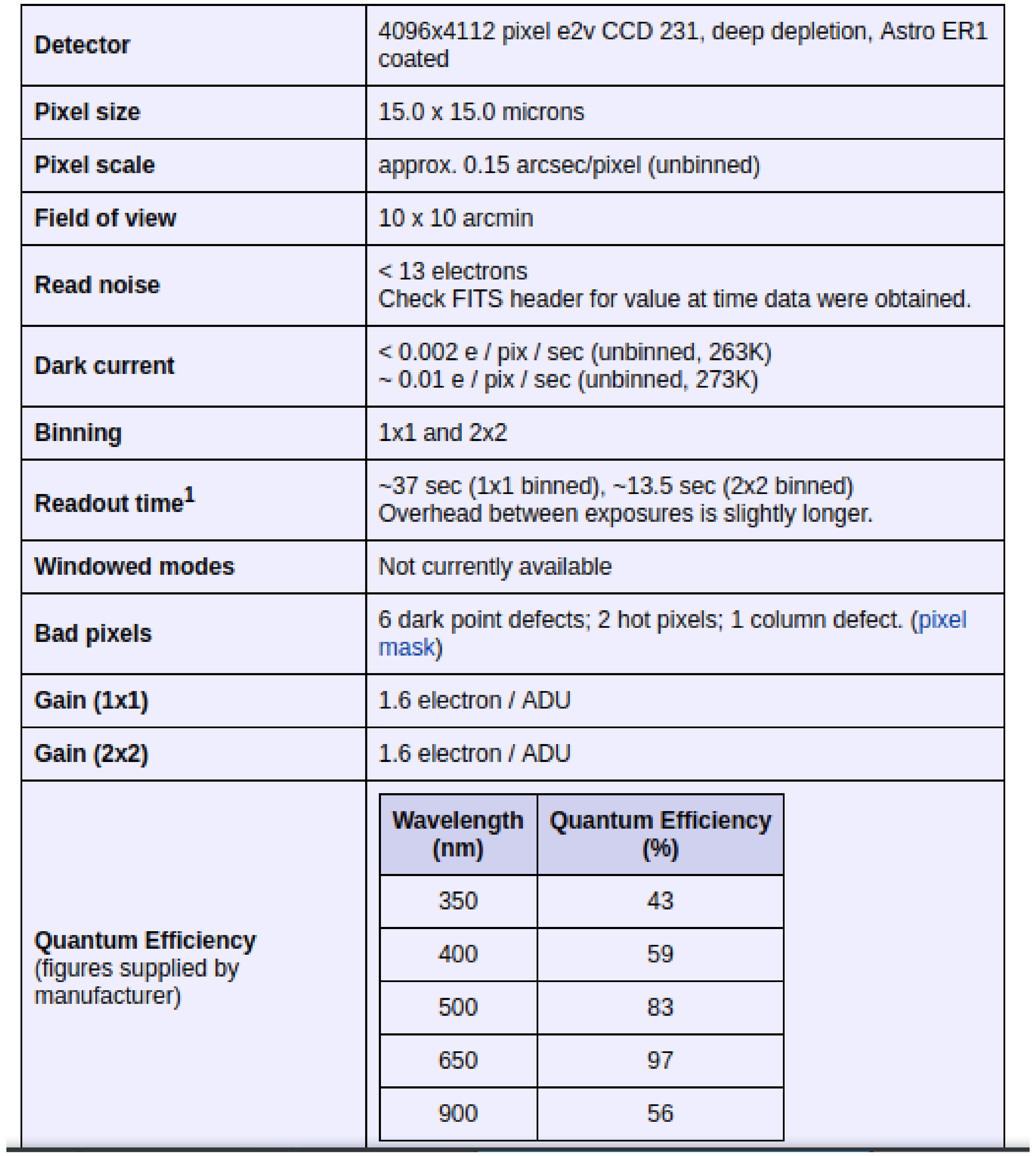
MOPTOP's design enables the measurement of polarisation and photometric variability on timescales as short as a few seconds.



Technical Spec

Optical Performance	• 16 wave plate angle positions per revolution • field of view 7x7 arcmin • exposure time vs polarization accuracy for sources of magnitude 12-17:
Cameras	**Current** cameras (20th March 2022 – present): • **pco.edge 4.2** science grade CMOS detectors • 2048x2048 6.5µm pixels • peak QE 82% • read noise 0.8e$^-$ (median)
	Previous cameras (10th October 2020 – 19th March 2022): • **Andor Zyla 4.2+** science grade CMOS detectors • 2048x2048 6.5µm pixels • 82% peak QE • 0.9e$^-$ read noise (median)
Half-wave Plate	• ThorLabs Achromatic half-wave plate, 400-800nm • Two user-selectable rotation speed modes: fast (8s period) and slow (80s period) • Exposure time per waveplate position 0.4 seconds (fast) or 4.0 seconds (slow) (linked to rotation rate)
Beamsplitter	• ThorLabs Wire-Grid Polarising Beamsplitter 400-700nm

IO:O



Detector	4096x4112 pixel e2v CCD 231, deep depletion, Astro ER1 coated
Pixel size	15.0 x 15.0 microns
Pixel scale	approx. 0.15 arcsec/pixel (unbinned)
Field of view	10 x 10 arcmin
Read noise	< 13 electrons Check FITS header for value at time data were obtained.
Dark current	< 0.002 e / pix / sec (unbinned, 263K) ~ 0.01 e / pix / sec (unbinned, 273K)
Binning	1x1 and 2x2
Readout time[1]	~37 sec (1x1 binned), ~13.5 sec (2x2 binned) Overhead between exposures is slightly longer.
Windowed modes	Not currently available
Bad pixels	6 dark point defects; 2 hot pixels; 1 column defect. (pixel mask)
Gain (1x1)	1.6 electron / ADU
Gain (2x2)	1.6 electron / ADU
Quantum Efficiency (figures supplied by manufacturer)	

Wavelength (nm)	Quantum Efficiency (%)
350	43
400	59
500	83
650	97
900	56