Sensitivity of strong lenses to DM substructure

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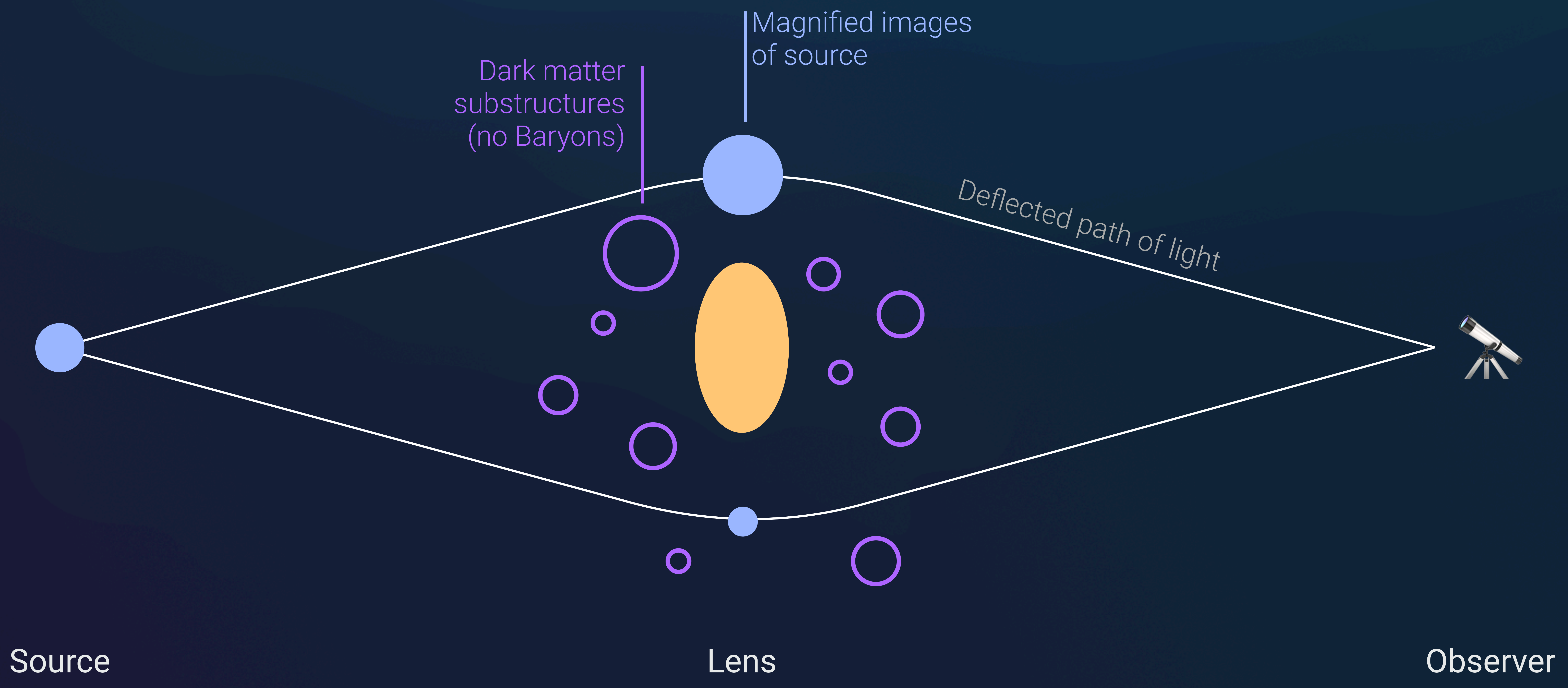
FOR ASTROPHYSICS

Background:

Strong lensing



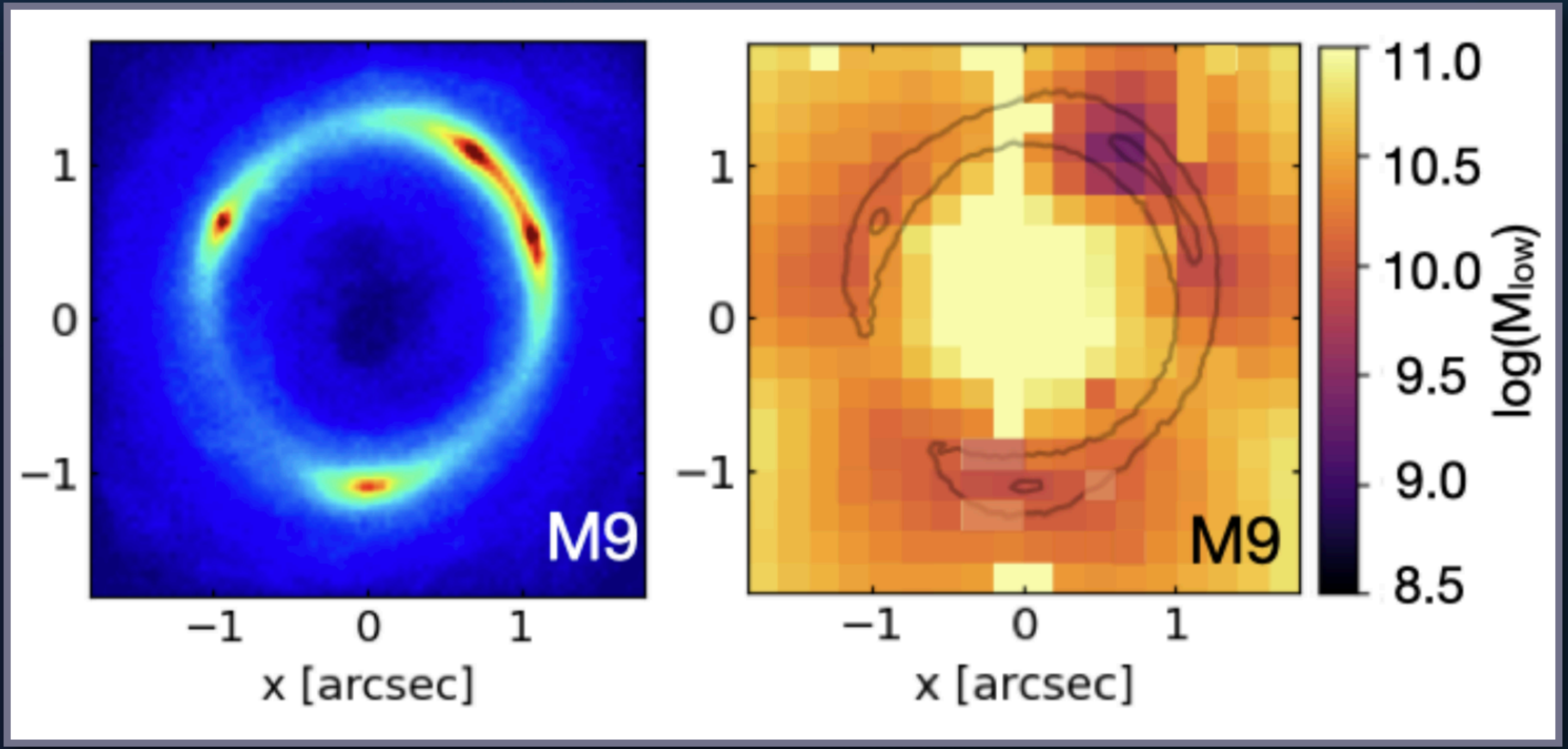
Background:

Sensitivity function

Find the best *smooth* model

Find corrections to the potential → Yields subhalo detections

Calculate the *sensitivity* of the observation* → Places limits on non-detections

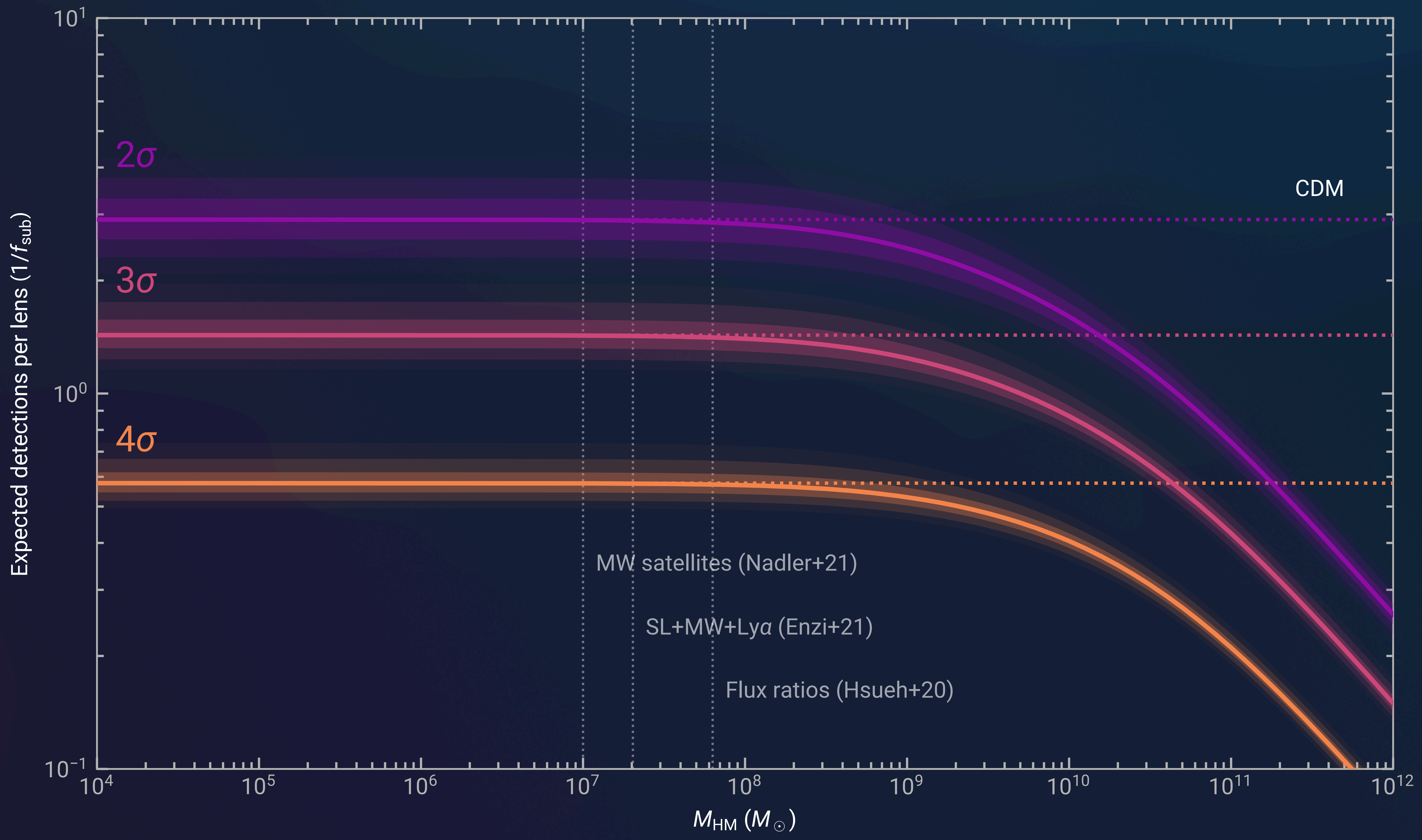


Despali et al (2021)

**exppensive!*

Background:
Sensitivity mapping in *Euclid*

O'Riordan et al (2023)



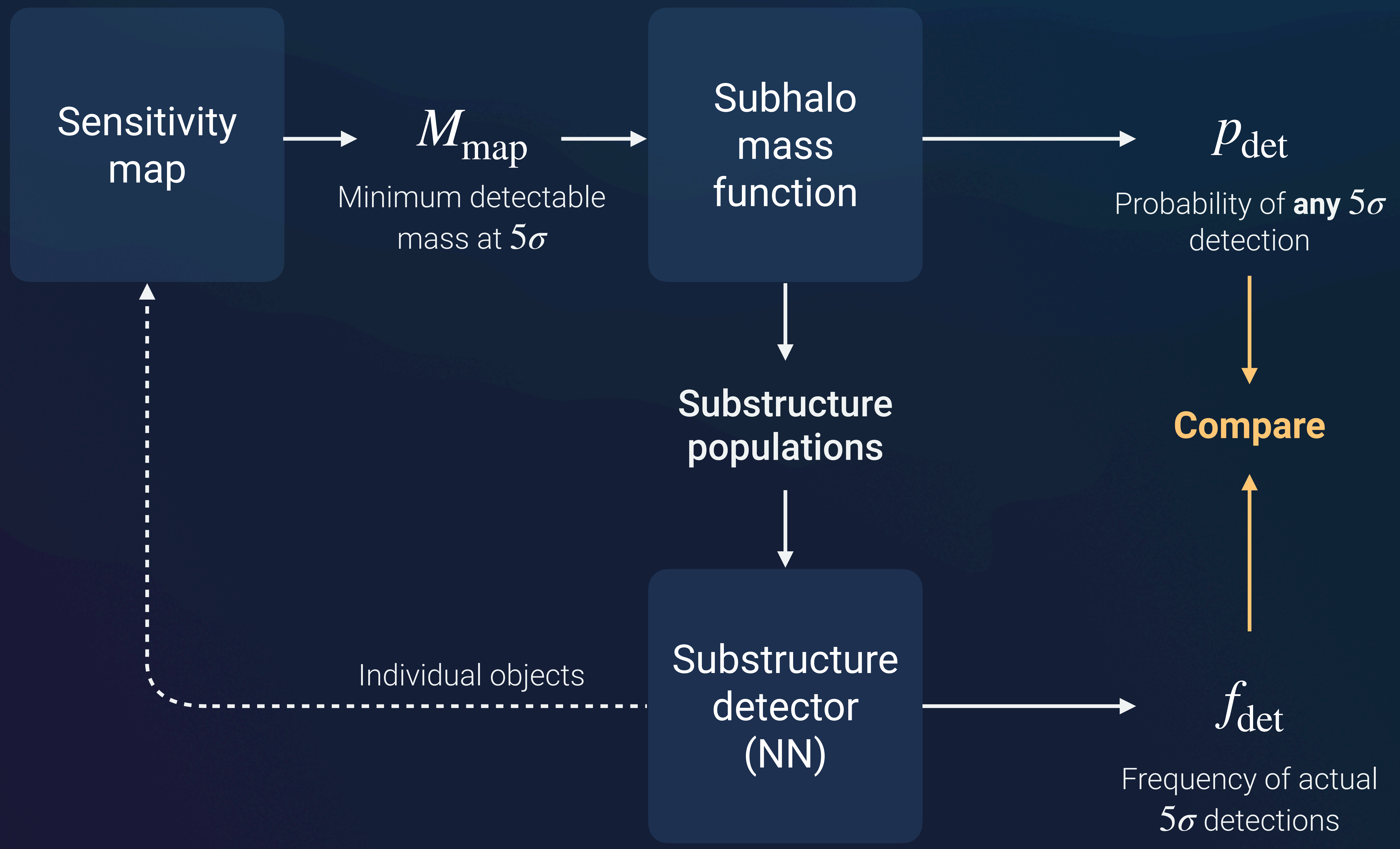
At 3σ, we expect $1.43^{+0.14}_{-0.11}[f_{\rm sub}^{-1}]$ detections per lens.

Assuming $f_{\rm sub} = 10^{-2}$, that's one detection in every ~ 70 lenses.

But, the number of detections is consistent with CDM for any interesting value of $M_{\rm hm}$.

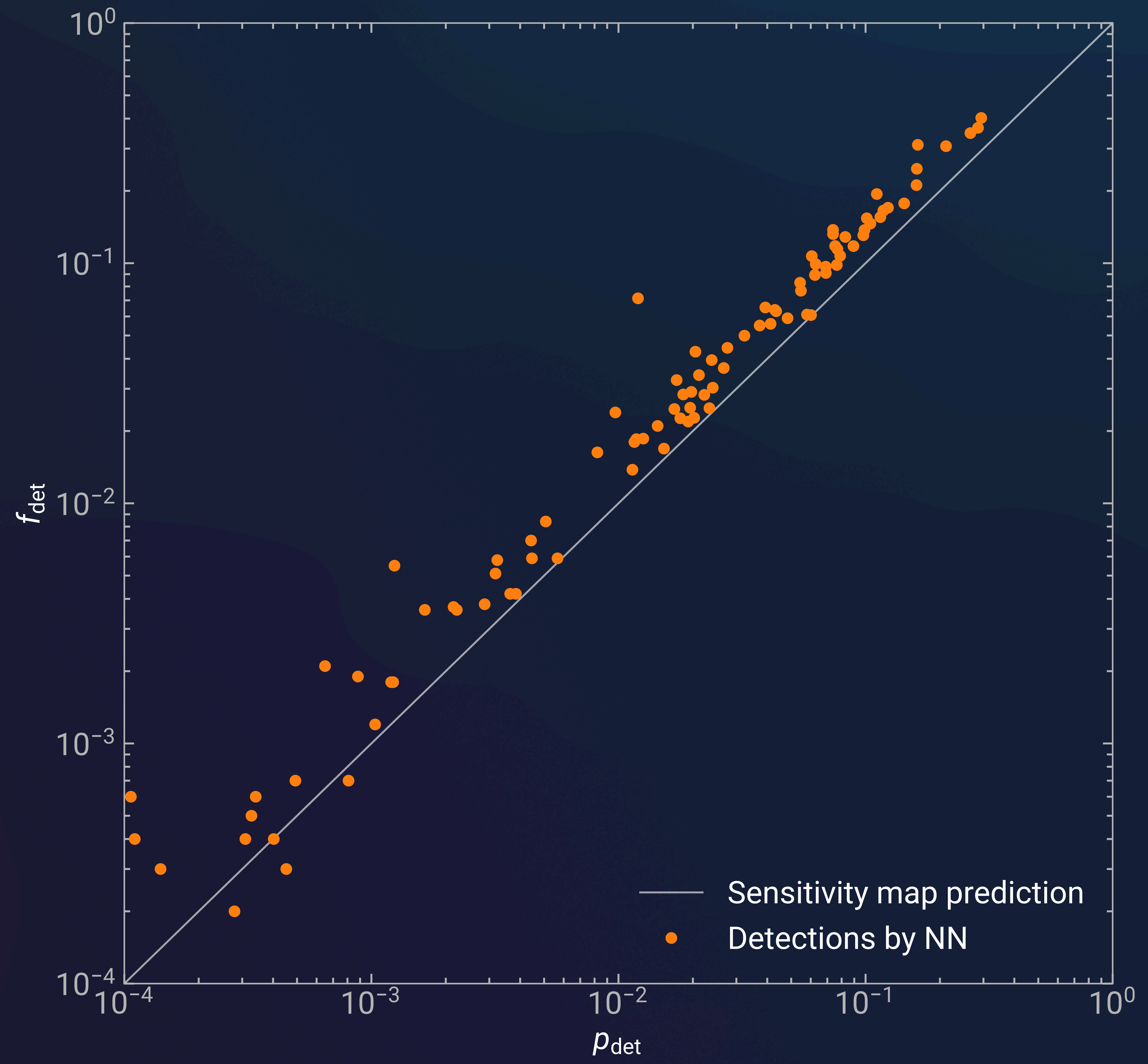
Method:

Comparing individual and population detections



Results:

Detections from subhalo populations

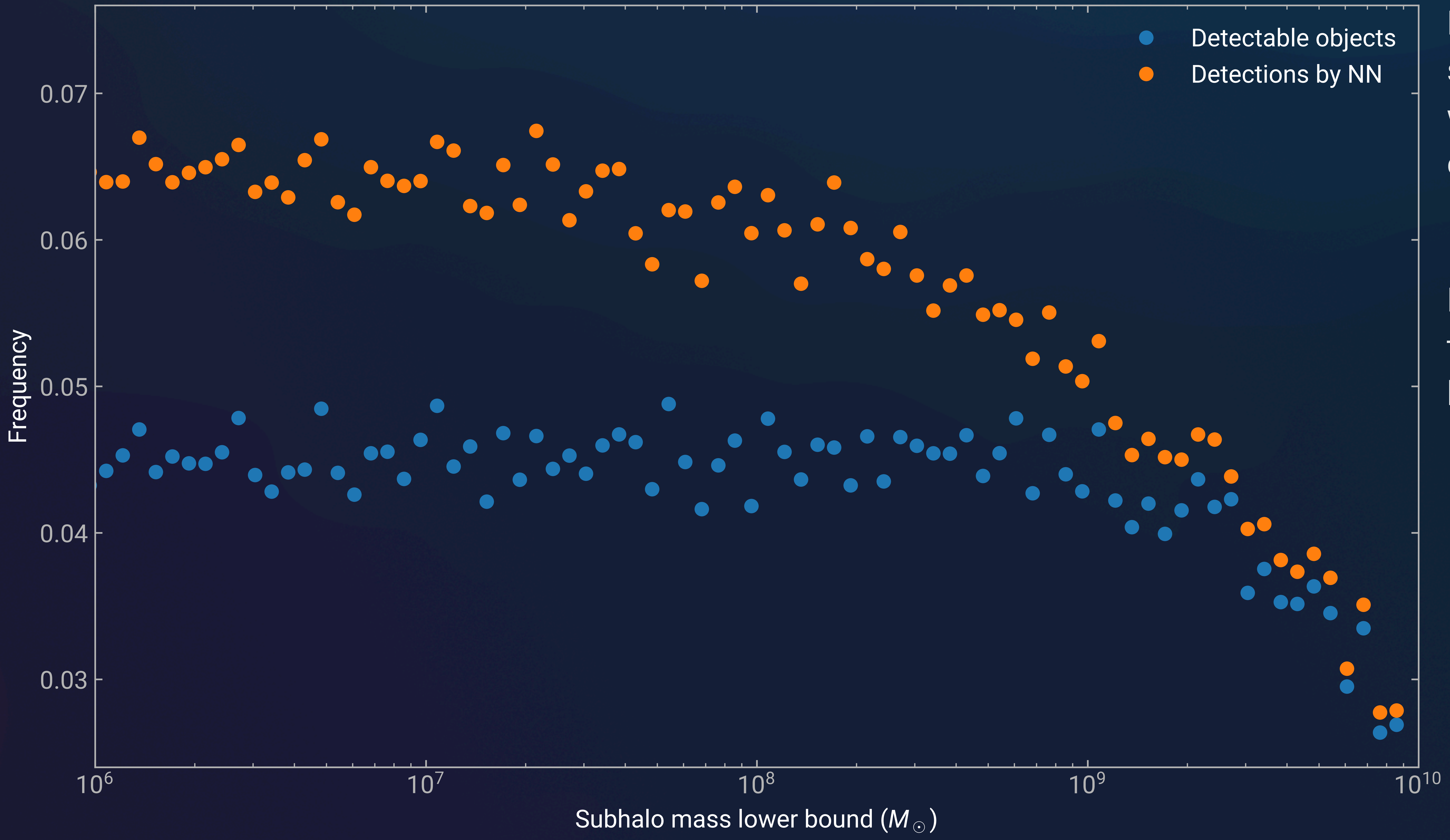


In data with CDM populations of subhaloes, our NN detects substructure ~1.5x more often than the sensitivity map predicts

This excess is consistent across all lenses.

Results:

Detections from subhalo populations

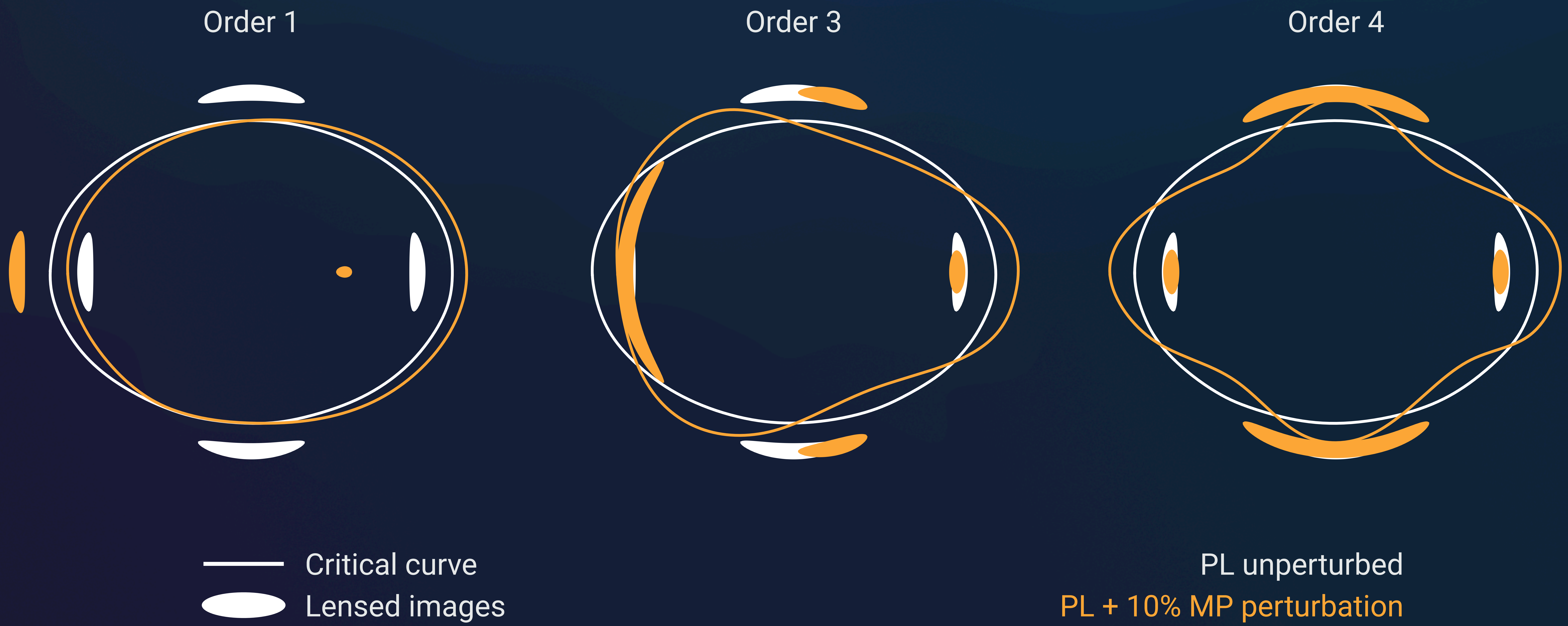


By removing lower mass subhaloes from the population, we isolate the source of the excess.

Do objects below the detection threshold become detectable in large numbers…?

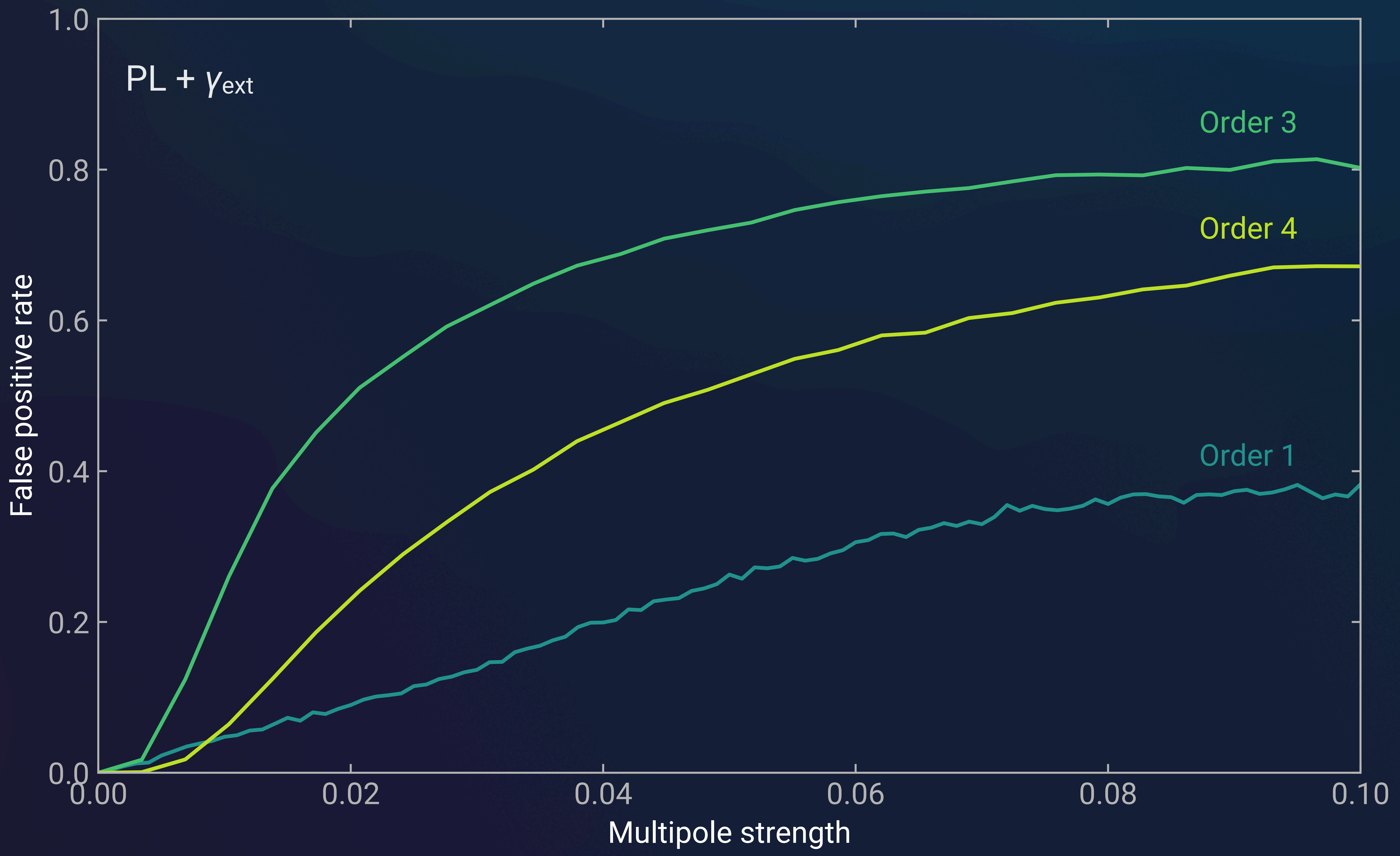
Method:

Modelling angular structure



Results:

Substructure false positives



We add multipoles to our mock HST data and run the images through our PL-only model.

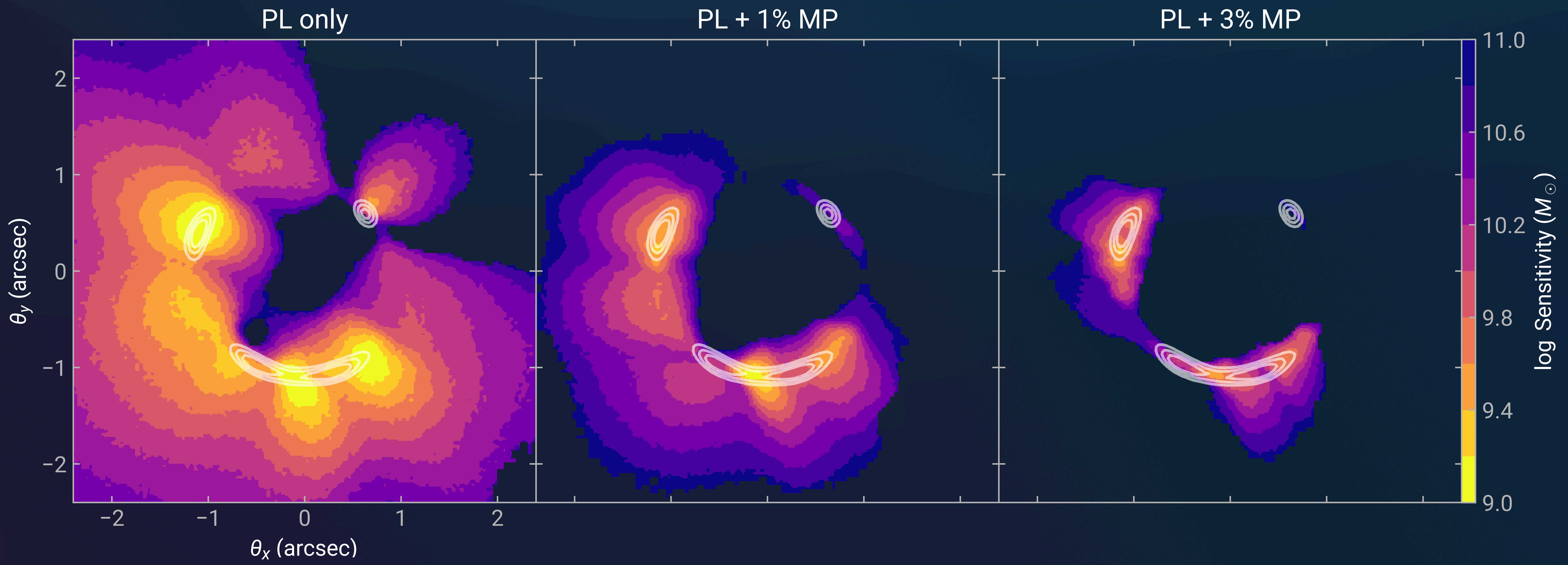
Substructure is detected very often for even modest multipole strengths.

Order 3 multipoles have the strongest degeneracy, followed closely by order 4.

Models with 1% and 3% MPs have zero false positives in this range.

Results:

Sensitivity mapping with multipoles

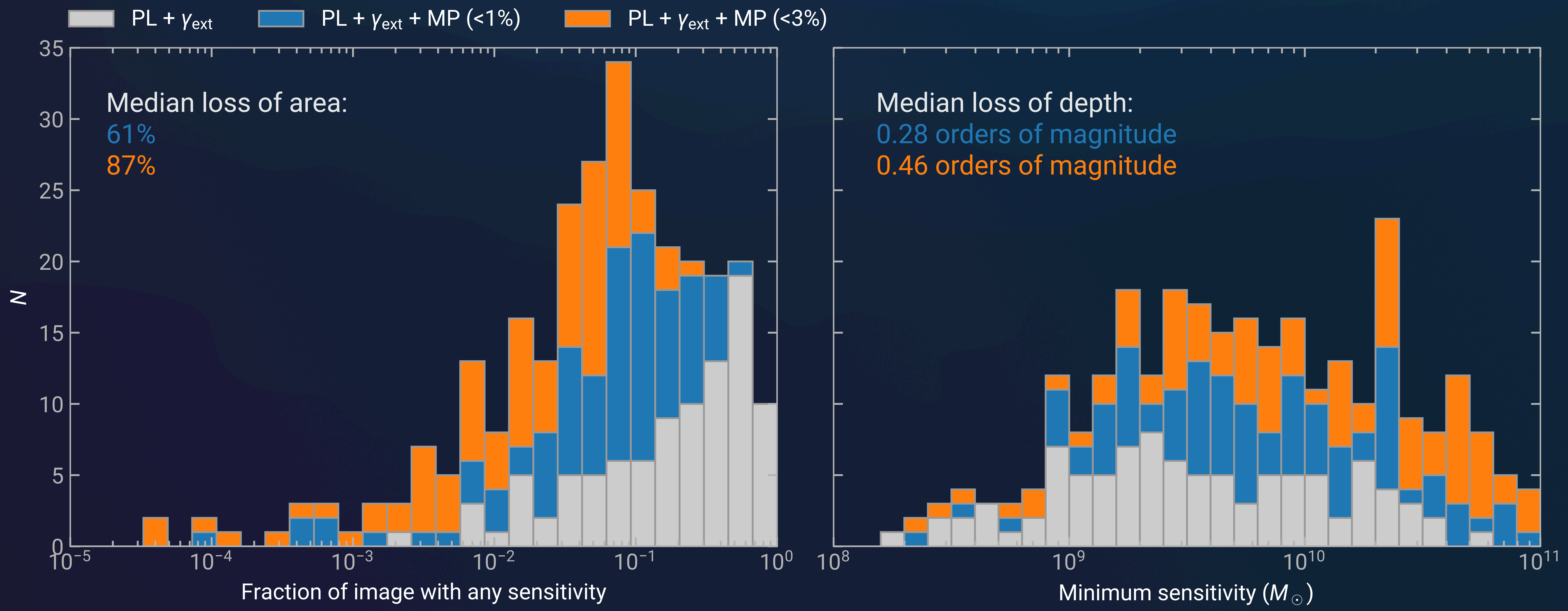


Including multipoles in the macro-model removes sensitivity away from the arc

Sensitivity in and close to the arc remains similar, especially when going from modest to extreme multipoles

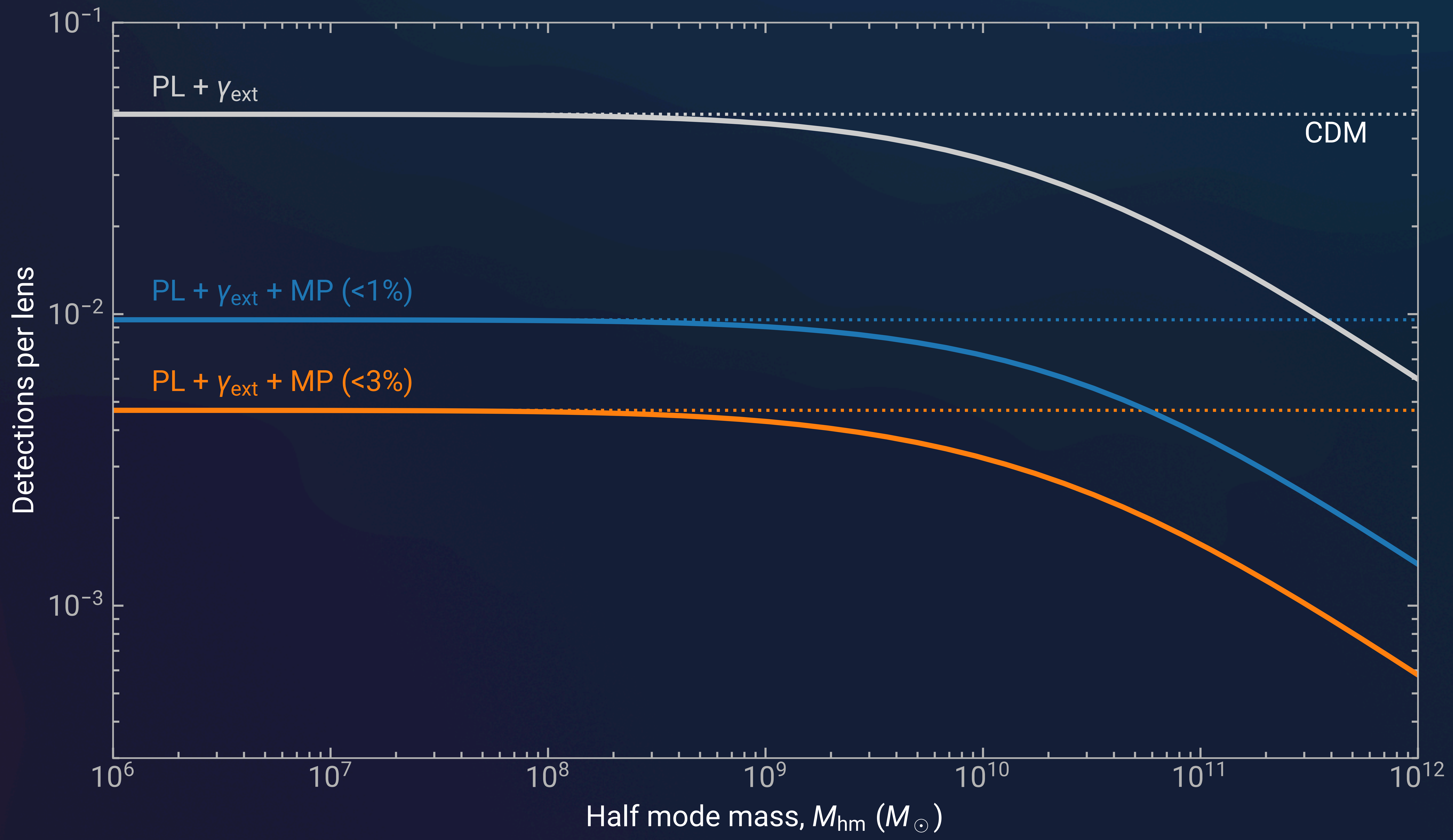
Results:

Sensitivity mapping with multipoles



Results:

Expected detections with multipoles

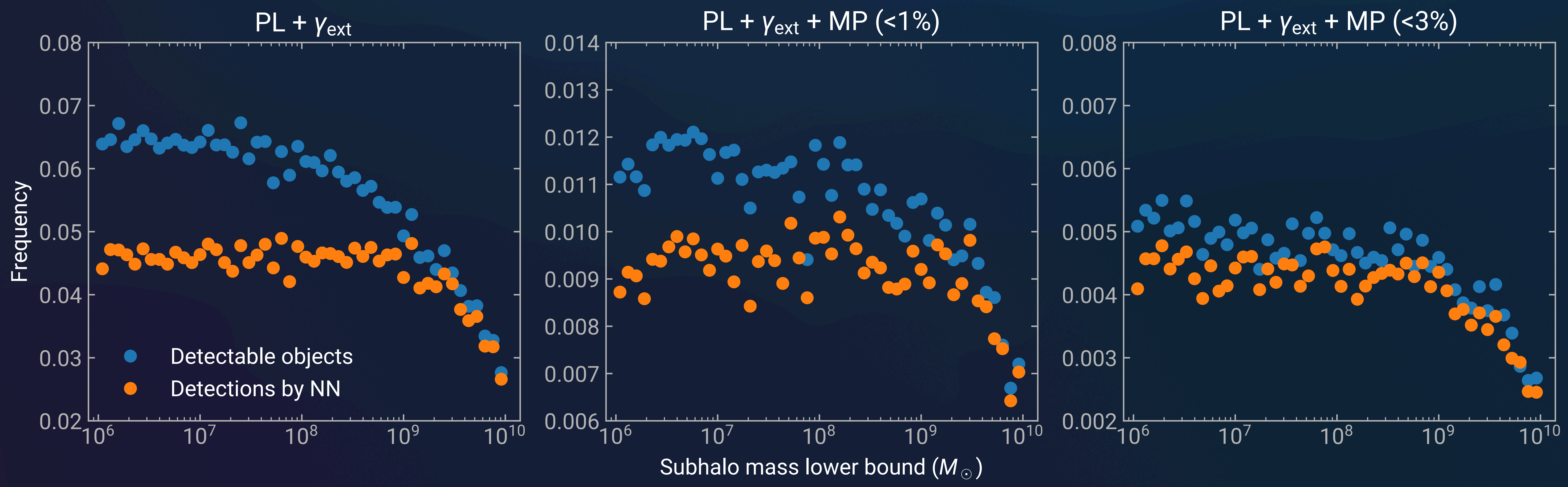


With a smaller sensitive area, the number of expected detections drops by a factor of 4 for the 1% case.

But with only a small change in depth, the number of detections deviate from CDM at similar HM masses.

Results:

Detections from subhalo populations



Do objects below the detection threshold become detectable in large numbers… maybe?

Conclusions

Populations of CDM substructures have an effect degenerate with small amounts of angular structure in the lens.

For multipoles up to 1% amplitude we find…

20% False positive detection rate

61% Loss in sensitivity area

0.28 Orders of magnitude loss in depth

Substructure detection efforts must allow for angular structure in the lens to avoid biased DM inferences.

See O'Riordan et al (2023, MNRAS) for
ML method, v_{max}-r_{max} relation, *Euclid* forecasts

and coming soon O'Riordan et al (2023, in prep) for:
DM inference, population degeneracy, subhalo interactions

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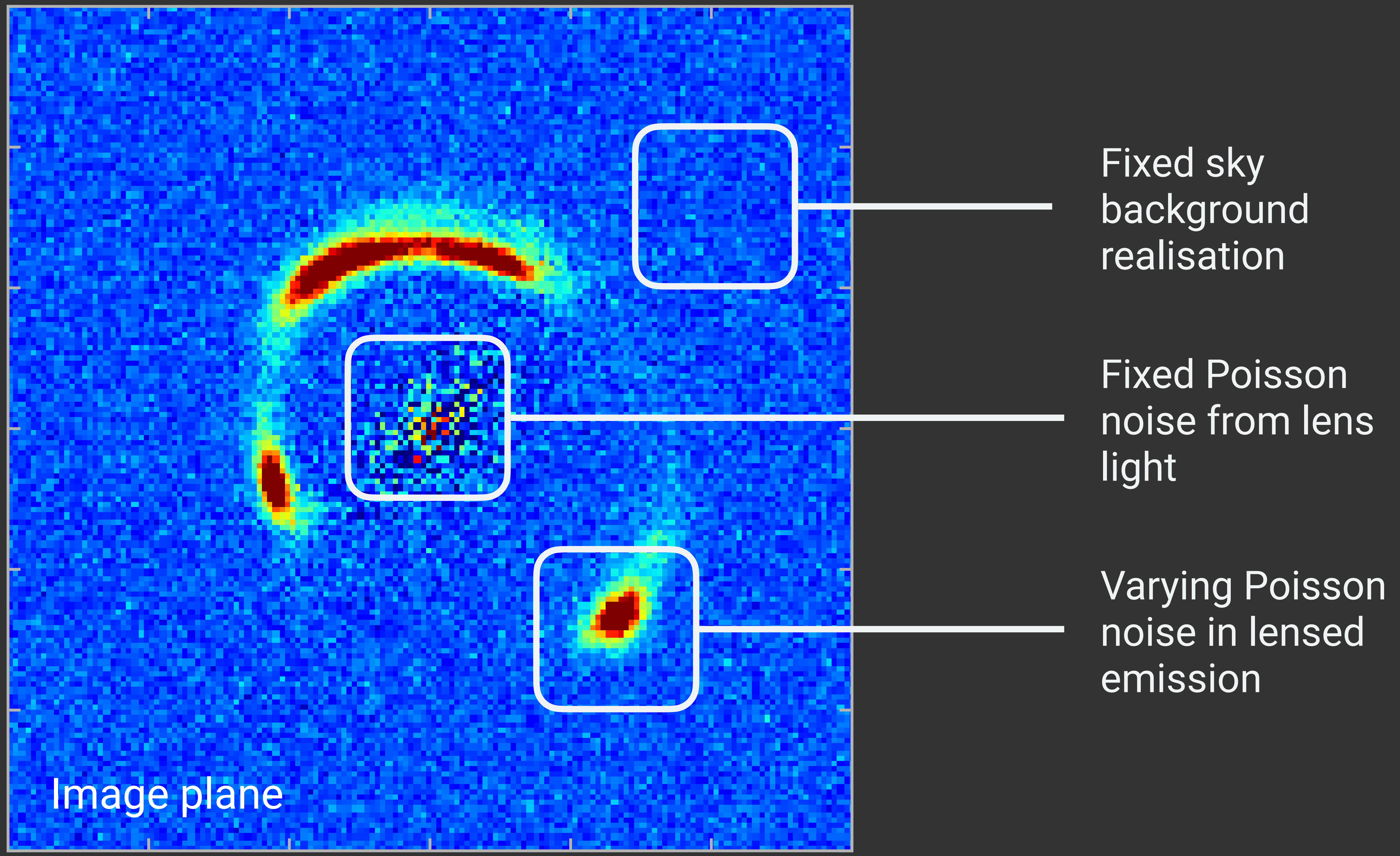
Extra slides

Method:

Modelling angular structure

		Lensing components	Observation	Subhaloes
		Hubble deep field sources	S/N from 10^1 to 10^3	$v_{\rm max} - r_{\rm max}$ to set concentration
PL + $\gamma_{\rm ext}$		Elliptical power-law mass	HST pixel scale and PSF	$M_{\rm max}$ from $10^{7.6}$ to 10^{11}
		External shear	Poisson limited lens subtraction	Zero or 1-4, randomly placed
PL + $\gamma_{\rm ext}$ + MP (<1%)	+	Order 1, 3, 4 MPs <1%		
PL + $\gamma_{\rm ext}$ + MP (<1%)	+	Order 1, 3, 4 MPs <3%		

Sensitivity map uncertainty



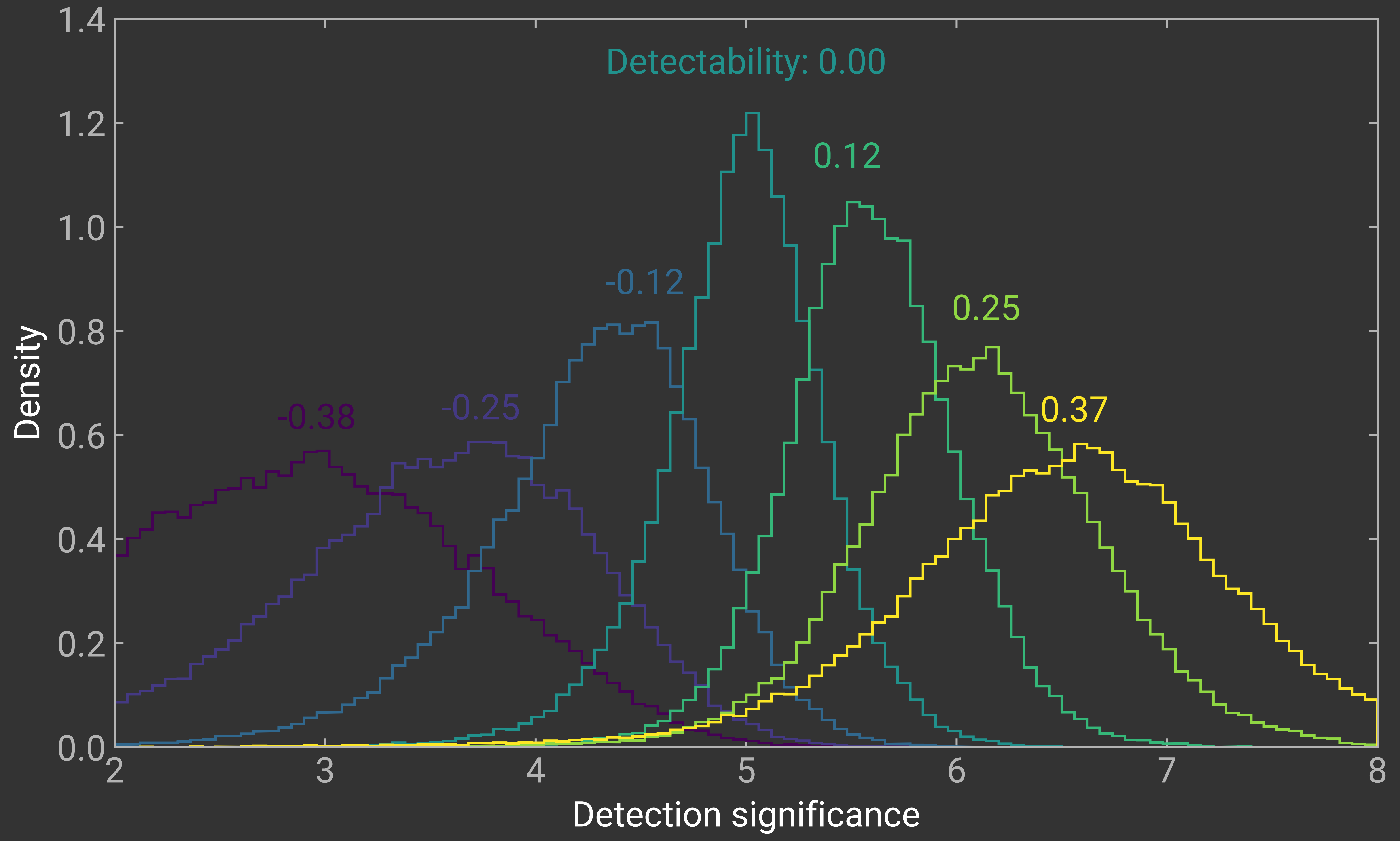
Some of the noise in the image changes between making the sensitivity map and running the subhalo detections

This introduces uncertainty - what was detectable at 5σ in the SM realisation, might not be when we run the detections, and vice versa

Accounting for uncertainty will always boost the number of expected detections because the mass function is steep.

Sensitivity map uncertainty

Here I define the detectability of a subhalo: $\log\left(M_{\rm max}/M_{\rm map}\right)$



Running many realisations of the same single subhalo through the detector gives a distribution of detection significances, as a function of how detectable the subhalo is.

Repeating for many lenses and masses we can estimate the uncertainty as a function of mass

At all masses, $\sigma_{M_{\rm map}}/M_{\rm map} < 10^{-1}$

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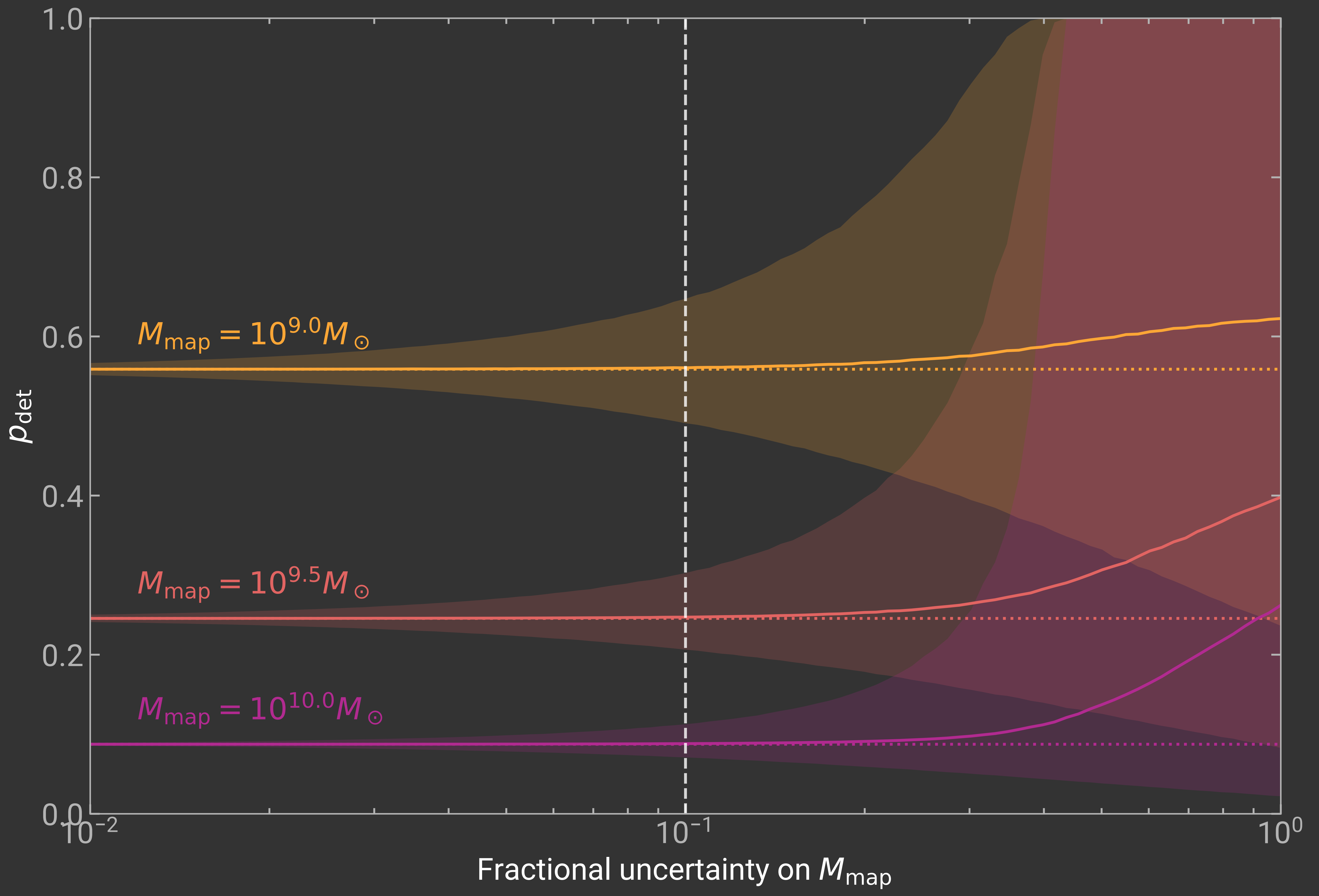

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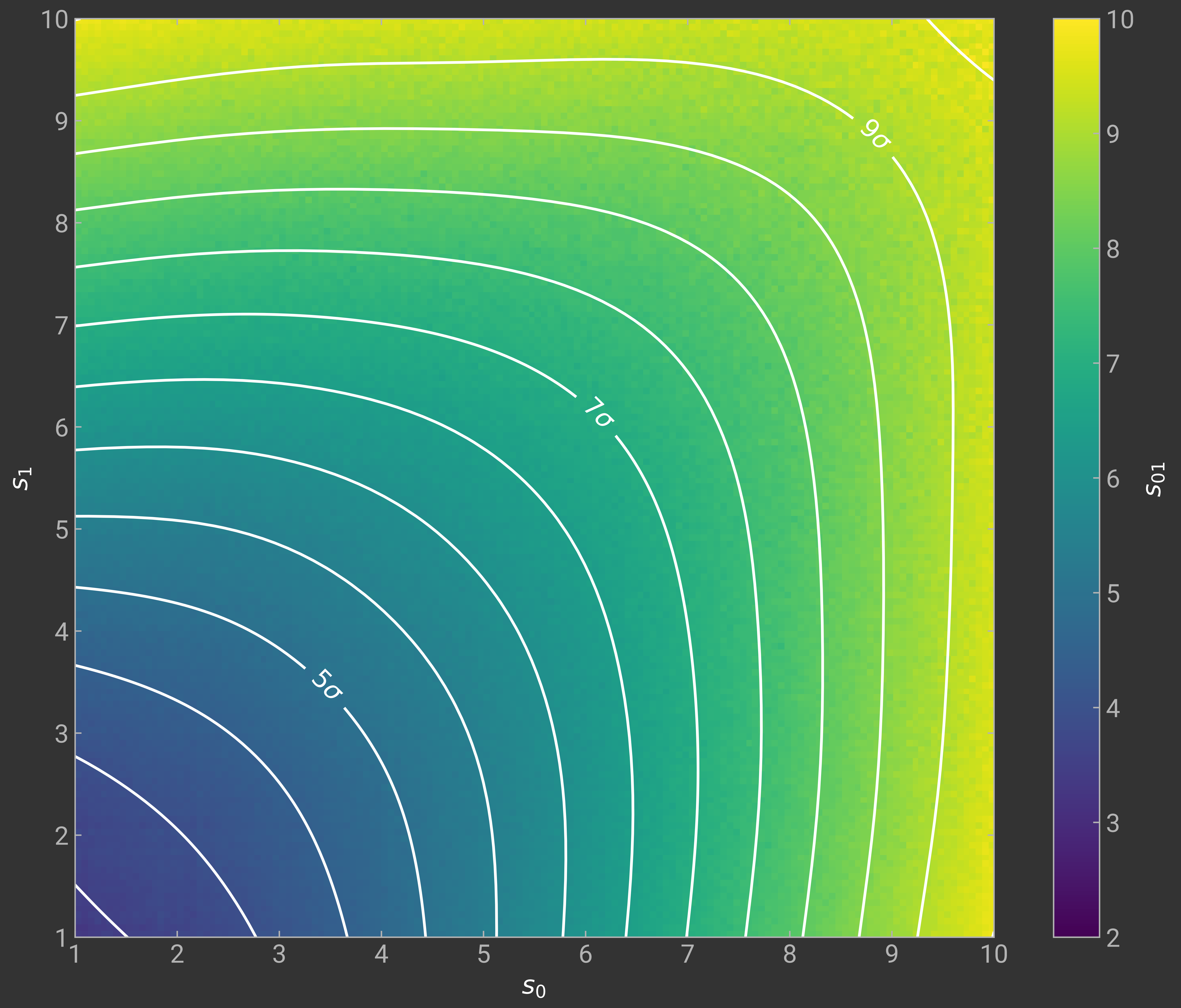
At all masses, $\sigma_{M_{\mathrm{map}}}/M_{\mathrm{map}} < 10^{-1}$

Sensitivity map uncertainty is too small to fully explain the boost.

Multiple object detections



We draw pairs of substructures and record:

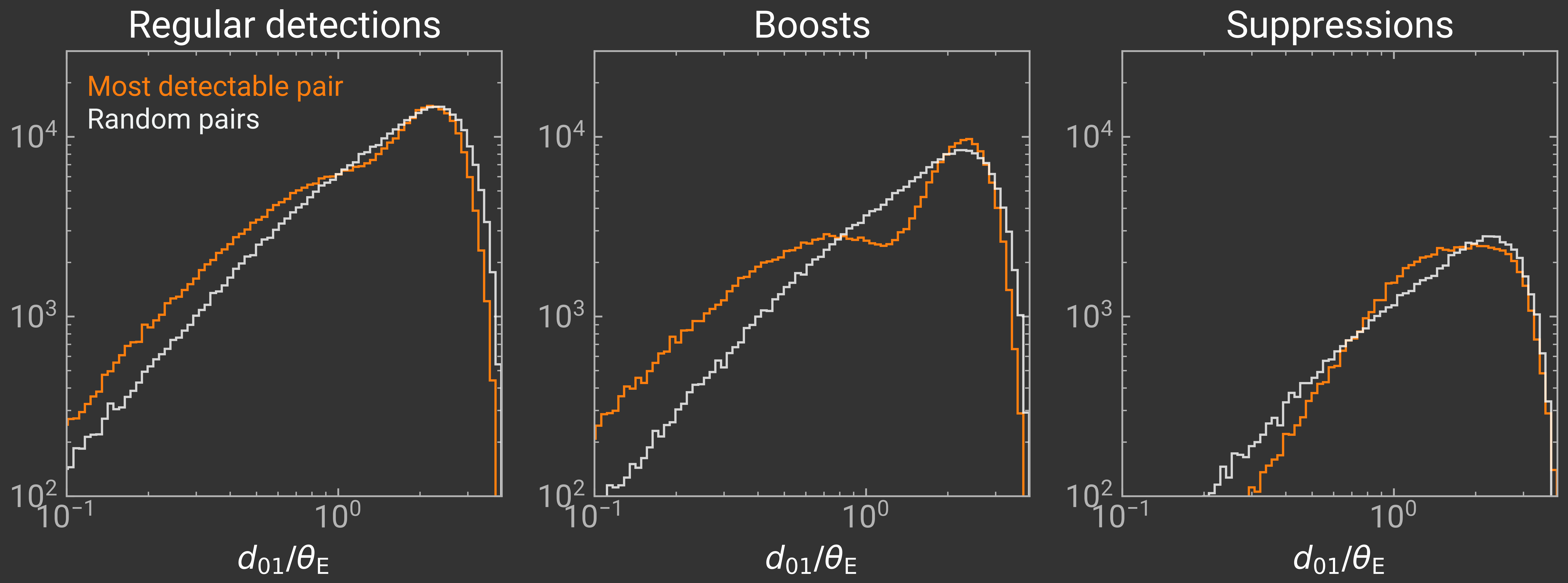
- Individual isolated detection significances s_0 and s_1
- Joint detection significance s_{01}

We already compute s_0 and s_1 for all positions and masses when we produce the sensitivity maps.

We can map the substructures in the realisations to those in the map data and compute s_{01} for the two largest subhaloes in each realisation.

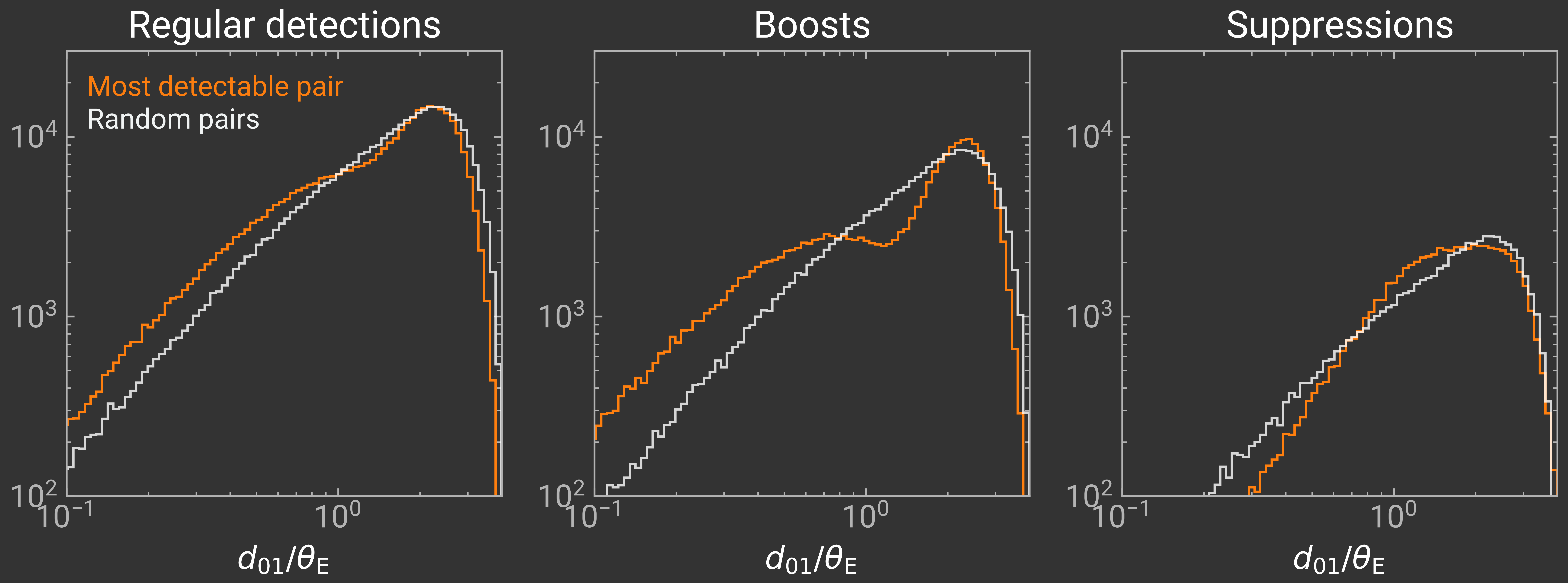
Accounting for the situation with two large but not quite detectable subhaloes in this way, we gain more expected detections…

Interactions between substructures



d_{01} is the separation between the two most detectable substructures in each realisation

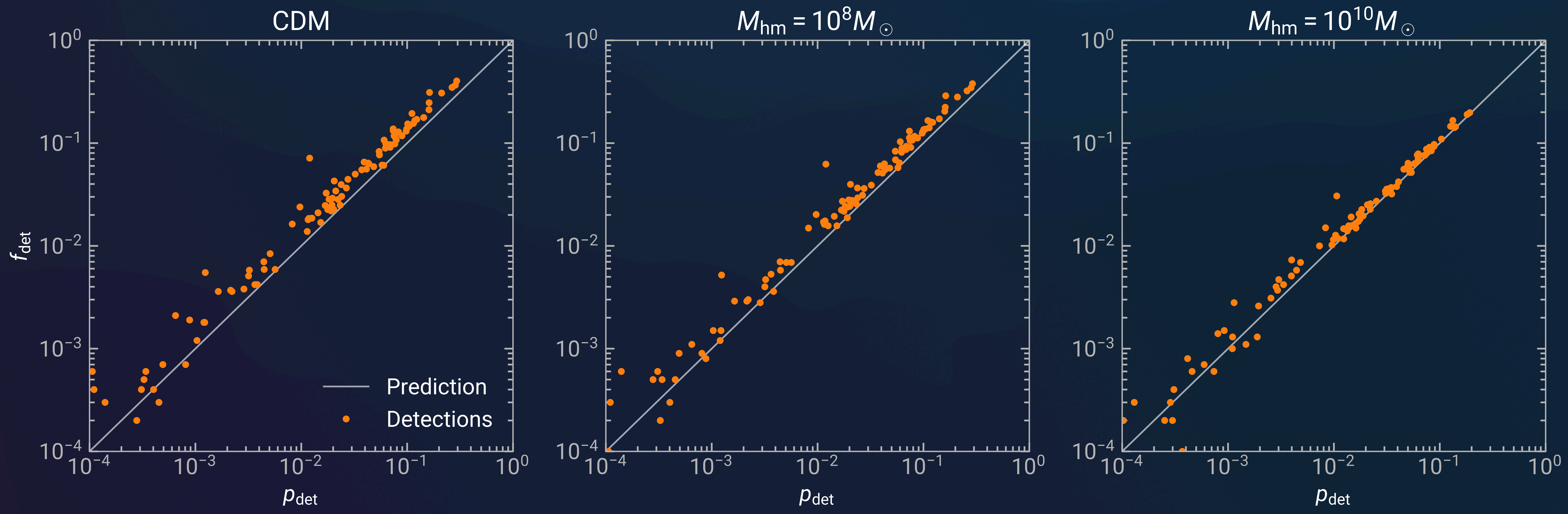
Interactions between substructures



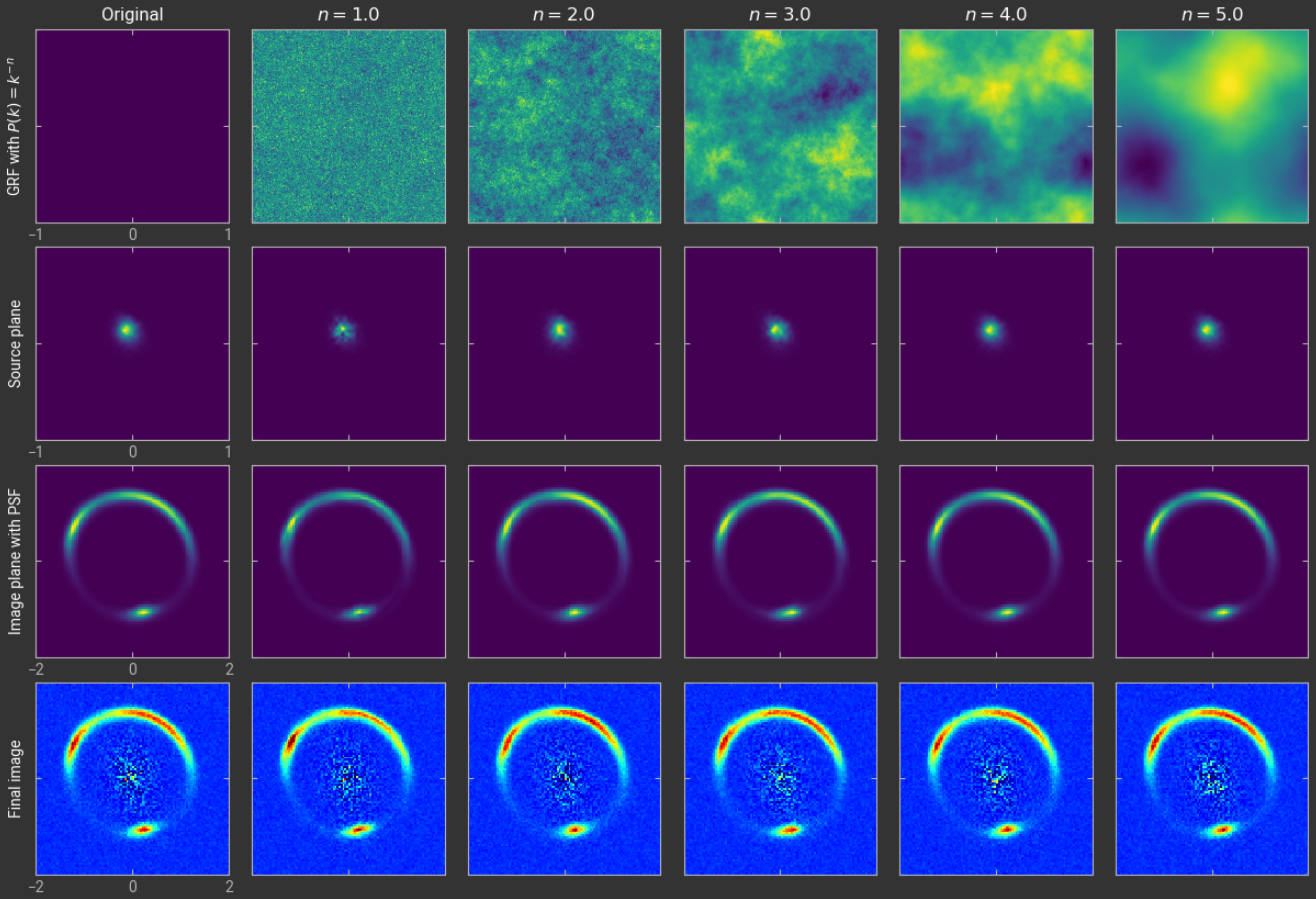
In realisations where we did not expect a detection, the largest substructures were on average closer than in the rest of the population

Results:

Detections from subhalo populations



In warmer DM models, the excess of detections seen in CDM disappears.



Original
$n = 1.0$
$n = 2.0$
$n = 3.0$
$n = 4.0$
$n = 5.0$
GRF with $P(k) = k^{-n}$
Source plane
Image plane with PSF
Final image
−1
0
1
−2
0
2