New methods to constrain the radio transient rate: results from a survey of four fields with LOFAR

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New methods to constrain the radio transient ~~rate~~: surface density!!!

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Introduction

- 4 Medium Deep Fields from PanSTARRS, the most suitable for LOFAR
- Observing campaign from March to August 2013
- Sensitive to transients with timescales from minutes to months

Field	RA (J2000)	Dec (J2000)
MD03	08:42:22	+44:19:00
MD05	10:47:40	+58:05:00
MD06	12:20:00	+47:07:00
MD07	14:14:49	+53:05:00

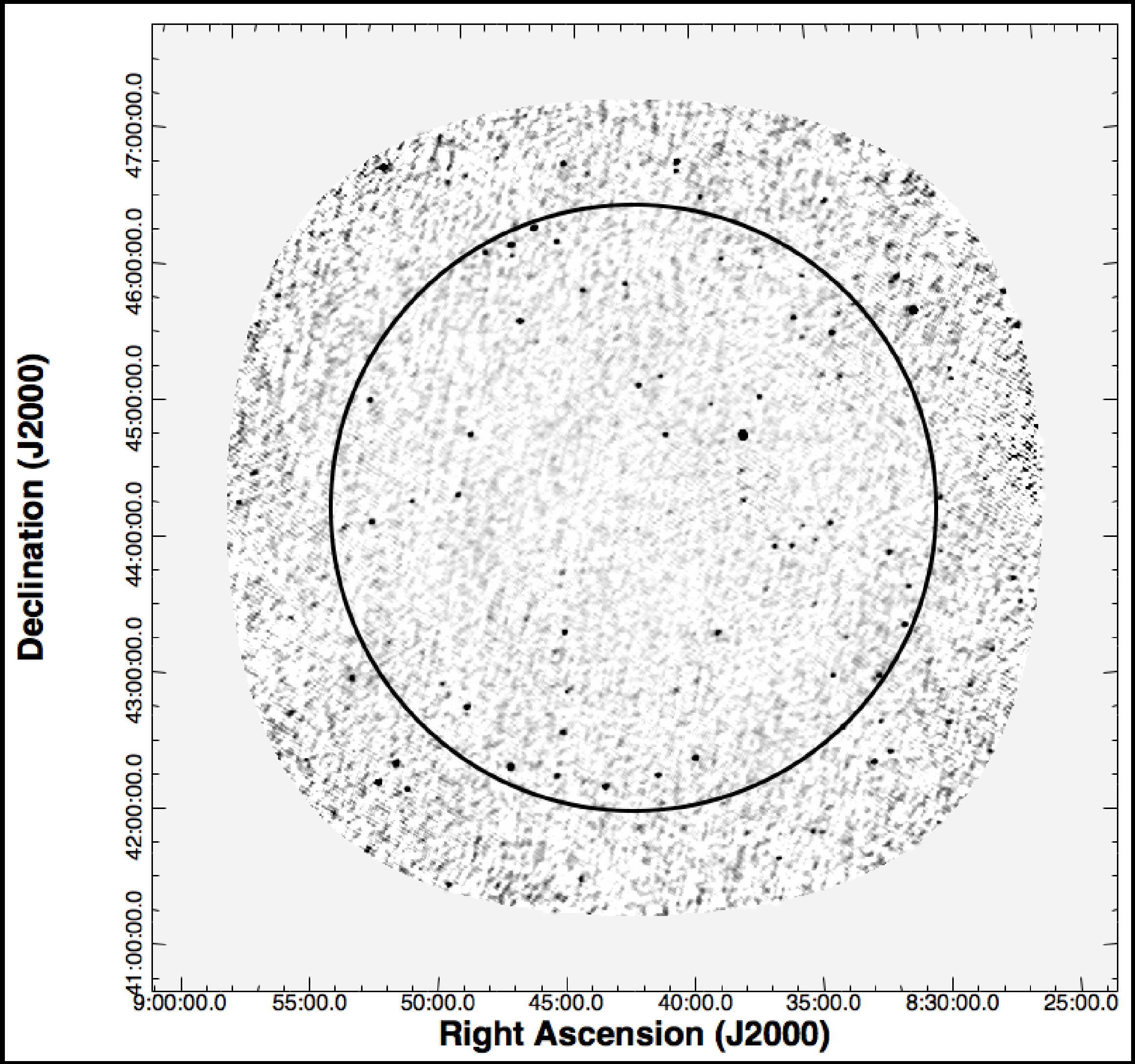
Observations

- HBA_dual configuration
- Snapshots of 11 min
- 2 min on calibrator
- 6 bands (115–188 MHz)
- Bandwidth 48 MHz
- FOV 27.92 deg^2

Run	Target	Date	Time on field (min)
1	MD03-05	2013-03-02	88
2	MD03-05	2013-03-30	88
3	MD03-05	2013-04-13	88
4	MD03-05	2013-04-27	88
5	MD03-05	2013-05-11	88
6	MD03-05-06-07	2013-06-08	44
7	MD03-05-06-07	2013-06-16	44
8	MD03-05-06-07	2013-06-30	44
9	MD03-05-06-07	2013-07-12	44
10	MD03-05-06-07	2013-07-20	44
11	MD03-05-06-07	2013-07-25	44
12	MD03-05-06-07	2013-08-10	44
13	MD03-05-06-07	2013-08-17	44
14	MD03-05-06-07	2013-08-24	44
15	MD03-05-06-07	2013-08-30	44

Data Analysis

- Analysis of the central 15.48 deg^2
- Average noise of 30 mJy in the inner part
- Angular resolution of 2 arcmin



Transients Search

- 1212 images total ran through the TraP
- Rejection according to noise and beam
- 809 images left
- Source finding in the central area
- Detection threshold of 8σ
- Build light curves
- No credible transients found

Upper limits on transients surface density

Classical method

- Poisson distribution:

$$P(n) = \frac{\lambda^n}{n!} e^{-\lambda}$$

$\lambda = \rho\, \Omega_{tot}; n = 0$

$\Omega = N_{trials}\, \Omega_i$

$P(0) = e^{-\rho\, \Omega_{tot}}$

95% C.L. $\longrightarrow$ $P(0) > 0.05$

$$\rho < -\frac{\ln(0.05)}{\Omega}$$

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- This method gives an upper limit at the flux of the sensitivity of the worst image in the dataset (S_*).

- Counting only one image per snapshot, we have 151 images.

$N_{trials} = 151 - 4 = 147$

$\Omega_i = 15.48\ \mathrm{deg}^2$

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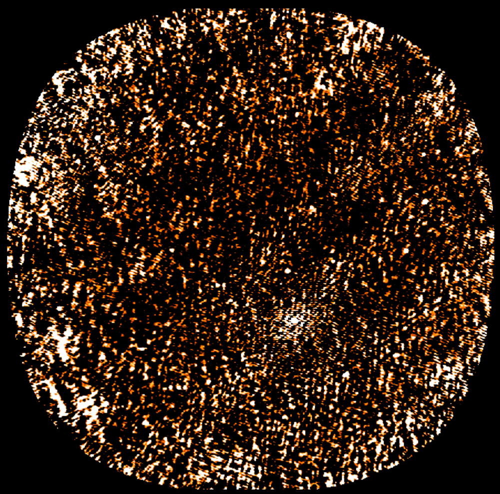
$N_{trials} = 151 - 4 = 147$

$\Omega_i = 15.48\ deg^2$

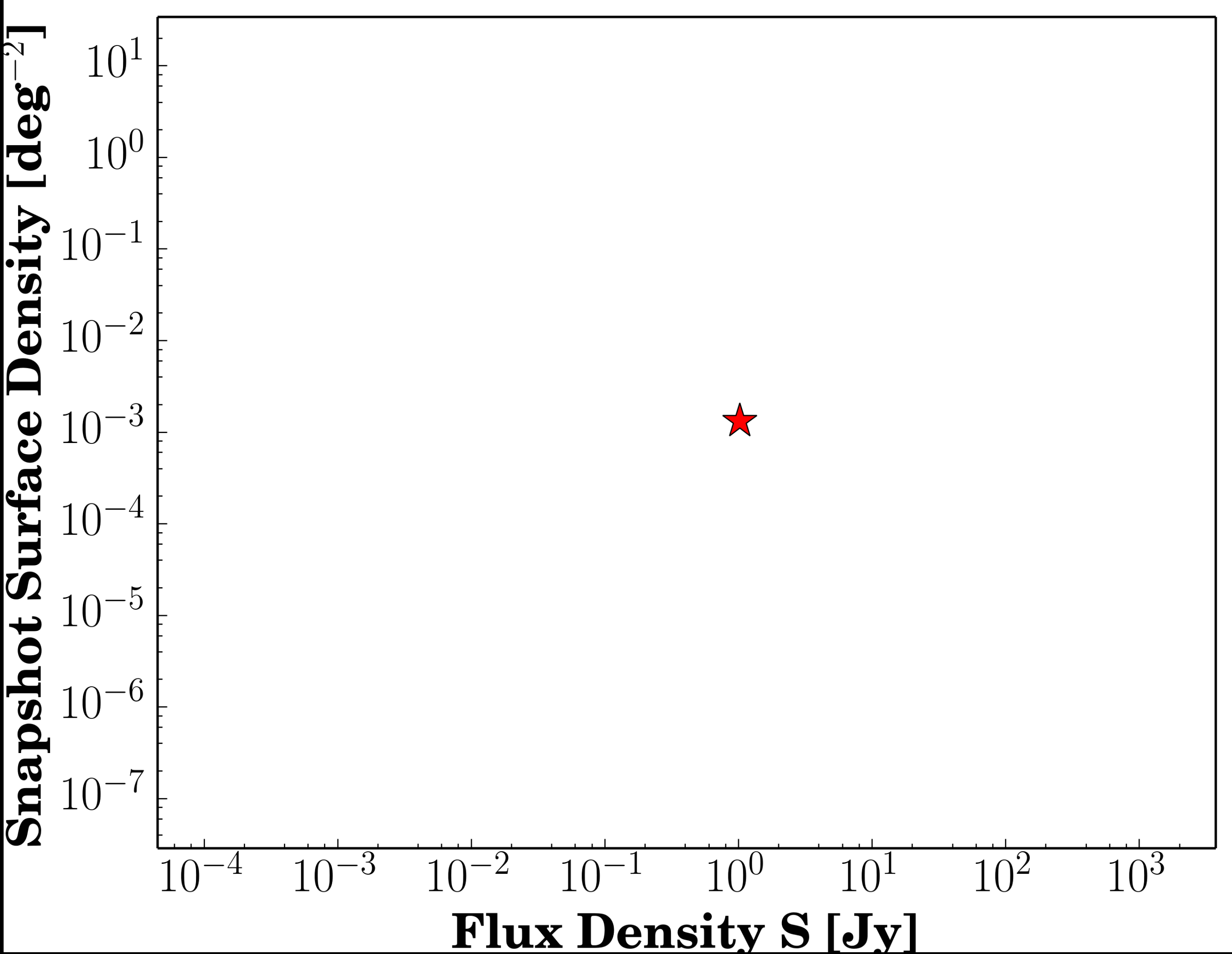
$\rho < 1.28\ 10^{-3}\ deg^{-2}$

$S_* = 1\ Jy$

Beyond the classical method

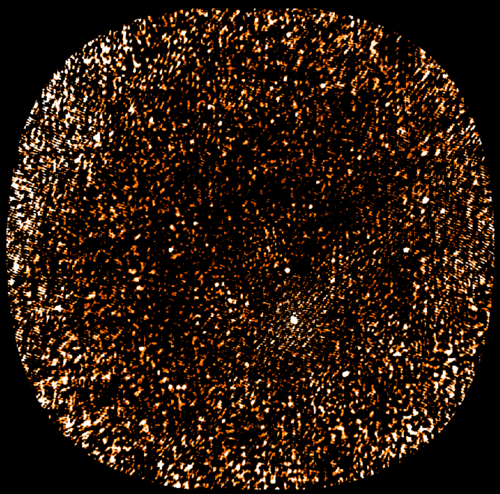


Sensitivity = 1.02 Jy
Number of images = 151
ρ = 1.28 10^{-3} deg^{-2}

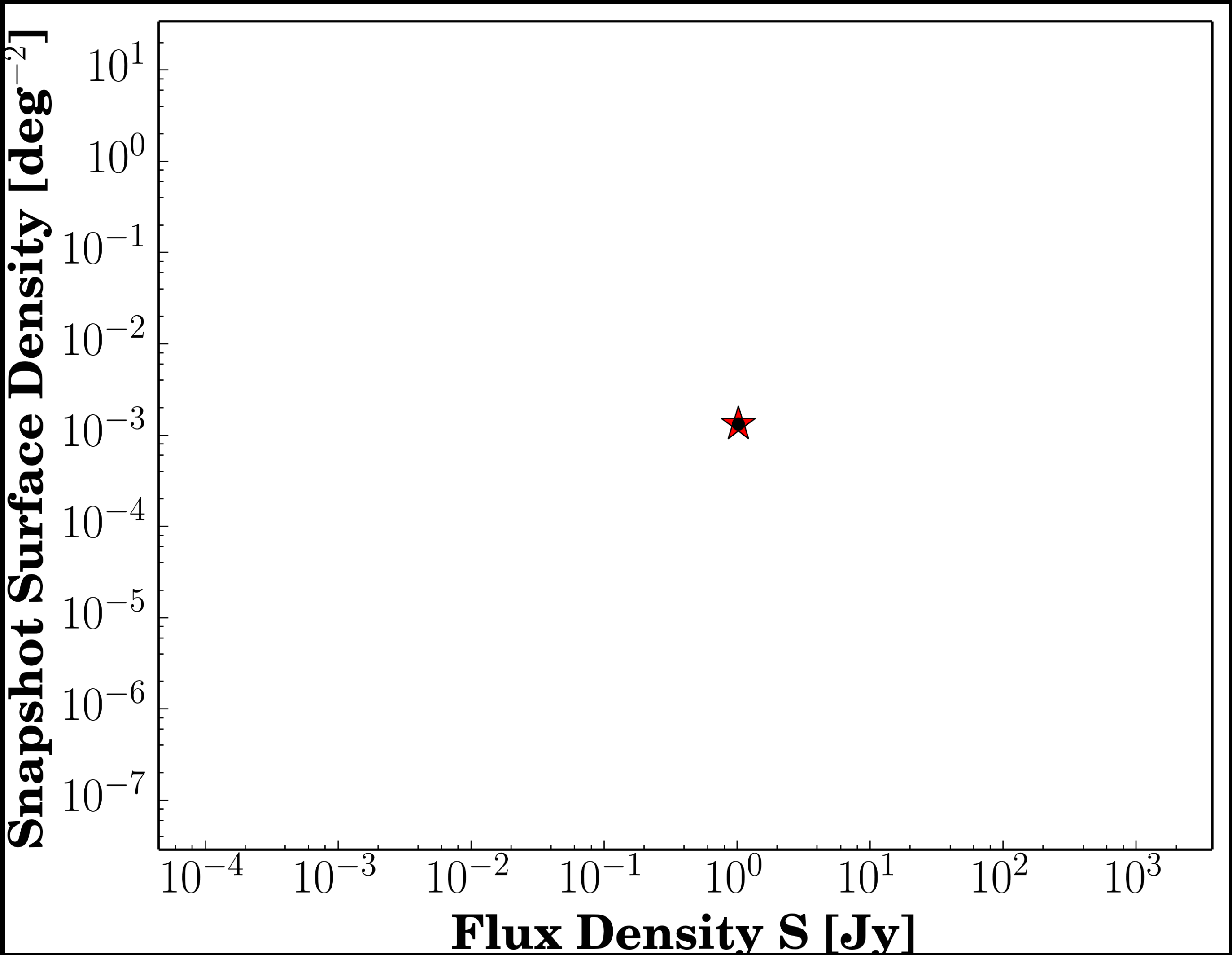


Remove the worst image, recalculate ρ and iterate

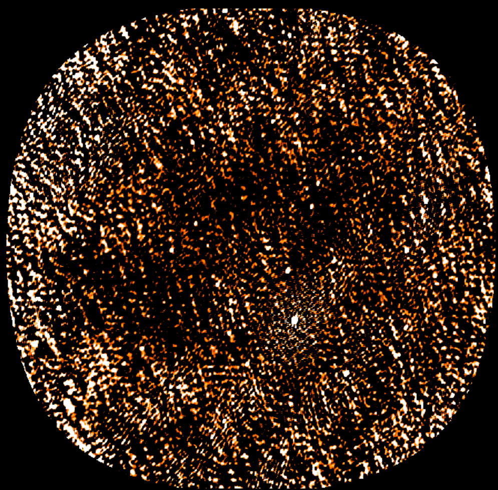
Beyond the classical method

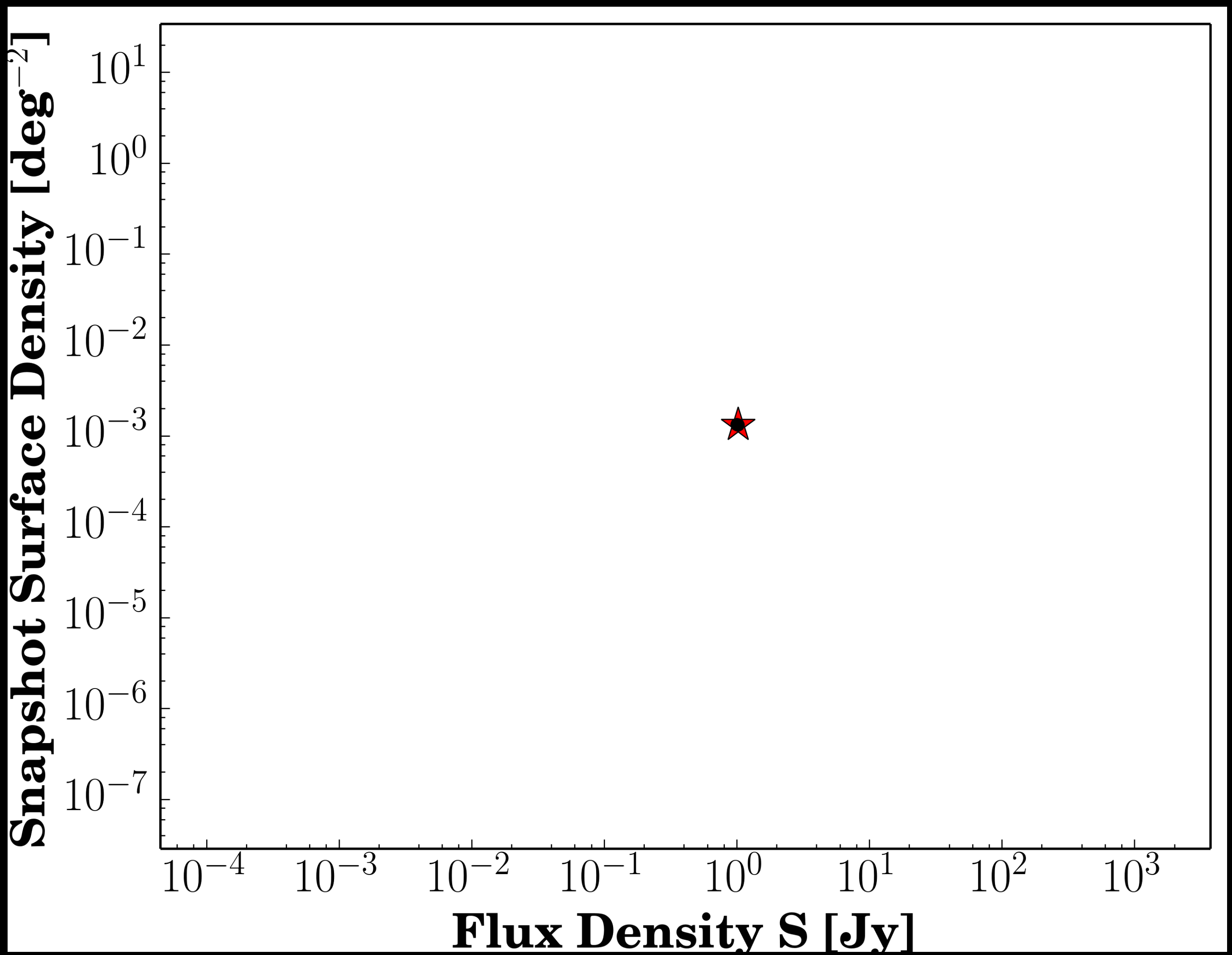


Sensitivity = 1.01 Jy
Number of images = 150
ρ = 1.31 10^{-3} deg^{-2}



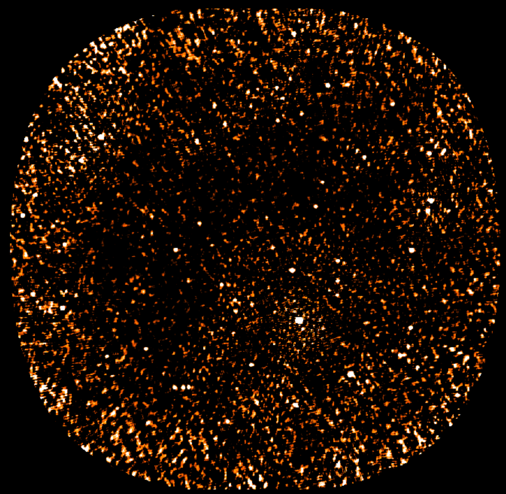
Beyond the classical method



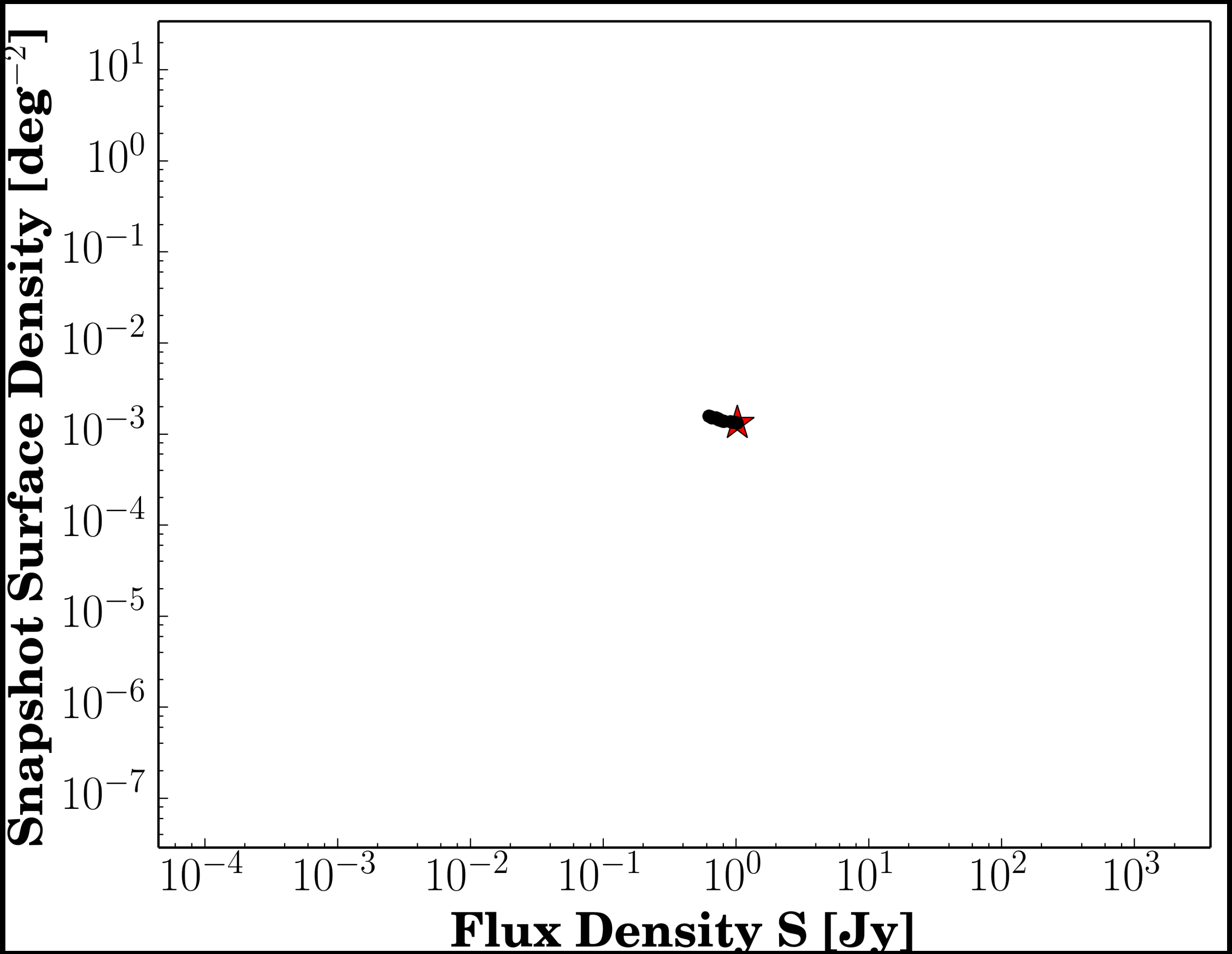


Sensitivity = 1.00 Jy
Number of images = 148
ρ = 1.33 10^{-3} deg^{-2}

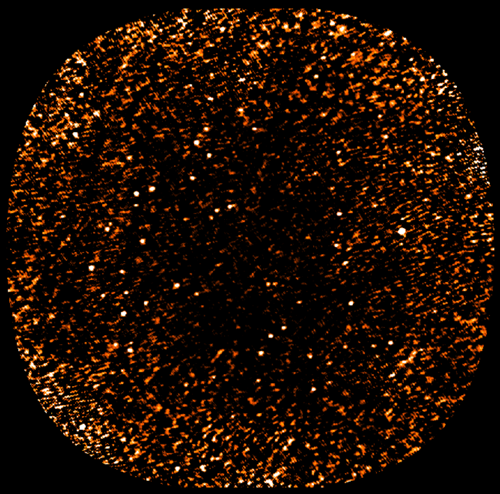
Beyond the classical method



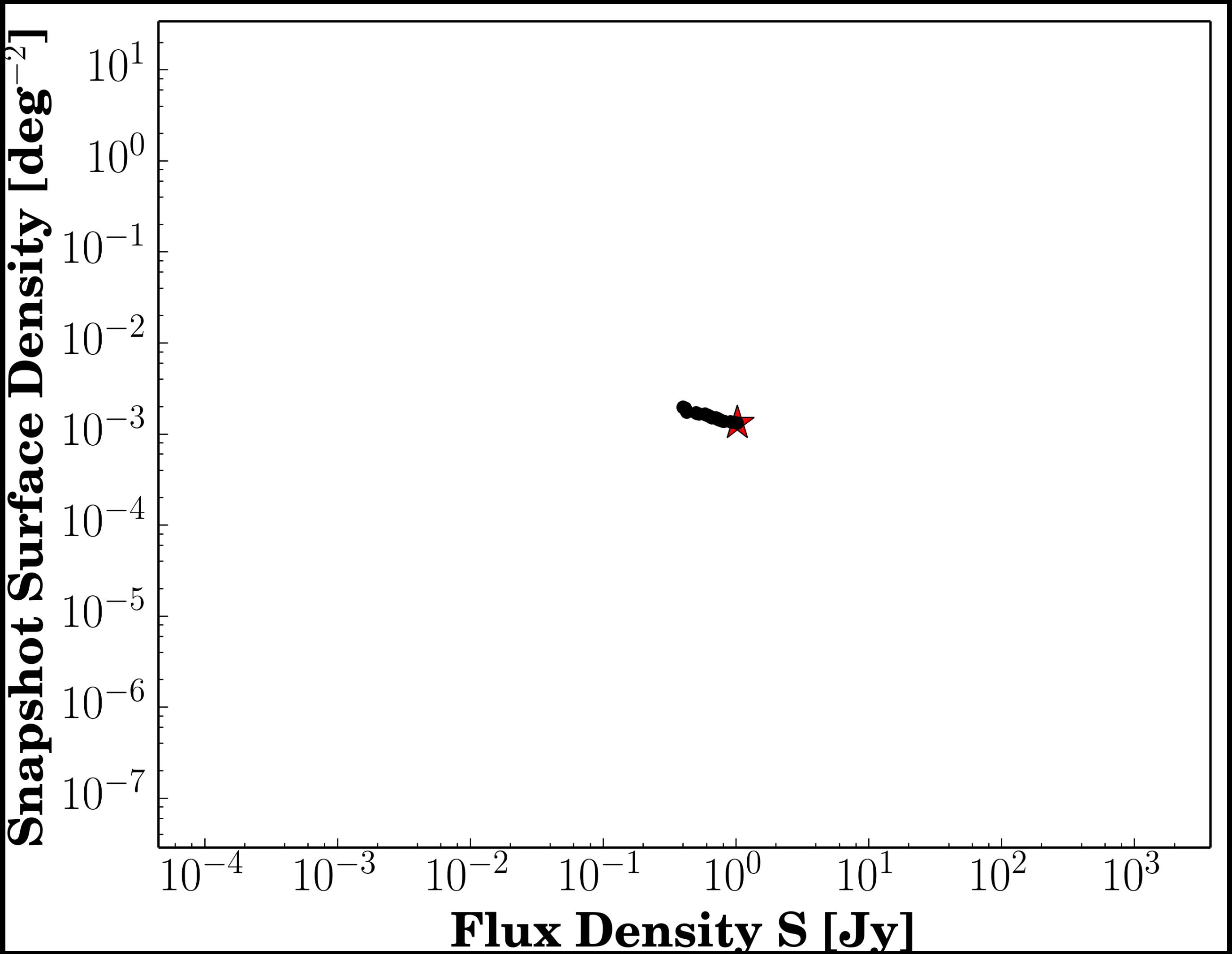
Sensitivity = 0.61 Jy
Number of images = 126
ρ = 1.59 10^{-3} deg^{-2}



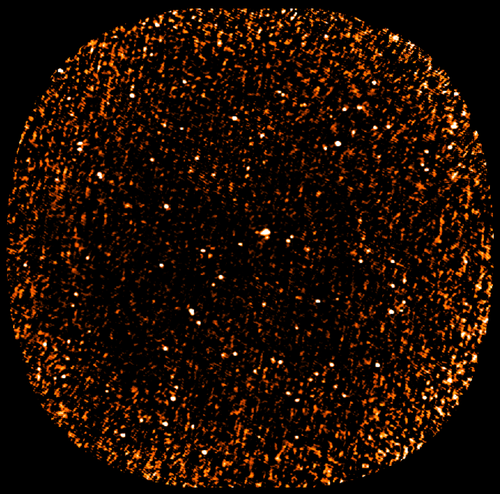
Beyond the classical method



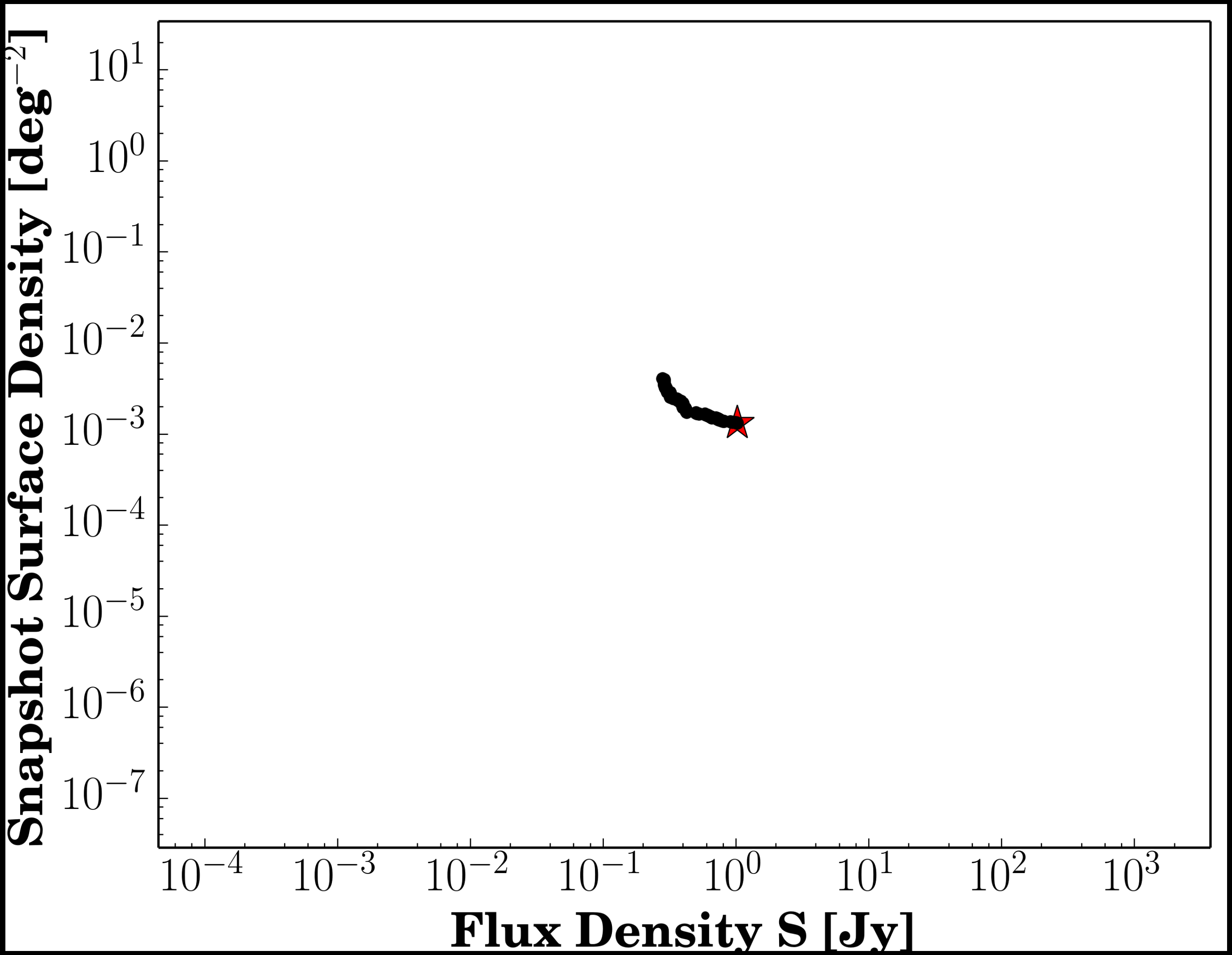
Sensitivity = 0.40 Jy
Number of images = 101
ρ = 2.00 10^{-3} deg^{-2}



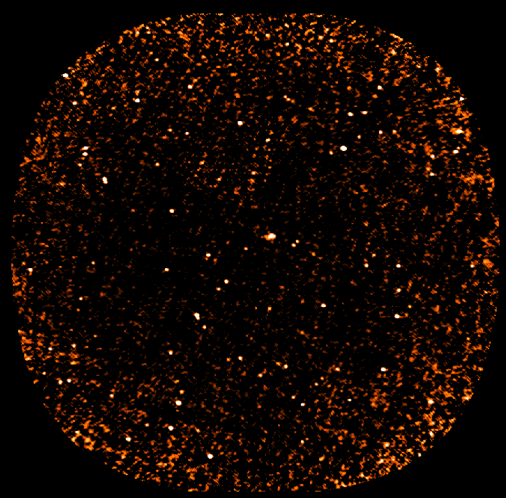
Beyond the classical method

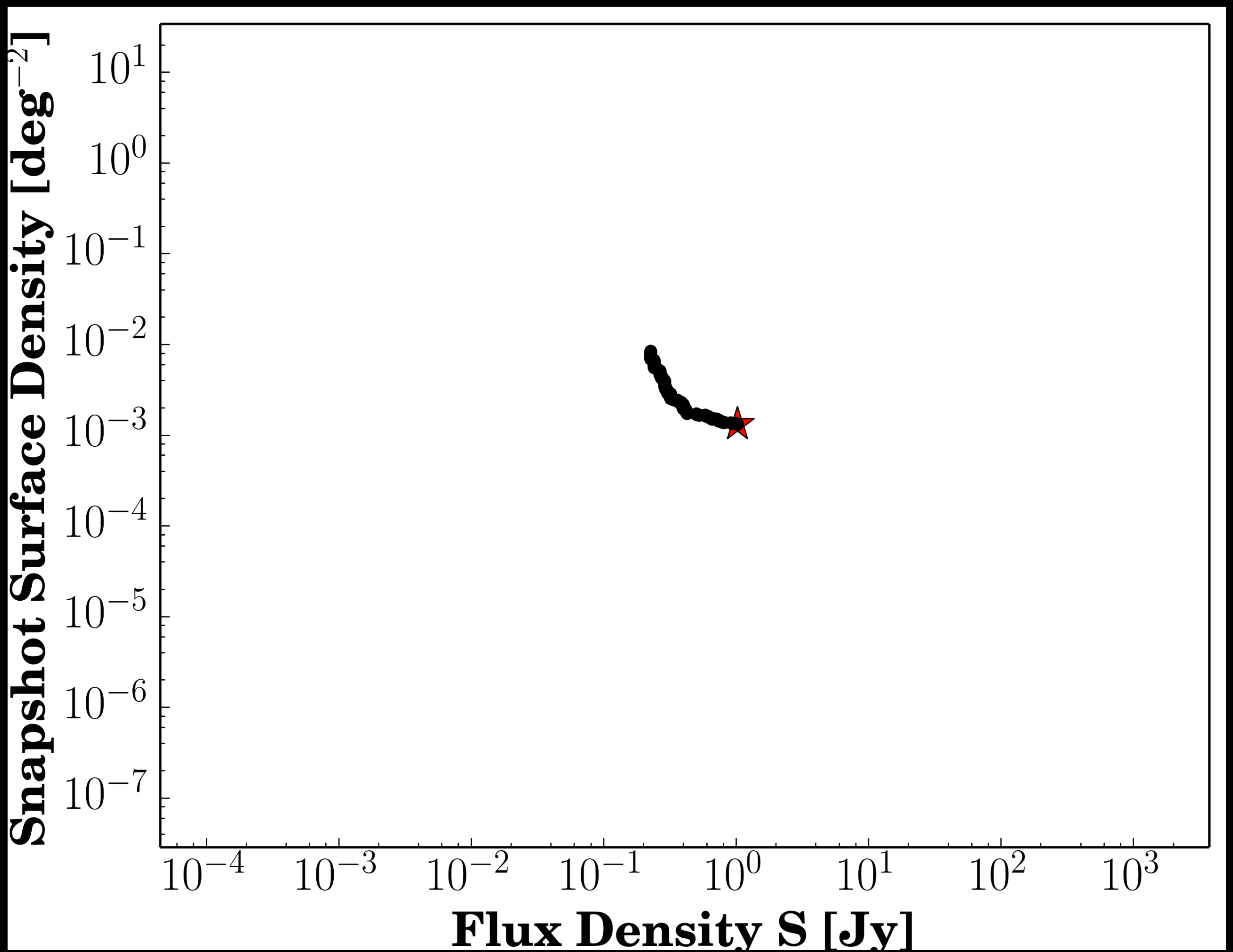


Sensitivity = 0.28 Jy
Number of images = 51
ρ = 4.12 10^{-3} deg^{-2}



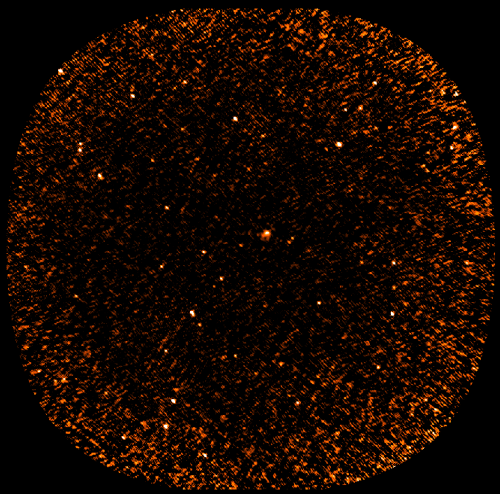
Beyond the classical method

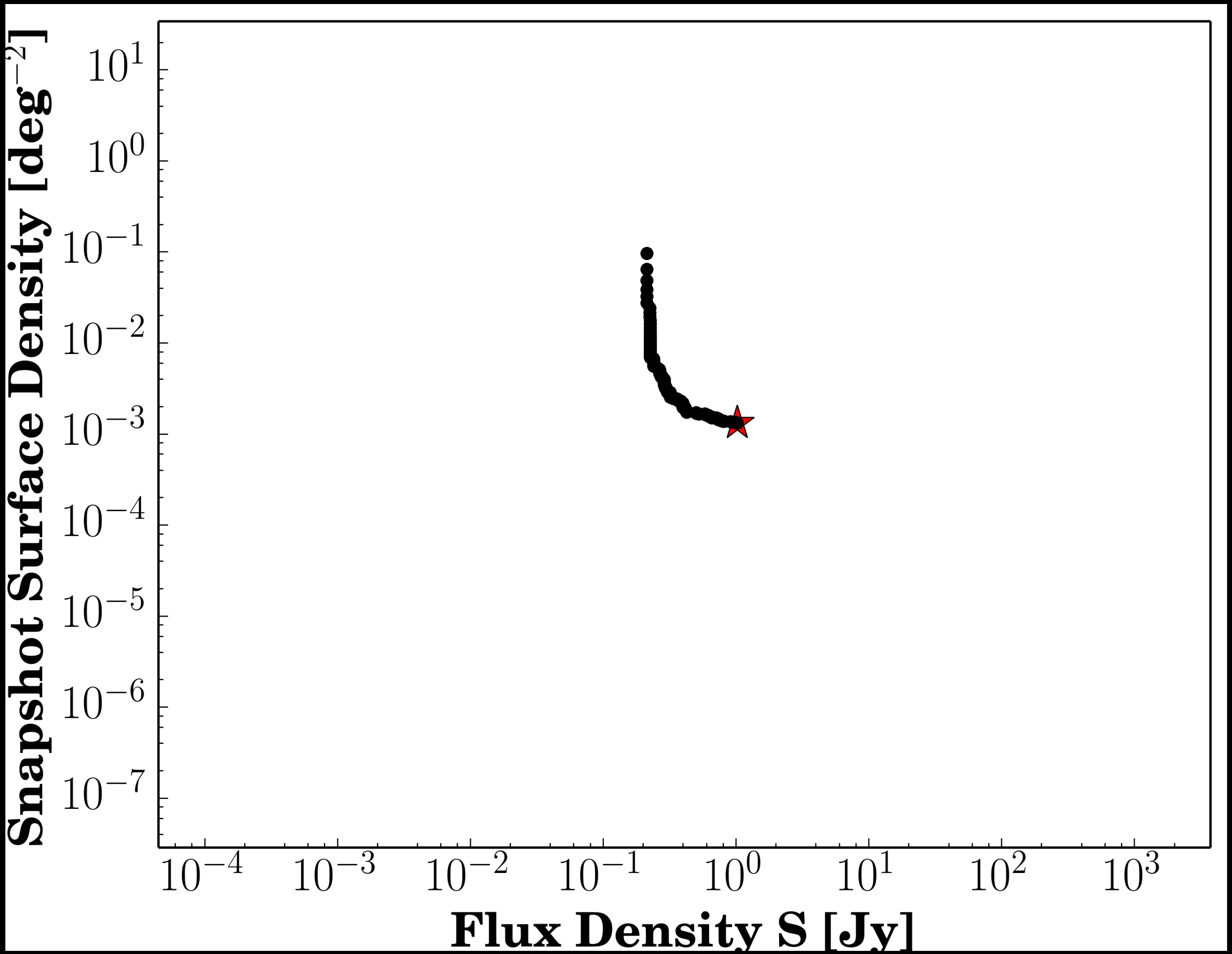




Sensitivity = 0.23 Jy
Number of images = 26
$\rho = 8.80\ 10^{-3}\ deg^{-2}$

Beyond the classical method





Sensitivity = 0.21 Jy
Number of images = 5
ρ = 0.19 deg^{-2}

Transient surface density vs flux distribution

$$N\,(S > \hat{S}) = N_*\left(\frac{\hat{S}}{S_*}\right)^{-\gamma}$$

N: Number density of sources brighter than $\hat{S}$

N_*: Transient surface density at S_*

Number of transients detected in image i

$$N\,(S > \hat{S}) = N_*\left(\frac{\hat{S}}{S_*}\right)^{-\gamma}$$

$$n_i\,(S > D\,\sigma_i) = N_*\left(\frac{D\,\sigma_i}{S_*}\right)^{-\gamma}\Omega_i$$

N: Number density of sources brighter than $\hat{S}$

N_*: Transient surface density at S_*

n: Number of sources brighter than $D\sigma_i$

D: Detection threshold

σ: Noise in an image

Ω: FoV of an image

Number of transients detected in the whole survey

$$N\,(S > \hat{S}) = N_*\left(\frac{\hat{S}}{S_*}\right)^{-\gamma}$$

$$n_i\,(S > D\,\sigma_i) = N_*\left(\frac{D\,\sigma_i}{S_*}\right)^{-\gamma}\Omega_i$$

$$n_{tot} = \sum_i n_i = N_* \sum_i \Omega_i \left(\frac{D_i\,\sigma_i}{S_*}\right)^{-\gamma}$$

N: Number density of sources brighter than $\hat{S}$

N_*: Transient surface density at S_*

n: Number of sources brighter than $D\sigma_i$

D: Detection threshold

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Upper limits on the transient surface density

$$N(S > \hat{S}) = N_*\left(\frac{\hat{S}}{S_*}\right)^{-\gamma}$$

$$n_i(S > D\,\sigma_i) = N_*\left(\frac{D\,\sigma_i}{S_*}\right)^{-\gamma}\Omega_i$$

$$n_{tot} = \sum_i n_i = N_* \sum_i \Omega_i \left(\frac{D_i\,\sigma_i}{S_*}\right)^{-\gamma}$$

Poisson's law:
$P(0) = e^{-n_{tot}}$

95% C.L. $\longrightarrow$ $P(0) > 0.05$

$$N_* < -\frac{\ln(0.05)}{\Omega}\left(\frac{S_*}{D}\right)^{-\gamma}\frac{1}{\sum_i \sigma_i^{-\gamma}}$$

N: Number density of sources brighter than $\hat{S}$

N_*: Transient surface density at S_*

n: Number of sources brighter than $D\sigma_i$

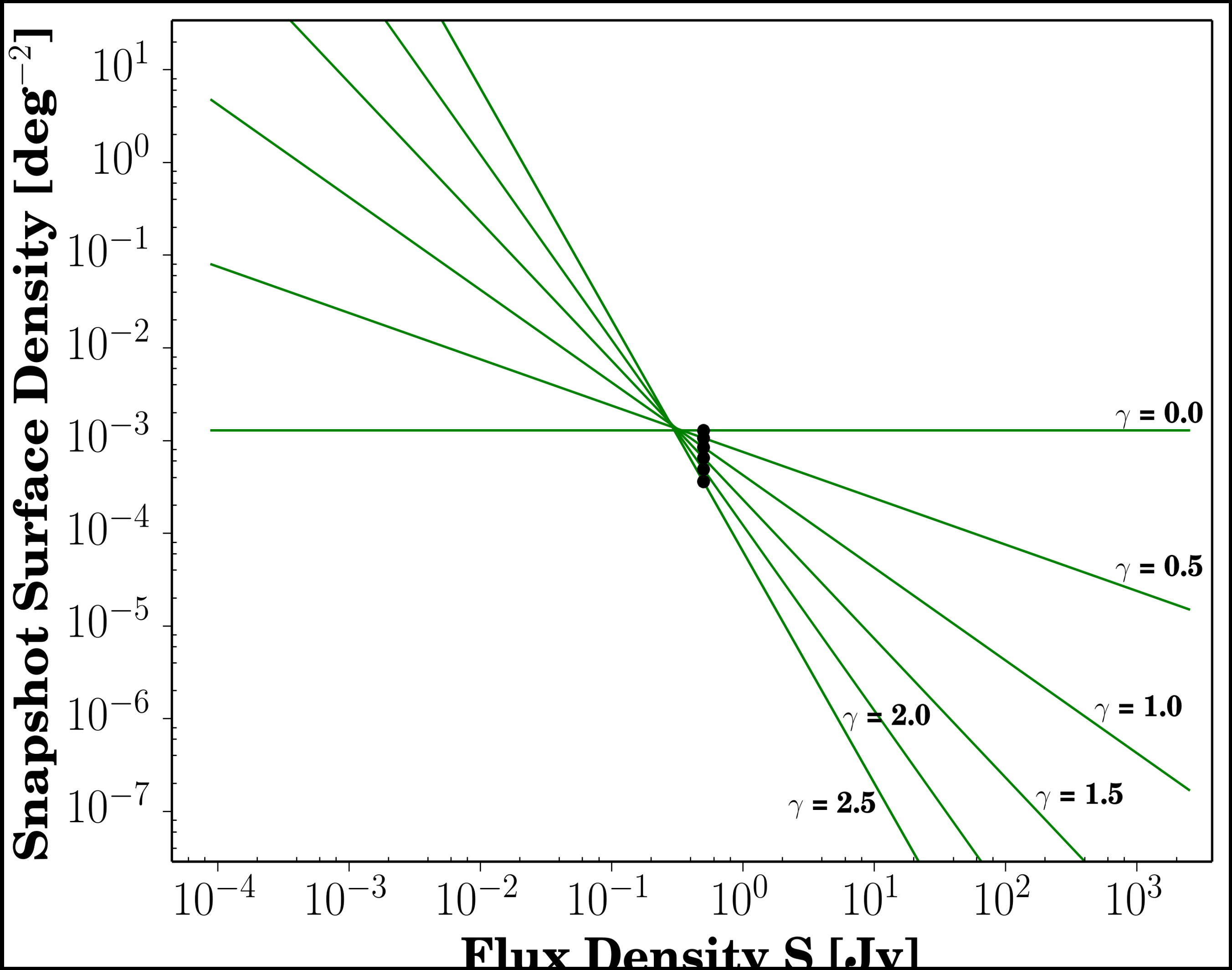
D: Detection threshold

σ: Noise in an image

Ω: FoV of an image

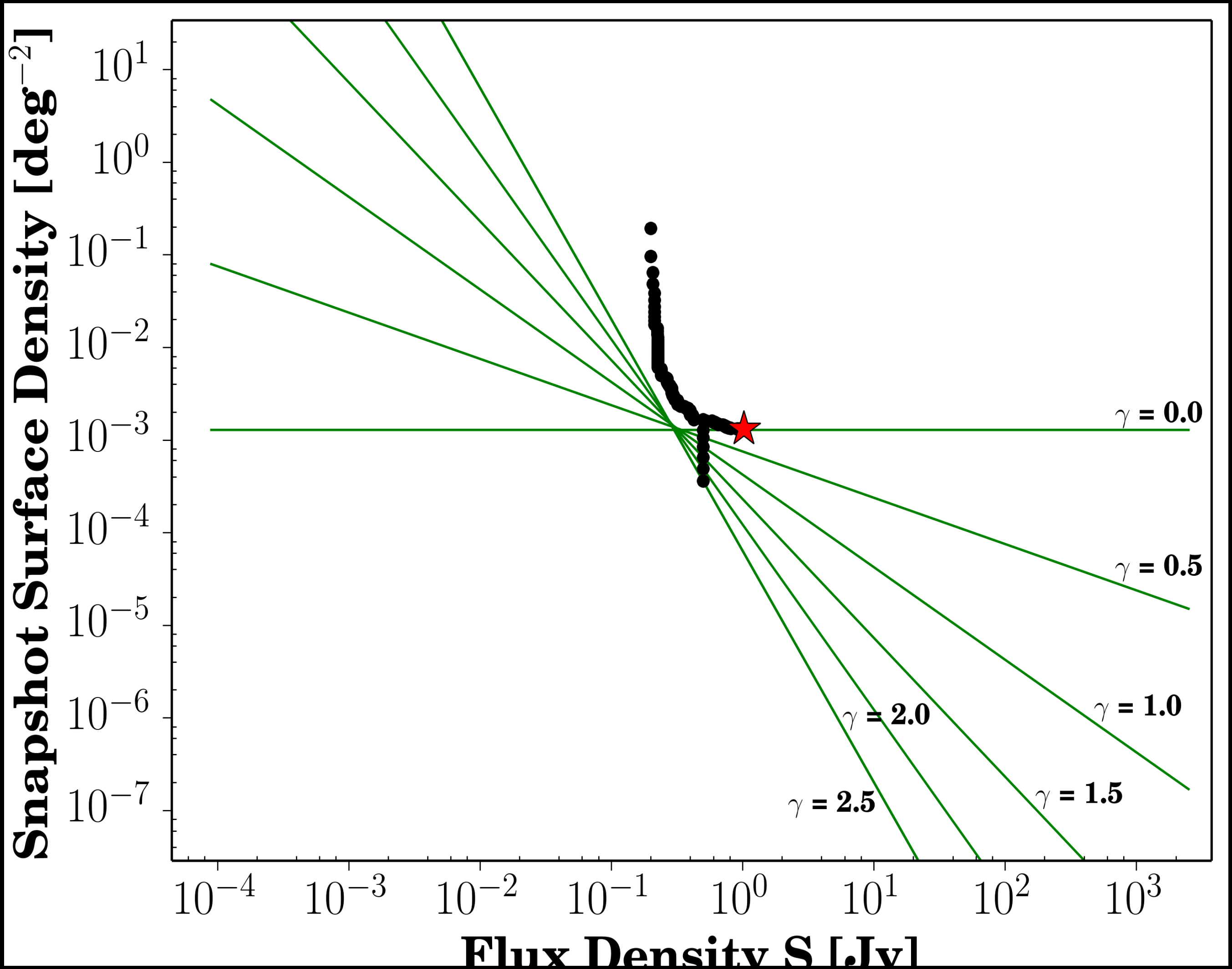
N_* depends only on S_* and γ!

Discussion



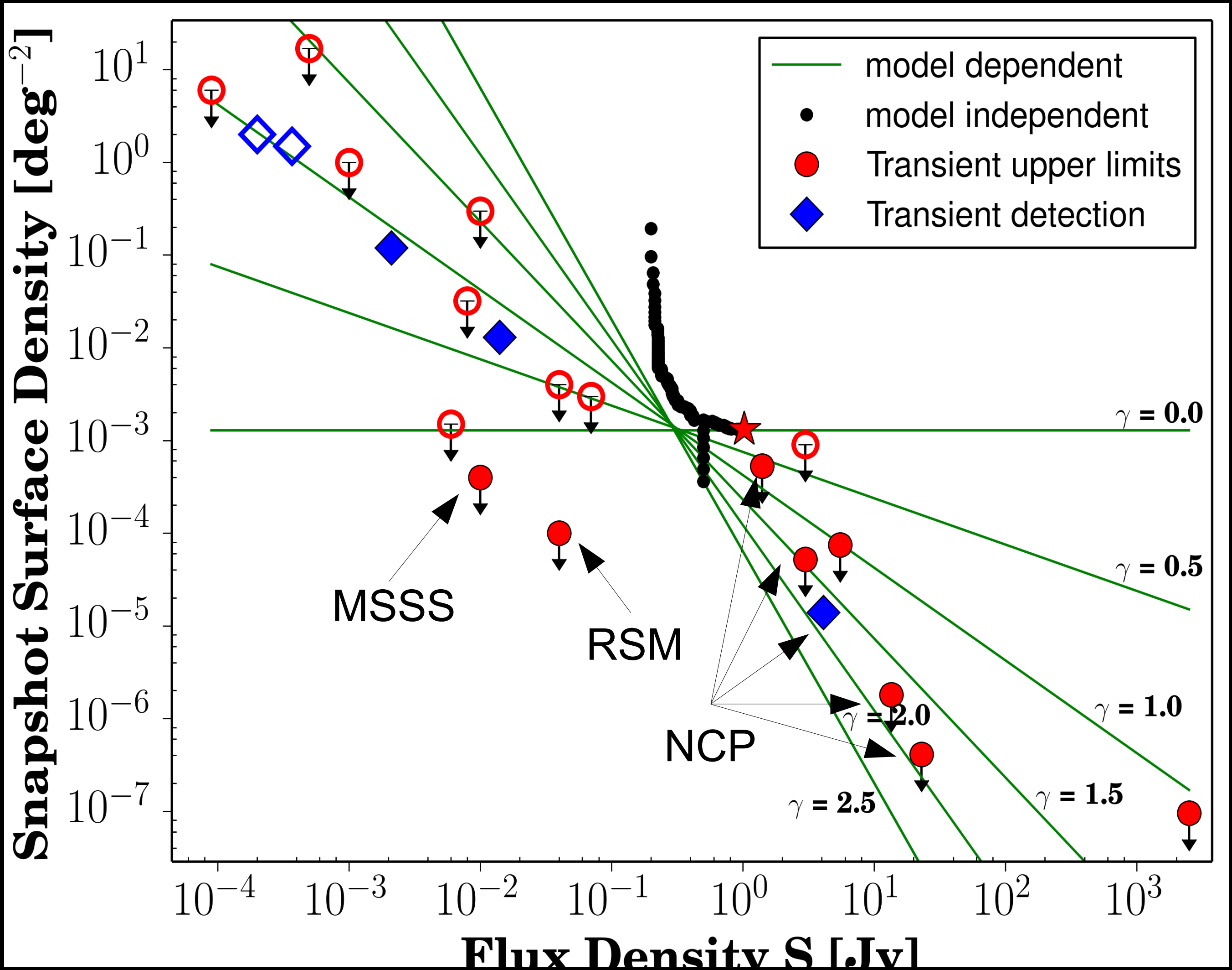
S_* (Jy)	γ	N_* UL (deg^{-2})
0.5	2.5	3.6 10^{-4}
0.5	2.0	4.9 10^{-4}
0.5	1.5	6.5 10^{-4}
0.5	1.0	8.5 10^{-4}
0.5	0.5	1.06 10^{-3}
0.5	0.0	1.28 10^{-3}

Discussion



More stringent upper limits than the previous method

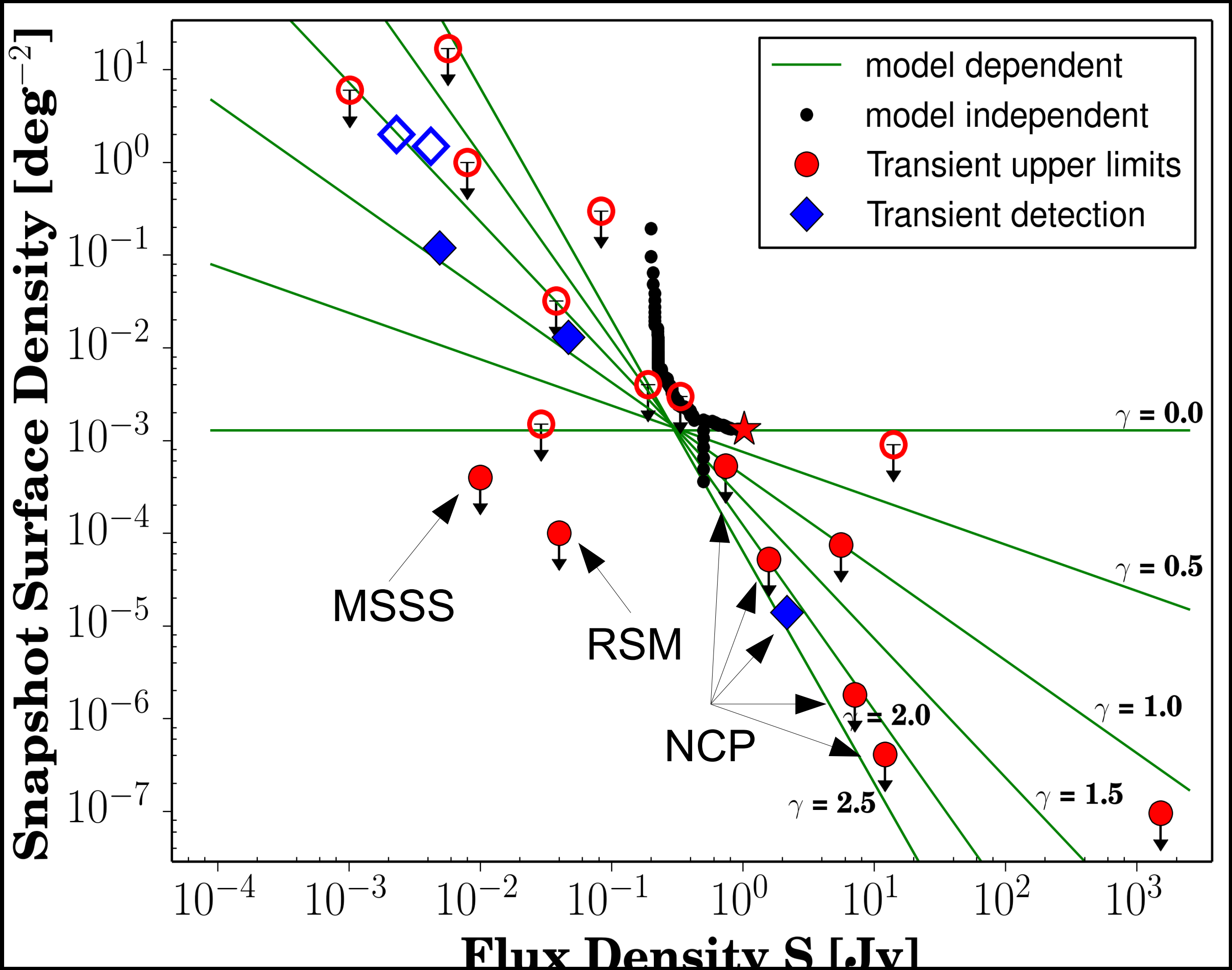
Discussion



Open symbols represent surveys above 1GHz

Extrapolation of detections from other surveys suggests we are close to detection

Discussion



Fluxes extrapolated with spectral index of -0.7

Error bars?

Transient surface density vs timescale

- Pairs of observations with a certain time difference give sensitivity to transients of a certain timescale
- Calculate how many pairs of observations we have with various time differences
- Be aware of double counting!

Transient surface density vs timescale

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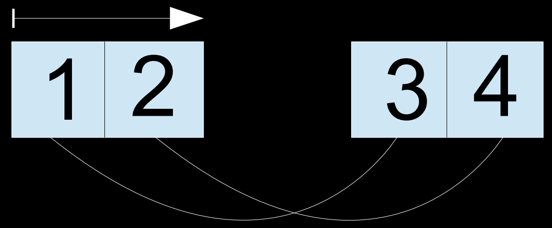
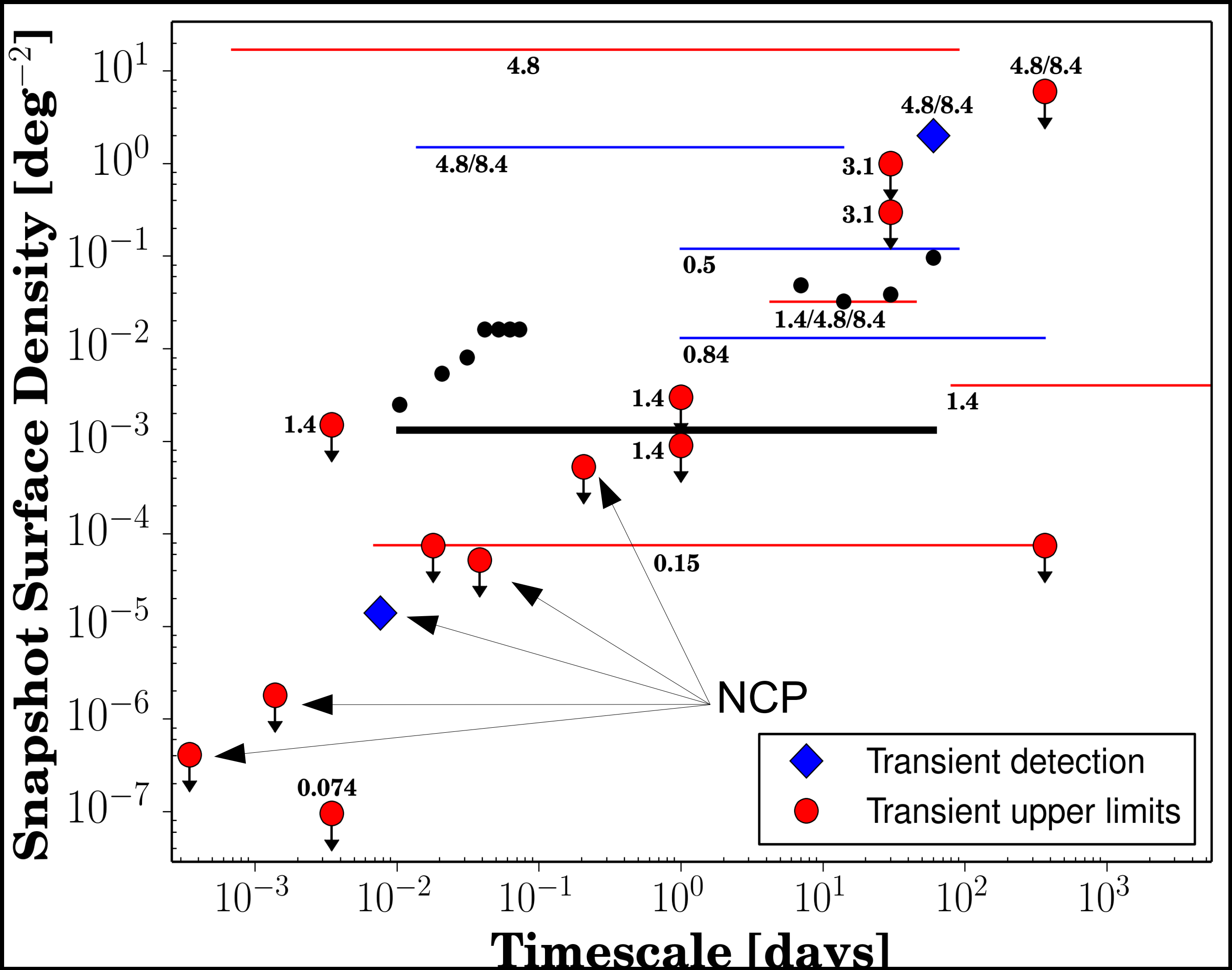
- Calculate how many pairs of observations we have with various time differences
- Be aware of double counting!

Pairs 1-3 and 2-4 are counting the same transient event and that would appear as two separate transients.



Transients timescale



- Cannot state one upper limit for all the timescales
- Can vary by 2-3 orders of magnitude (2.4 10^{-3} @15 min – 9.6 10^{-2} @2 months)
- Most sensitive to 15 min transients

Conclusions

- No transients were detected
- We developed two new methods to constrain the transient surface density
- Comparing with other surveys we should be close to a detection
- We showed the transient surface density varies strongly as a function of timescale (up to 2 orders of magnitude)

Survey	Sensitivity (mJy)	ρ (deg^{-2})	t_{char}	ν (GHz)
This work	> 500	< 0.001	minutes - months	0.150
Bell et al. 2011	> 8	< 0.032	4.3 - 45.3 days	8.4, 4.8 and 1.4
Gal-Yam et al. 2006	> 6	$< 1.5 \cdot 10^{-3}$	-	1.4
Croft et al. 2010	> 40	< 0.004	81 days - 15 years	1.4
Bower et al. 2007	> 0.09	< 6	1 year	8.4 and 4.8
Bower et al 2010(A)	> 1	< 1	1 month	3.1
Bower et al 2010(B)	> 10	< 0.3	1 month	3.1
Bower & Saul 2010(A)	> 70	< 0.003	1 day	1.4
Bower & Saul 2010(B)	> 3000	$< 9 \cdot 10^{-4}$	1 day	1.4
Lazio et al. 2010	$> 2.5 \cdot 10^{6}$	$< 9.5 \cdot 10^{-8}$	5 minutes	0.0738
Bell et al. 2014	> 5500	$< 7.5 \cdot 10^{-5}$	minutes - year[1]	0.154
Alexander et al. 2014	> 0.5	< 17	minutes - months	4.9
Bannister et al. 2011	14	$1.3 \cdot 10^{-2}$	days - years	0.843
Bower et al. 2007	0.37	1.5 ± 0.4	20 minutes - week	8.4 and 4.8
Bower et al. 2007	0.20	2	2 months	8.4 and 4.8
Jaeger et al. 2012	2.1	0.12	1 day - 3 months	0.500