

# Imaging pulsar echoes at low frequencies

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für Radioastronomie

# Imaging pulsar echoes at low frequencies

- LOFAR
- The ghost in B1508+55
- Offline VLBI with LOFAR
- First attempt 2016
- Relative motion 2016–2018
- New deconvolution method

# LOFAR station (Tautenburg)



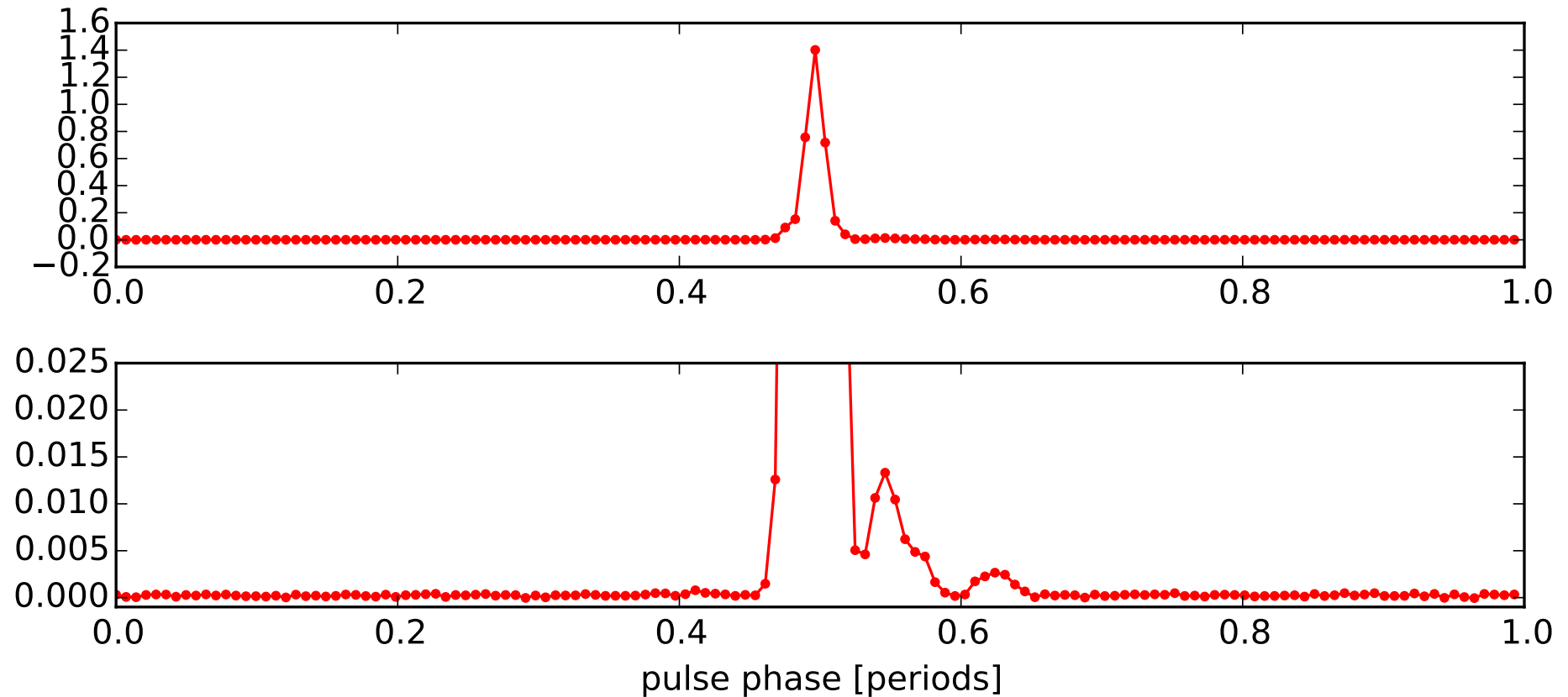
# Low-band antennas (10-80 MHz, Ireland)



# High-band antennas (110-250 MHz)

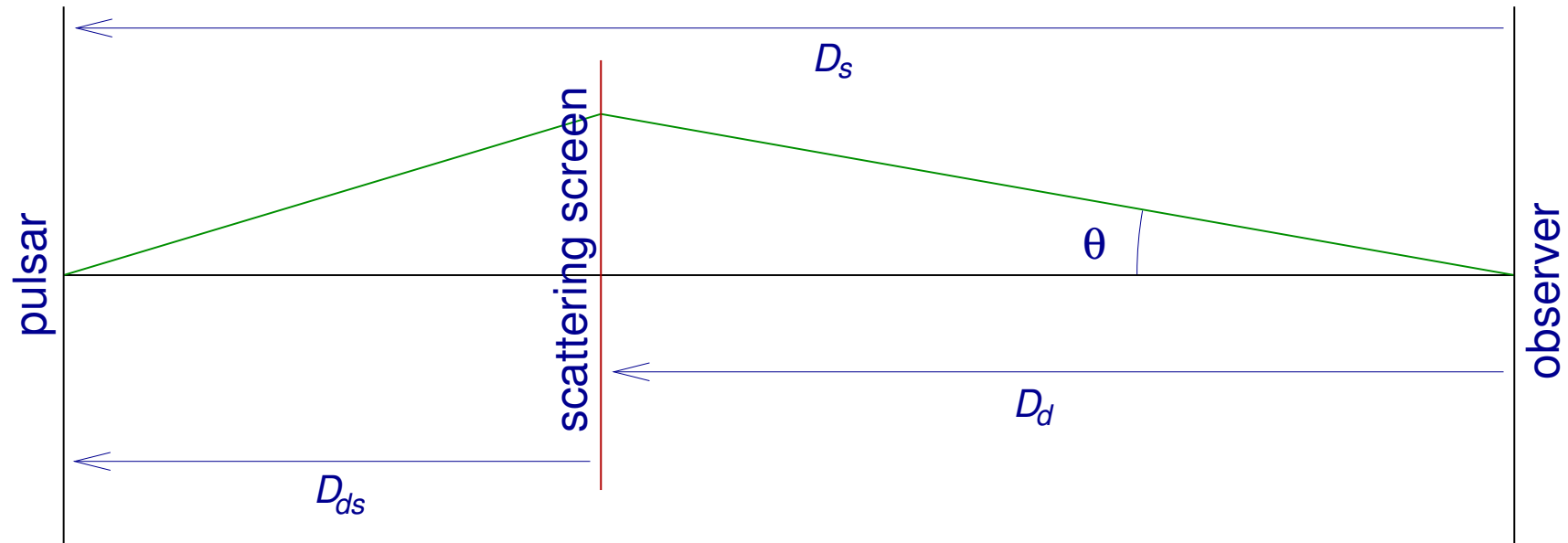


# B1508+55: a pulsar and its ghost?



- 'ghost' component found by Stefan Ośłowski with LOFAR
- moving relative to main component
- interpretation: scattering 'echo' [ Ośłowski & Macquart in prep. ]

# Interstellar scattering: geometric delay



$$c\tau = \frac{1}{2}\theta^2 D$$

$$D = \frac{D_s D_d}{D_{ds}}$$

Does the echo have a positional offset?

# Can we localise the echo of B1508+55 ?

- $\tau \approx 50 \text{ msec}$  (period  $\approx 0.74 \text{ sec}$ )
- $D_s = 2.13 \text{ kpc} = 2.19 \cdot 10^{11} \text{ sec} \cdot c$
- assumption:  $D_d \approx D_{ds} \rightsquigarrow D = D_s$
- $\theta = \sqrt{\frac{2c\tau}{D}} = 0''.14$  (more if closer to us)
- at high SNR this can be measured with LOFAR-VLBI !
- can test echo hypothesis and maybe determine  $D$
- later: use two paths as interstellar interferometer



# VLBI: German LOFAR (GLOW) baselines



length, fringe-spacing at 150 MHz

	[km]	[arcsec]
DE601–DE602	390	1.06
DE601–DE603	344	1.20
DE601–DE604	476	0.87
<b>DE601–DE605</b>	<b>53</b>	<b>7.80</b>
DE601–DE609	412	1.00
DE602–DE603	277	1.49
DE602–DE604	455	0.91
DE602–DE605	440	0.94
<b>DE602–DE609</b>	<b>585</b>	<b>0.70</b>
DE603–DE604	186	2.22
DE603–DE605	372	1.11
DE603–DE609	325	1.27
DE604–DE605	487	0.85
DE604–DE609	248	1.66
DE605–DE609	394	1.05

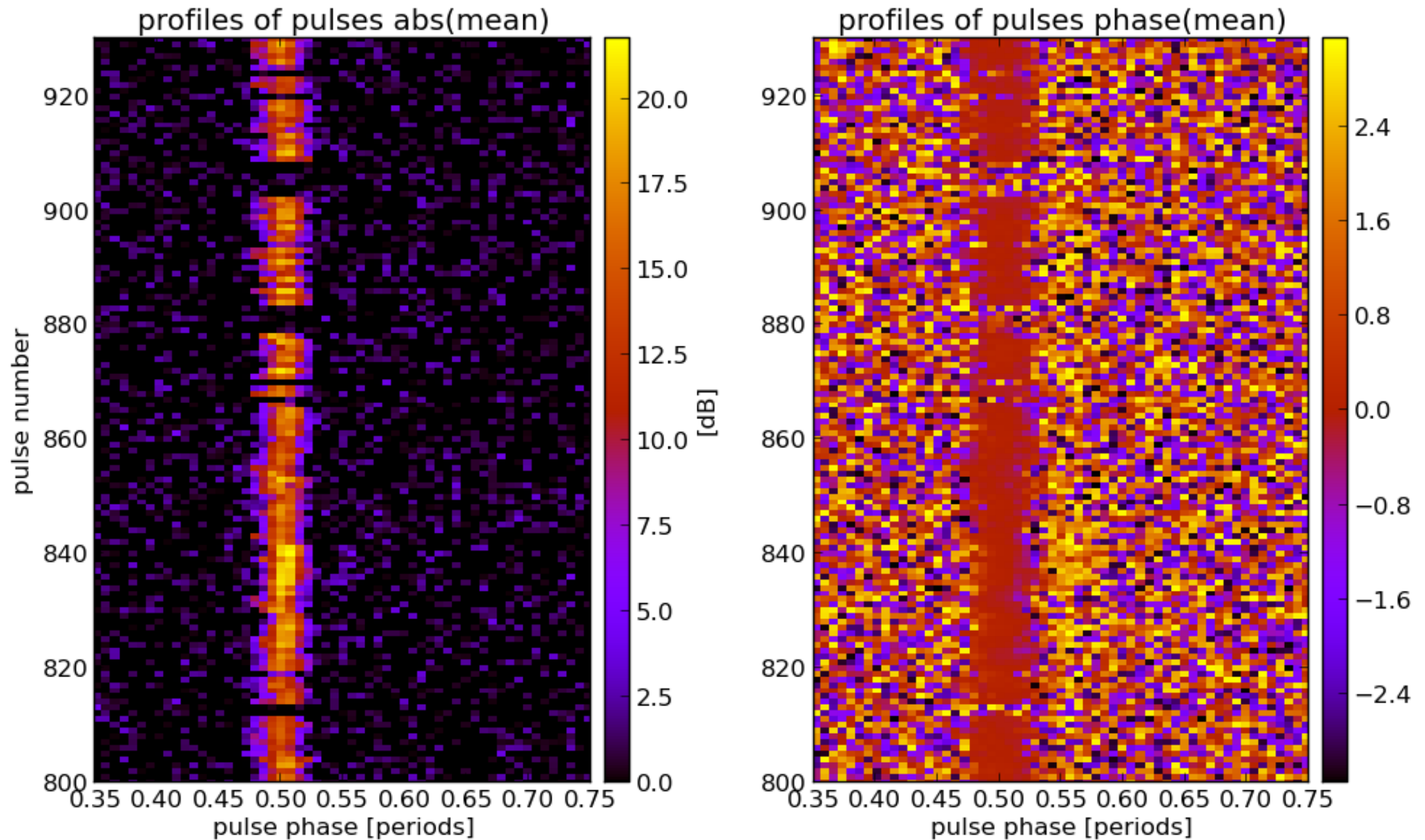
# Offline VLBI with LOFAR

- LOFAR correlator limited (e.g. time resolution)
  - need more flexibility
    - ★ arbitrary resolution
    - ★ pulsar gating
    - ★ re-correlations
- ⇒ record locally, correlate centrally! (non-*e* VLBI)
- ★ GLOW recording in Bonn, Jülich
  - ★ other stations recording locally (3 Gbps / station)
  - ★ core centrally in Groningen
  - ★ demanding logistics, huge effort

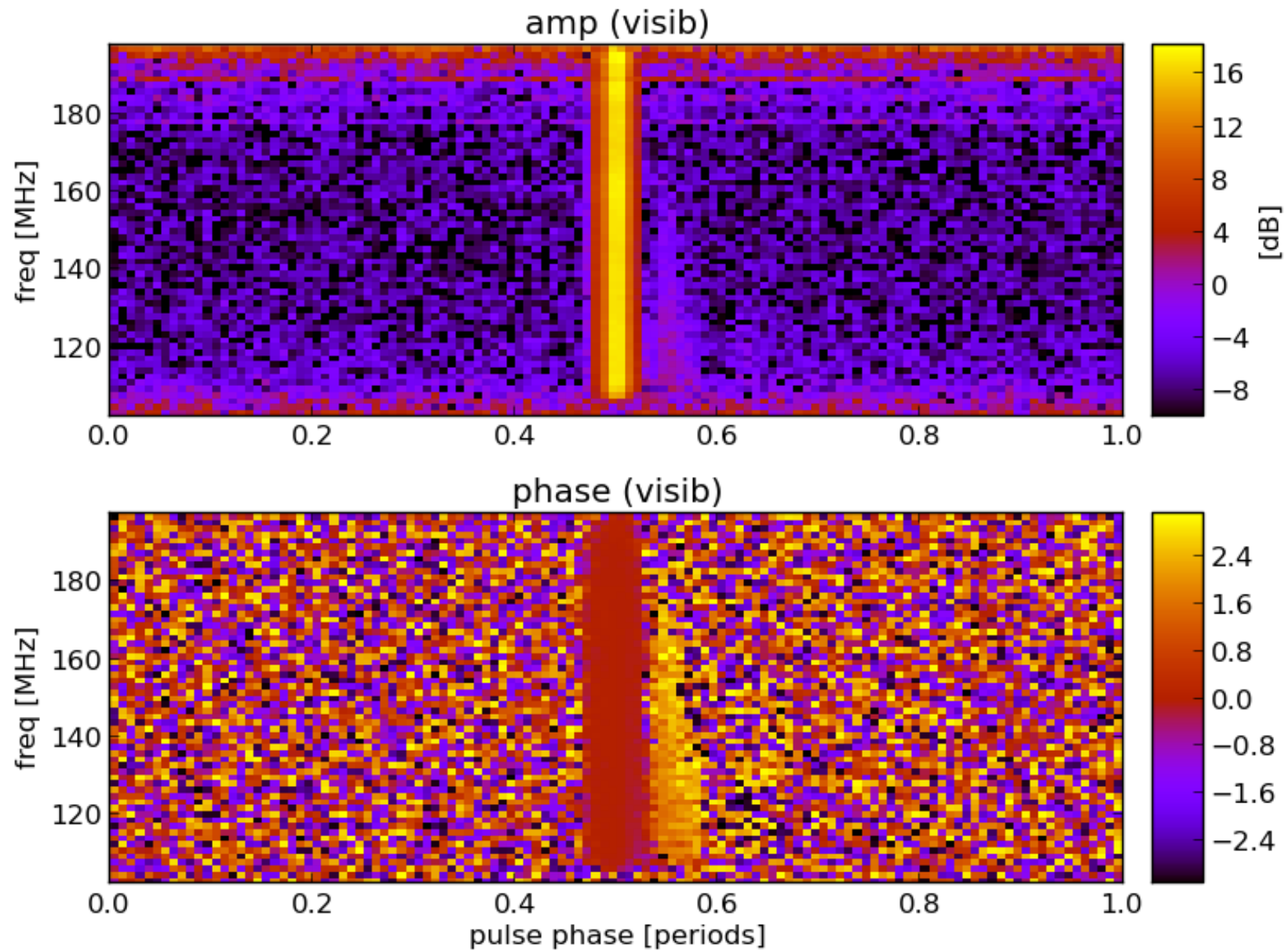
# Correlation and calibration

- own software correlator
  - ★ standard FX architecture
  - ★ flexibility, not efficiency!
- calibration (own software)
  - ★ pulsar gating, main pulse as reference
  - ★ full station-based fringe-fitting for phases
    - with dispersive/non-dispersive delays, rates, DFR
  - ★ bandpass calibration
- imaging and non-imaging analysis

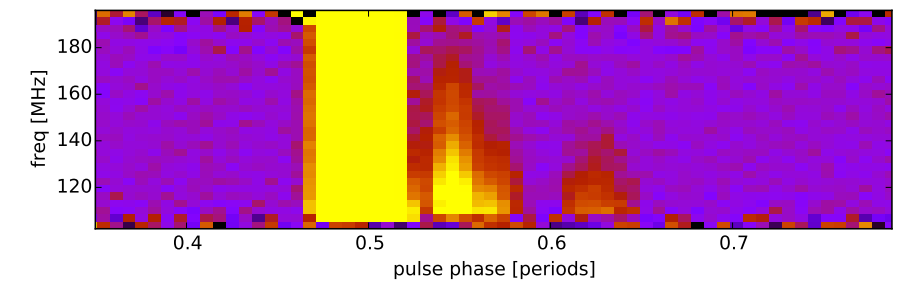
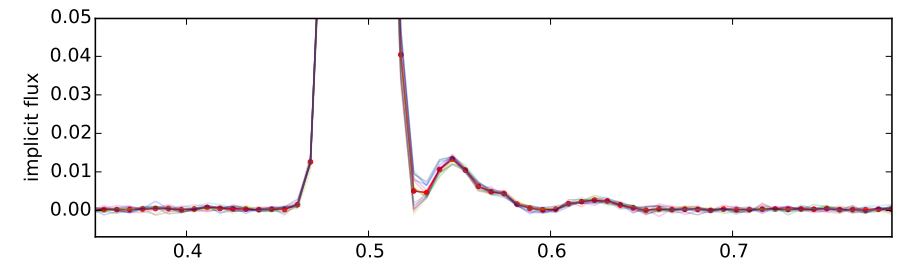
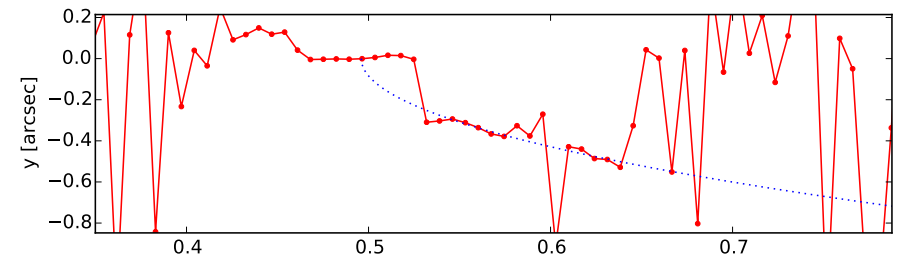
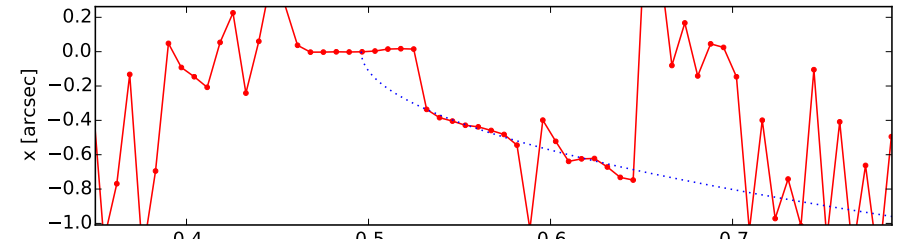
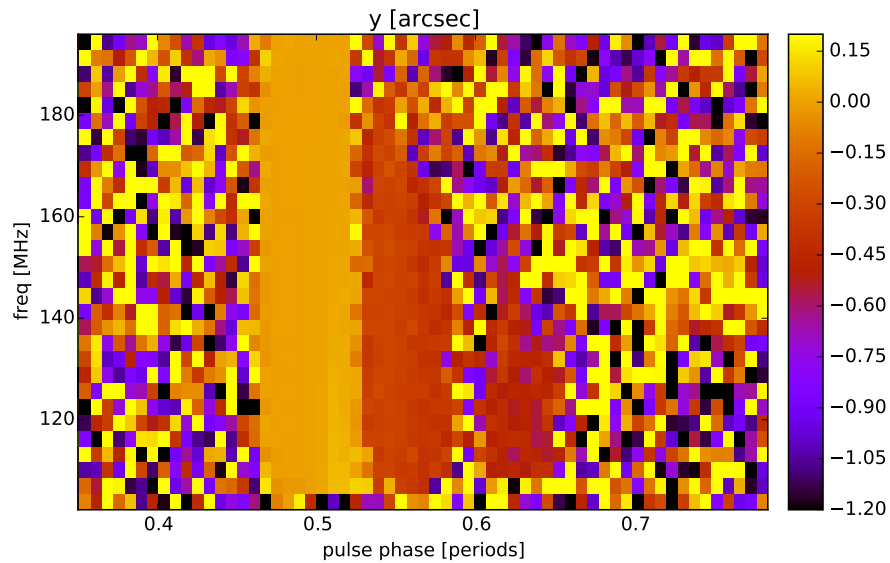
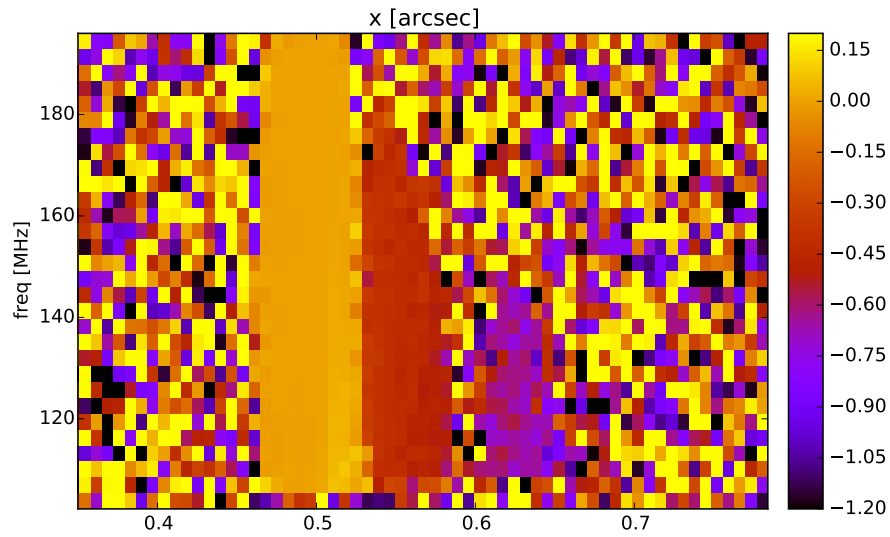
# GLOW Oct 2016: Pulses (DE603–DE605)



# Folded amplitudes and phases (DE603–DE605)



# Echo position(s)



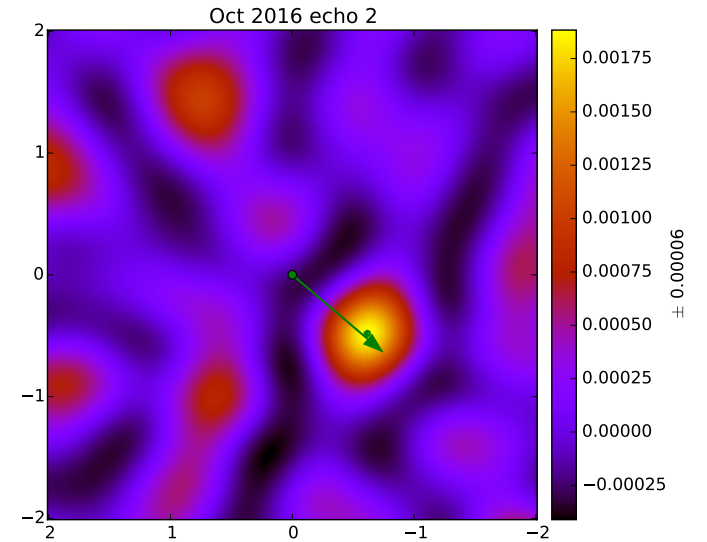
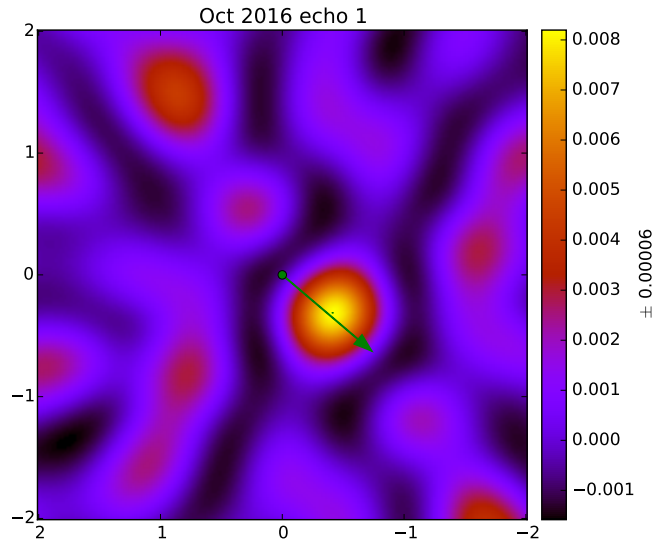
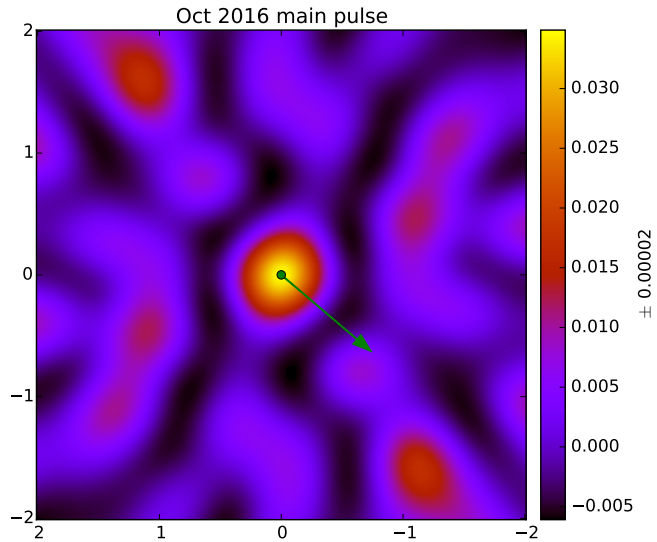
preliminary distance: 124 pc, very close to us!

# The full array: LOFAR + KAIRA

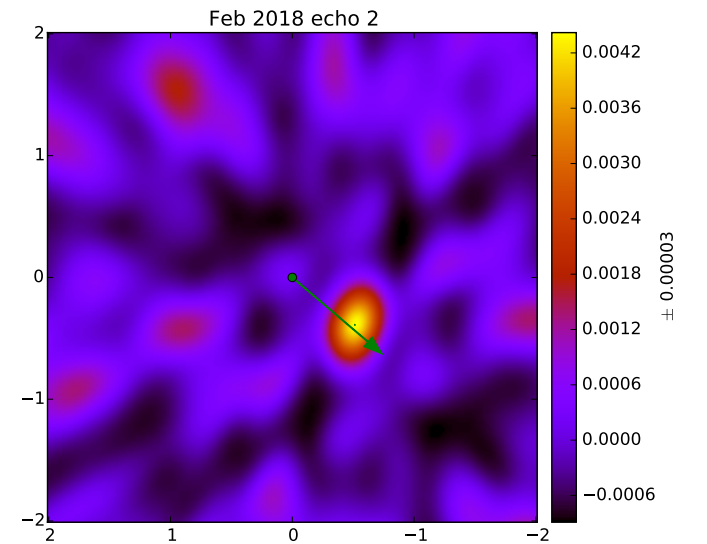
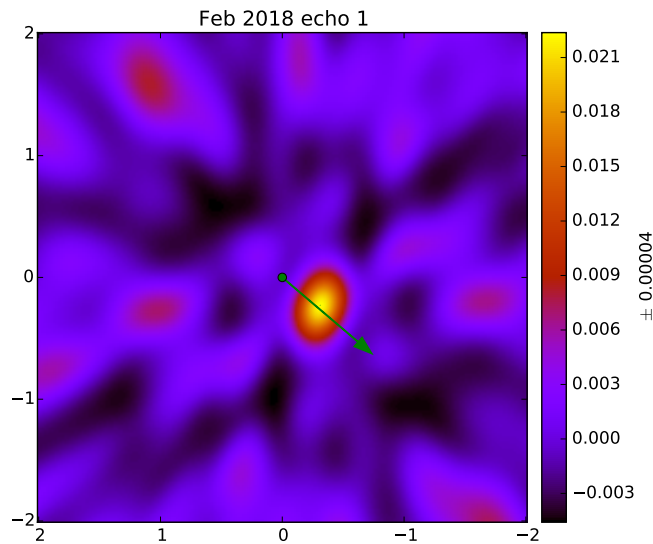
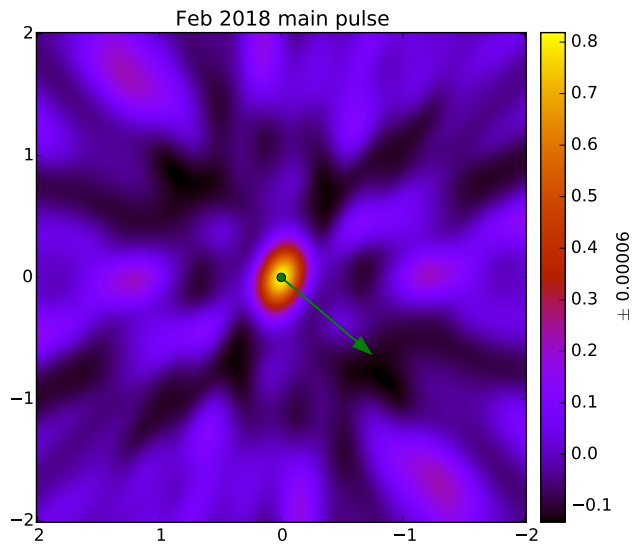


# Main pulse and echoes (dirty maps)

October 2016 GLOW



February 2018 international

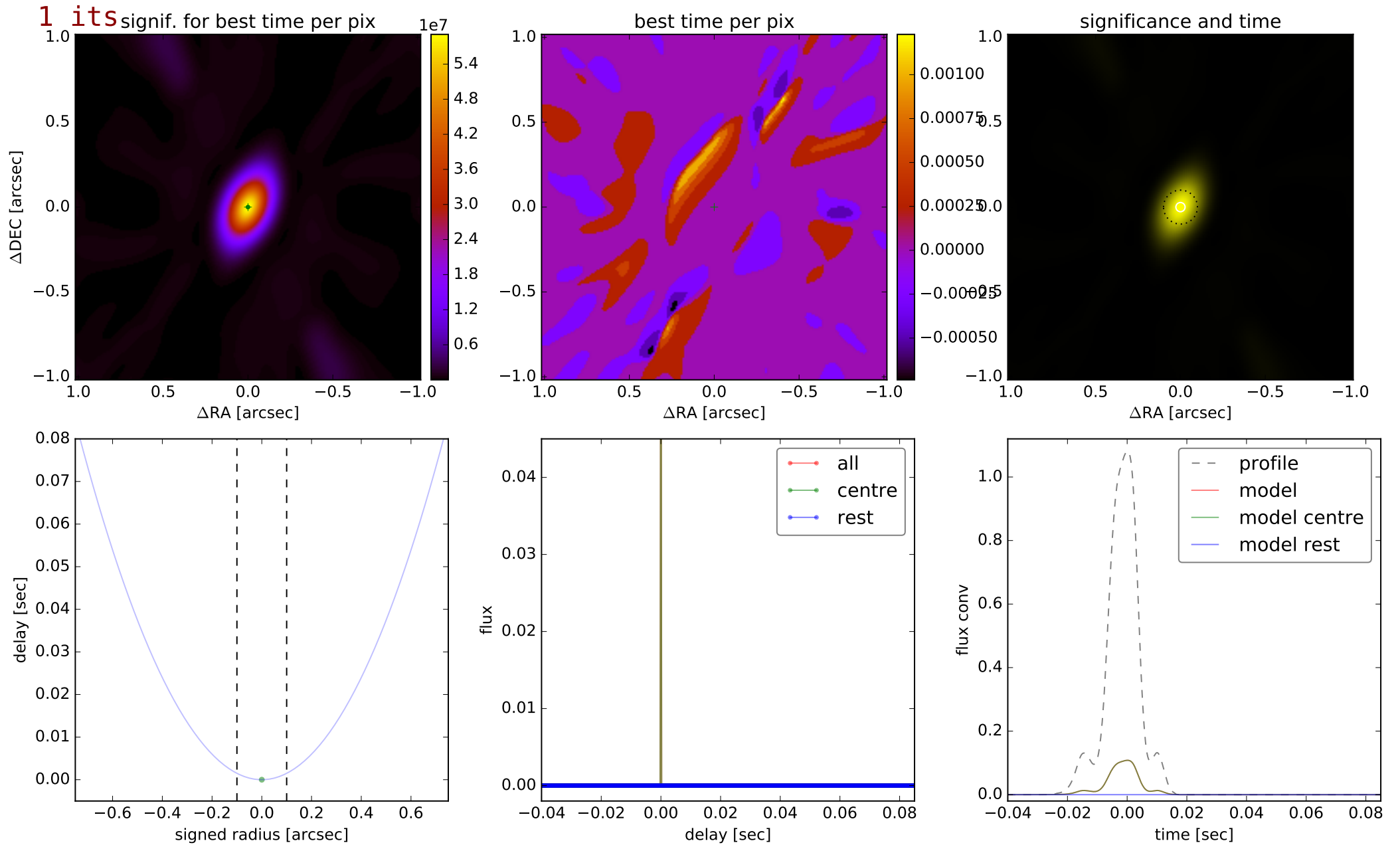




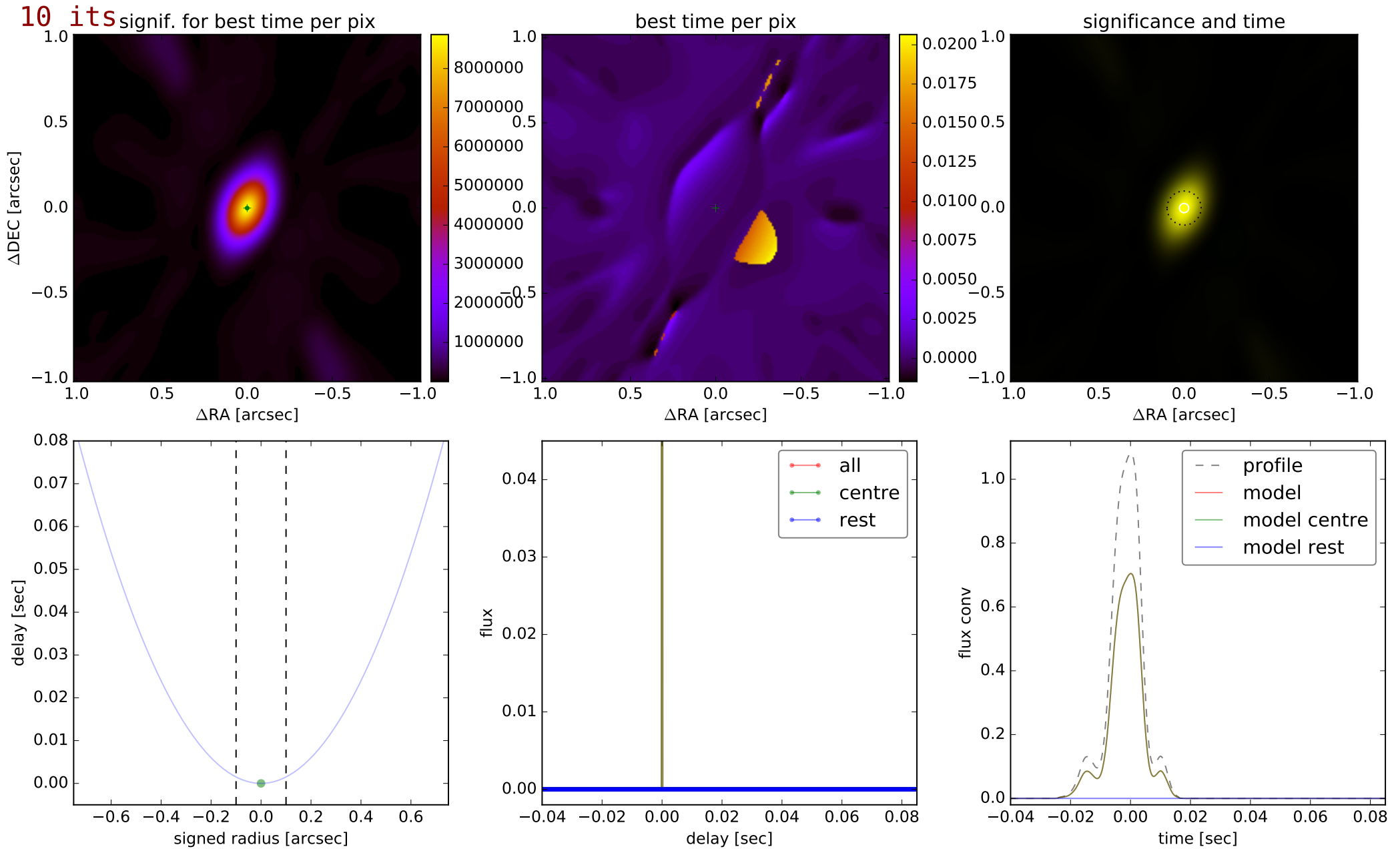
# Delayed-profile-aware CLEAN

- gating mixes intrinsic tail and echo
- deconvolve dirty beam *and* intrinsic profile
- standard CLEAN components
  - ★ explicit: position
  - ★ implicit: flux
- generalised CLEAN components
  - ★ explicit: position (offset), delay
  - ★ implicit: flux, spectrum

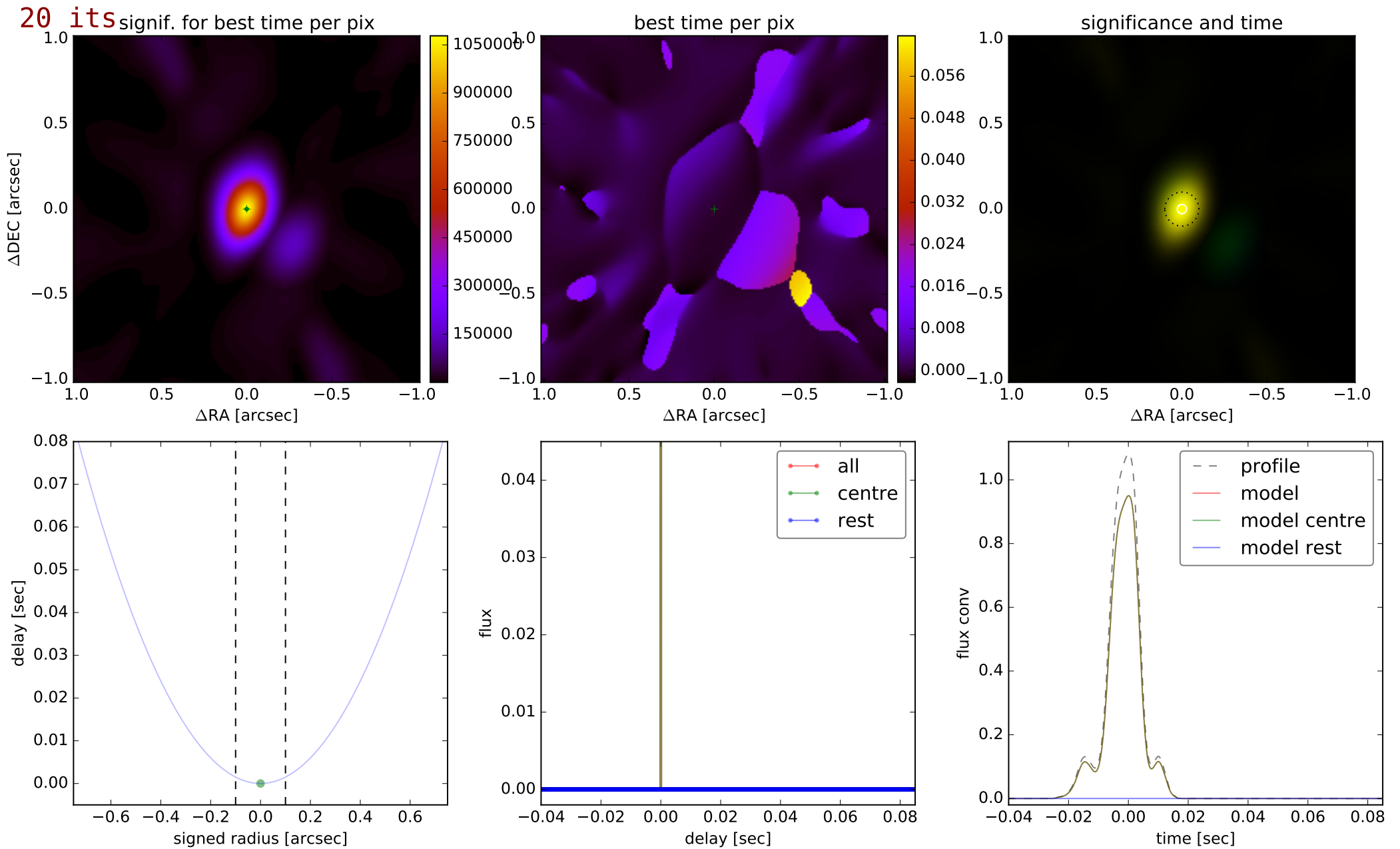
# Delayed-profile-aware CLEAN (1 iteration)



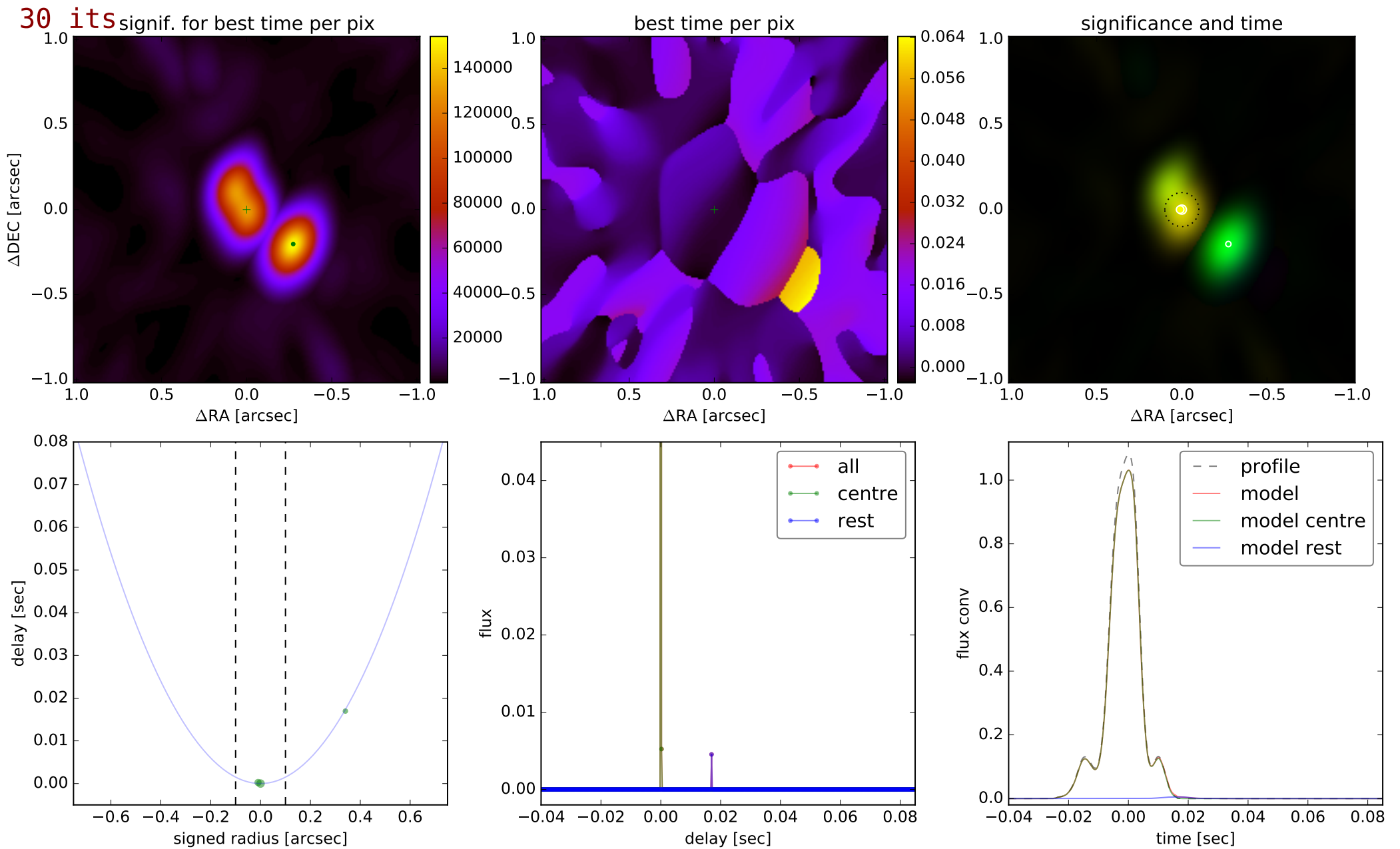
# Delayed-profile-aware CLEAN (10 iterations)



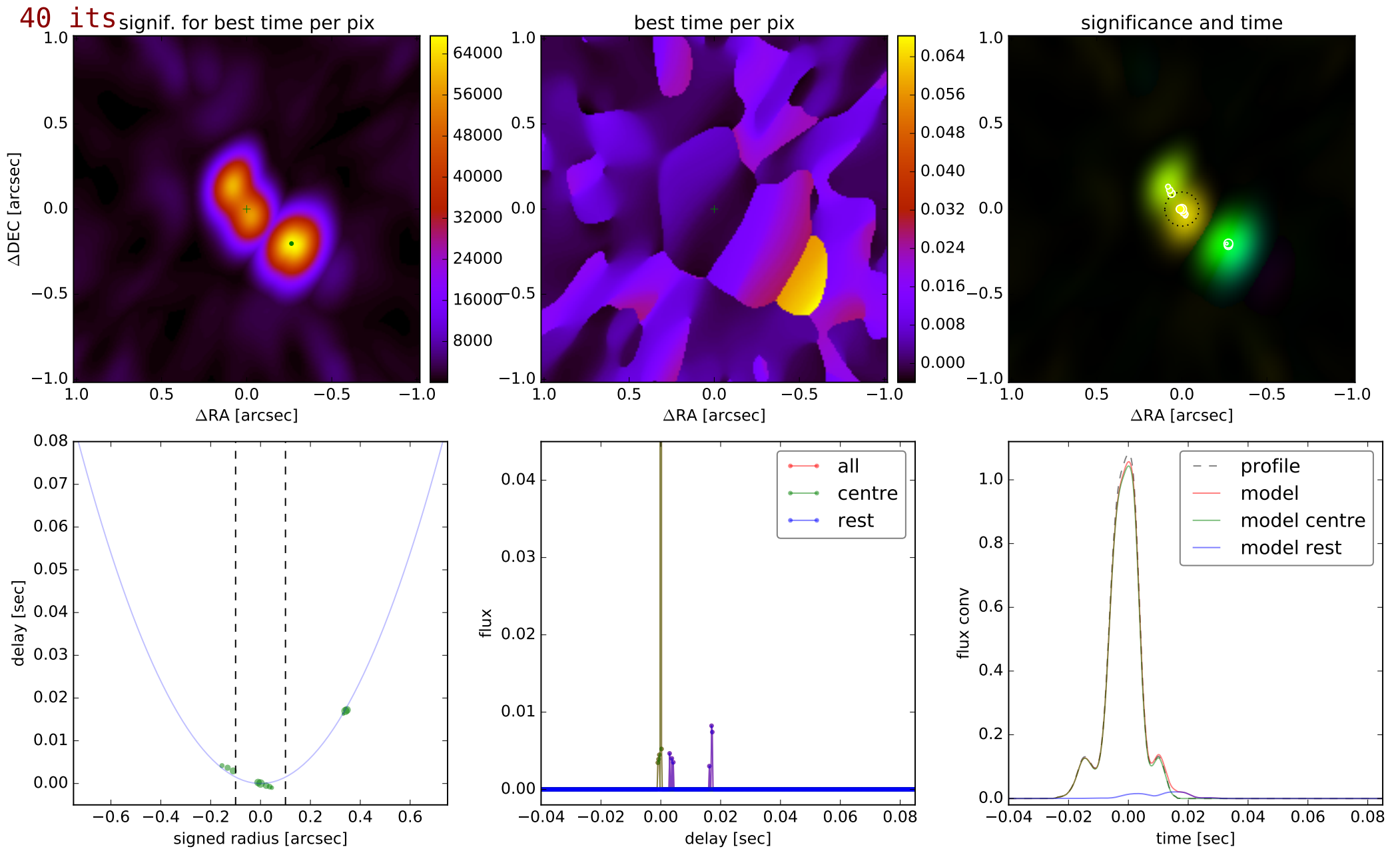
# Delayed-profile-aware CLEAN (20 iterations)



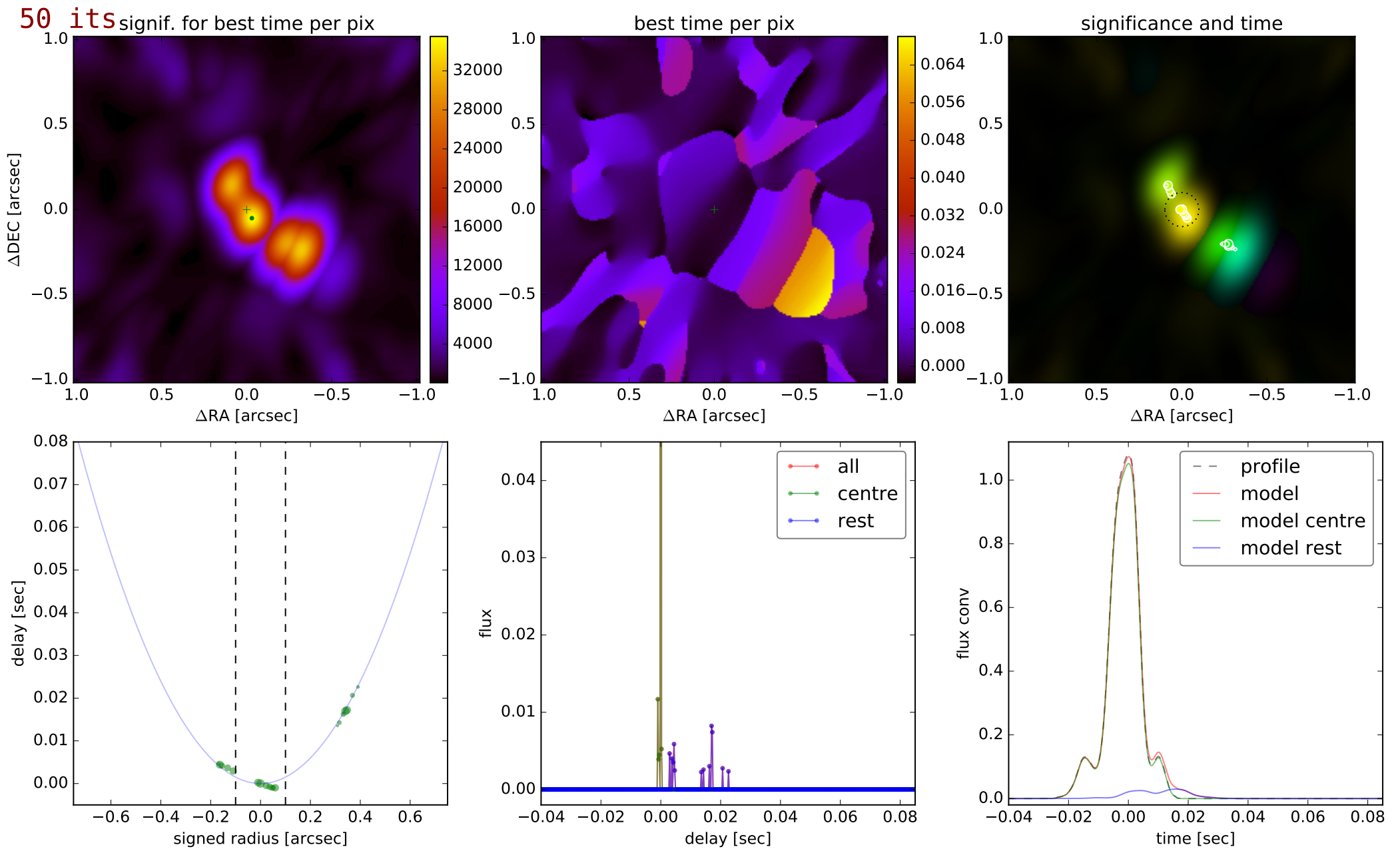
# Delayed-profile-aware CLEAN (30 iterations)



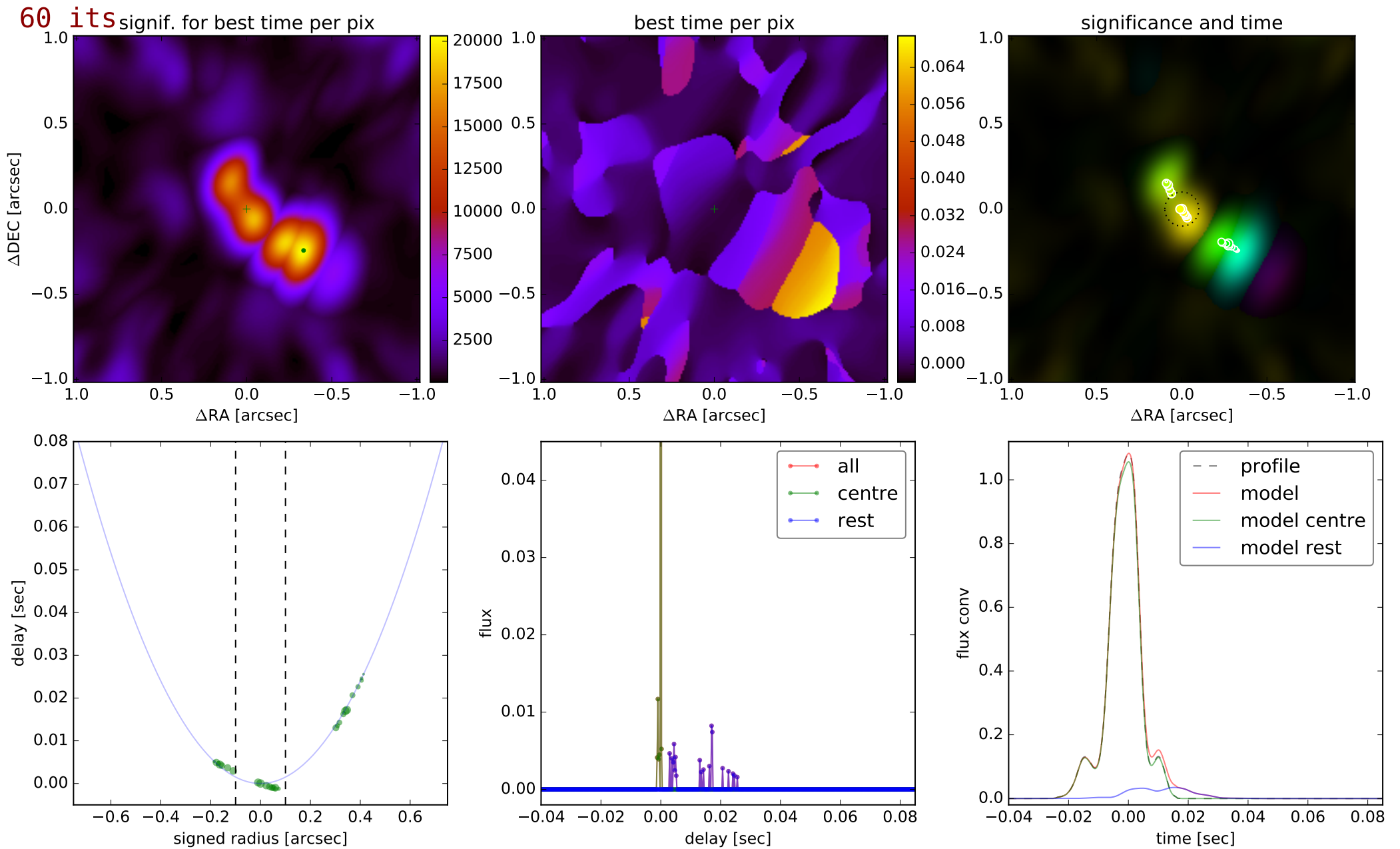
# Delayed-profile-aware CLEAN (40 iterations)



# Delayed-profile-aware CLEAN (50 iterations)

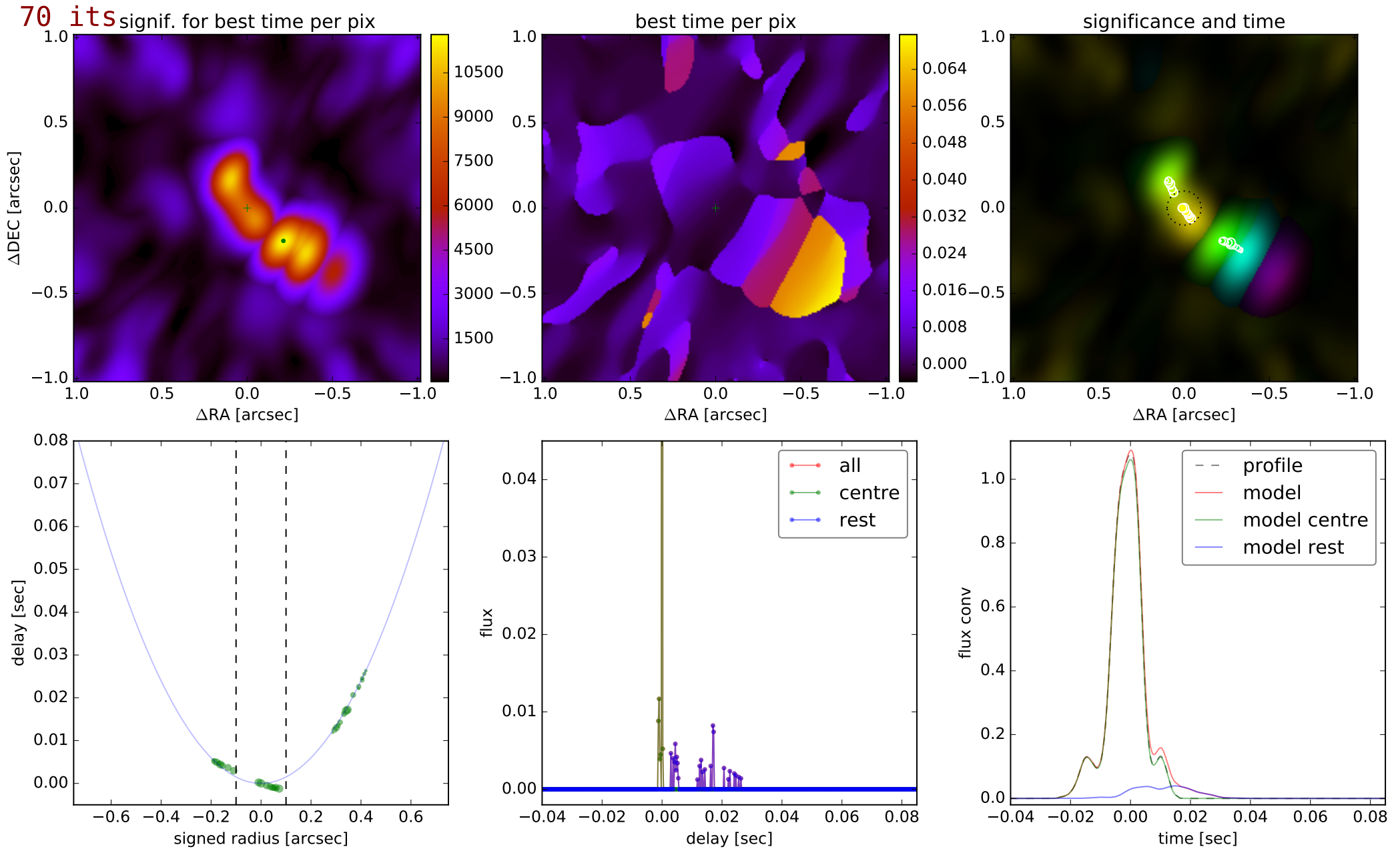


# Delayed-profile-aware CLEAN (60 iterations)

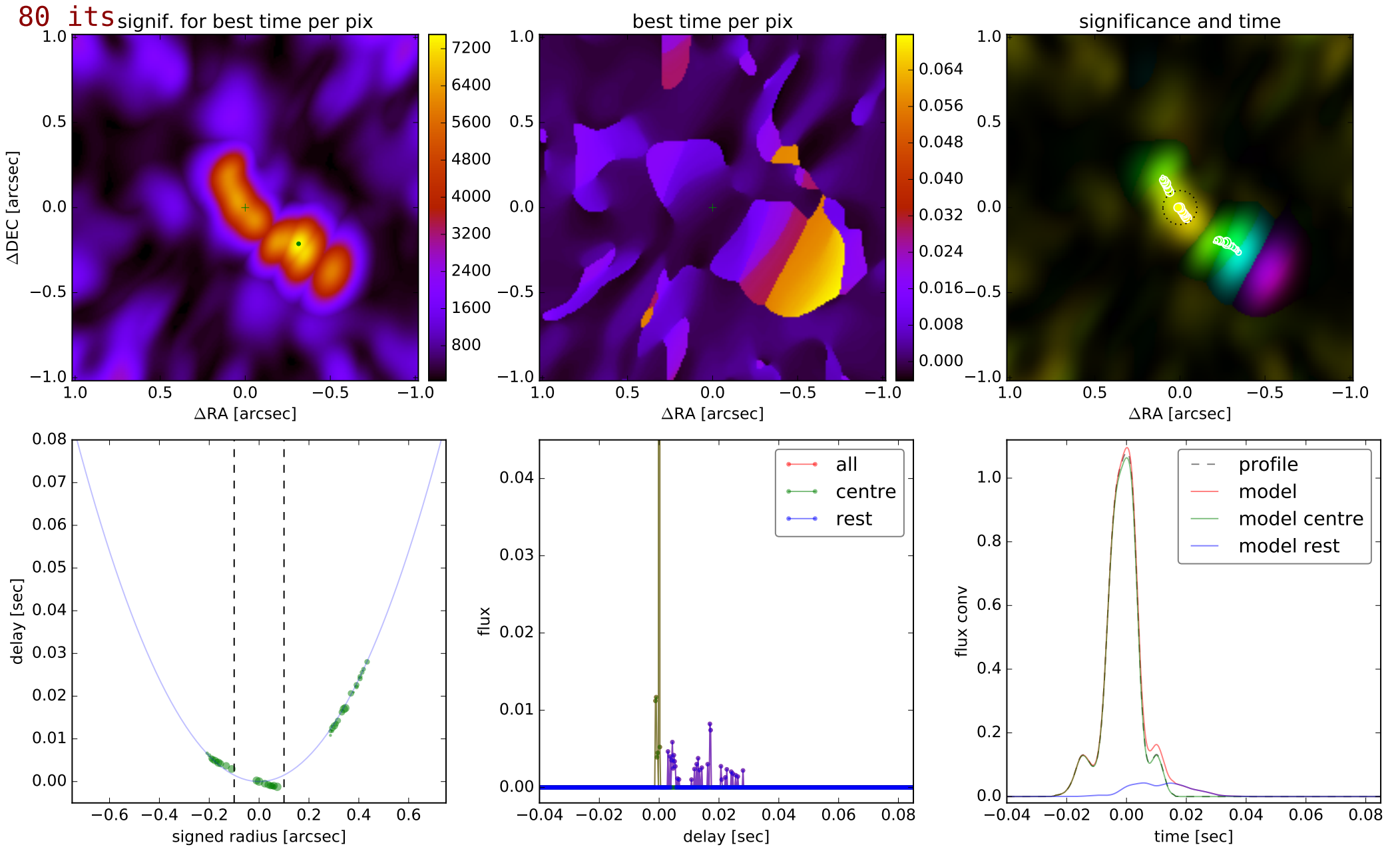




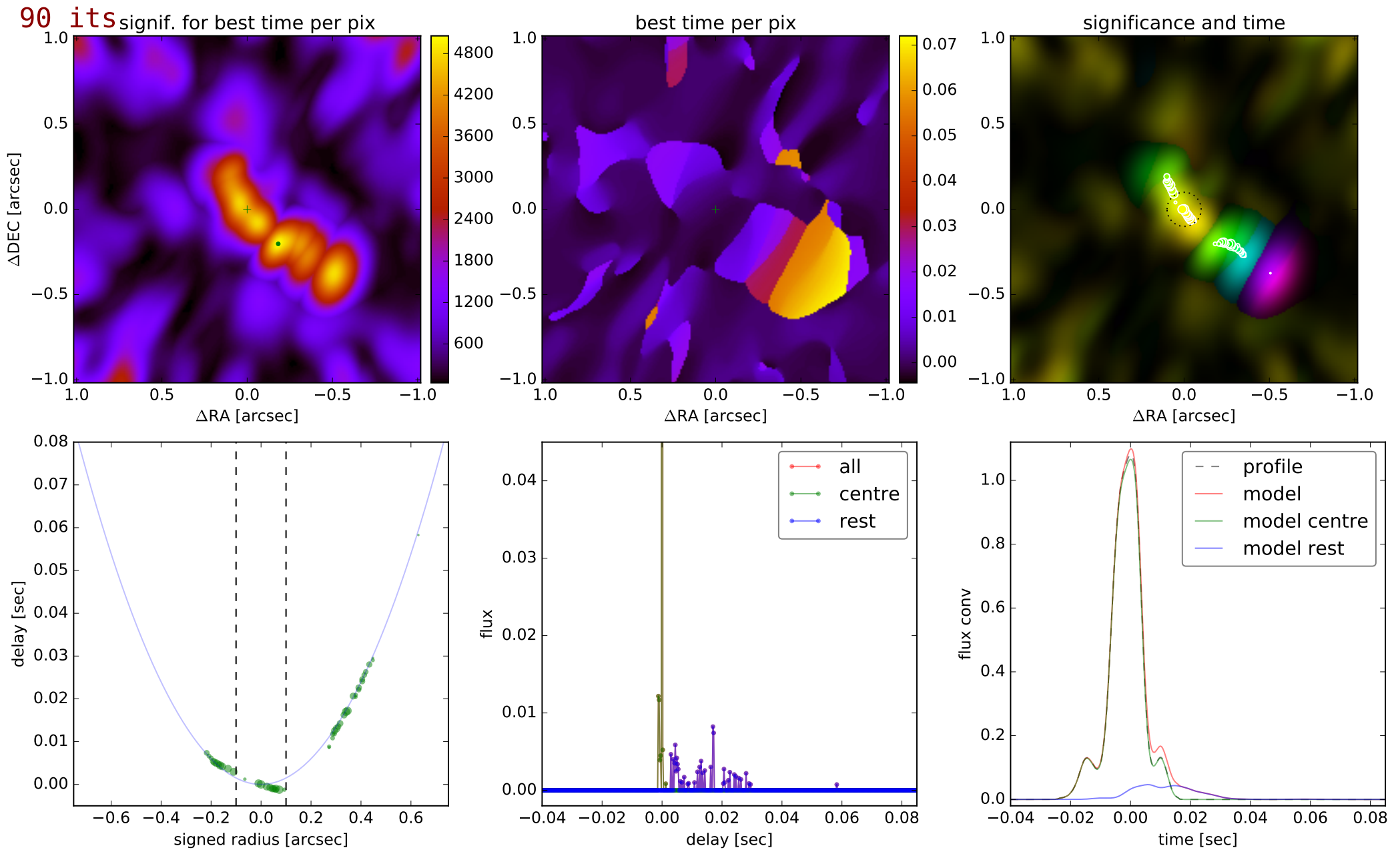
# Delayed-profile-aware CLEAN (70 iterations)



# Delayed-profile-aware CLEAN (80 iterations)

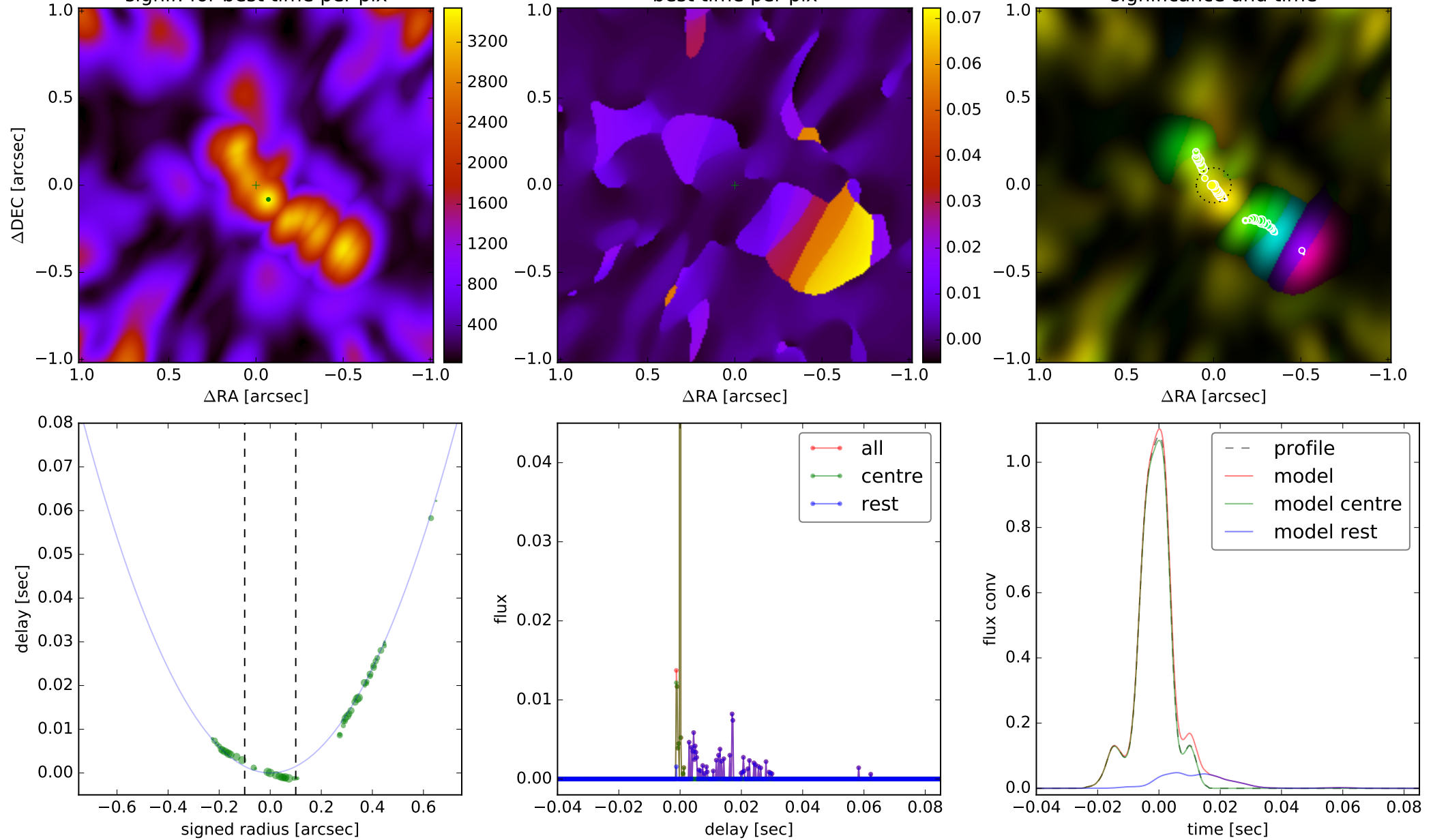


# Delayed-profile-aware CLEAN (90 iterations)



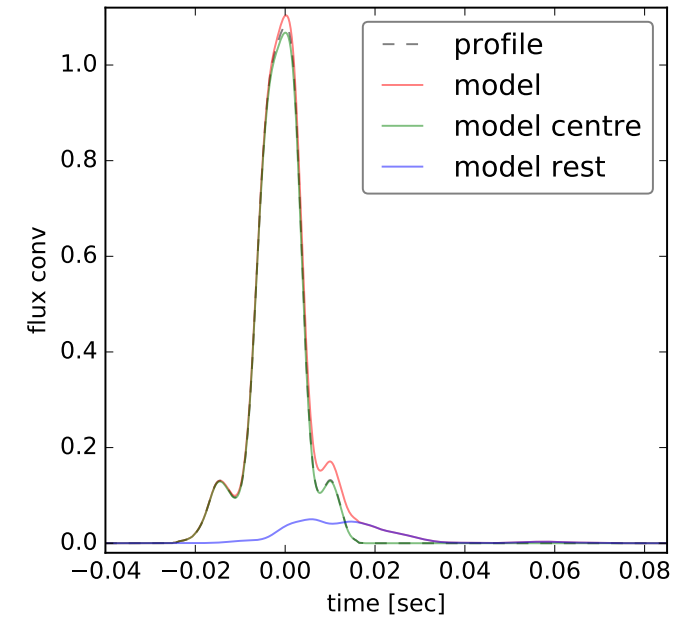
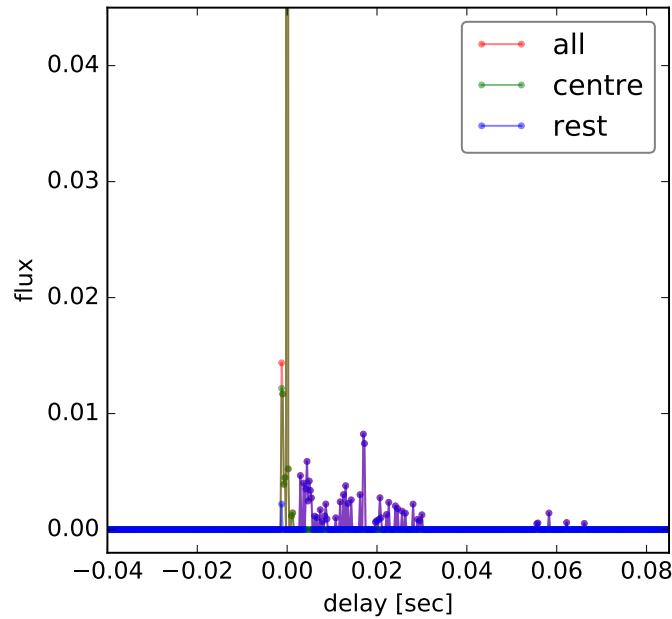
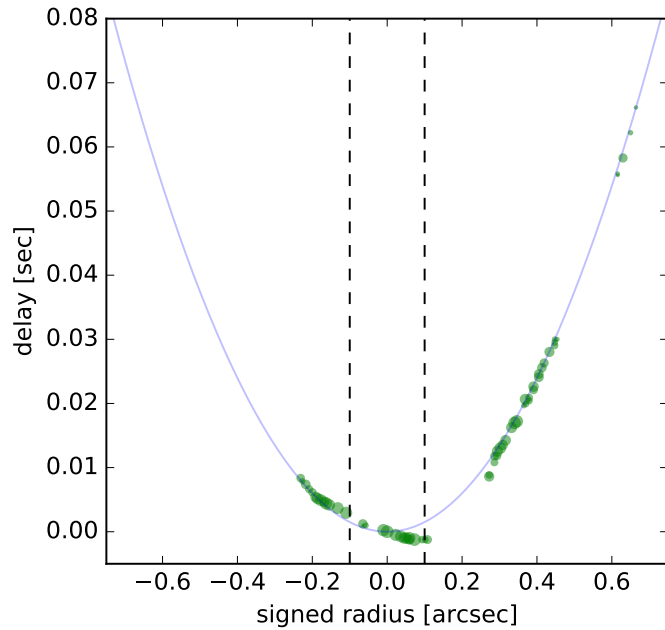
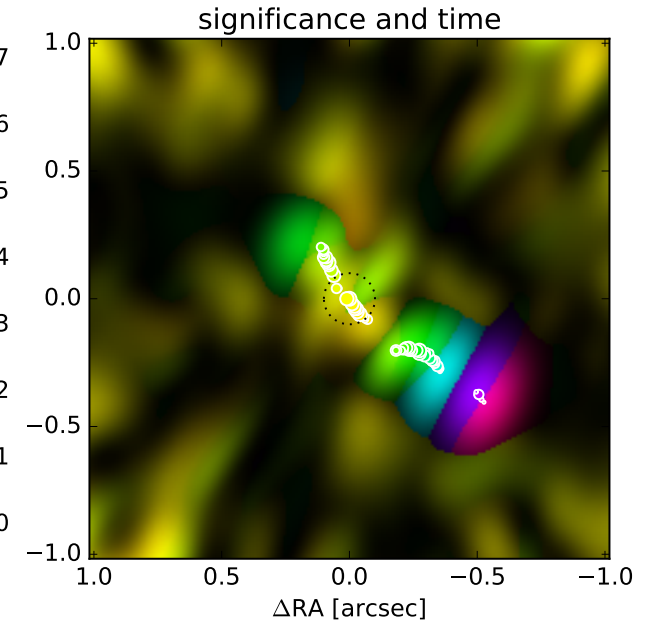
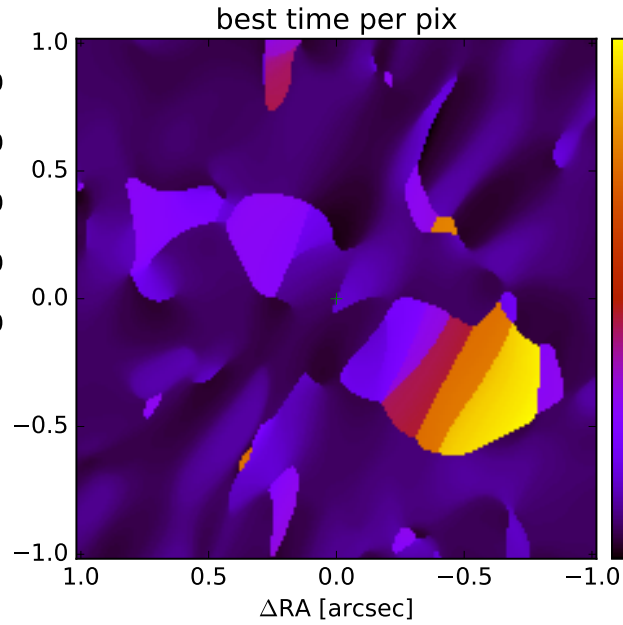
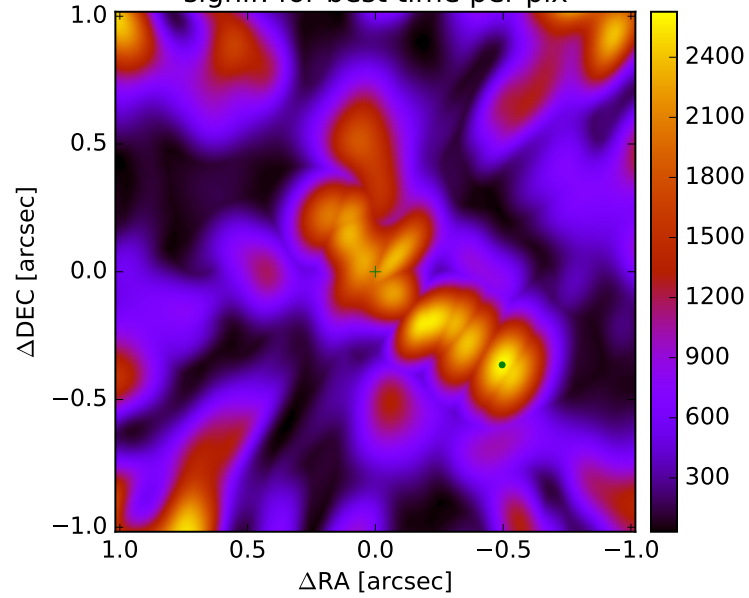
# Delayed-profile-aware CLEAN (100 iterations)

100 its signif. for best time per pix



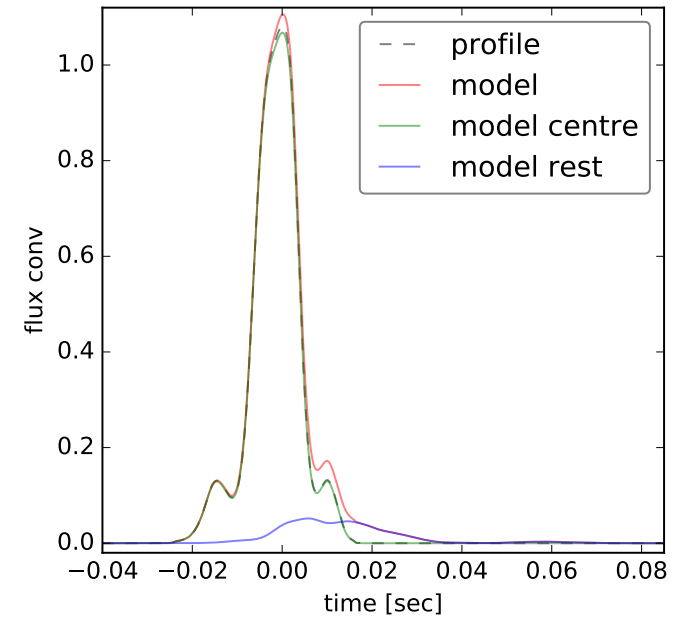
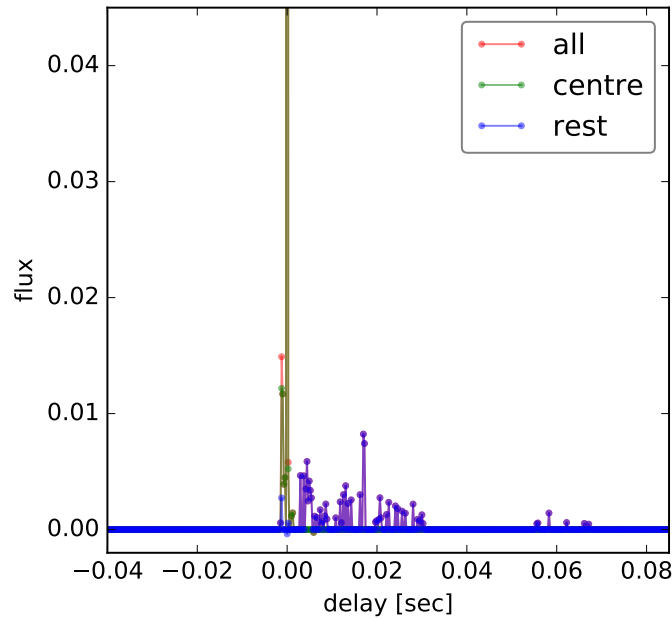
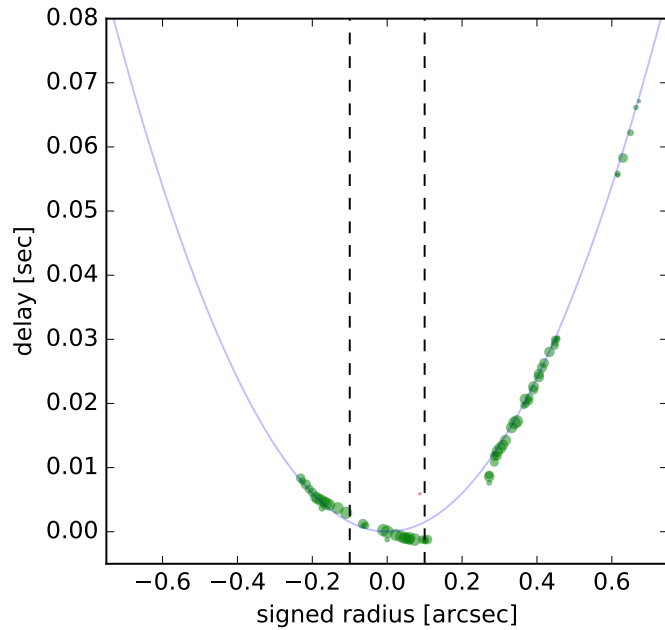
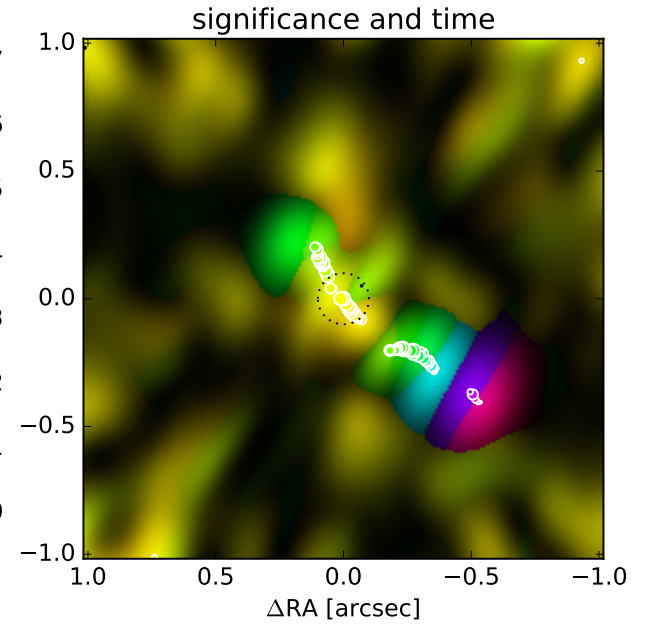
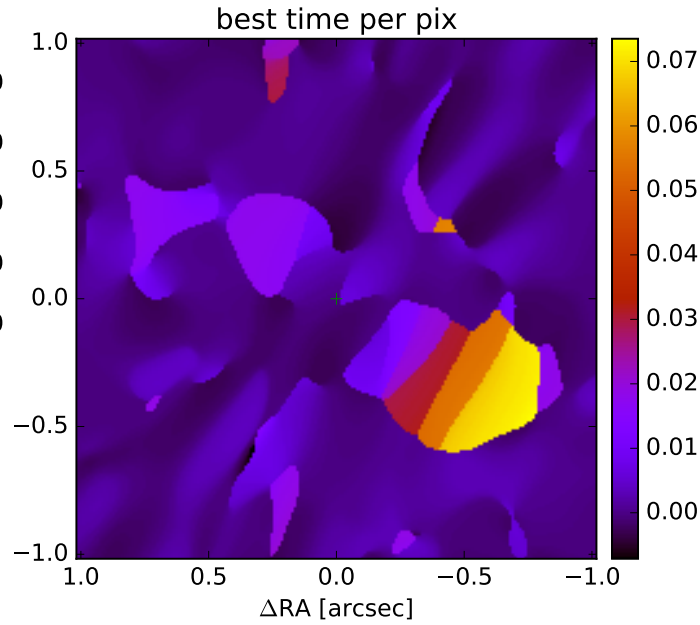
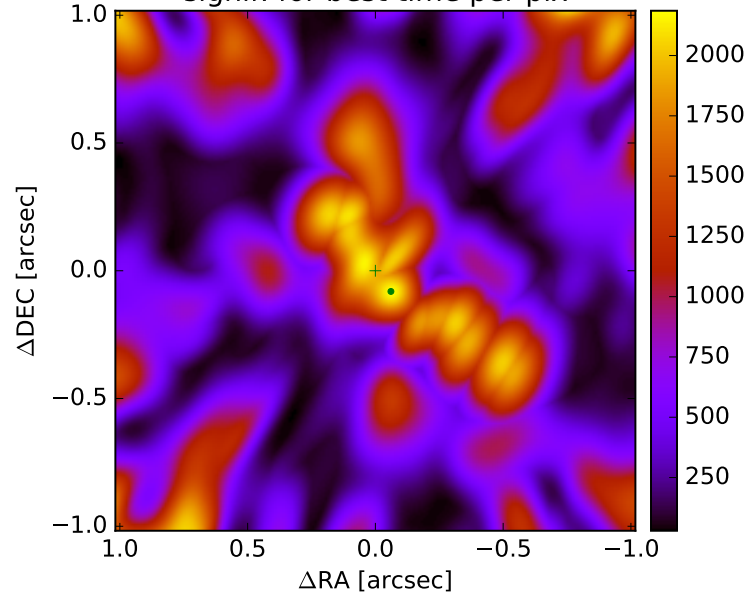
# Delayed-profile-aware CLEAN (110 iterations)

110 its signif. for best time per pix



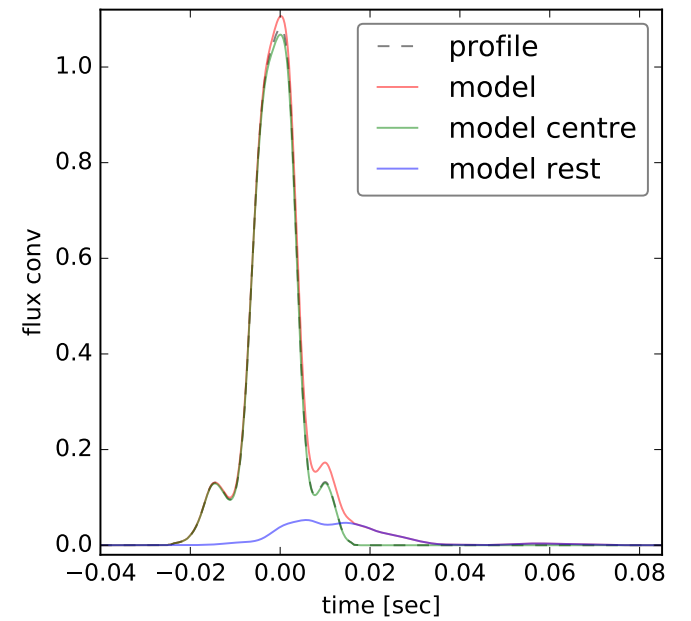
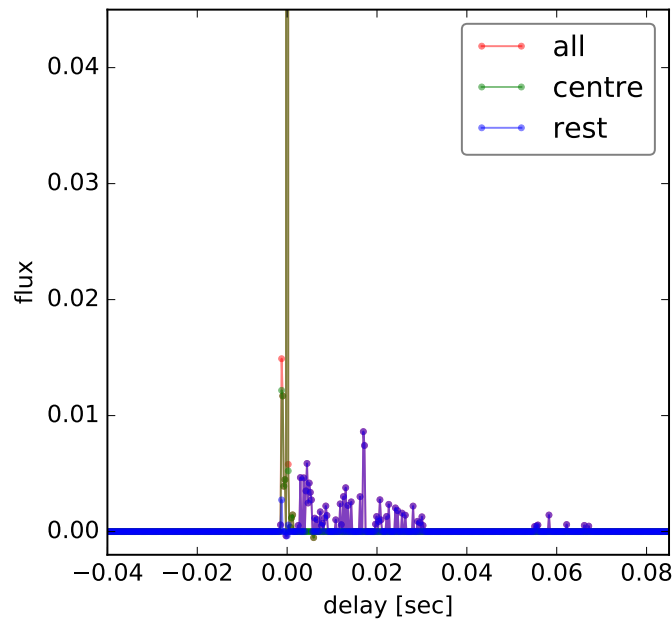
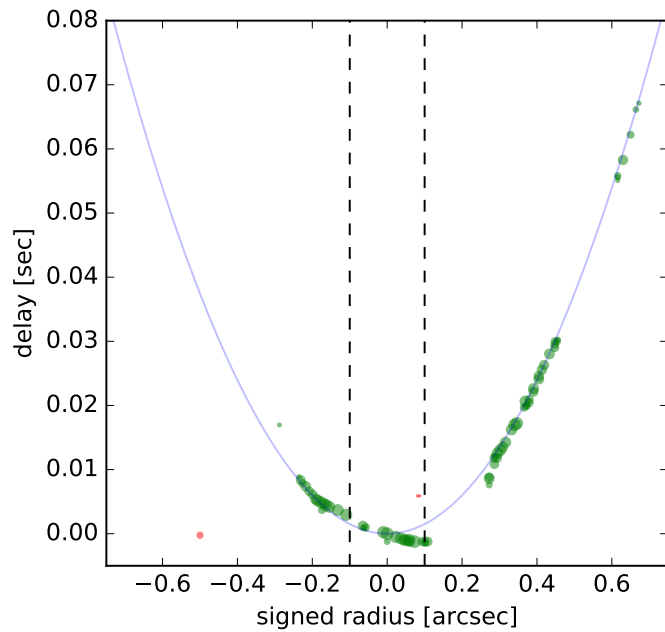
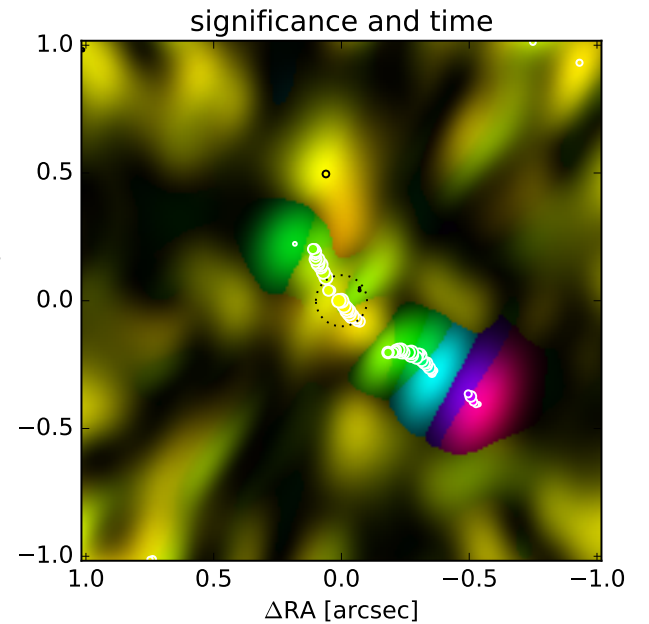
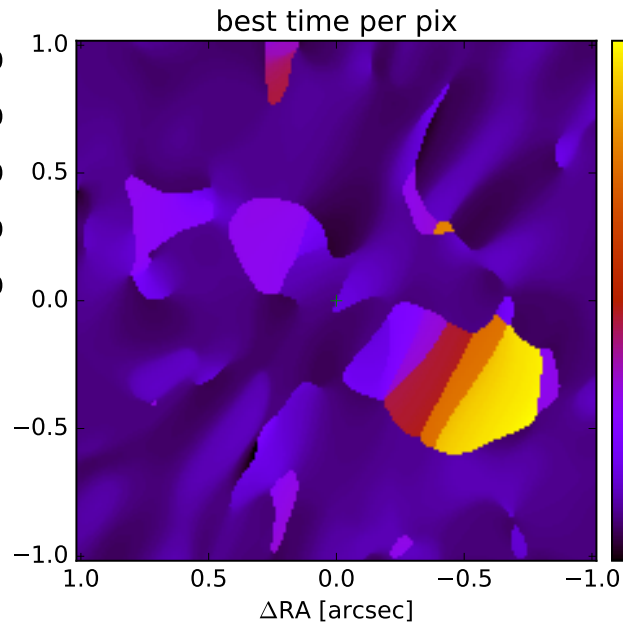
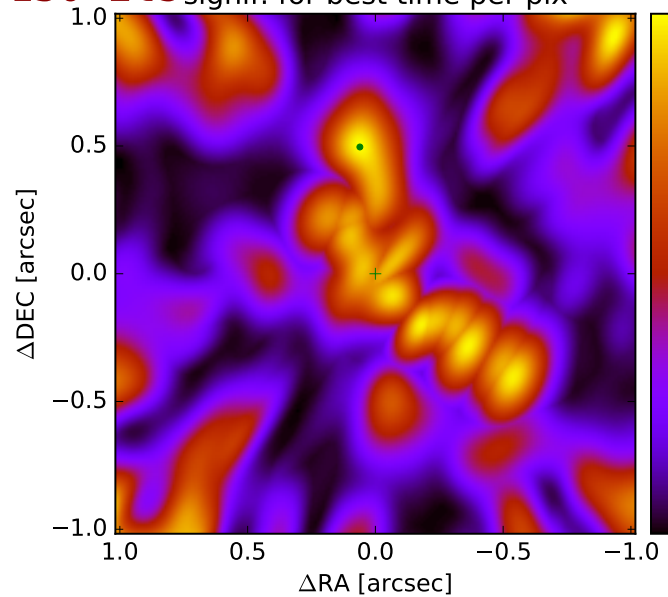
# Delayed-profile-aware CLEAN (120 iterations)

120 its signif. for best time per pix



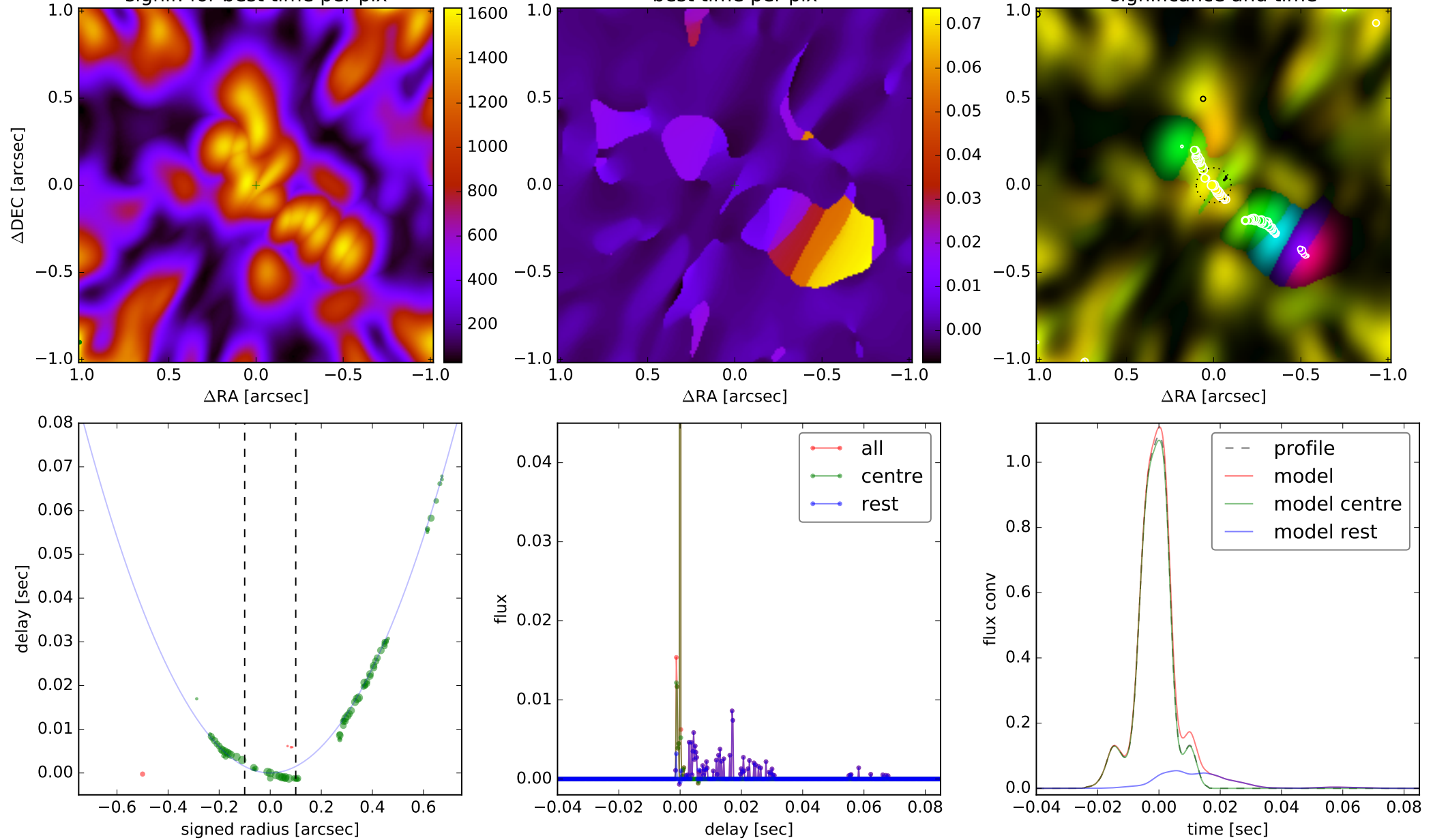
# Delayed-profile-aware CLEAN (130 iterations)

130 its signif. for best time per pix



# Delayed-profile-aware CLEAN (140 iterations)

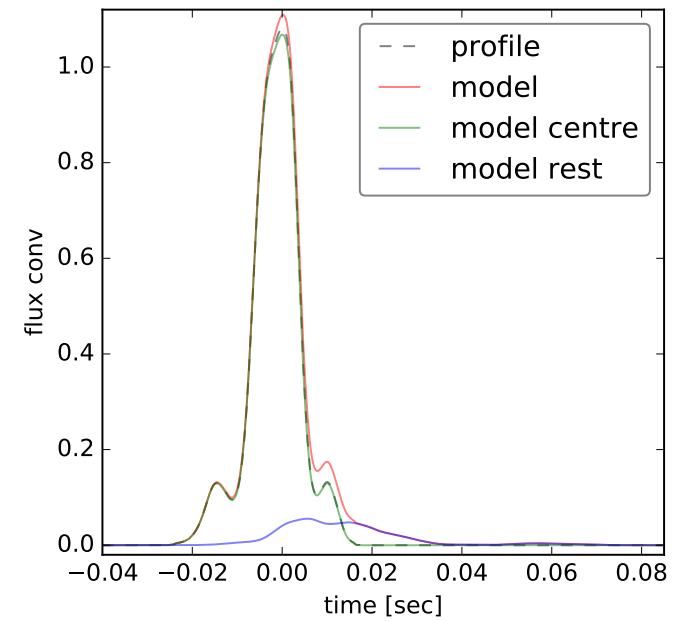
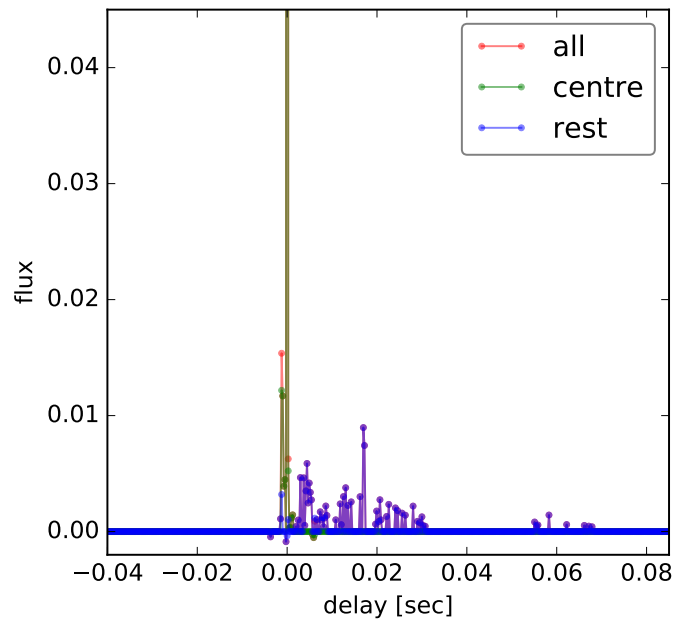
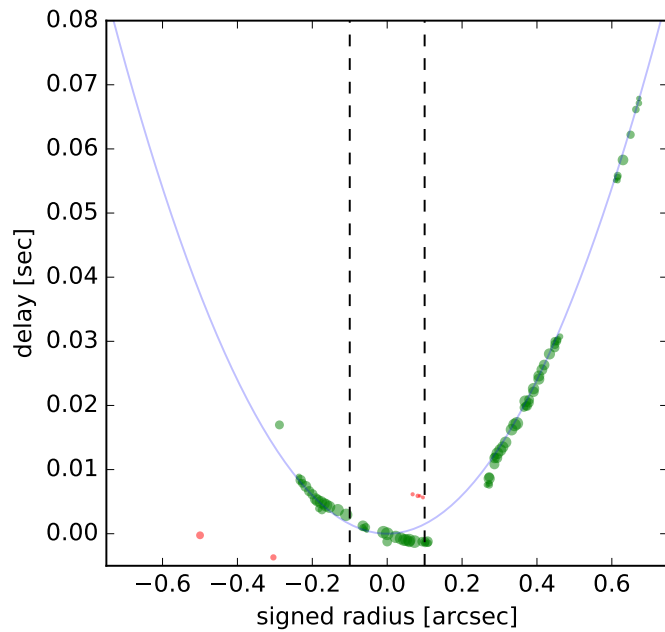
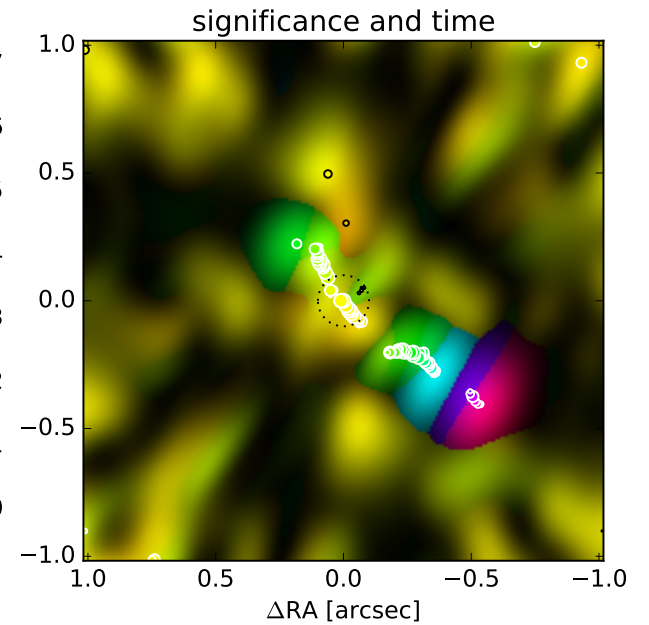
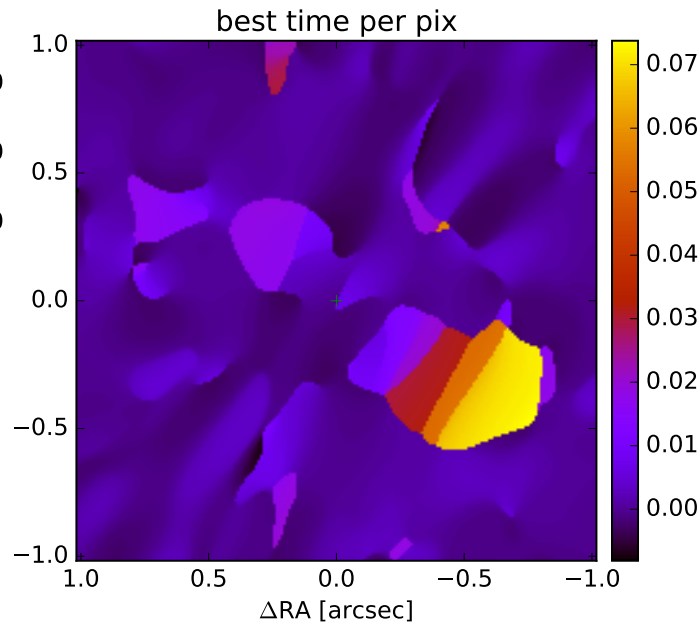
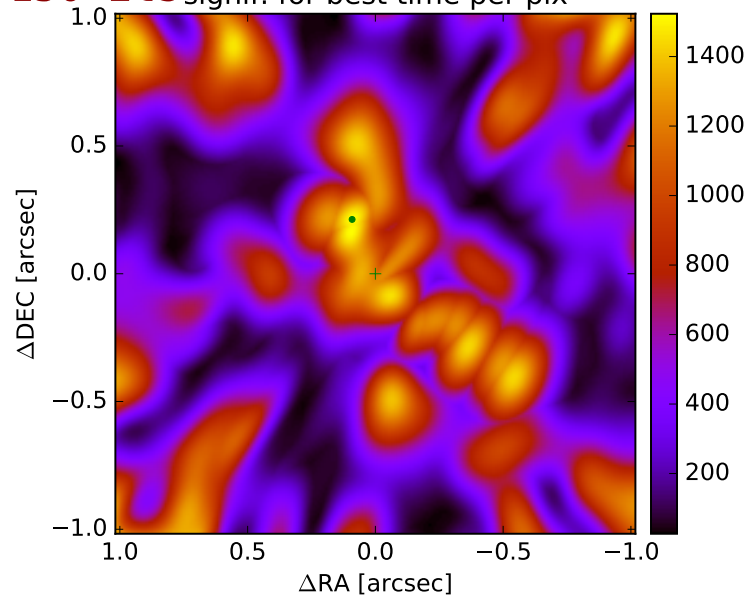
140 its signif. for best time per pix





# Delayed-profile-aware CLEAN (150 iterations)

150 its signif. for best time per pix



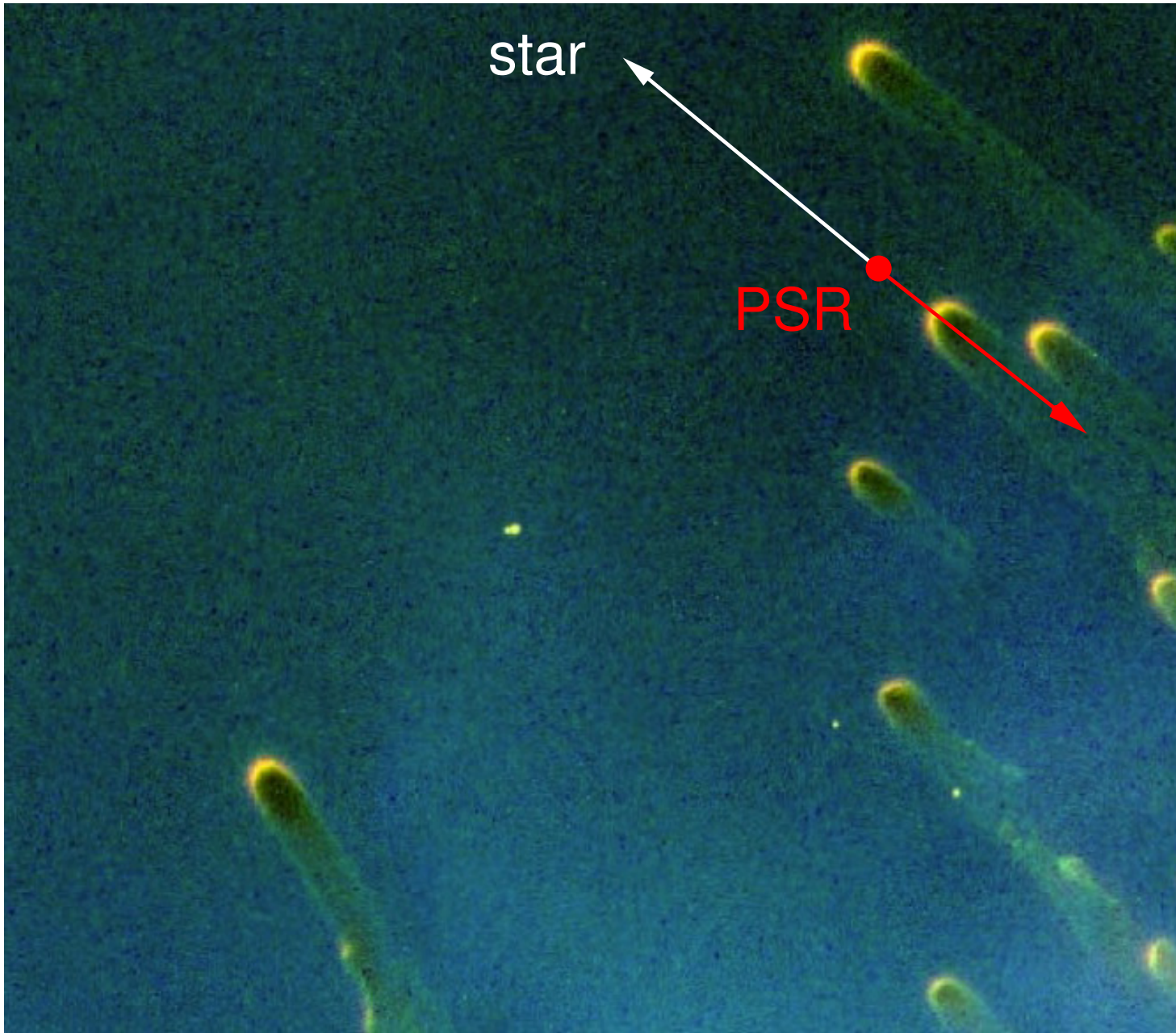
# Ionised matter around hot stars?

- *Walker et al. (2017): Extreme Radio-wave Scattering Associated with Hot Stars*
- IDV sources with (hot) stars near l.o.s.
  - ★ J1819+3845 with Vega
  - ★ PKS 1322–110 with Spica (8'5)
  - ★ PKS 1257–326 with Alhakim
- 'dense' neutral matter around star, ionised by UV
- elongated 'elephant's trunks' may cause transverse lensing
- distances and orientation fit

# Stars around B1508+55 ?

- A0 star Hip 74377 at 2.73 pc from l.o.s.
  - ★ distance from us ca. 260 pc
- A2 star Hip 74458 at 1.37 pc from l.o.s.
  - ★  $\pi = (8.36 \pm 0.57)$  mas
  - ★ distance  $(120 \pm 8.2)$  pc
- compare with  $D_d = 124$  pc
- thanks to Mark Walker and Artem Tuntsov

# Elephant's trunk lensing ?



# Thanks to all people involved!

Mostly informal collaboration, great VLBI spirit!

GLOW: Andreas Horneffer, Caterina Tiburzi, Jörn Künsemöller,  
Julian Donner, Natasha Porayko

FR606: Jean-Mathias Grießmeier

SE607: Tobia Carozzi

UK608: Aris Karastergiou

PL610: Mariusz Pozoga, Barbara Matyjasiak, Hanna Rotkaehl

PL611: Marian Soida, Wojciech Lewandowski,  
Bartosz Smierciak

PL612: Tomasz Sidorowicz, Leszek Blaszkiewicz,  
Andrzej Krankowski

KAIRA: Derek McKay

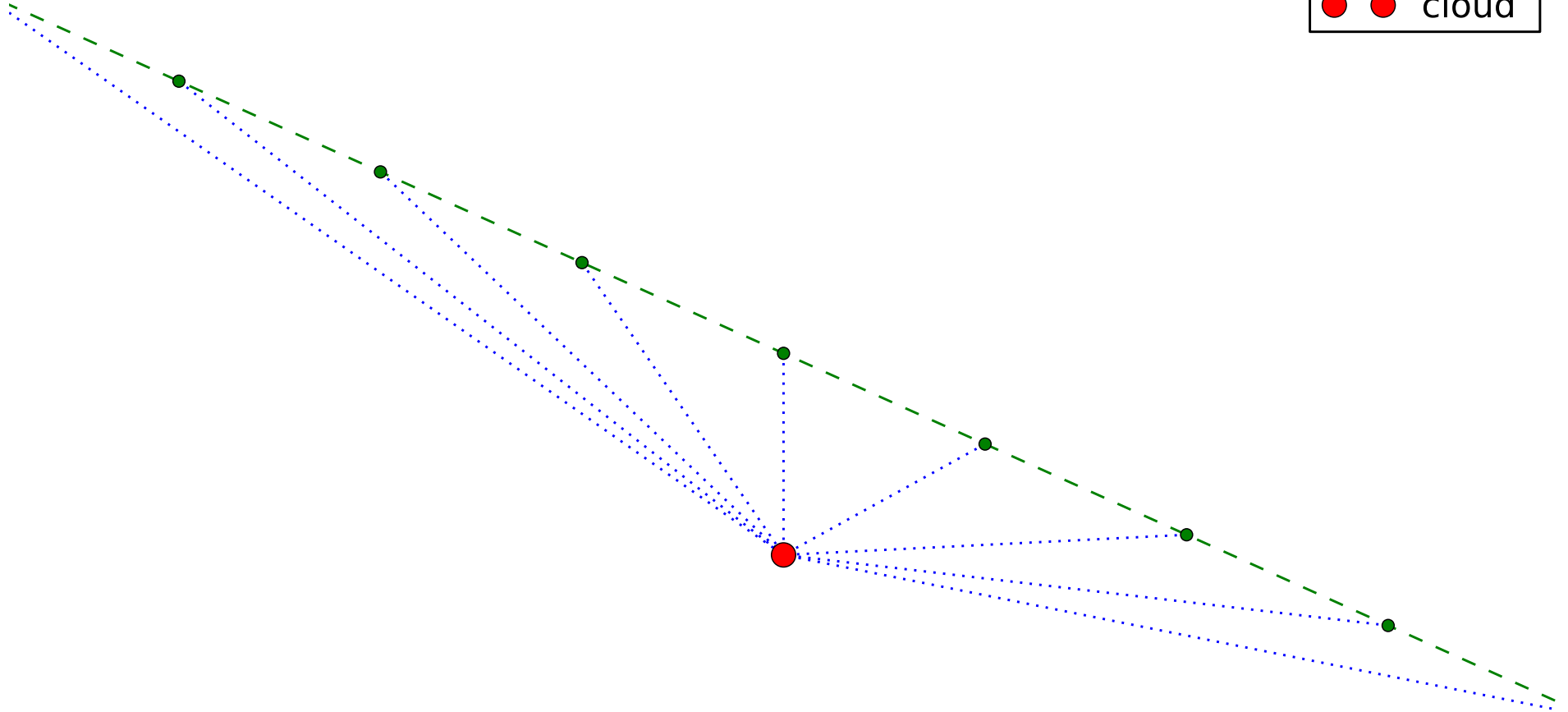
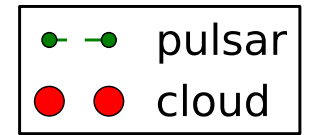
# Summary

- offline-VLBI with LOFAR works!
  - data can be calibrated
  - ghost of B1508+55 really is echo
  - distance of screen determined
  - alignment with proper motion
  - ongoing monitoring (data approaching 300 TB)
  - will include GMRT, maybe others
- ↪ other objects and projects

# Bonus: Relative alignment in nature



# Bonus: Cloud: no alignment





# Bonus: Filament: relative alignment

