PTFIDE: PTF Image Differencing & Extraction

Frank Masci & the PTF Collaboration

November 2013



Goals

- **Difference imaging**: to support transient discovery by suppressing everything that's static in time and space within the instrumental noise

- Given the complexity and heterogeneity of the PTF survey, we wanted a tool that:

  - was **flexible:** robust to instrumental artifacts, bad astrometry, adaptable to all seeing, little tuning
  - could operate in a **range of environments:** high source density, complex backgrounds and emission
  - could probe a **large discovery space:** pulsating & eruptive variables, eclipsing binaries, SNe, asteroids
  - **maximized** the reliability of candidates to streamline vetting process downstream
  - was **photometrically accurate:** obtain reasonably accurate light curves, also to support vetting/follow-up
  - had **preprocessing steps** customized for the PTF instrument/detector system: "relative" calibration of input images is crucial for good difference-imaging

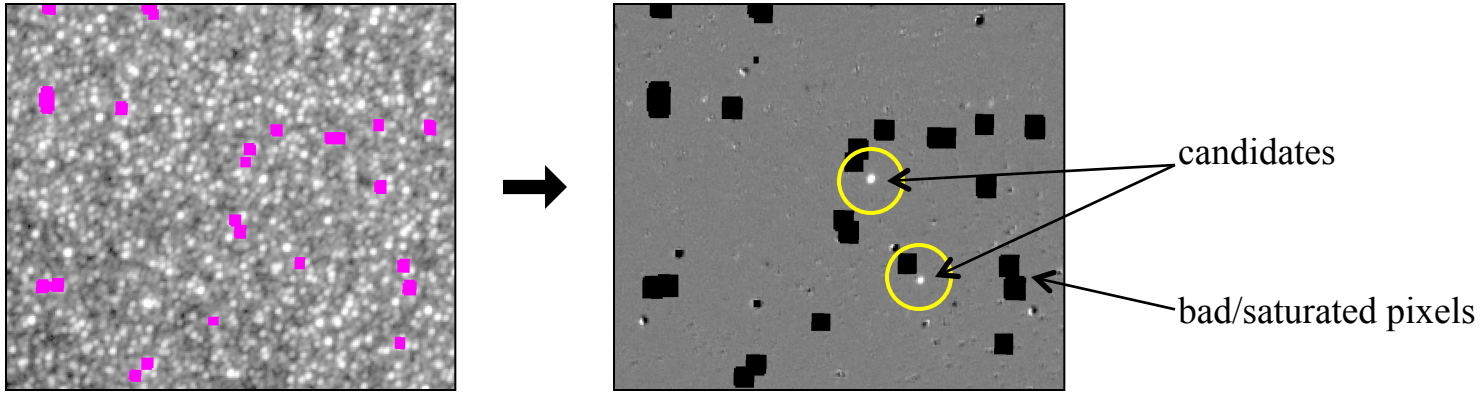
- Existing off-the-shelf methods and tools (as of ~2 years ago) were not flexible enough

PTFIDE – a generic discovery engine

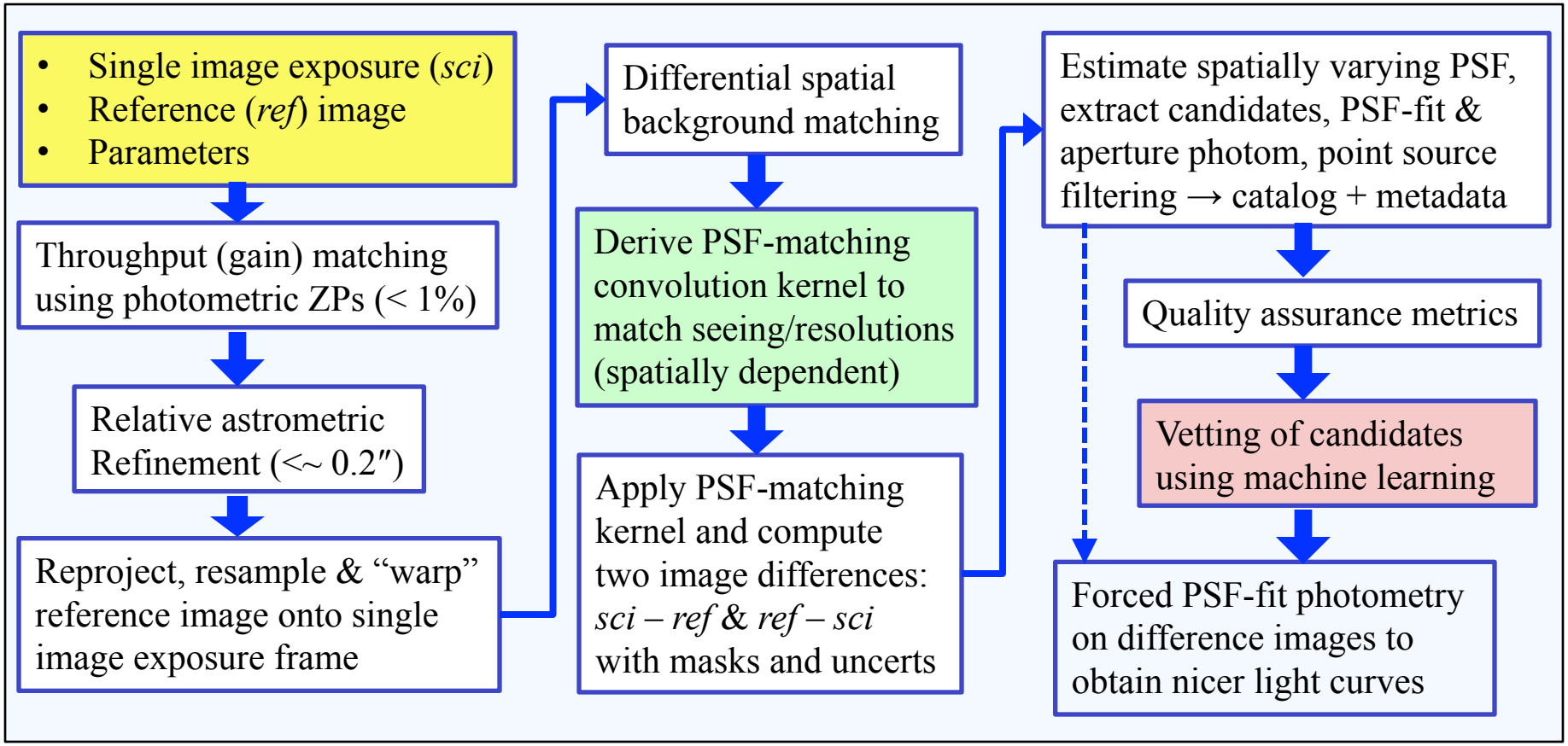
- Near real-time transient discovery currently occurs at LBNL, using mostly off-the-shelf software
- Wanted something more optimal, to meet the broader scientific goals of iPTF and ZTF

- PTFIDE currently runs in the operations environment at IPAC/Caltech to support:
  - archival research requests (previously missed supernovae; more accurate light curves)
  - the moving object pipeline to discover asteroids
  - ancillary projects, e.g., a Galactic Plane Survey (snapshot below)

near galactic bulge
~ 5 arcmin stamp



PTFIDE processing flow



http://web.ipac.caltech.edu/staff/fmasci/home/miscscience/ptfide-v4.0.pdf

Downside of an atmosphere: PSF-matching!

- In general, an observed image *I* (exposure) can be modeled as a reference image *R* and convolution kernel *K*:

$$I_{ij} = \left[K_{lm} \otimes R_{ij} \right] + dB + \varepsilon_{ij}$$

- PSF-matching entails finding an optimum convolution kernel *K* by minimizing some cost function:

$$C = \sum_{i,j} \left[I_{ij} - \left(K_{lm} \otimes R_{ij} \right) - dB \right]^2$$

- **Traditional method (until about 2008, but still in use today):**

  Decompose *K* into a sum of Gaussian basis functions × by polynomials (e.g., Alard & Lupton, 1998; Alard 2000). The coefficients are then fit for.

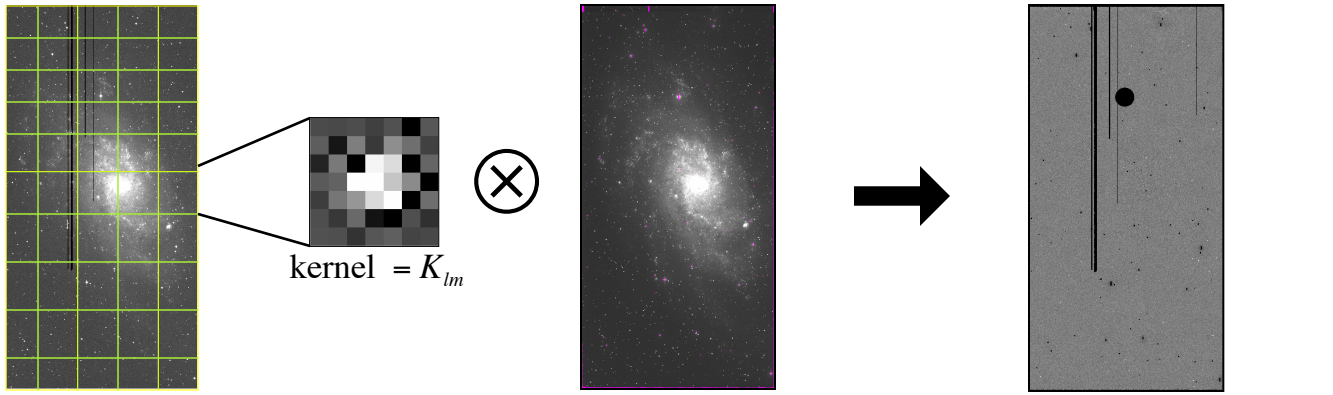
  - implemented in Andy Becker's *HOTPANTS* software. Also *ISIS* software (Woźniak 2000)
  - user must specify number of basis functions, Gaussian widths, polynomial orders, including spatial orders
  - no simple rules of thumb to ensure optimality for all images.
  - hard to tune for a survey like PTF!

PSF-matching in PTFIDE

- Instead, PTFIDE solves for each of the individual kernel pixel values K_{lm} (= 7 × 7 parameters) directly using a linear least squares minimization of the cost function:

$$C = \sum_{i,j} \left[I_{ij} - \left(K_{lm} \otimes R_{ij} \right) - dB \right]^2$$

  - similar to method proposed by Bramich (2008)
  - more flexible, K can take on more general shape, and also compensate for bad astrometry
  - since PSF is spatially dependent, we grid images into 5 × 10 overlapping squares, then solve for K in each



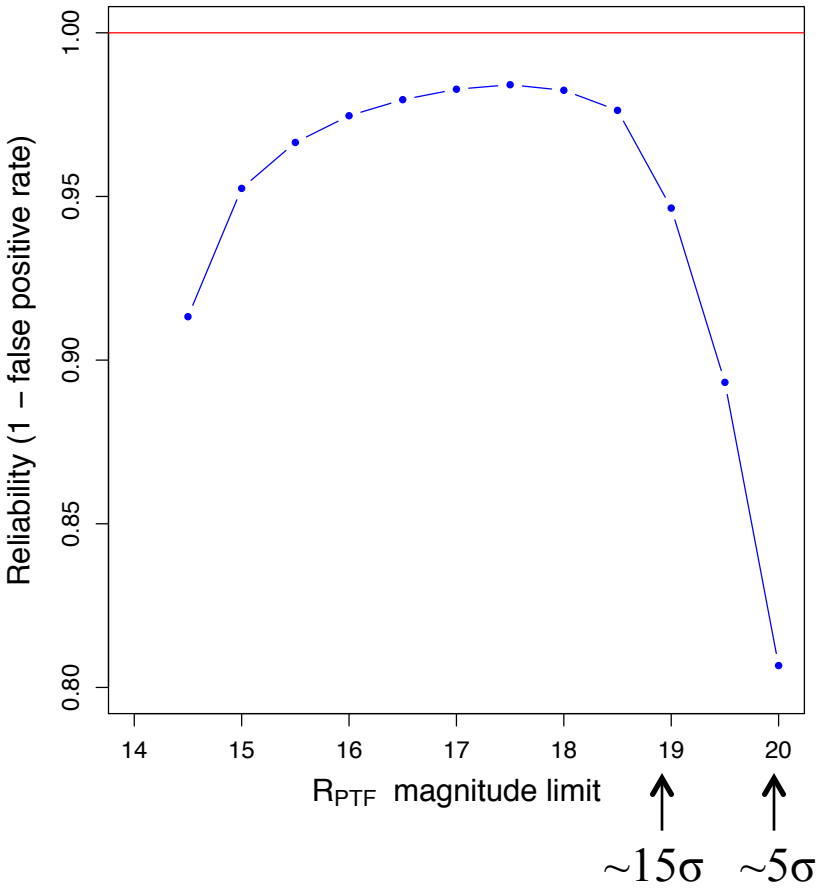
(single chip with **M33**)

Candidate transient photometry

- Performed using PSF-fitting
- Provides better photometric accuracy for moderate to faint fluxes
- Provides diagnostics to distinguish point sources from glitches (false-positives) in diff. images
  - maximizes reliability of difference-image extractions since most transients are point sources
- Above assumes accurate PSF-estimation (over chip) and image registration prior to differencing

Performance: real vs. bogus (reliability)

- took ~350 real, moderately dense *R*-band frames, derived spatially-varying PSFs, then simulated point source transients with random positions and fluxes.
- executed PTFIDE to create diff images and extract candidates with **fixed** threshold (S/N = 4) and filter params.

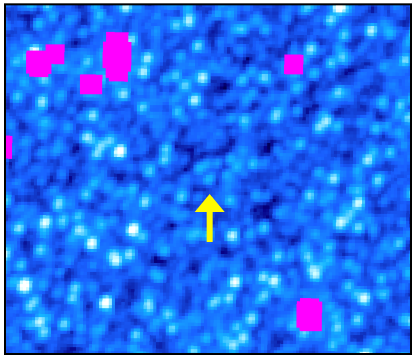


$$R = \frac{\#\text{ matched to truth } (< R_{mag})}{\#\text{ total extracted } (< R_{mag})}$$

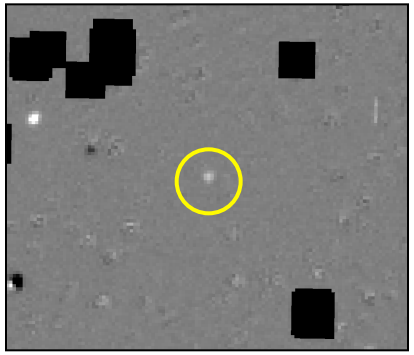
From difference-images to light curves

- Recall PTFIDE uses a fixed detection threshold (S/N ~ 4) to aid **discovery only**

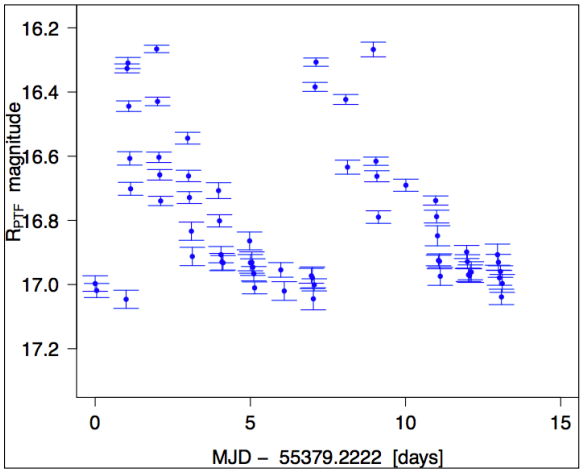
- To generate light curves for candidates of interest: can use forced PSF-photometry at fixed sky position through stack of difference images with no threshold
  - ➢ enables unbiased measurements down to low S/N;
  - ➢ obtain tighter upper limits and better S/N by combining light-curve data
  - ➢ implemented as a new pipeline in operations environment at Caltech



galactic bulge field
~ 2.2 arcmin

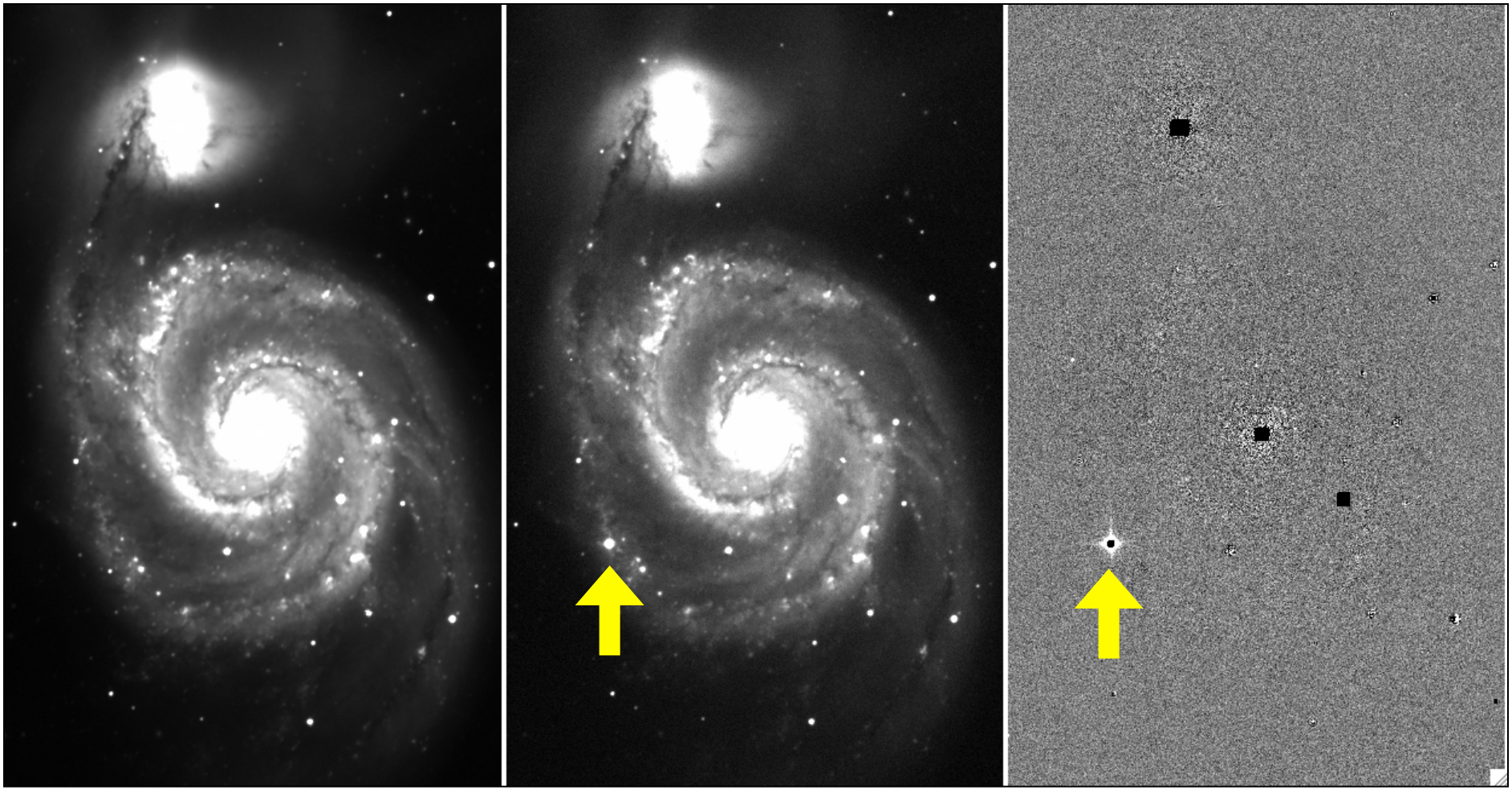


difference image



Cepheid variable (?)

SN 2011dh (PTF11eon) in Messier 51



Reference image = co-add of 20 *R* exposures (pre-outburst)

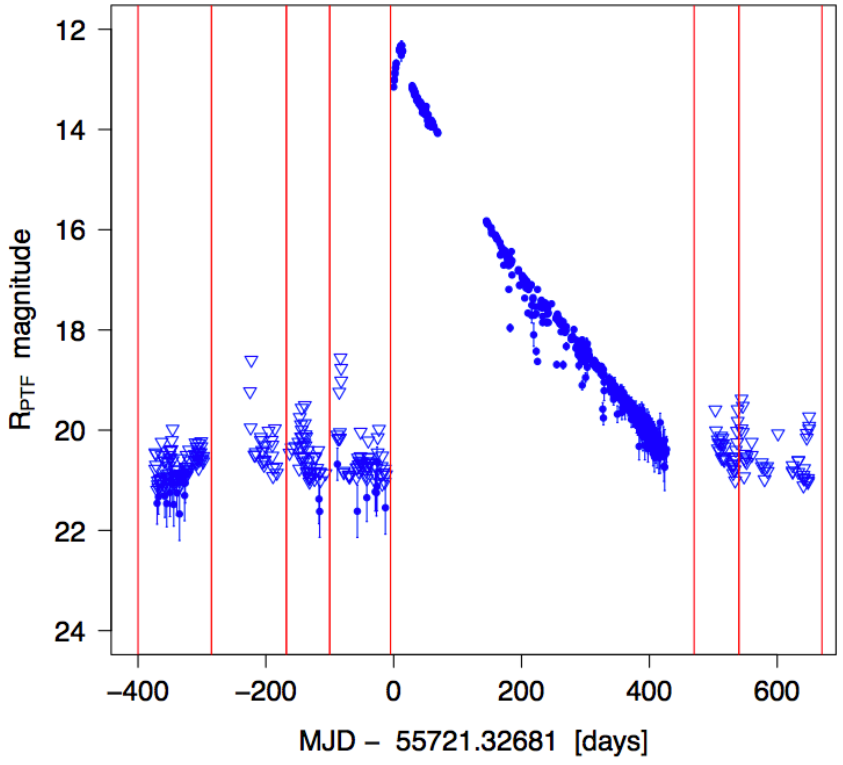
R exposure on June 19, 2011
Type IIb supernova ~ $10^9 L_\odot$

Difference image:
exposure - reference

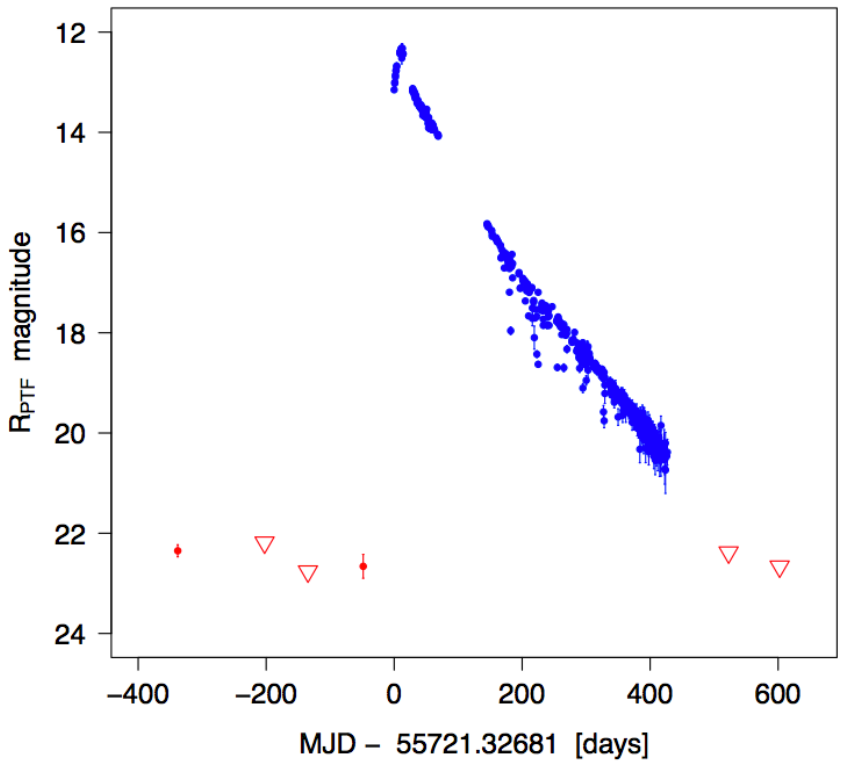
SN 2011dh *R*-band light-curve from windowed-averaging

Combine difference-image photometry (weighted averaging) within windows to improve S/N and obtain tighter upper limits on non-detections => method is faster than co-adding images!

R-band raw

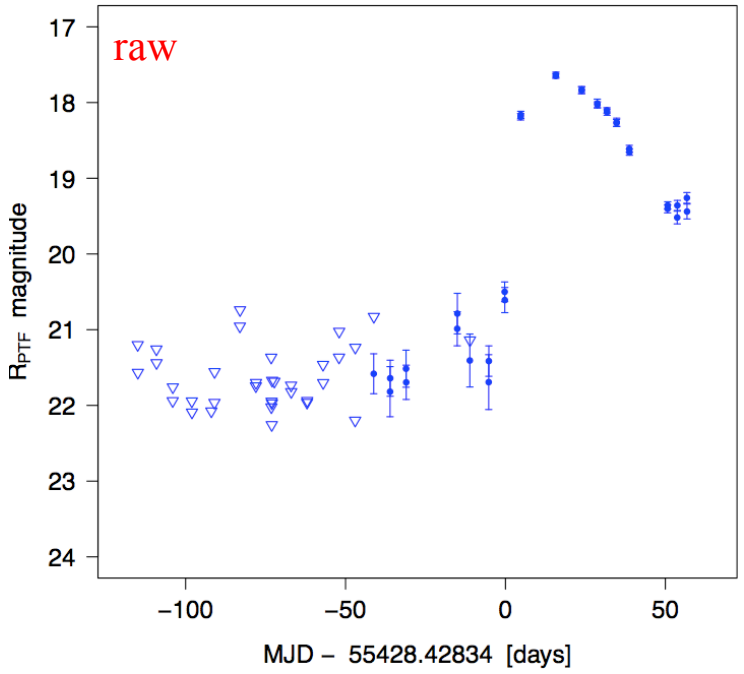


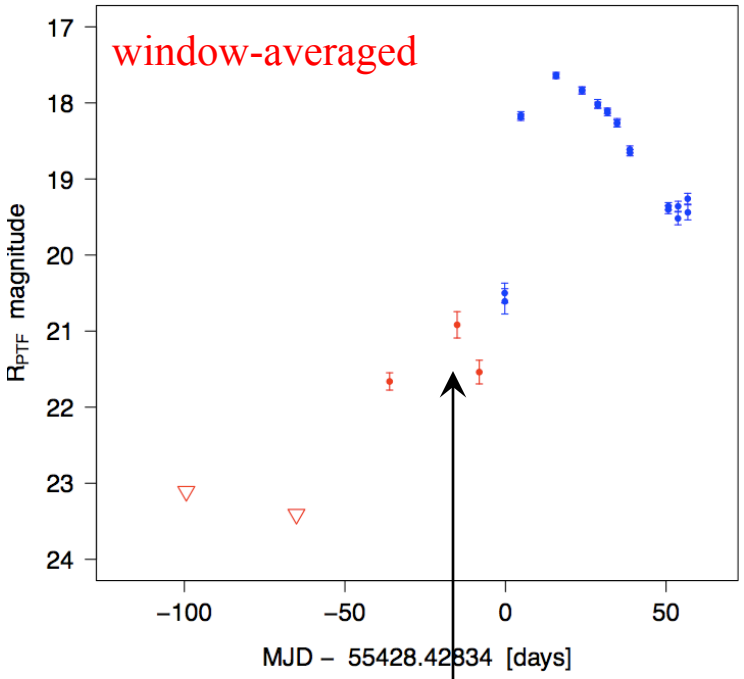
combined measurements (red)

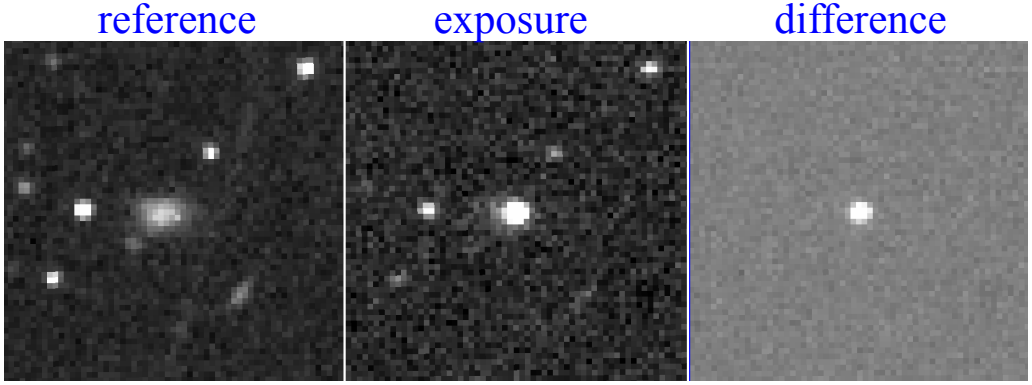


SN 2010mc (PTF10tel)

Type IIn supernova in unknown galaxy at ~ 153 Mpc





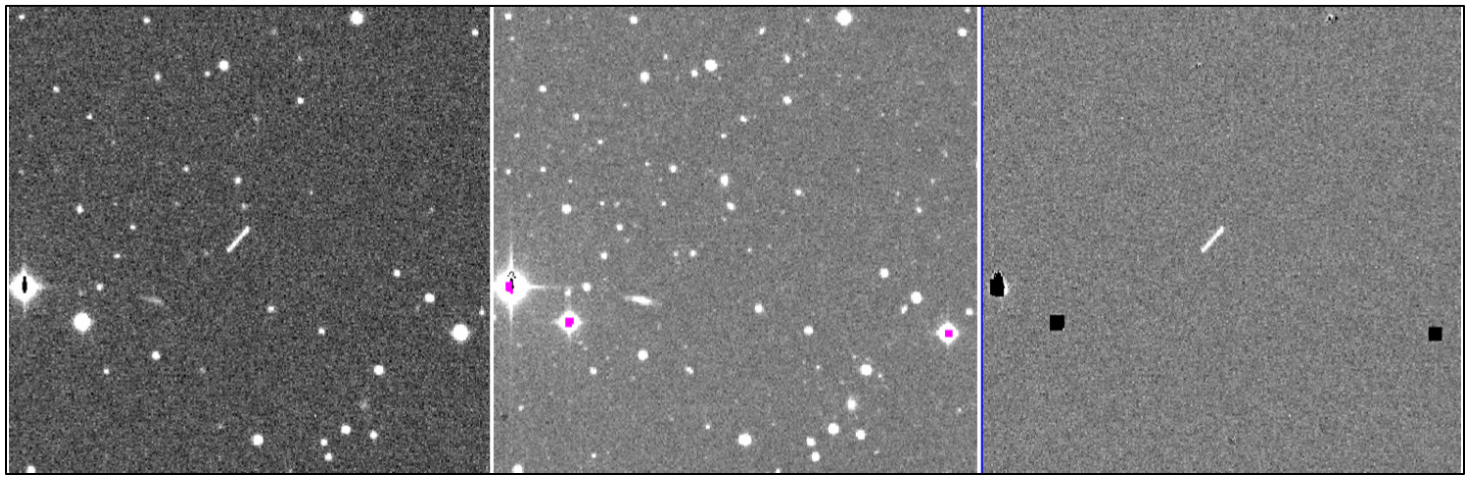


Outburst 40 days before explosion:
Ofek et al. (2013), Nature, 494, 65

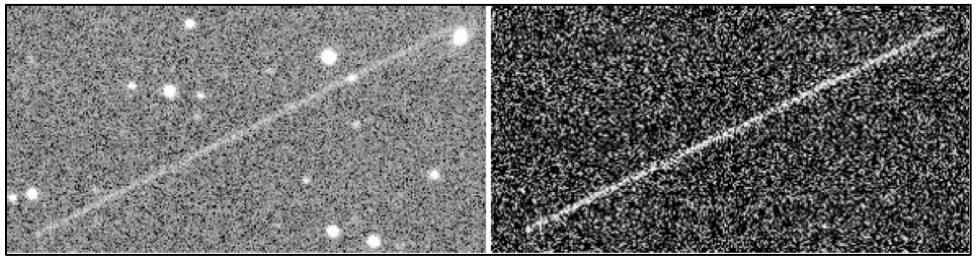
A powerful asteroid discovery engine!

Some examples from the PTFIDE production pipeline

known asteroid: 2009 HK73



exposure image | reference image | difference image



unknown moving object: exposure (left) and difference (right)

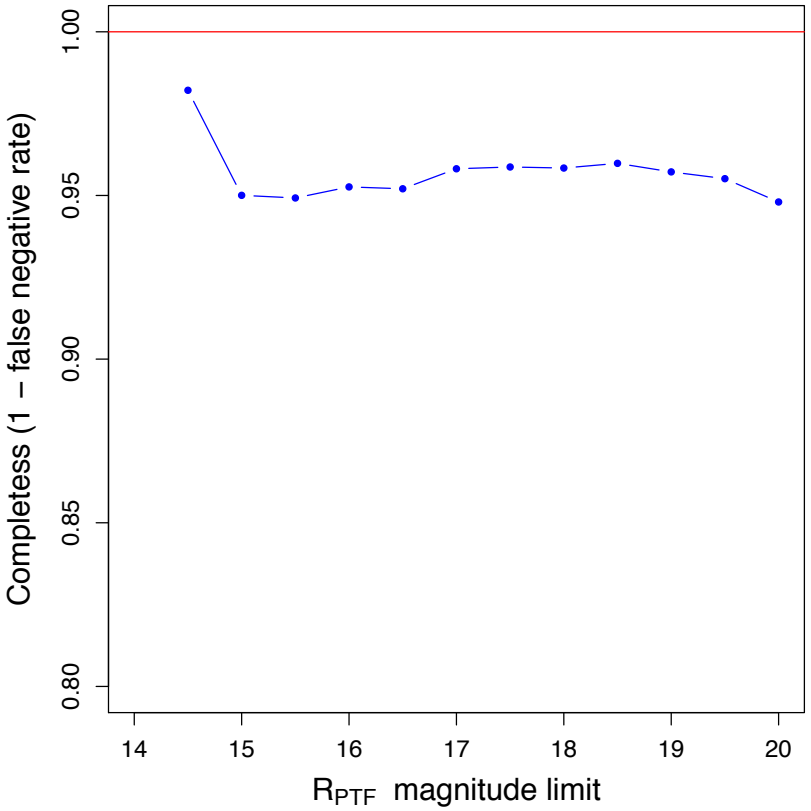
Summary

- A new discovery engine (PTFIDE) is currently in production to support asteroid discovery and general archival research
- Plan to use for real-time discovery of all transients in the near future
- Infrastructure is equipped with a forced photometry (post-processing) pipeline for candidates of interest to obtain accurate light curves
- Good image calibration, reference image quality, and flexible PSF-matching are key to obtaining good difference images
  - metrics associated with PSF-fit photometry are crucial to minimize false positives
  - relieves stress on real vs. bogus vetting for faster follow-up of candidates

Back up slides

Performance: completeness

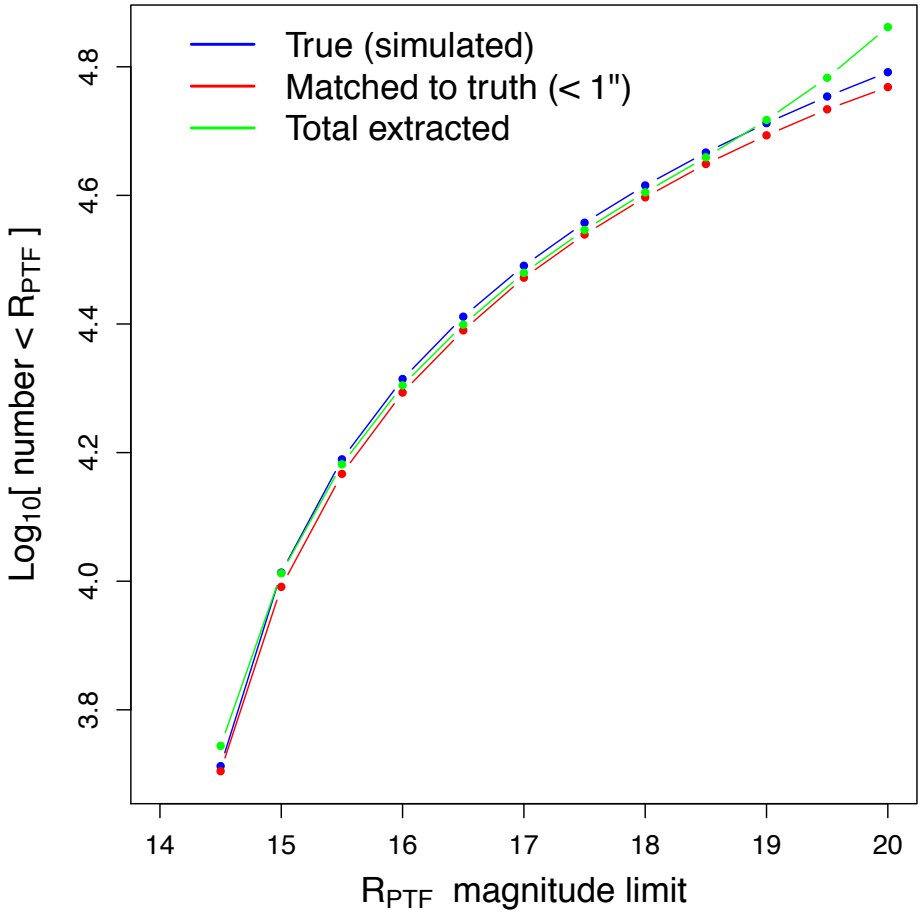
- took ~350 real, moderately dense *R*-band frames, derived spatially-varying PSFs, then simulated point source transients with random positions and fluxes.
- executed PTFIDE to create diff images and extract candidates with **fixed** threshold (S/N = 4) and filter params.



$$C = \frac{\#\,\text{matched to truth } (< R)}{\#\,\text{total truth } (< R)}$$

Performance: #extractions vs "truth"

- took ~350 real, moderately dense *R*-band frames, derived spatially-varying PSFs, then simulated point source transients with random positions and fluxes.
- executed PTFIDE to create diff images and extract candidates with **fixed** threshold (S/N = 4) and filter params.

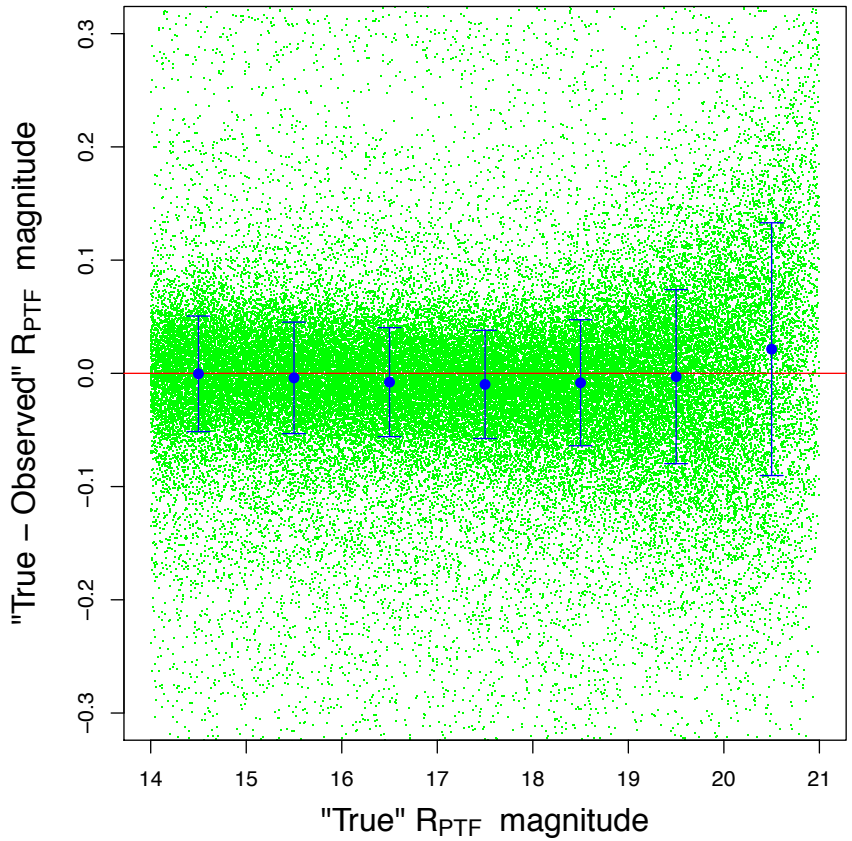


$$R = \frac{\#\,\text{matched to truth}\ (< R)}{\#\,\text{total extracted}\ (< R)}$$

$$C = \frac{\#\,\text{matched to truth}\ (< R)}{\#\,\text{total truth}\ (< R)}$$

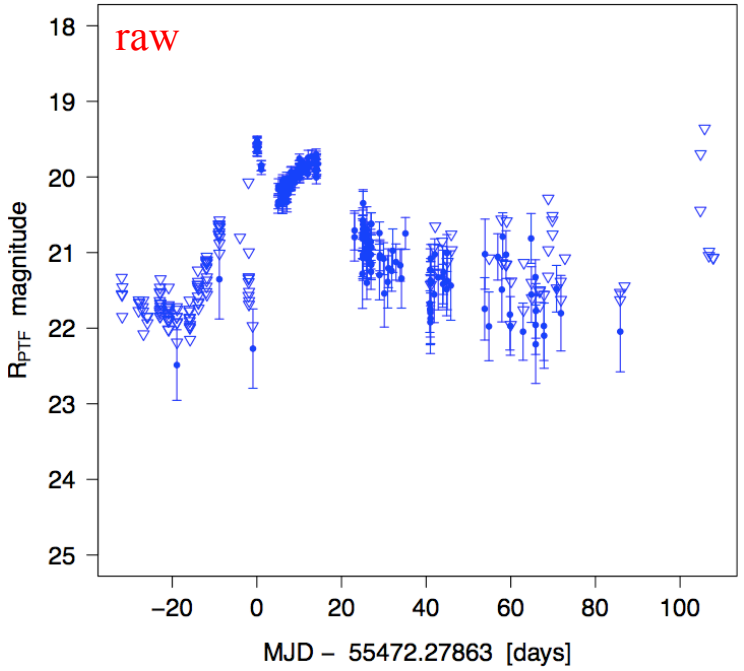
Performance of PSF-fit (AC) photometry

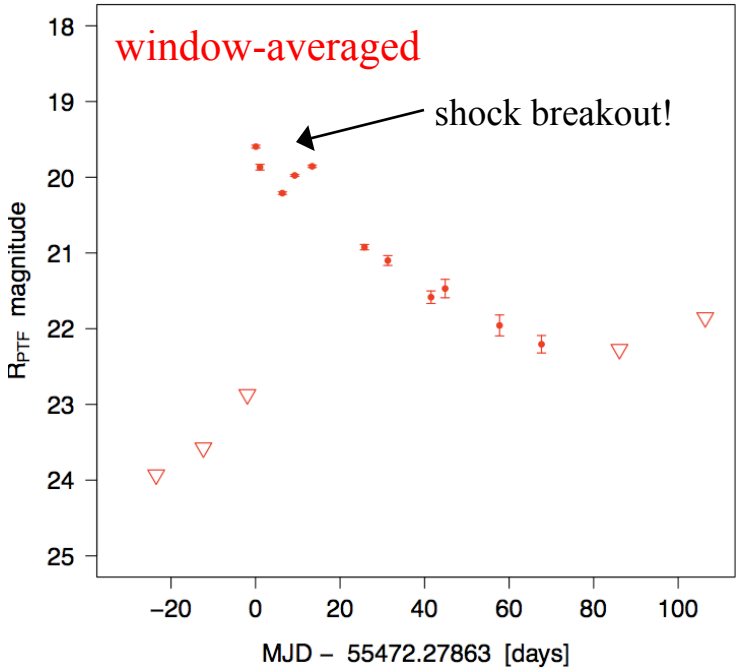
- took ~350 real, moderately dense *R*-band frames, derived spatially-varying PSFs, then simulated point source transients with random positions and fluxes.
- then executed PTFIDE to create diff images and extract candidates.
- difference image (AC) fluxes consistent with truth.

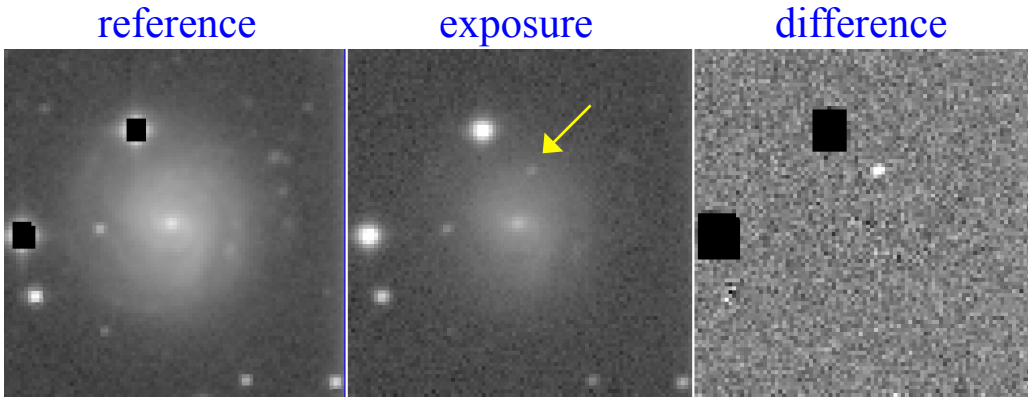


SN PTF10xfh

Type Ic supernova in NGC 717 at ~ 65 Mpc (Yi Cao, private communication)







SN PTF13ai
(or PSN J12541585+0926259)

- Type Ia Supernova in galaxy PGC 43884 (~197 Mpc); discovered Feb 5, 2013
- One of the first to be discovered for iPTF