Optical Imaging Follow-up of GW190814: the First Possible Black Hole - Neutron Star Merger

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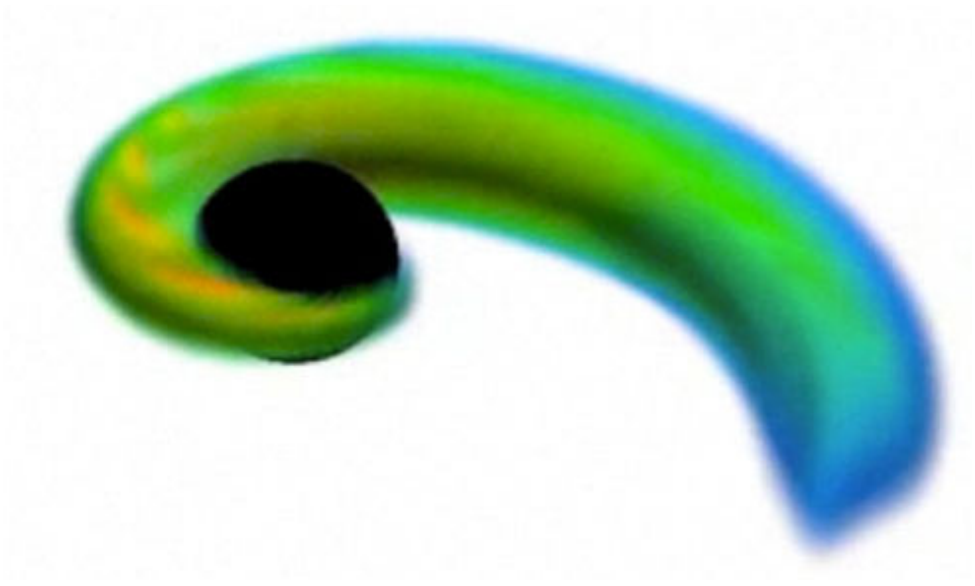

Institut Spatial de McGill
McGill Space Institute

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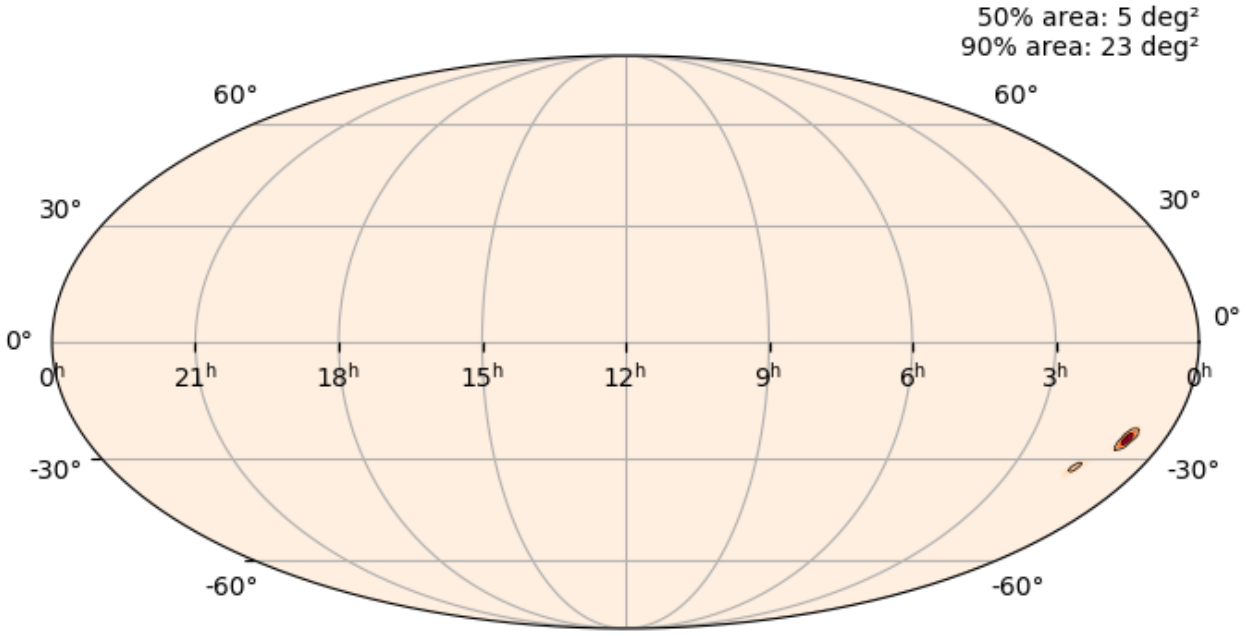
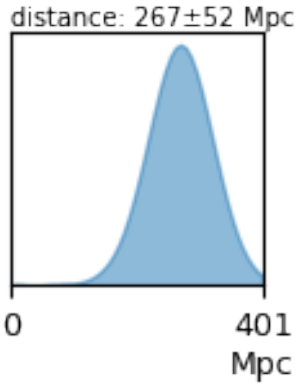
NSERC CRSNG

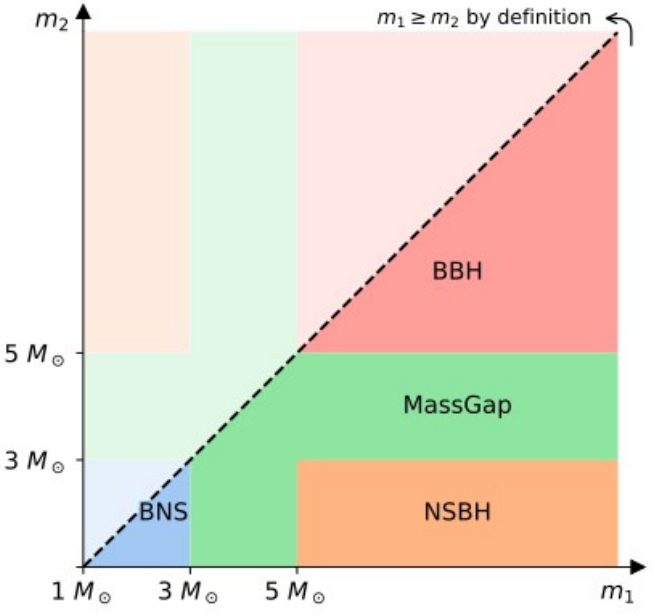
Outline

- Science case
- Observing campaign
- Data pipeline
- Preliminary results

GW190814


50% area: 5 deg²
90% area: 23 deg²
60°
30°
0°
-30°
-60°
0h
21h
18h
15h
12h
9h
6h
3h


distance: 267±52 Mpc
0
401
Mpc

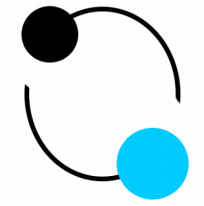

m_2
$m_1 \geq m_2$ by definition
BBH
MassGap
BNS
NSBH
5 $M_\odot$
3 $M_\odot$
1 $M_\odot$
3 $M_\odot$
5 $M_\odot$
m_1

Why go after it?

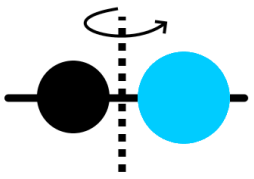
- **First-ever** potential merger between a BH and NS
- Binary NS mergers cannot produce observed abundances of the heaviest r-process elements – can NS-BH mergers explain?
- Bonuses:
  - Constraints on NS equation of state
  - Independent measurement of H_0

Kilonovae from NS-BH mergers

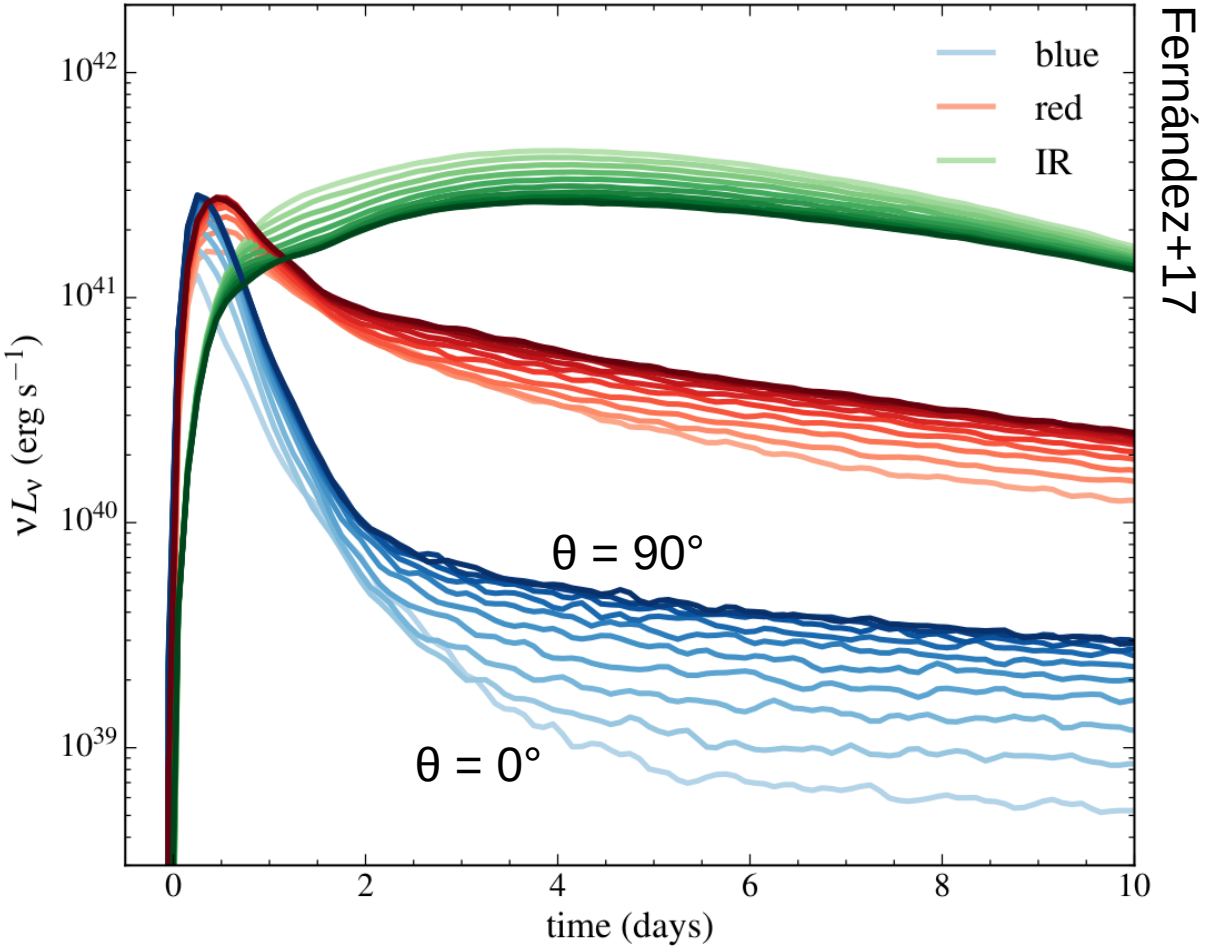
- Early peak, rapid fading in bluer wavelengths
- Slower fading in red/IR wavelengths
- Dependence on viewing angle



polar
θ = 0°



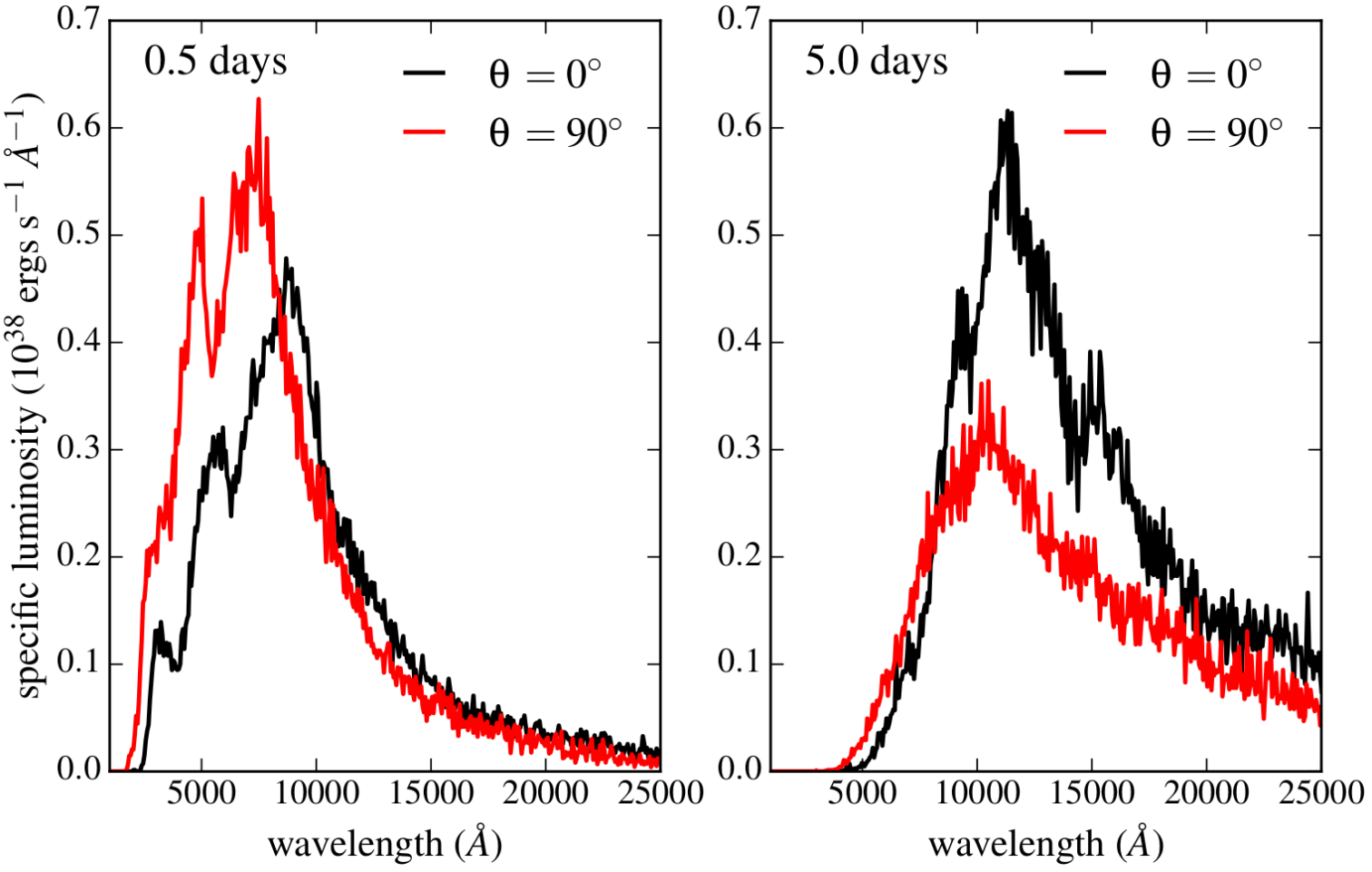
equatorial
θ = 90°



Fernández+17

Spectra

Fernández+17

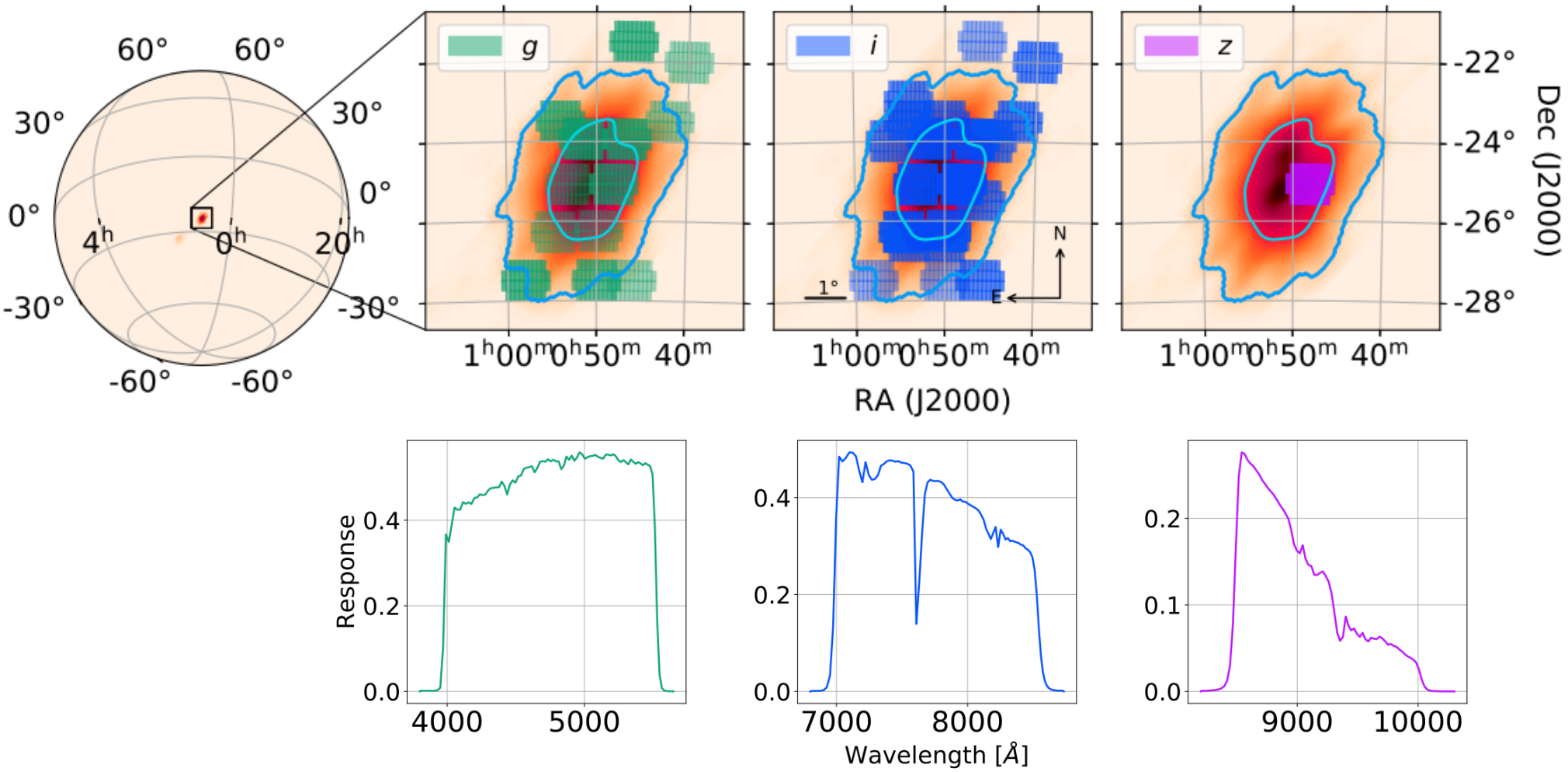


Canada-France-Hawaii Telescope (CFHT)

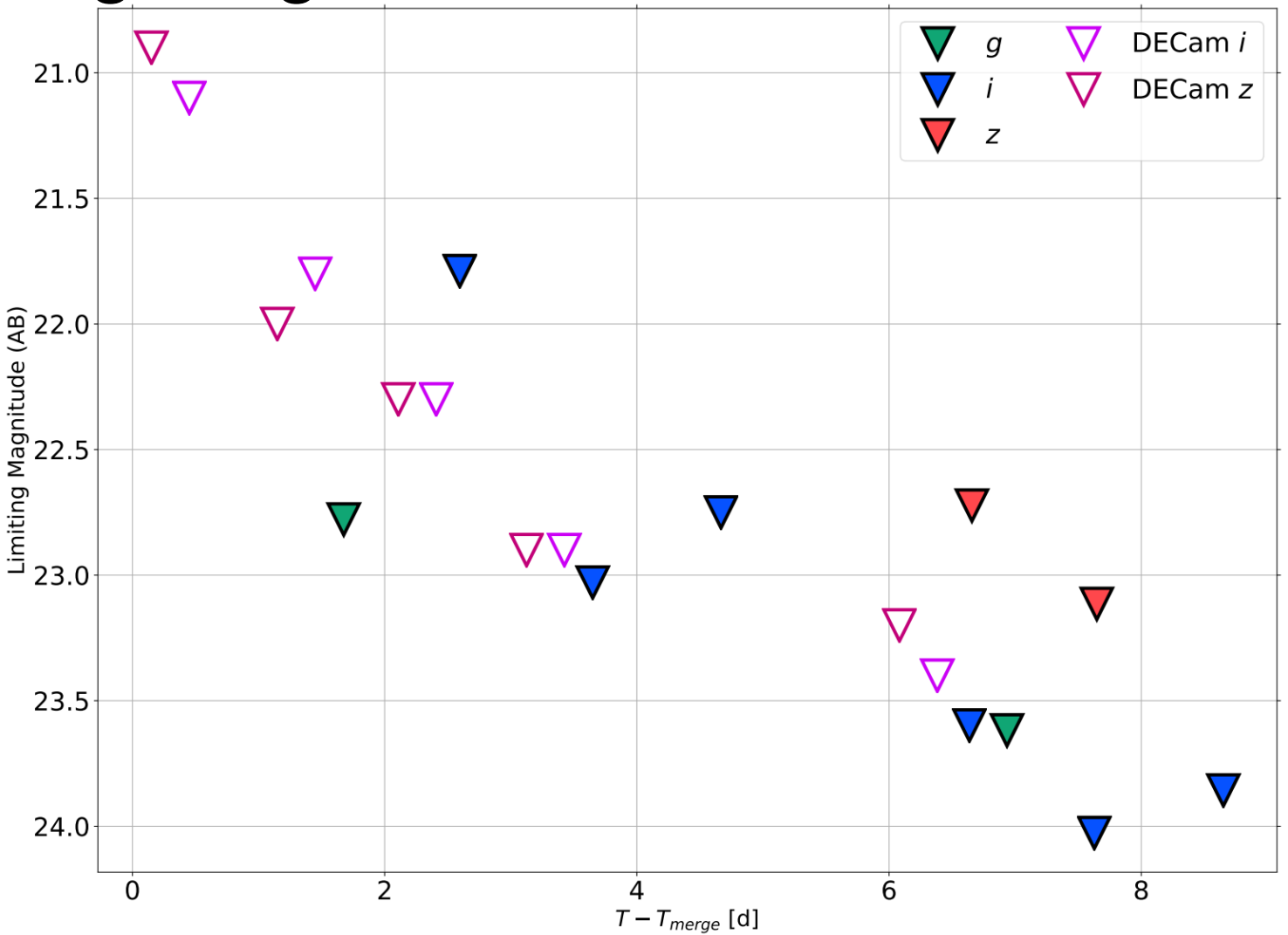
- Find and follow-up on EM counterparts with **MegaCam** and Wide-field Infra-Red Camera (WIRCam) on **3.6m CFHT**
- MegaCam: wide-field optical and near-IR camera
- Fast, deep imaging of large sections of the sky
- Companion programs with Gemini (optical/near-IR), Chandra (X-ray), Very Large Array (radio)

(c) Jean-Charles Cuillandre

g-, *i*-, *z*-band observation strategy

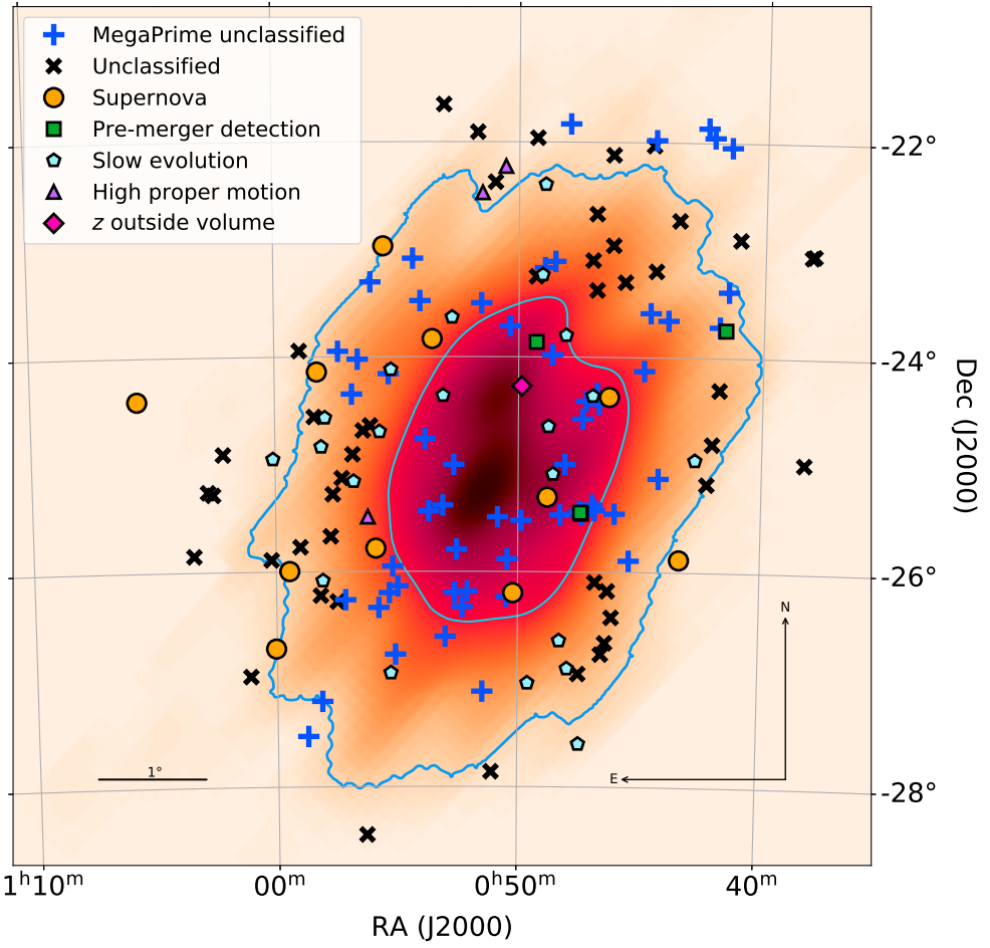


Limiting magnitudes



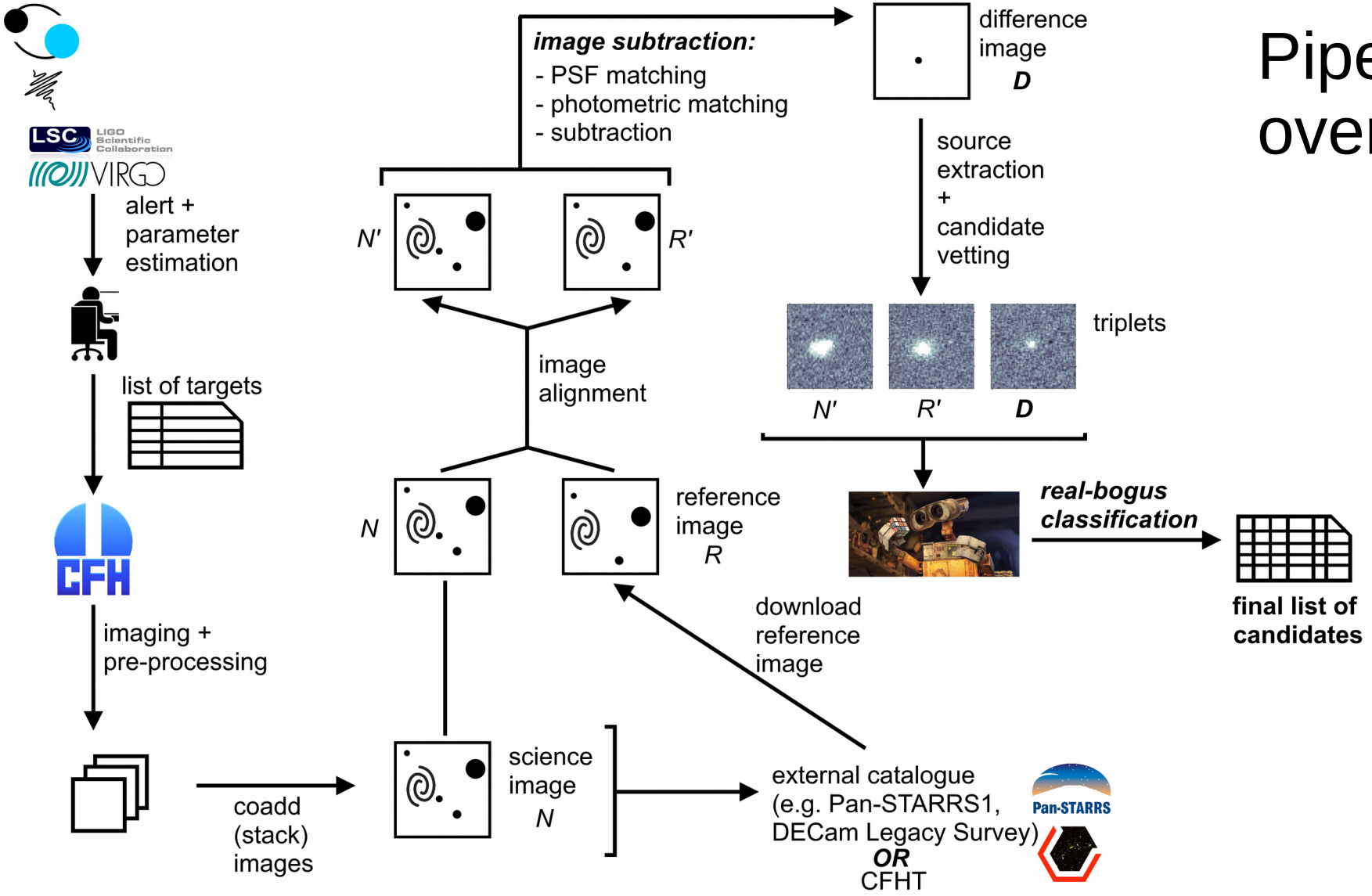
DECam limits:
Andreoni+19

Hunt for a counterpart

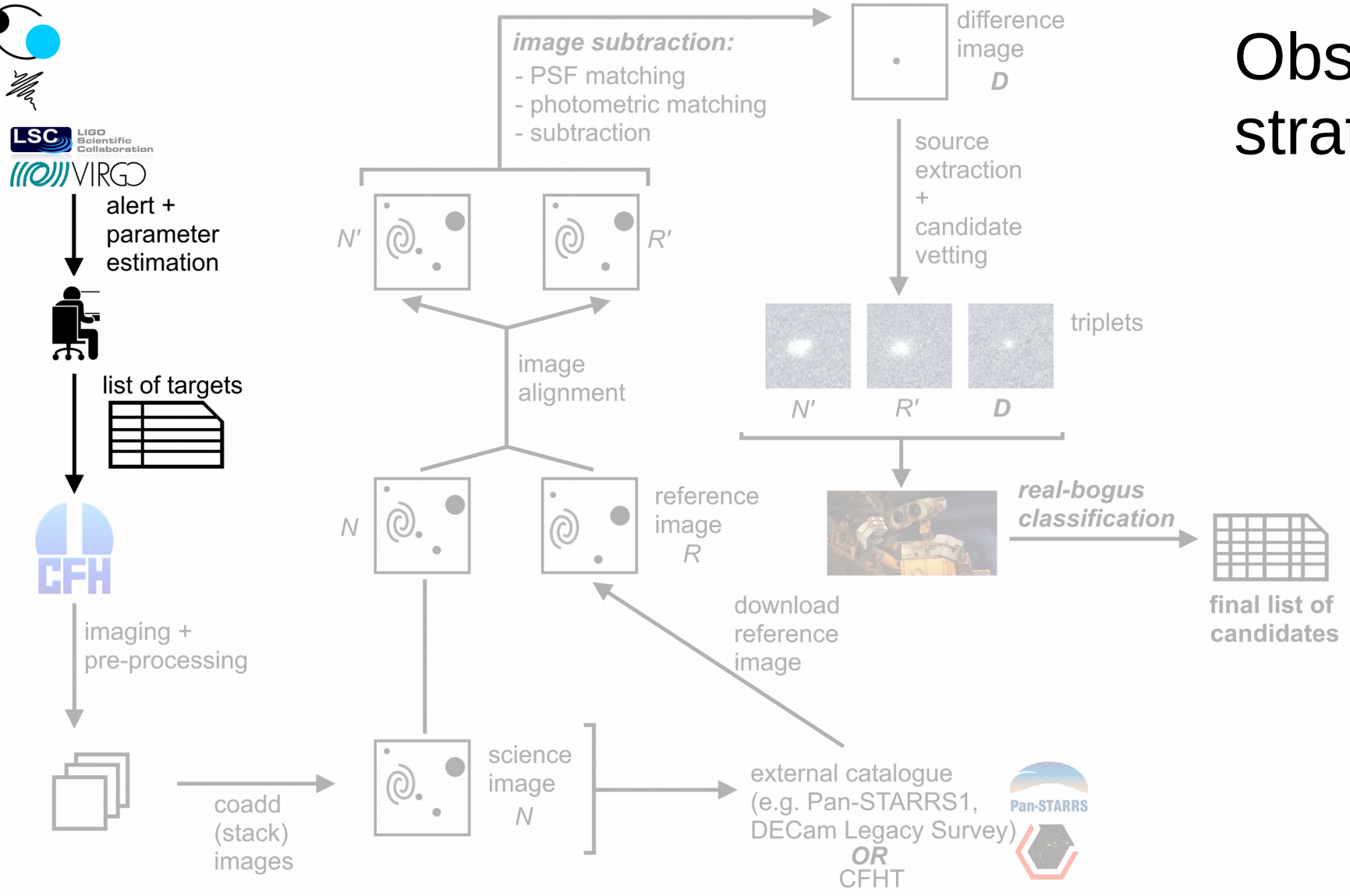


- >100 candidates reported in 2 weeks
- Compelling sources received spectral/photometric classification
- Early hunt: visual inspection
- Most sources came from **image differencing** pipelines

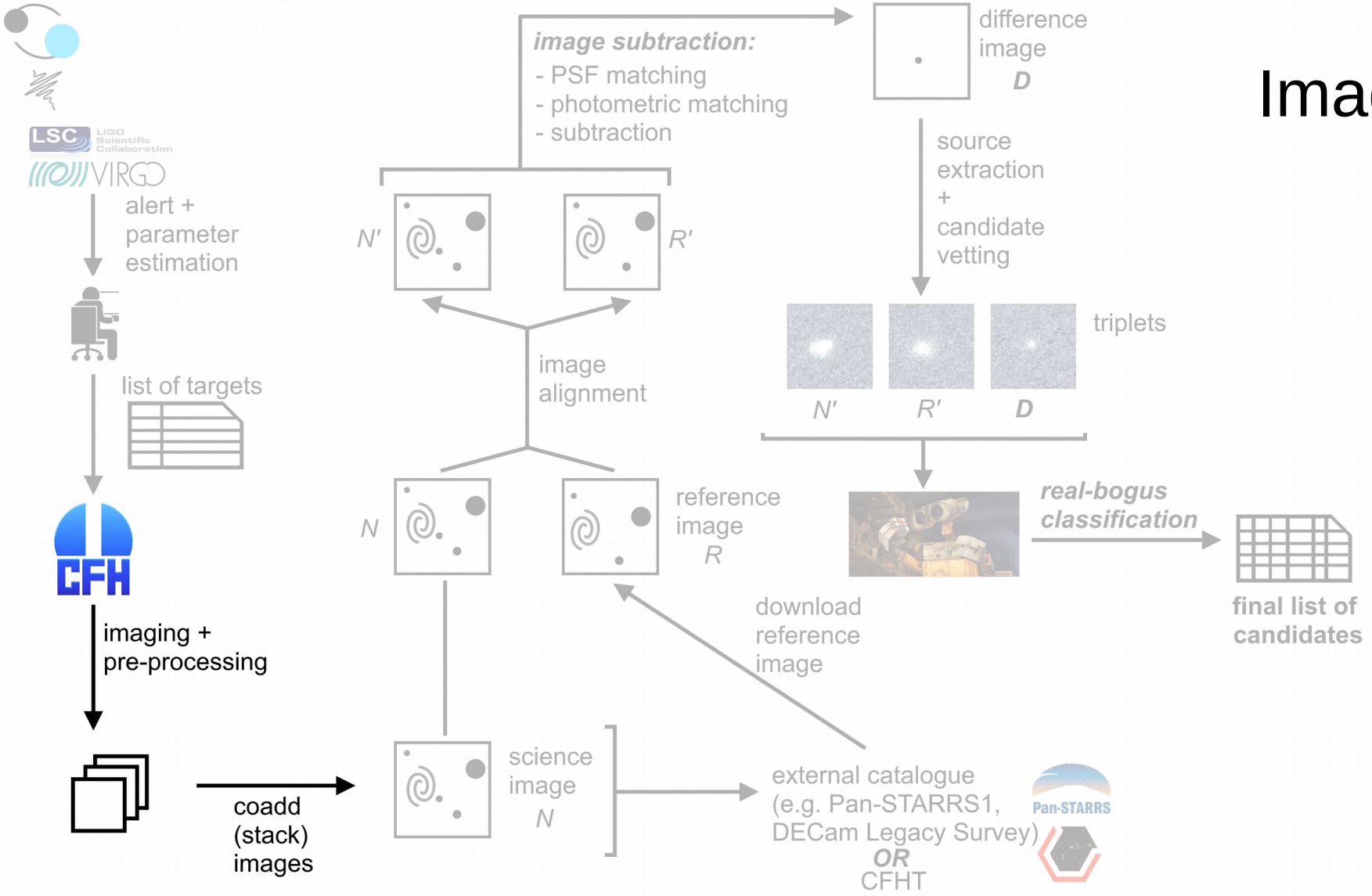
Pipeline overview



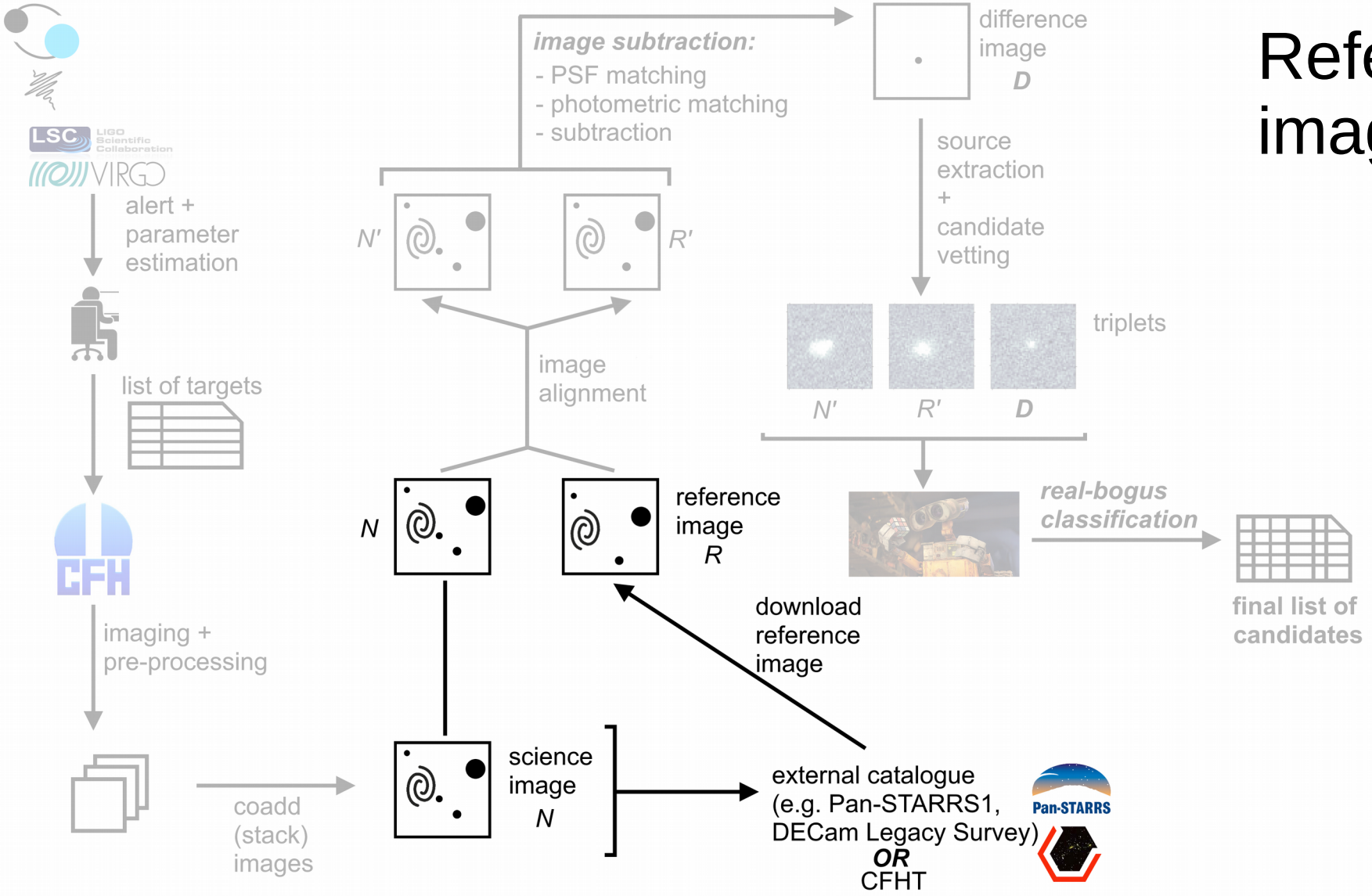
Observation strategy



Imaging


LSC LIGO Scientific Collaboration
VIRGO
alert + parameter estimation
list of targets
CFH
imaging + pre-processing
coadd (stack) images
science image N
image subtraction:
- PSF matching
- photometric matching
- subtraction
N′
R′
image alignment
N
reference image R
difference image D
source extraction + candidate vetting
triplets
N′ R′ D
real-bogus classification
final list of candidates
download reference image
external catalogue (e.g. Pan-STARRS1, DECam Legacy Survey) OR CFHT
Pan-STARRS

Reference images



Reference images

Band	**Instrument/Survey**	$T - T_{merger}$
i	MegaCam	+20.5 days
g	Pan-STARRS1 3π survey	-3 years
z	Dark Energy Camera Legacy Survey	-2 years

Image alignment

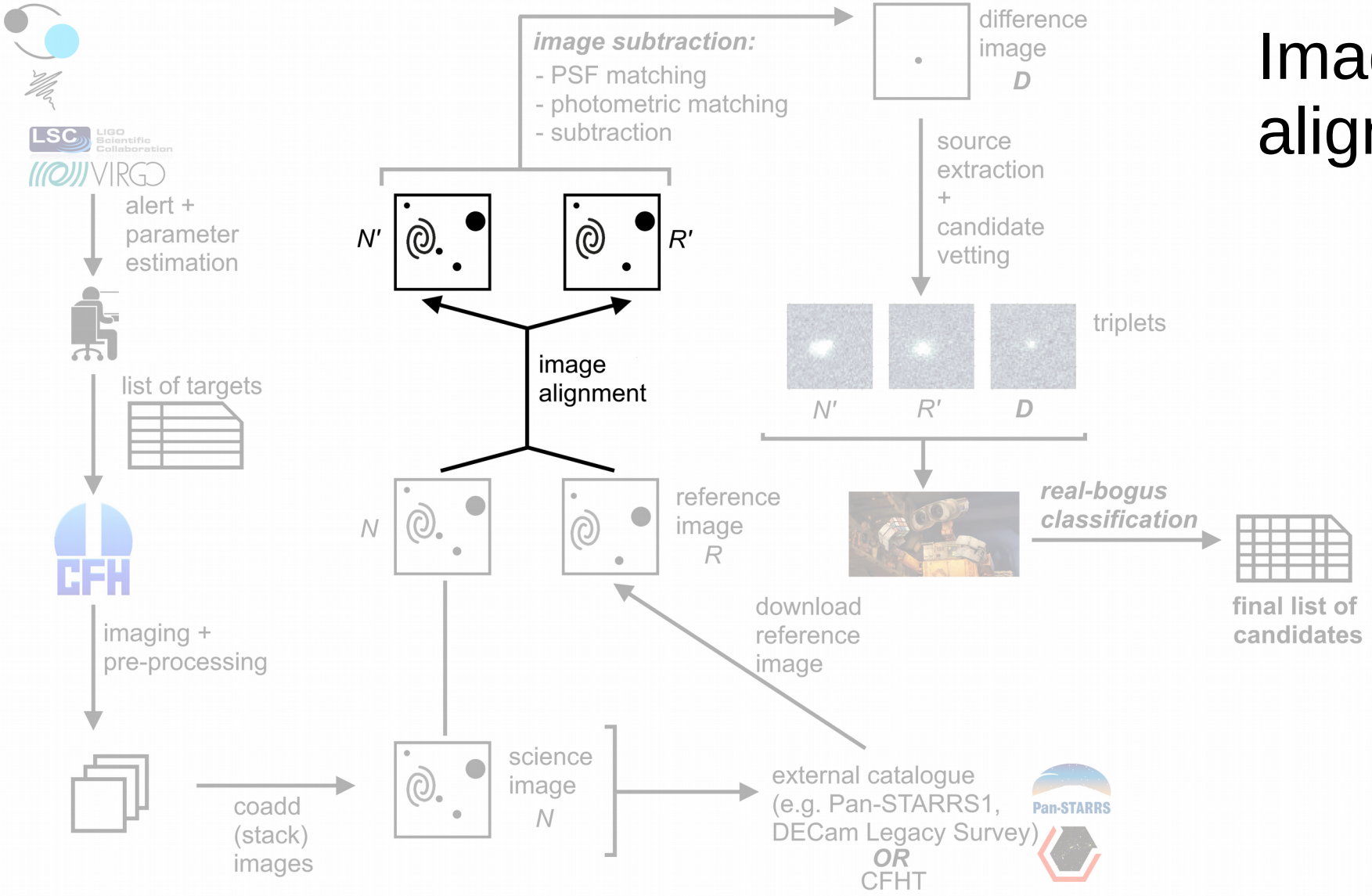


Image alignment

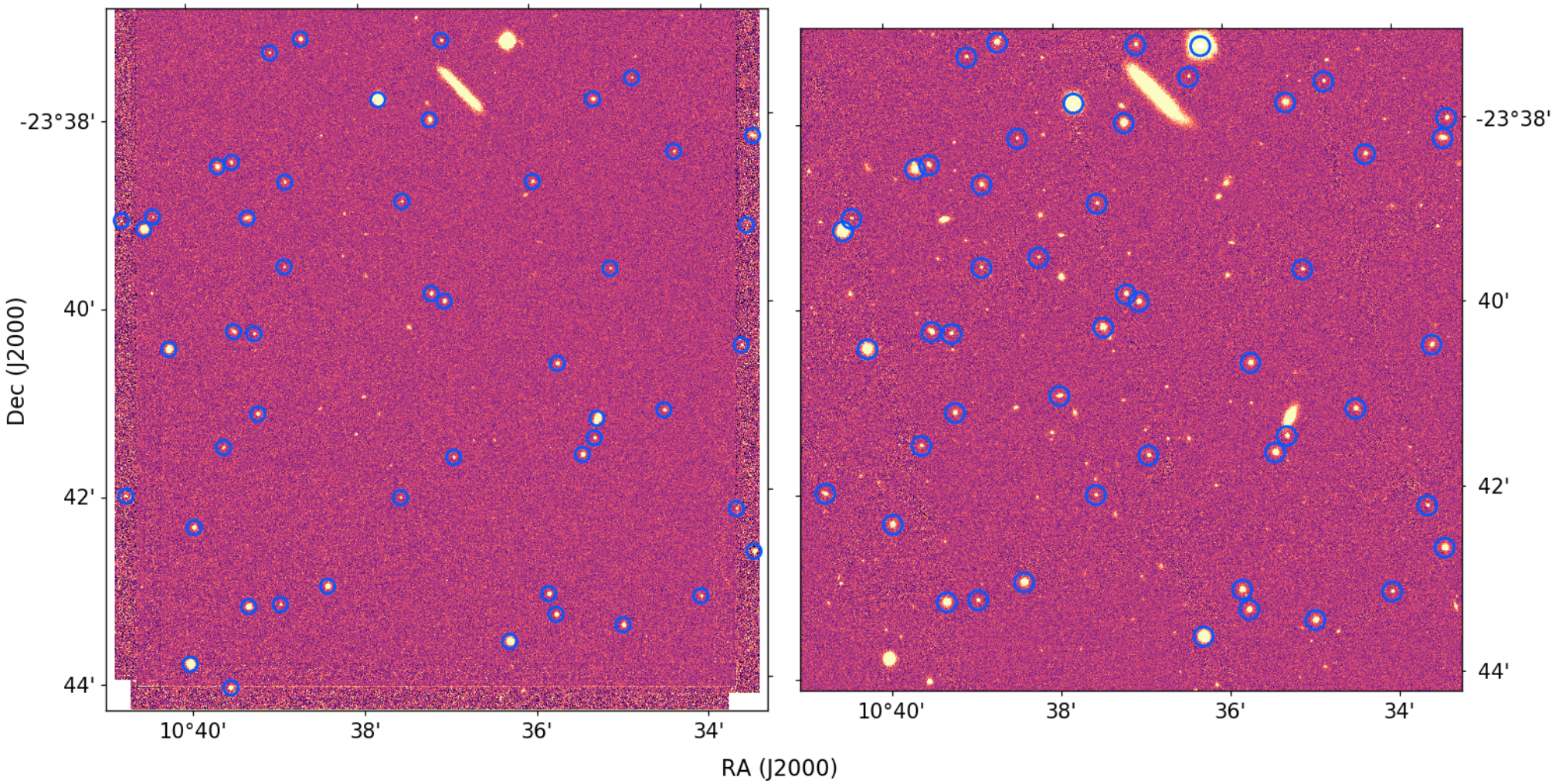


Image subtraction

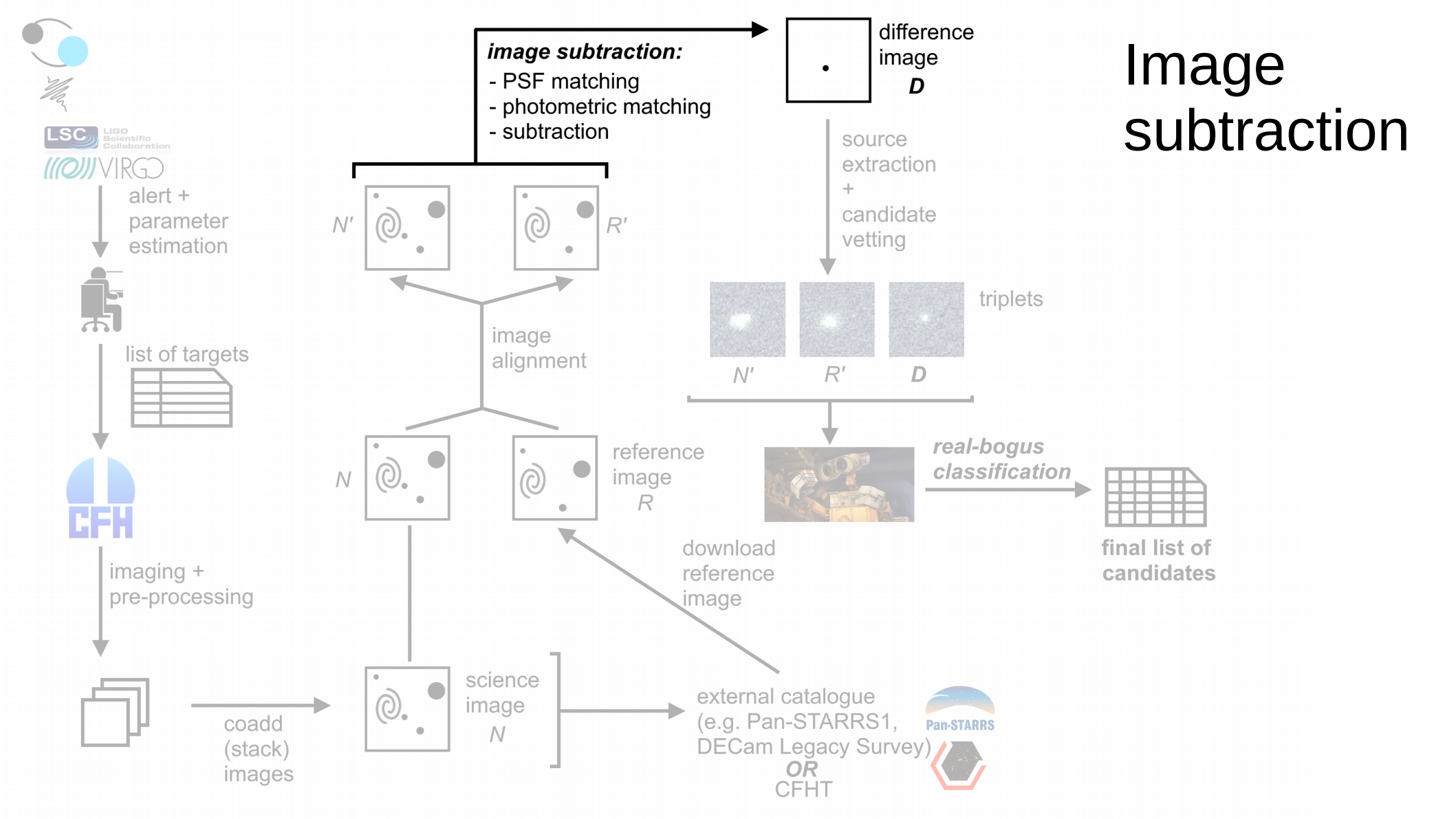
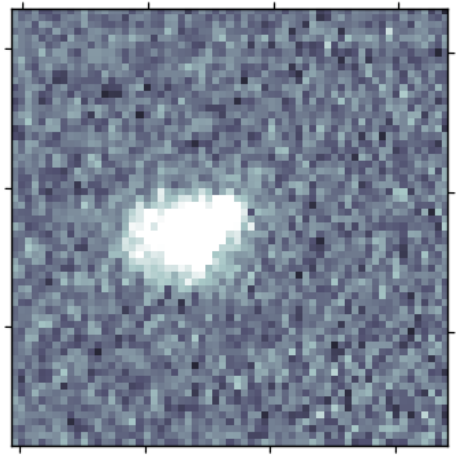
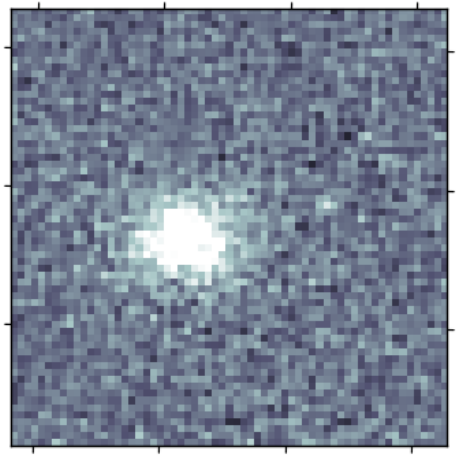


Image subtraction

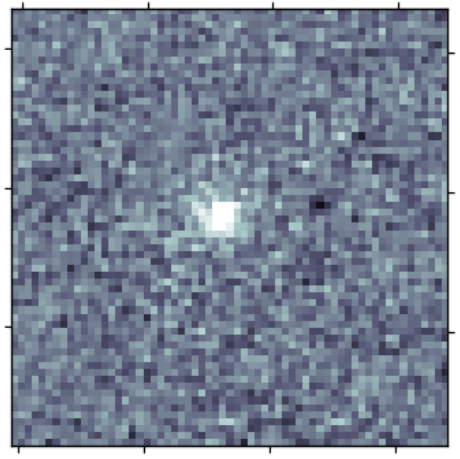
- Match Point-Spread-Function (PSF)
- Match photometry
- Subtract



science image
N'

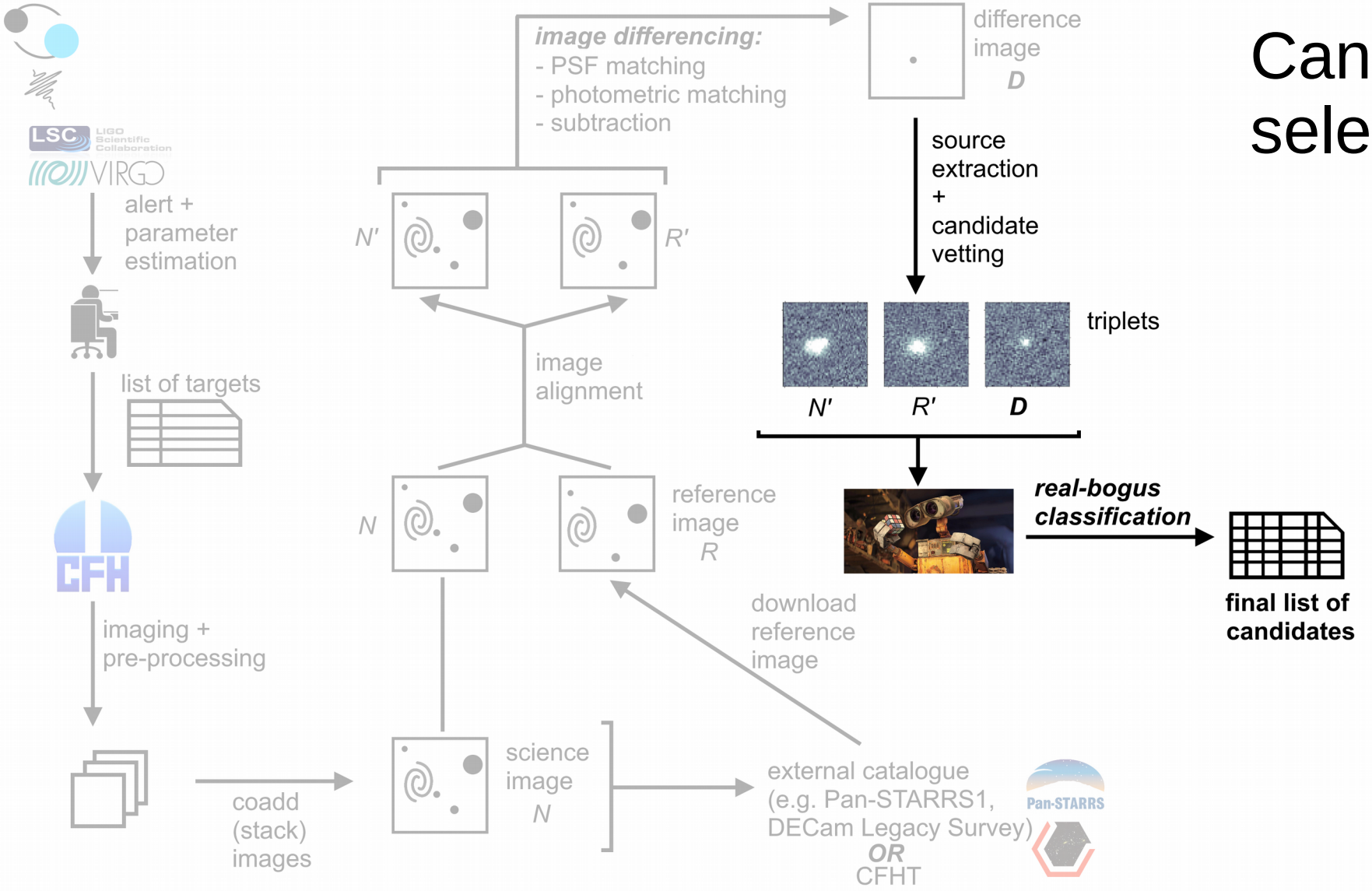


reference image
R'



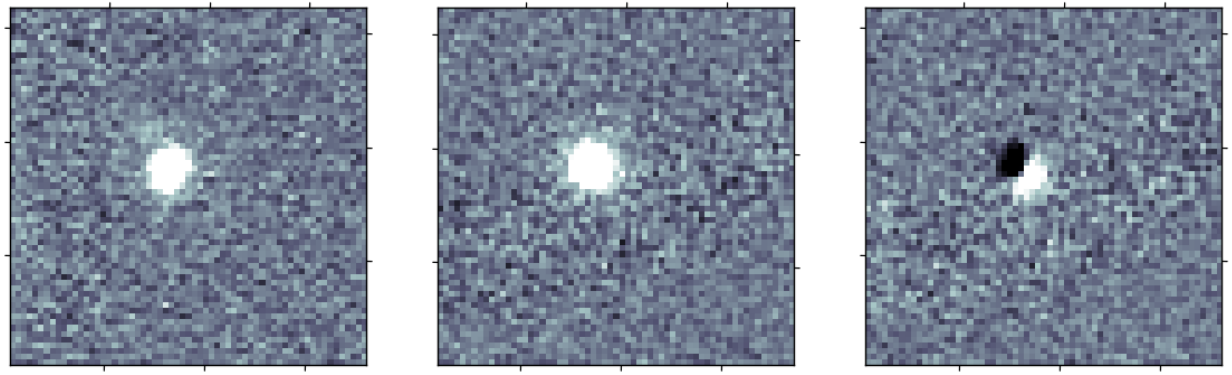
difference image
D
with known supernova
SN2019nxe

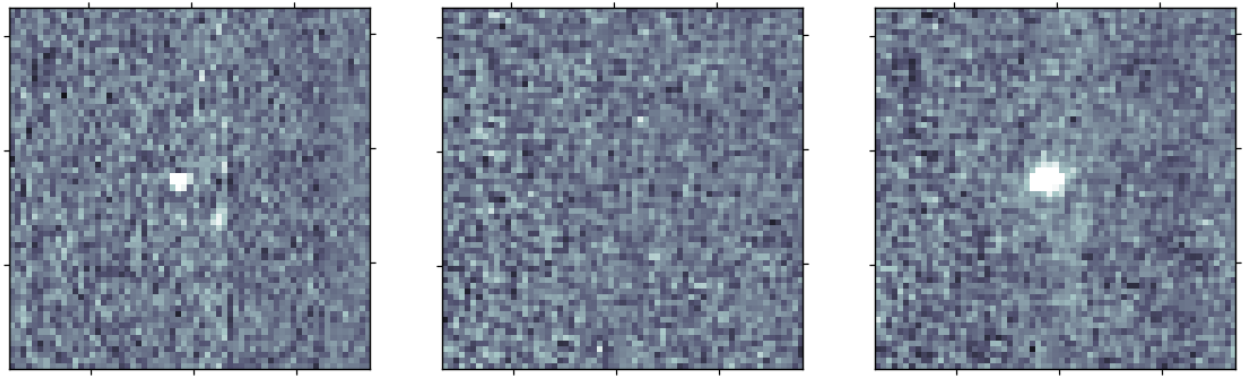
Candidate selection



After preliminary vetting, many candidates still remain

poor image alignment



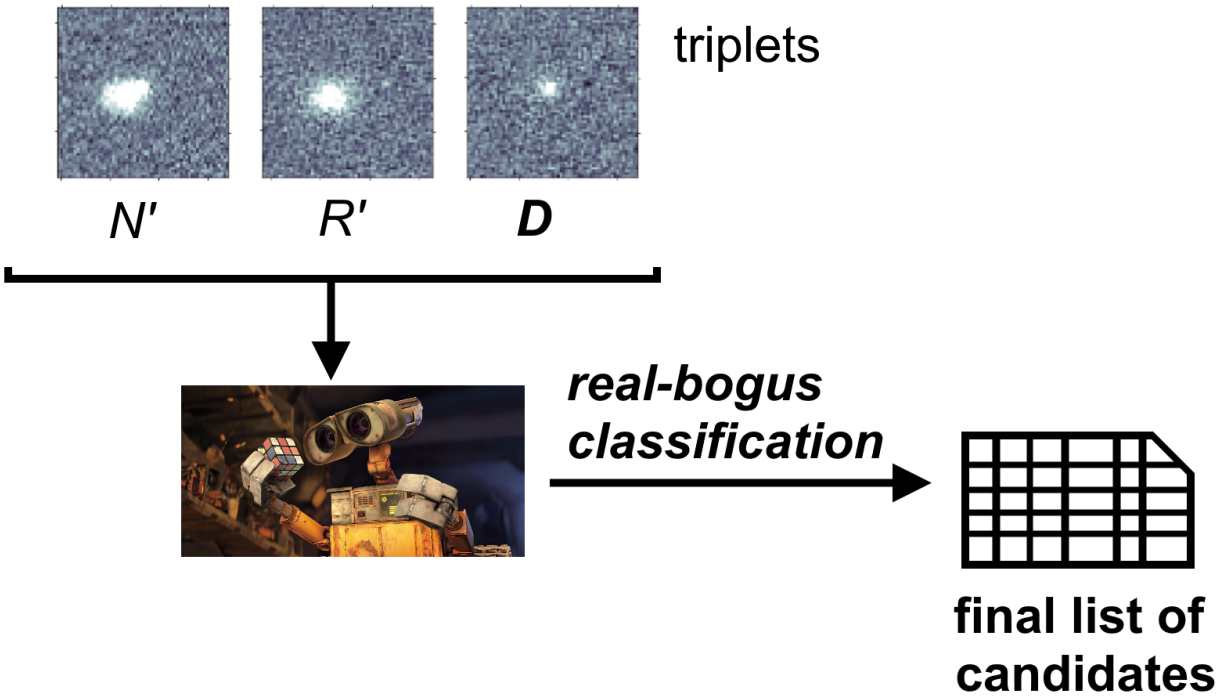


cosmic ray hit

→ Use machine learning to filter candidates as **real** or **bogus**

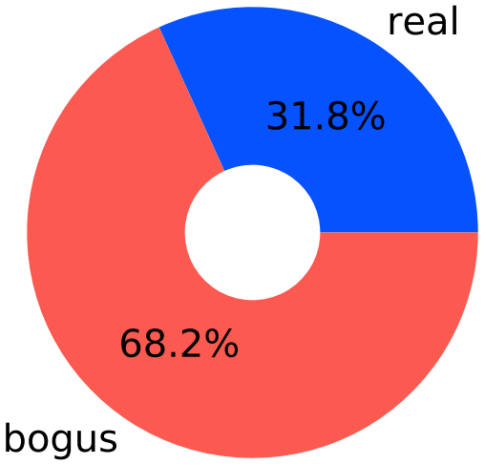
Bogus-Real Adversarial Artificial Intelligence (**braai**)

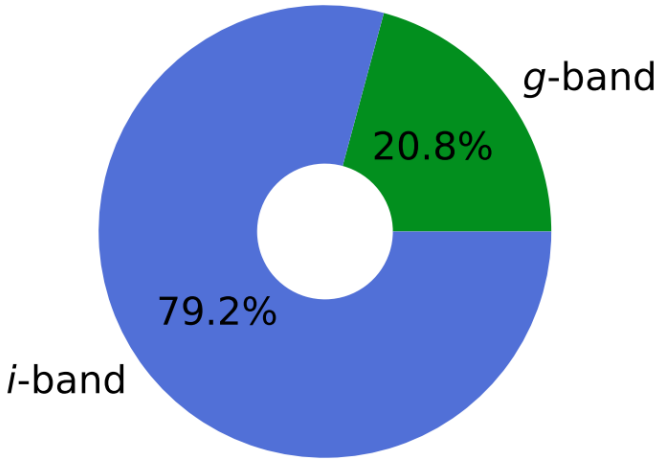
- **Input:** triplets
- **Output:** real-bogus (RB) score from 0 (definite bogus) to 1 (definite real)
- Set RB score threshold (e.g. RB > 0.5) → make list of candidates of interest



Train the neural network

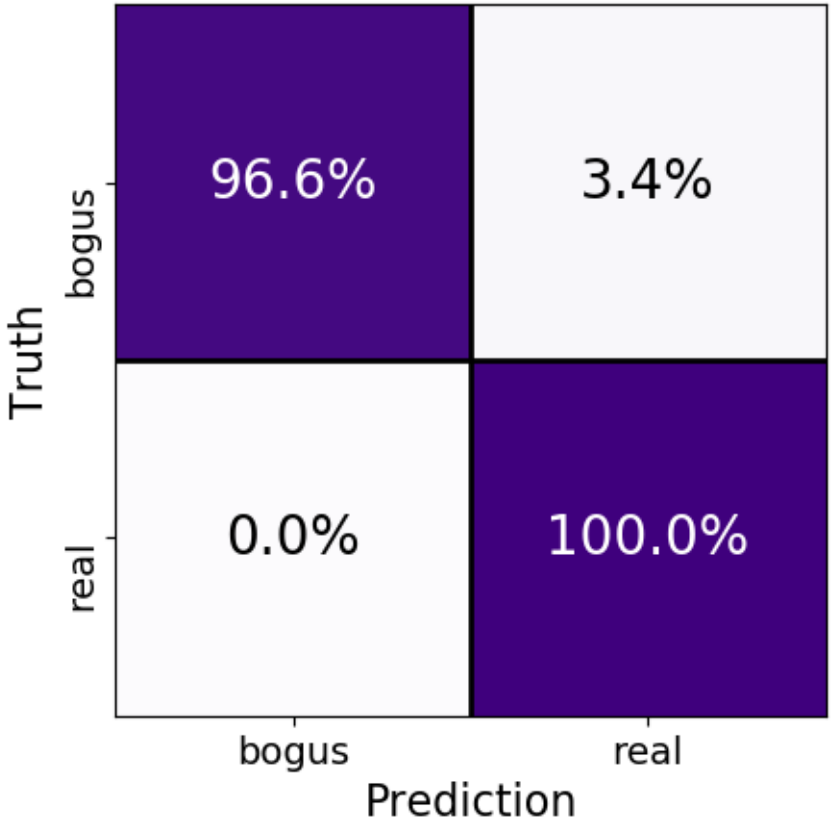
- Visually inspect selection of triplets, flag as bogus (0) or real (1)
- Add in known transients
- Augment real data
- Train!
- Evaluate



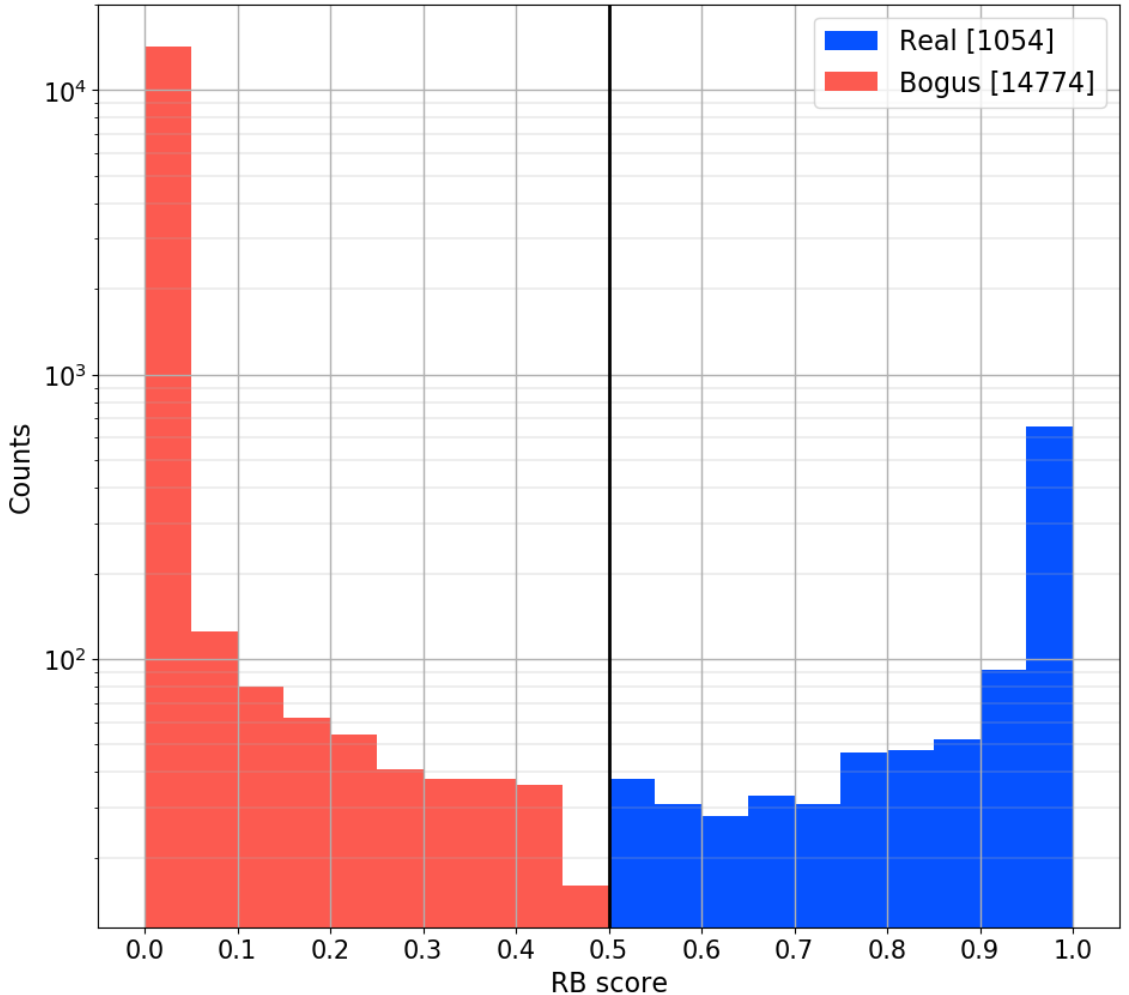


Training results

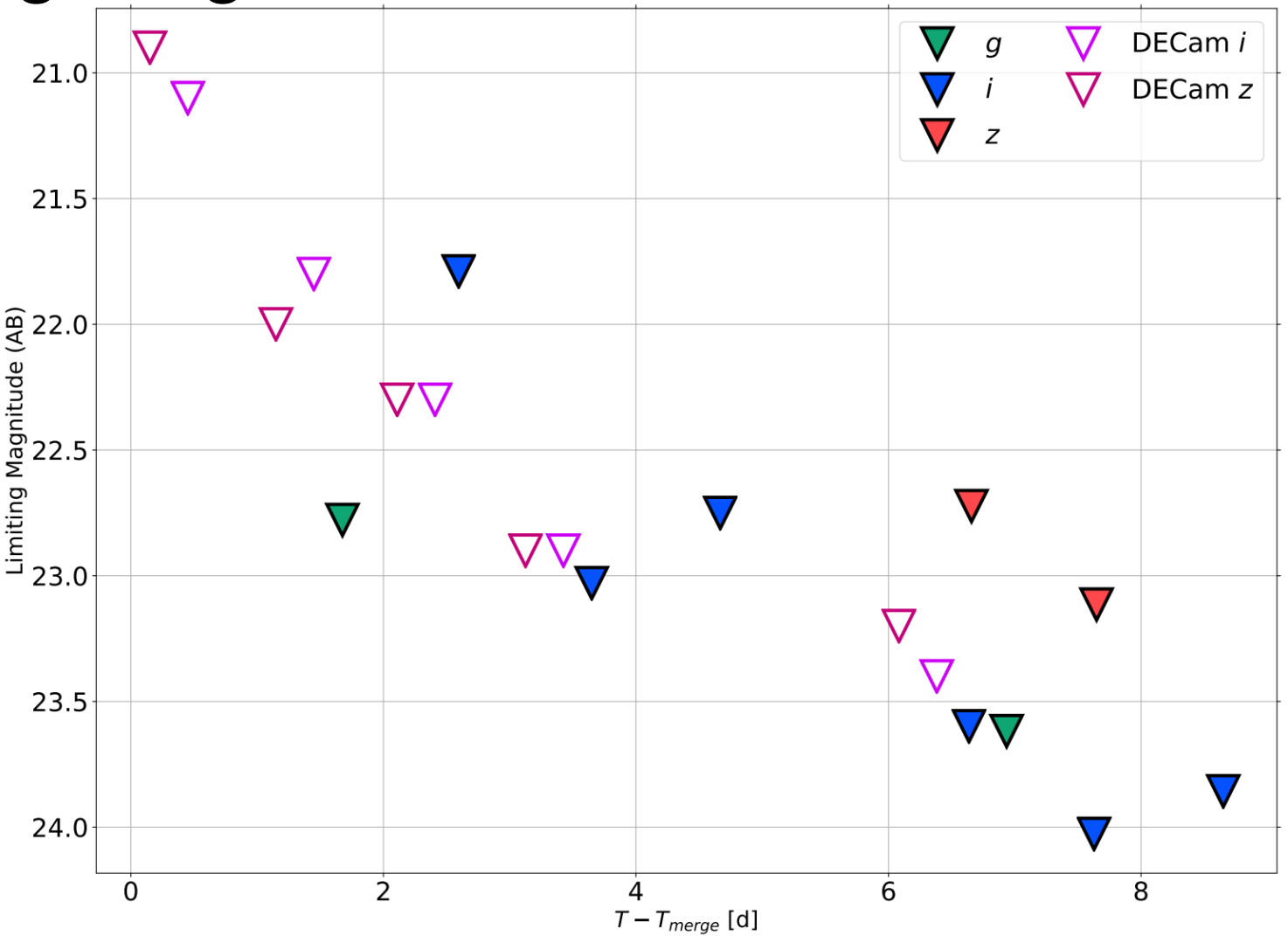
- “Confusion matrix”
- False Positive Rate (FPR) of 3.4% competitive with other RB classifiers
- False Negative Rate (FNR) of 0%
- Model will only improve with more data!



Work in progress!



Limiting magnitudes



Conclusions

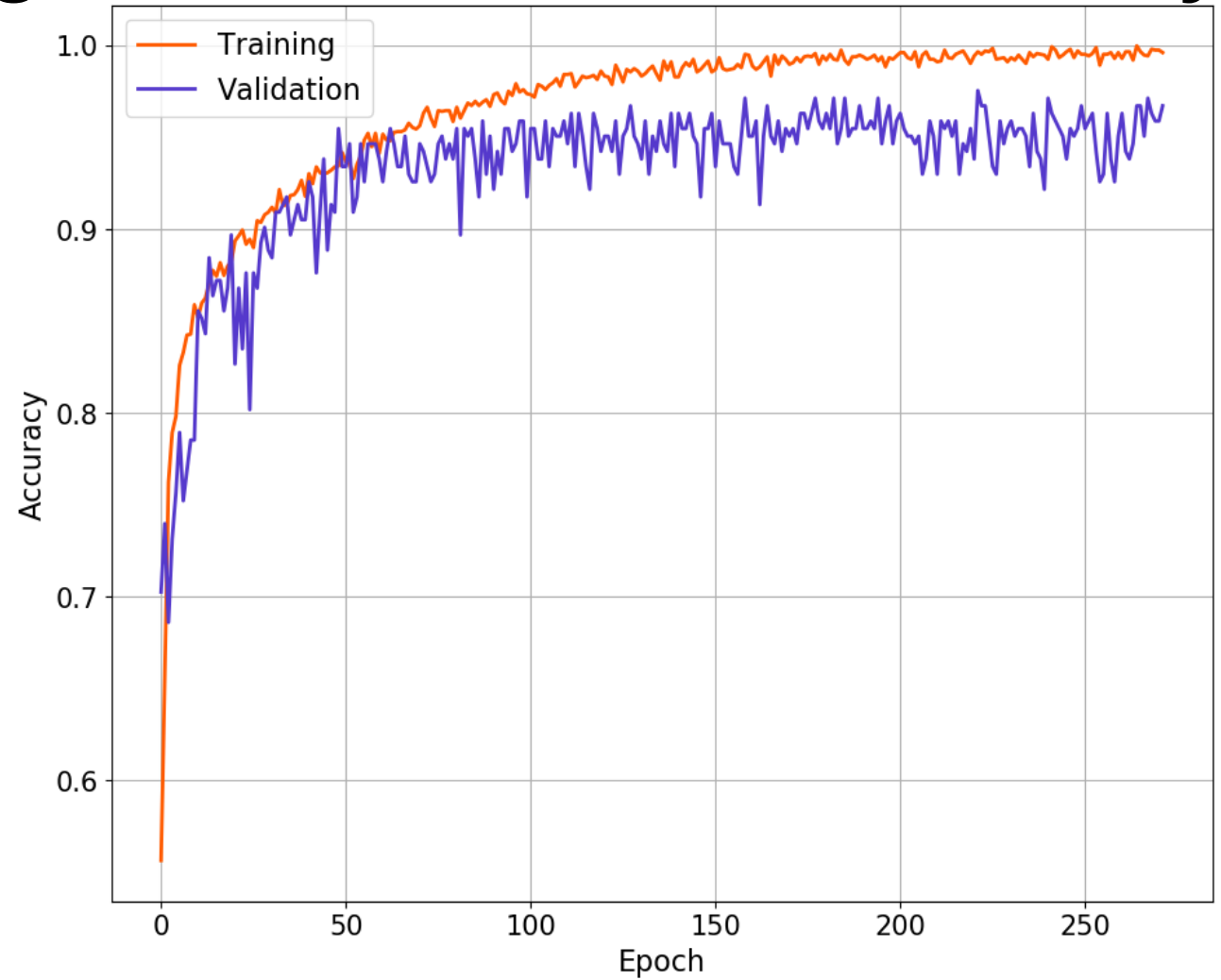
- Work in progress – stay tuned!
- We can produce competitive, valuable constraints on the first-ever high-confidence NS-BH merger
- End-to-end CFHT pipeline ready for any new GWs in O3 and O4

Title slide image: (c) Simulating eXtreme Spacetimes

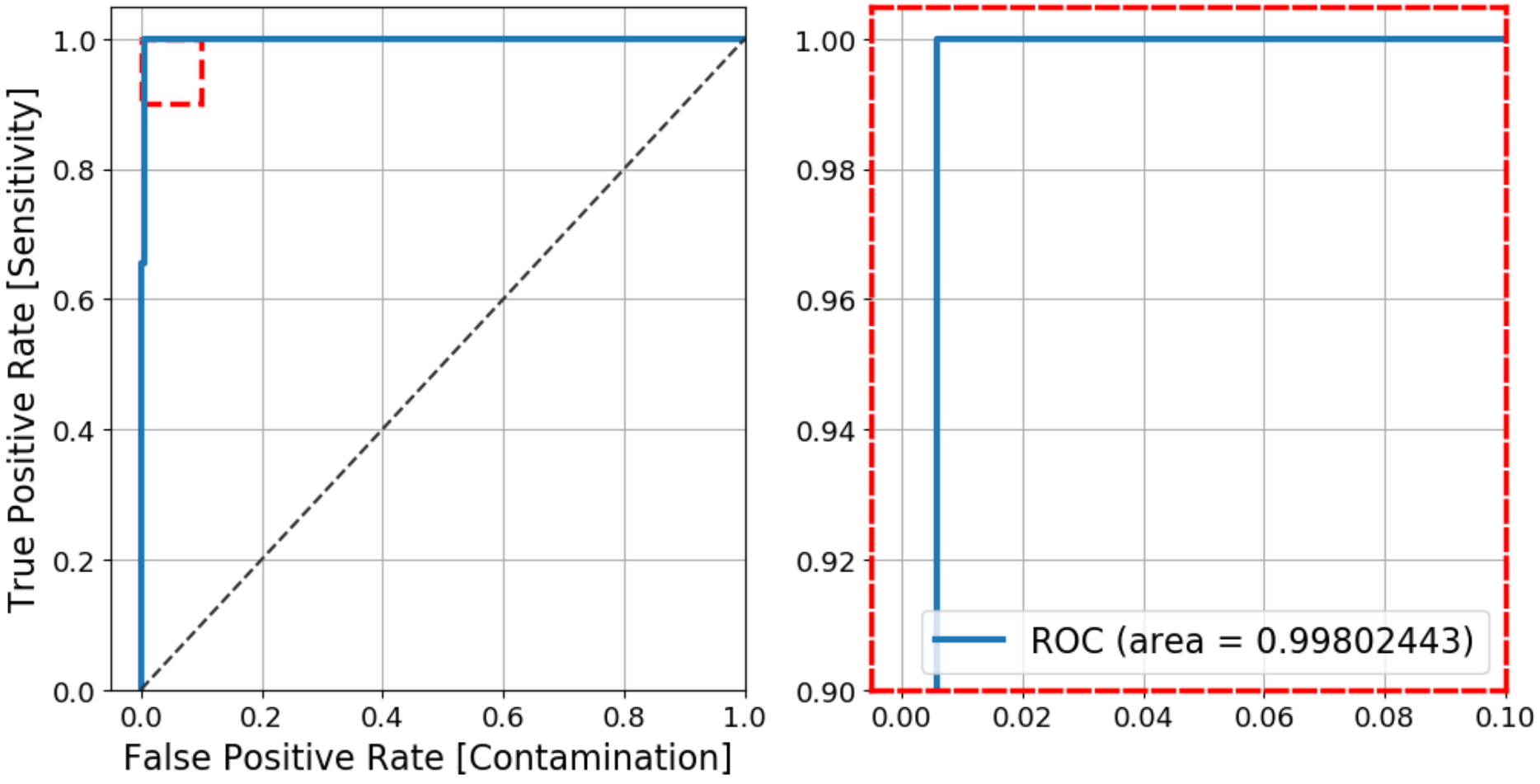
Acknowledgements

- CFHT observing staff
- John Ruan, Daryl Haggard, and Maria Drout
- The entire MEGA research group
- NSERC for Summer 2019 funding
- Bob Wares Science Innovation Prospectors Fund for current funding

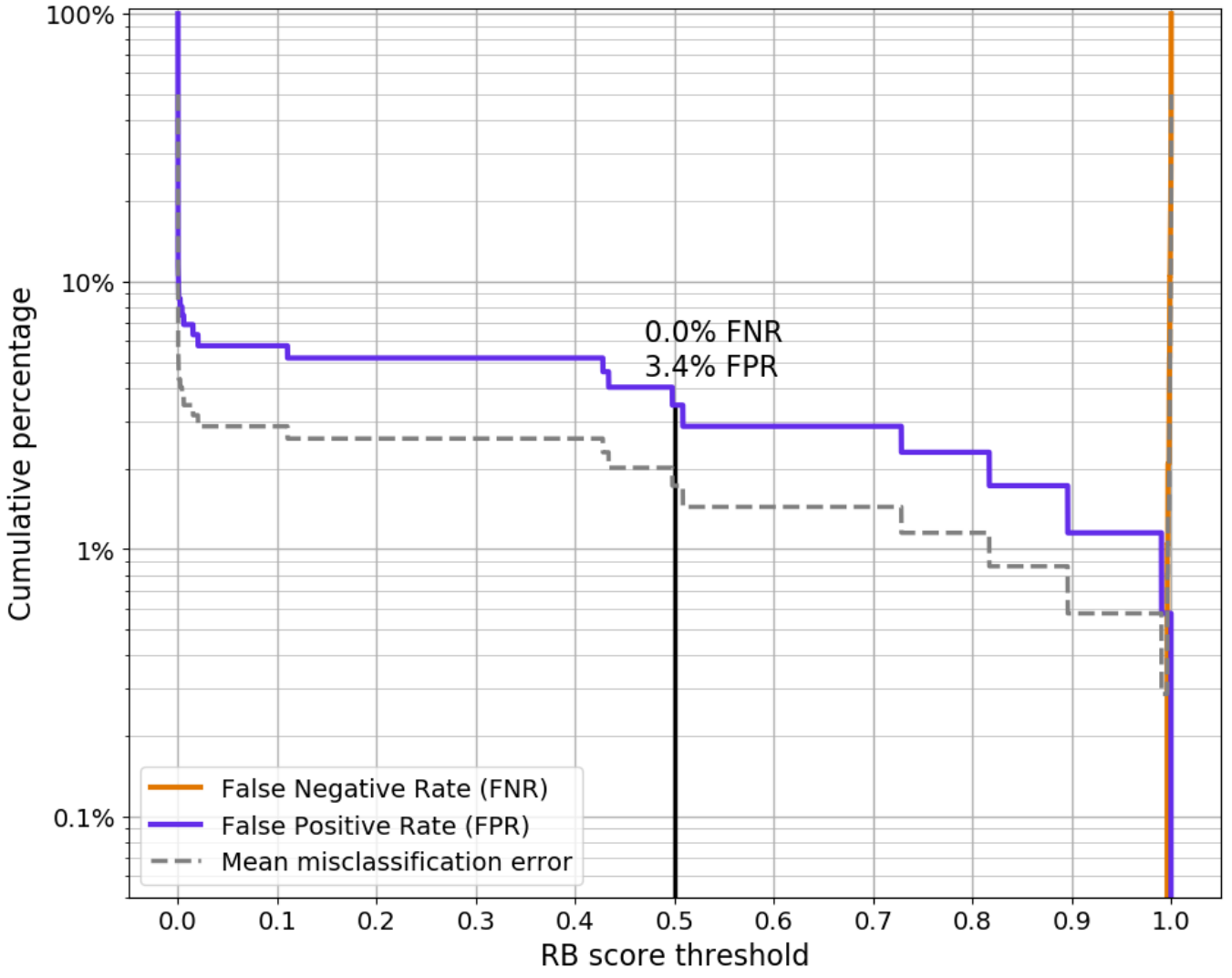
Training and validation accuracy



Receiver operating characteristic (ROC)



FPR and FNR


100%
10%
1%
0.1%
Cumulative percentage
0.0% FNR
3.4% FPR
False Negative Rate (FNR)
False Positive Rate (FPR)
Mean misclassification error
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
RB score threshold