Identifying Optical GW Counterparts with Image Processing

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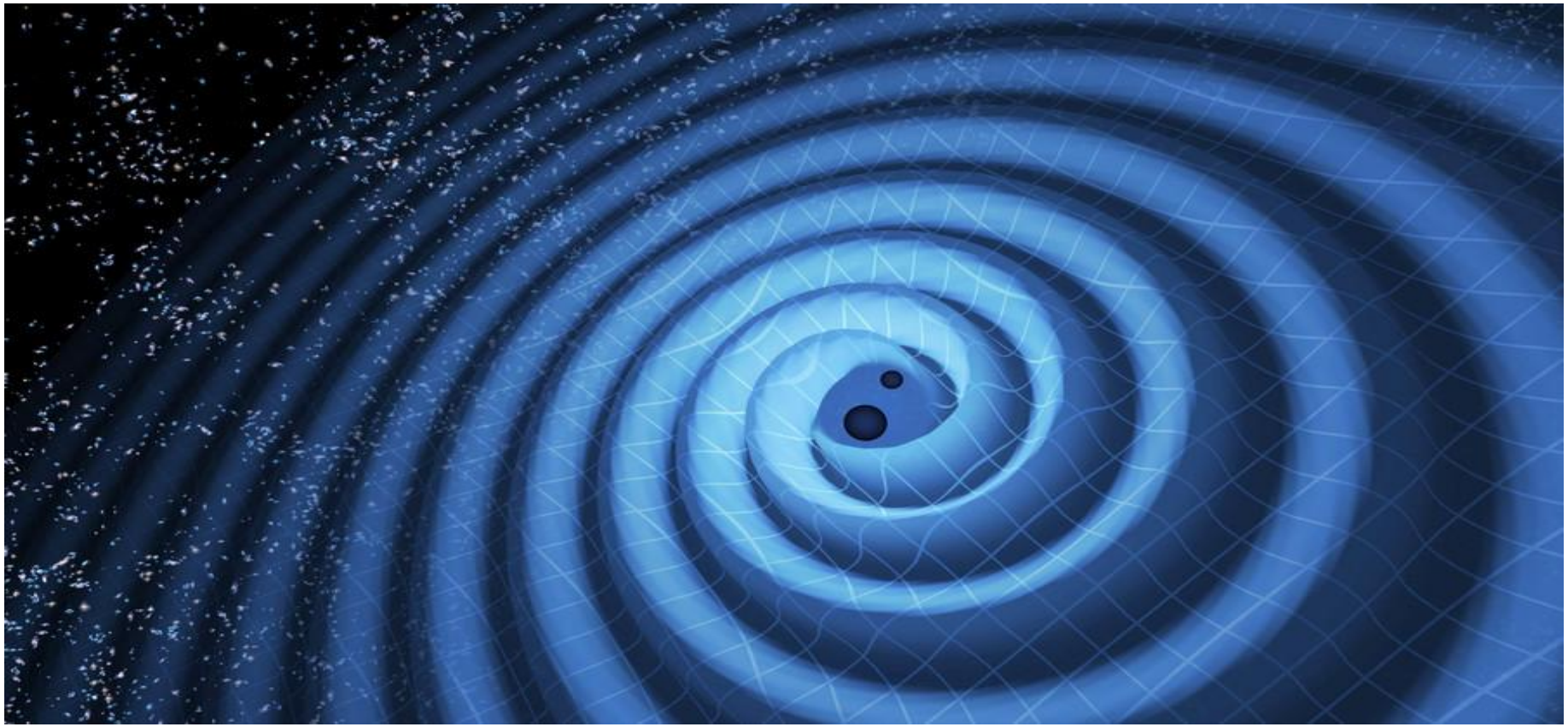
SIST Final Talk

6 August 2018

Overview

- Background
  - GW
  - DES
- The DES-GW pipeline
  - SE
  - DiffImg
- Next steps

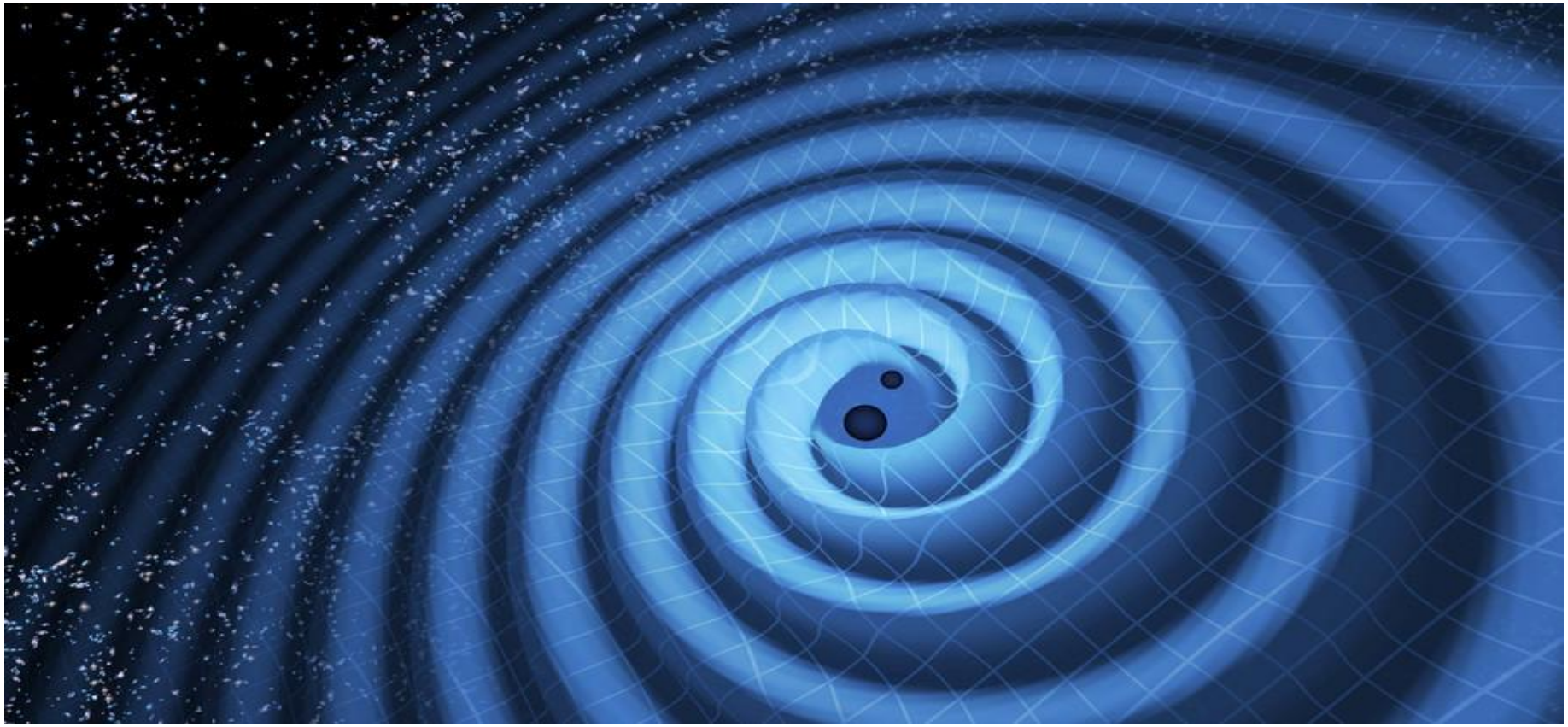
Gravitational Waves



LIGO/T. Pyle 2016

"Perpetuating changes in the gravitational field caused by accelerating masses"

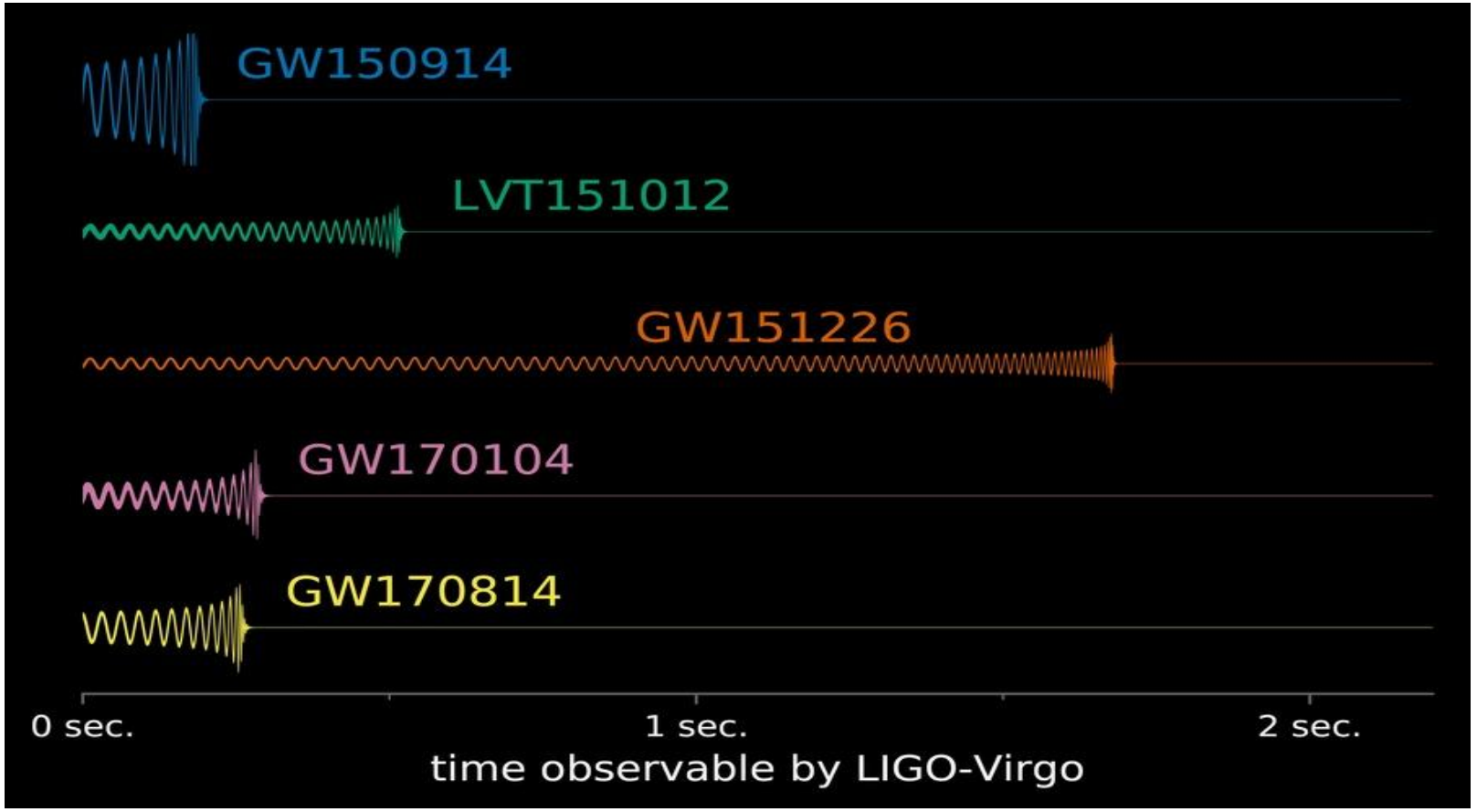
Gravitational Waves



LIGO/T. Pyle 2016

Binary Black Hole (BBH)
Black Hole-Neutron Star (BH-NS)
Binary Neutron Star (BNS)

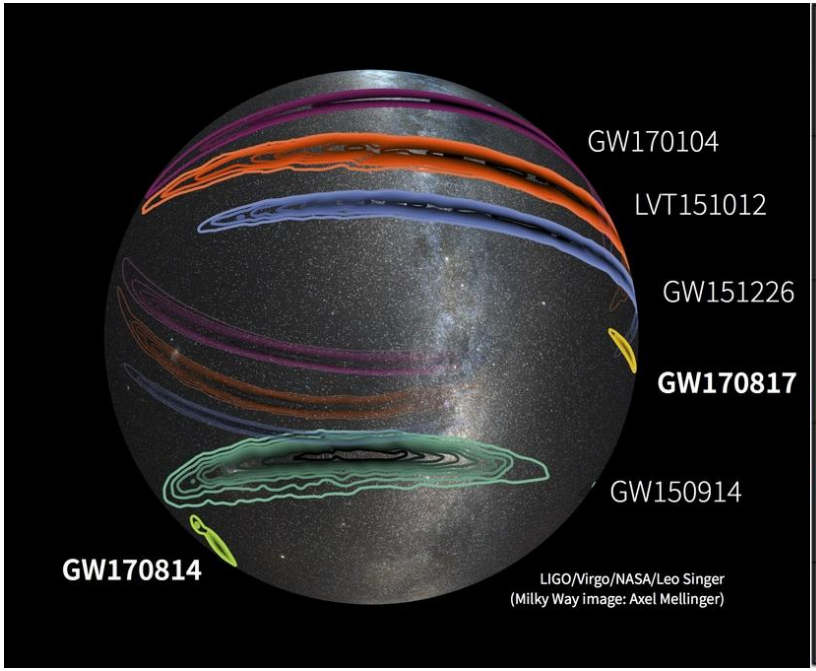
Gravitational Waves



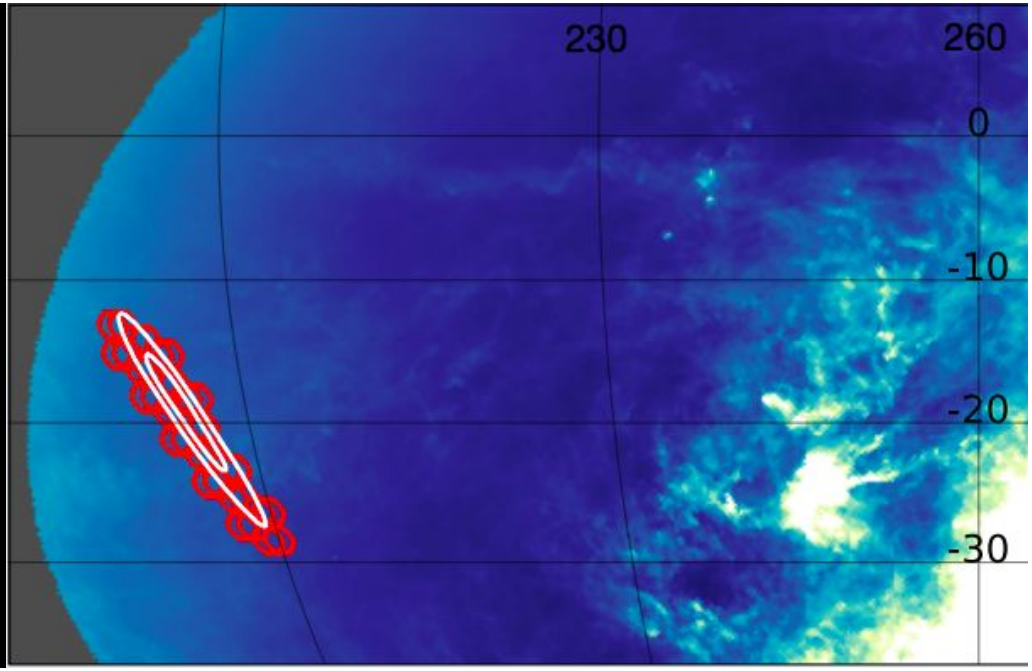
LIGO/Caltech/MIT/LSC 2017

Wave shape → event type
Amplitude → distance

Gravitational Waves



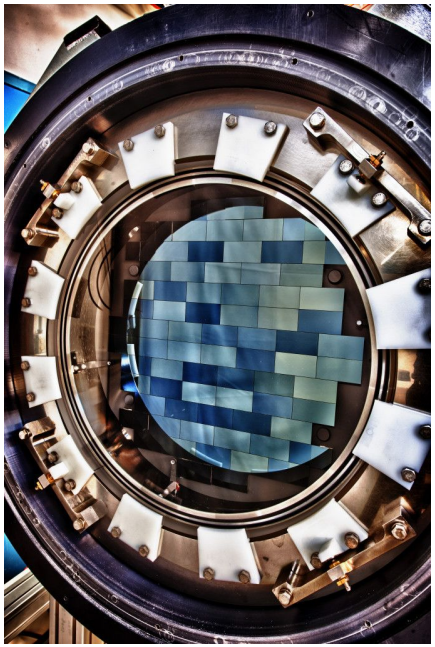
LIGO/Virgo/NASA/Leo Singer 2017
(Milky Way image: Axel Mellinger)



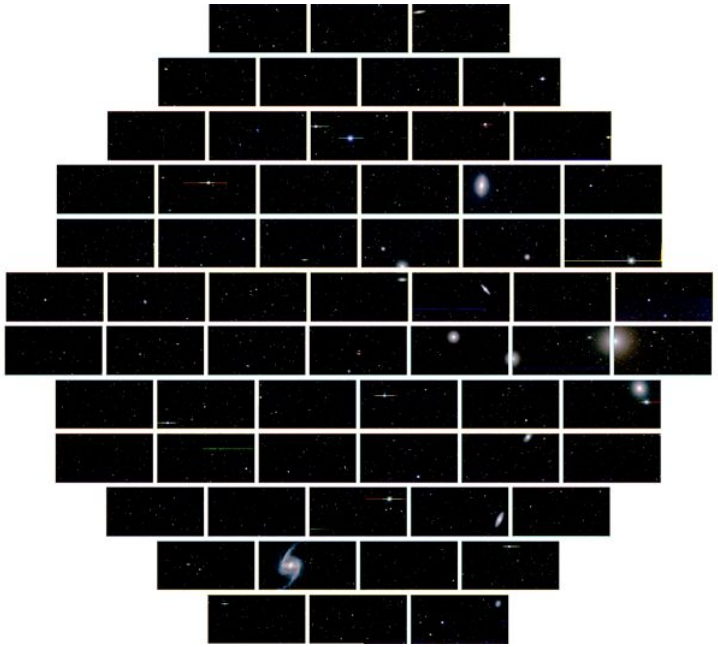
Dark Energy Survey Collaboration

Dark Energy Survey (DES)

Reidar Hahn (Fermilab)



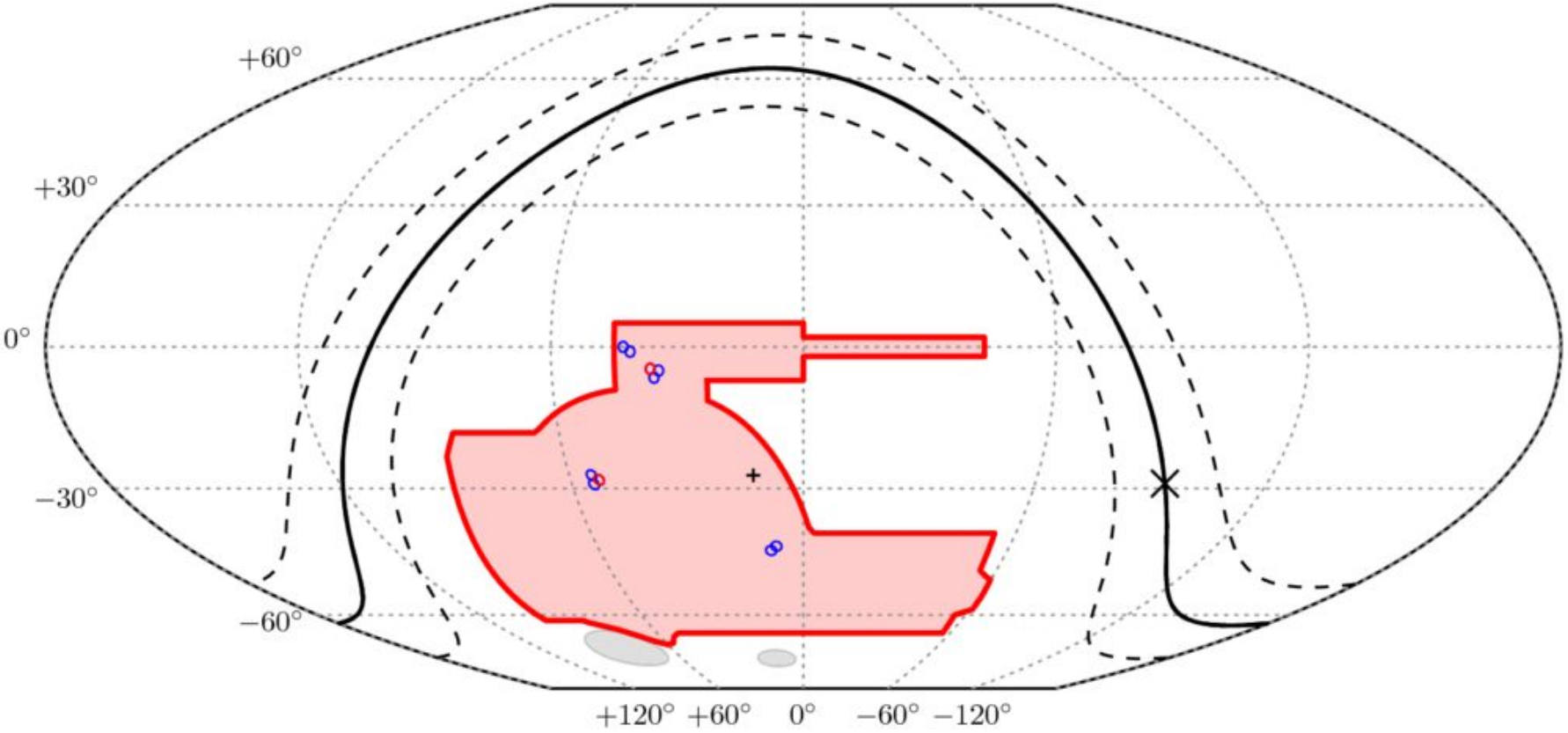
DES Collaboration



DES Collaboration

DECam, assembled at Fermilab, now mounted on the Blanco telescope in Chile

Dark Energy Survey (DES)



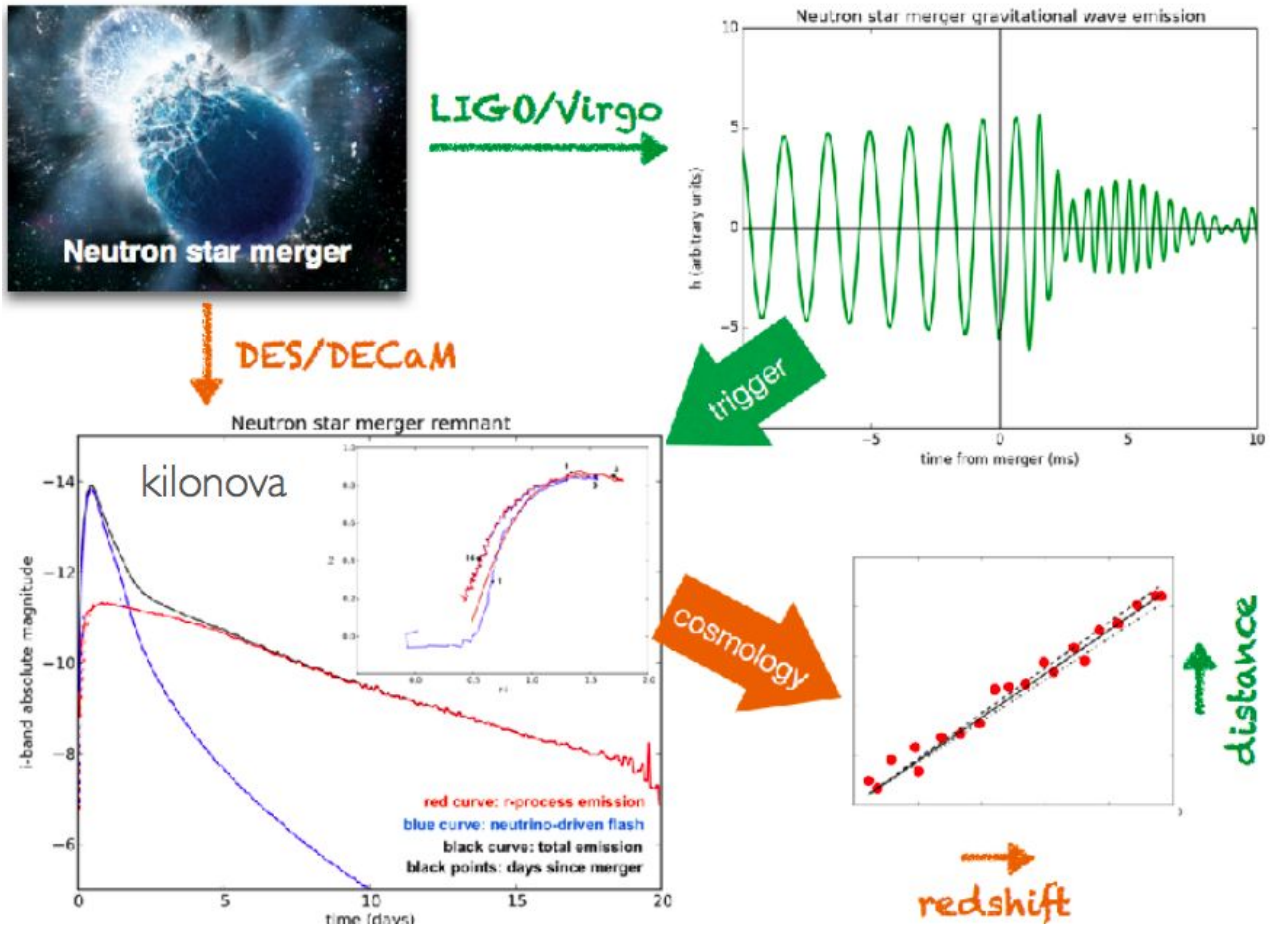
DES Collaboration

The DES footprint spans ~5000 square degrees (⅛ of the sky)

Fermilab

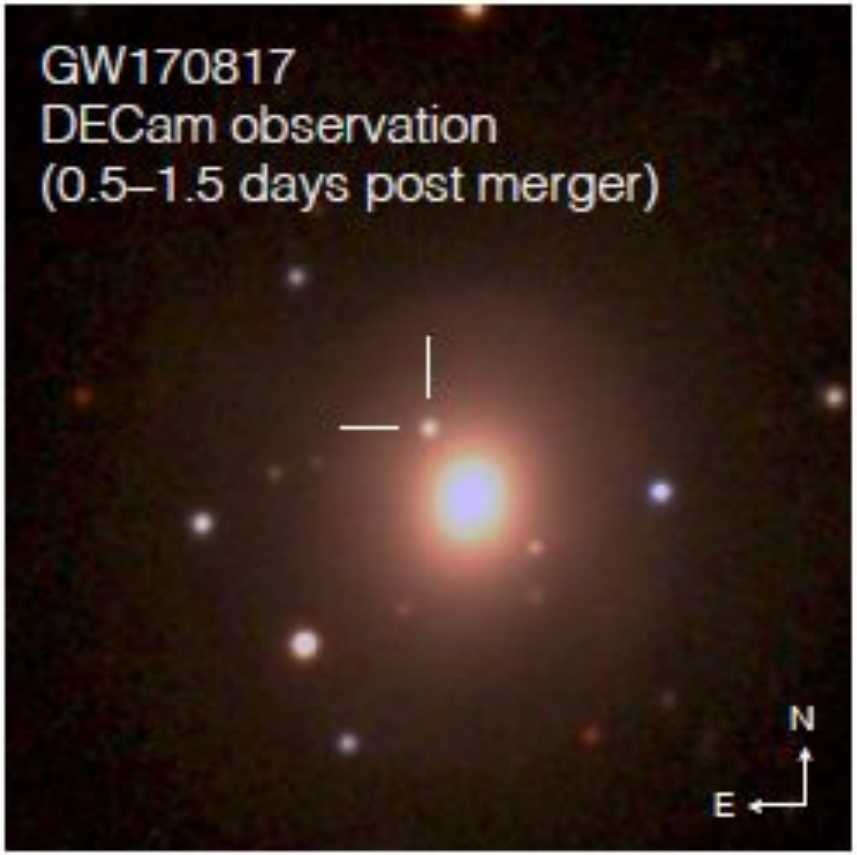
Dark Energy Survey (DES): Why?

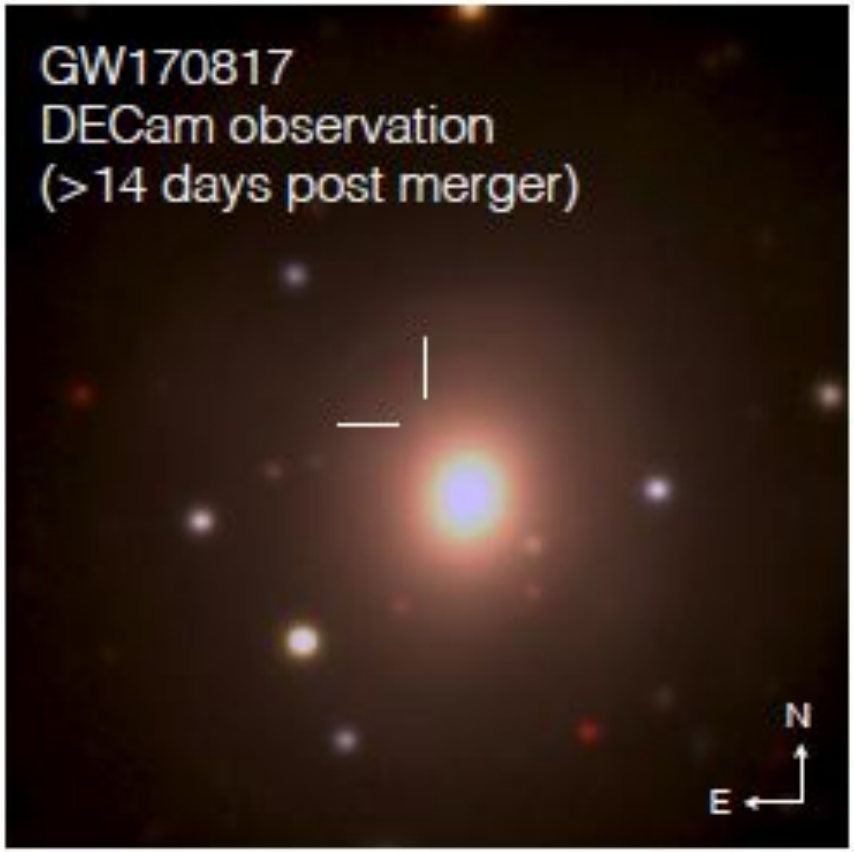
Independent measure of the Hubble parameter and other cosmological parameters



DES Collaboration

Dark Energy Survey (DES): GW170817



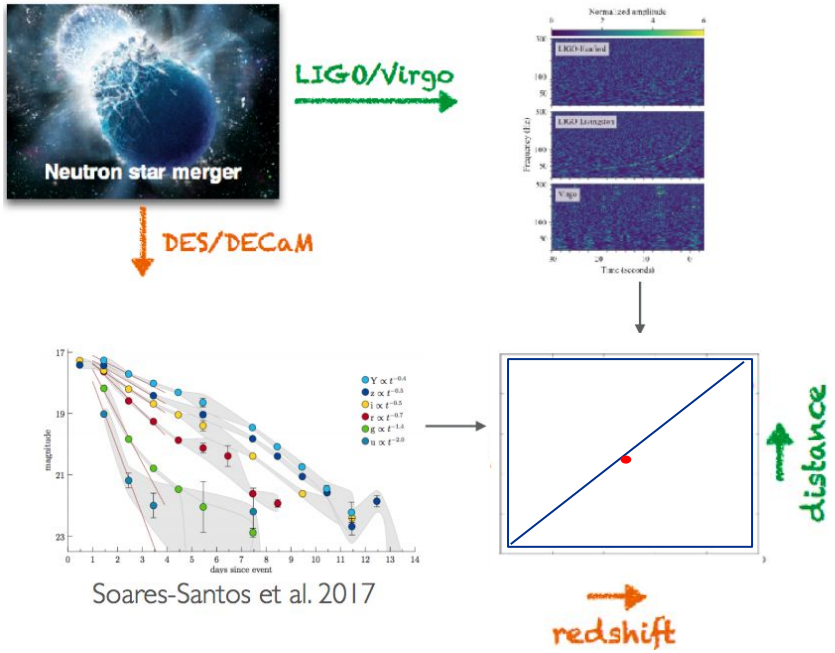


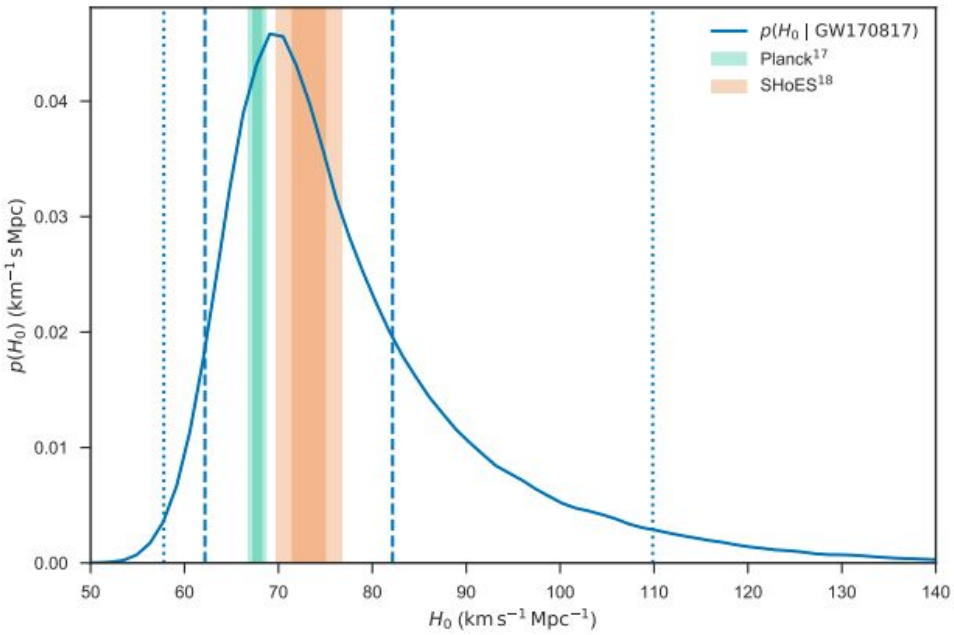
GW170817 Optical Counterpart composite detection images (Soares-Santos et al. 2017)

- The first optical counterpart of a GW event was observed by DES in August 2017!
  - One point on the distance-redshift plot
- In O3 we expect ~10x as many events

Dark Energy Survey (DES): Why?

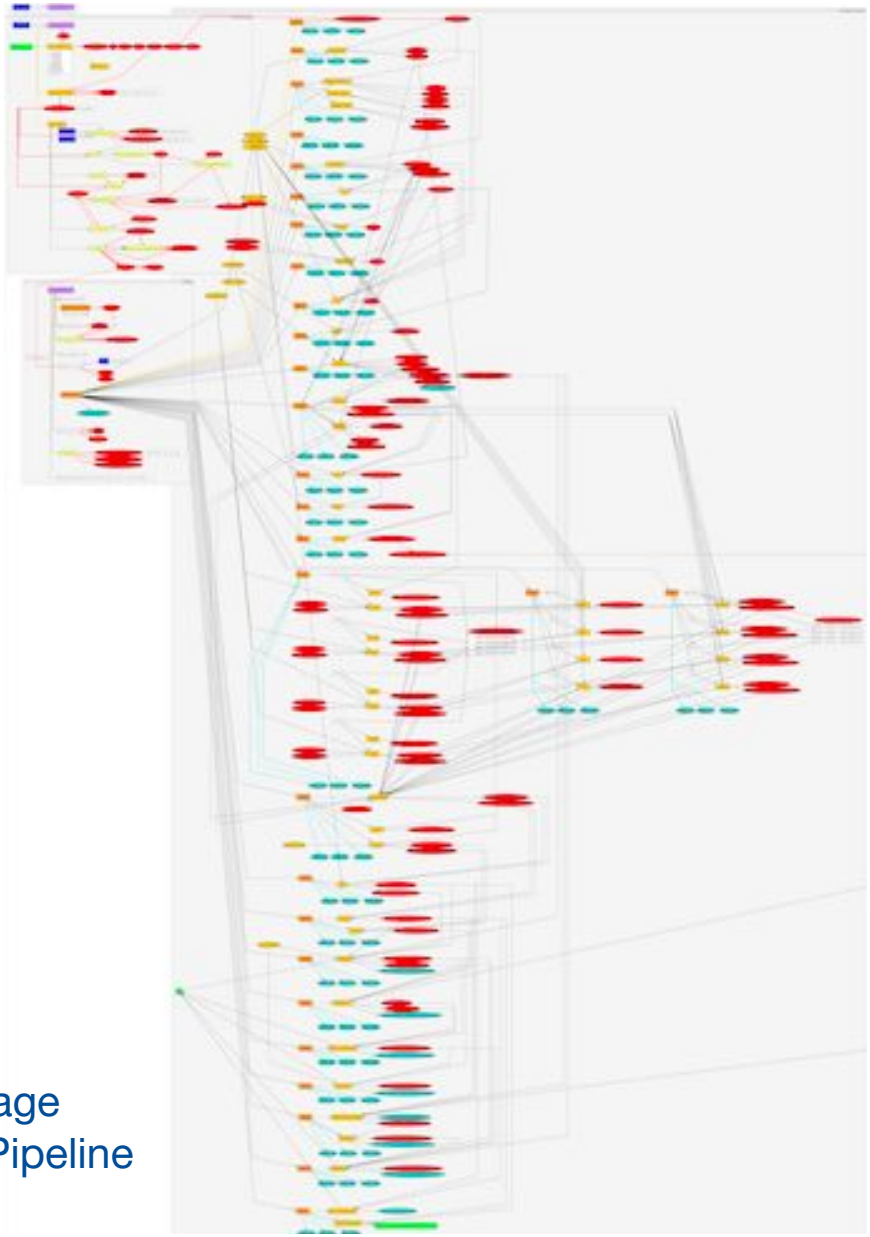
Independent measure of the Hubble parameter and other cosmological parameters





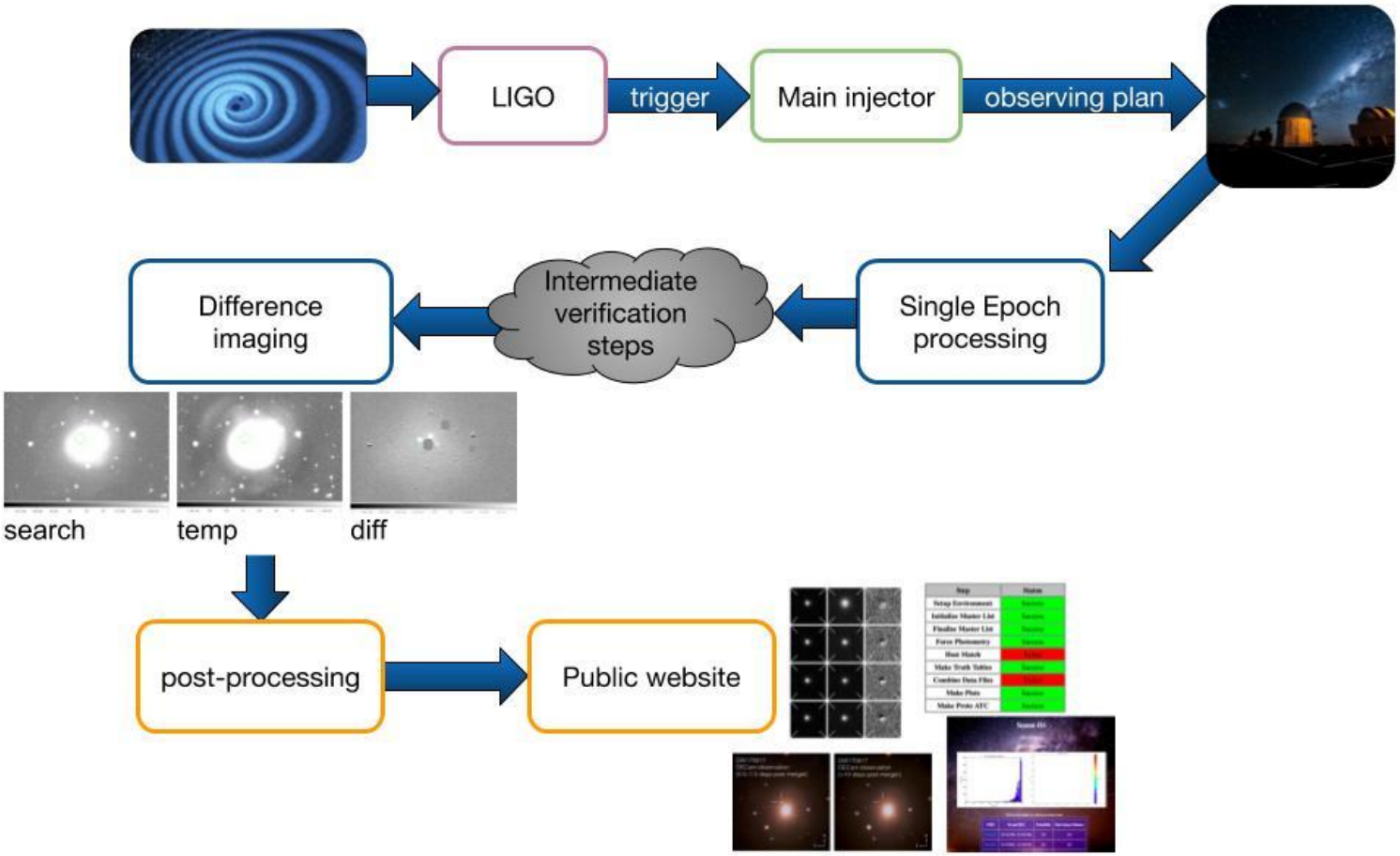
DES Collaboration

Fermilab



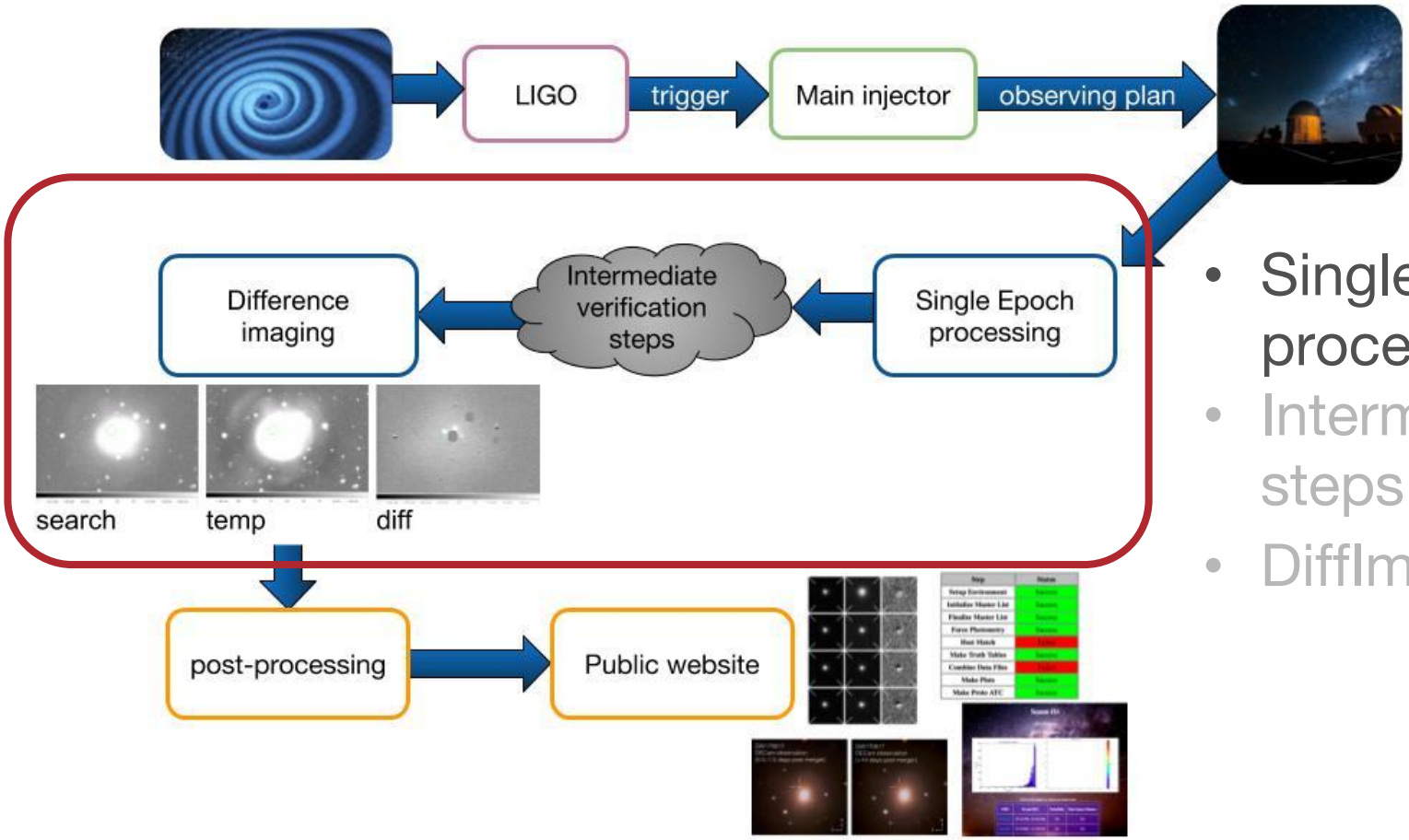
DES-GW Image Processing Pipeline

DES-GW Pipeline



Full Pipeline

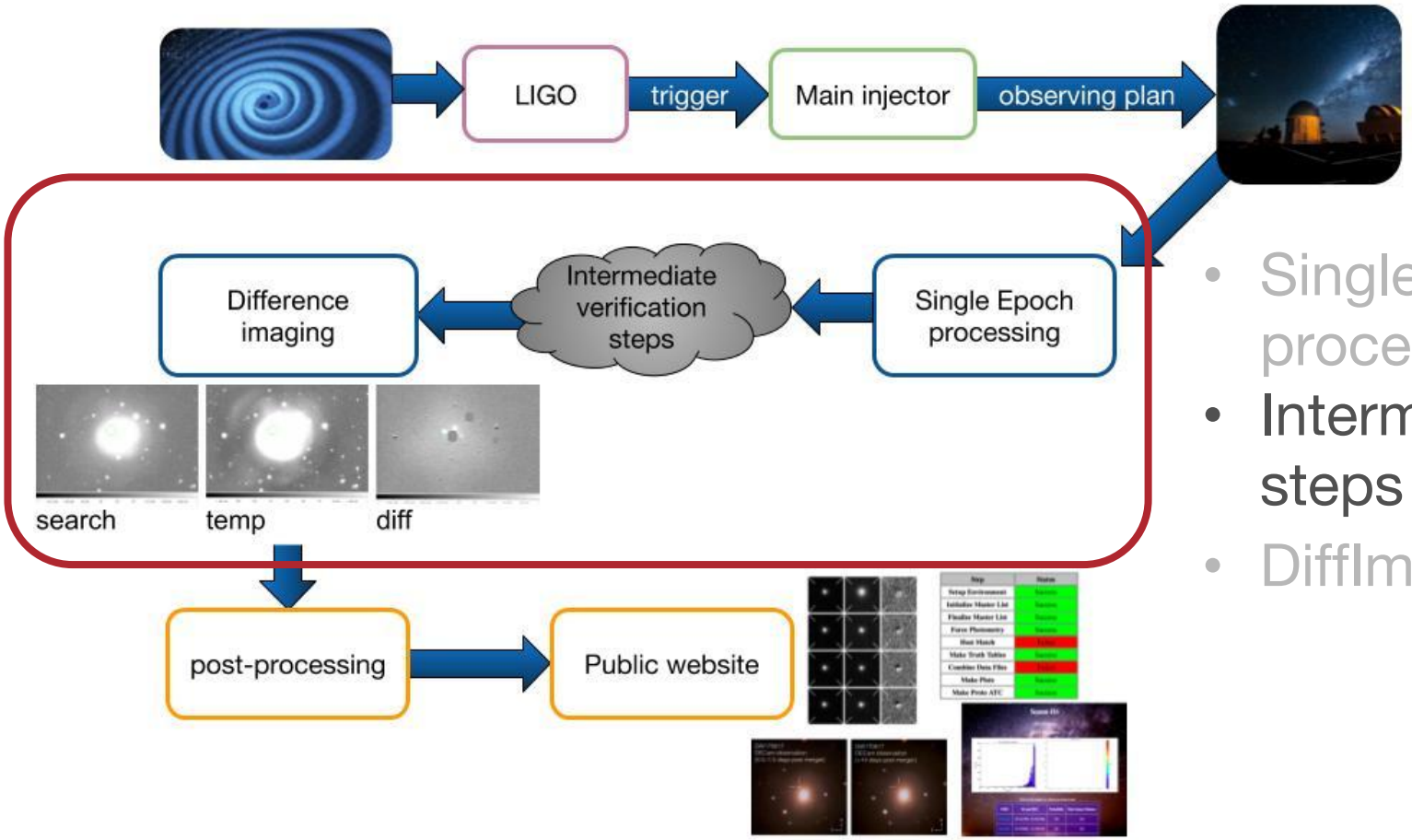
DES-GW Pipeline



- Single Epoch (SE) processing
- Intermediate steps
- DiffImg

Full Pipeline

DES-GW Pipeline



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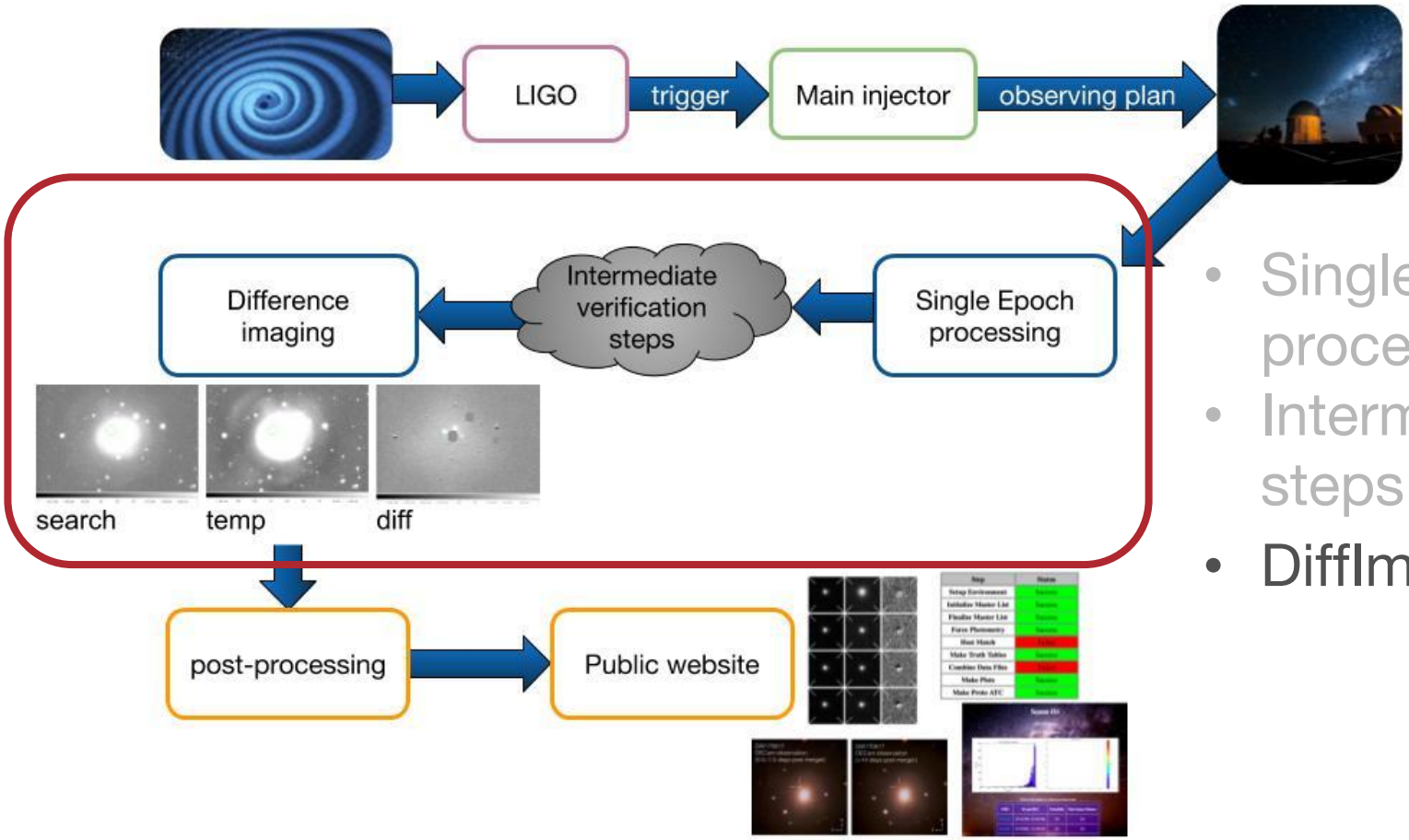

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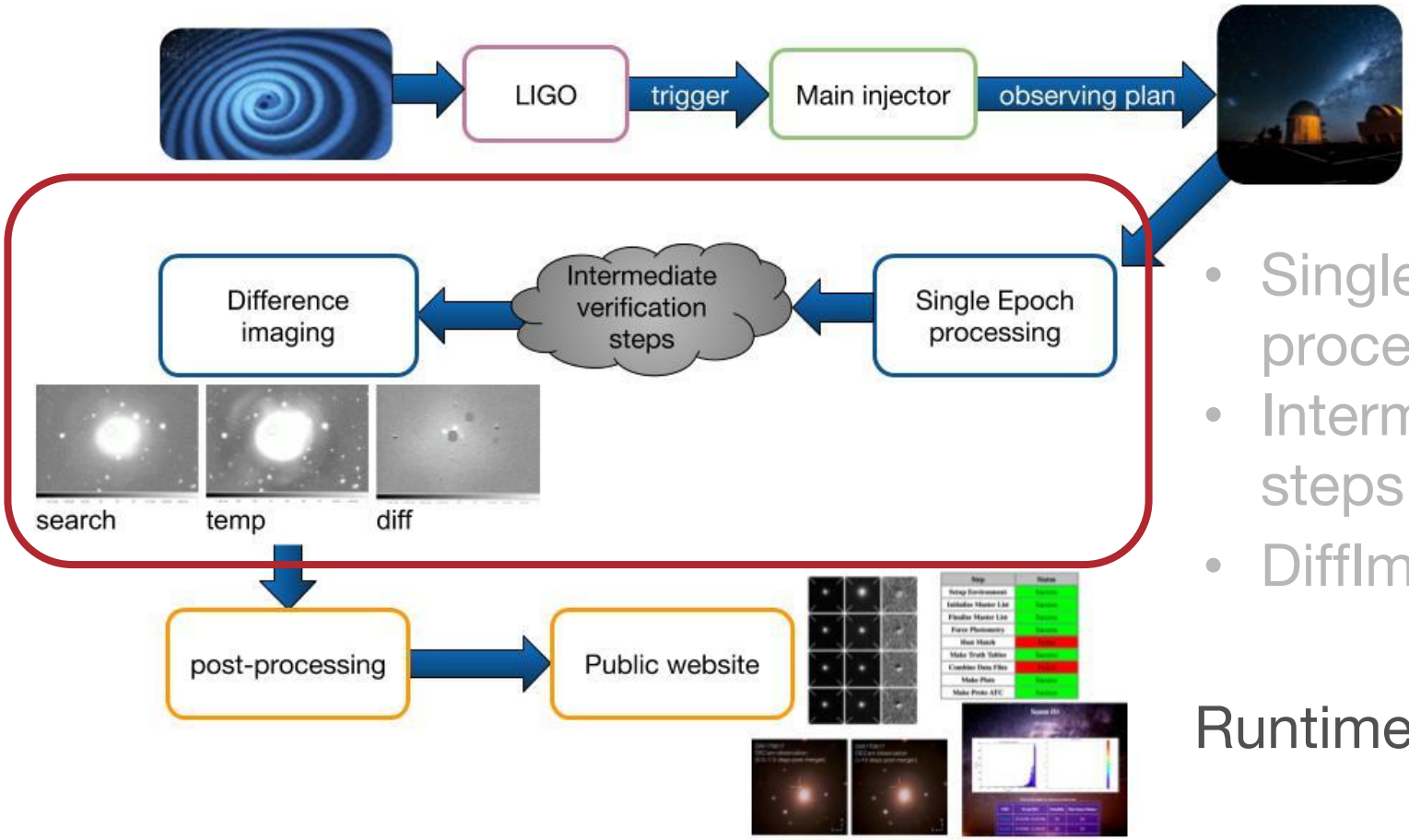

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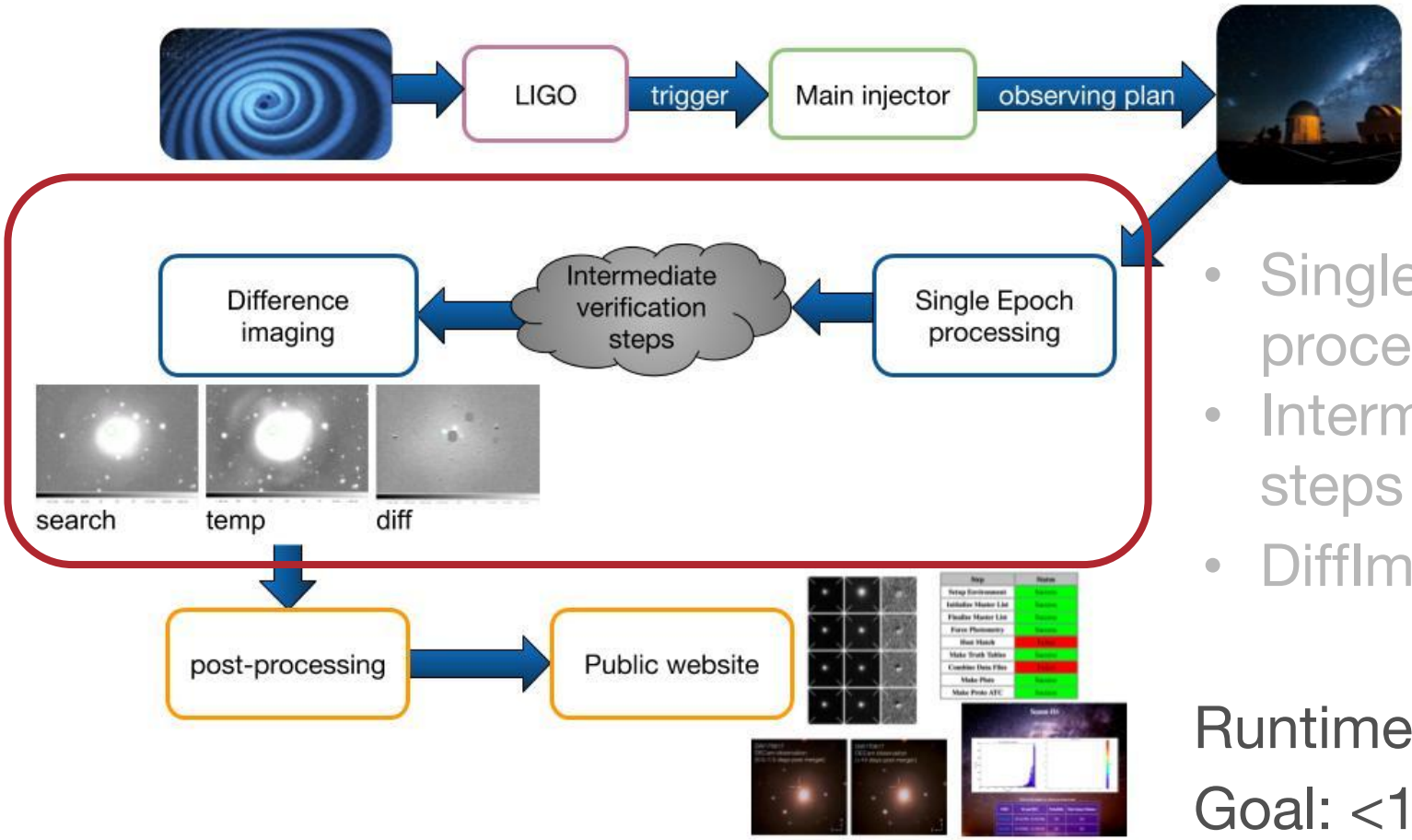
Runtime: ~5-8 hr

Full Pipeline

DES-GW Pipeline



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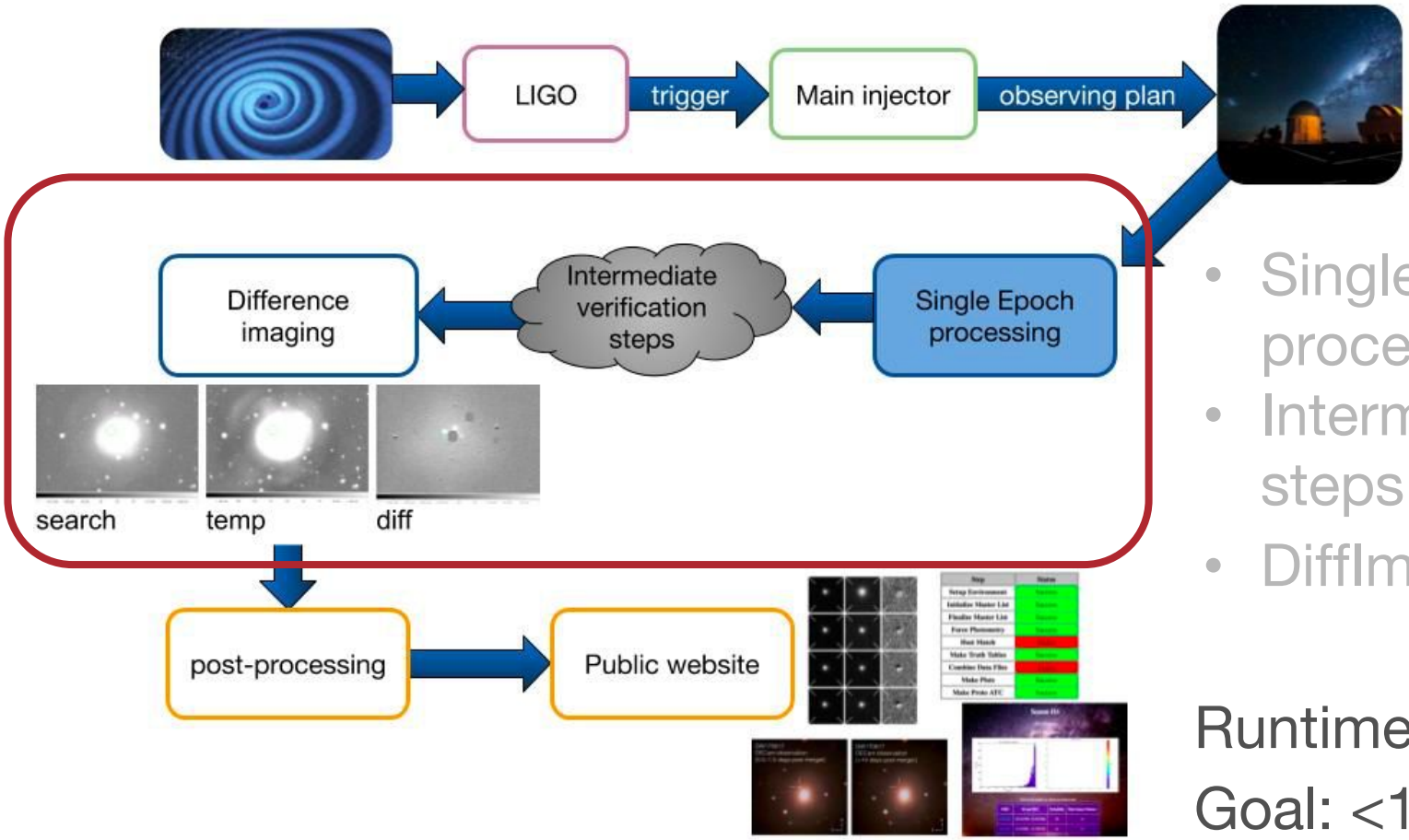
Goal: <1 hr

Full Pipeline

Fermilab

DES-GW Pipeline



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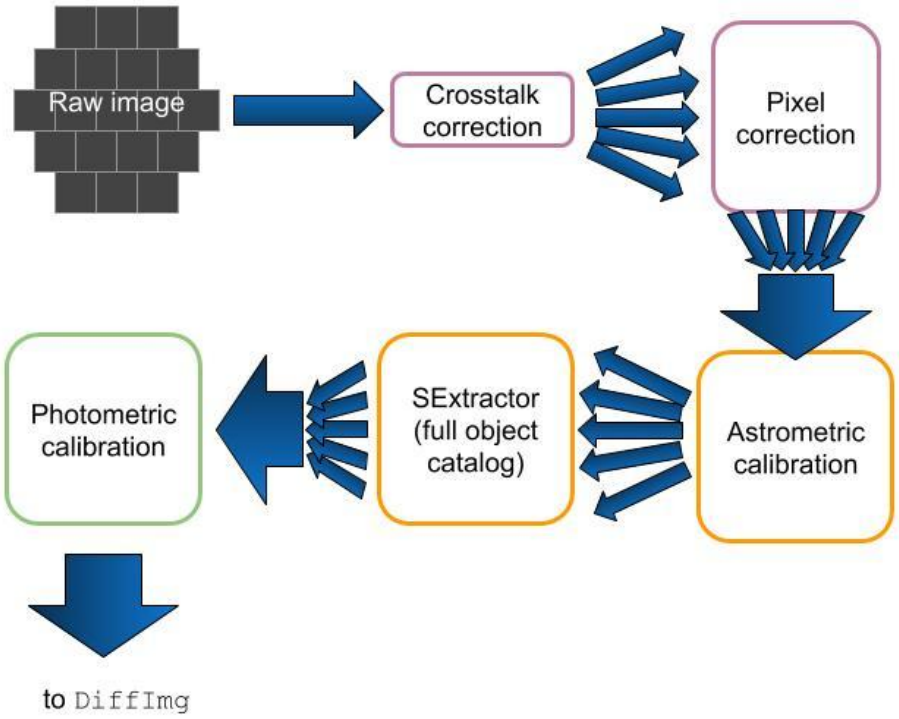
Full Pipeline

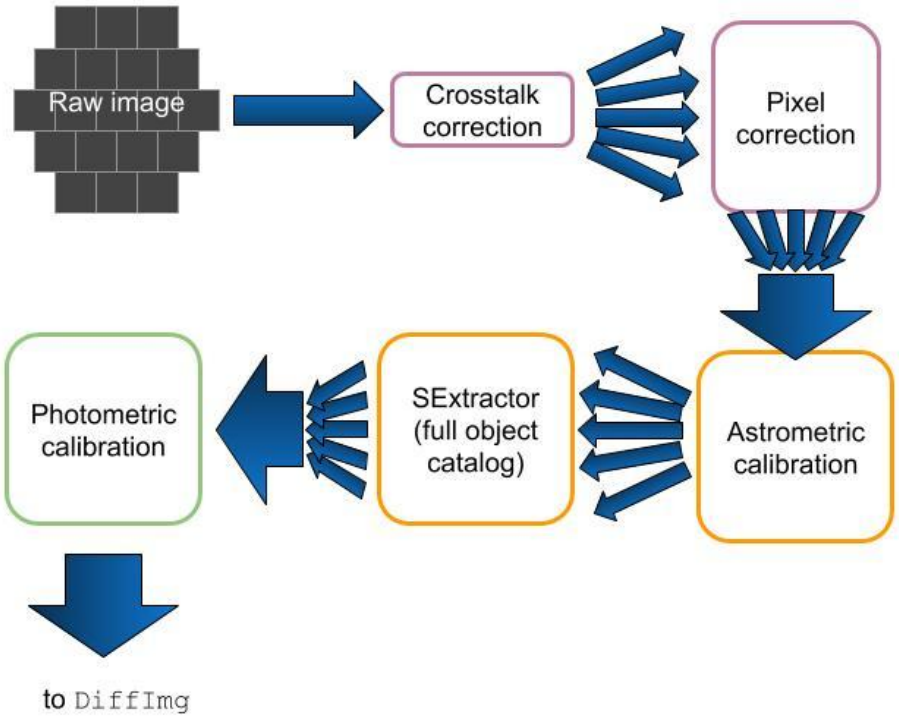
Image Processing Pipeline: SE processing



- Image Correction
  - Raw Images → "science-ready"
- Astrometric calibration: 2MASS
- Object Cataloguing
- Photometric Calibration: 2MASS

Single Epoch Processing

Image Processing Pipeline: SE processing



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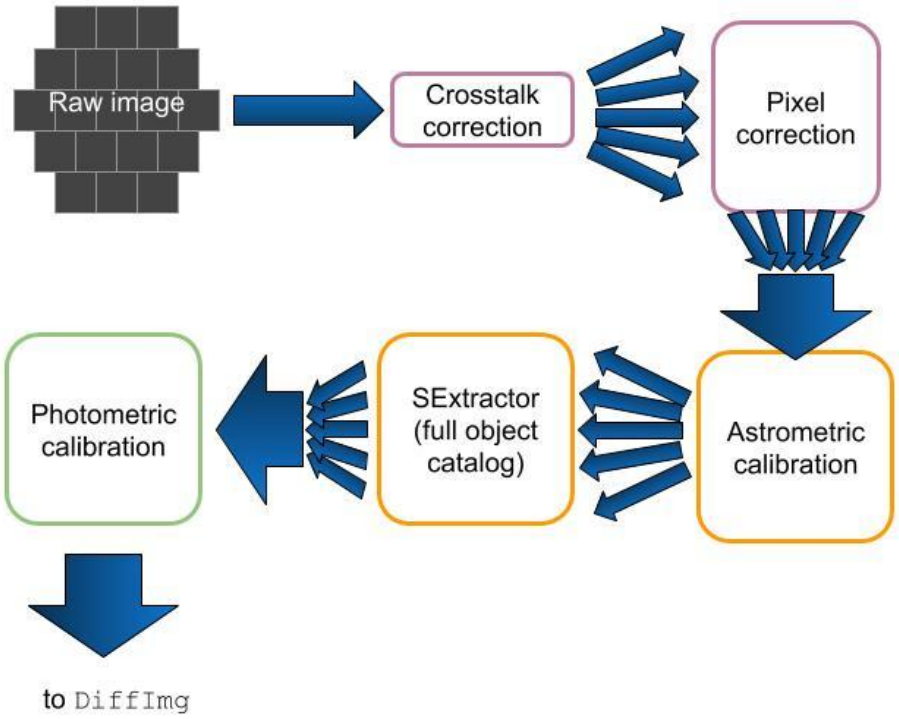

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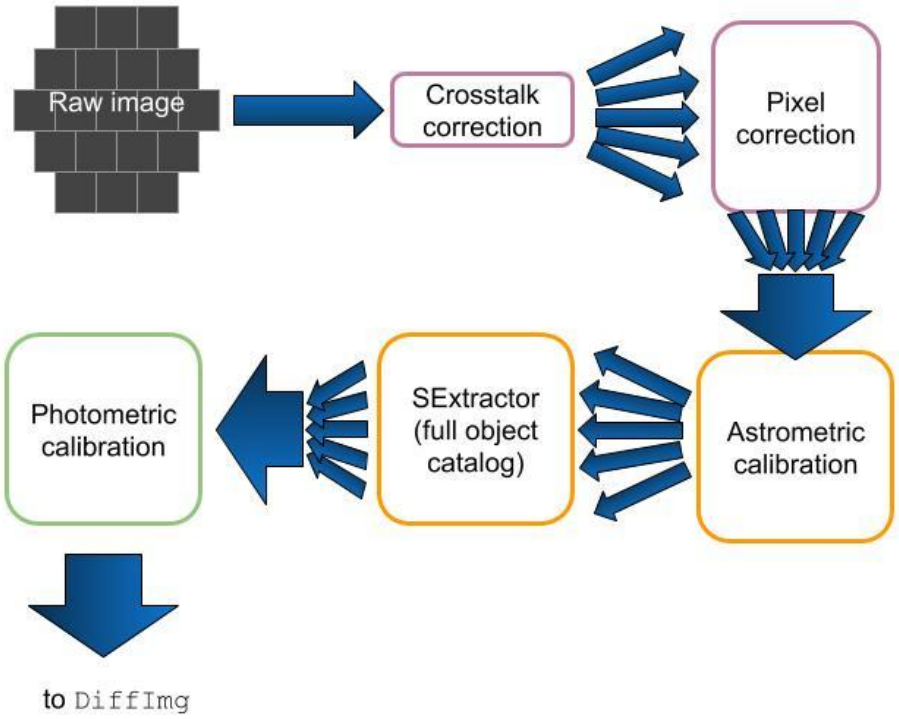

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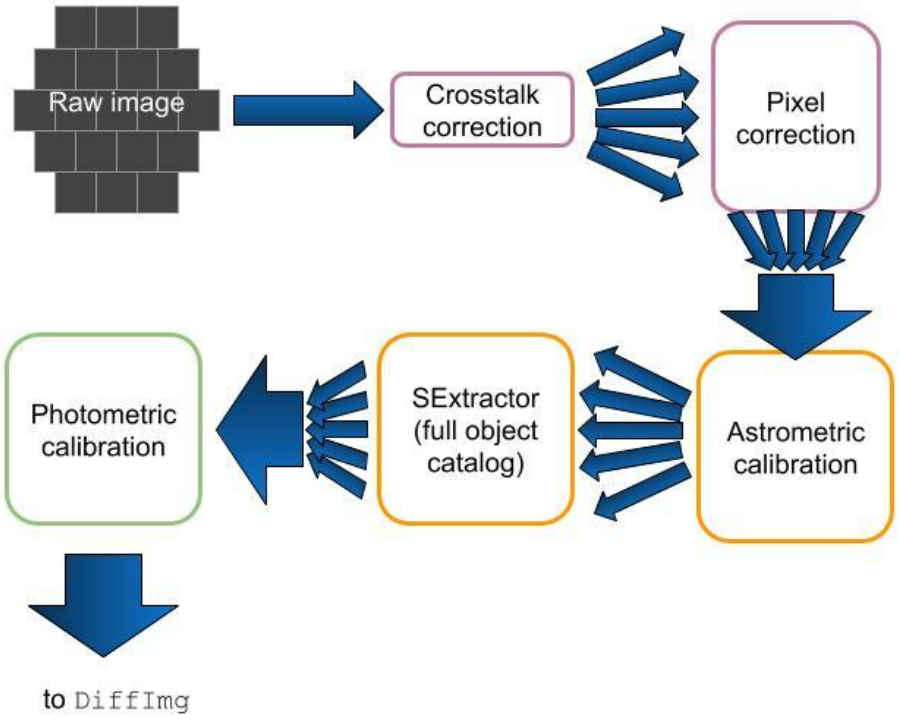

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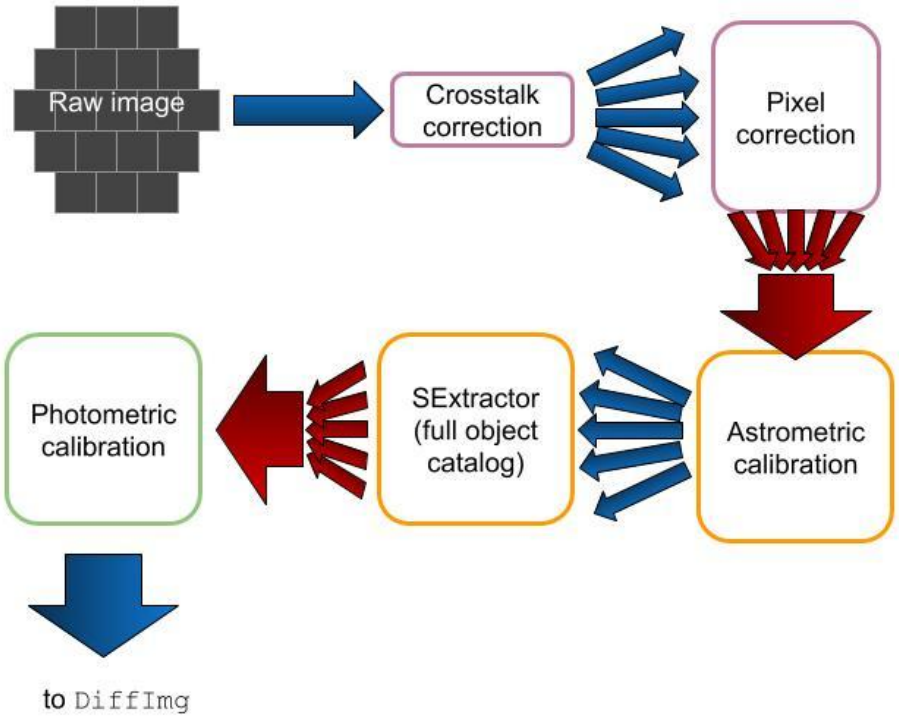

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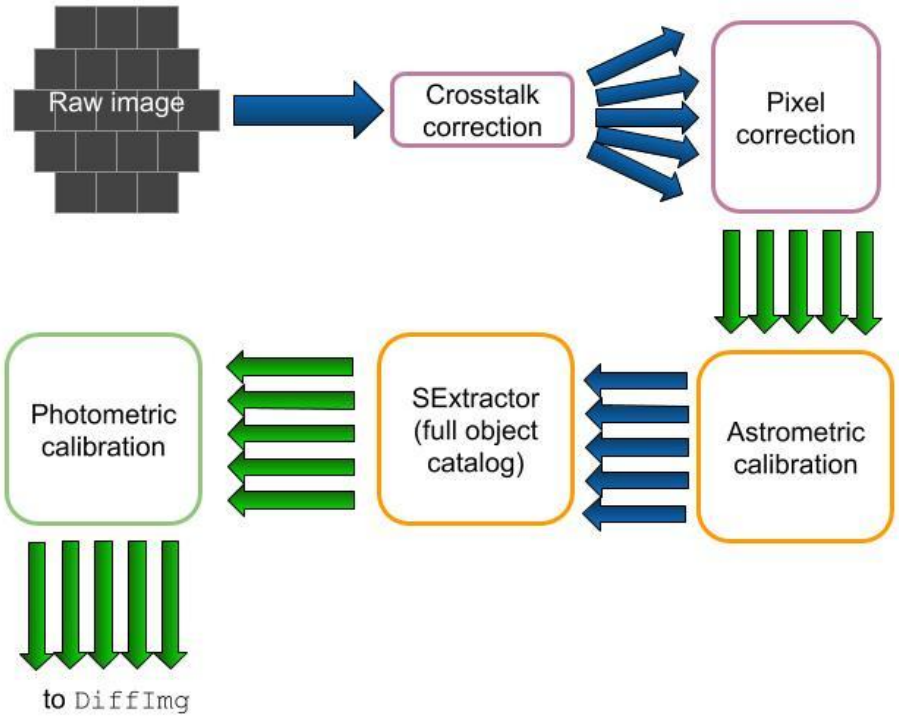
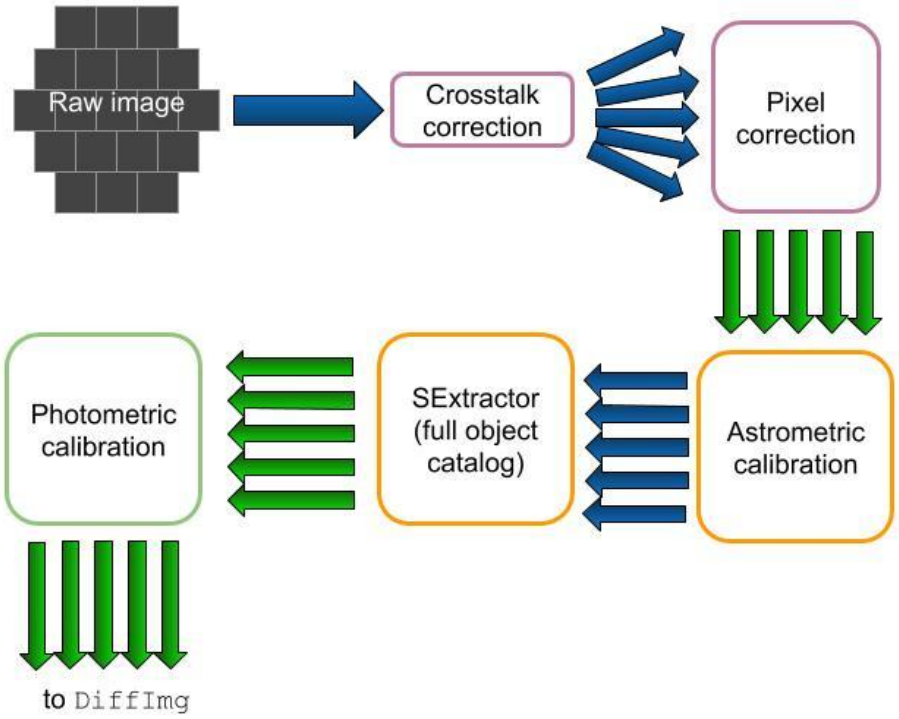


Single Epoch Processing

- Image Correction
  - Raw Images → "science-ready"
- Astrometric calibration: 2MASS
  - CCD-by-CCD
- Object Cataloguing
- Photometric Calibration: 2MASS
  - CCD-by-CCD

Image Processing Pipeline: SE processing



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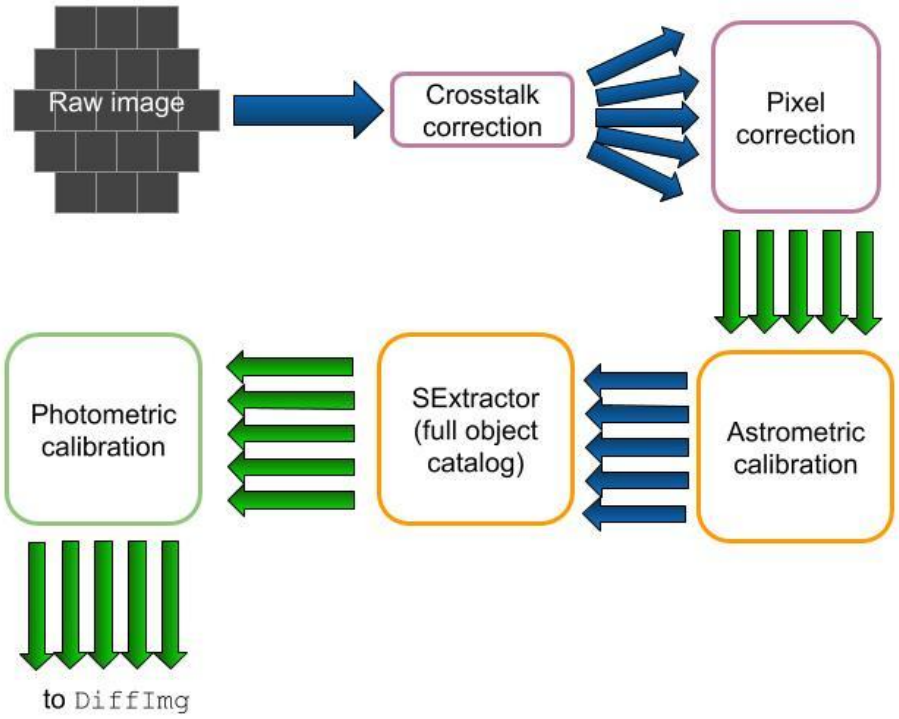

Single Epoch Processing

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- Photometric Calibration: GAIA-DR2
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Image Processing Pipeline: SE processing

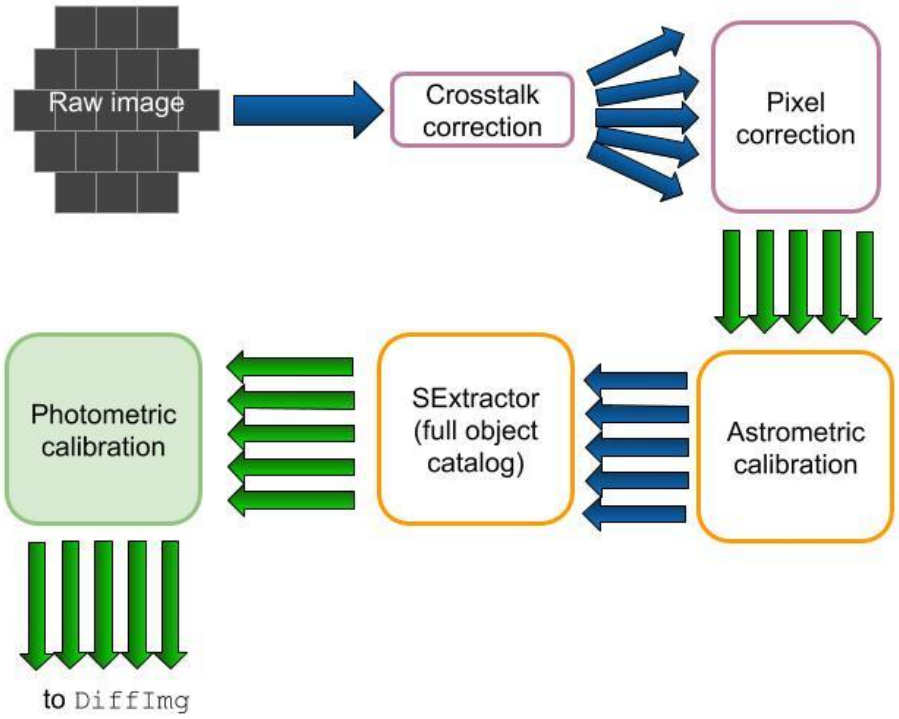

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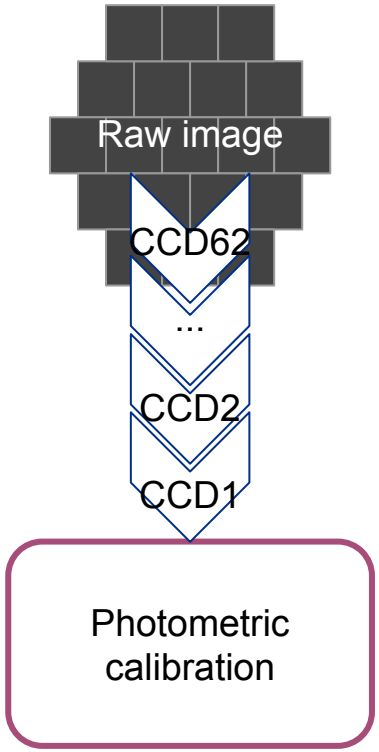
Image Processing Pipeline: SE Modifications



- “Fast” CCDs don’t have to wait for slower ones

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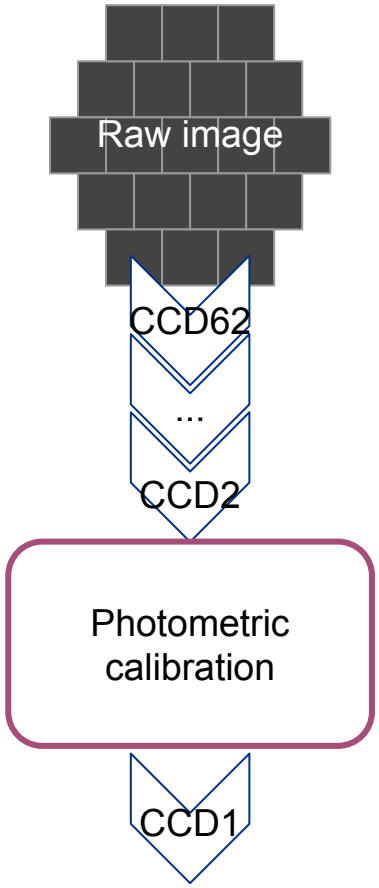

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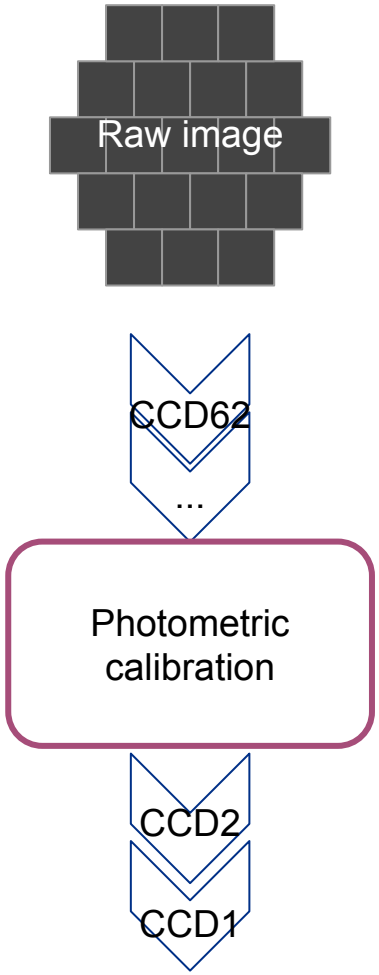

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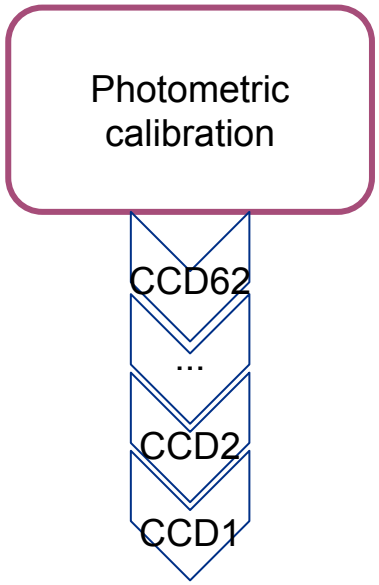

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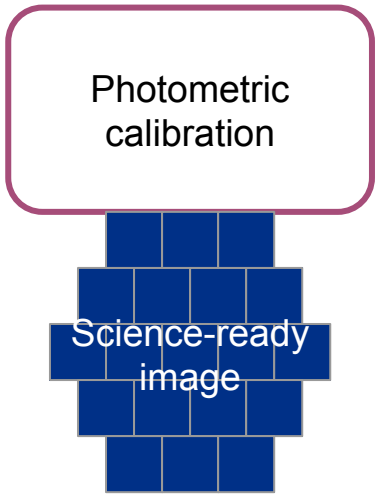

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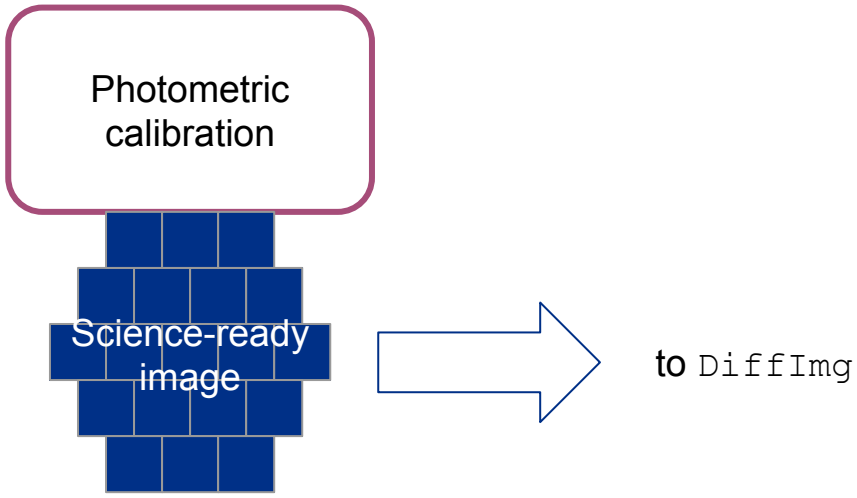

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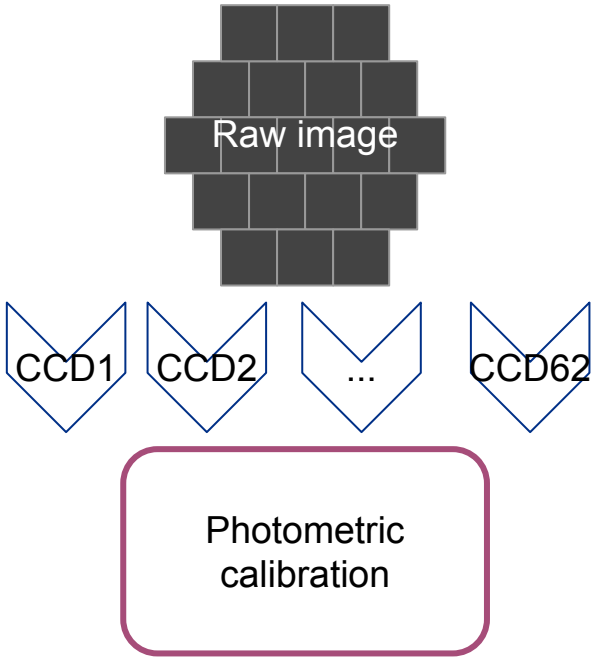

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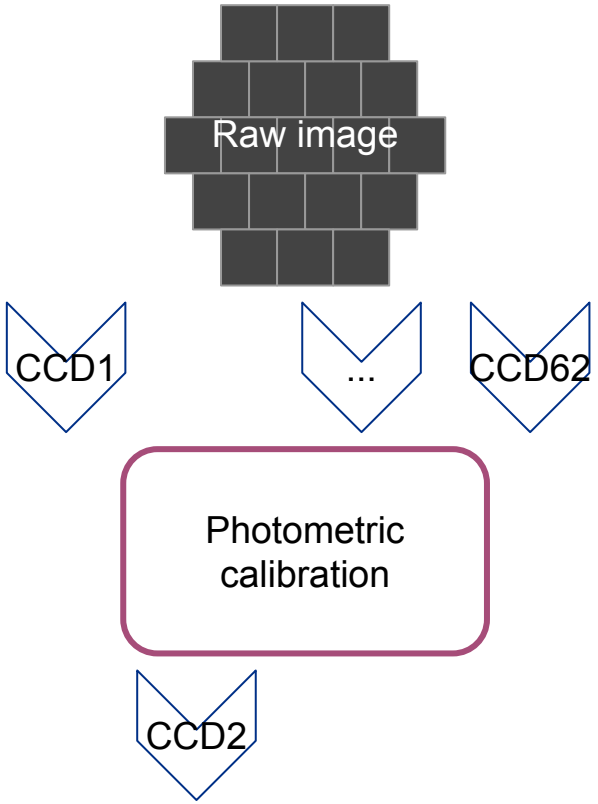

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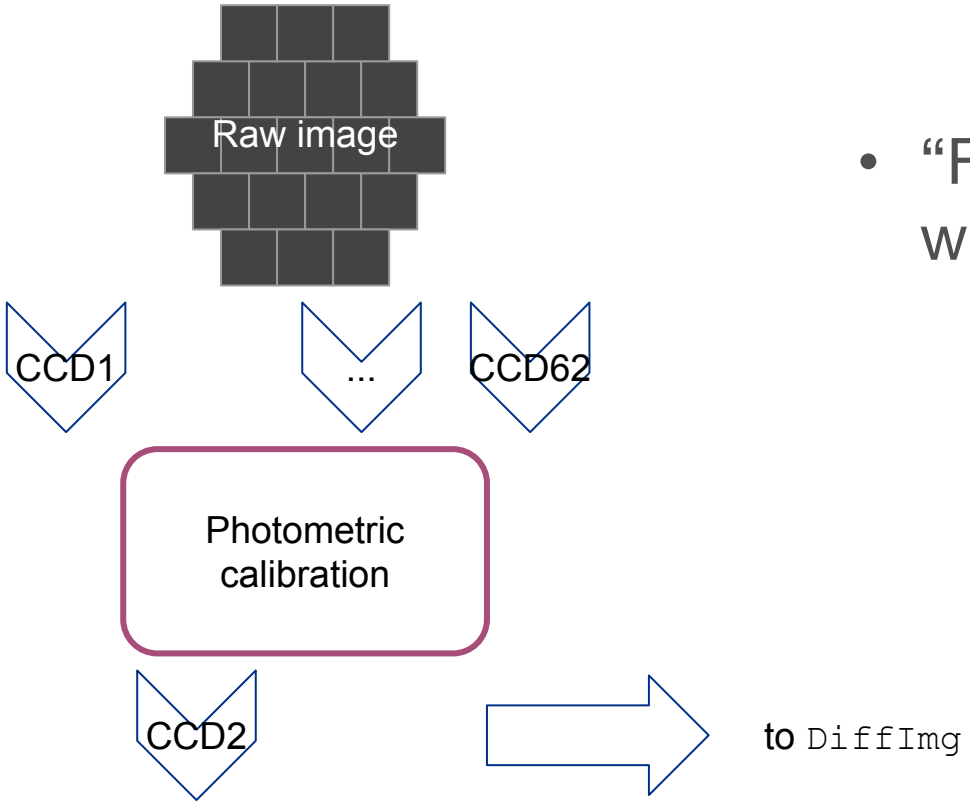

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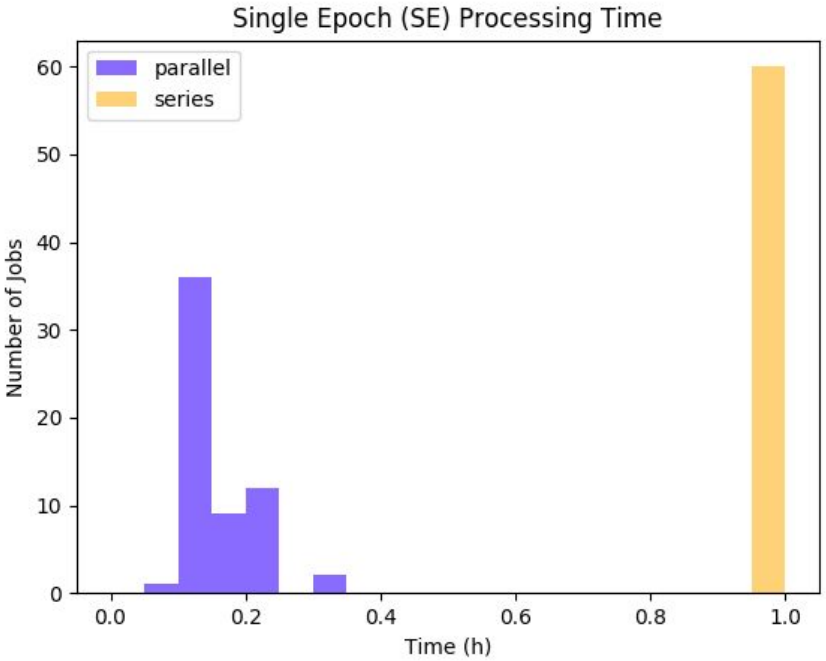
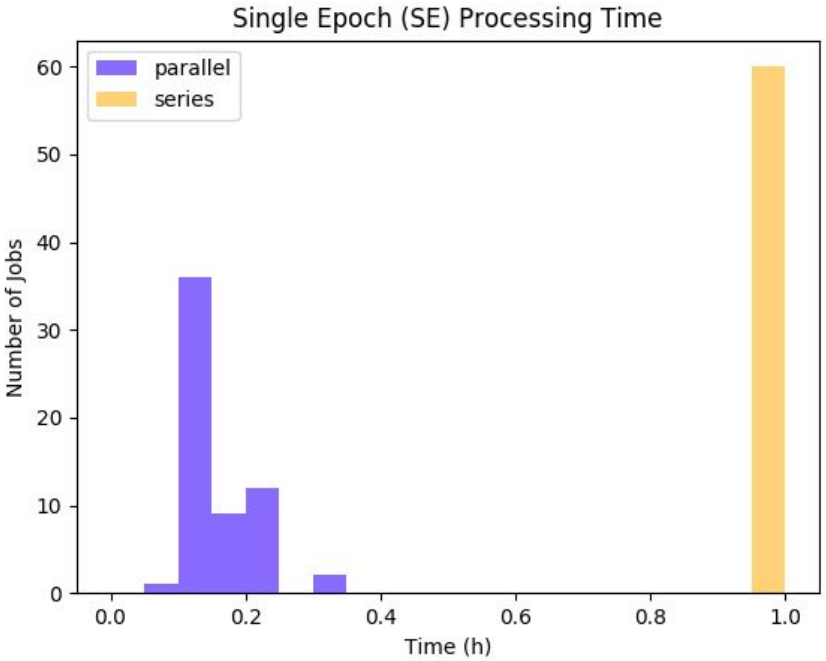


Single Epoch Parallelization Speedup (**series**: 0.9625 h; **parallel**: μ=0.15, median=0.13, σ=0.05)

- "Fast" CCDs don't have to wait for slower ones

Image Processing Pipeline: SE Modifications



Single Epoch Parallelization Speedup (**series**: 0.9625 h; **parallel**: μ=0.15, median=0.13, σ=0.05)

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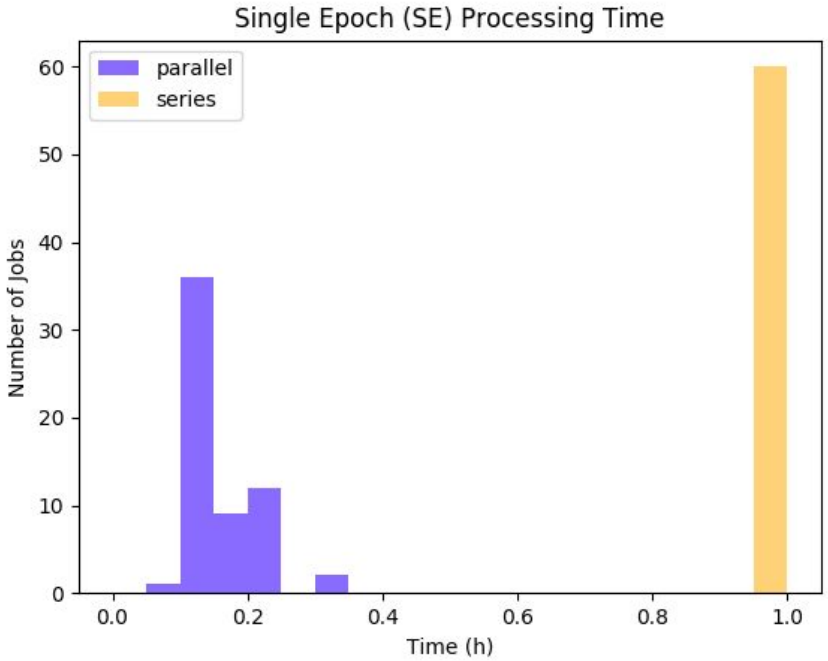
- But…

Image Processing Pipeline: SE Modifications



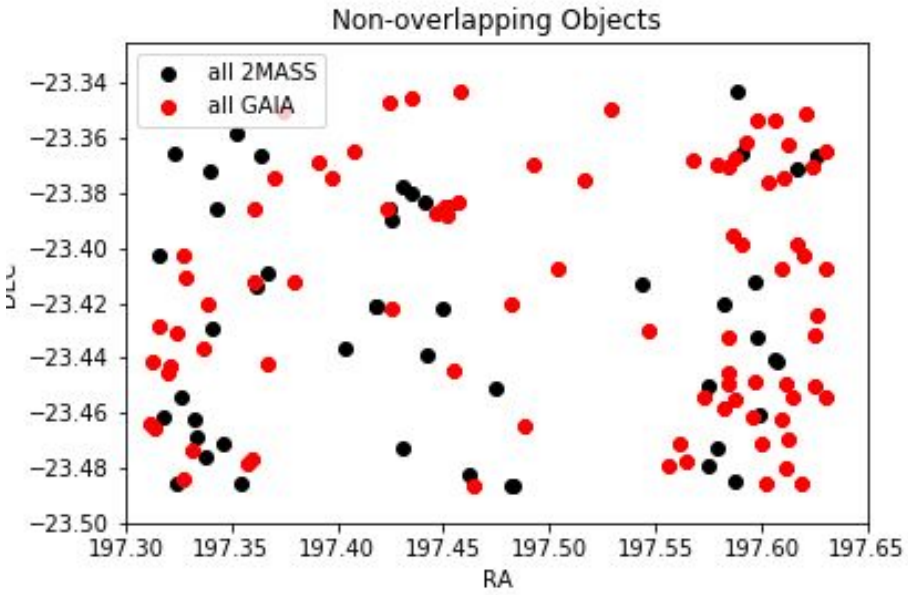
Single Epoch Parallelization Speedup (**series**: 0.9625 h; **parallel**: μ=0.15, median=0.13, σ=0.05)

- "Fast" CCDs don't have to wait for slower ones
- But…
  - do the results still make sense?
  - did we break something down the line?
  - Test on GW170817

Image Processing Pipeline: SE Modifications

- Run newly SE-processed images through DiffImg
  - Make sure we still identify the counterpart

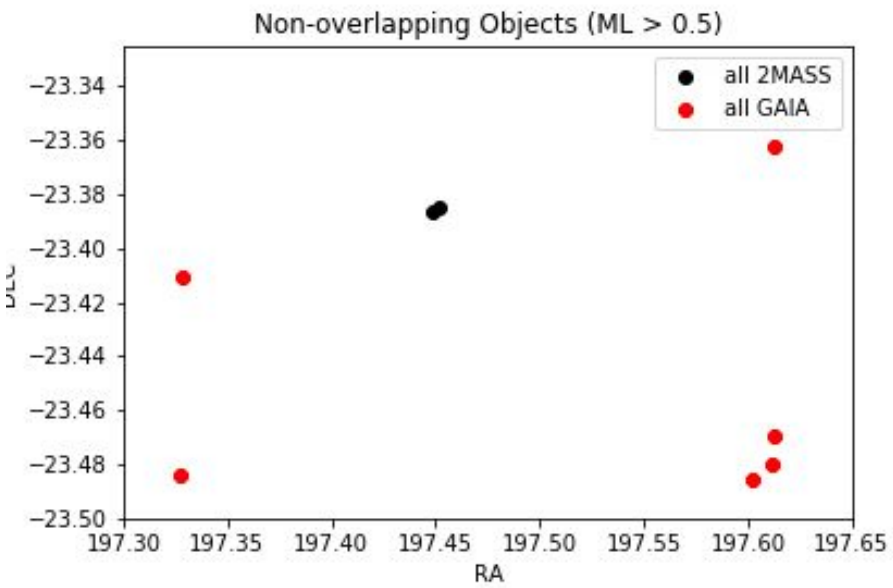
Image Processing Pipeline: SE Modifications



Non-matching candidates with **old SE (all 2MASS)** vs. **new SE (all GAIA)**

- Run newly SE-processed images through DiffImg
  - Make sure we still identify the counterpart
- 135 unmatched objects (45%)!

Image Processing Pipeline: SE Modifications



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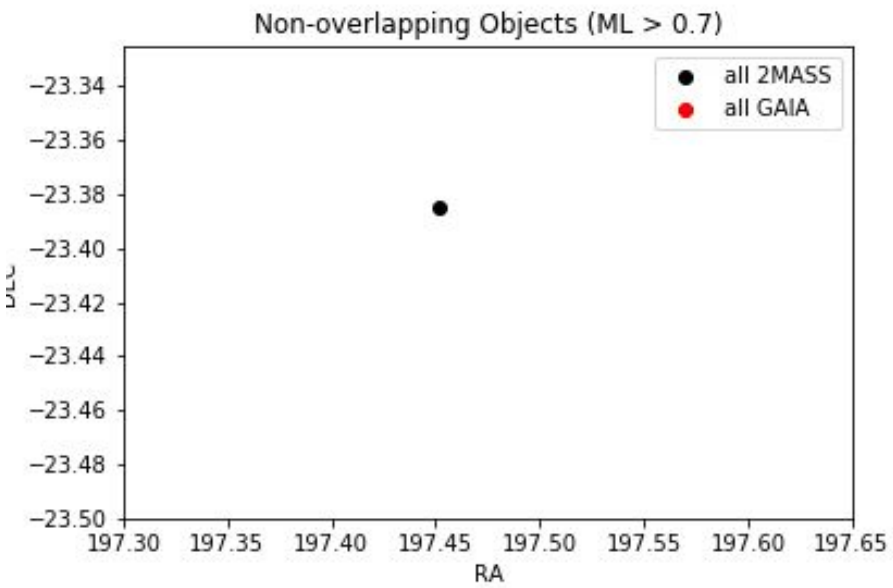

Non-matching candidates with **old SE (all 2MASS)** vs. **new SE (all GAIA)**

- Run newly SE-processed images through DiffImg
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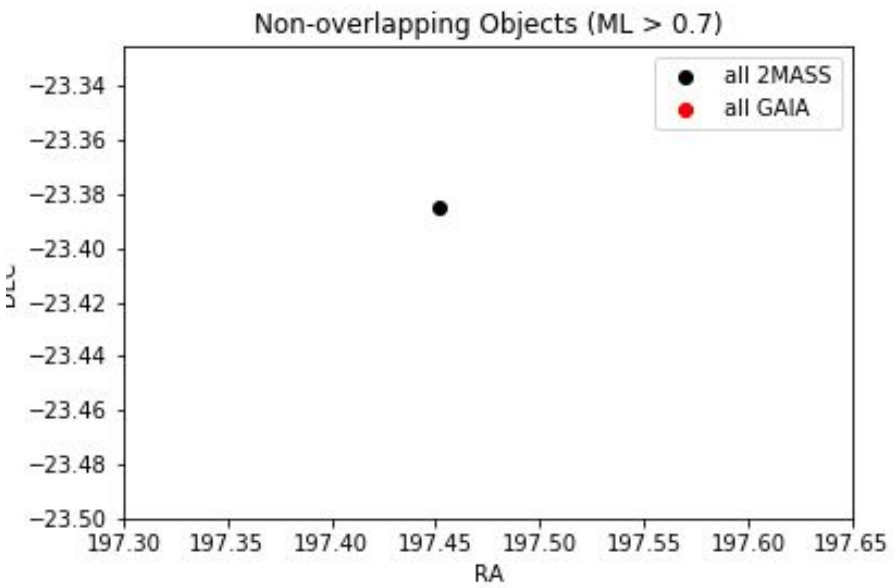
- 135 unmatched objects (45%)!
  - 8 with ML score > 0.5
  - 1 with ML score > 0.7 (ML=0.96)

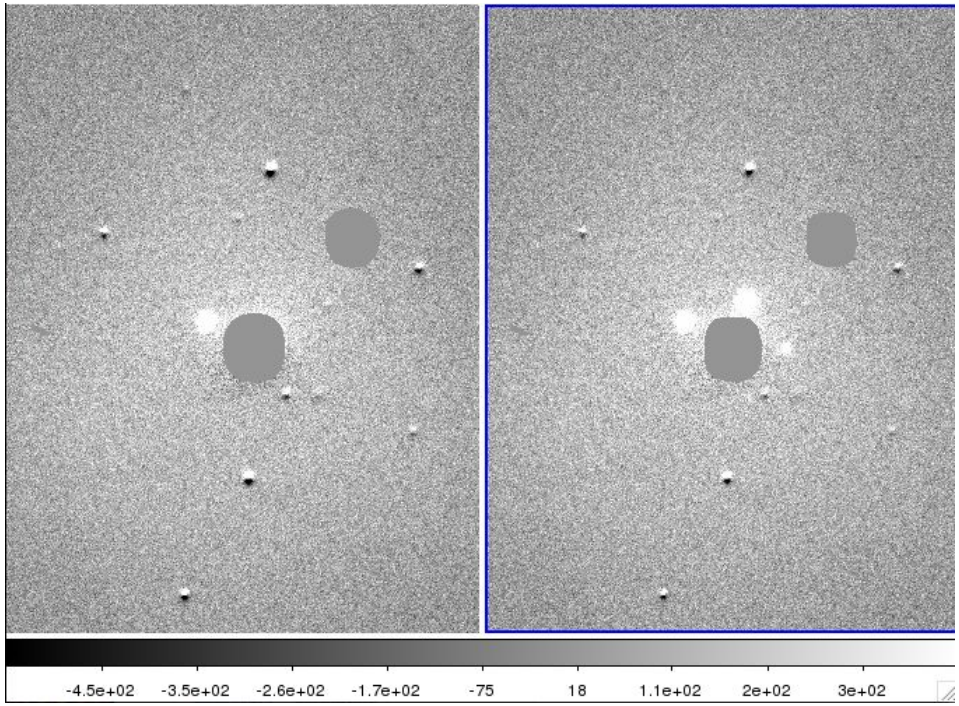
Image Processing Pipeline: SE Modifications



Non-matching candidates with **old SE (all 2MASS)** vs. **new SE (all GAIA)**

- Run newly SE-processed images through DiffImg
  - Make sure we still identify the counterpart
- Unmatched objects are mostly junk

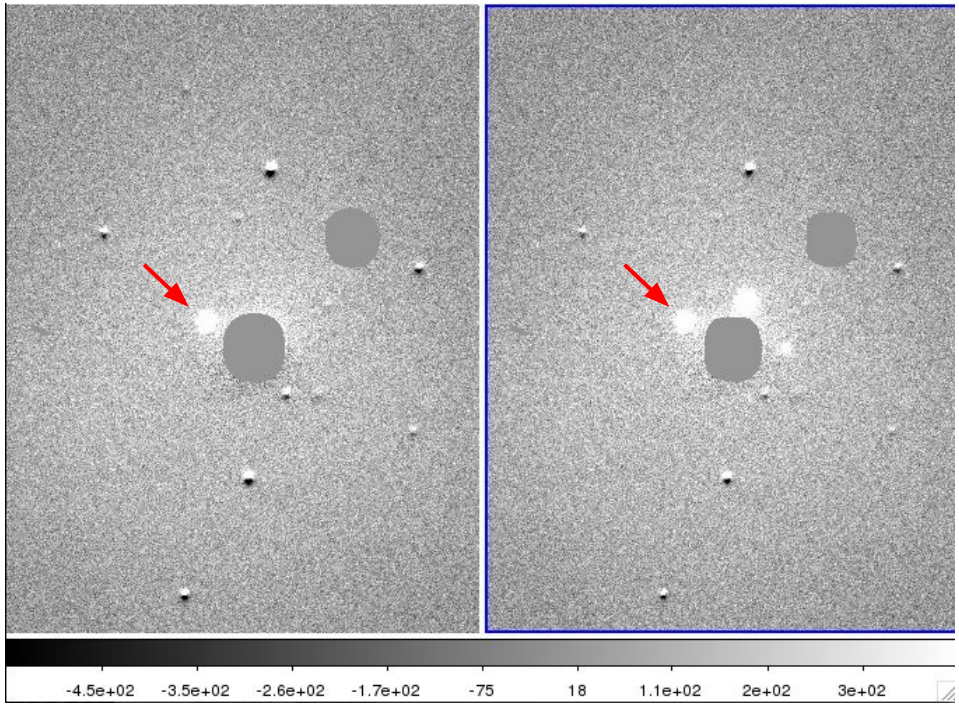
Image Processing Pipeline: SE Modifications



Difference images: new SE (left) vs. old SE (right)

- Run newly SE-processed images through DiffImg
  - Make sure we still identify the counterpart
- Unmatched objects are mostly junk
- Almost identical difference images

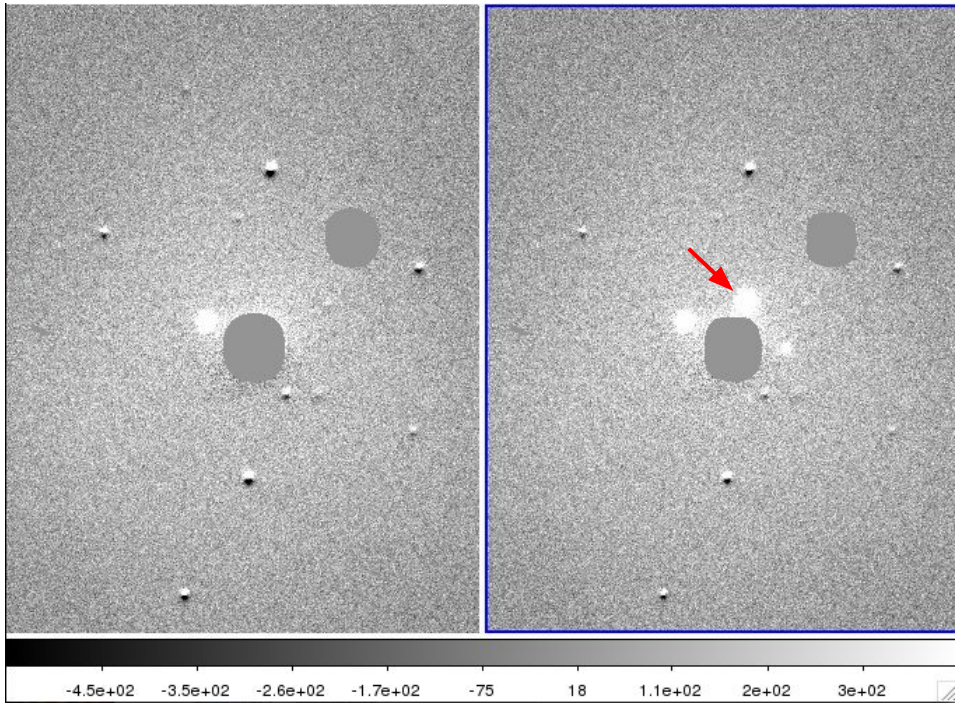
Image Processing Pipeline: SE Modifications



Difference images: new SE (left) vs. old SE (right) with counterpart

- Run newly SE-processed images through DiffImg
  - **Make sure we still identify the counterpart**
- Unmatched objects are mostly junk
- Almost identical difference images
  - Still found the counterpart!

Image Processing Pipeline: SE Modifications



Difference images: new SE (left) vs. old SE (right) with unmatched object (ML=0.96)

- Run newly SE-processed images through DiffImg
  - Make sure we still identify the counterpart
- Unmatched objects are mostly junk
- Almost identical difference images
  - ...Remember the lone unmatched object?

Next Steps

- **Both** search & template image calibration in parallel with GAIA (instead of 2MASS)
  - Understand the results
    - Was the 0.96 ML object an anomaly in camera pointing?
    - Why was it ultimately eliminated as a candidate?
- Integrate SE, verifySE, and DiffImg into one script
  - raw image → counterpart identification
- Test the full DES-GW pipeline in the mock observing run next week

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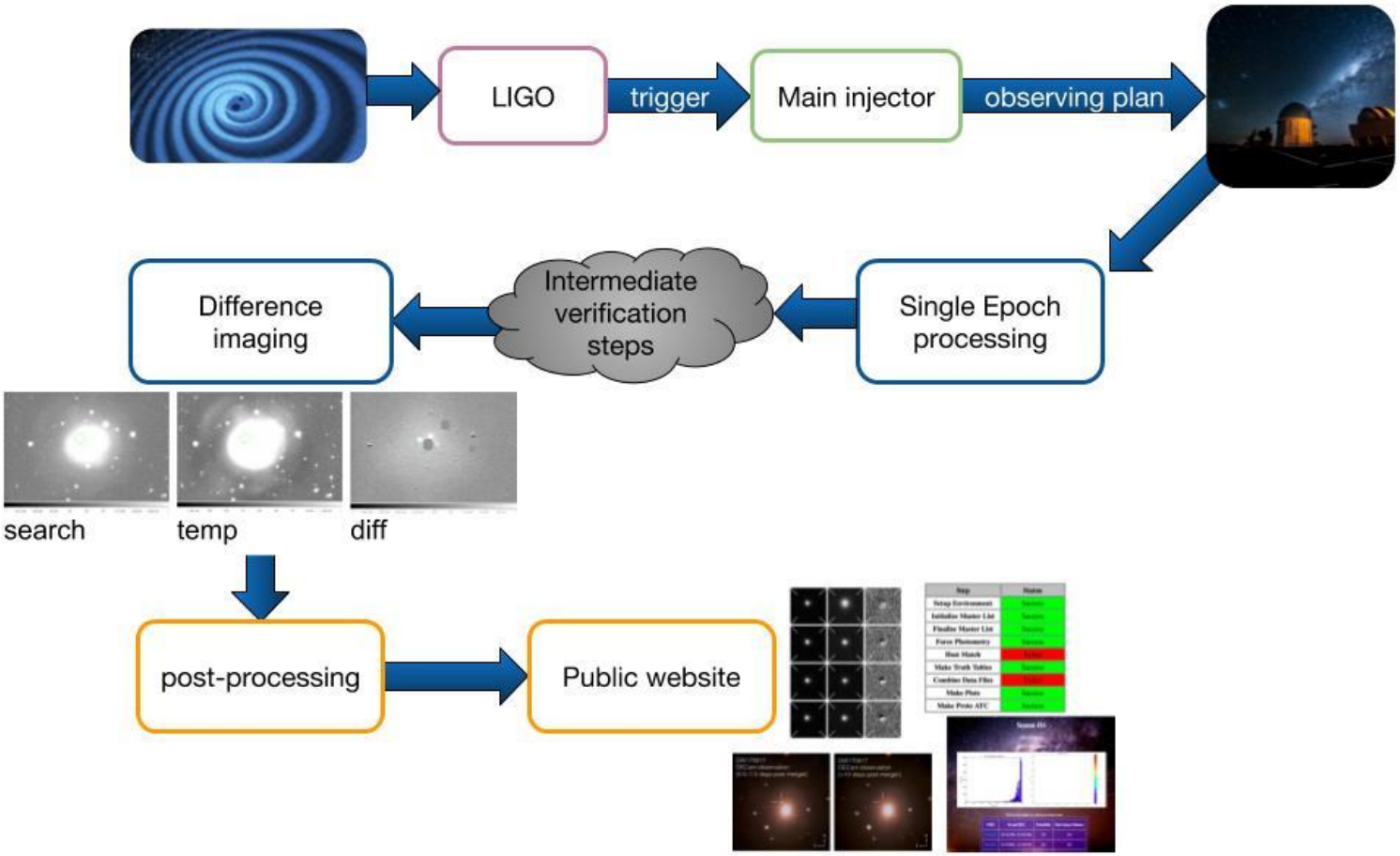
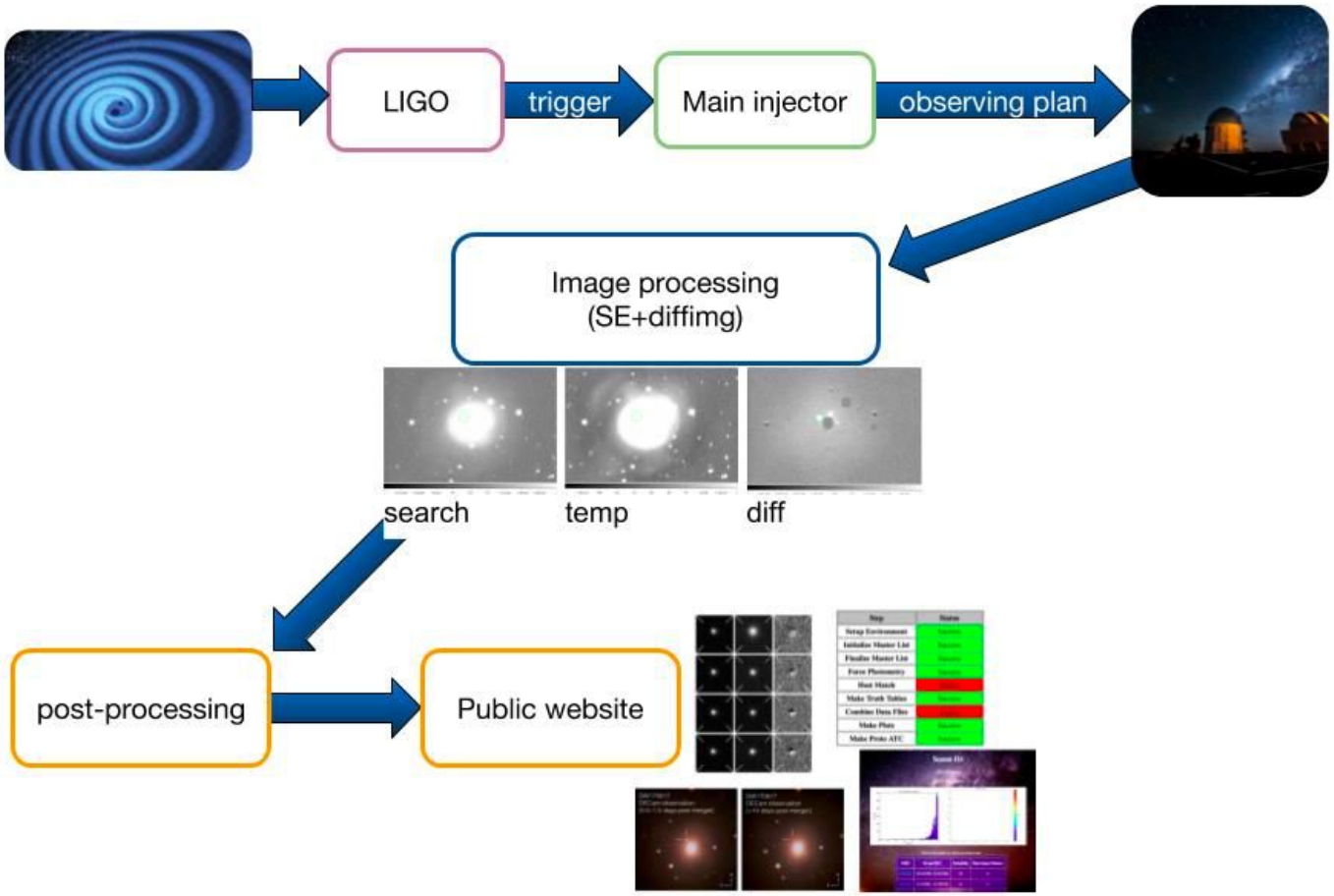
DES-GW Pipeline



Full Pipeline

DES-GW Pipeline



Full Pipeline

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Conclusion

- **Parallelization:** DES-GW image processing pipeline is faster without sacrificing accuracy
  - Allows us to discover counterpart ASAP, enabling detailed spectroscopic follow-up from the early stages of the kilonova
- **Integration:** Full process, from image capture to counterpart identification, is more streamlined

- The new pipeline will be employed by DES-GW in LIGO O3 in early 2019

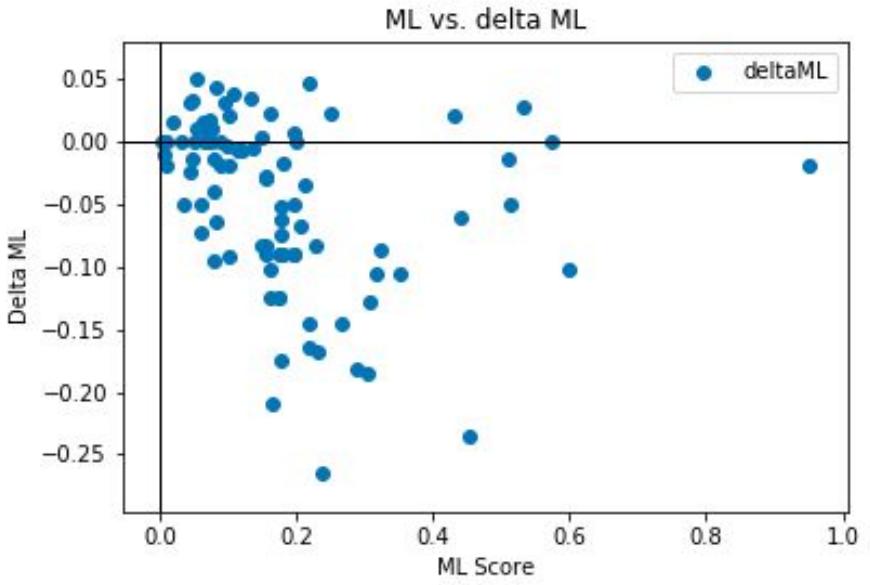
Acknowledgements

- The Department of Energy
- The SIST Committee & the Computing Division
- Ken Herner, Jim Annis, Marcelle Soares-Santos, and the remainder of the DES-GW group

Questions?

Backup

Image Processing Pipeline: SE Modifications



Plot of ΔML as a function of averaged ML score: mostly clustered around 0, but many negative values for low ML scores

- Run newly SE-processed images through DiffImg
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- Unmatched objects are mostly junk
- Similar machine learning (ML) scores

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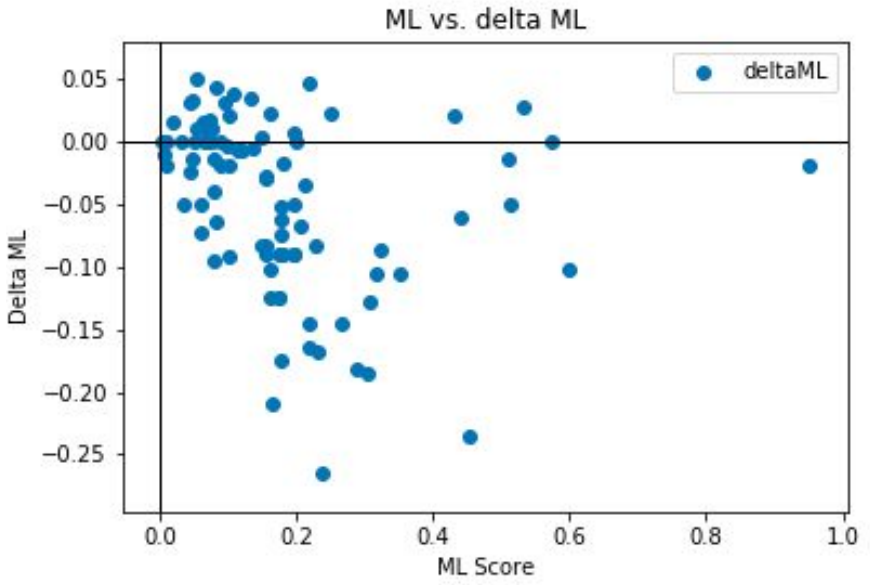

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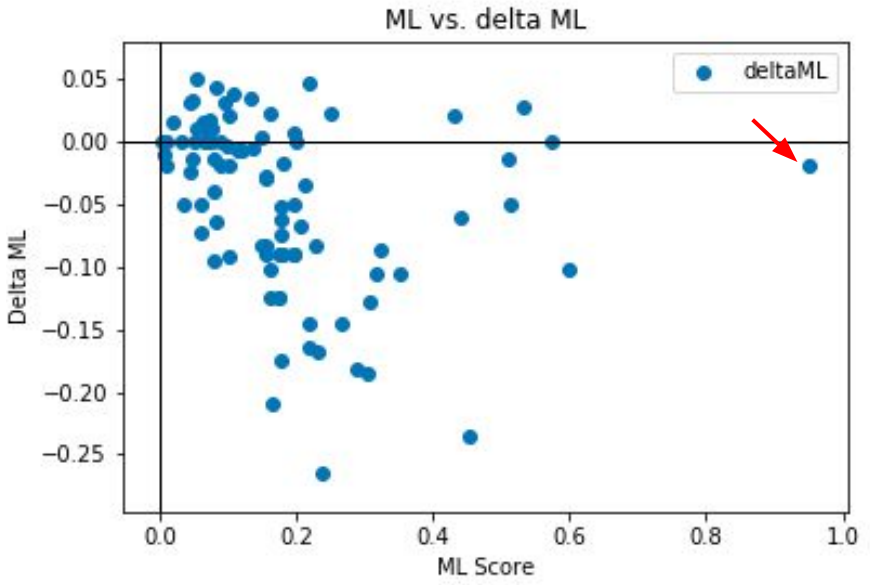

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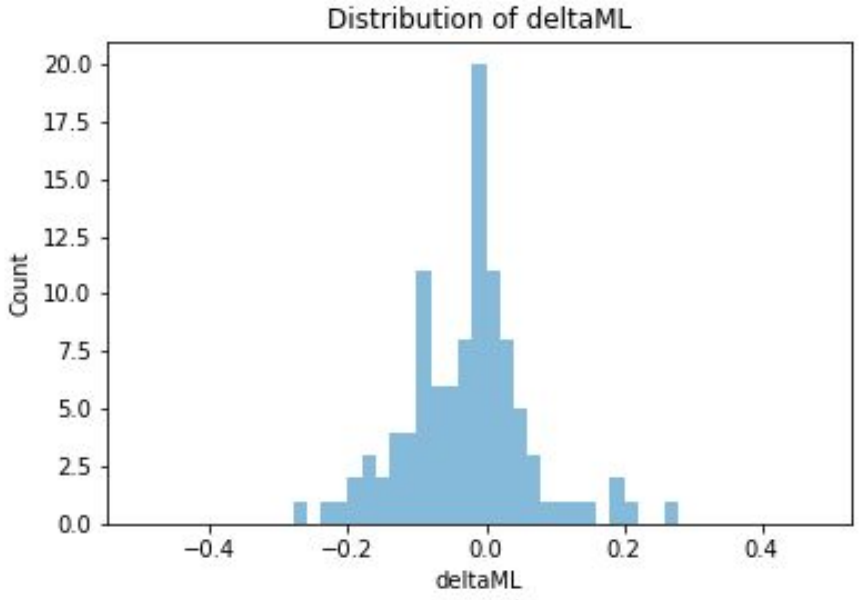
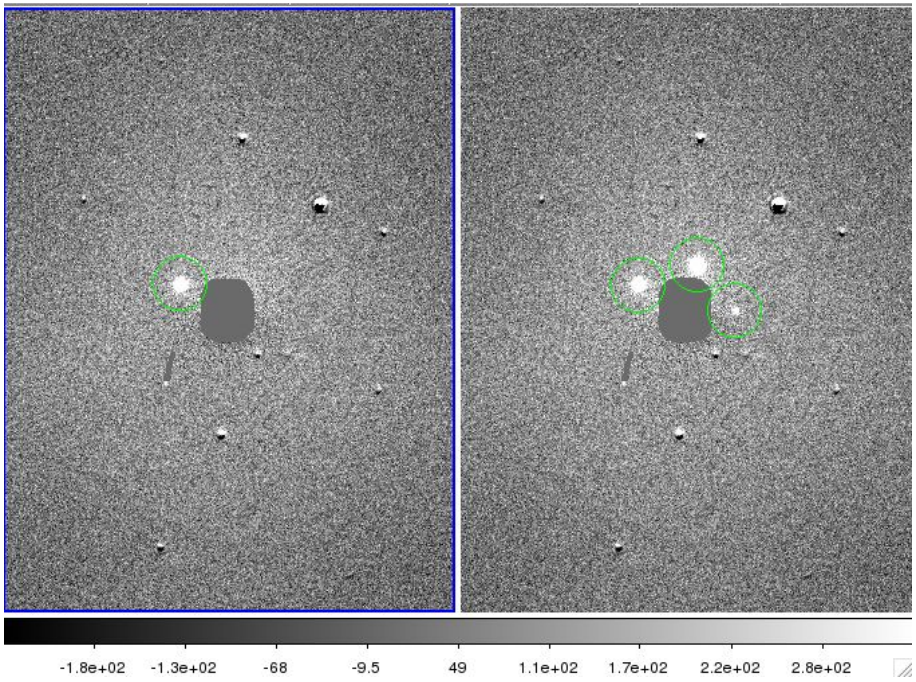


ΔML spread

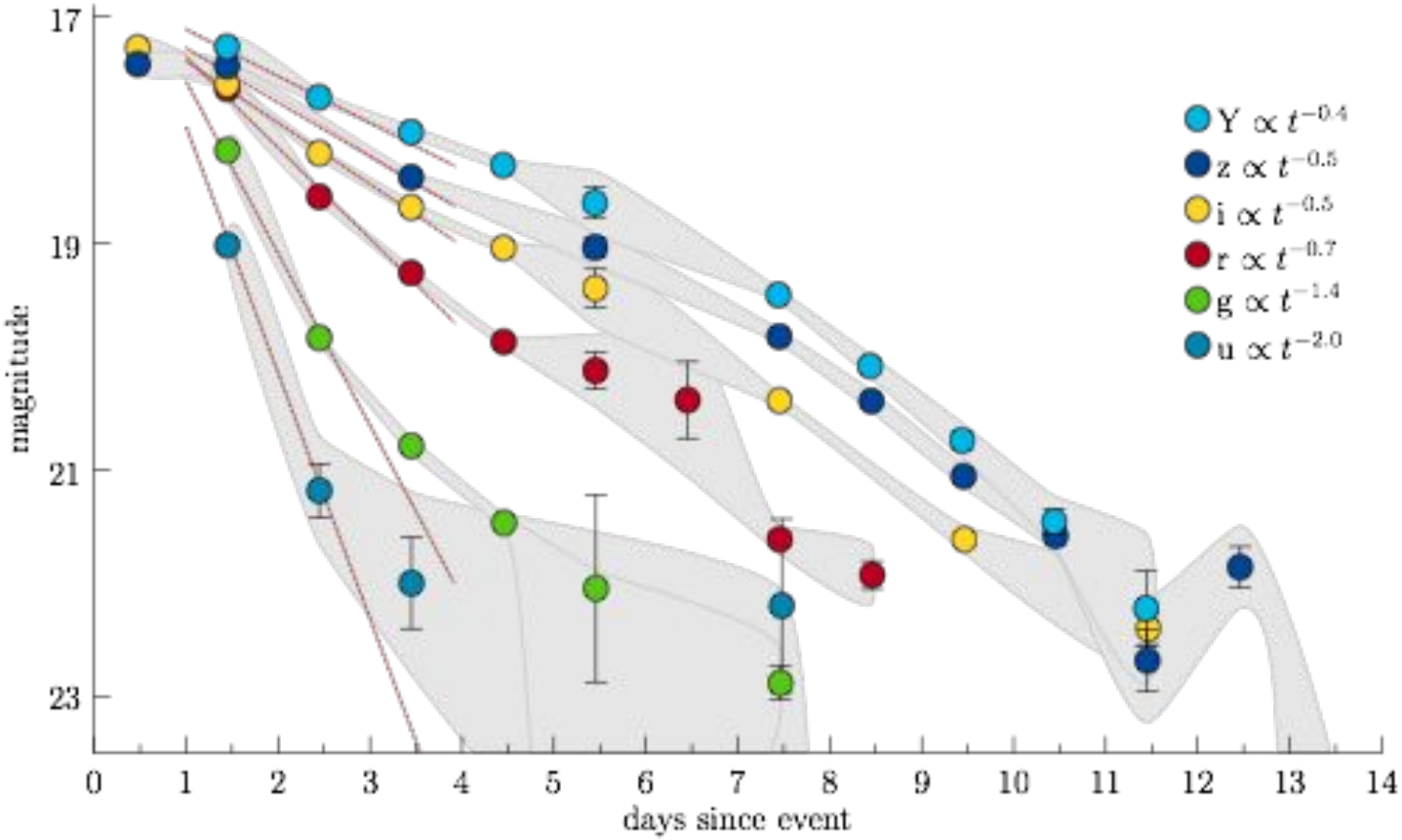
- Run newly SE-processed images through DiffImg
  - Make sure we still identify the counterpart
- Unmatched objects are mostly junk
- Similar machine learning (ML) scores
  - Left-skewed normal distribution

The Mysterious ML=0.96 Object



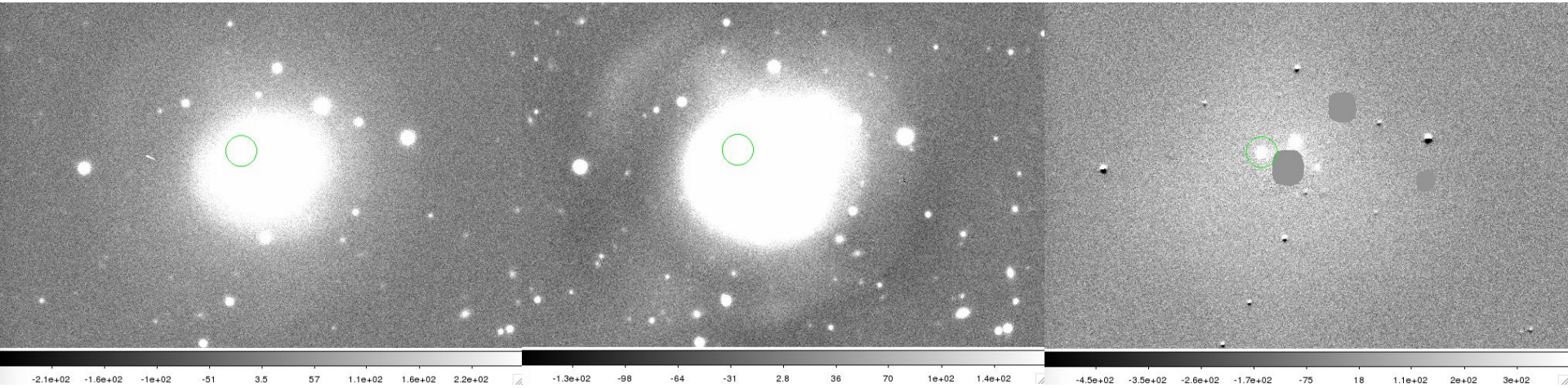
- Also found in the z-band

Kilonova Light Curve



Detailed spectroscopic follow-up of GW170817 counterpart. This shows the importance of fast counterpart identification, which is enabled by the new pipeline. (Soares-Santos et al.)

Search-Temp = Diff



Fermilab