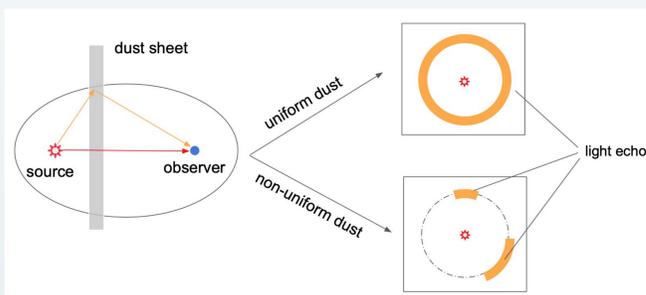


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## Light Echoes

Light Echoes (LEs) are the reflections of astrophysical transients on interstellar dust. They are fascinating astronomical phenomena that enable studies of the dust that reflects them as well as of the original transients, including supernova and variables stars.



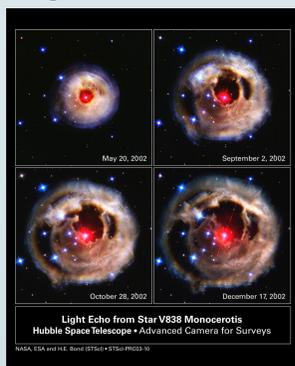
Geometry of the LE phenomenon (left) and its projection on the plane of the sky (right) in the case of a uniform sheet of dust (top), and of a non-uniform, "gappy" sheet (bottom). At each point in time for every transient there is an ellipsoidal surface with foci the earth and the transient. All points on the ellipsoid reflect light from the transient that arrive on earth at the same time and the ellipsoid itself expands over time. On the plane of the sky we see the cross-section of the reflection ellipsoid; this creates a morphologically complex, faint, time-evolving signal.

**To date, there is no automated way to detect LEs: they are detected by visual inspection. But modern astrophysical surveys can collect 10,000s images per night**

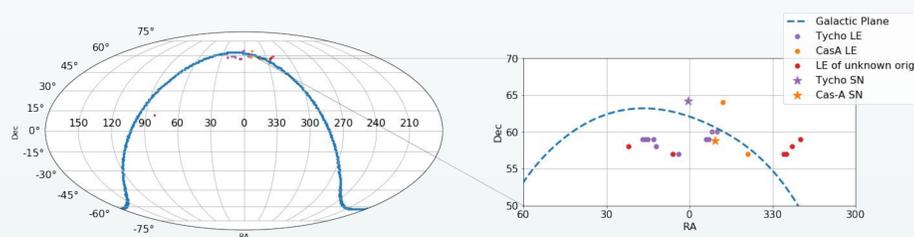
Challenges to automation:

- Morphologically Diverse
- Faint and diffusive
- Time-evolving

Extremely Rare  
 need to search in  
 huge data volumes

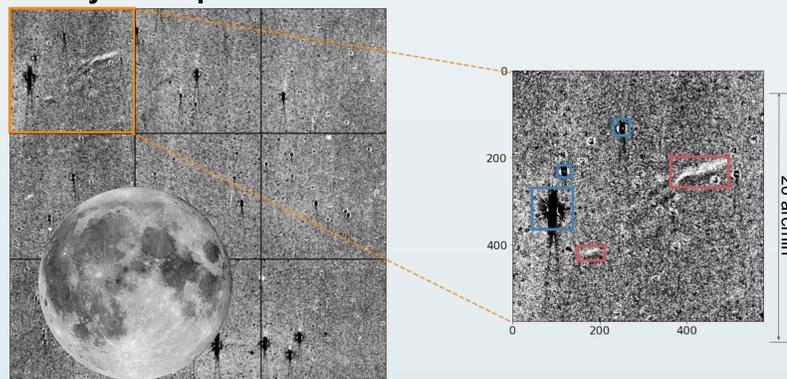


## Exploring the ATLAS dataset



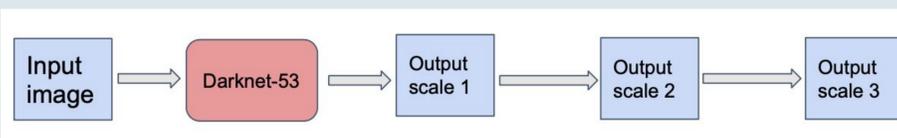
The sky positions of 19 LEs found by visual inspection of 40,000 images from the ATLAS sky survey. They are the reflection of light from ancient stellar explosions (Tycho SN, CasA). LEs are preferentially found in high-dust content regions, such as near the Galactic plane.

## Binary class prediction: LE or star?



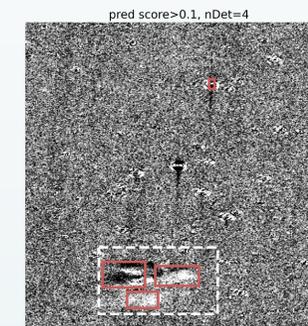
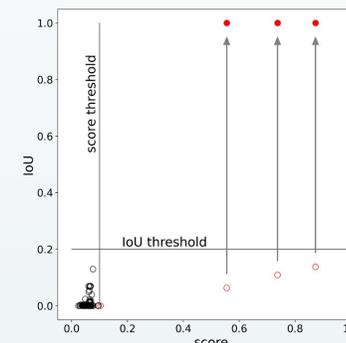
An example of a template-subtracted image from the ATLAS survey. we split each ATLAS image into 9 tiles and select only the tiles that contains LEs. The top-left tile of this image that contains a LE is marked by an orange frame and reproduced to the right with boxes corresponding to saturated stars and LEs shown in blue and red respectively. The Moon is overlaid on the image for comparison.

## Model



Architecture of YOLOv3. **YOLO** is a one-stage object detection framework. Images are passed into a single deep neural network model to detect and classify objects at once (bounding box regression and prediction).

## Modification to YOLO to enable detection of LEs



Traditional of IoU loss need to be modified because the boundaries of the LEs are poorly defined

$$mIoU = \begin{cases} 1 & \text{if predicted boxes are inside labeled boxes} \\ IoU & \text{otherwise} \end{cases}$$

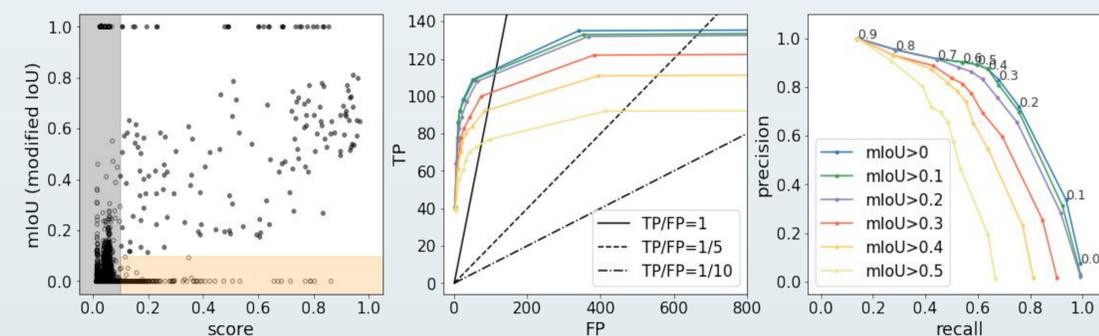
$$IoU = \frac{A \cap B}{A \cup B}$$

## Results

- True Positives (TP):
- class predicted predicted a P above threshold (*score*)
  - overlap of predicted and label box above threshold (*mIoU*);

$$Precision = \frac{TP}{TP + FP}$$

$$Recall = \frac{TP}{TP + FN}$$



Results from YOLOv3 for LE detection on the test set.

The left panel shows a scatter plot of classification *score* vs. *mIoU*. The grey regions in the left plots delimit the region of rejected predictions (below a *score* threshold of 0.1) and the orange regions represent the location where false positives are found (*IoU* or *mIoU* smaller than 0.2).

The middle panels show ROC and the right panels show PR curves. The ROC and PR are plotted for different *score* thresholds (points along each curve) and different *IoU* or *mIoU* (as labeled). Three black lines indicate TP/FP=1/1, 1/5 and 1/10. **~70% recall is achieved at a precision of ~80% at score=0.3** but only if we choose *mIoU* > 0.1. This means that we have to tolerate a 20% percent false positives rate to detect 70% LEs. But remember: **our training set only contains 19 examples.**

As these results are obtain with an extremely small size of 19 LE examples (augmented to 240), this study is a pathfinder to automated detection of light echoes in upcoming sky surveys that will collect millions of images.

## References

Chan, M. C., & Stott, J. P. 2019; Girshick, R. 2015; He, K., Zhang, X., Ren, S., & Sun, J. 2016; Armin, R, et al. 2008; LeCun, Y., Bengio, Y., & Hinton, G. 2015; Redmon, J., & Farhadi, A. 2018.