

Strong Lensing with Rubin

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LSST:UK SL POC

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SL in the Rubin/SC ecosystem



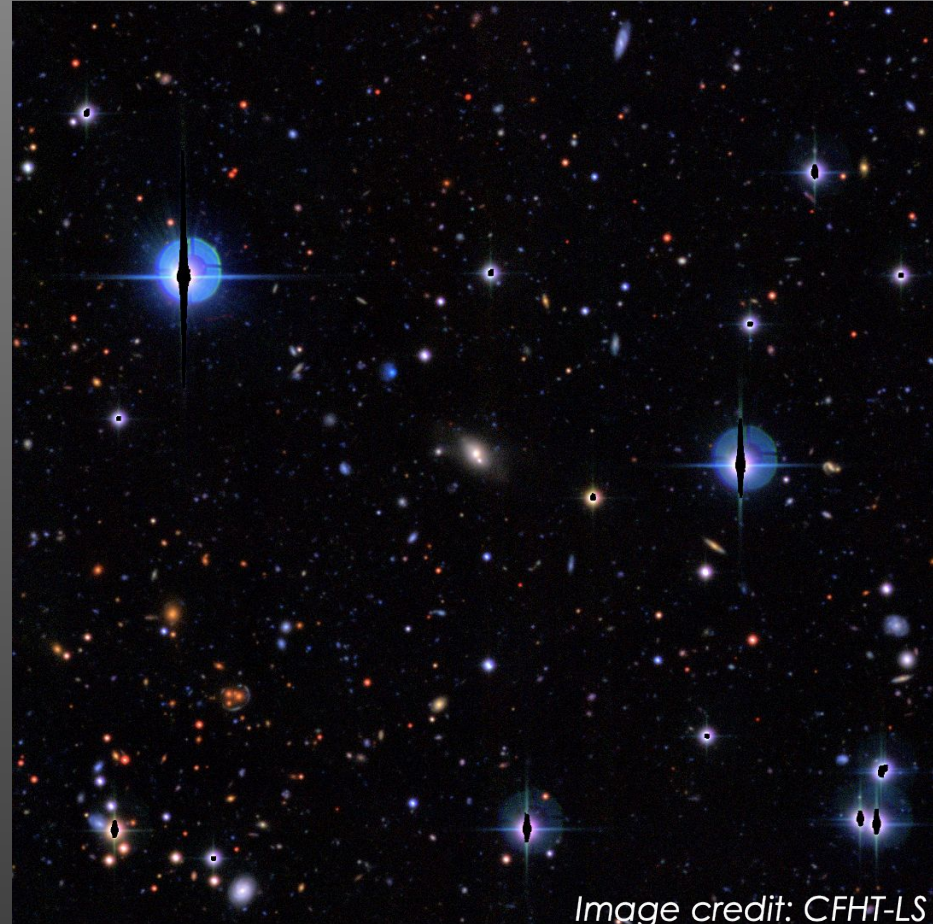
Strong Lenses are rare!

- 1 in 10^4 massive galaxies capable of being a lens
- Only ~thousand known to date in 40y

Rubin will be transformational in all aspects of strong lensing science

Expectations (OM10; Goldstein+17,18)

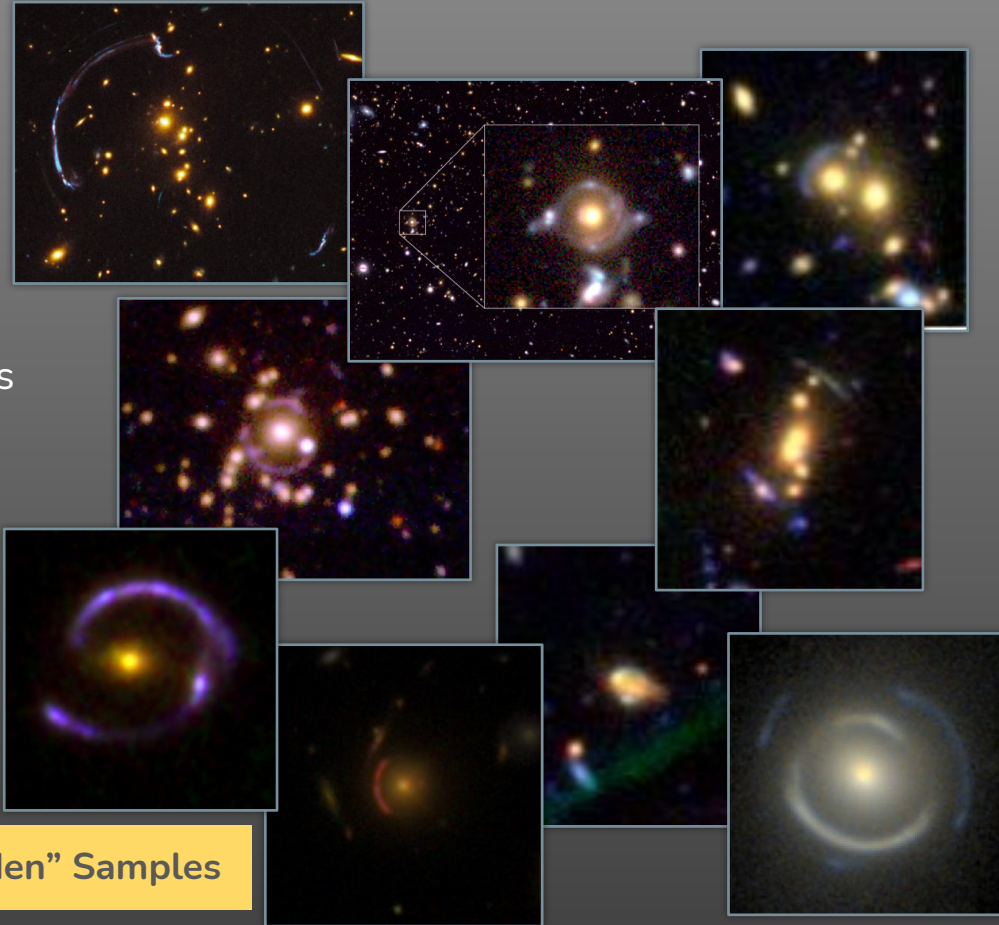
- 1000s lensed AGN
- 10^{4-5} galaxy-scale & galaxy-group-scale lenses
- 1000s of lensing clusters
- 100s of lensed SNe...
- 100 double source plane lenses



Example Science Drivers

- **Weighing galaxies:** Galaxy Mass and structure of 10^{4-5} lenses
- **Cosmography:** Lensed QSO, SNe & transients, double source plane lenses - **DESC-SLWG**
- **Calibrating the cluster mass function:** SL+WL constraints on DM in 100 clusters
- **Quasar microlensing:** accretion disk structure of 1000 lensed AGN + IMF of lensing galaxies
- **Cosmic Telescopes:** Hi-res properties of high-redshift galaxies
- **Rare and Exotic lenses**
- *many more...*

Large samples: Statistical studies - Select “Golden” Samples



Discovery

- Rarity (1 in 10^4), complex morphologies, high FPR
- Work towards build multi-method discovery system including ML algorithms, visual inspection (CS/EPO) & fast modelling

Modelling

- Fast (ML-assisted) modelling methods development

Observing strategy considerations

- Good seeing in the blue, Early Reference Survey, ToO, longer seasons (non-rolling cadences)

Commissioning and Early Science (G. Smith's talk)

DM considerations

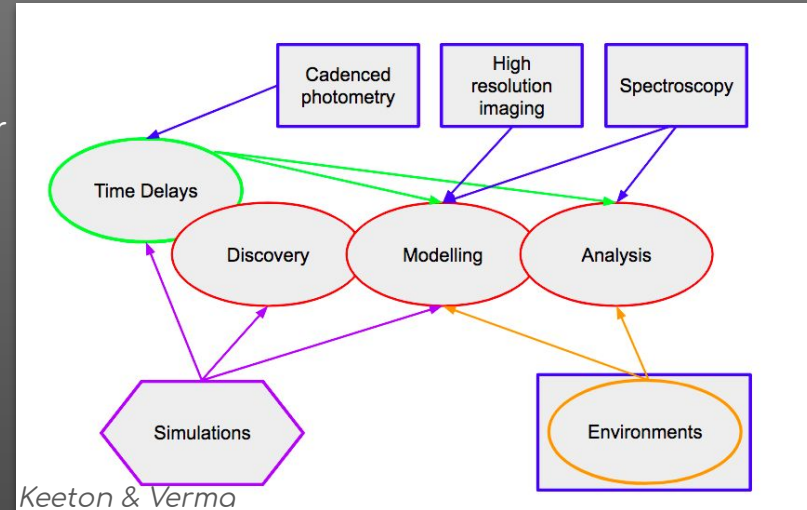
- SL queries to DM (Jim Bosch): ongoing, pixel level data, high image quality stacks, deblending, photometry (phot-z, lens/source parameters) ... A. Watkins, P Hatfield talks

Synergies with Euclid - SL DDPs (T. Collett - Thursday session)

Science Roadmap Tasks

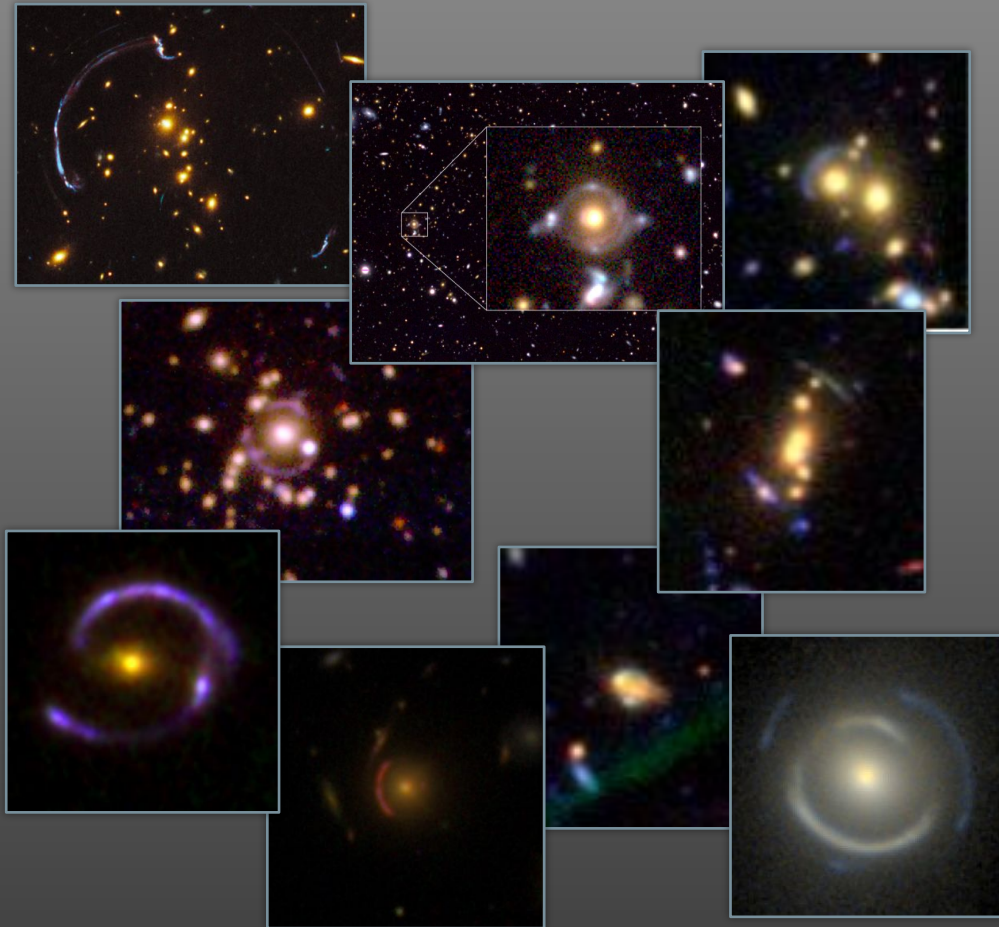
- Strategy, in-kind contributions

Follow-up requirements and strategies



Discovery is a challenge!

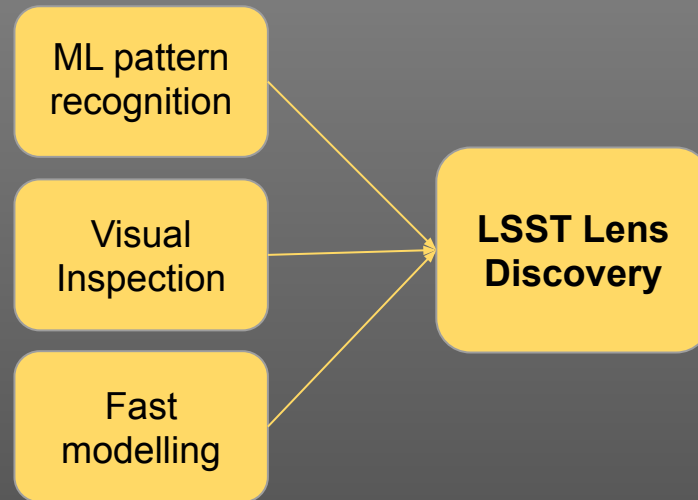
- ★ **Rare:** Only 1 in 10^4 galaxies are strong lenses ($\sim 1 \text{ deg}^{-2}$)
- ★ Lenses are **complex** and **varied** systems
- ★ No single method is complete
- ★ High ($\sim 10^{1-3}:1$) ML FPR **requiring human visual inspection**
 - **Unsustainable** in the next era of sensitive, wide area surveys
- ★ Large scale “optimal” lens finding strategies are undetermined and untested on such a large, sensitive & time resolved datasets



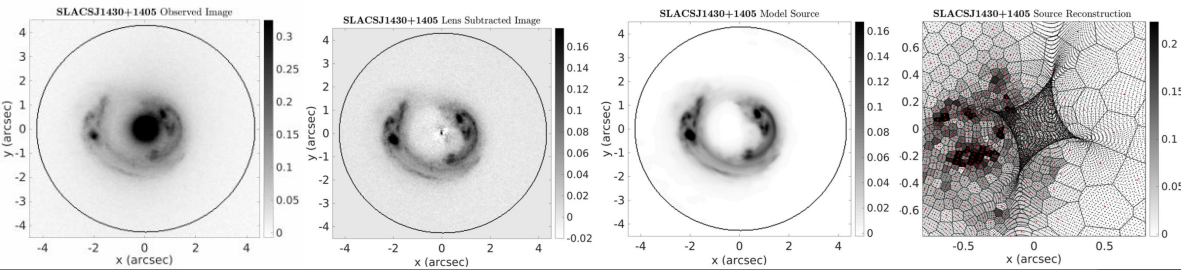
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- Multi-method approach



- ML alone TP:FP 1:tens
- Intermediate goal reduce TP:FP ML 1 : few-ten
- Longer-term goal: ML TP:FP 1 : 1



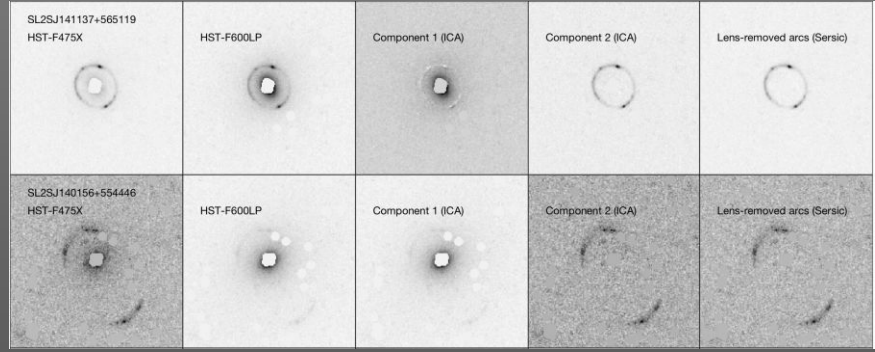
Fast Lens Modelling

UK leadership
Synergy with Euclid

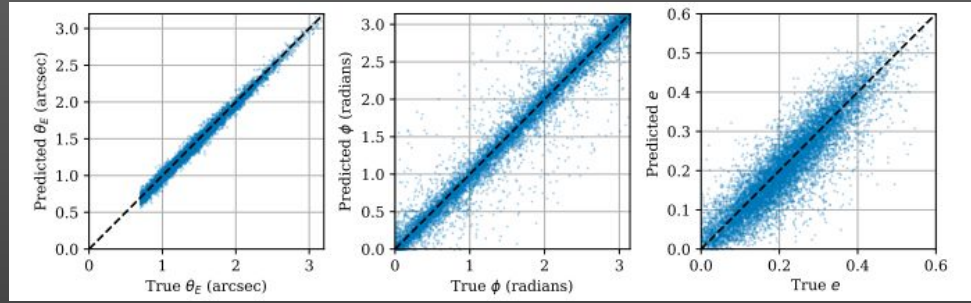
(Py)AutoLens - *Nightingale et al. 15, 18, 21*

Reduce FPR by folding fast modelling into lens discovery

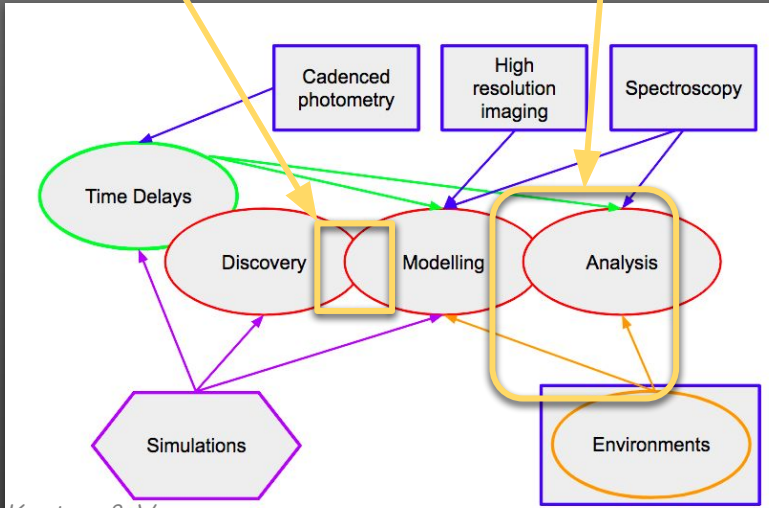
Detailed modelling still required (outliers and improved analysis)



Hezaveh, Perreault-Levasseur, Marshall Nature 2017



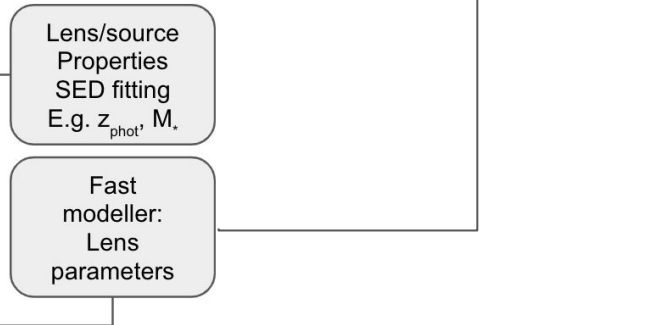
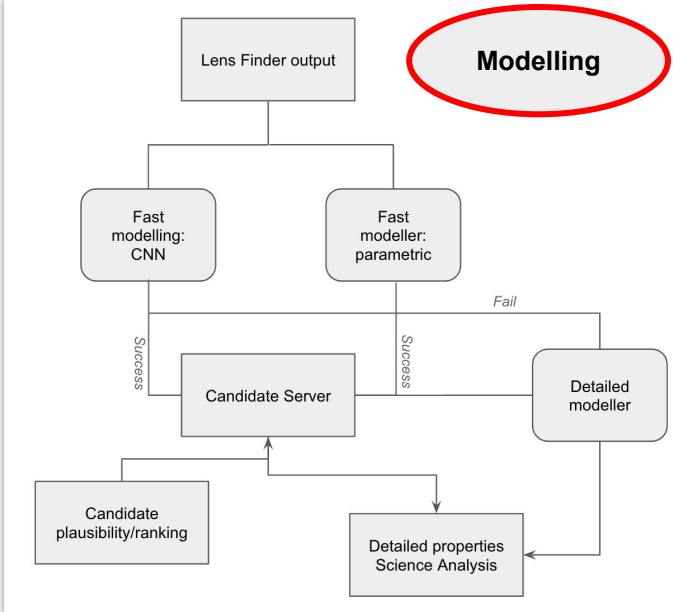
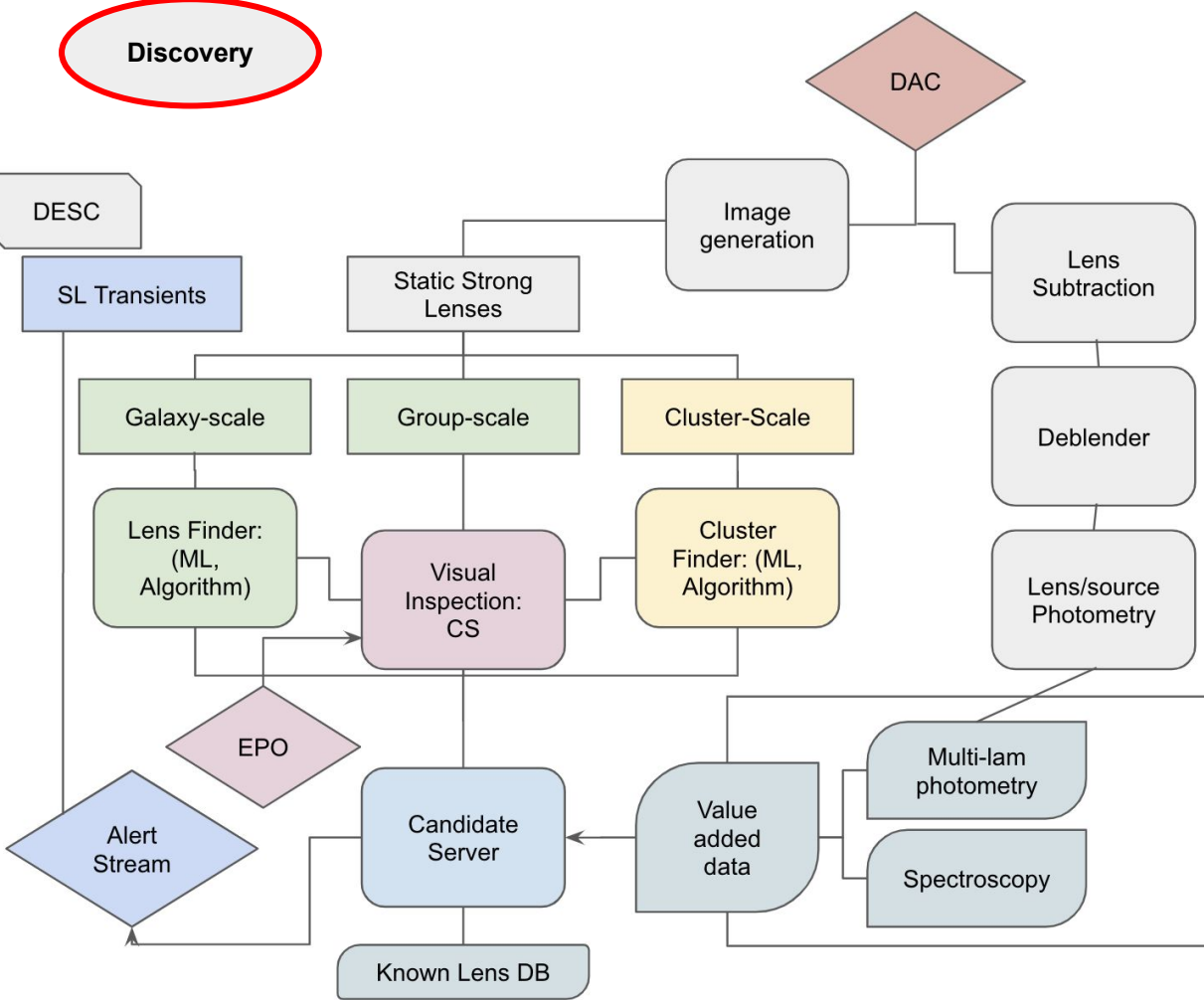
Pearson, Li, Dye 2019



Keeton & Verma

Discovery

Modelling



Verma - SLSC Roadmap schematics

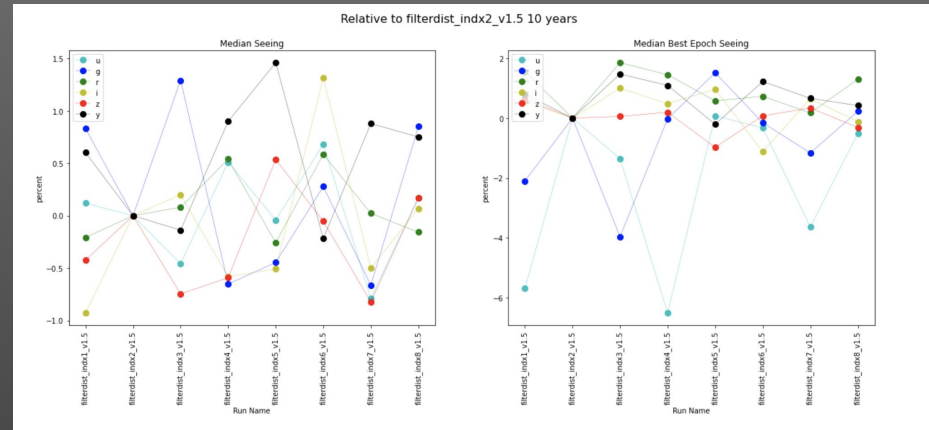
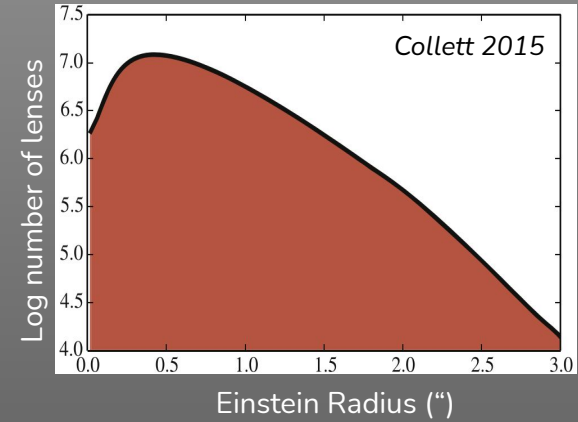
★ Requirements for general strong lens discovery *Verma, Collett+ arXiv:1902.05141*

- Wide area with reasonable sensitivity in all bands (increases sample size) - early reference survey
- Good image quality (to discern lensed images from lenses, better R_{ein} sampling, accurate image positions, majority have low R_{ein})
- Blue sensitivity (detect typically blue SFGs)
 - Good “blue”/g-band seeing

★ Strongly Lensed Gravitational Wave events *Smith+ arXiv:1902.05140*

- ToO modes & early reference survey

Theoretical Einstein Radius distribution



Early Science - much can be achieved with ERS/Y1

Anguita, Verma, Collett et al. 2021

Lens model Predict the delays

$$t = \frac{1}{c} \frac{D_d D_s}{D_{ds}} (1 + z_d) \left[\frac{1}{2} (\Theta - \beta)^2 - \psi(\Theta) \right]$$

$1/H_0$

Image position
Astrometry

Source position

Lens potential

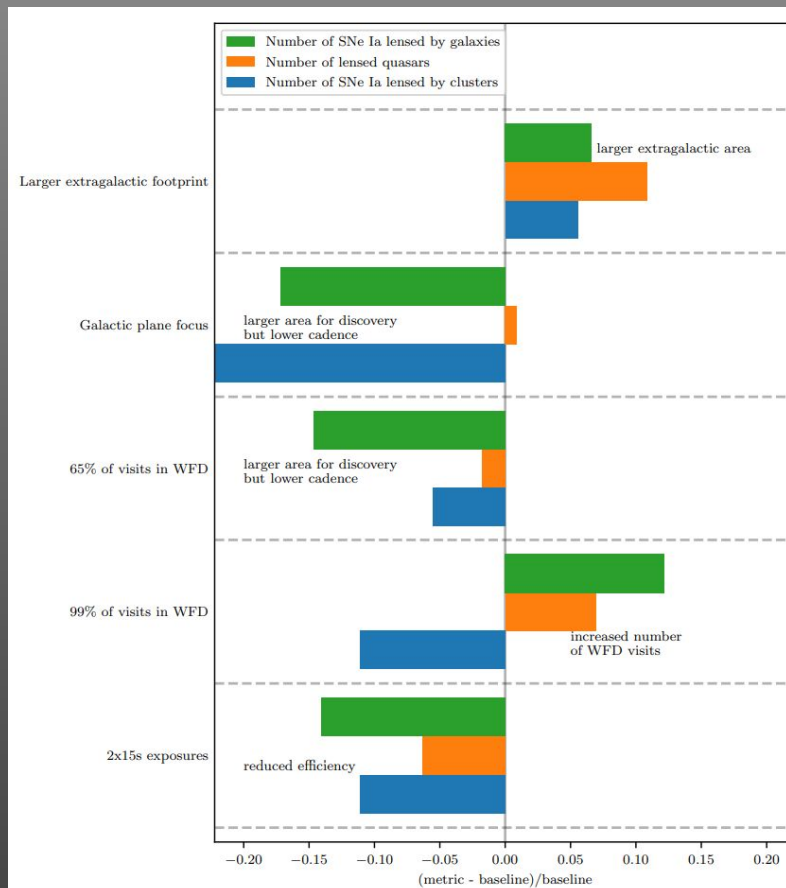
Long cumulative season length

Improved sampling frequency (cadence)

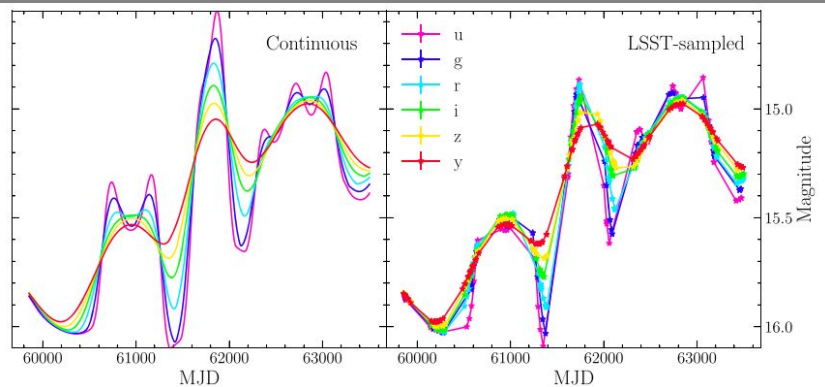
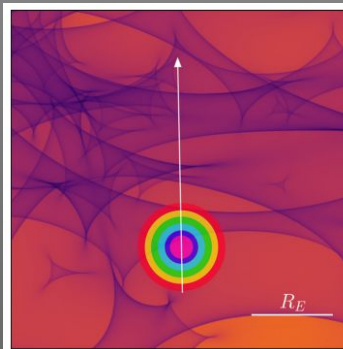
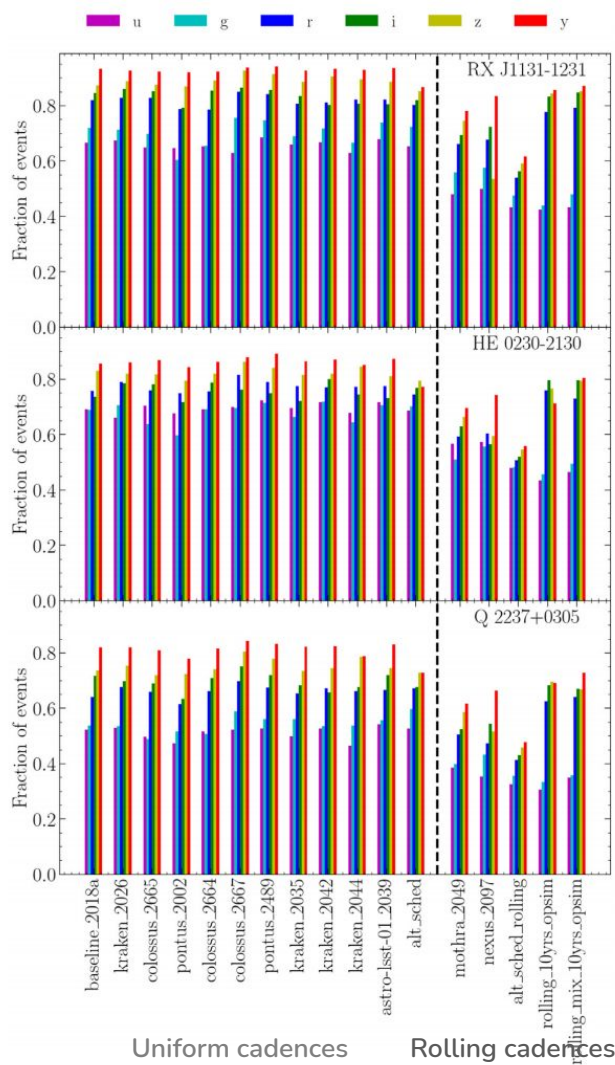
Rolling cadences disfavoured (Huber+ 19)

Different filters same night revisits, single snaps,
increase area golden “lensed quasars”

Time Delay Constraints



Microlensing Constraints



~300 high magnification events with $\Delta\text{mag} > 1$ mag could potentially be observed by LSST p.a.

Select high mag events from simulated LSST light curves

Rolling cadences generally worse

Need Rubin's alert stream to trigger monitoring for high magnification events

Neira, Anquita & Vernardos, 2020

Summary

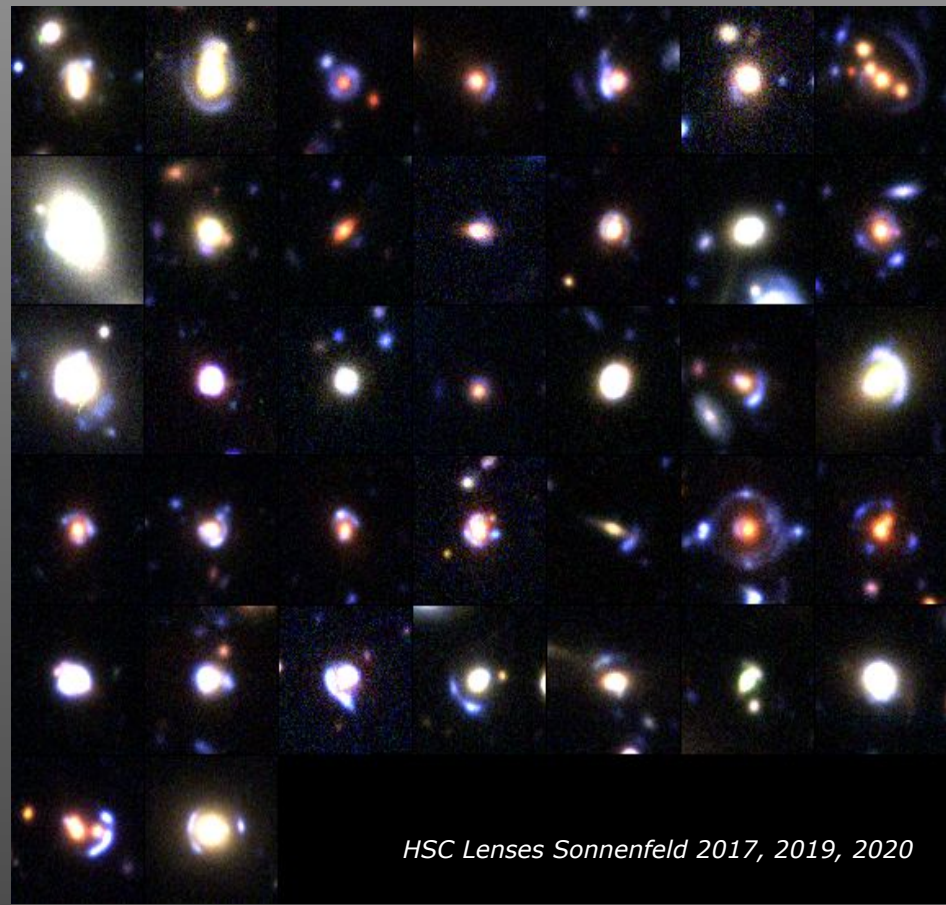
- Discovery and modelling challenges
- Infrastructure to deliver SL candidates, connect to the alert stream and analysis
- Commissioning and early science planning
- Develop objectives with DM - best seeing images, deblending, photometry, photo-z...
- Develop stronger inter SC connections, synergies with external surveys
- Science analysis requirements and s/w development

Join us!

Anyone (at any career stage) with interests related to strong lensing enabled science is welcome to join. No minimum requirement.

<https://sites.google.com/view/lsst-stronglensing>

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LSST:UK PoC for SL: aprajita.verma@physics.ox.ac.uk



HSC Lenses Sonnenfeld 2017, 2019, 2020