Stockholm University

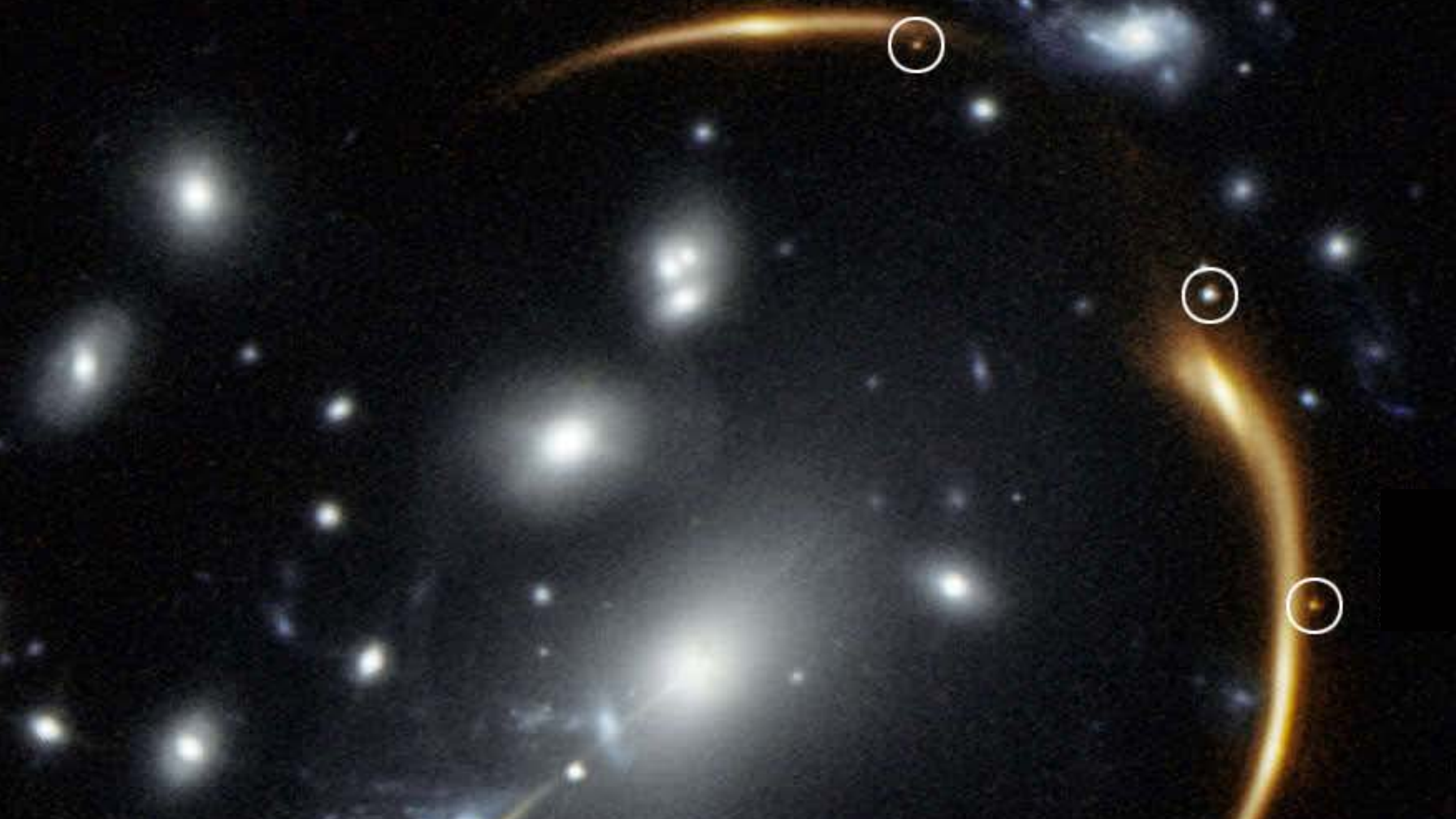
Kavli Focus Meeting | 27th of March 2023

Oskar Klein centre

Gravitationally lensed supernovae in the Rubin era

NIKKI ARENDSE

Collaborators: Suhail Dhawan, Hiranya Peiris, Ariel Goobar, Edvard Mörtsell, Ana Sagués Carracedo, Joel Johansson, Steve Schulze, Rémy Joseph, Justin Pierel, Brian Nord, Doogesh Kodi Ramanah, Radek Wojtak, Justin Alsing, Simon Huber, Sherry Suyu, Catarina Alves

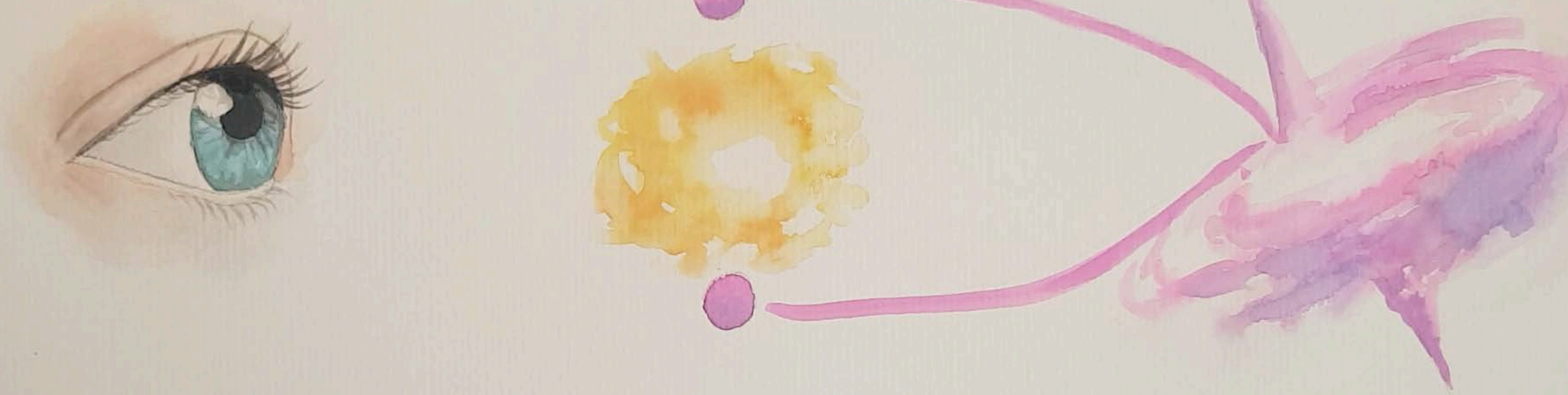


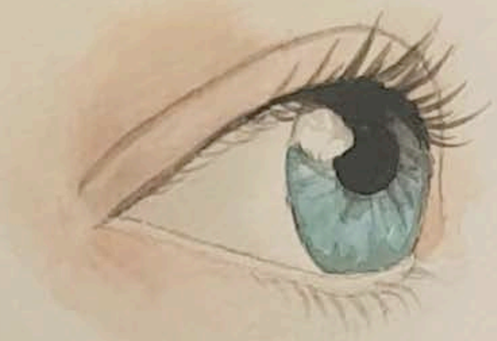
Time-delay cosmography

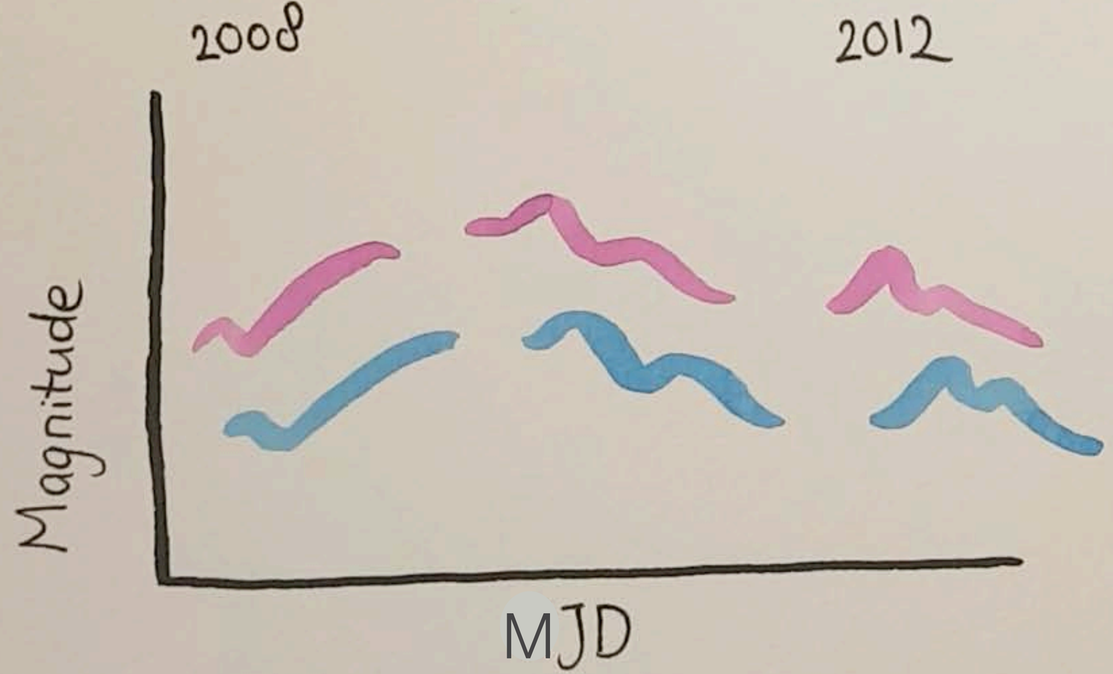
Lensed supernova discoveries

Predictions and challenges in LSST

Finder's Guide for lensed supernovae





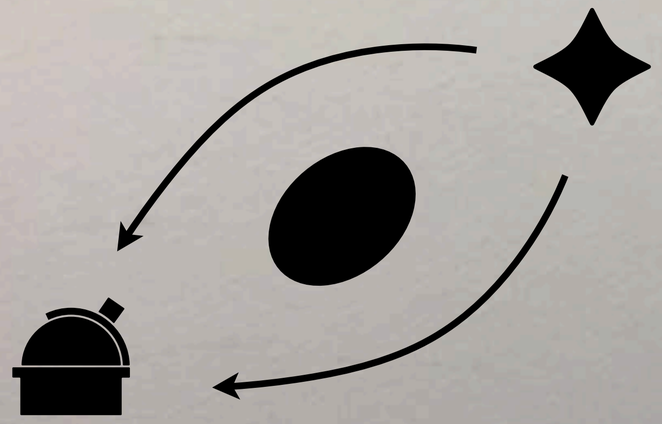


$$\Delta t \propto \phi_{lens} \frac{D_L D_S}{D_{LS}}$$

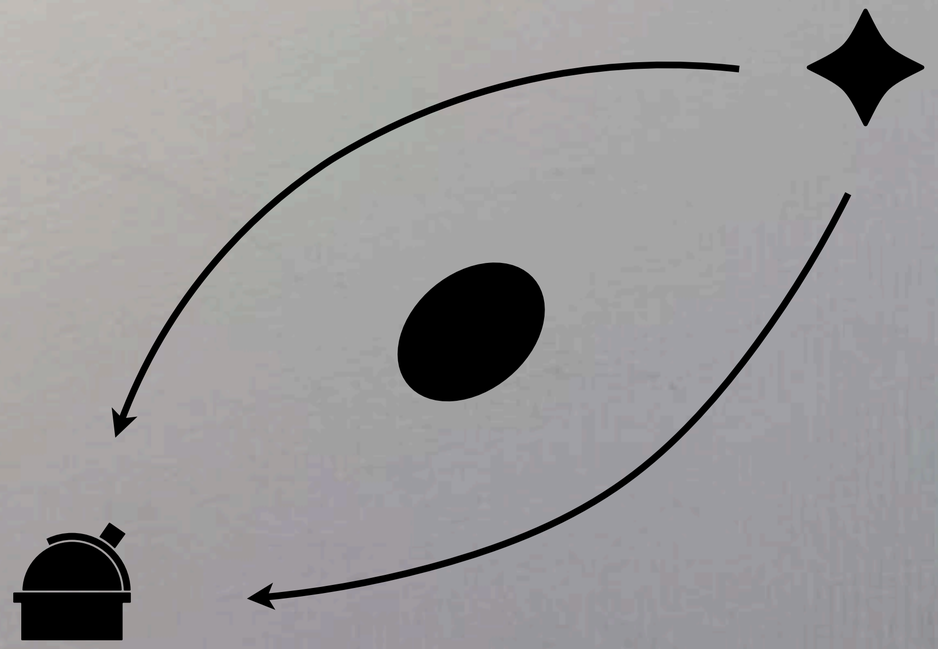
$D_{\Delta t}$

Expansion rate of the Universe:

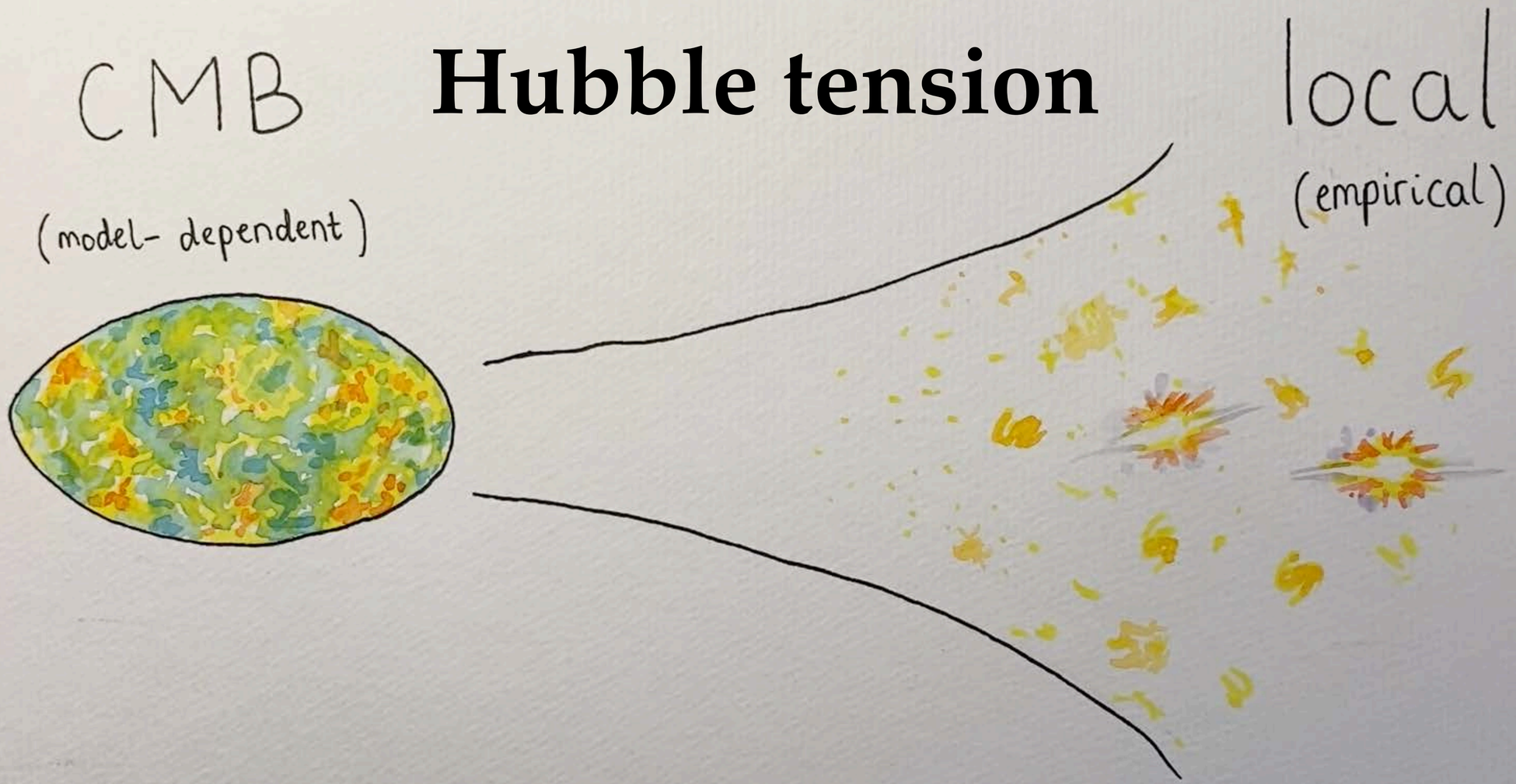
Fast



Slowly



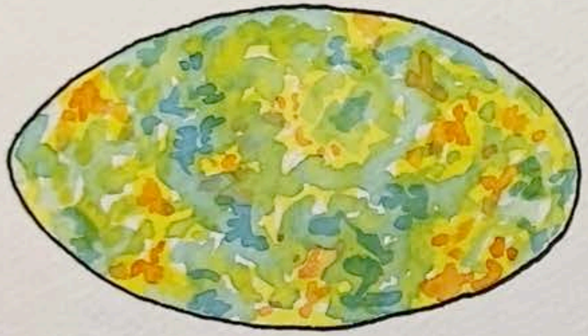
Hubble tension



Hubble tension

CMB

(model- dependent)



67.4

± 0.5 km/s/Mpc

from Planck

local

(empirical)

5 sigma tension

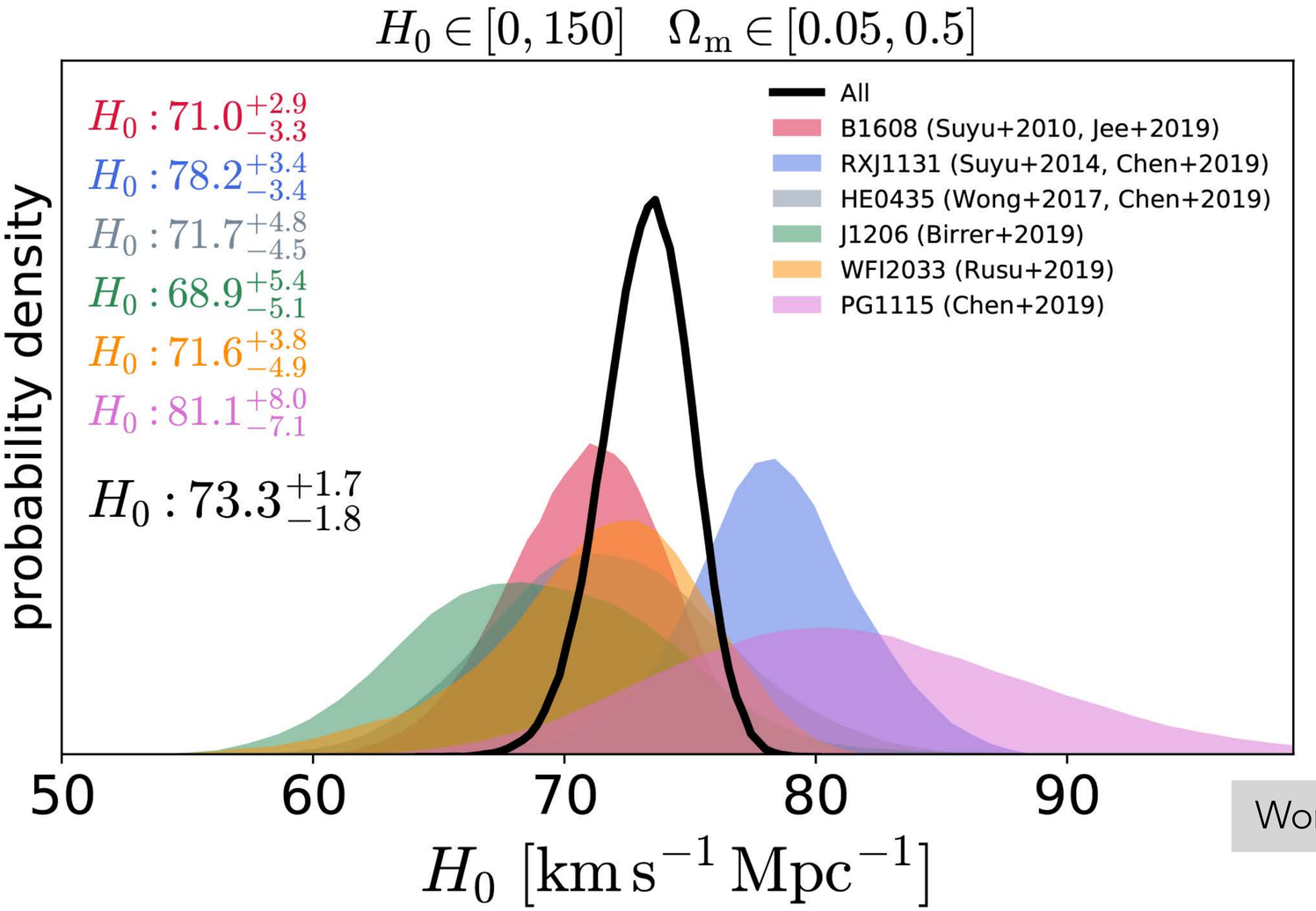
73.0

± 1.0 km/s/Mpc

from Cepheids

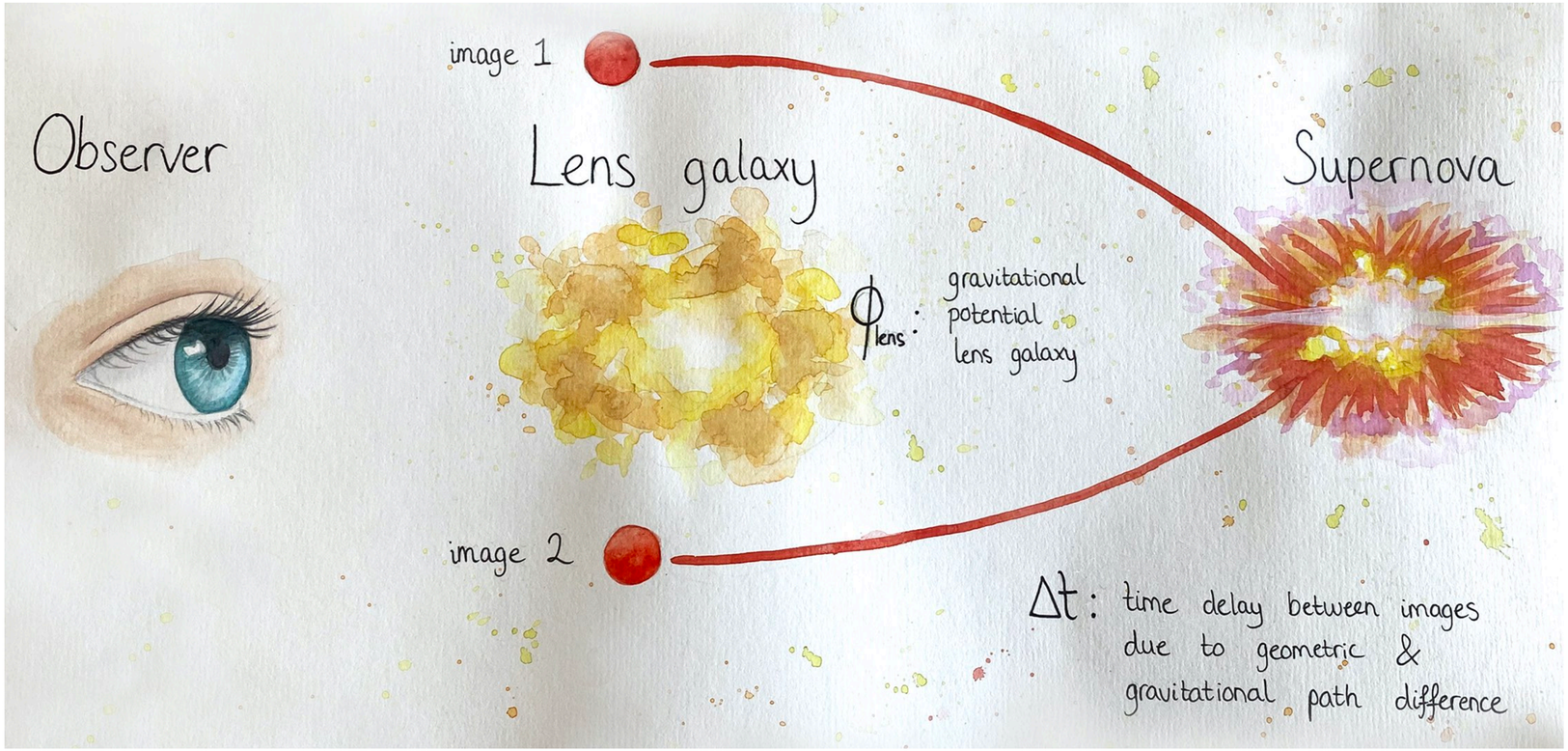
Time-delay cosmography with lensed quasars

Challenges:
constrain lens mass model & difficult to increase quasar sample



Wong et al. (2020)

Time-delay cosmography with lensed supernovae

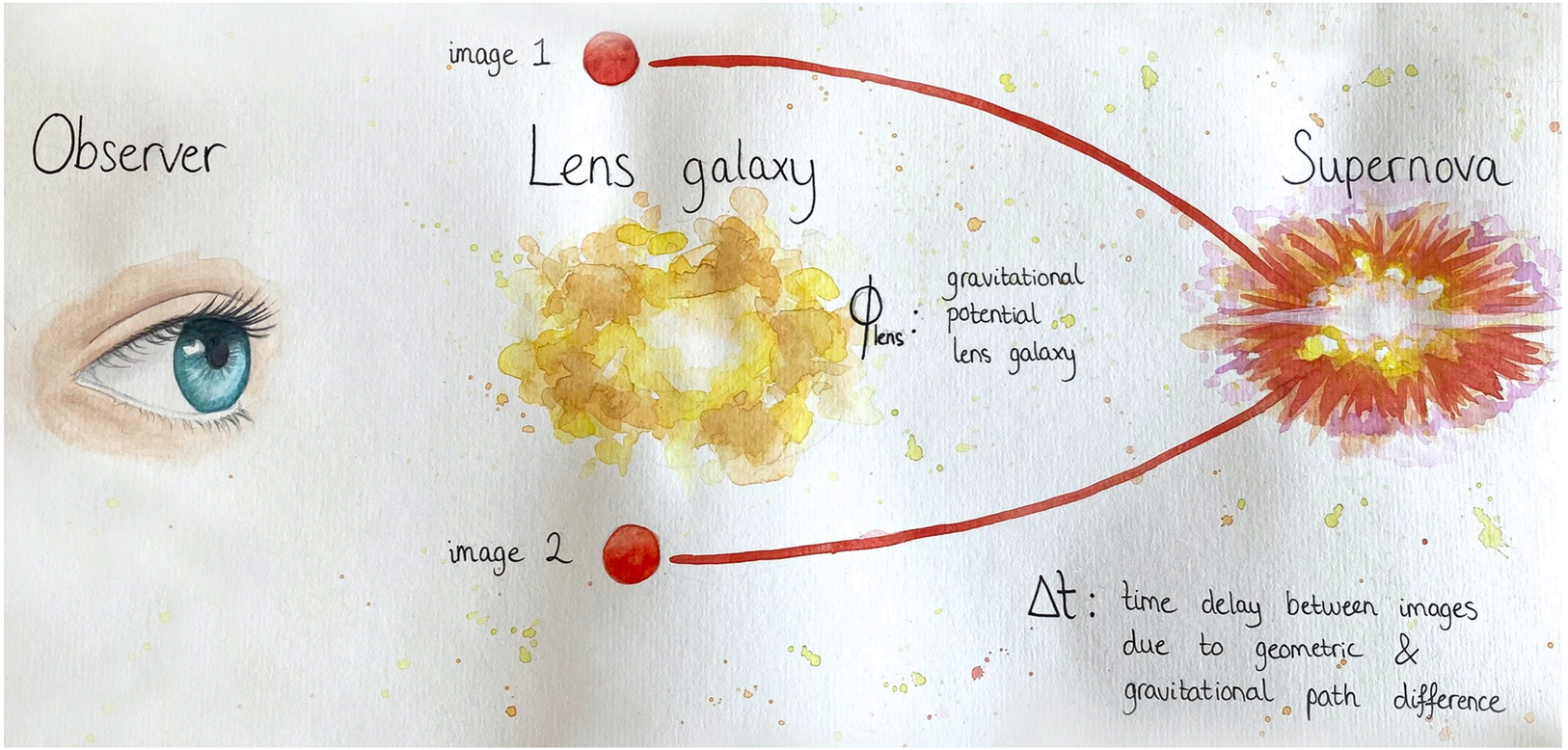


ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

Sjur Refsdal

(Received 1964 January 27)

Time-delay cosmography with lensed supernovae



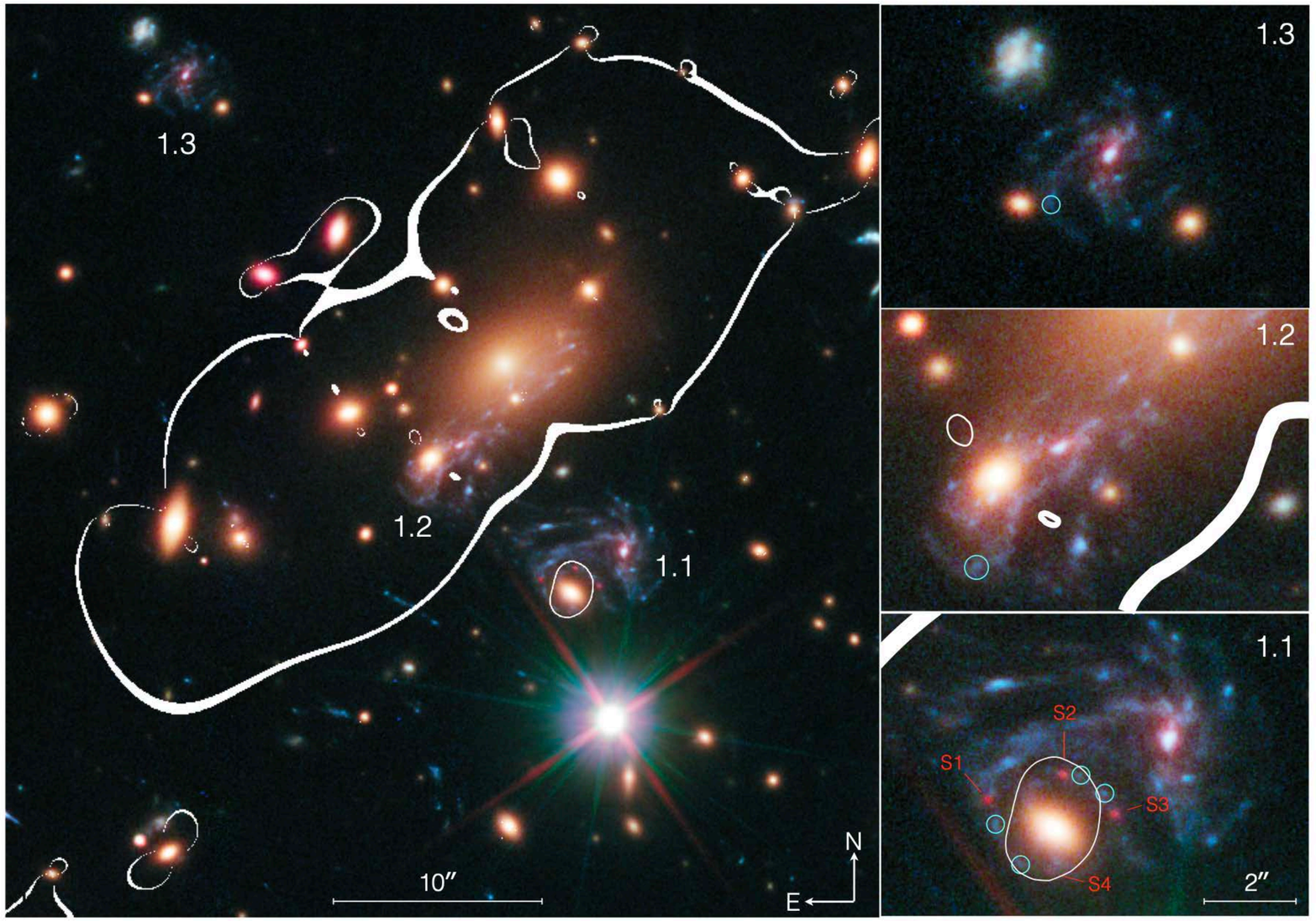
- 'Standard candles' (type Ia): extra magnification constraint
- Supernova fades away: better view of lens and host galaxy
- Well-defined light curves and shorter time delays: shorter monitoring required
- Learn about high-redshift supernova physics

ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

Sjur Refsdal

(Received 1964 January 27)

SN ‘Refsdal’: the first multiply-imaged lensed supernova



Kelly et al. (2015)

HST imaging data

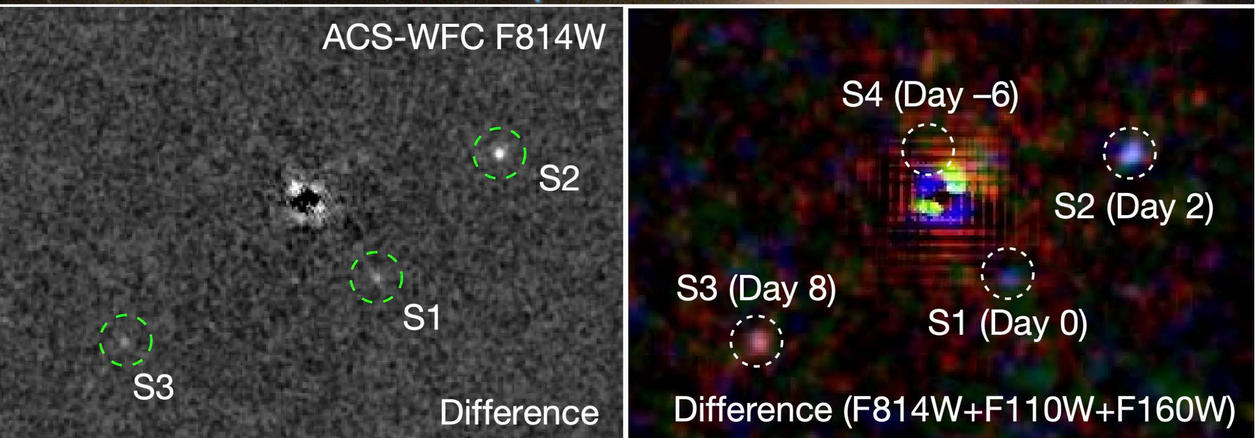
Cluster MACS J1149.6

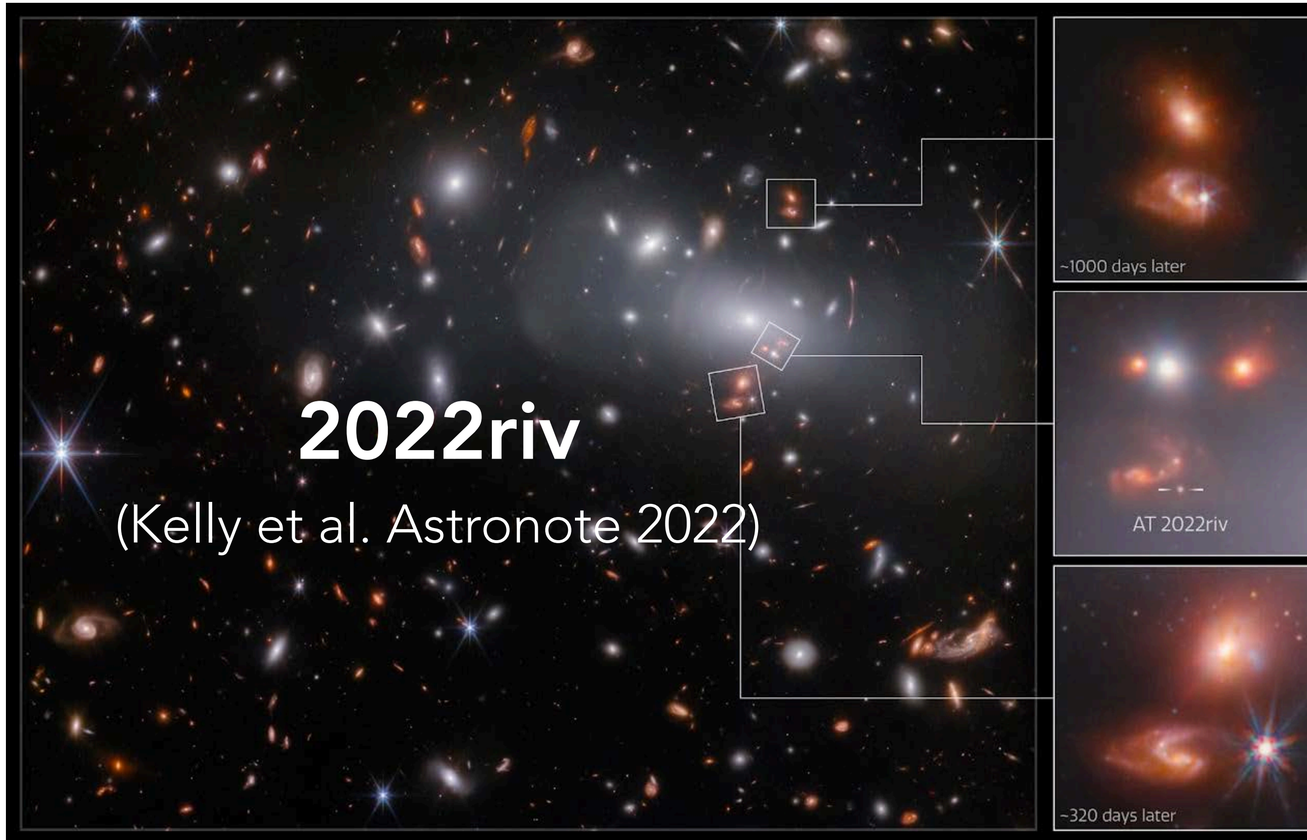
6% precision

H_0 estimate

Grillo et al. (2018)

3 more supernovae lensed by galaxy clusters…



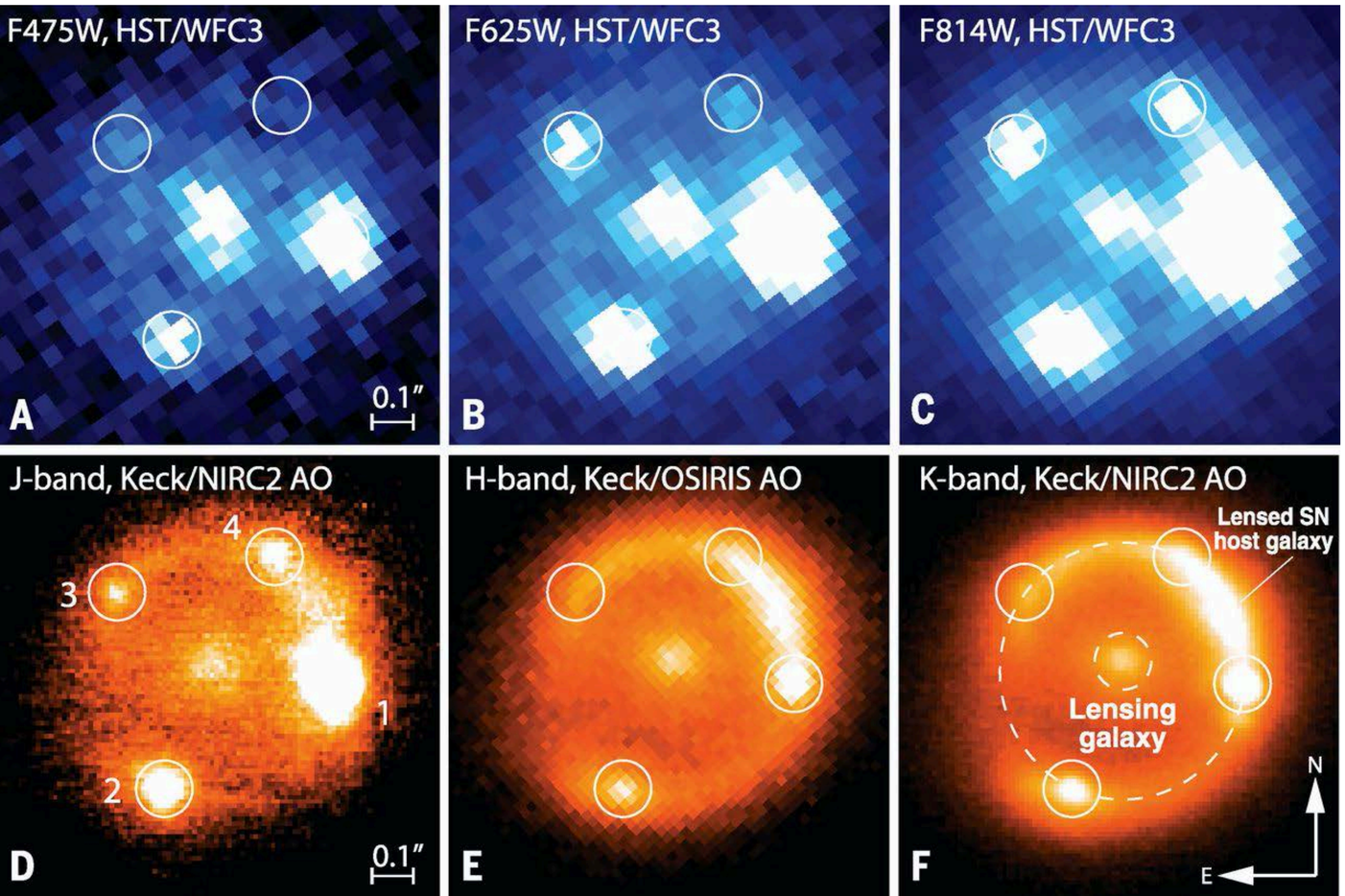


…and two lensed by single galaxies

iPTF16geu

(Goobar et al. 2017)

$\Delta t \sim 1.5$ day



SN Zwicky

(Goobar, Johansson, Schulze, Arendse, et al. 2023)

$\Delta t < 1$ day

LSST: Galaxy survey starting in ~2024 that will map the Southern sky in u,g,r,i,z,y bands in unprecedented depth

Predicted yearly lensed SN rates with the Vera Rubin Observatory:

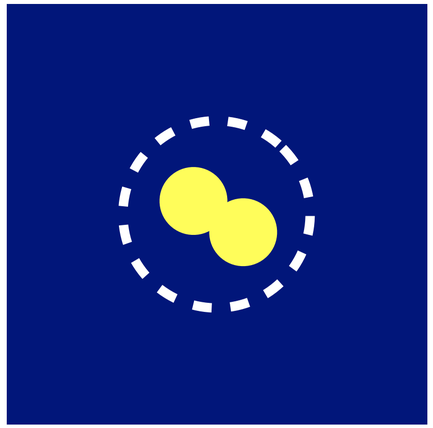
89 Ia and 250 core collapse

Wojtak et al. (2019)

LSST: Galaxy survey starting in ~2024 that will map the Southern sky in u,g,r,i,z,y bands in unprecedented depth

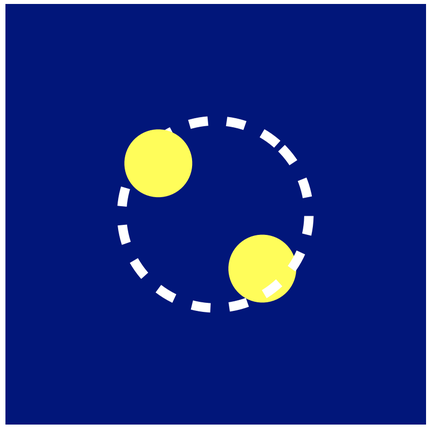
Challenge: **detection**

Unresolved



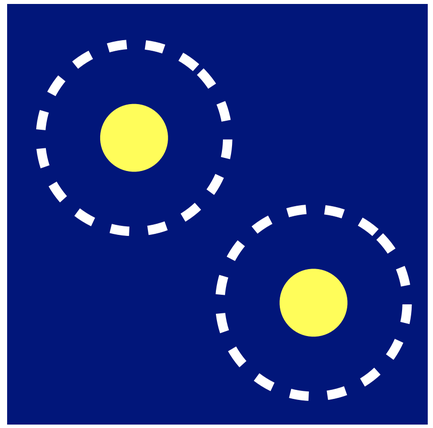
Visually very similar to unlensed transients

Partially resolved



Not point-like anymore: danger of being discarded by detection algorithms!

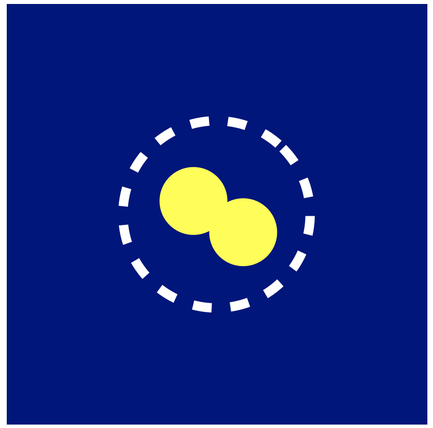
Resolved



Outnumbered by false positives & difficult to identify early

Synergy with static science: cross-match with known lenses

Unresolved



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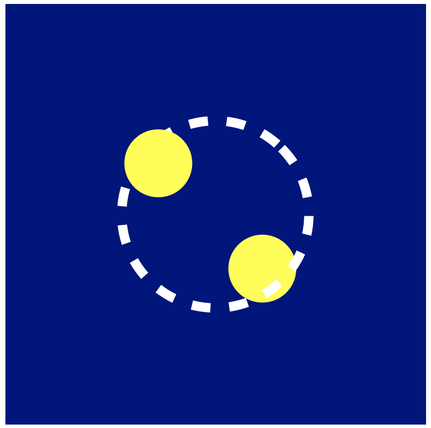

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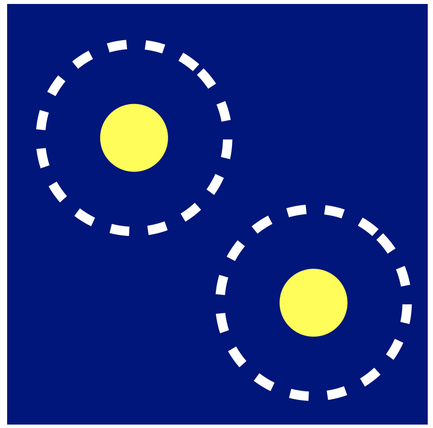
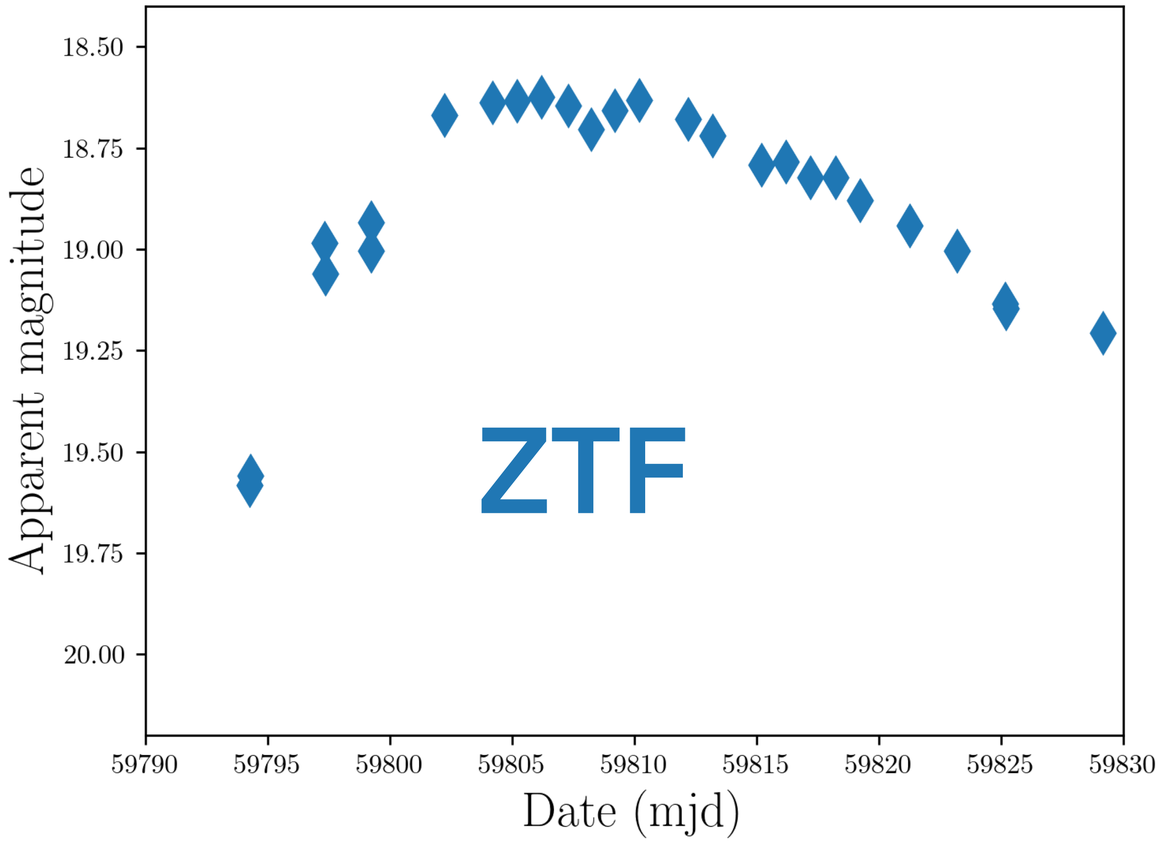


Outnumbered by false positives & difficult to identify early

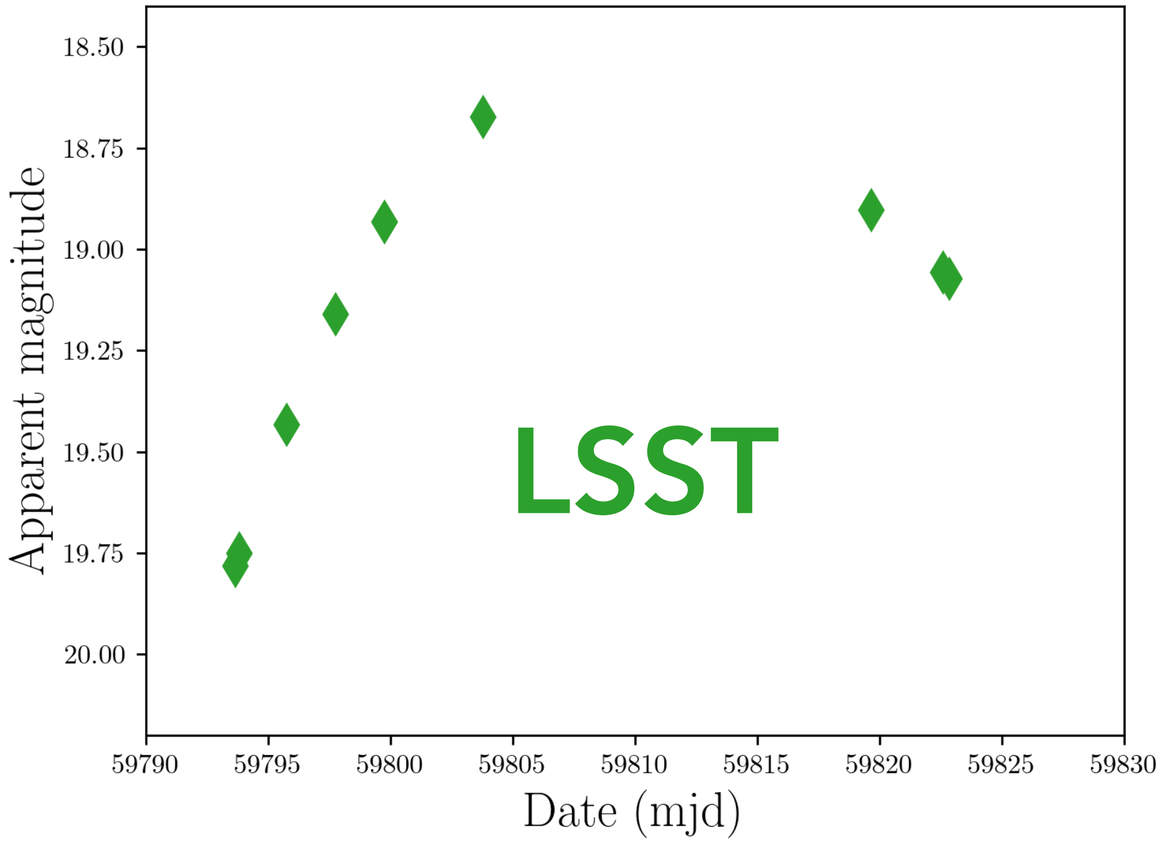
Challenge: **observing strategy**

SN Zwicky observed in *r*-band



Median inter-night gap: 2 days

SN Zwicky simulated in *r*-band



Median inter-night gap:

r-band: 6 days, *i*-band: 8 days

z-band: 9 days, *y*-band: 12 days

Challenge: **follow-up resources**

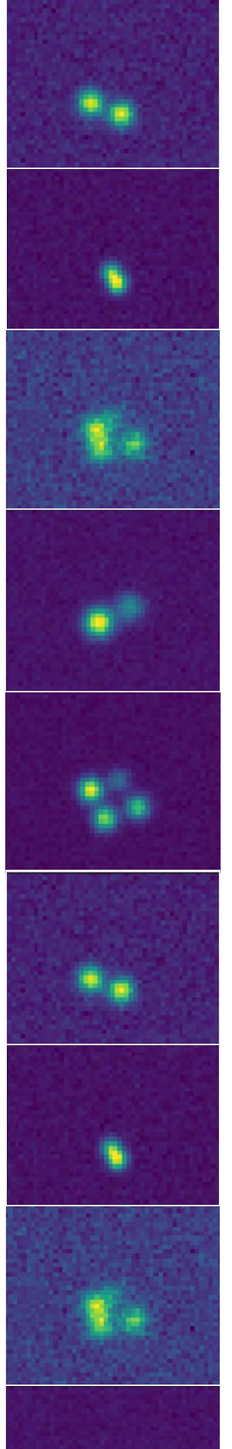
Spectrum: identify SN type and redshift to verify it's lensed

Multiple epochs of imaging: sample the light curve

High-resolution image (HST, Keck, JWST): constrain image positions and lens mass model

Finder's Guide to lensed type Ia supernovae in LSST

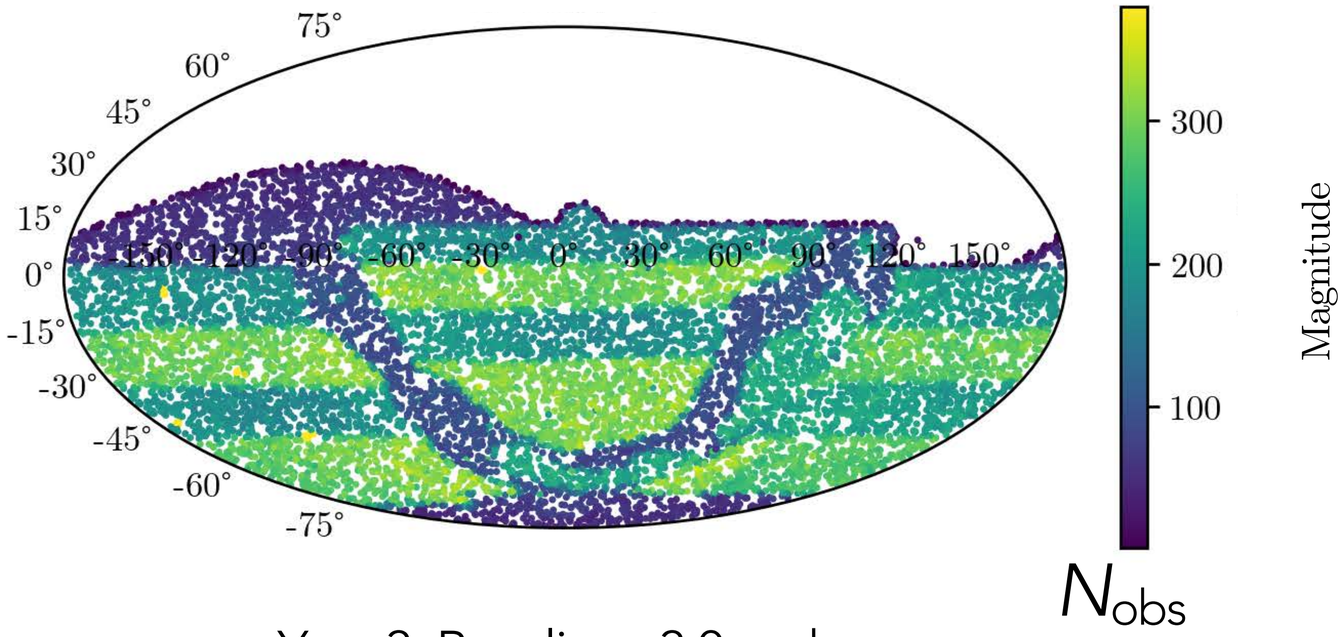
Nikki Arendse, Suhail Dhawan, Ana Sagués Carracedo, Hiranya Peiris, Ariel Goobar, et al.



How many lensed SNe will be observed?

Taking into account the newest observing strategy

Sky pointings



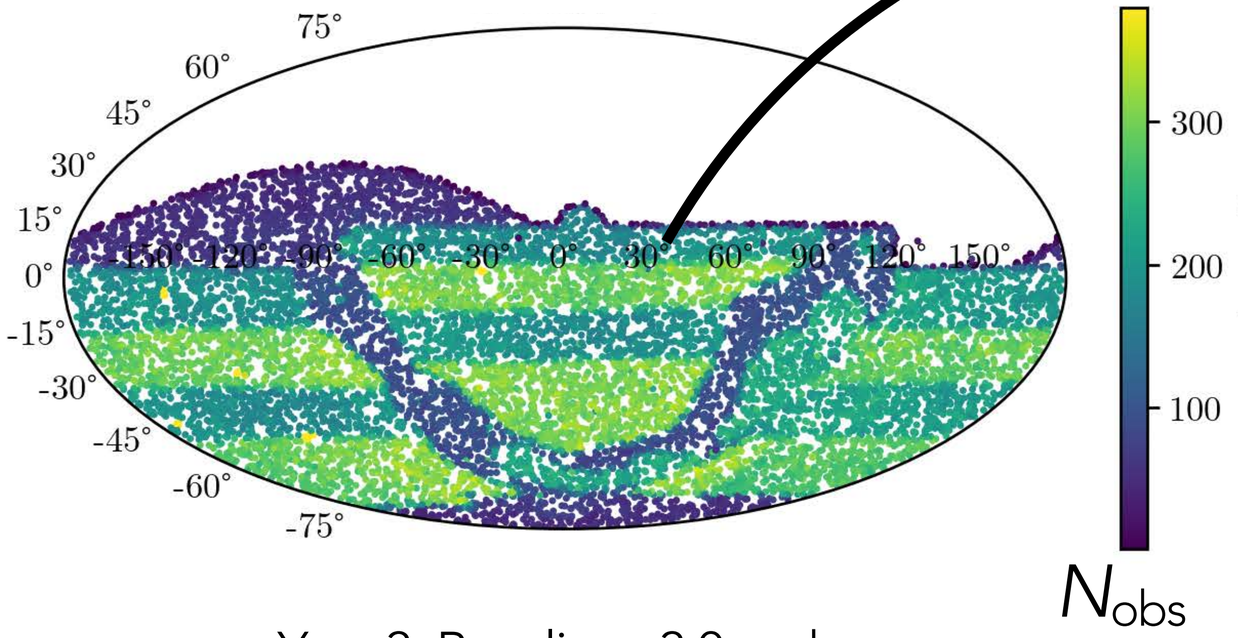
Year 3, Baseline v3.0 cadence

(LSST observation scheduler OpSim)

How many lensed SNe will be observed?

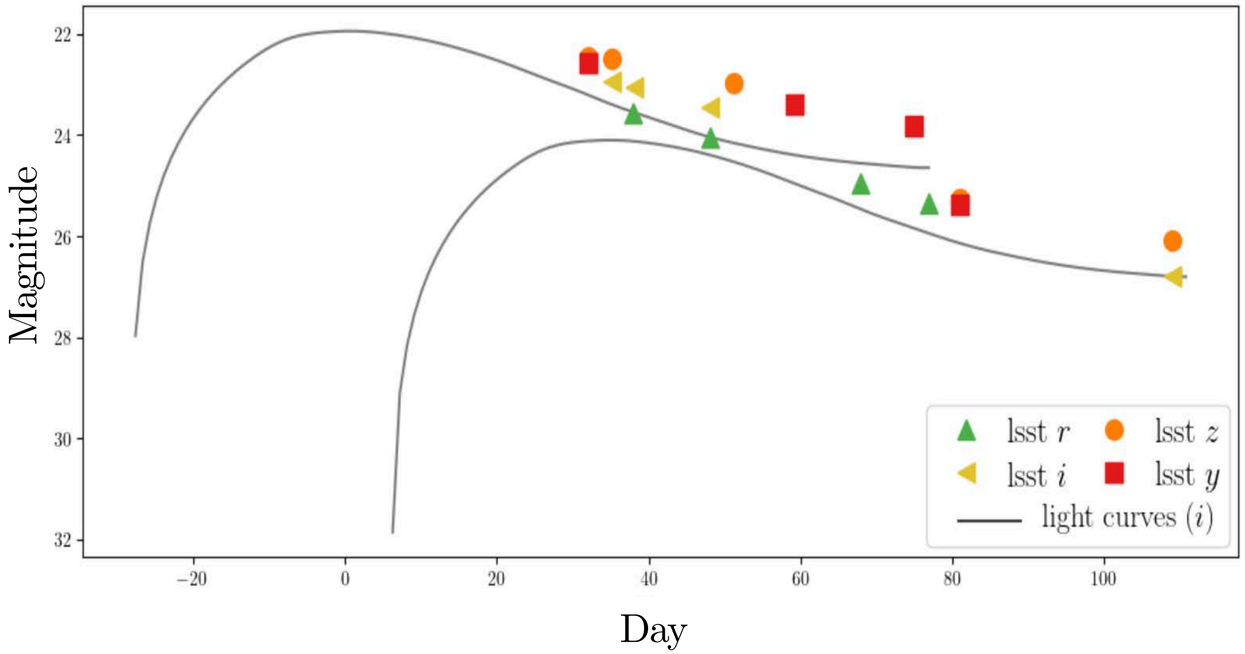
Taking into account the newest observing strategy

Sky pointings



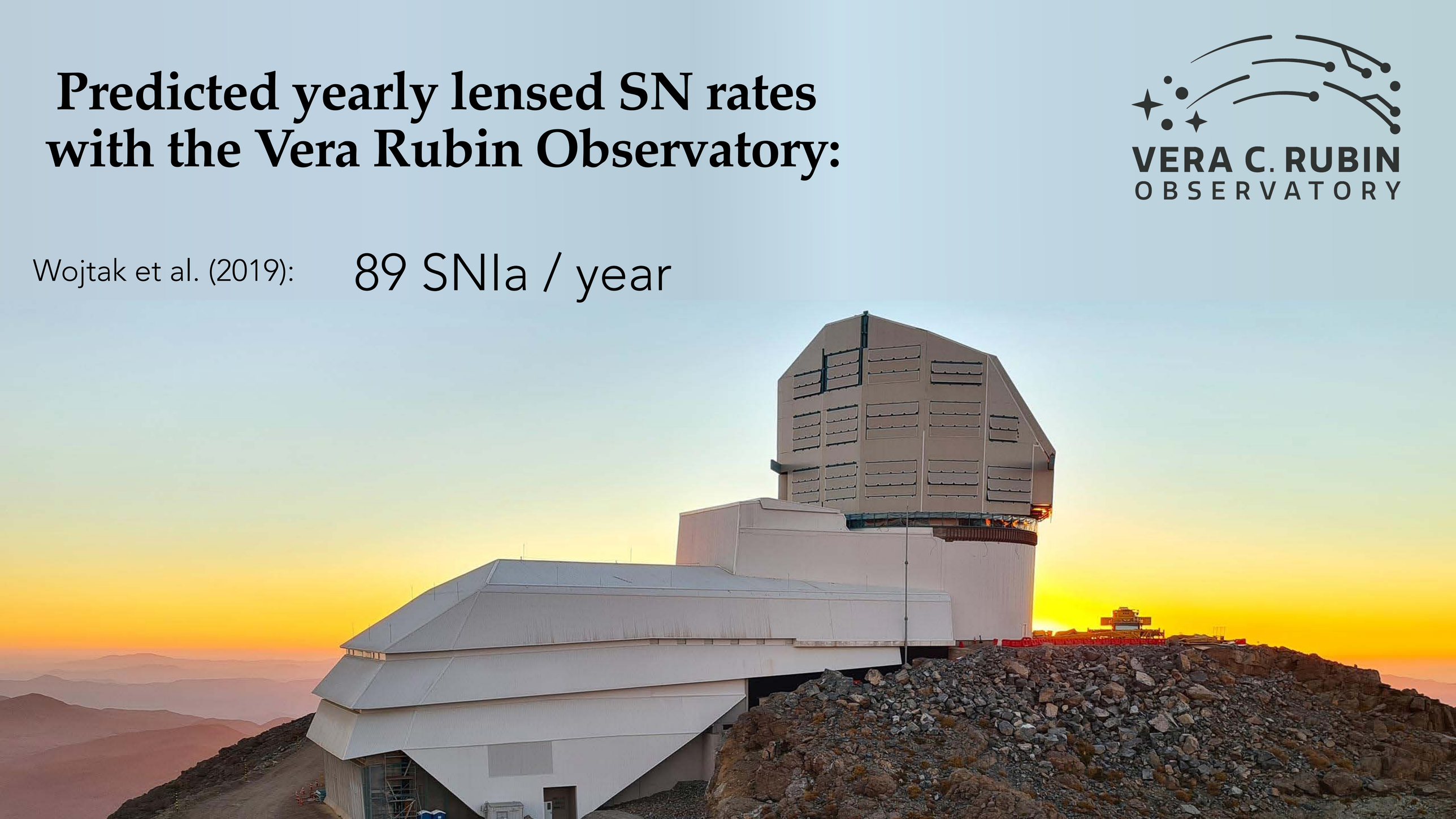
Year 3, Baseline v3.0 cadence
(LSST observation scheduler OpSim)

Doubly-imaged supernova



Predicted yearly lensed SN rates with the Vera Rubin Observatory:

Wojtak et al. (2019): 89 SNIa / year



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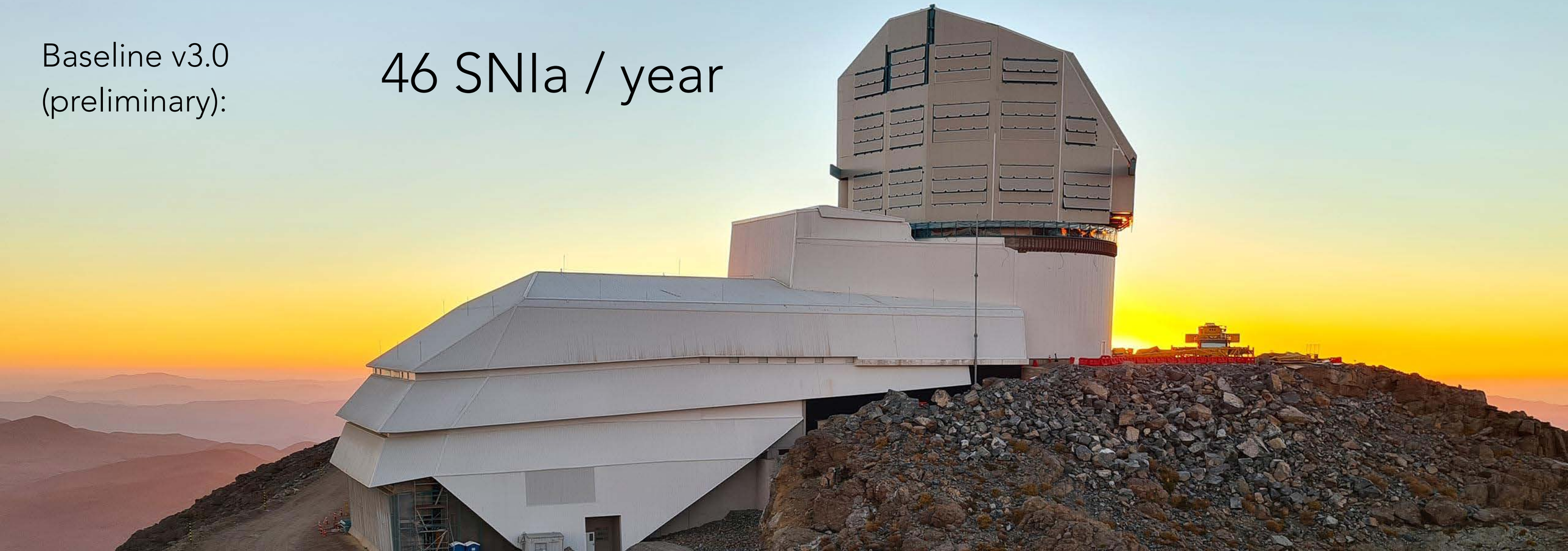


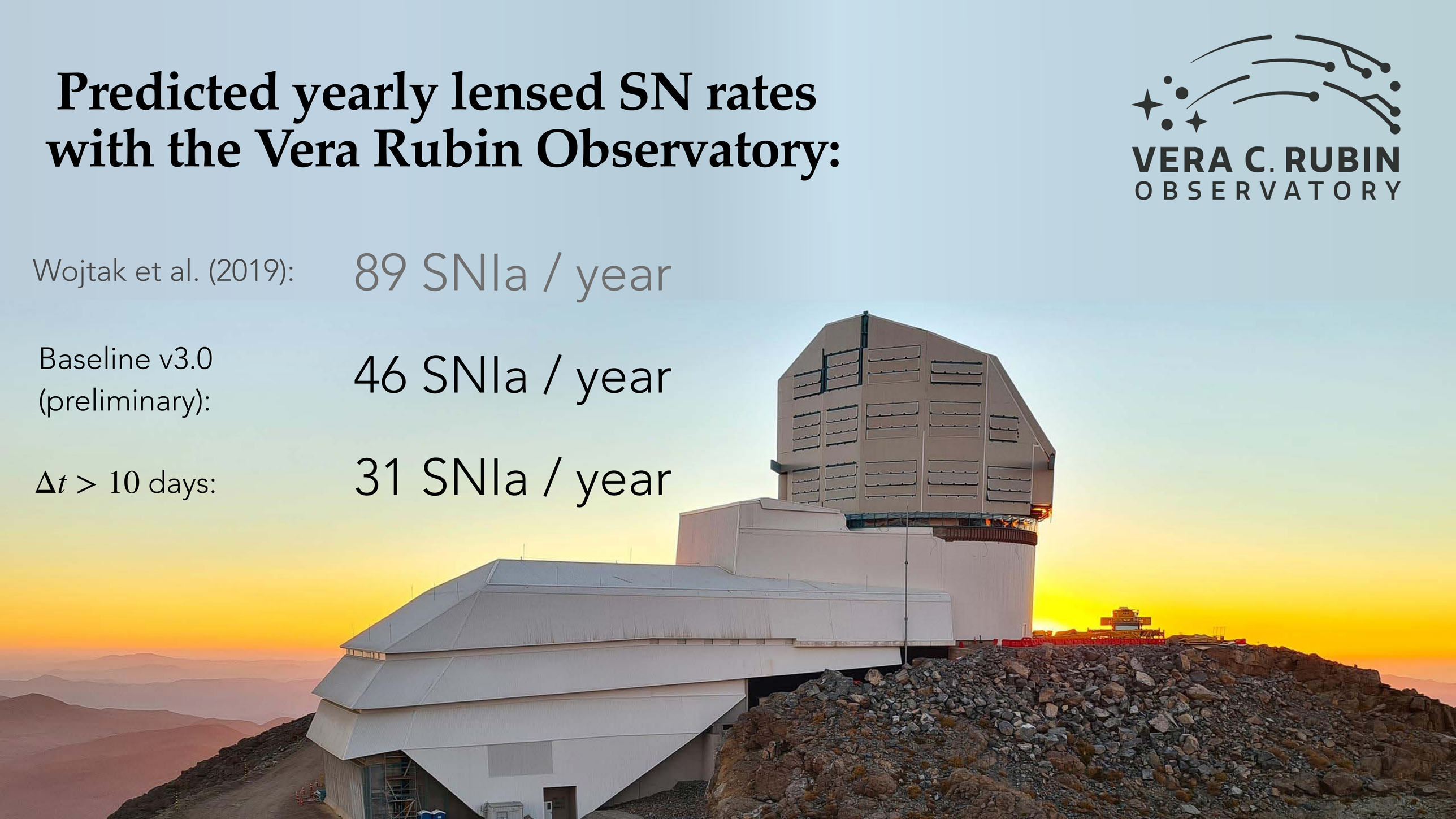
Predicted yearly lensed SN rates with the Vera Rubin Observatory:

VERA C. RUBIN OBSERVATORY

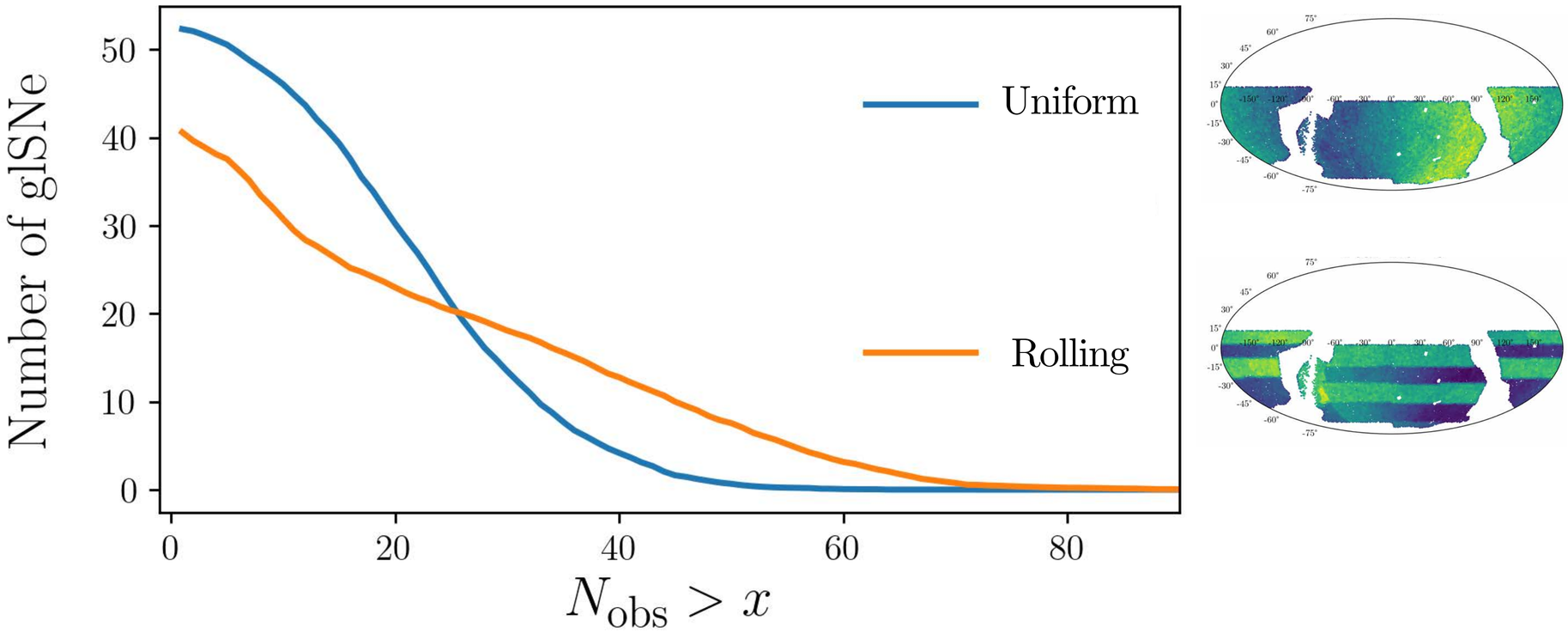
Wojtak et al. (2019): 89 SNIa / year

Baseline v3.0 (preliminary): 46 SNIa / year

$\Delta t > 10$ days: 31 SNIa / year



What is the impact of the rolling cadence?



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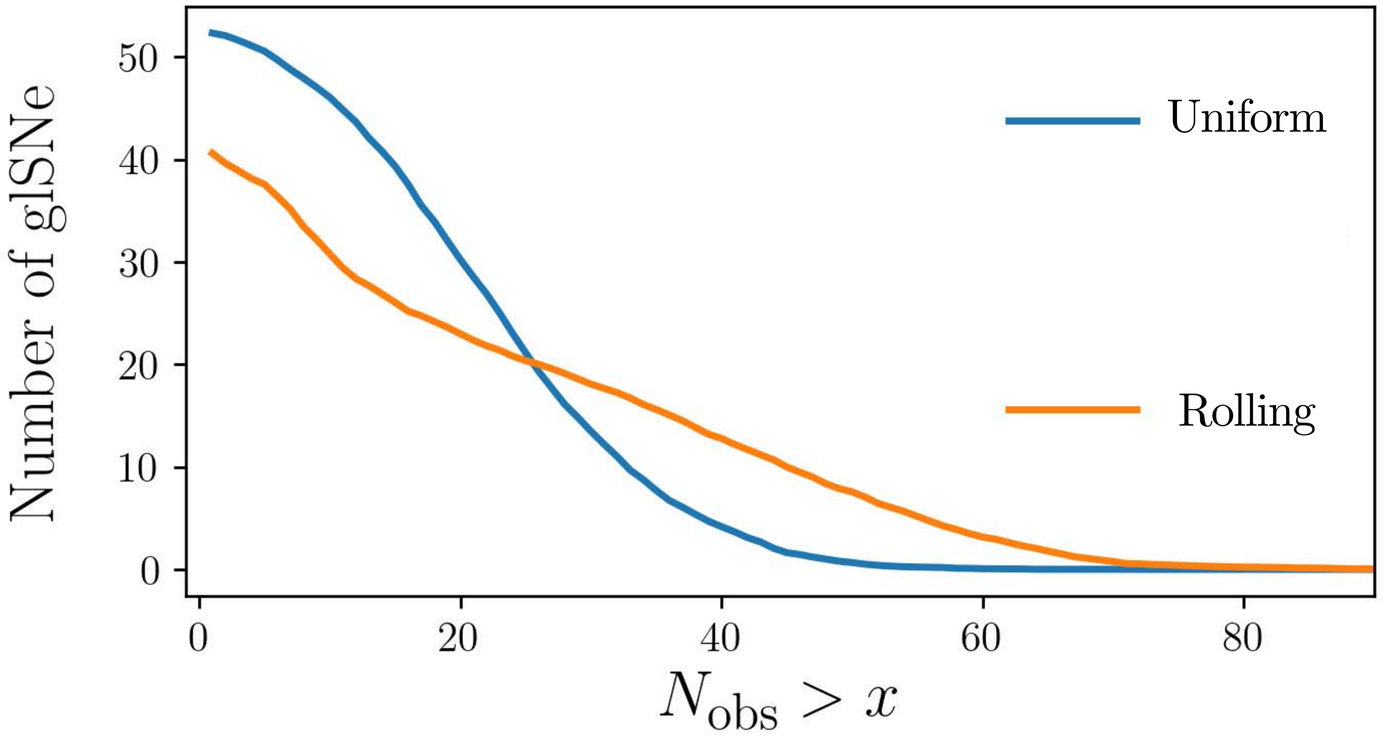
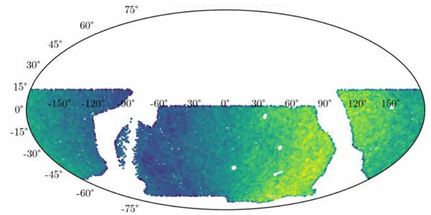
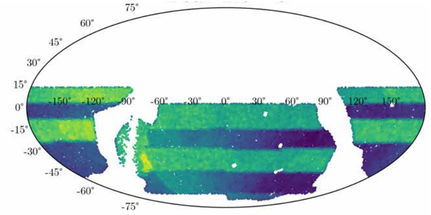






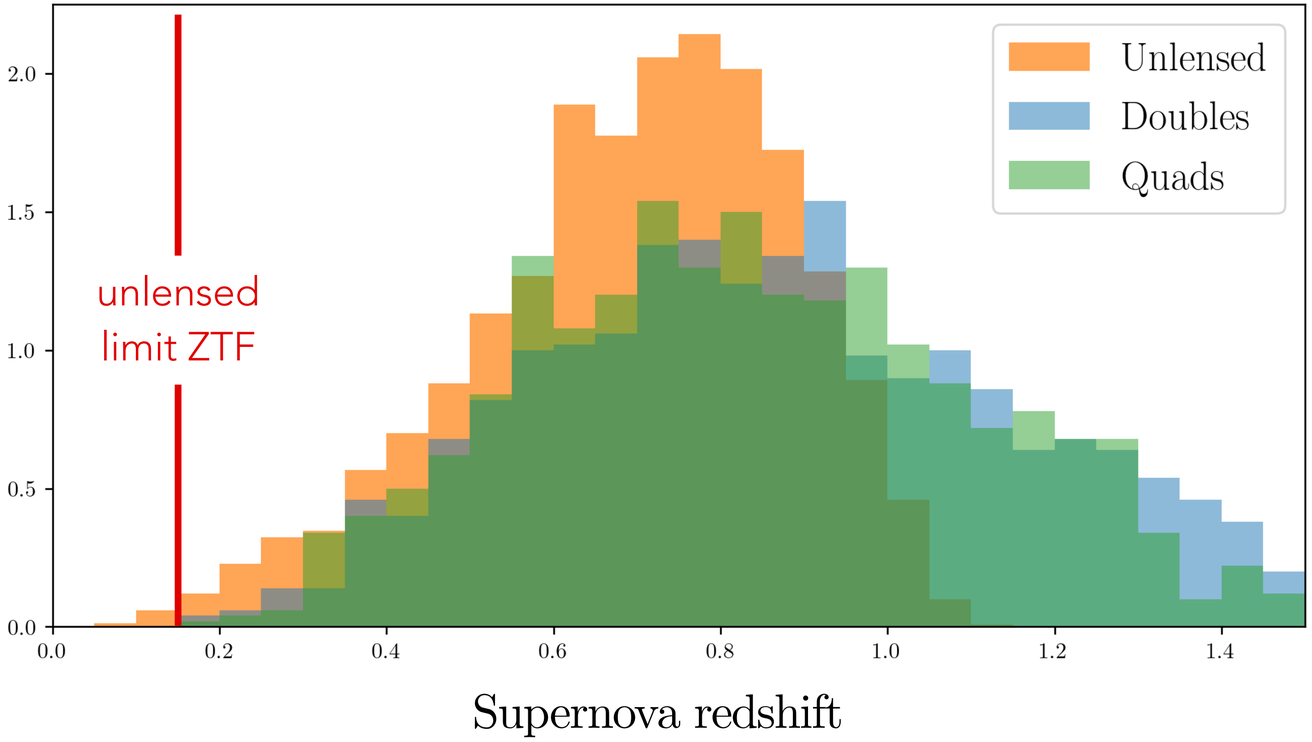
Non-rolling ⟶ more lensed SNe

Rolling ⟶ denser light curve sampling

How many will stand out from unlensed SNe?

In terms of brightness, colours, and light curve shapes

Ana Sagués Carracedo



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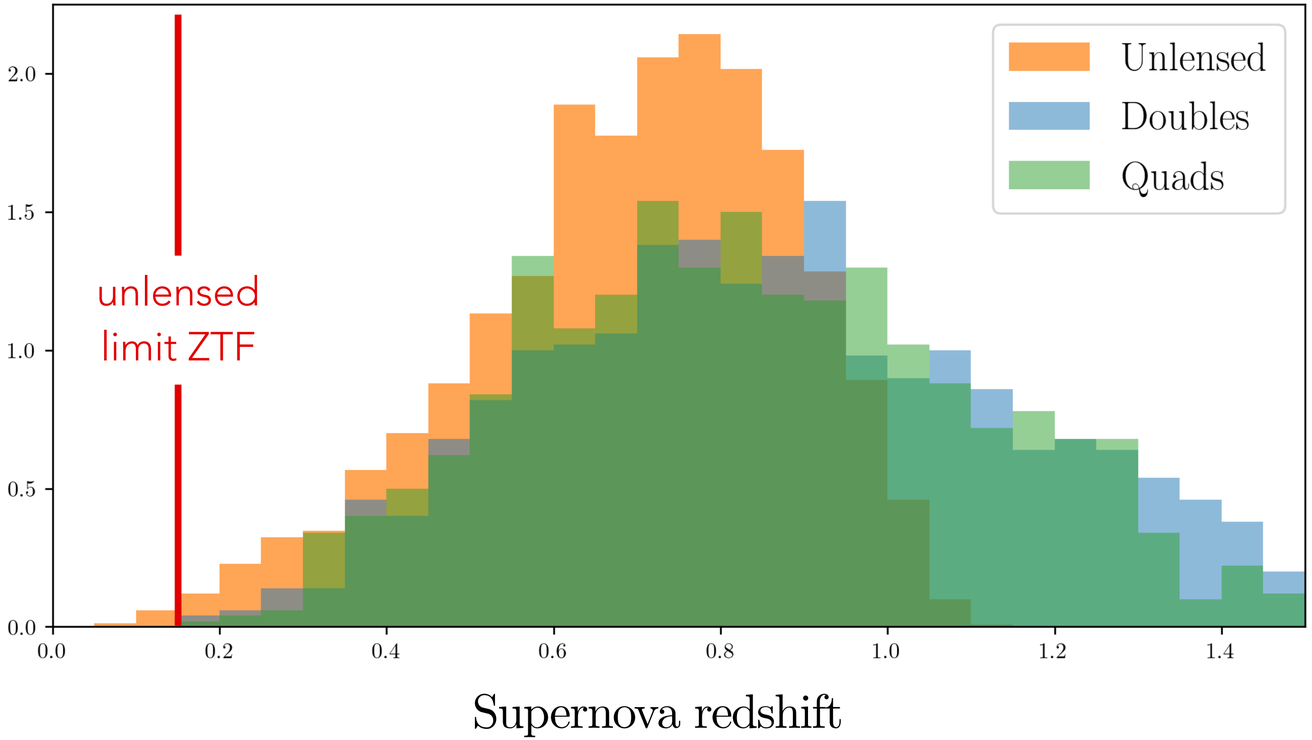


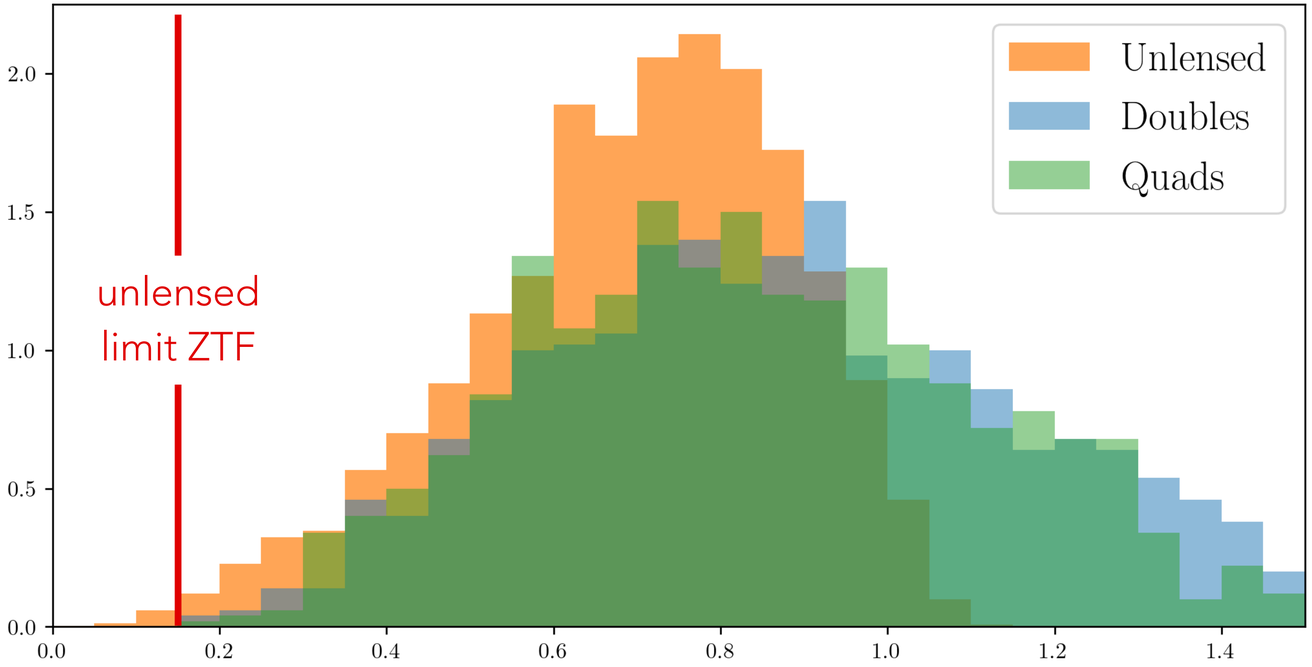
Redshift distributions of lensed and unlensed supernovae in LSST show large overlap:

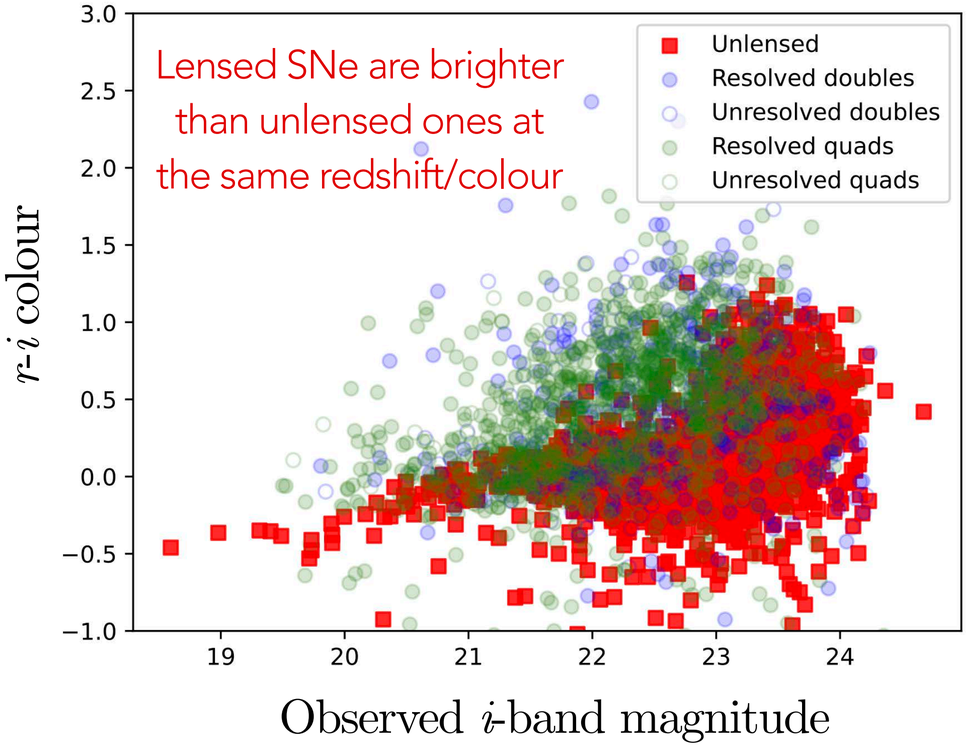
observed colours are similar!

How many will stand out from unlensed SNe?

In terms of brightness, colours, and light curve shapes

Ana Sagués Carracedo



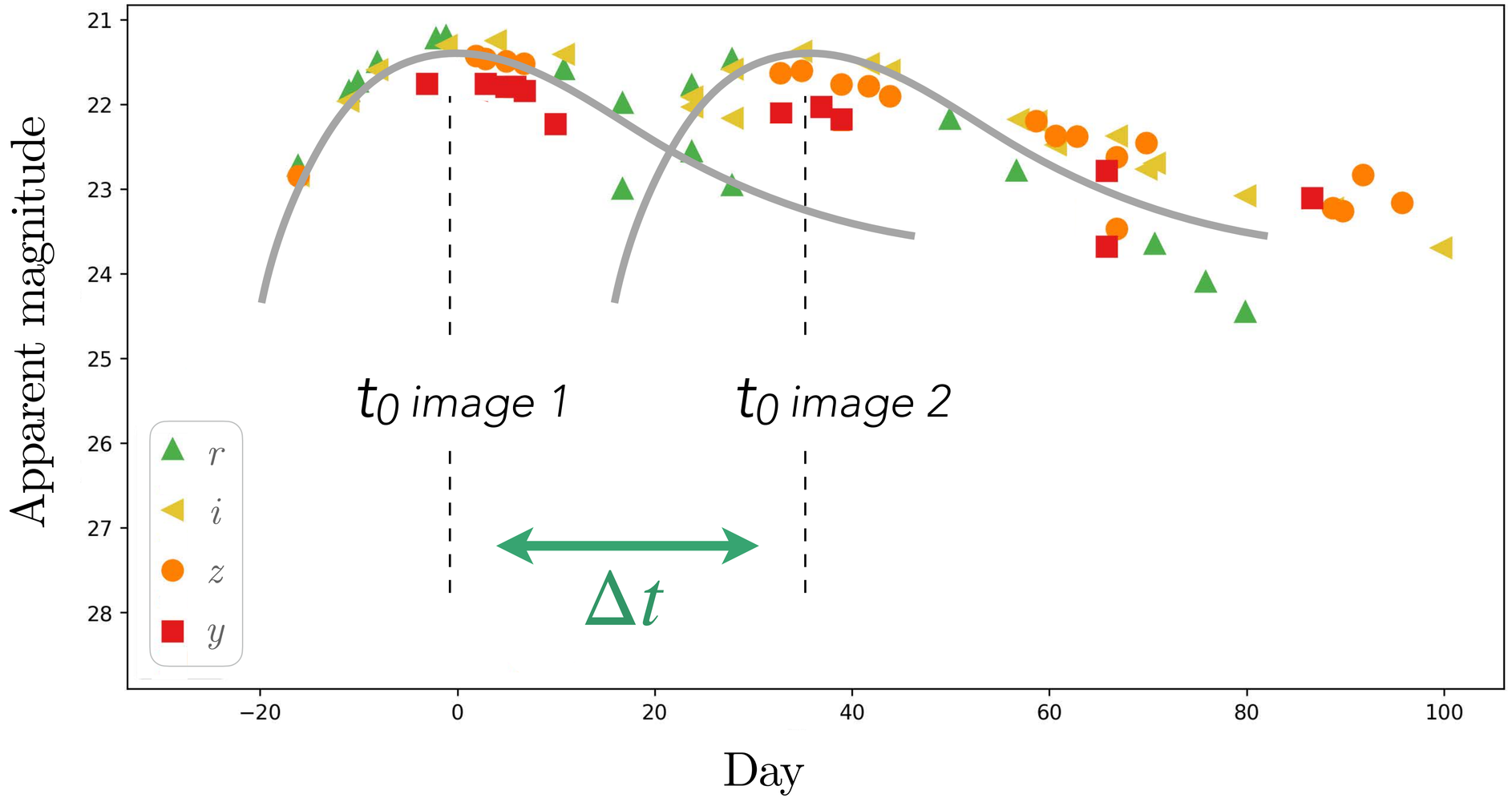


Redshift distributions of lensed and unlensed supernovae in LSST show large overlap:

observed colours are similar!

How many will have well-measured time delays?

Use SALT2 to fit resolved lensed supernova light curves



Suhail Dhawan

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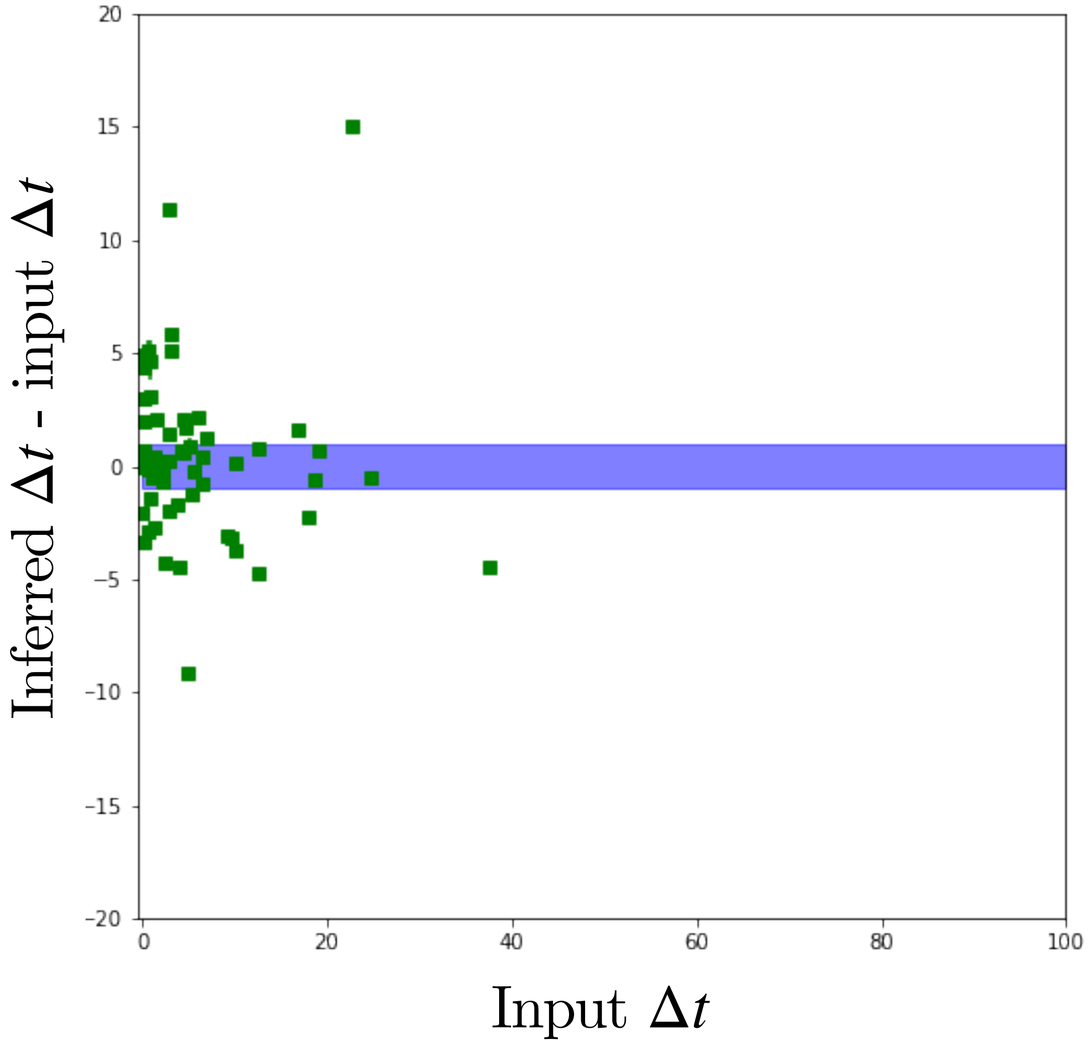

Suhail Dhawan

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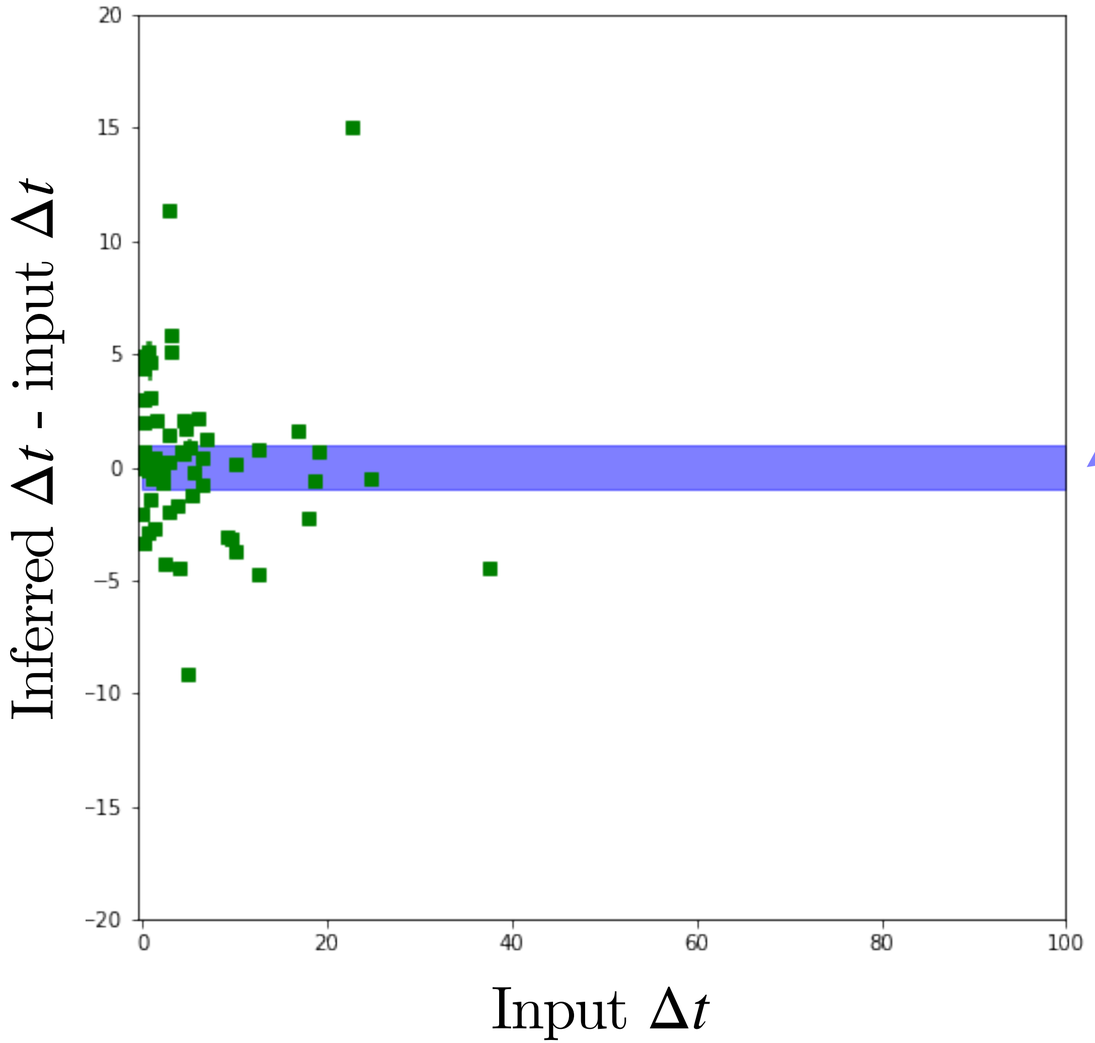


5 - 8 % of the systems have time-delay estimates within a day accuracy

Only from LSST data, without follow-up!

Suhail Dhawan

Want to get involved preparing for lensed SNe with LSST?

Justin Pierel

We're developing a **Strong Lensing simulation pipeline**
for realistic, scalable, and flexible simulations
to test lens finders and cosmology tools

- Bi-weekly telecons on Monday at 16 GMT with the lensed SN team
- Slack channel: **#lensed-sn-integration**

Conclusions

- Lensed supernovae: promising cosmological probes but many challenges to overcome related to identification

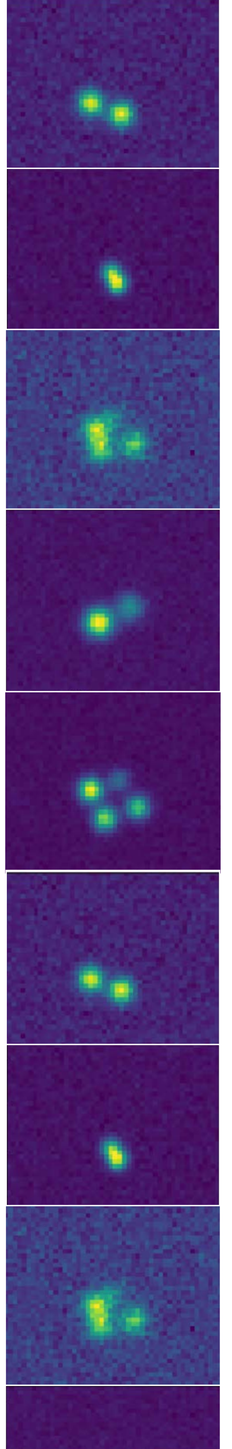
- **Lensed supernova Finder's Guide:**

  ~ 46 lensed SNIa / year in LSST (using Baseline v3.0 cadence)

  Rolling cadence: ~ 15% fewer objects but denser light curve sampling

  Require both colours and magnitudes to separate lensed/unlensed SNIa

  A few objects per year with well-measured time delays only from LSST



The future is bright for lensed supernovae