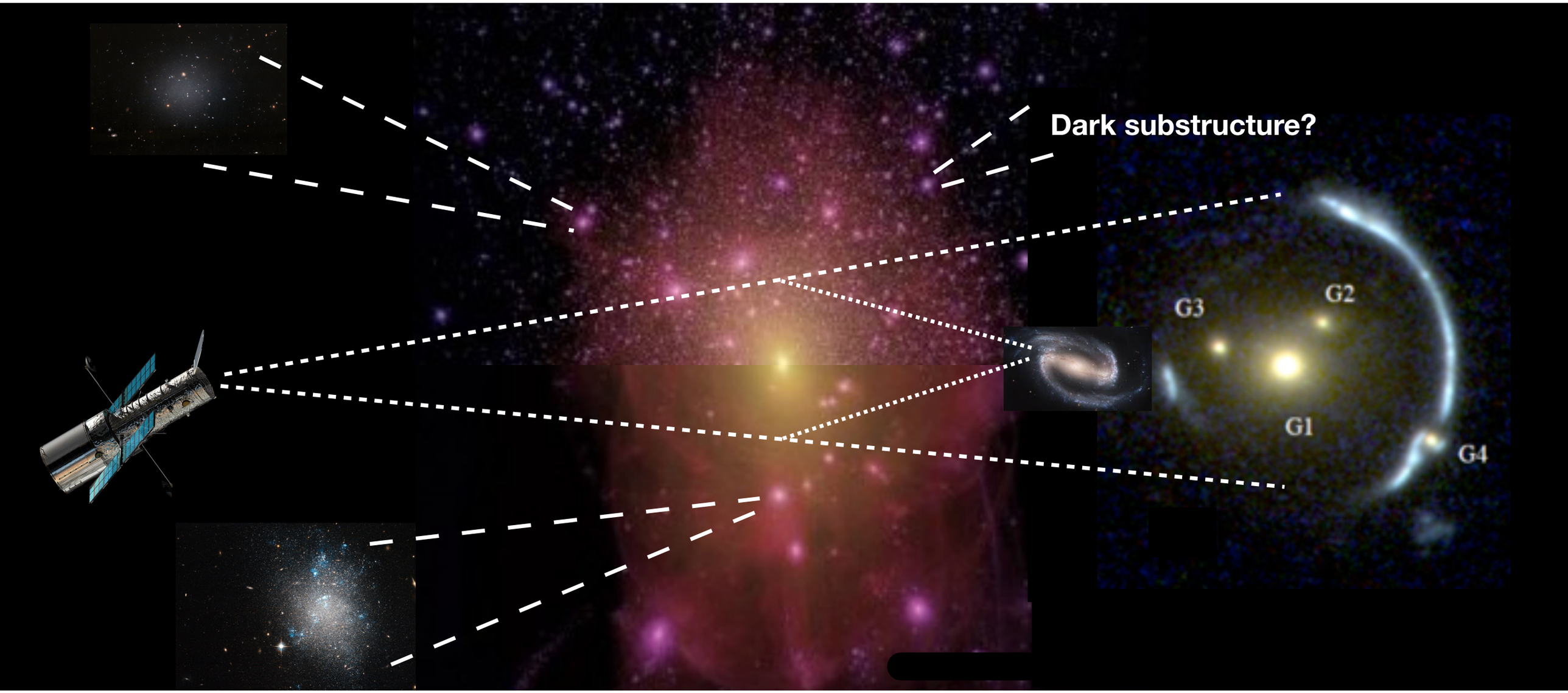
Stanford University

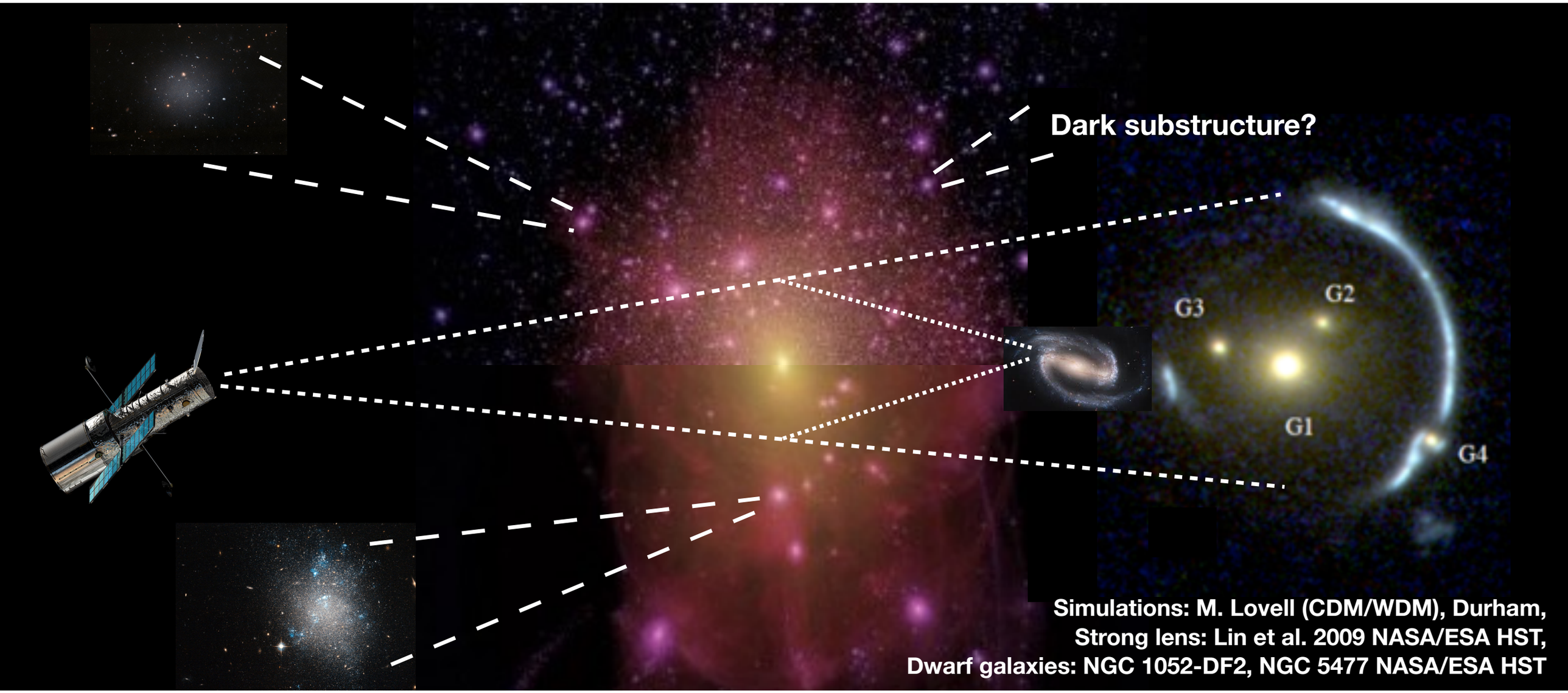
Shedding light on Dark Matter and Dark Energy



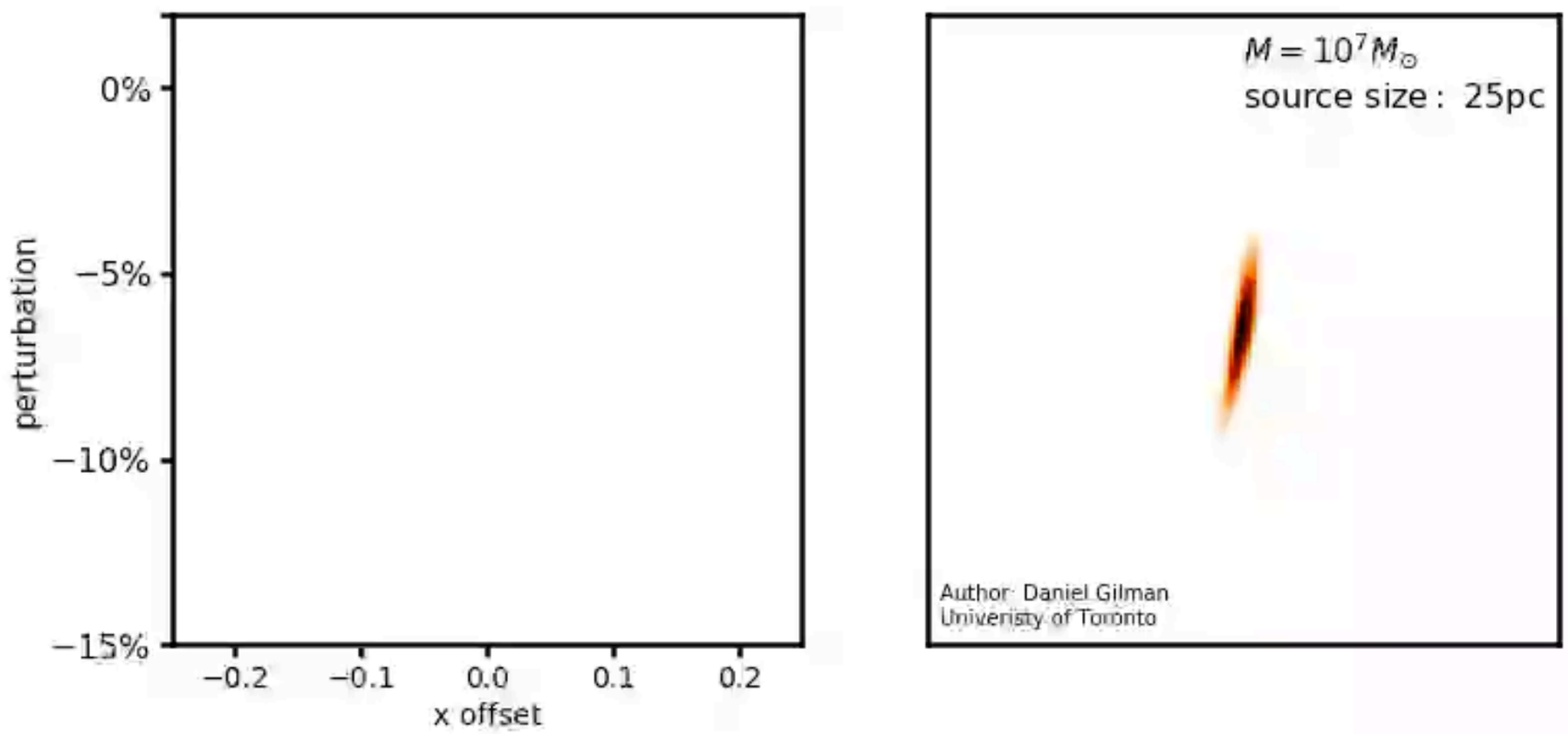
Simon Birrer

Cosmology from home 2021

Dark Matter Constraints from a Unified Analysis of Strong Gravitational Lenses and Milky Way Satellite Galaxies



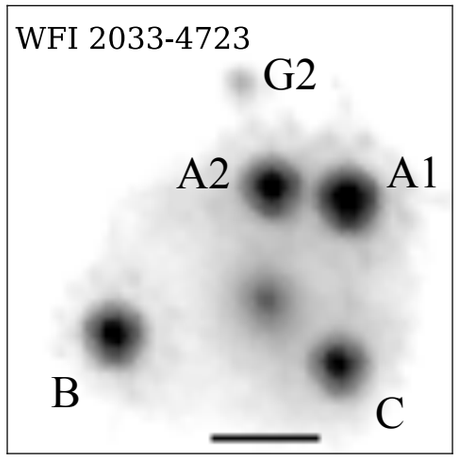
Flux-ratios are sensitive to completely dark structure

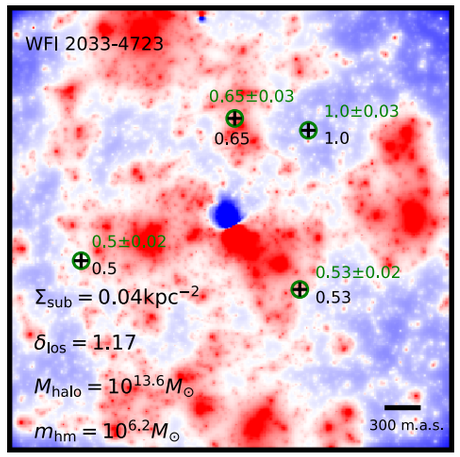


Mao & Schneider 1998, Dalal & Kochanek 2002, Moustakas & Metcalf 2003, Nierenberg+2014, 2017
Hsueh+2016, 2017, 2019, Gilman, **SB**+2018, 2019a,b,c

End-to-end inference of dark matter microphysics

Flux ratio statistics



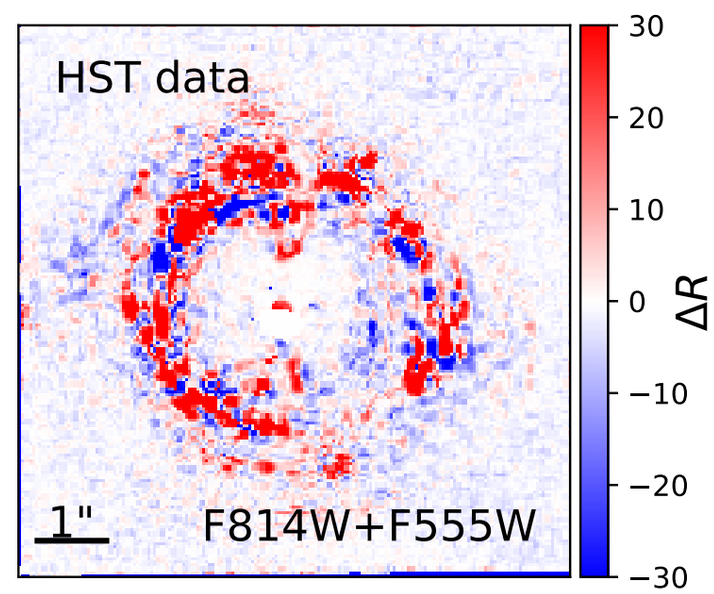


Forward modeling and **simulation based inferences** with Approximate Bayesian Computing

thermal relic mass **> 5.2 keV** from a sample of 8 quasar lenses, **> 2 keV** from1 lensing arc

SB+2015, **SB+**2017a, b, Gilman, **SB**+2019, 2020a, b

Gravitational imaging



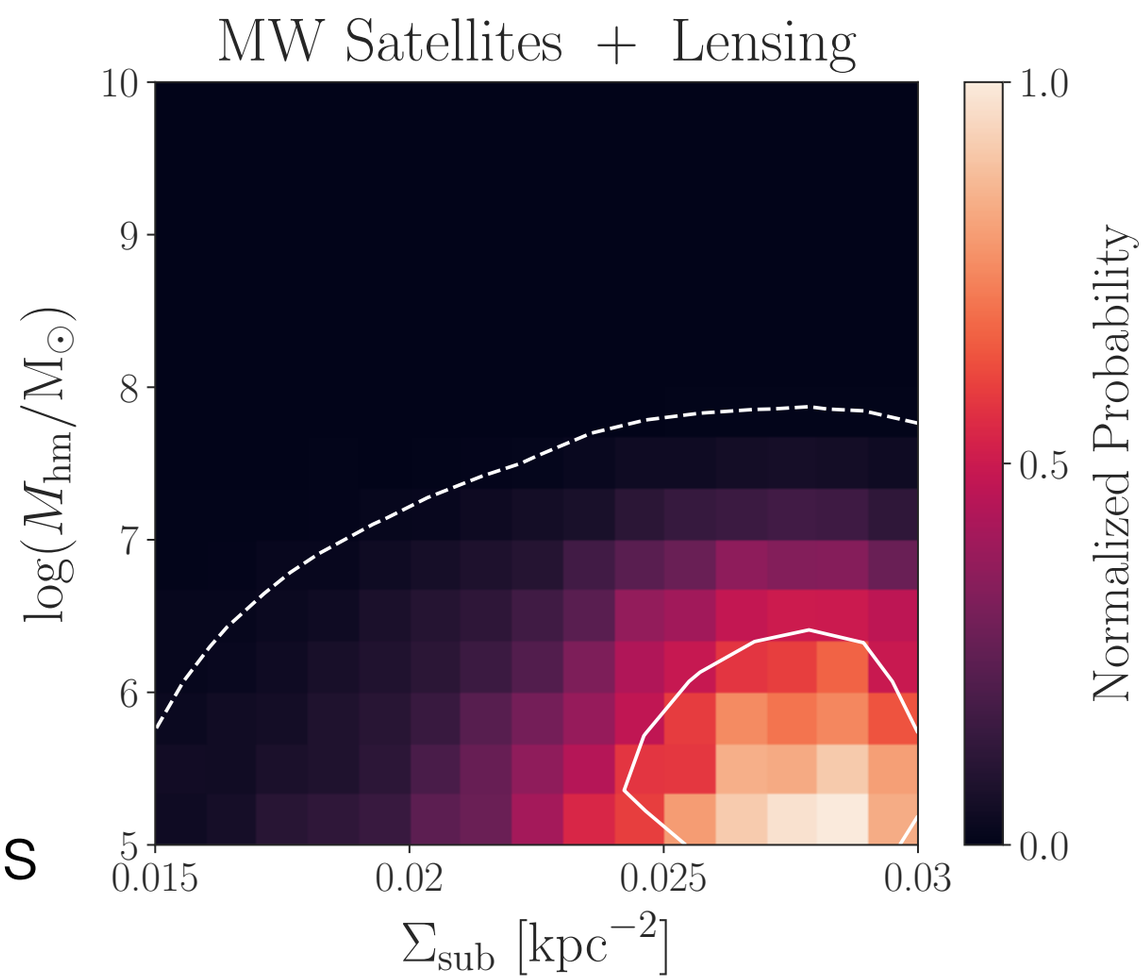
smooth preferred

clump preferred

Combining visible and invisible universe

self-consistent combined small-scale probe analysis

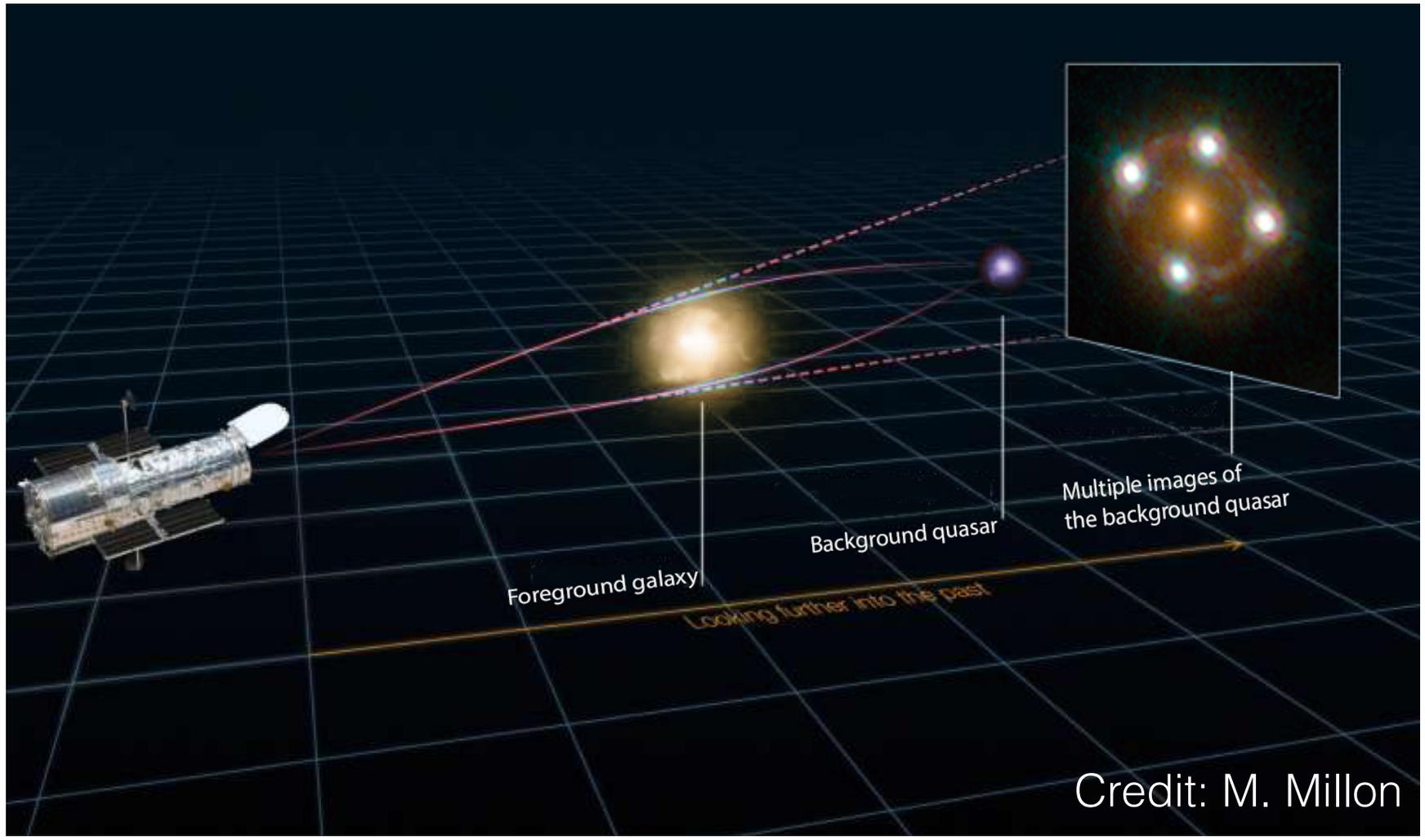
- Recent analyses of the Lyman-α forest, strong gravitational lenses, and Milky Way satellites achieve similar dark matter sensitivity
- Each individual measurement probes a **distinct aspect** of dark matter clustering
- **Joint analyses** of small-scale probes are key to break degeneracies and robustly detect non-CDM physics



thermal relic mass **> 9.7 keV** at 95% confidence

Nadler, **SB**, Gilman+2021, arXiv:2101.07810

Measuring the Hubble constant with time-delay cosmography



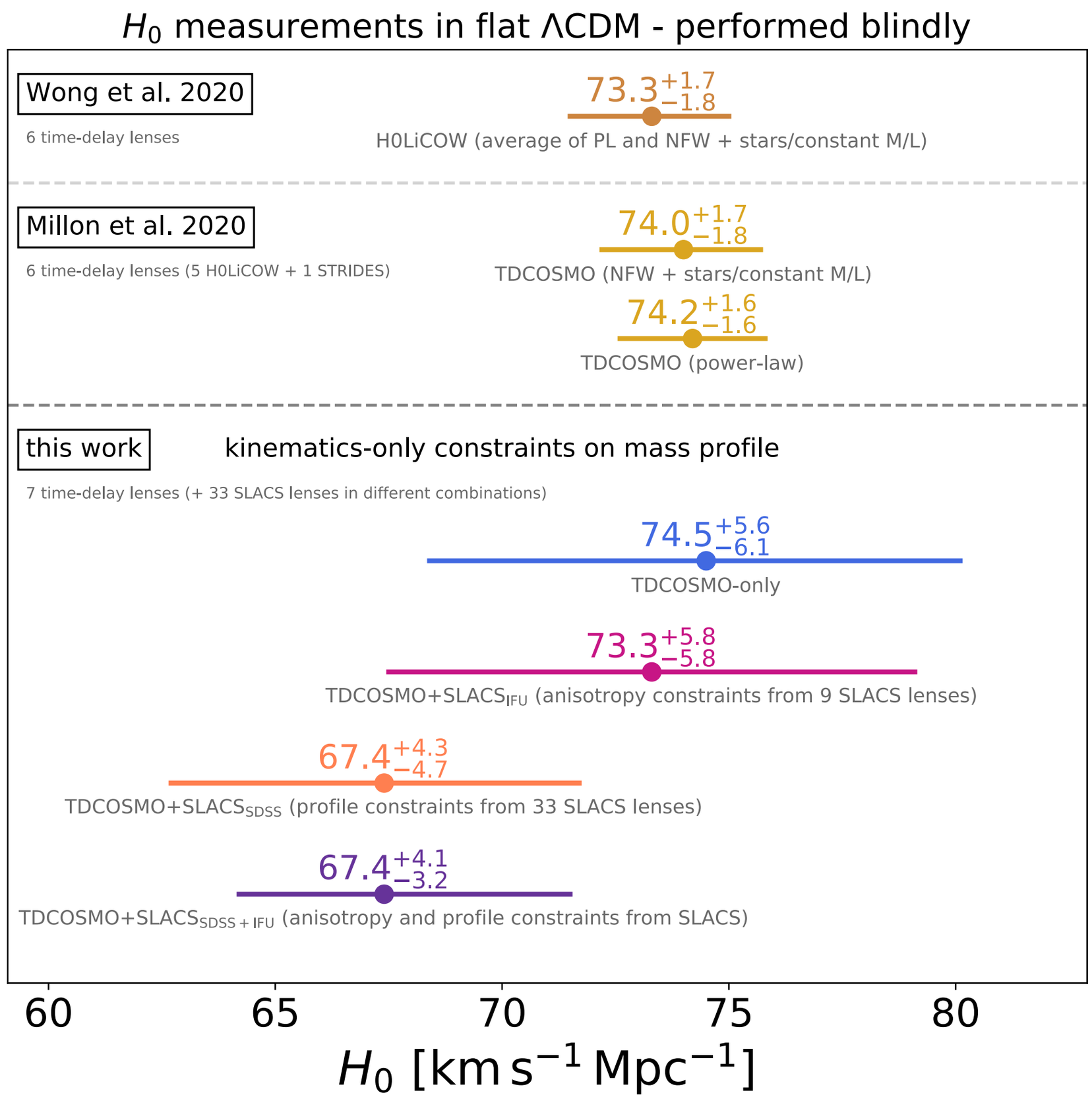
absolute scale

path difference

time delay

lensing potential

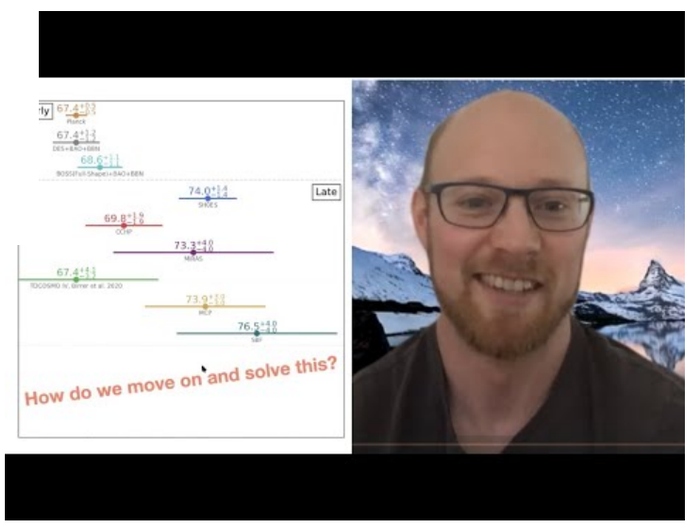
$$t(\boldsymbol{\theta}, \boldsymbol{\beta}) = \frac{(1+z_{\mathrm{d}})}{c} \frac{D_{\mathrm{d}} D_{\mathrm{s}}}{D_{\mathrm{ds}}} \left[\frac{(\boldsymbol{\theta} - \boldsymbol{\beta})^2}{2} - \psi(\boldsymbol{\theta}) \right]$$



SB+2020 TDCOSMO IV

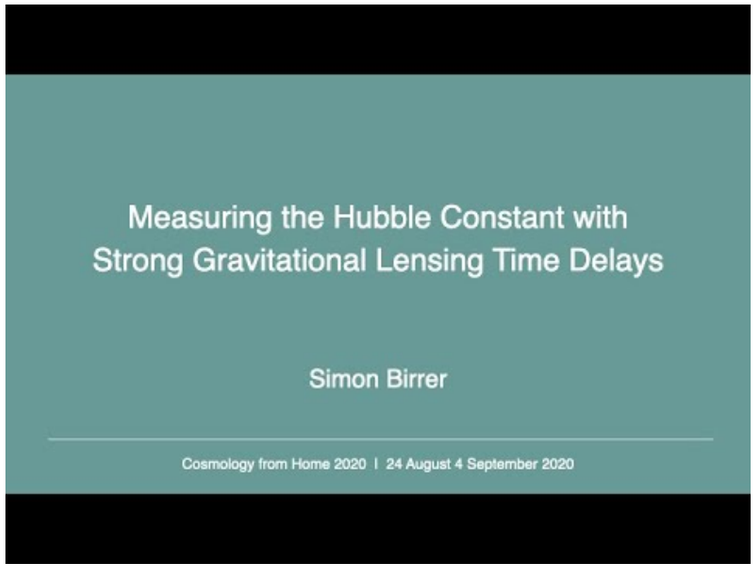
Talks on TDCOSMO results

Cosmology talk (16.07.2020)
(40 mins)



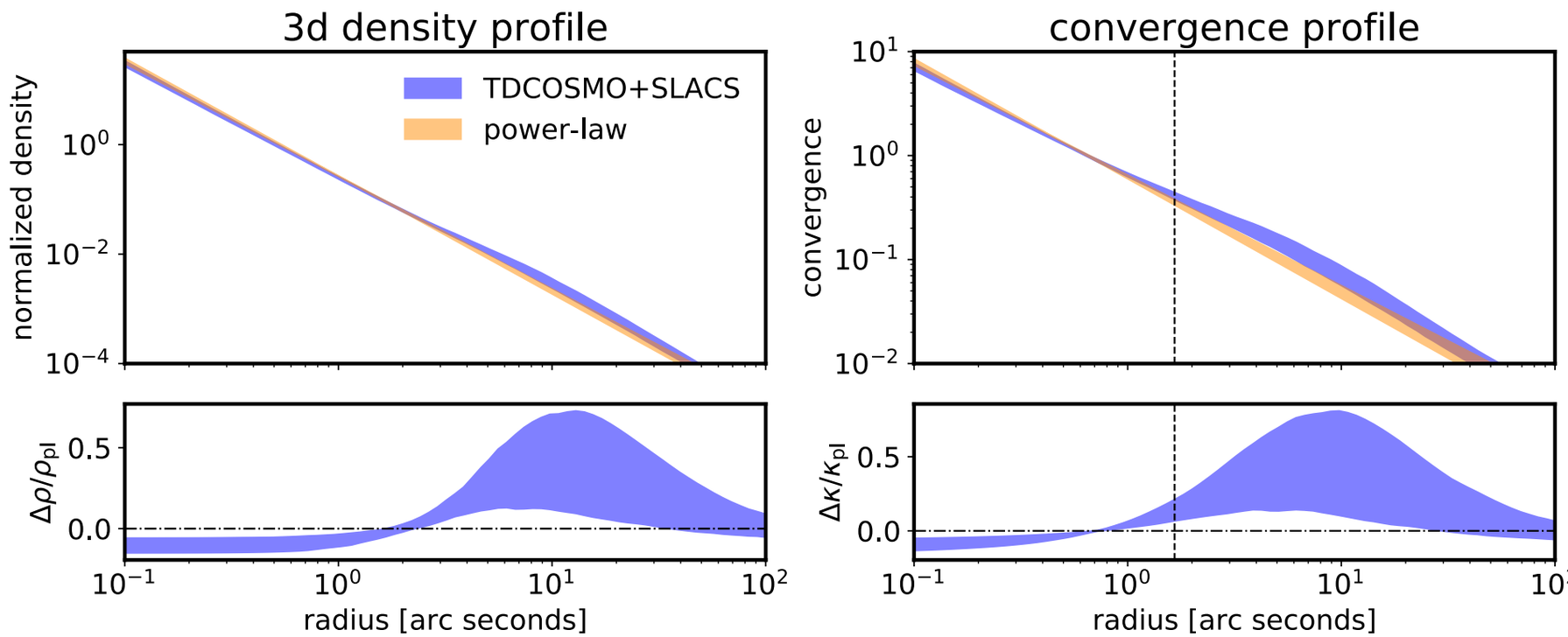
https://www.youtube.com/watch?v=QrdqbZv_tBs

Cosmology from home 2020
(20 mins)

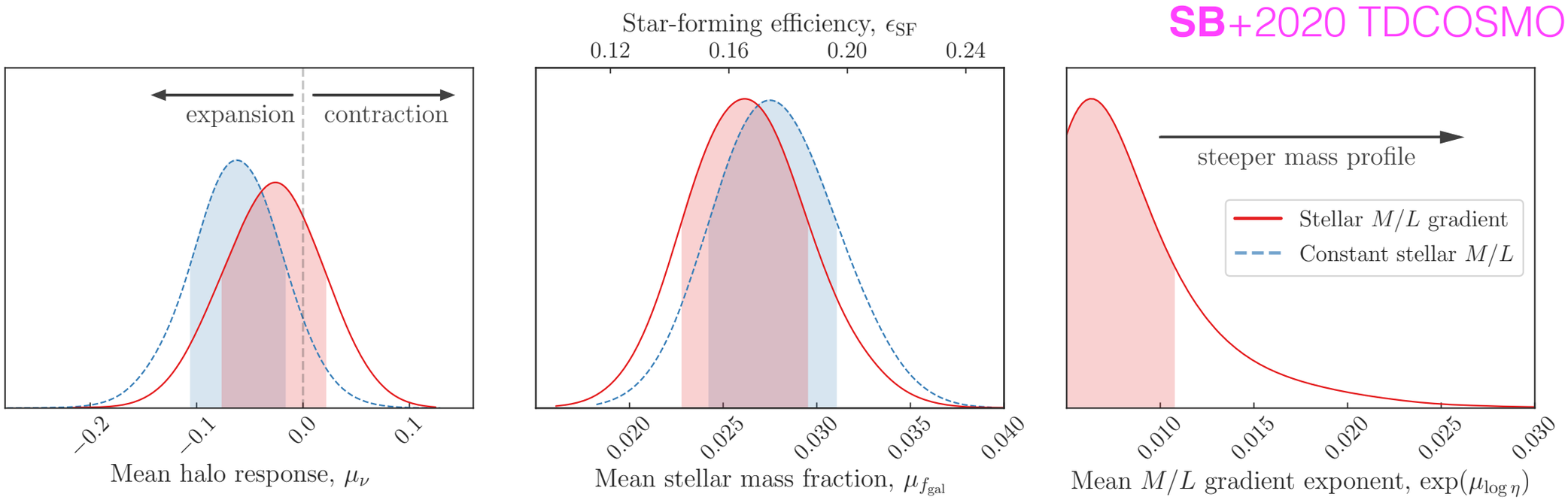


https://www.youtube.com/watch?v=2OeI5M7qS68

Constraining galaxy density profiles with lensing and kinematics



SB+2020 TDCOSMO IV



Shajib, Treu, **SB**+2020 2008.11724

Time Delay Cosmography (TDCOSMO) – H_0 determination

No assumption on the radial mass density profile of the lens galaxy

Galaxies are described by power law/stars+NFW mass profile

$73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}

H0LiCOW

$74.0^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}

TDCOSMO (NFW + stars/constant M/L)

$74.2^{+1.6}_{-1.6}$ km s^{-1} Mpc^{-1}

TDCOSMO (power-law)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property

$73.3^{+5.8}_{-5.8}$ km s^{-1} Mpc^{-1}

TDCOSMO+SLACS$_{IFU}$ (anisotropy constraints from 9 SLACS lenses)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy and radial mass density property

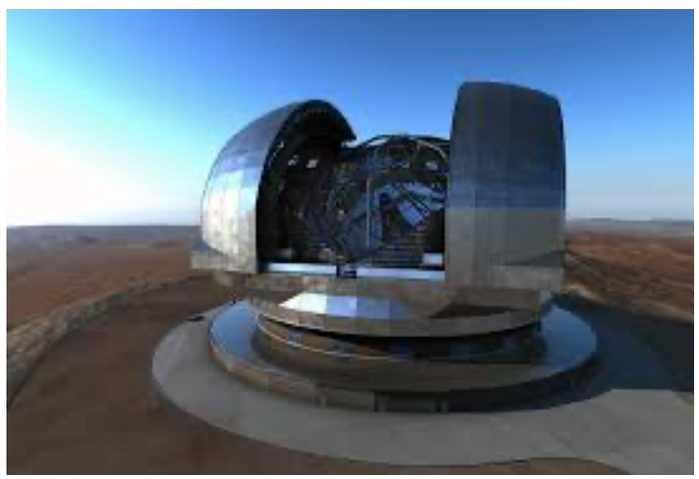
$67.4^{+4.1}_{-3.2}$ km s^{-1} Mpc^{-1}

TDCOSMO+SLACS$_{SDSS+IFU}$ (anisotropy and profile constraints from SLACS)

Birrer et al. 2020
Millon et al. 2020
Shajib et al. 2020
Wong et al. 2020
Chen et al. 2019

H0 - the near future

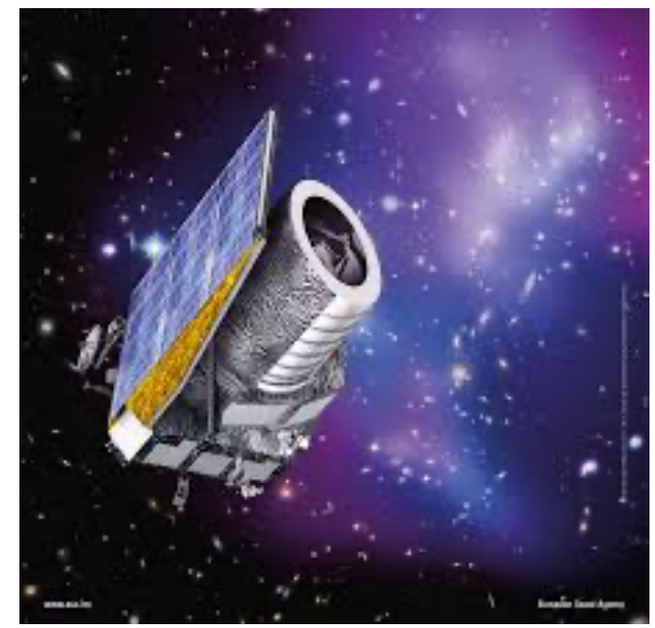
E-ELT, TMT, GMT



10’000+ strong lenses
200+ quasar lenses

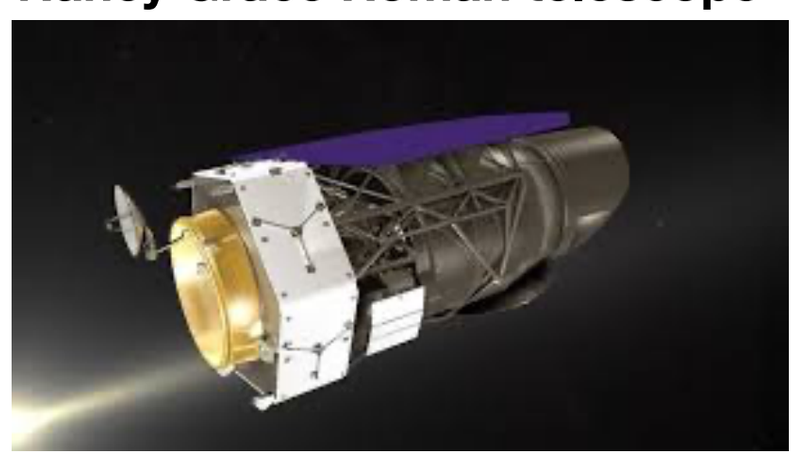
What data and what analysis is required to answer fundamental questions about the universe?

Euclid



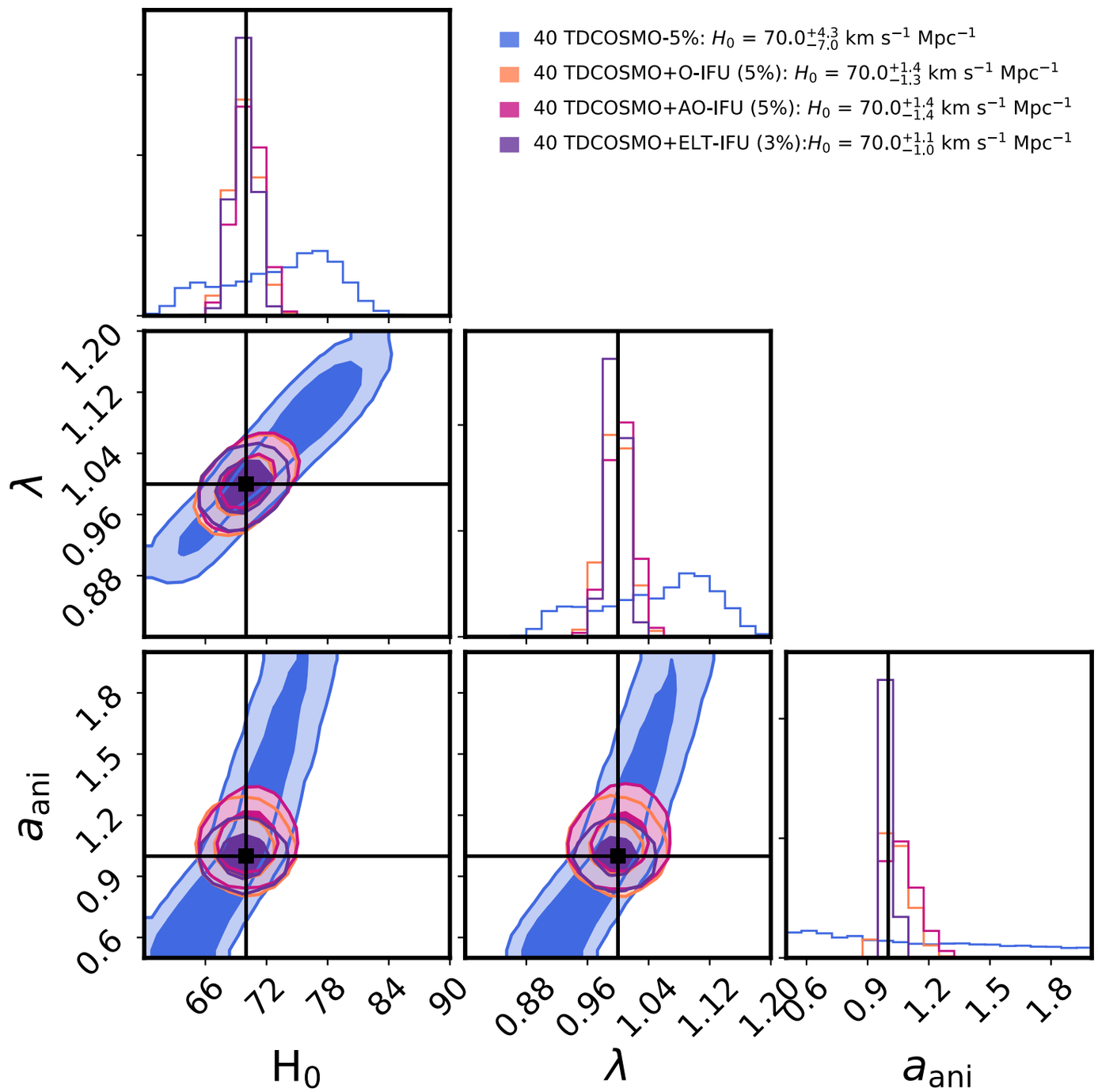
Vera Rubin Observatory

Nancy Grace Roman telescope



James Webb Space Telescope

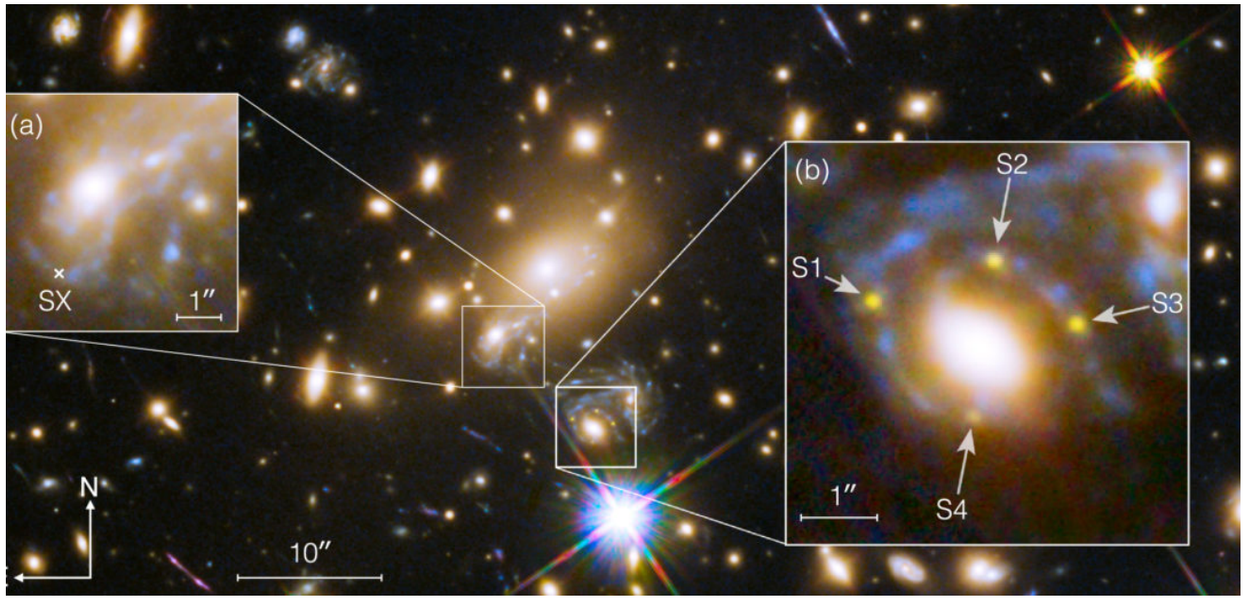
Spatially resolved stellar kinematics



- OSIRIS, KCWI, MUSE,…(programs underway)
- JWST (TDCOSMO proposal accepted, PI Yilidrim)
- ELT's
- Local galaxies

Lensed supernovae

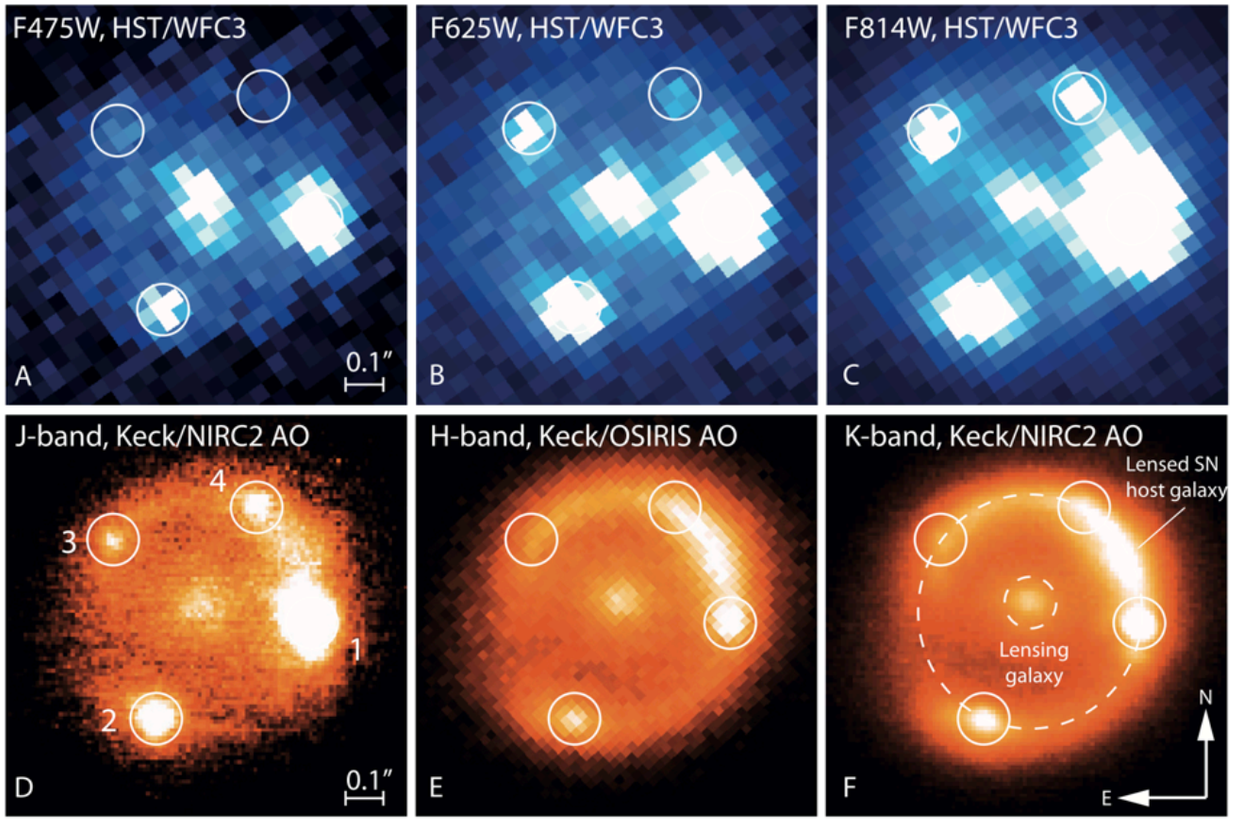
SN "Refsdal"



Kelly+2015

iPTF16geu

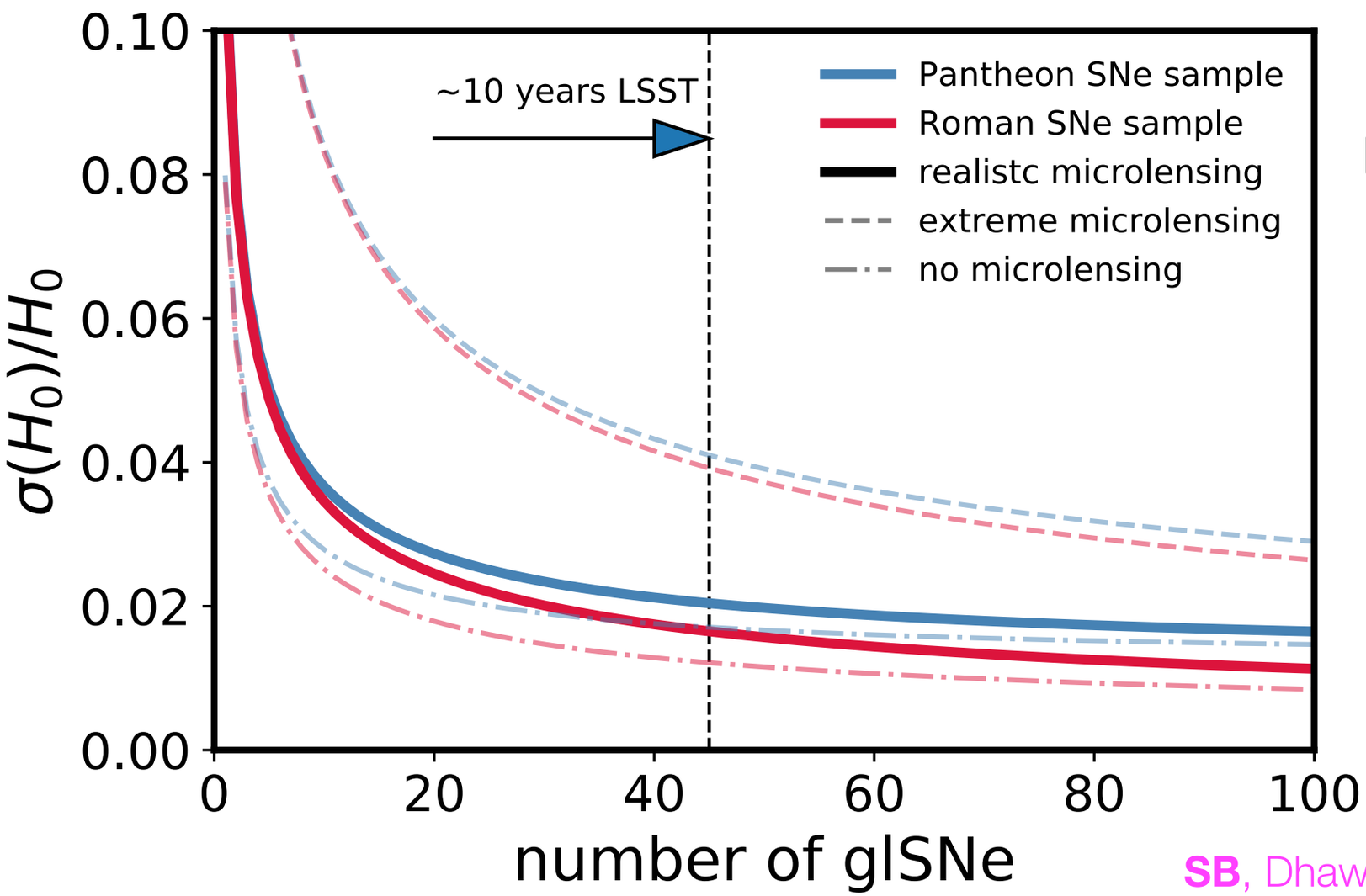
Goobar et al (2017), Science 356(6335):291–295



Goobar+2017

- characteristic light curve
- SNe fades away (no quasar contamination in kinematics)
- Standardizable magnification

The Hubble constant from lensed supernovae with standardizable magnifications

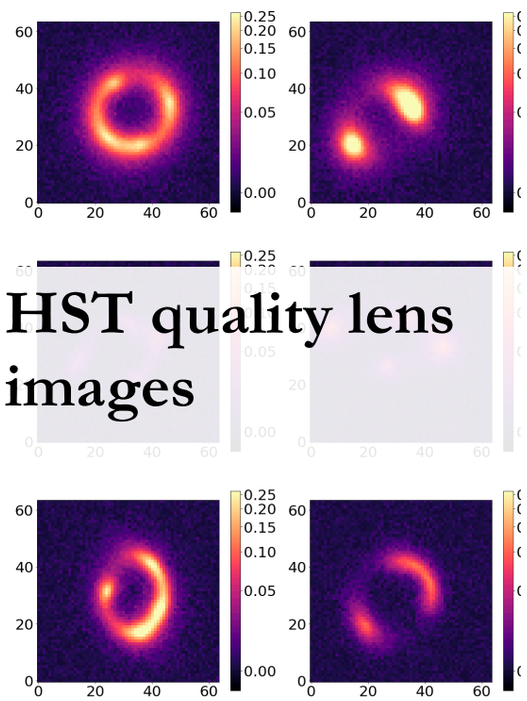


Micro-lensing?

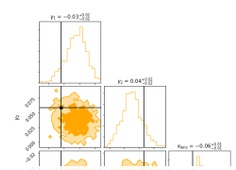
SB, Dhawan, Shajib in prep

Hierarchical Inference of Strong Lenses with Bayesian Neural Networks

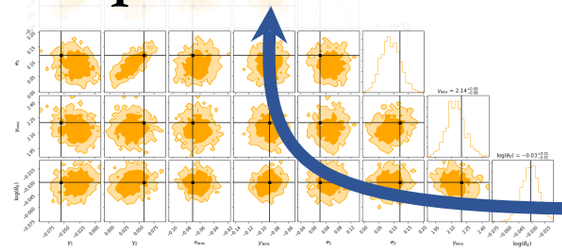
Assessing **speed** and **accuracy** of methods to scope with future data sets!

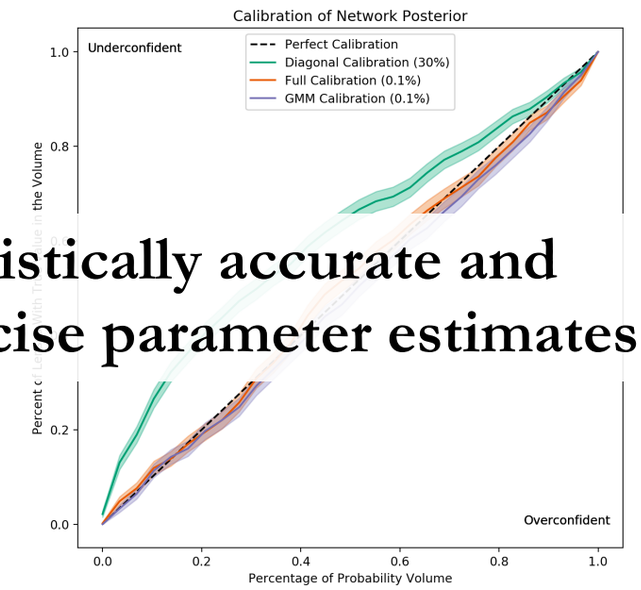


HST quality lens images

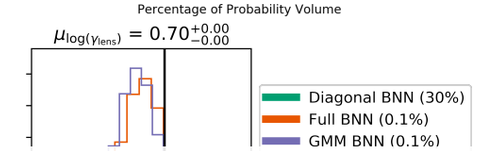


Sub-second posterior samples

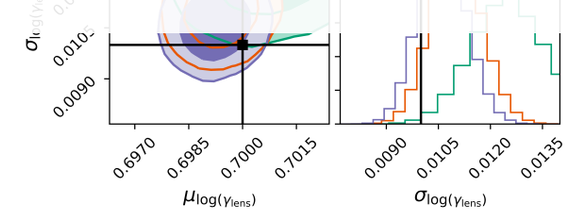




Statistically accurate and precise parameter estimates



Population constrains on matter profile and environment of thousands of lenses



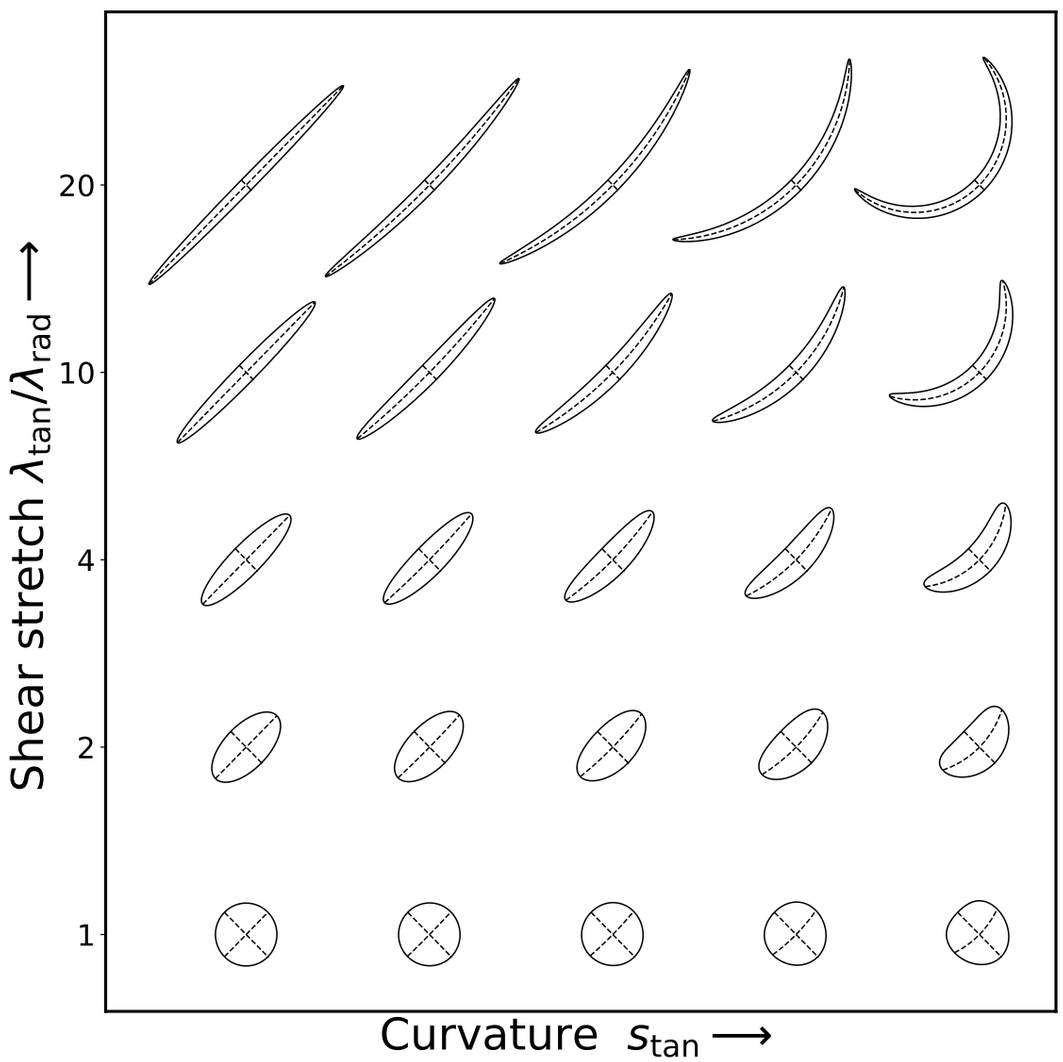
Carena-Wagner, Park, **SB**+2021
Park, Carena-Wagner, **SB**+2021
LSST-DESC collaboration

https://github.com/jiwoncpark/baobab
https://github.com/swagnercarena/ovejero
https://github.com/jiwoncpark/h0rton

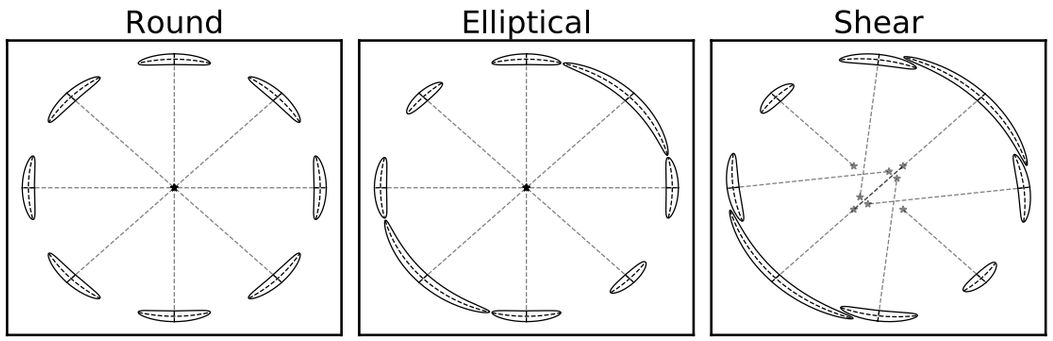
What does (strong) lensing measure?

Gravitational lensing formalism in a curved arc basis

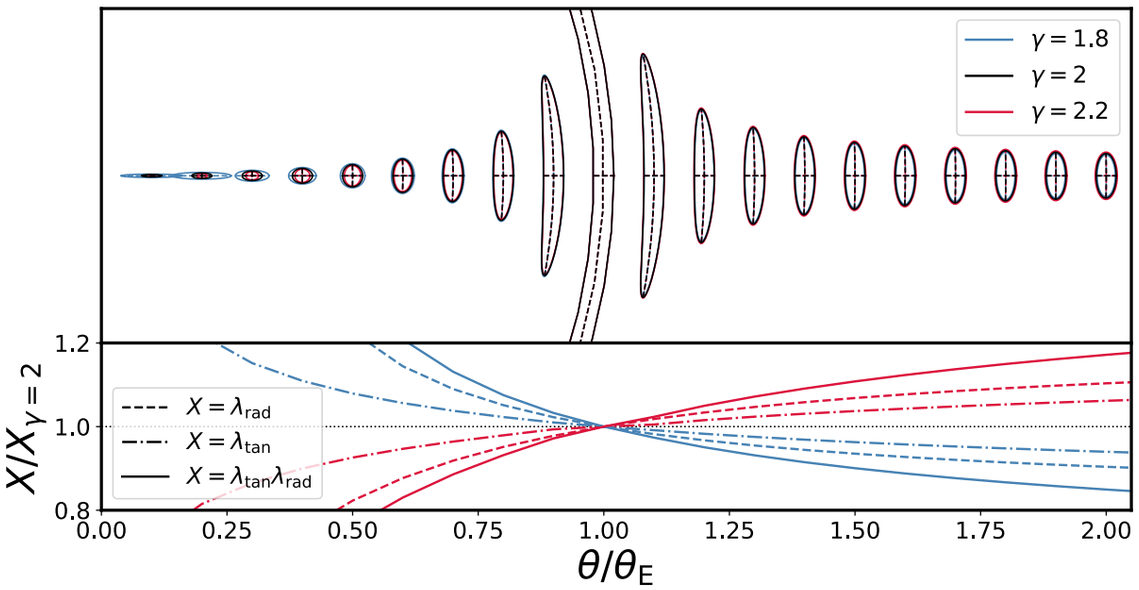
weak and strong lensing unified



Azimuthal constraints



Radial constraints



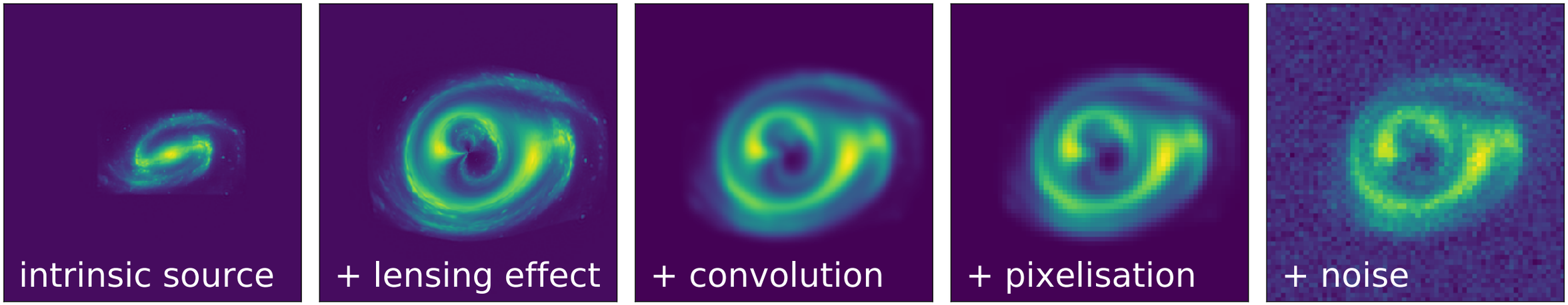
Birrer 2021, arXiv:2104.09522

Software

sibirrer / **lenstronomy**

Unwatch 14 | Star 89 | Fork 40

Code | Issues 8 | Pull requests 2 | Actions | Projects | Wiki | Security | Insights | Settings



pypi package 1.8.2 | build passing | docs passing | coverage 97% | license MIT | arXiv 1803.09746 | powered by AstroPy

JOSS 10.21105/joss.03283

Full software, scripts and data released for Birrer+19, 20, 21, …

Astropy affiliated!

astropy
A Community Python Library for Astronomy

The development is coordinated on GitHub and contributions are welcome. The documentation of `lenstronomy` is available at readthedocs.org and the package is distributed over PyPI.

Installation

SB+2015, **SB** & Amara 2018, **SB**+2021

```
$ pip install lenstronomy --user
```


https://github.com/sibirrer/lenstronomy