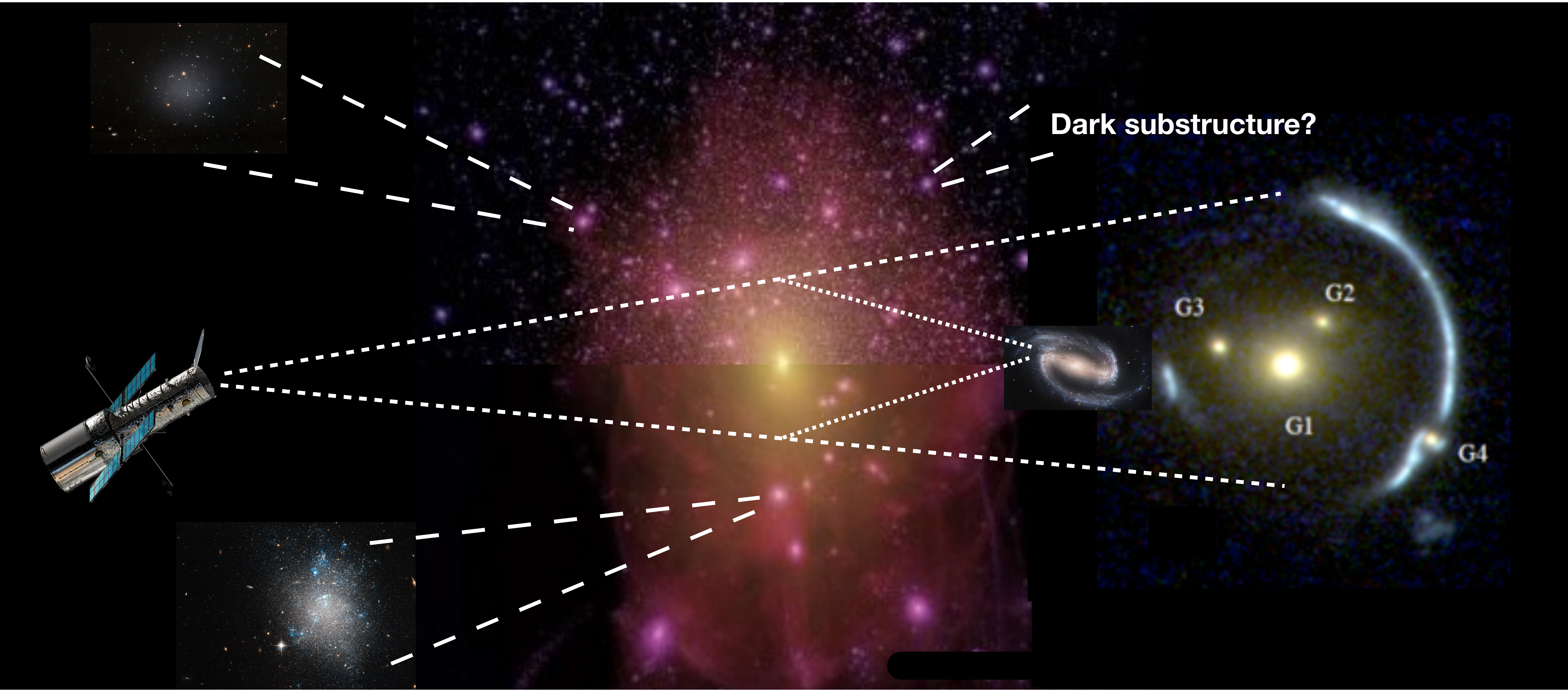
Stanford University

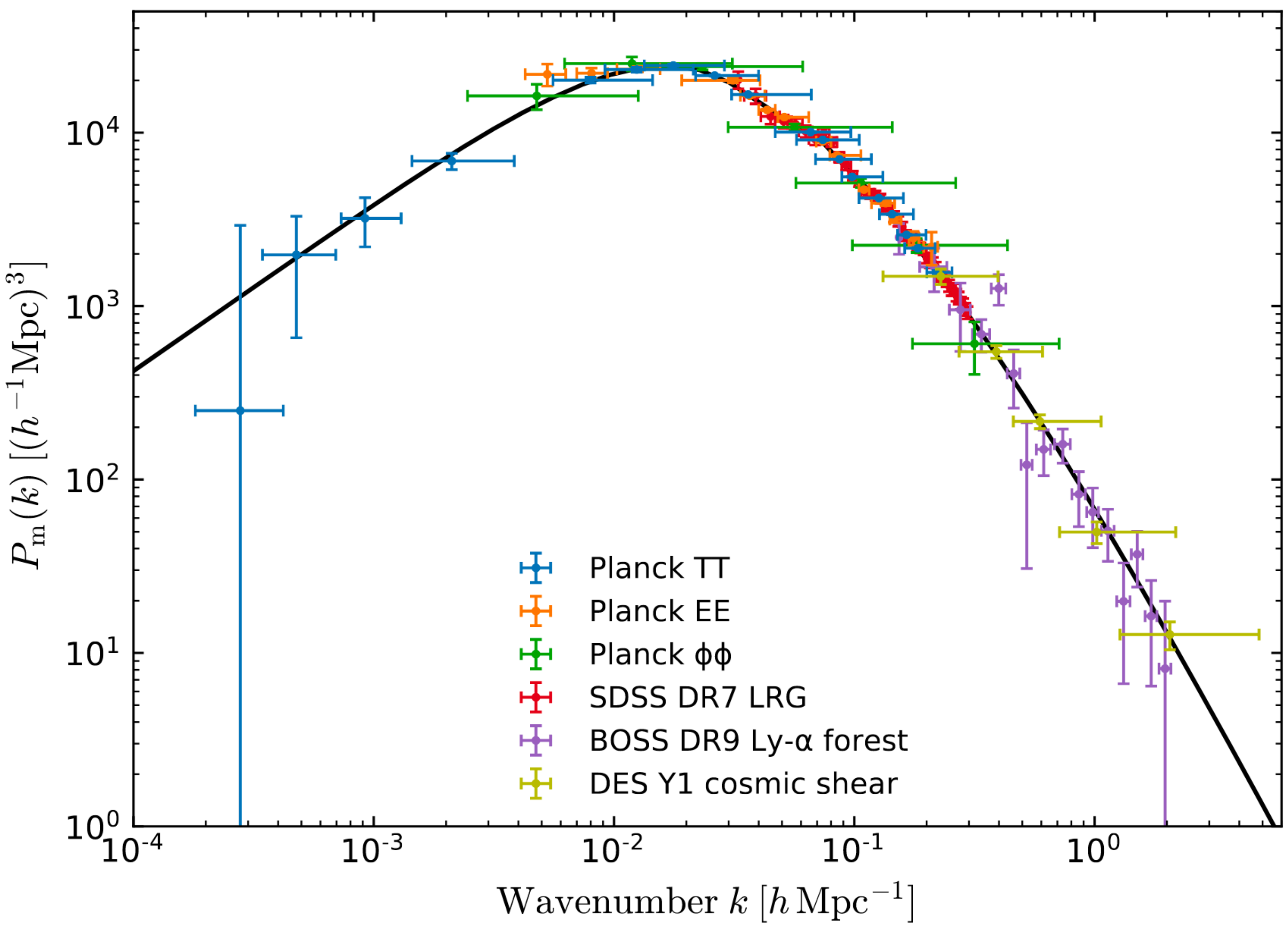
Probing Dark Matter and Dark Energy with strong gravitational lensing



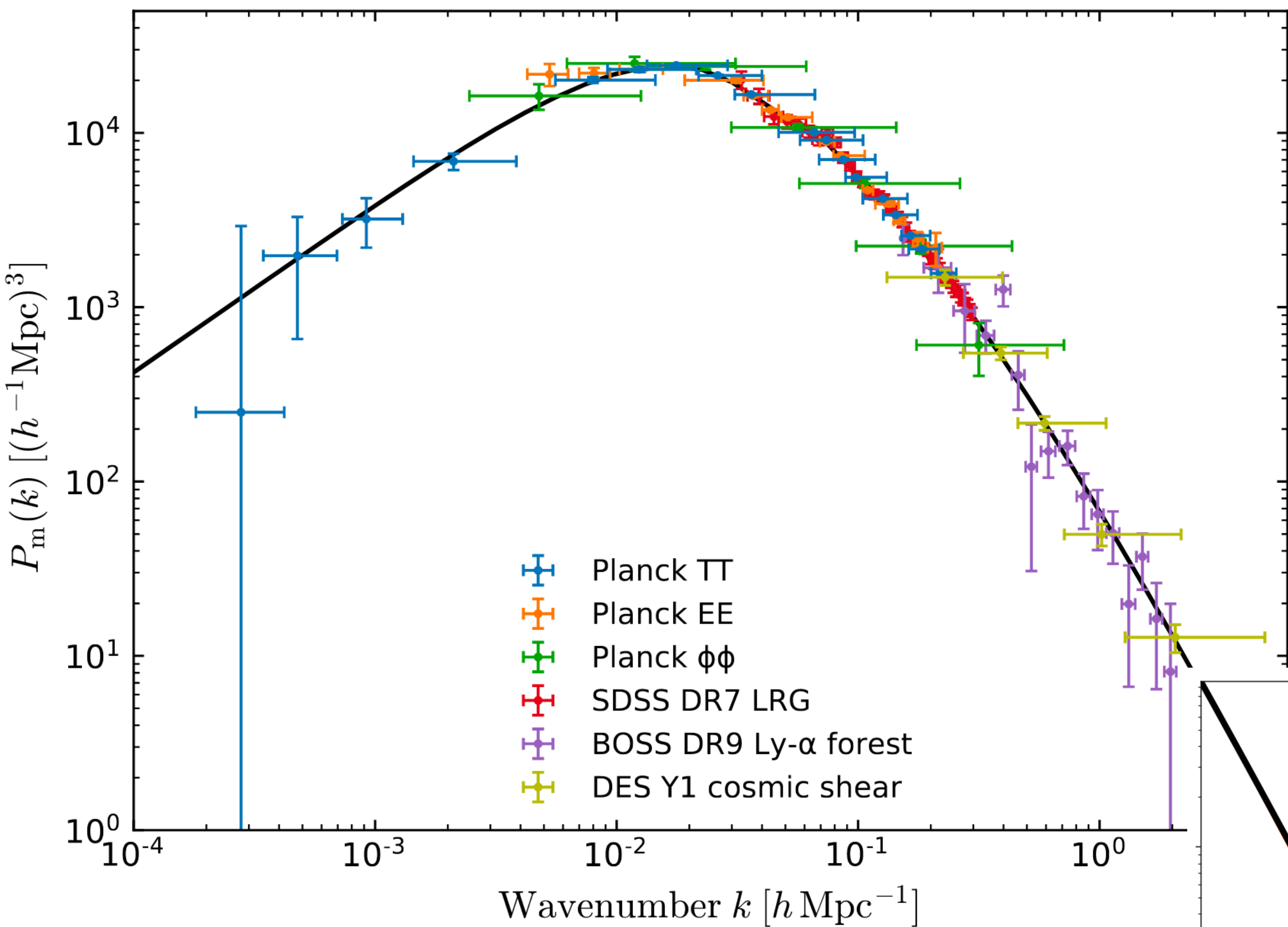
Simon Birrer

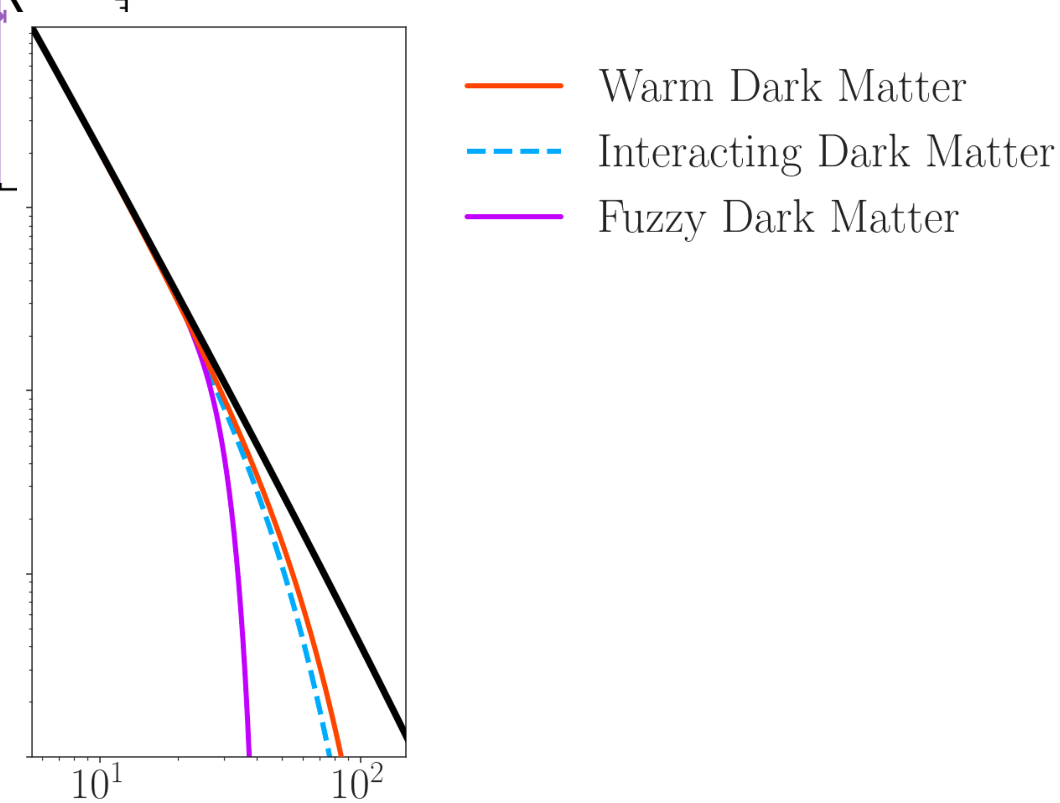
PPC 2021, May 19th 2021

Dark Matter and Structure Formation



Planck Collaboration 2019





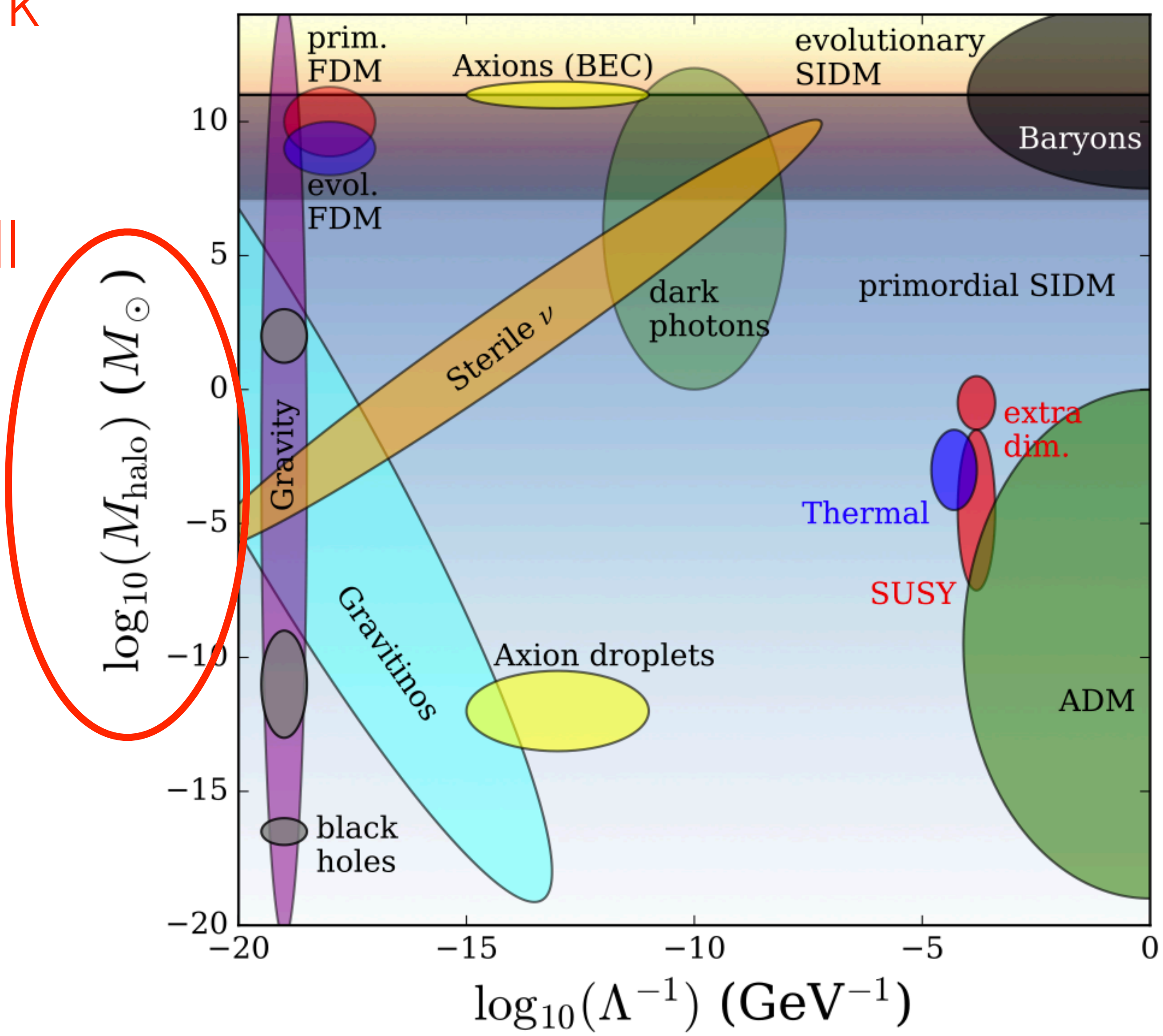
- Small scales contain information about a variety of dark matter physics: we are compelled to search there!

- **How do we measure the smallest scales?**

Planck Collaboration 2019
adopted by E. Nadler A. Drlica-Wagner

Dark Matter and Structure Formation

Microphysical dark matter properties affect structure formation on small scales



Buckley & Peter 2018

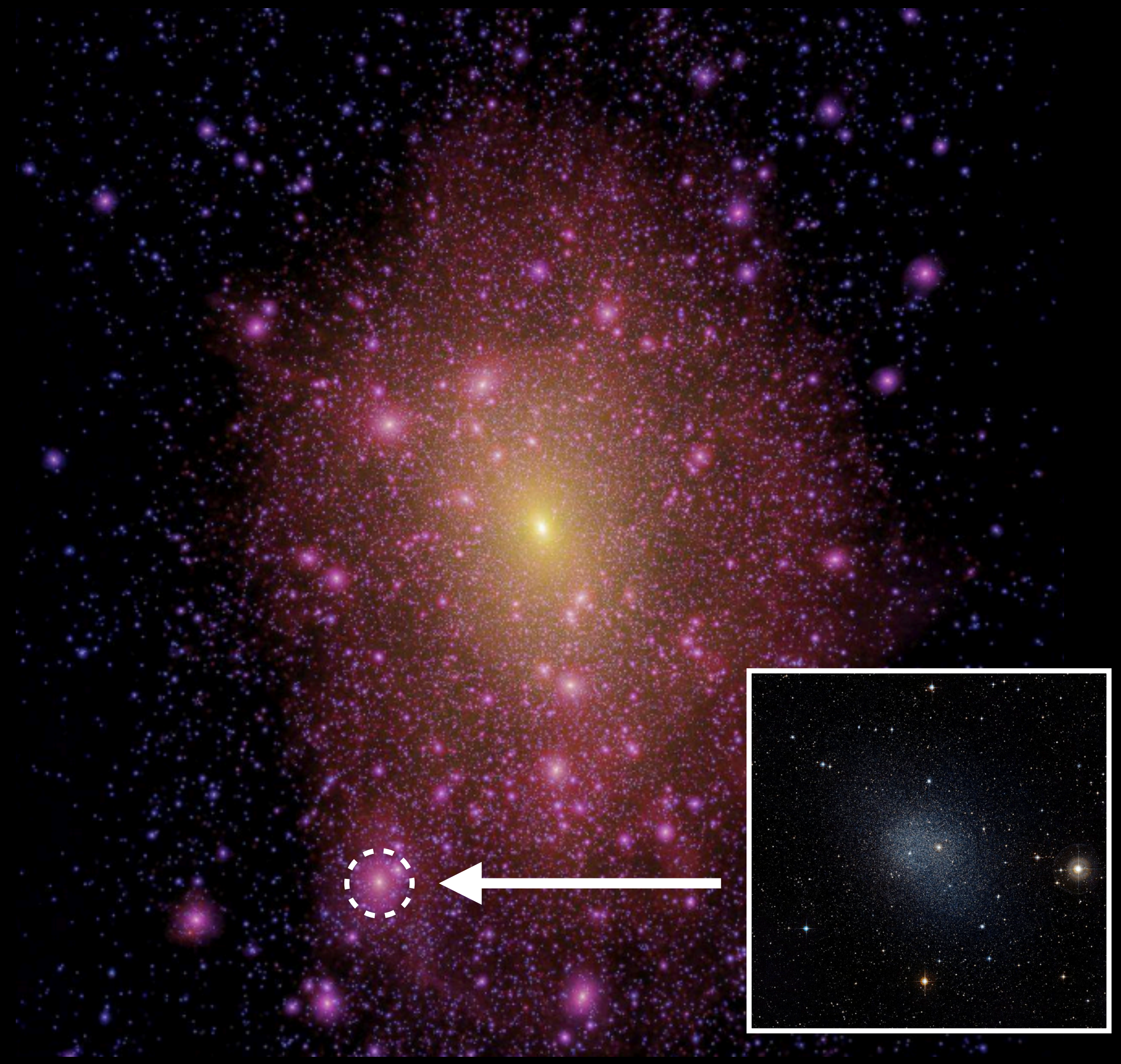
Probing Dark Matter

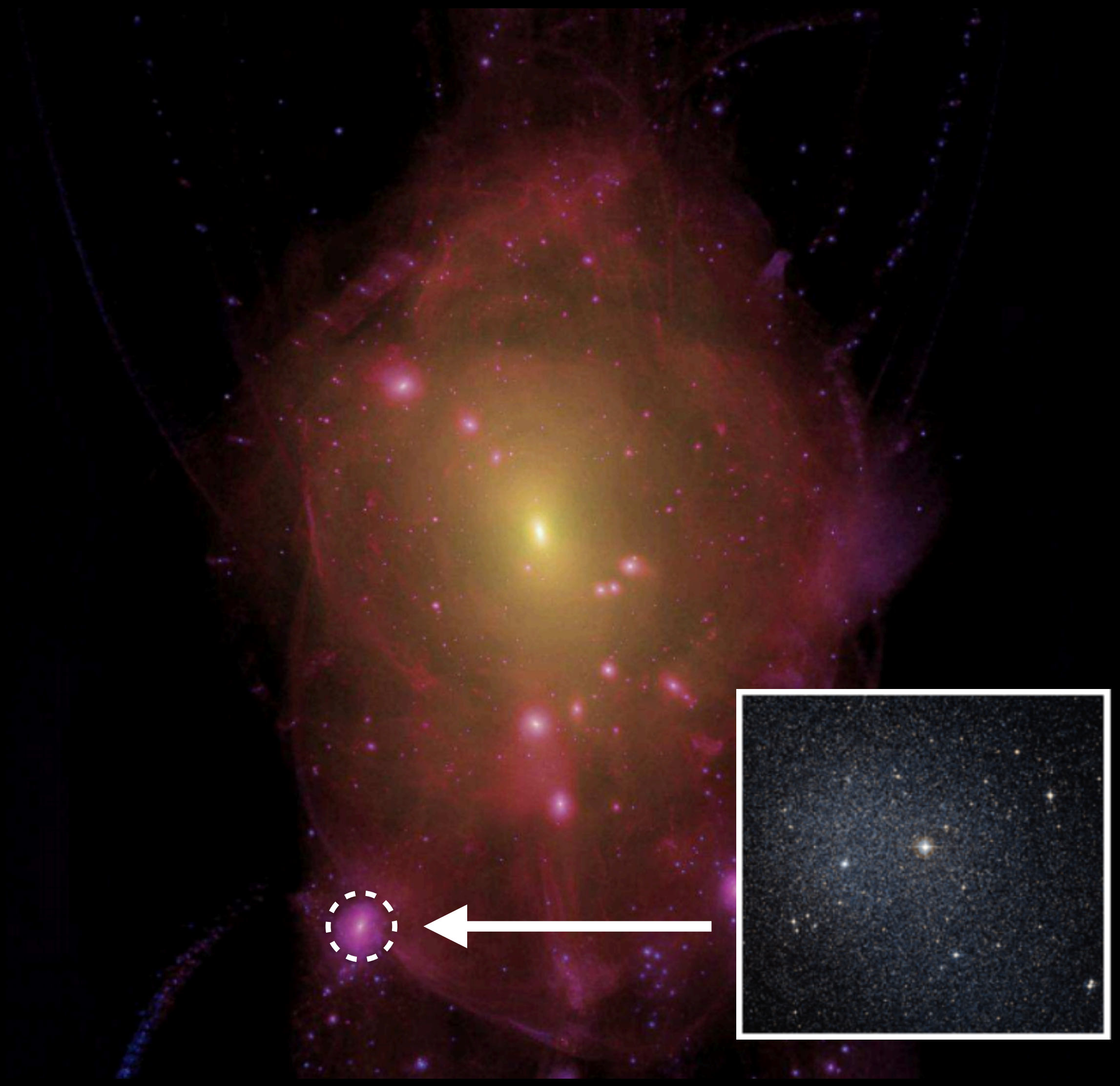
CDM

WDM

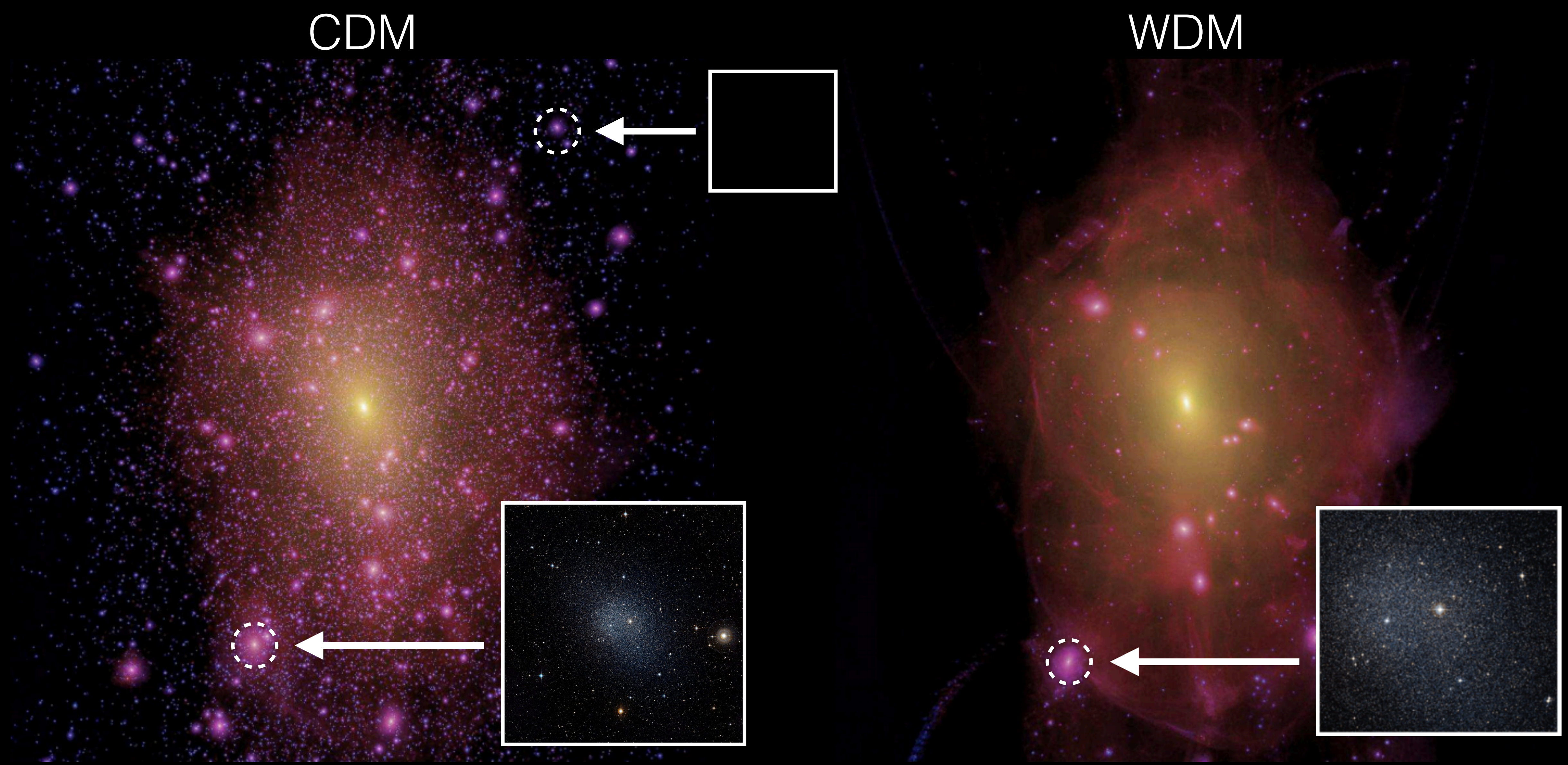
Lovell et al. 2011

Probing Dark Matter



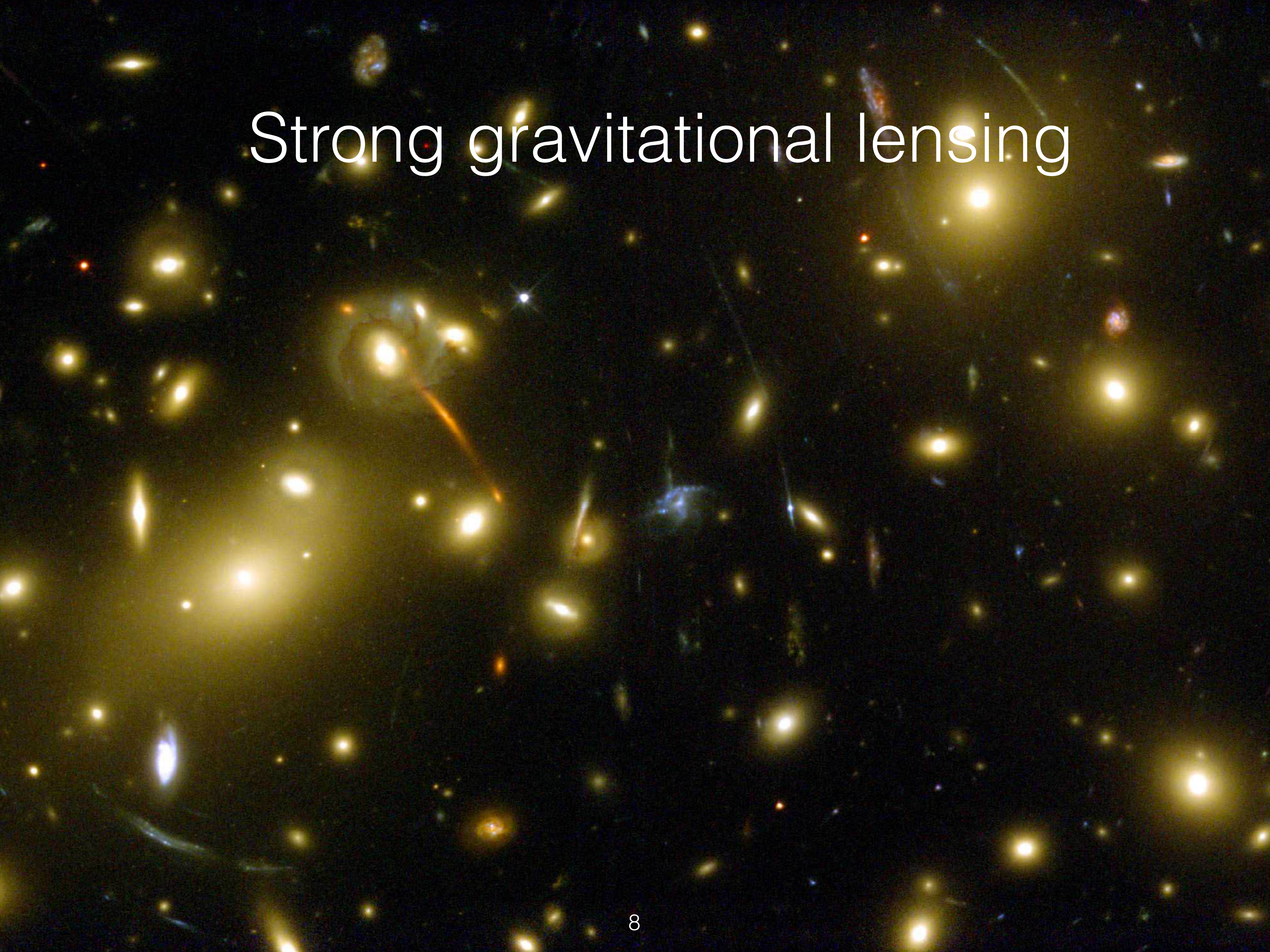


What if structure is completely dark?

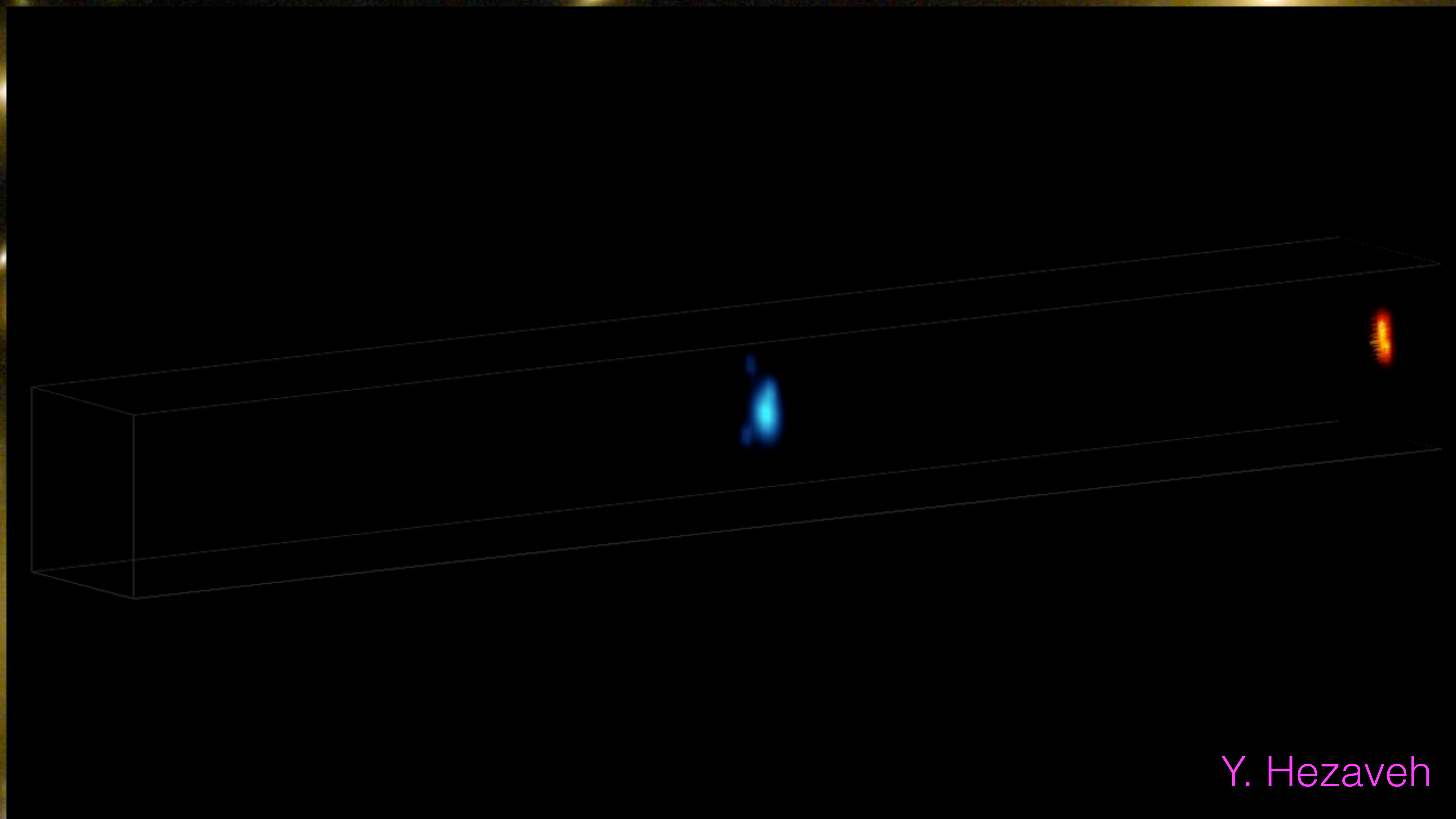


CDM predicts completely dark halos!

Strong gravitational lensing



Strong gravitational lensing

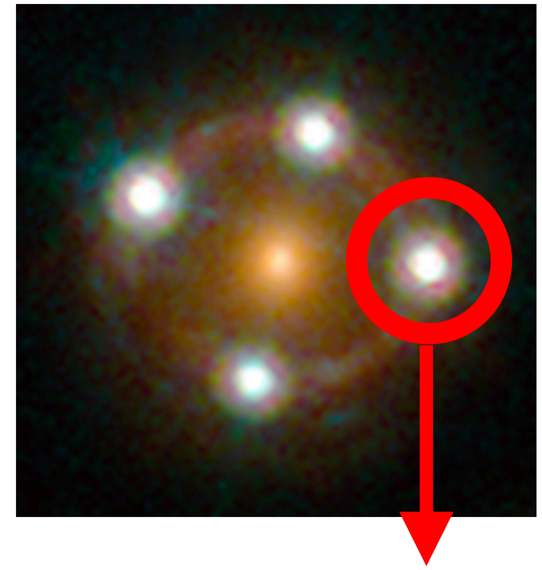


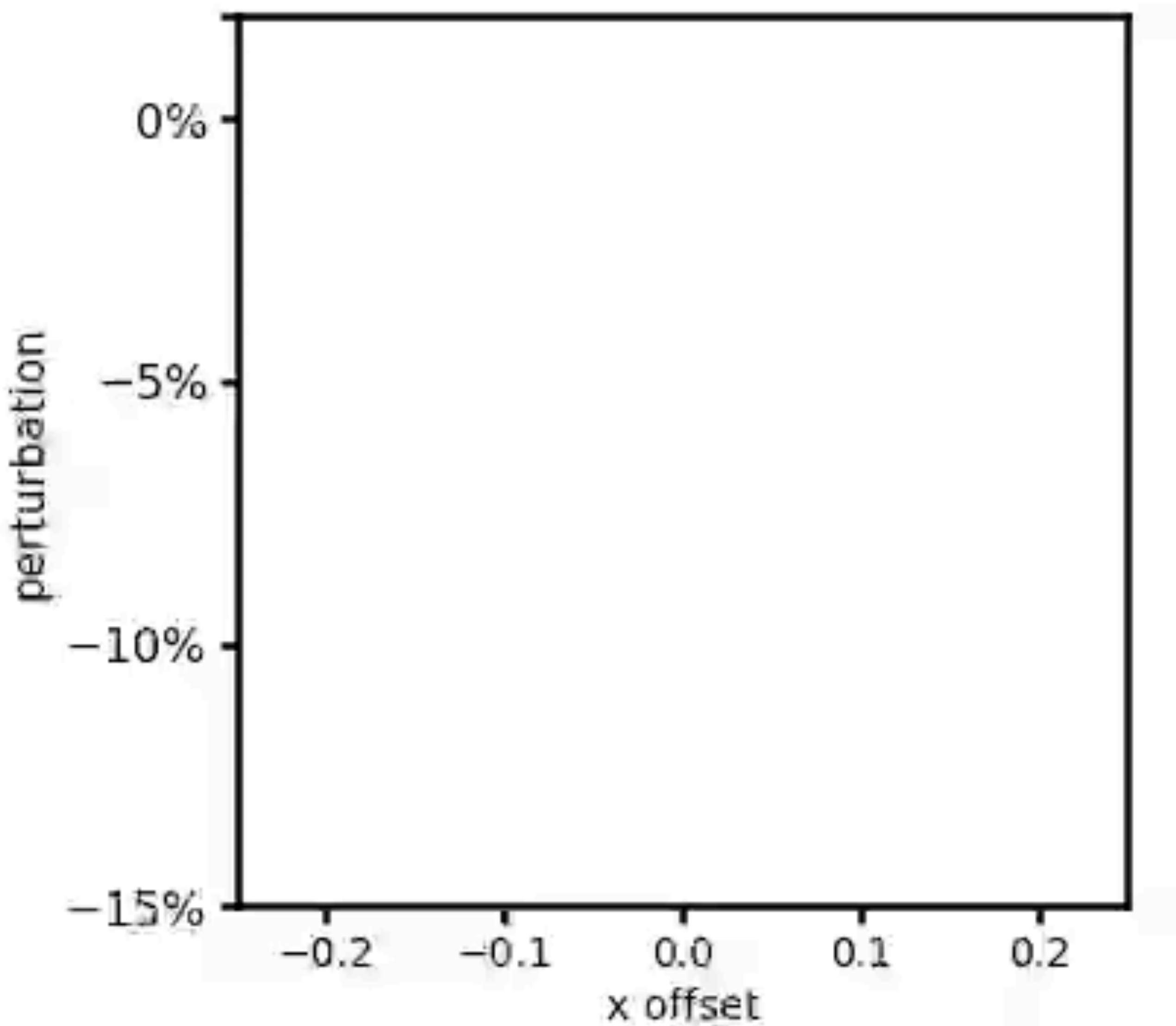
Dark Matter and Structure Formation

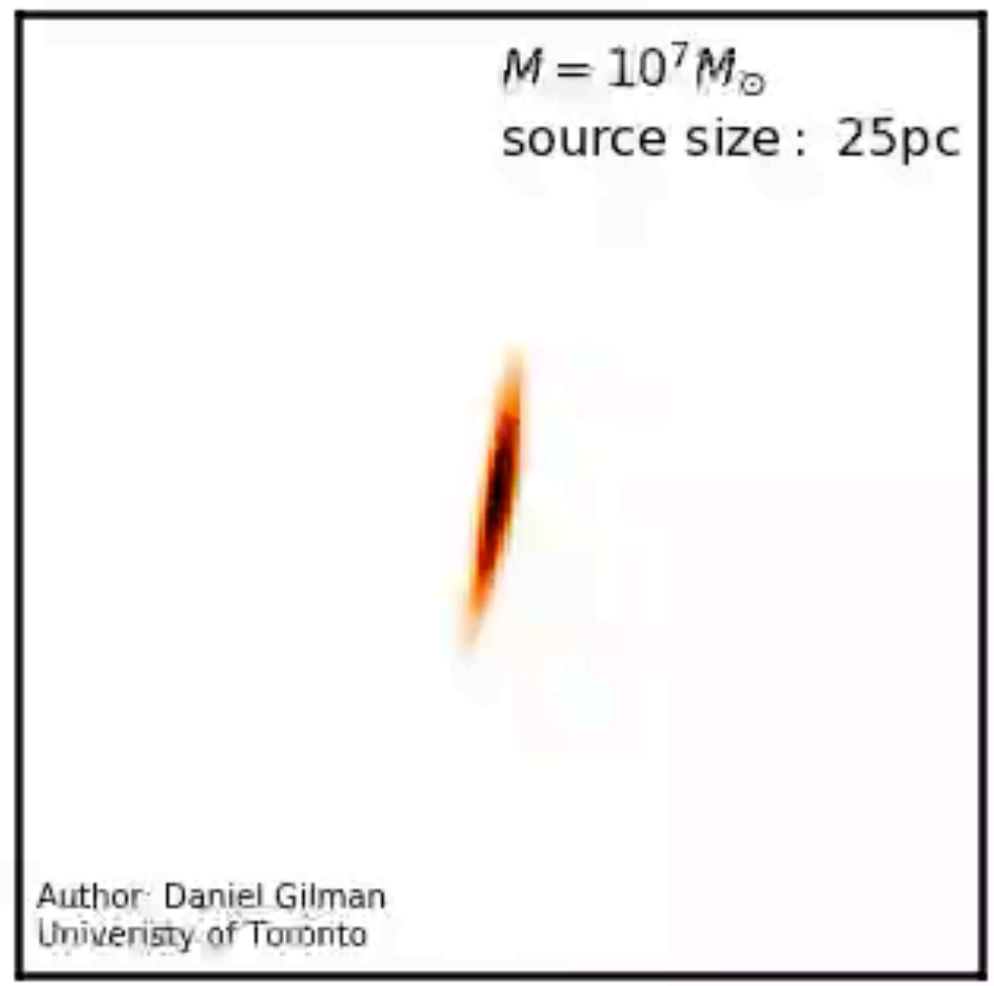
- **Dark matter** as a collision-less cold fluid is extremely successful in describing cosmological observations
- The sub-galactic scales offer a **laboratory for micro-physical properties** of dark matter
- Below the galaxy-formation limit, only gravitational probes are sensitive to dark matter physics, in particular **strong gravitational lensing**

…end of part 1

Flux-ratios are sensitive to completely dark structure



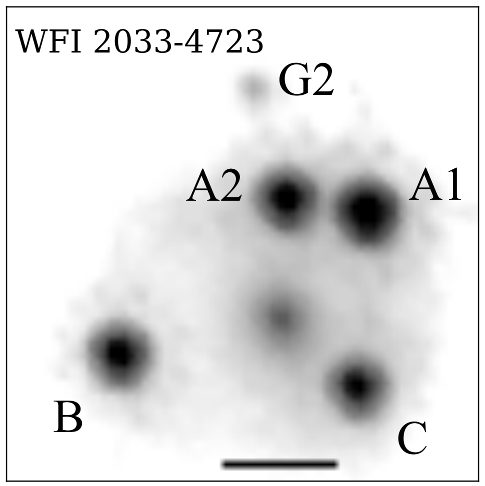


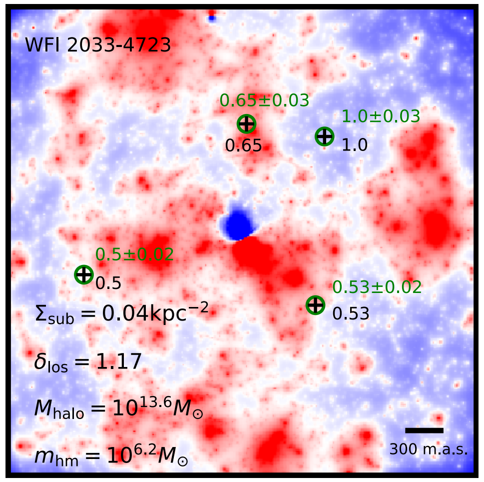


Mao & Schneider 1998, Dalal & Kochanek 2002, Moustakas & Metcalf 2003, Nierenberg+2014, 2017 Hsueh+2016, 2017, 2019, Gilman, **SB**+2018, 2019a,b,c

End-to-end inference of dark matter microphysics

Flux ratio statistics



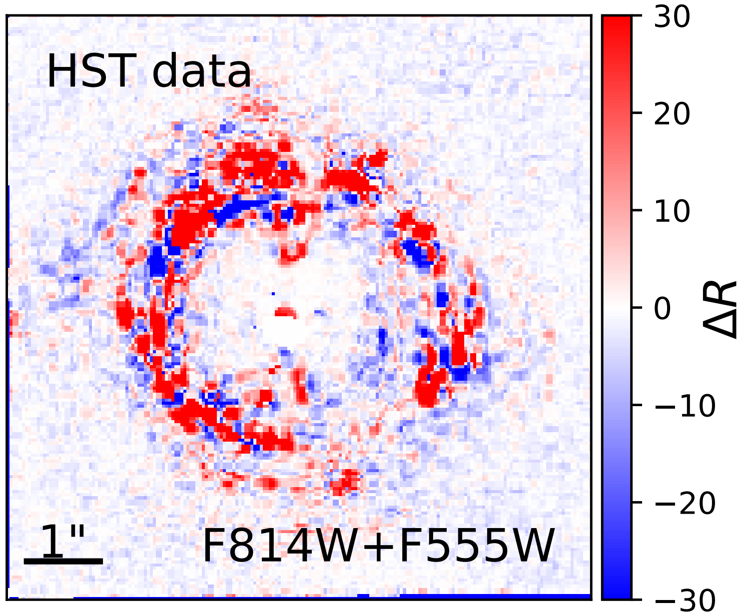


Forward modeling and **simulation based inferences** with Approximate Bayesian Computing

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

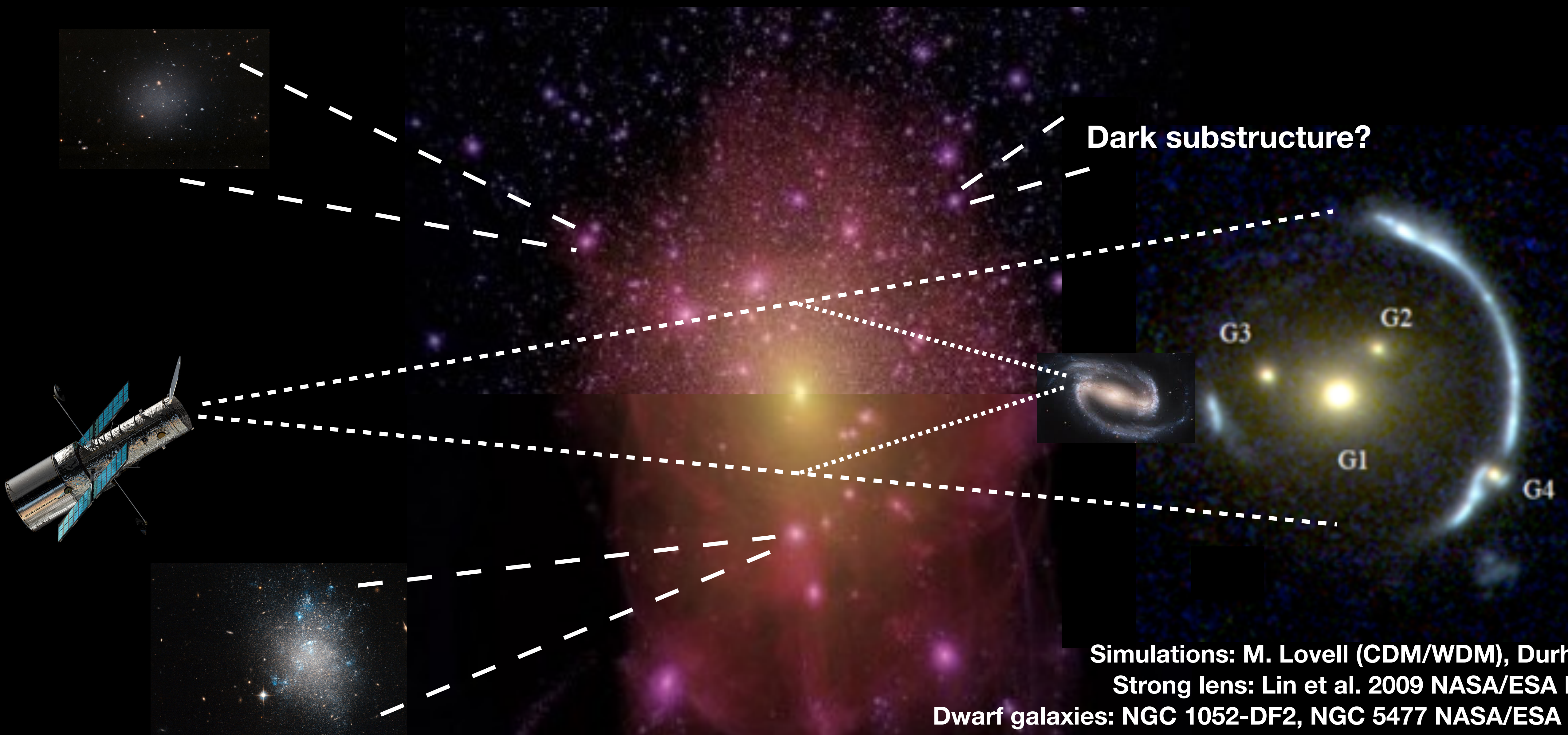
SB+2015, SB+2017a, b, Gilman, SB+2019, 2020a, b

Gravitational imaging



Combining visible and invisible universe

a self-consistent combined small-scale probe analysis



Simulations: M. Lovell (CDM/WDM), Durham,
Strong lens: Lin et al. 2009 NASA/ESA HST,
Dwarf galaxies: NGC 1052-DF2, NGC 5477 NASA/ESA HST

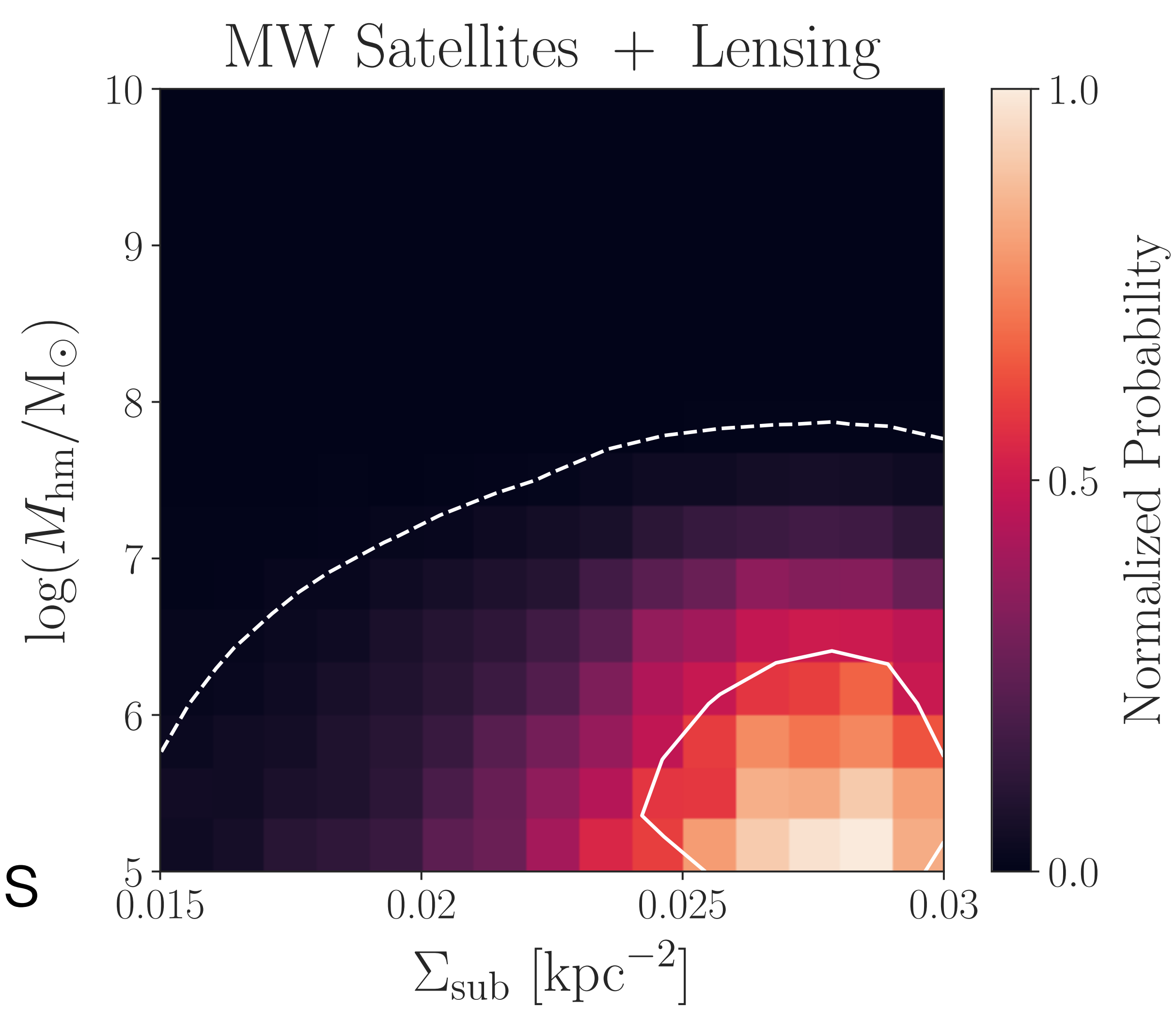
Combining visible and invisible universe

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

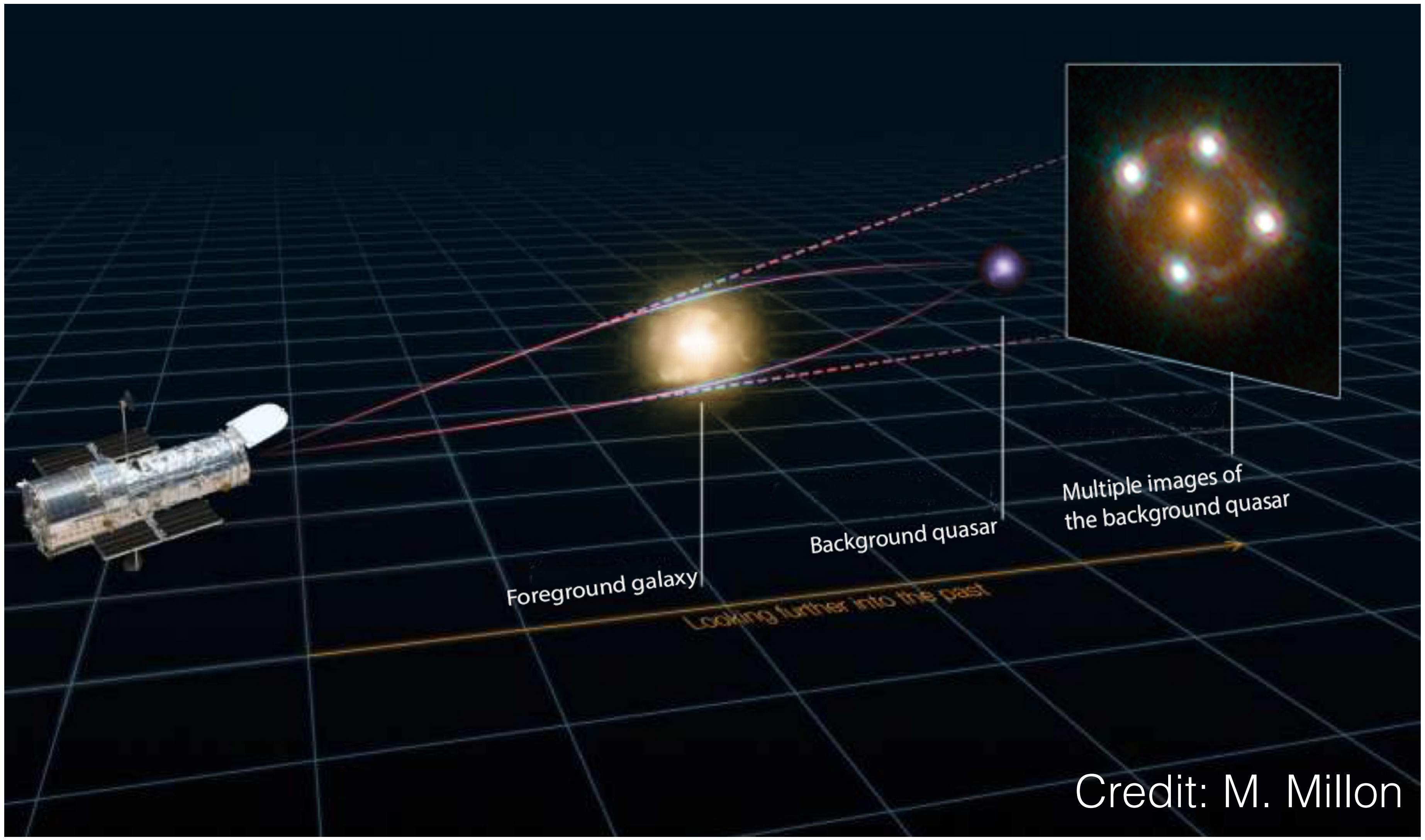
- **Joint analyses** of small-scale probes are key to break degeneracies and robustly detect non-CDM physics



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

Nadler, **SB**, Gilman et al. arXiv:2101.07810

Measuring the Hubble constant with time-delay cosmography



absolute scale

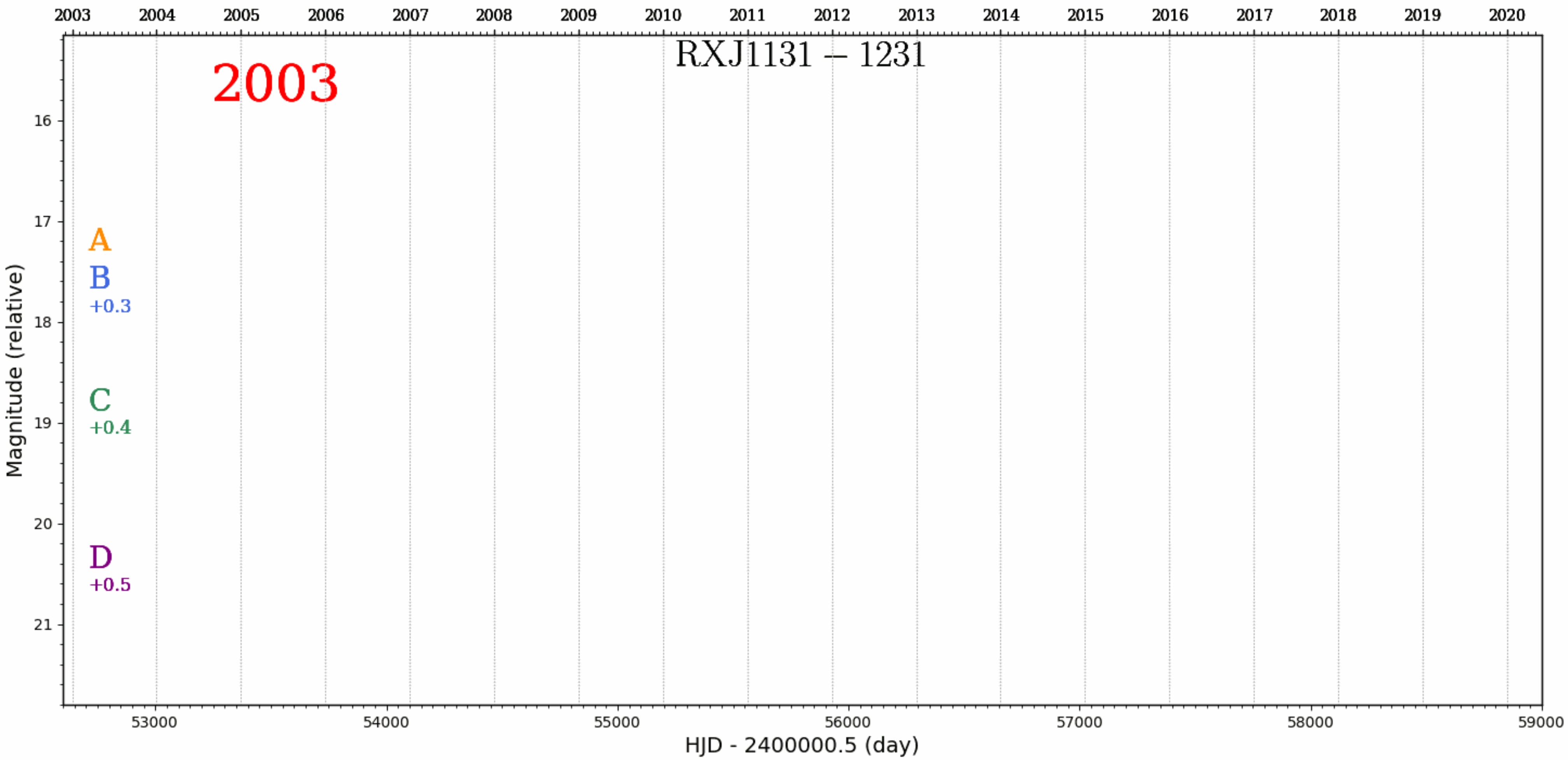
path difference

time delay

lensing potential

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

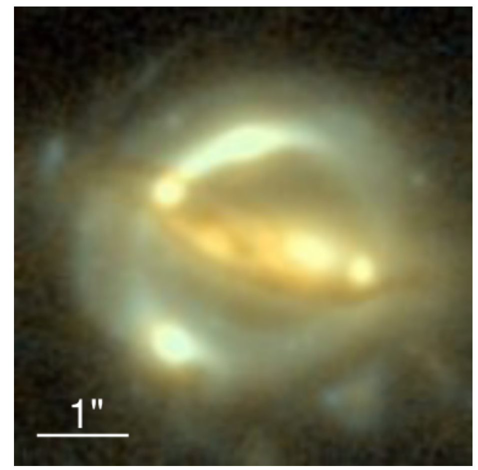
Measuring time delays with long-term monitoring



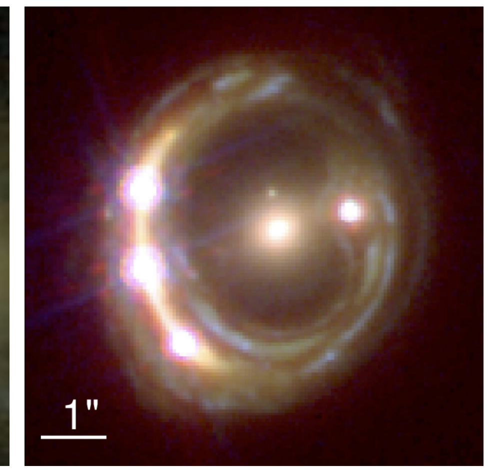
credit: Courbin & Millon

TDCOSMO project
(H0LiCOW+STRIDES+SHARP+COSMOGRAIL)

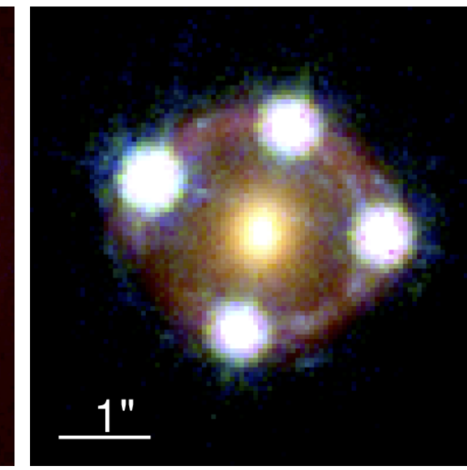
- Detailed analysis of several time-delay lenses (Suyu+2017)
  - long term monitoring from COSMOGRAIL (Courbin+2011) for accurate time delays
  - high-resolution *HST* imaging for detailed lens modeling
  - wide-field imaging/spectroscopy to characterize mass along LOS
- Goal is to constrain H_0 to ~few % precision
- Seven lenses have been analyzed (Suyu+2010, 2013; Wong+2017, Birrer+2019, Rusu+2019, Chen+2019, Shajib+2019), more coming



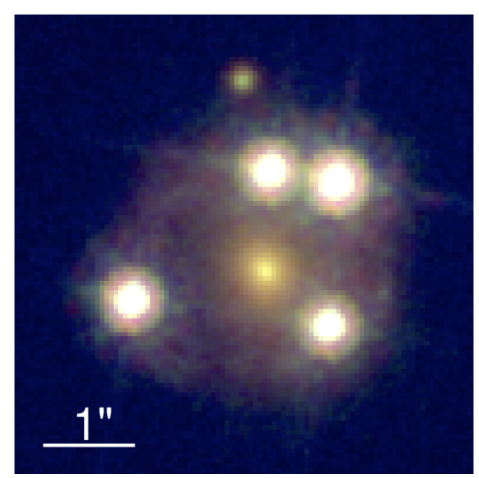
B1608+656



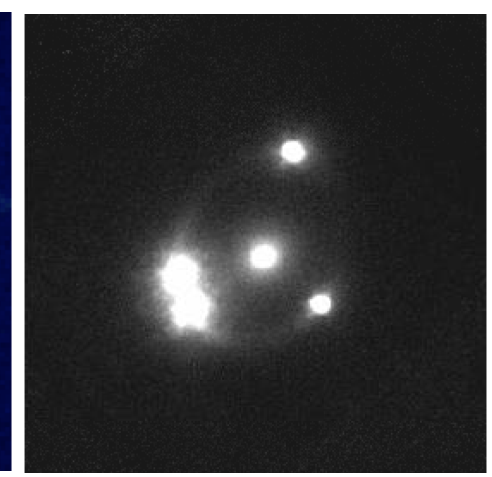
RXJ1131-1231



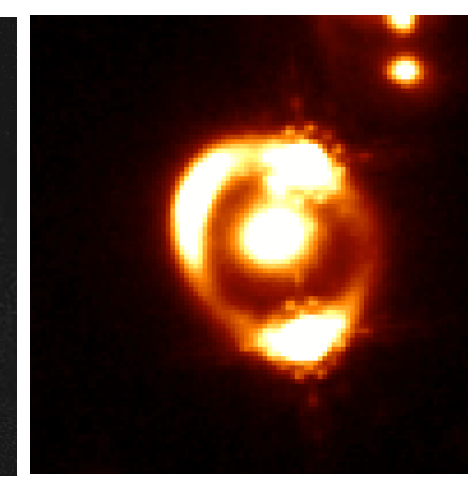
HE 0435-1223



WFI2033-4723



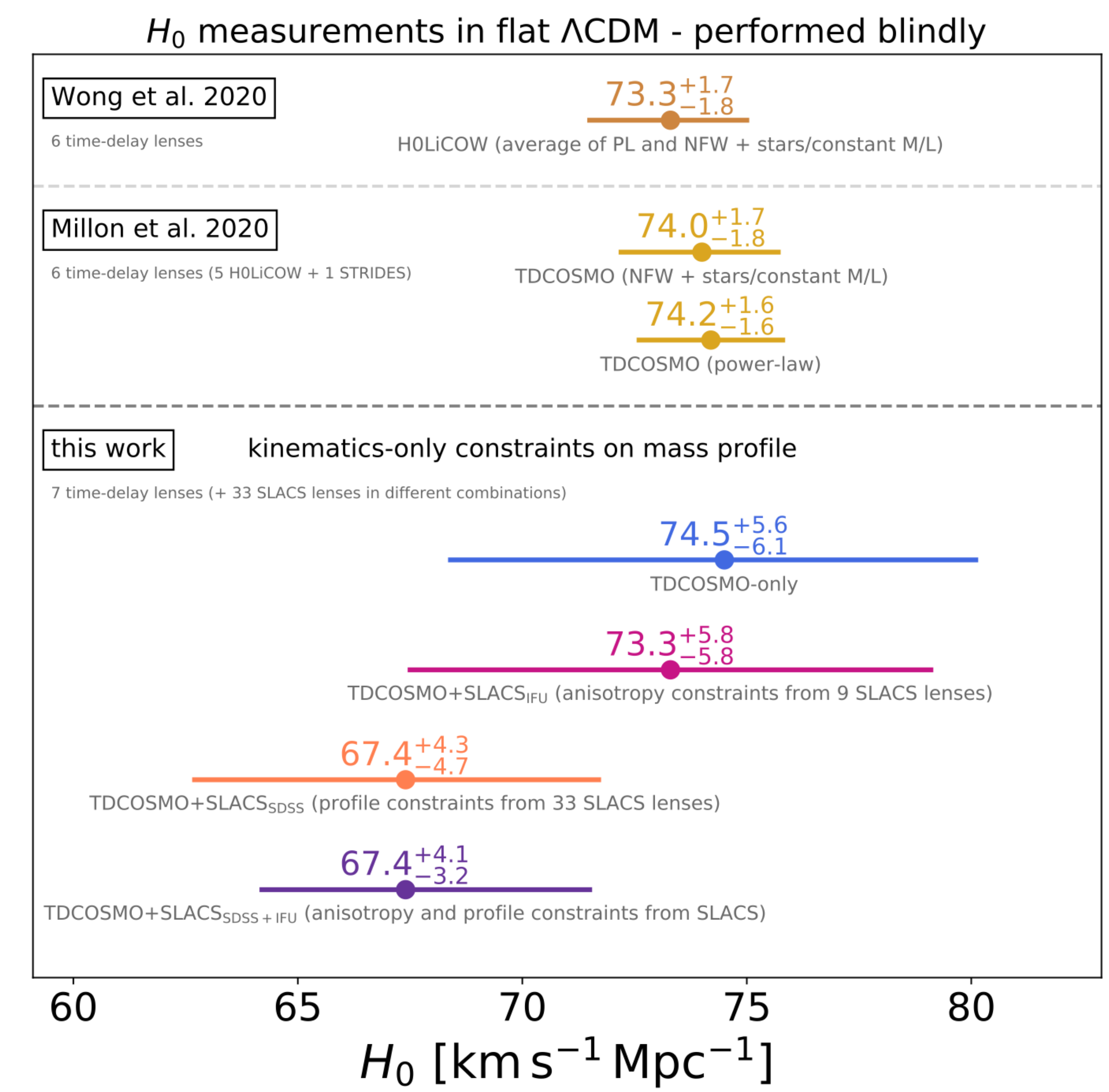
PG1115+080

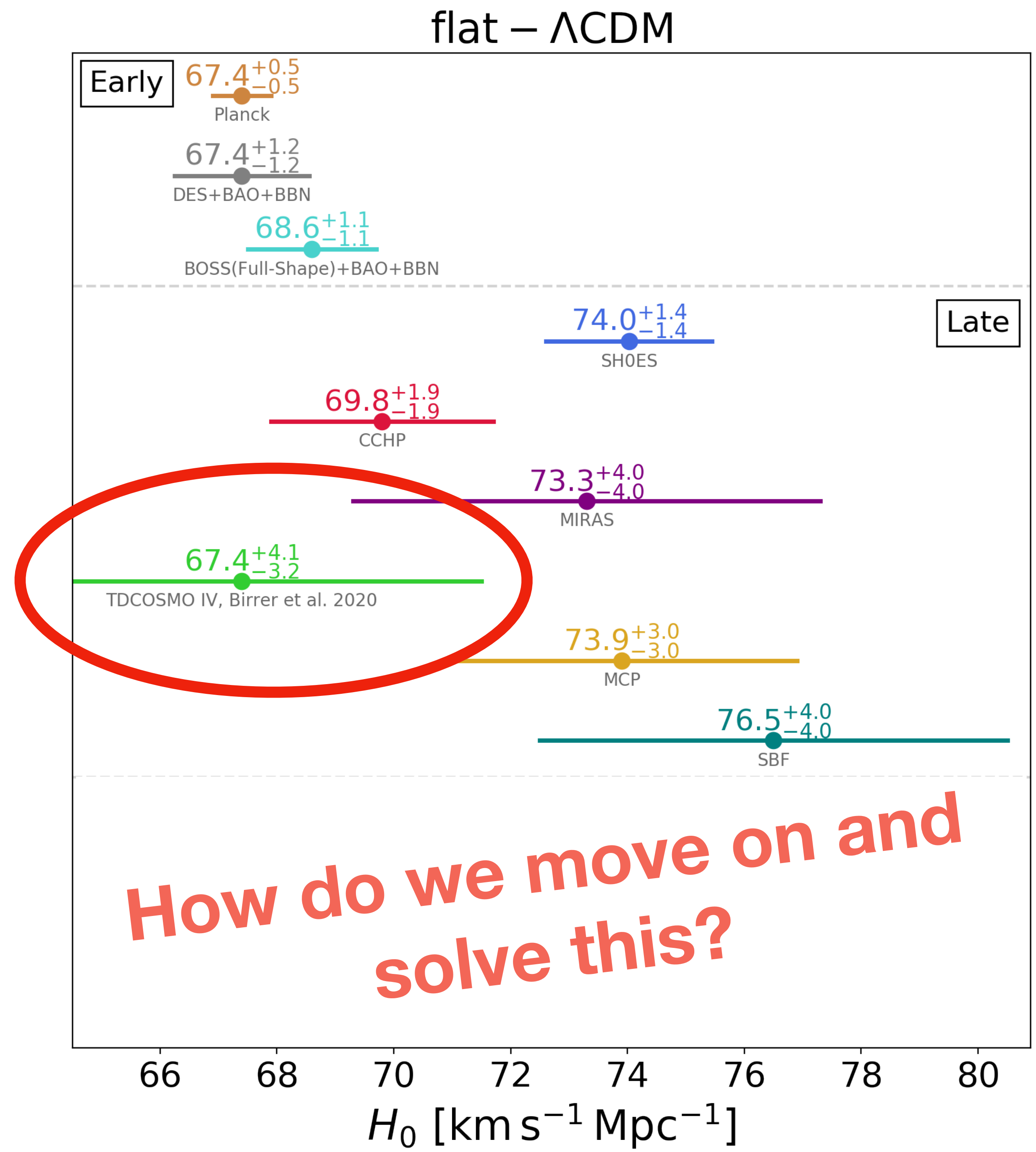


SDSS J1206+4432

www.tdcosmo.org

H0 - present

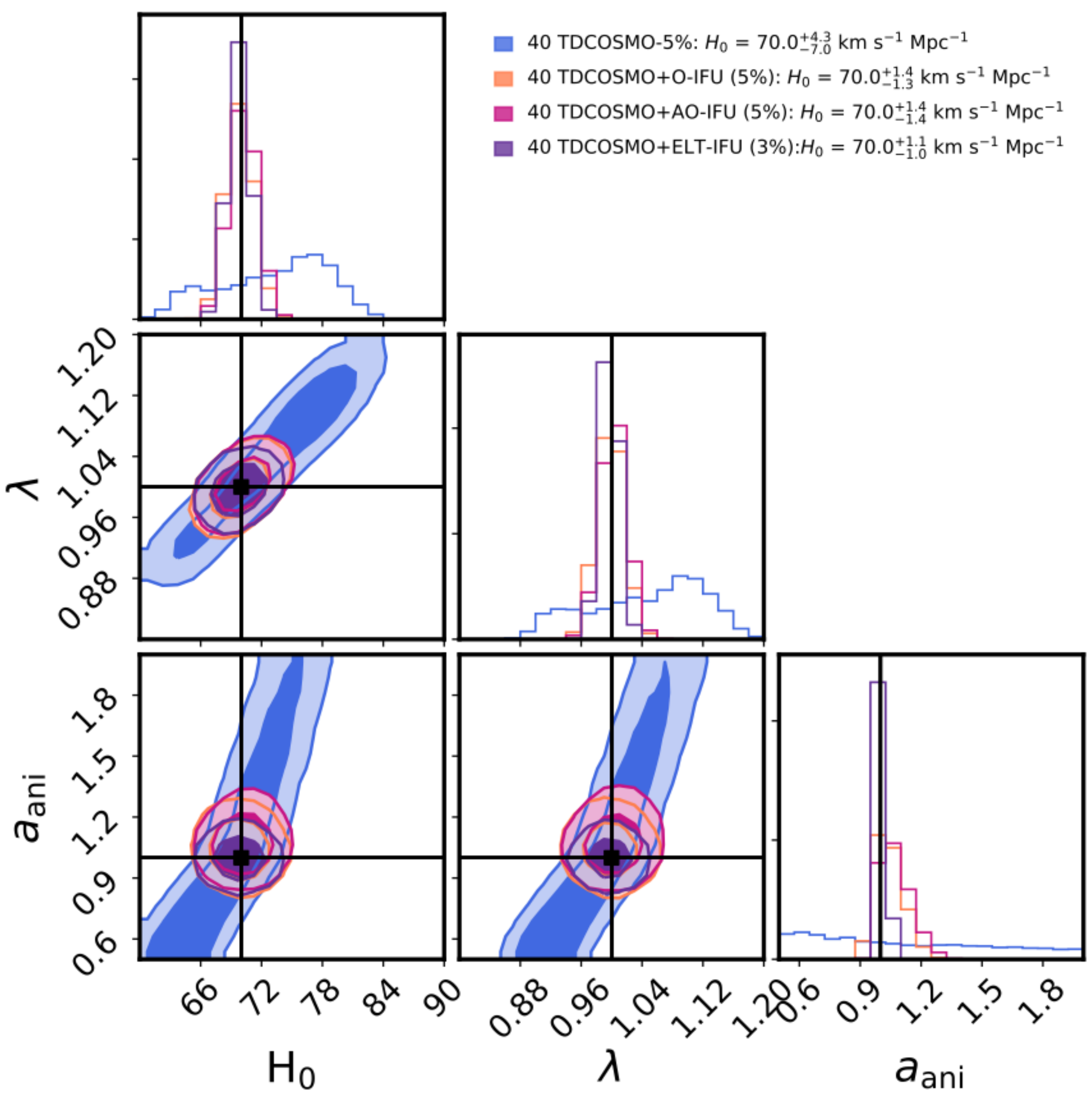




SB et al. 2020 TDCOSMO IV

H0 - near future - road to 1%

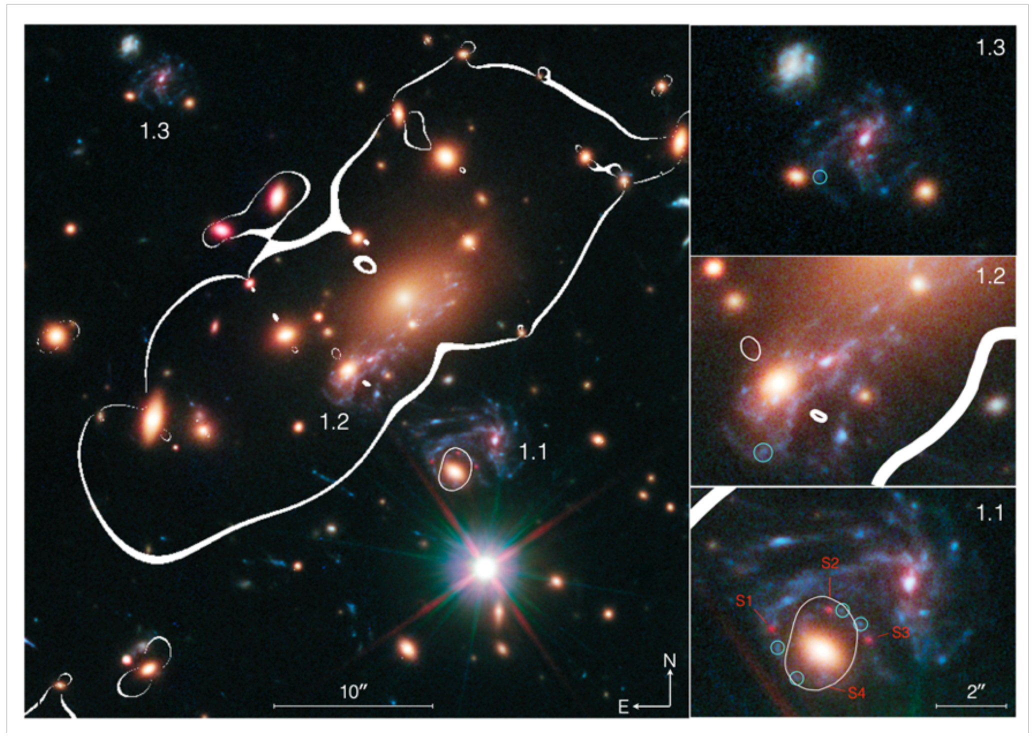
Resolved kinematics
(approved JWST program)



SB & Treu 2021 TDCOSMO V

SN 'Refsdal' 7% H_0 estimate

Kelly et al (2015), Science 347(6226):1123–1126

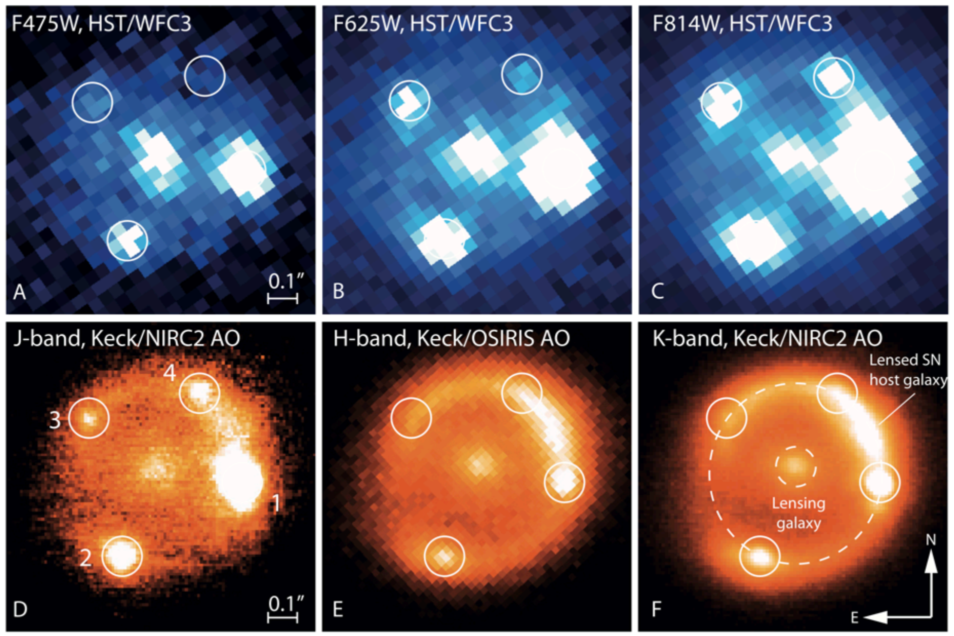


Kelly et al. 2015, Kelly (incl **SB**) et al. in prep

Lensed supernovae

iPTF16geu

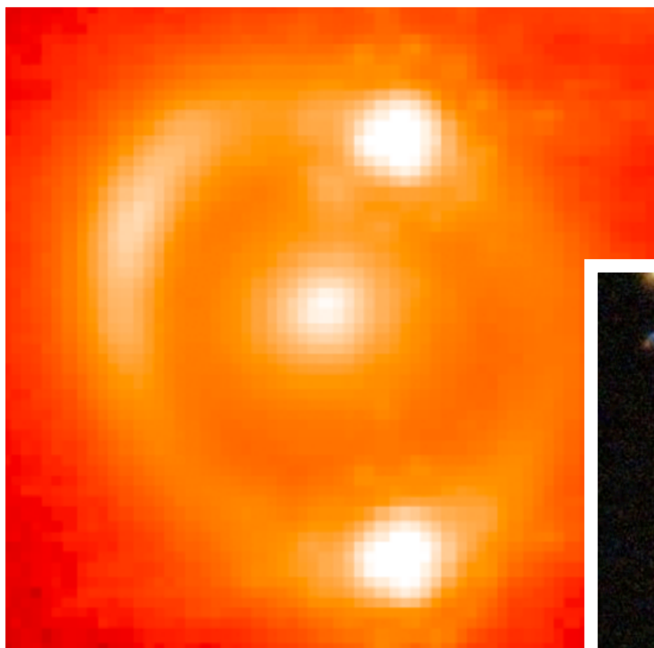
Goobar et al (2017), Science 356(6335):291–295

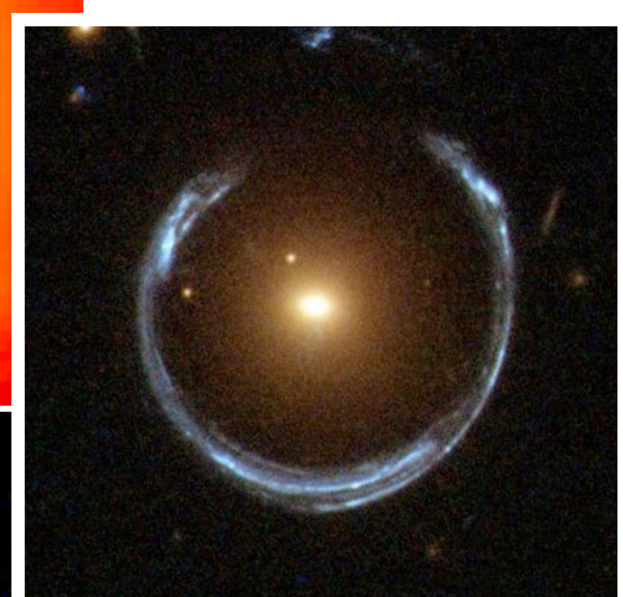


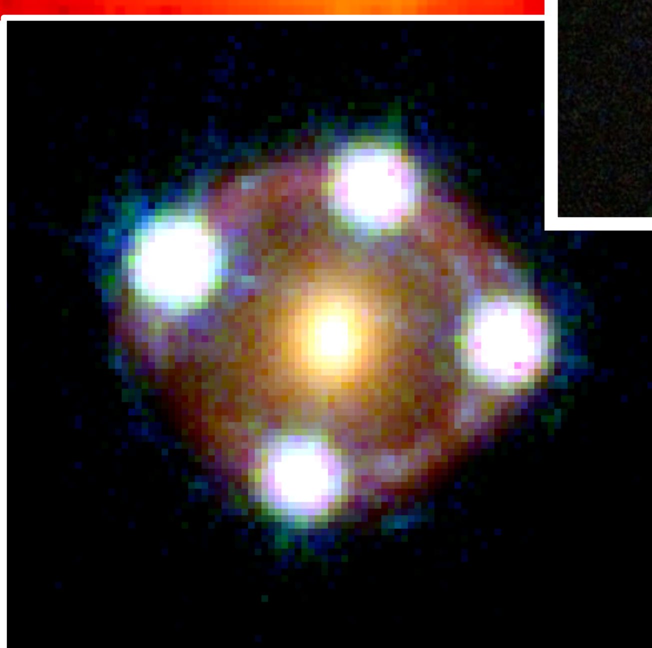
Goobar et al. 2017

Summary

Gravitational lensing is…







- **unique** window to the dark universe
  - probes small (**dark**) matter structure
- **independent** anchor of cosmological scales
- **competitive** with other cosmological probes
- **advancing** with increased sample size and improved observational capabilities!

https://github.com/sibirrer/lenstronomy

https://github.com/sibirrer/hierArc