Quantum fluctuations masquerade as halos: Bounds on ultra-light dark matter from quadruply-imaged quasars

Alexander Laroche

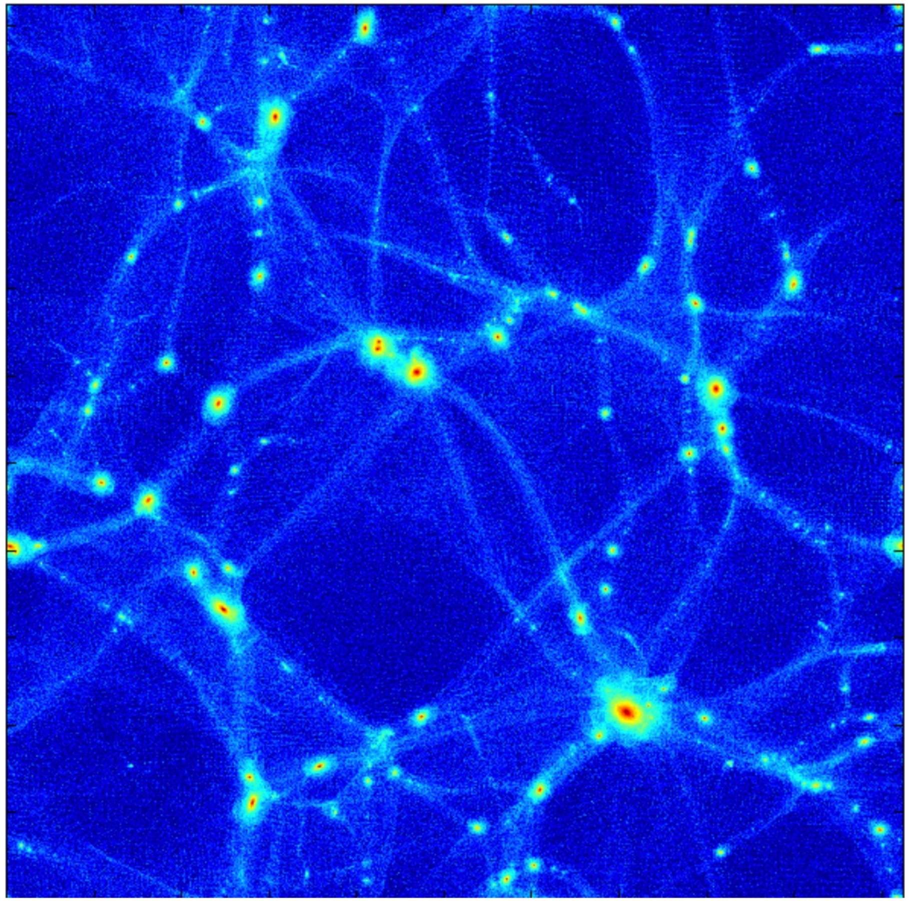
University of Toronto, McGill University

Collaborators: Daniel Gilman, Xinyu Li, Jo Bovy, Xiaolong Du

Motivation

- **Cold Dark Matter (CDM)** is the dominant theory for DM in astrophysics today
- **Small-scale issues** with CDM have motivated alternative DM theories
- To test DM alternatives, we need to probe **sub-galactic scales**

CDM simulation



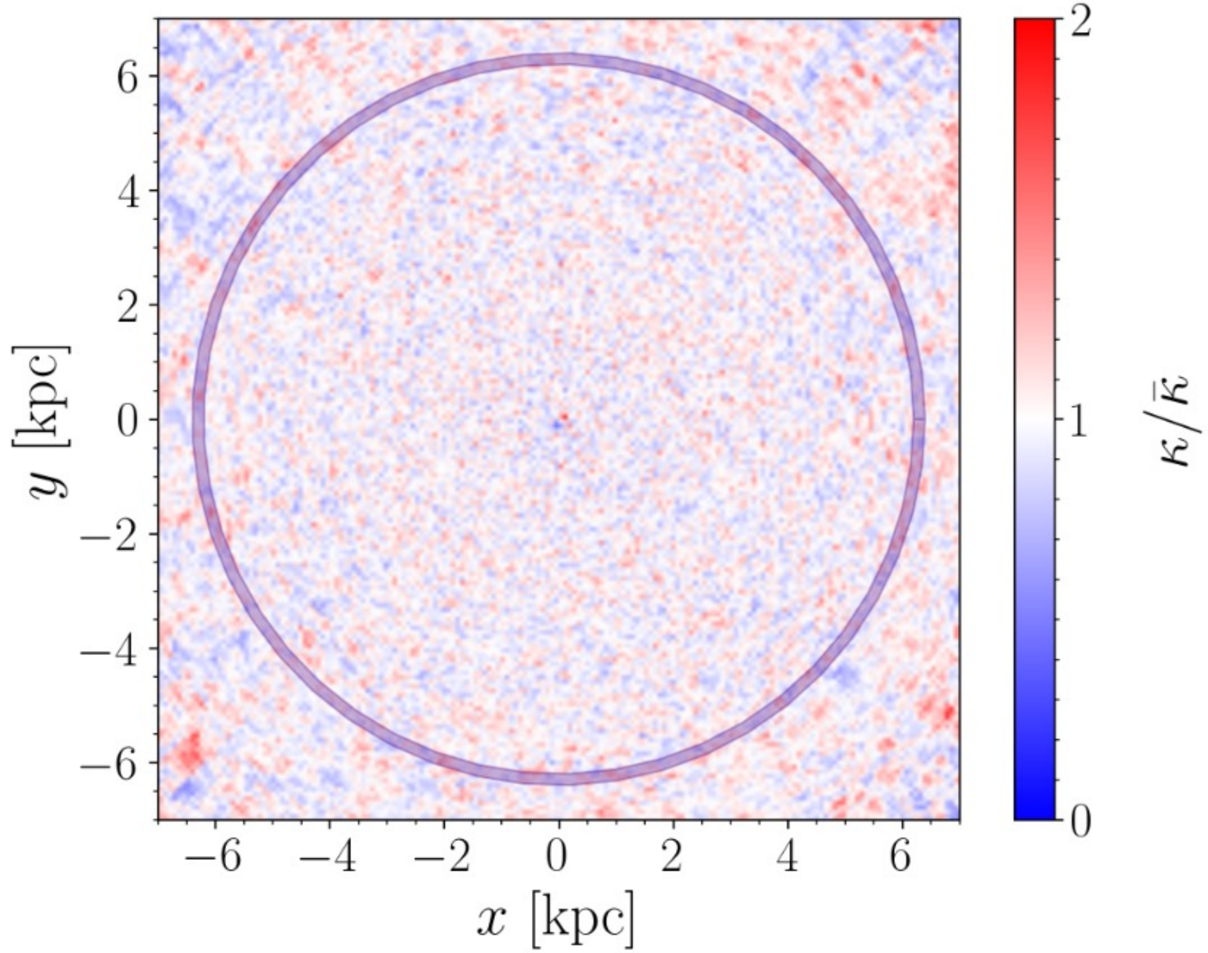
Schive et. al 2016 [1406.6586]

Ultra-light dark matter (ULDM)

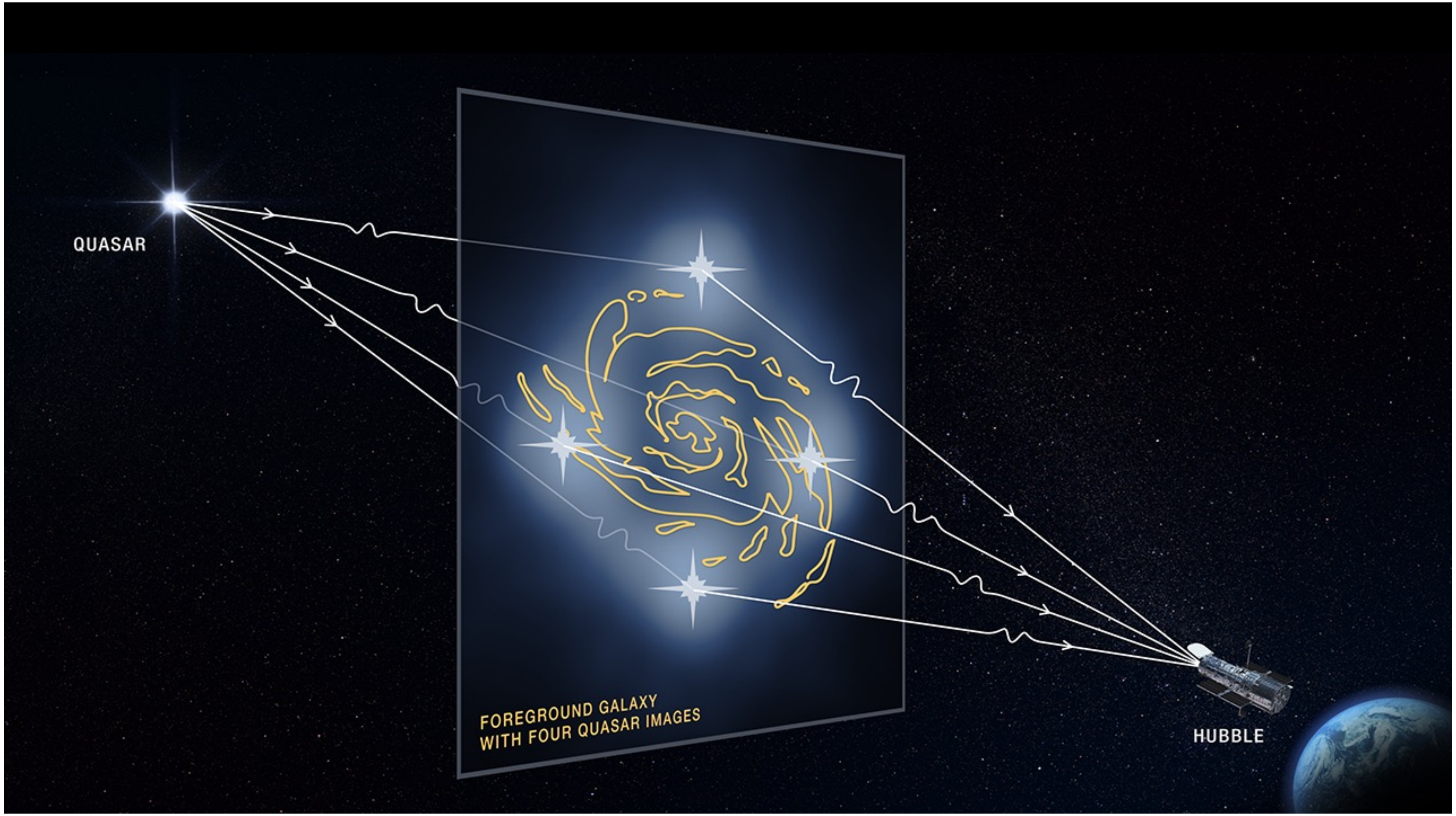
- Popular alternative theory in which the DM is made up of ultra-light bosons with particle mass $m_\psi \sim 10^{-22}$ eV
- **Quantum mechanical effects** manifest on galactic scales
- ULDM deviates from CDM in three interesting ways:

1. Small-scale structure suppression → less small halos than CDM
2. Soliton core formation → halo shapes are flat relative to CDM
3. **Quantum fluctuations → novel source of dark substructure**

Quantum fluctuations
Unique to ULDM!



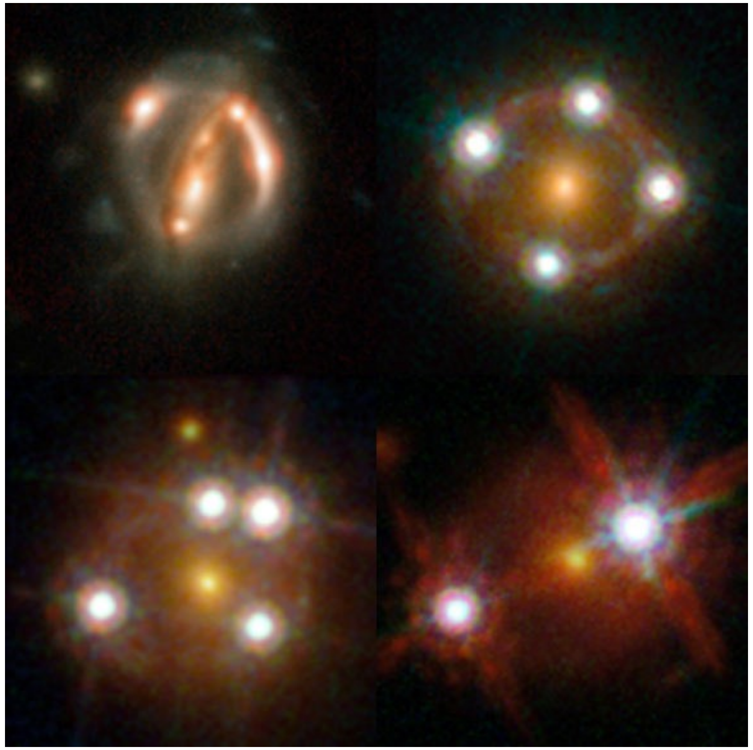
Quadruple image quasars



Nasa 2020

Strong gravitational lensing

- **Flux ratios** (relative magnifications) depend on the sub-galactic DM distribution in the lensing galaxy
- Gilman et al. 2018 [1712.04945] introduced a framework to relate a given DM model to observed strong lenses



Nasa 2017

Bayesian inference problem

$$p\left(\mathbf{q}_{\mathrm{s}}|\boldsymbol{D}\right) \propto \pi\left(\mathbf{q}_{\mathrm{s}}\right) \prod_{n=1}^{N} \mathcal{L}\left(\mathbf{d}_{\mathrm{n}}|\mathbf{q}_{\mathrm{s}}\right)$$

Constraints on DM parameters

DM parameter priors

N likelihoods for *N* observed strong gravitational lenses

Approximate Bayesian Computing (ABC)

- **Classical MCMC methods are very inefficient** because most *realizations* (simulated DM distributions) will not yield simulated flux ratios which match the data
- Circumvent computation of these intractable likelihoods with ABC

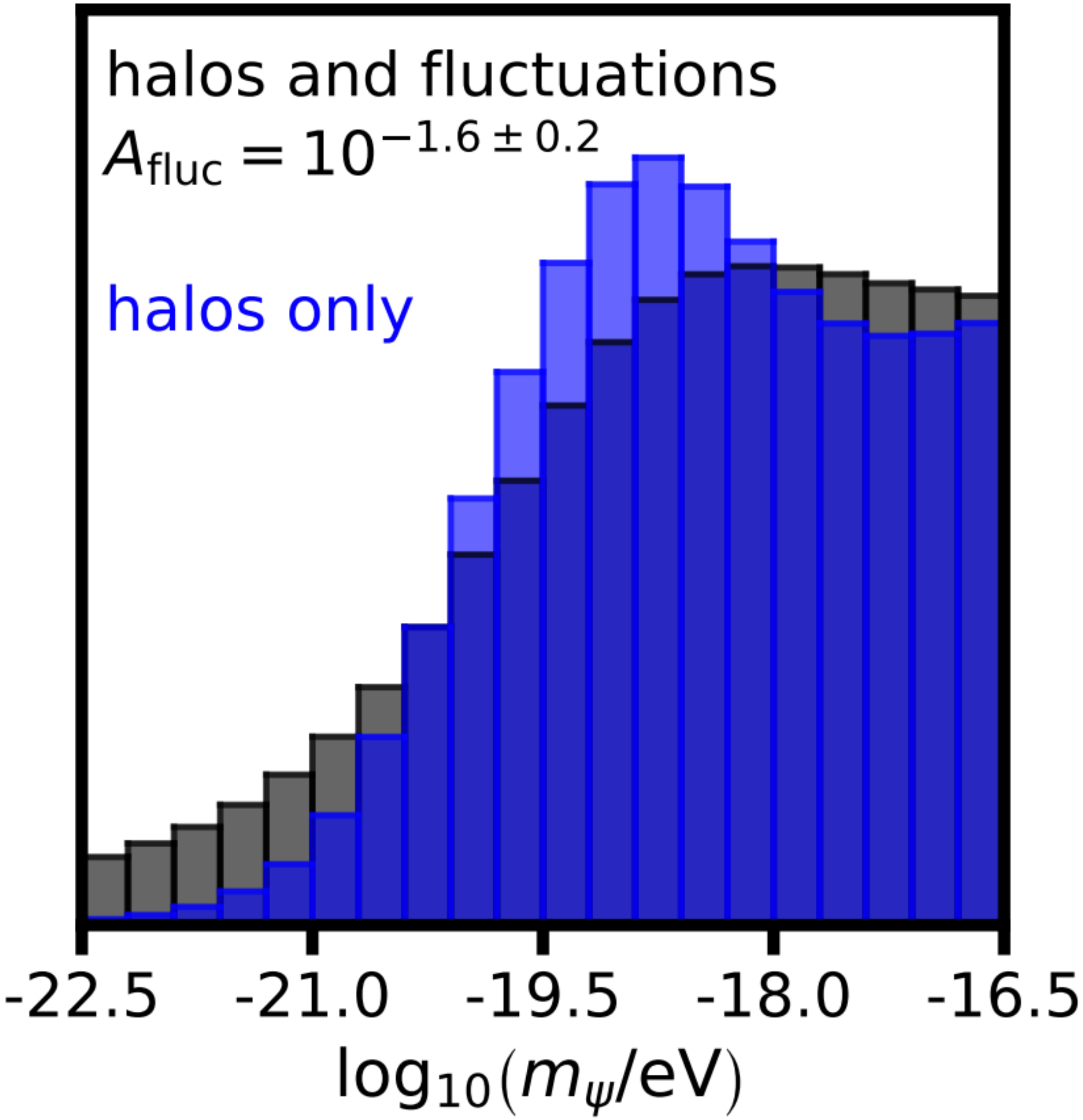
ABC Recipe

1. Sample some ULDM model parameters q
2. From q, simulate a ULDM realization in the strong lens
3. Compute light travelling from the quasar, through the simulated dark matter, get flux ratios f_{sim}
4. **Accept ULDM realizations if $S(f_{sim}, f_{obs}) < \epsilon$, where S is the 'distance' between simulations and observations and ϵ is a threshold**

- Do this many times to derive ULDM parameter posteriors

Results

- Previous analyses of ULDM have constrained m_ψ through lack of small-scale structure, we find the **opposite**
- Quantum fluctuations introduce **additional "substructure"** which perturb flux ratios
- Accounting for fluctuations alters lower bounds on the ULDM particle mass



Laroche et. al 2022 [2206.11269]

Conclusions

- Ultra-light dark matter is a viable dark matter candidate which is very different from cold dark matter on small scales
- Forward modeling flux ratios in strong gravitational lenses is a powerful tool for constraining ultra-light dark matter
- Quantum fluctuations should be accounted for in strong lensing analyses of ULDM because they can ***masquerade*** **as dark matter halo substructure**
- For additional details, see Laroche et al. 2022 [2206.11269]