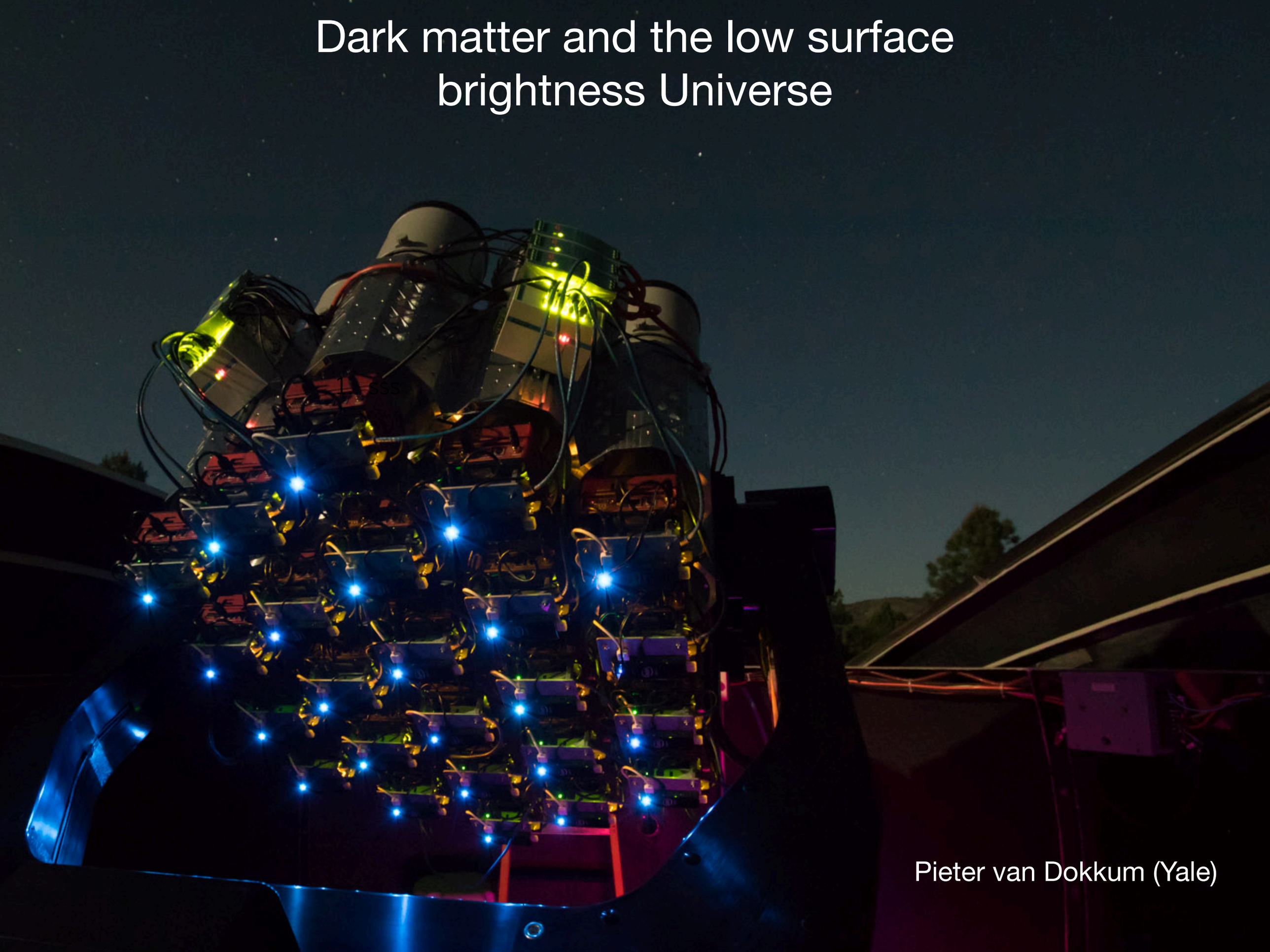
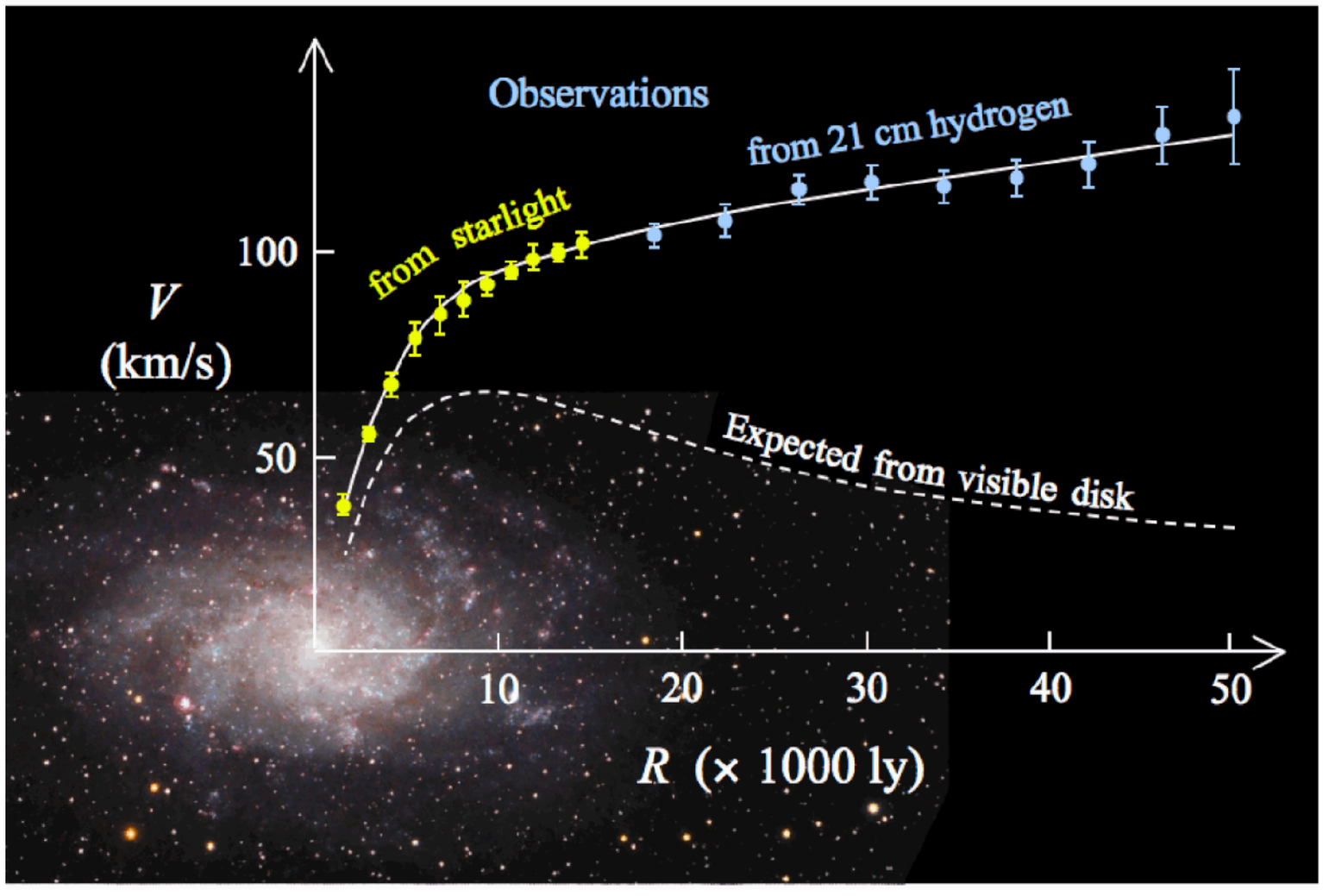
Dark matter and the low surface brightness Universe



Pieter van Dokkum (Yale)

Dark matter on “small” (~1 kpc, 10^{21} cm) scales

- Dark matter content of galaxies can be determined from kinematics: more mass than can be accounted for by stars, gas, etc



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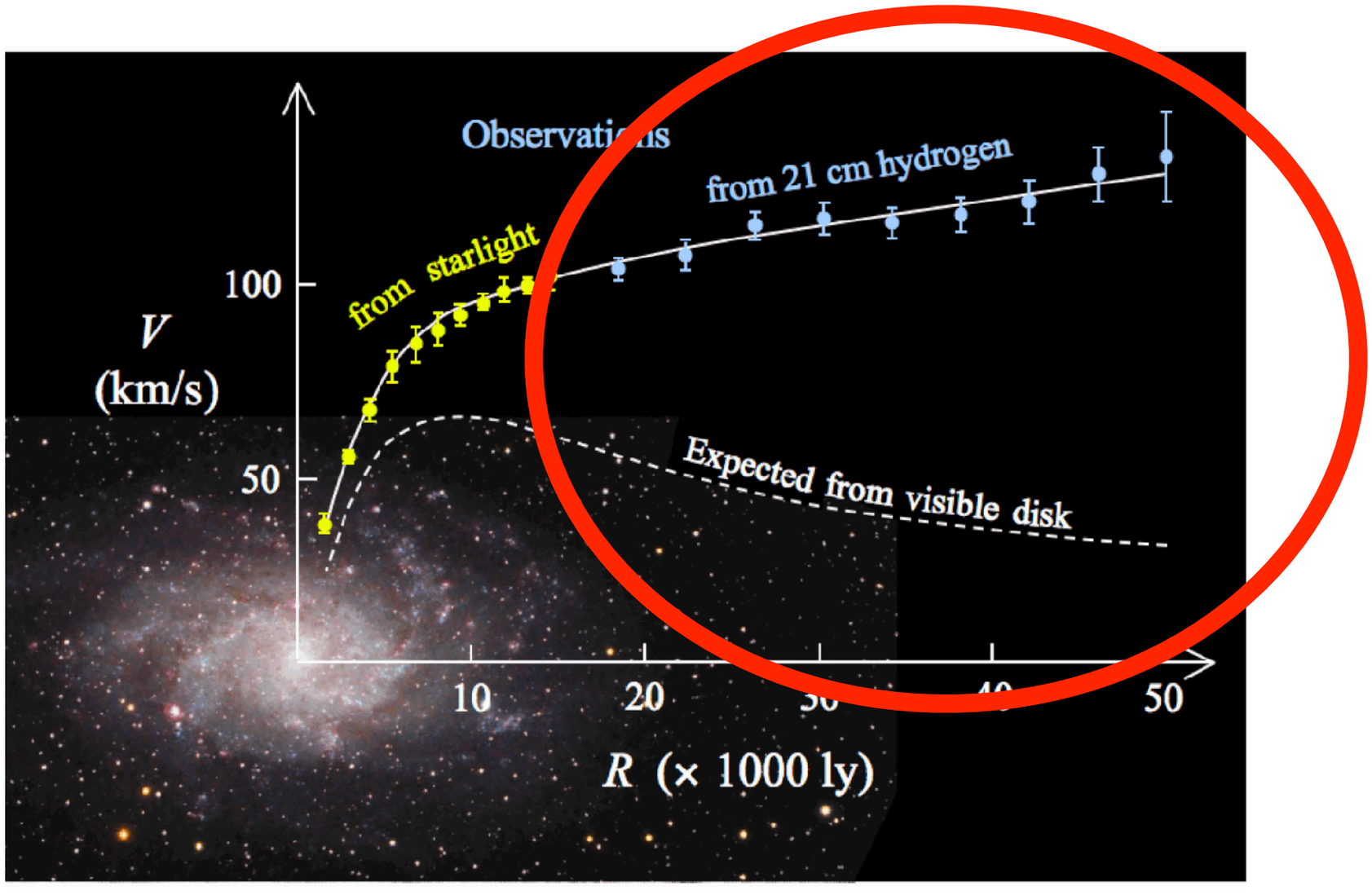

- Signature clearest on large scales, as dark matter extends beyond baryons

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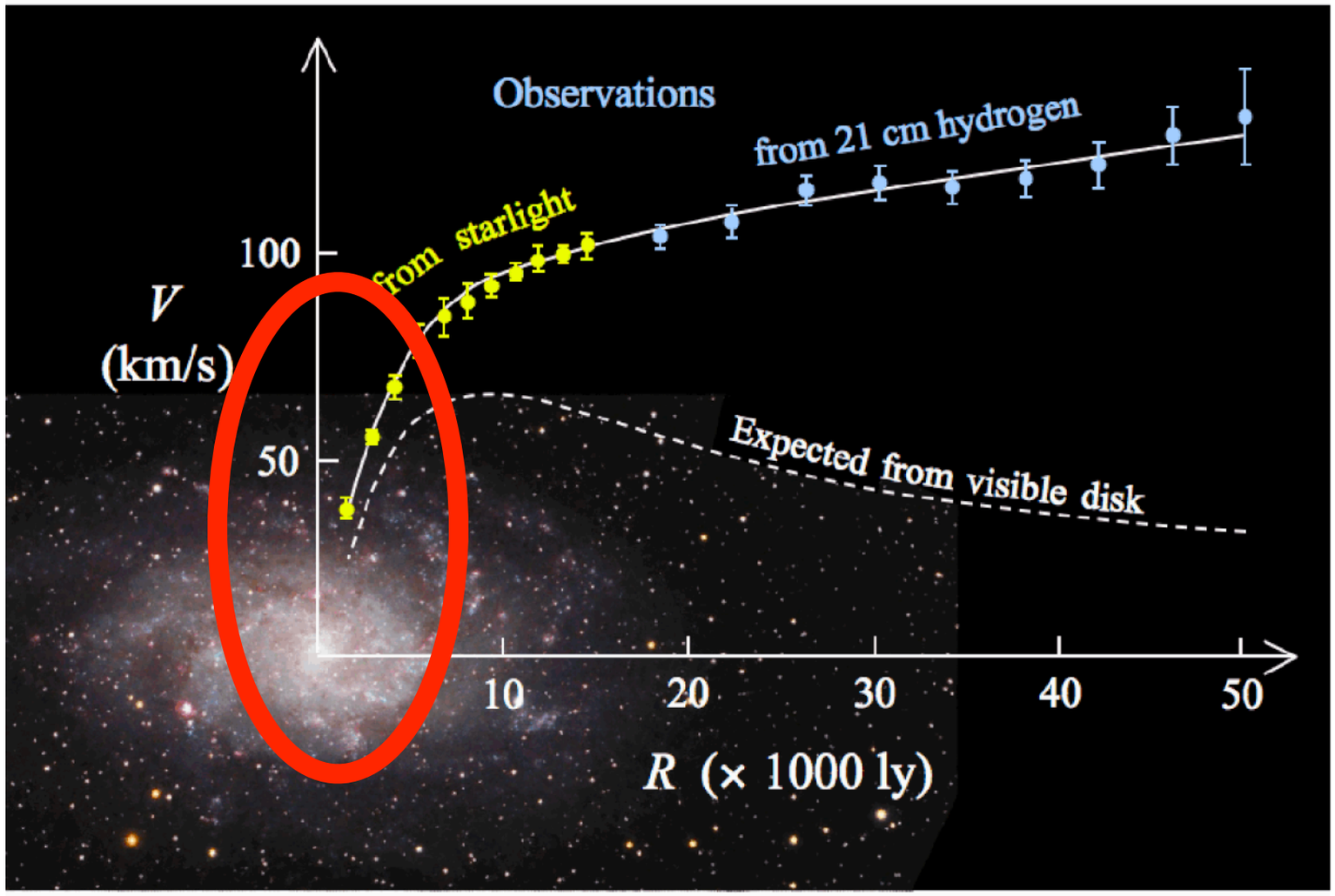
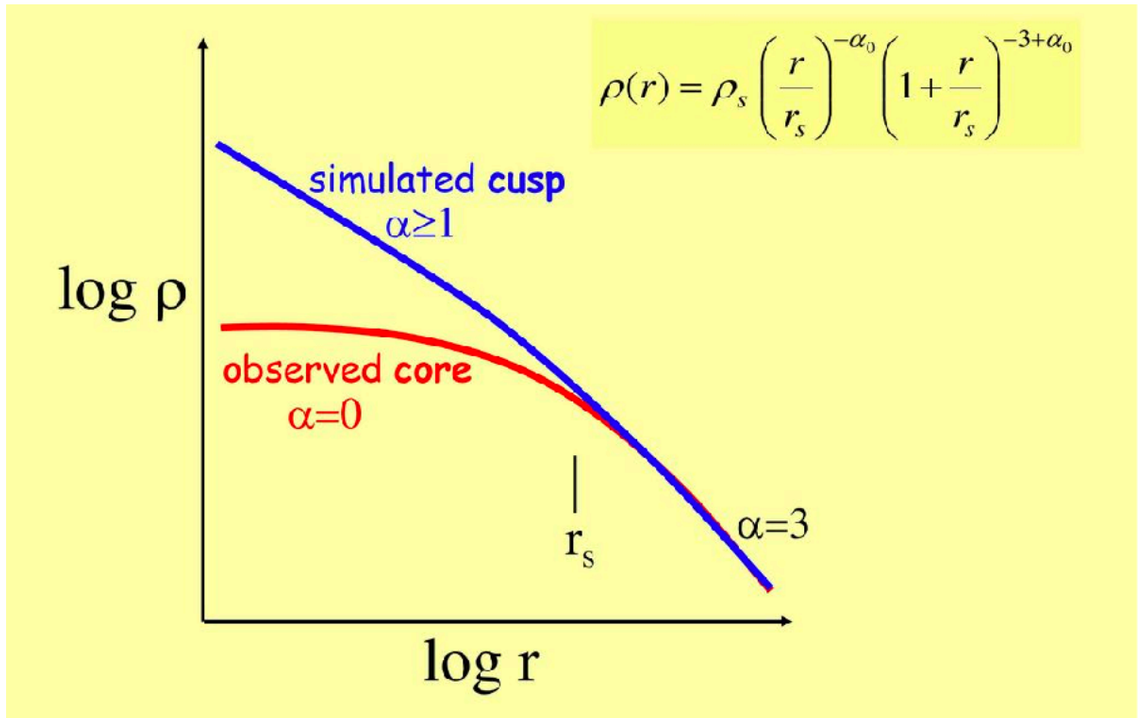


- However, also lot of interest in dark matter on smaller, ~kpc scales

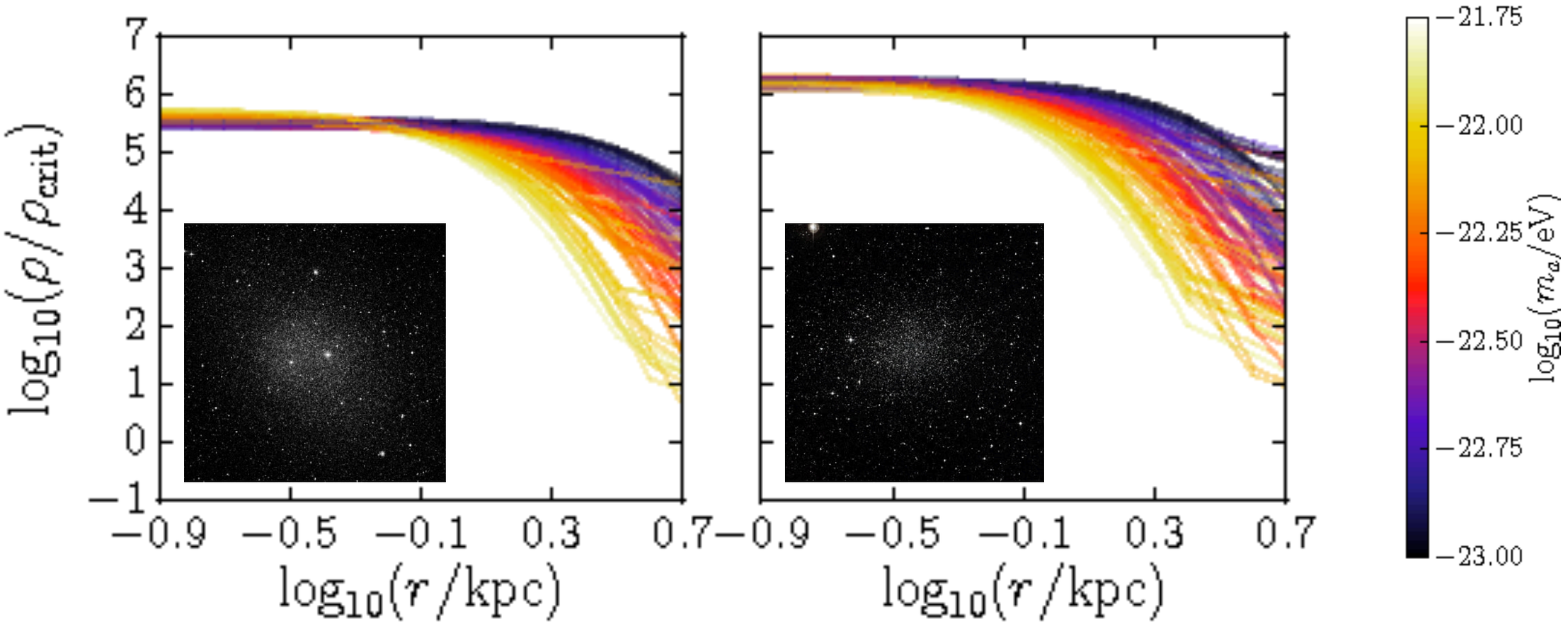
Dark matter on “small” (~1 kpc, 10^{21} cm) scales

- Dark matter dominates on scales of of 10-100 kpc, but lot of interest in the behavior on smaller scales
  - Annihilation signal goes as ~ρ^2, decay signal as ~ρ
  - “Missing satellite problem”: small dark matter halos do not exist, or are devoid of baryons
  - “Core/cusp problem”: observed central density profiles of dwarf galaxies do not match predictions from numerical simulations



Dark matter on “small” (~1 kpc, 10^{21} cm) scales

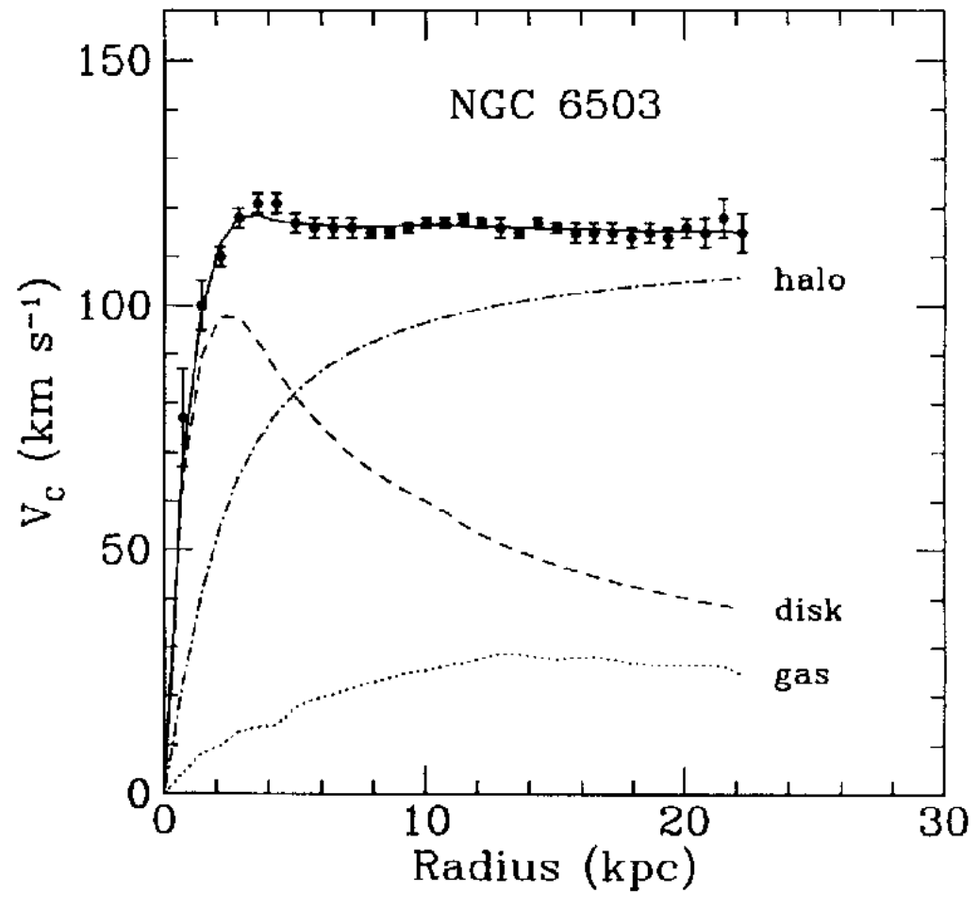
- Possible solutions include effects of baryons (outflows / churning of mass), or modifications to CDM: warm dark matter, ultra light axions (“solitons”)



soliton fits by Marsh & Pop 2015

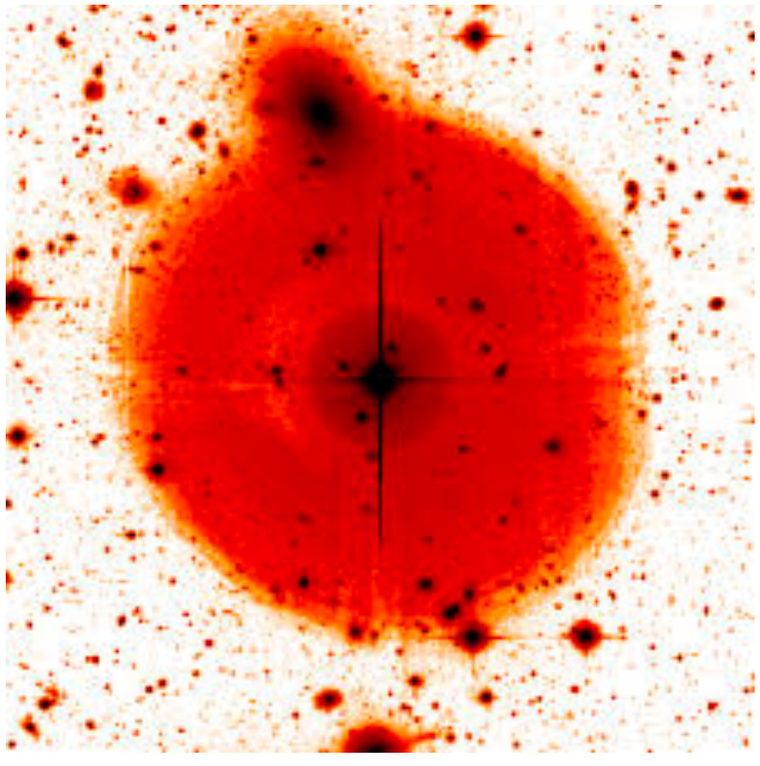
Dark matter on “small” (~1 kpc, 10^{21} cm) scales

- Possible solutions include effects of baryons (outflows / churning of mass), or modifications to CDM: warm dark matter, ultra light axions (“solitons”)
- Limitation: all work done on small sample of very low mass galaxies in the Local Group (actually mostly Fornax and Sculptor)
- Ideally study higher mass galaxies, as galactic outflows and also soliton solutions should scale with halo mass
- **Problem: high mass halos are baryon-dominated in their centers**



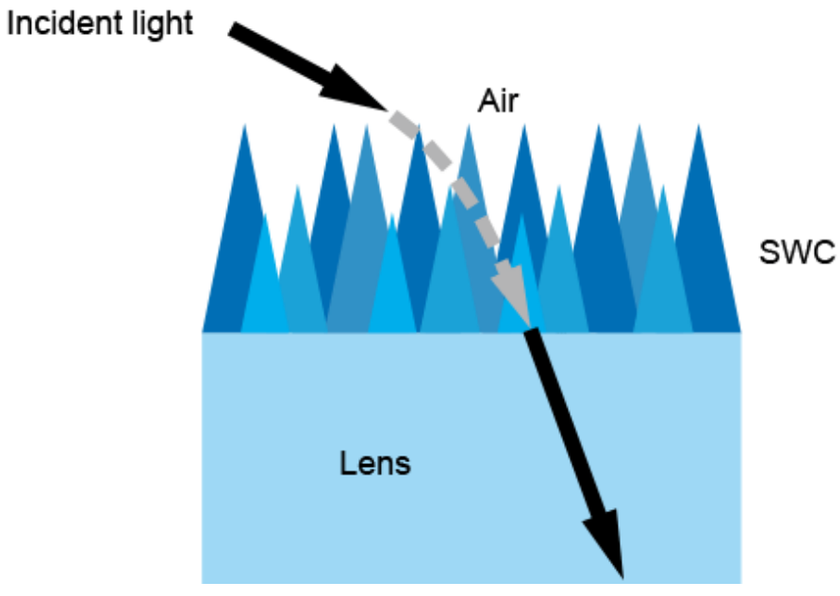
Search for large galaxies with low baryon content

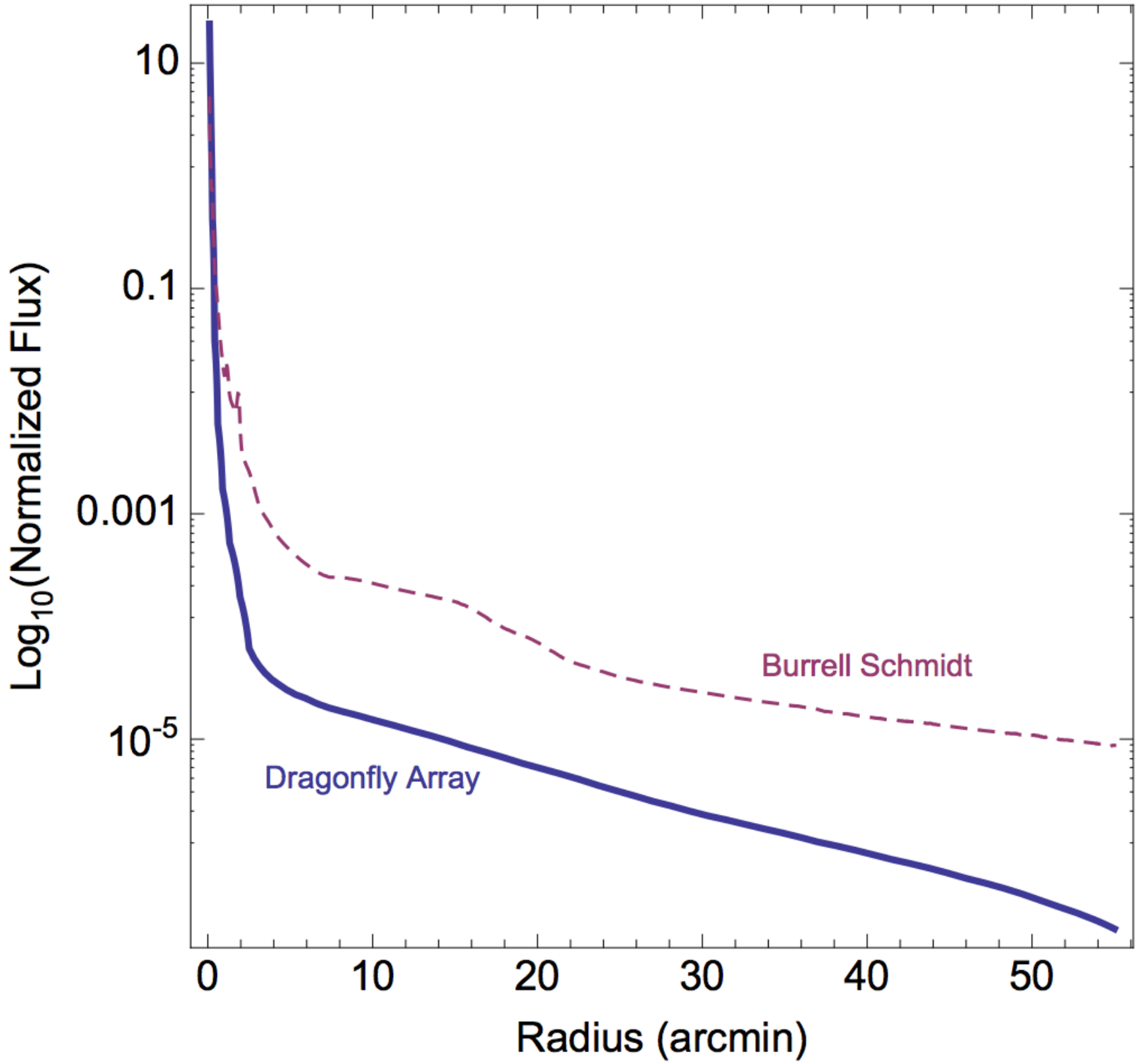
- In Local Group, only dark matter dominated galaxies are dwarf spheroidals: ~10^6 solar masses in stars, ~$10^{9\text{-}10}$ solar masses in dark matter
- Difficult to find large dark matter dominated galaxies outside of the Local Group due to low surface density of stars
- Need to find galaxies with very low surface brightness
- This is a hard problem, as conventional telescopes are not good at detecting low surface brightness emission



- **Developed Dragonfly, a low surface brightness-optimized telescope**

- Key requirements:
  - No central obstruction
  - Superb control of reflections, ghosts





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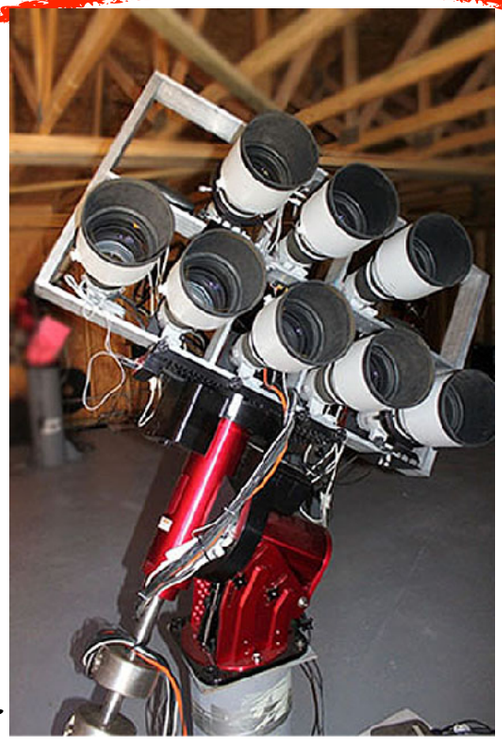
2012

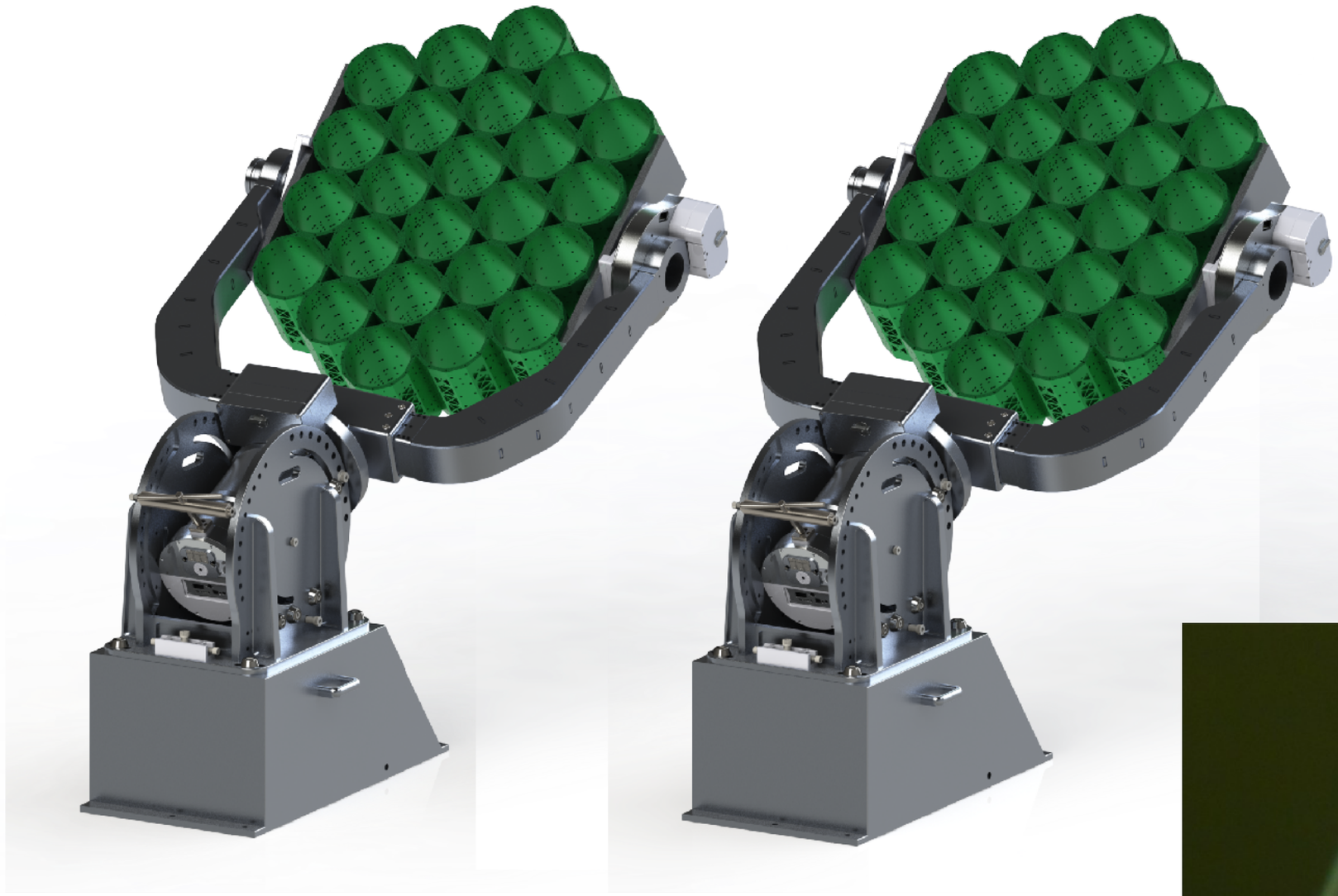
2013



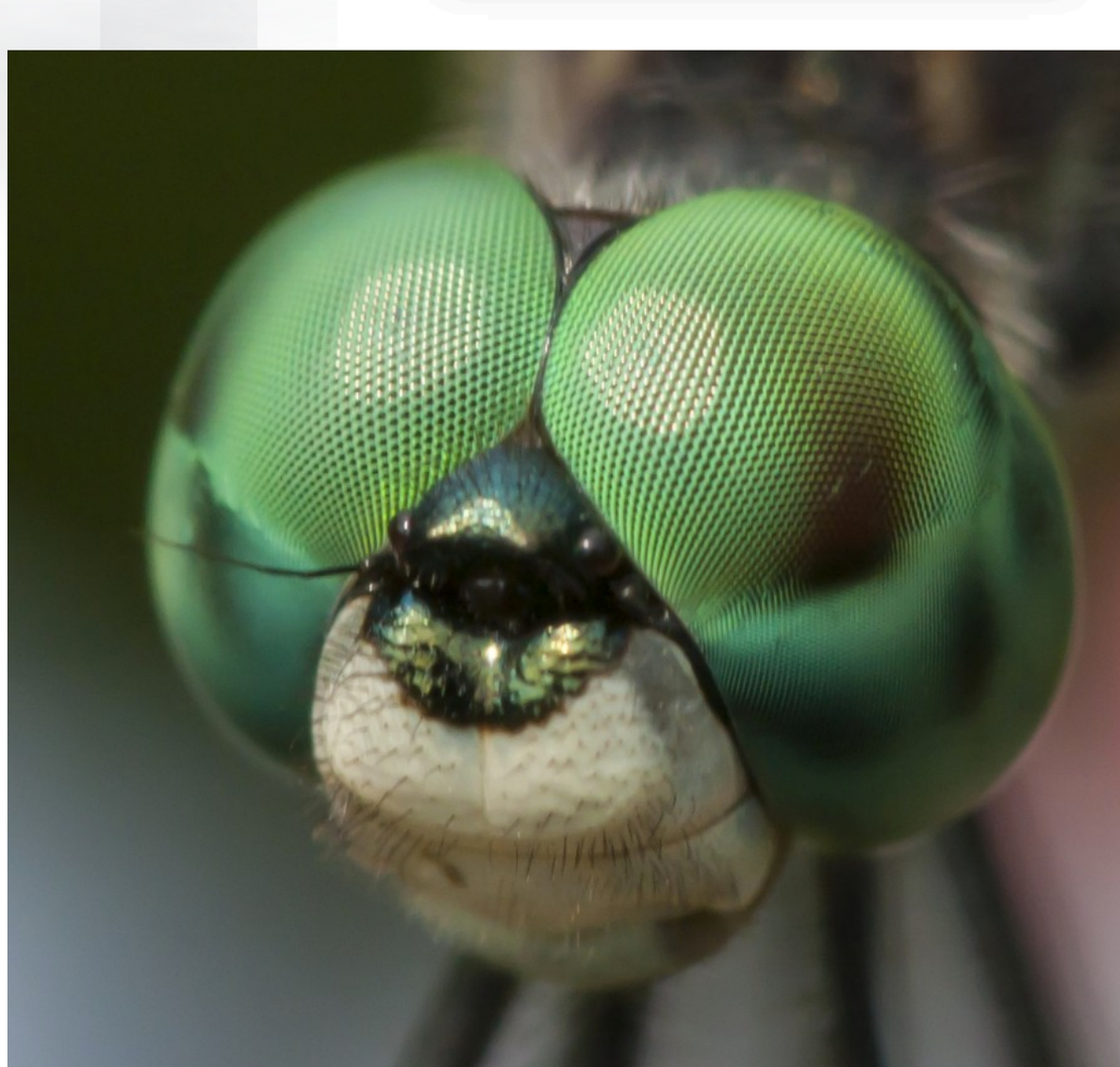
2014

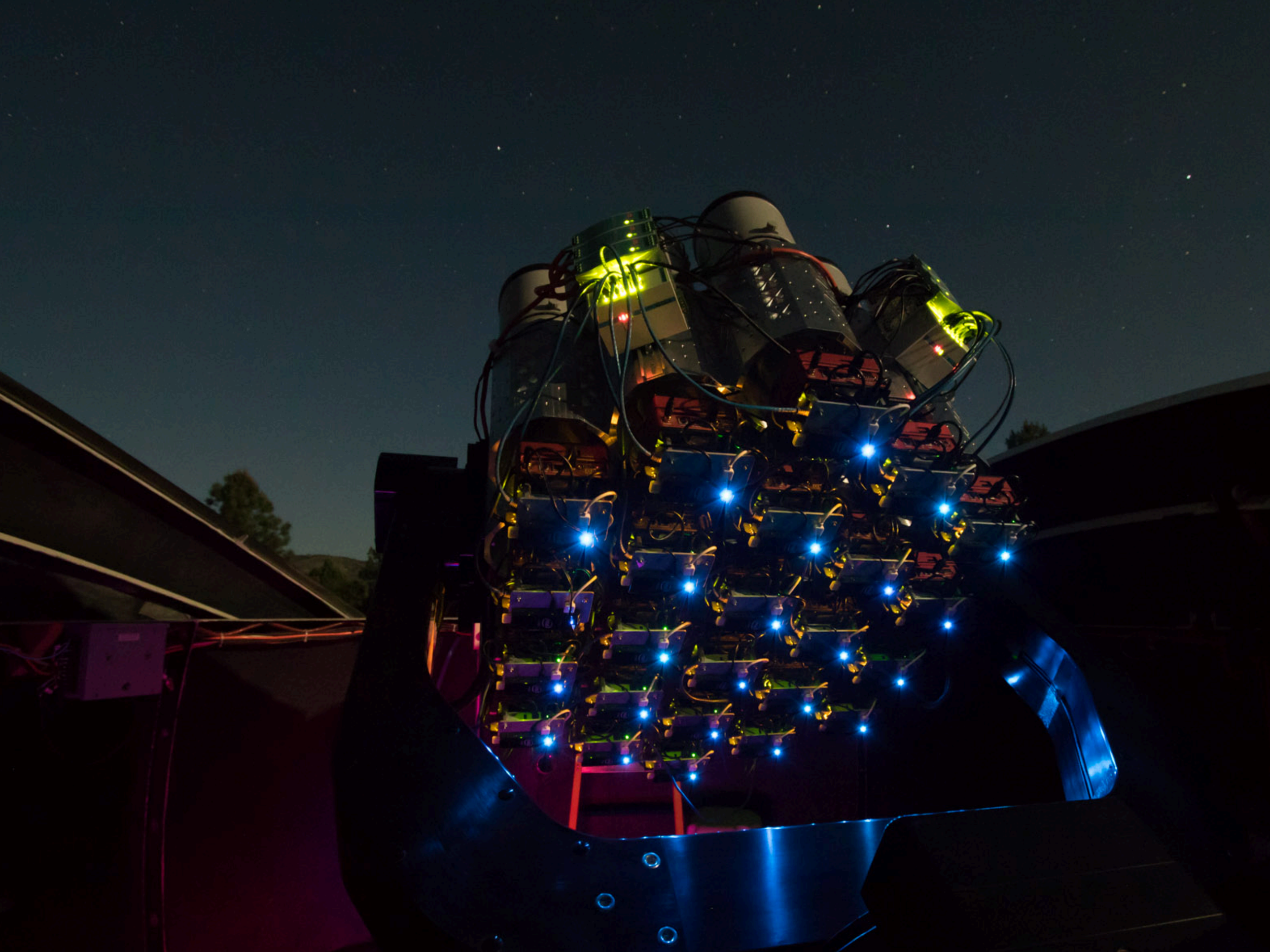
2015

2016



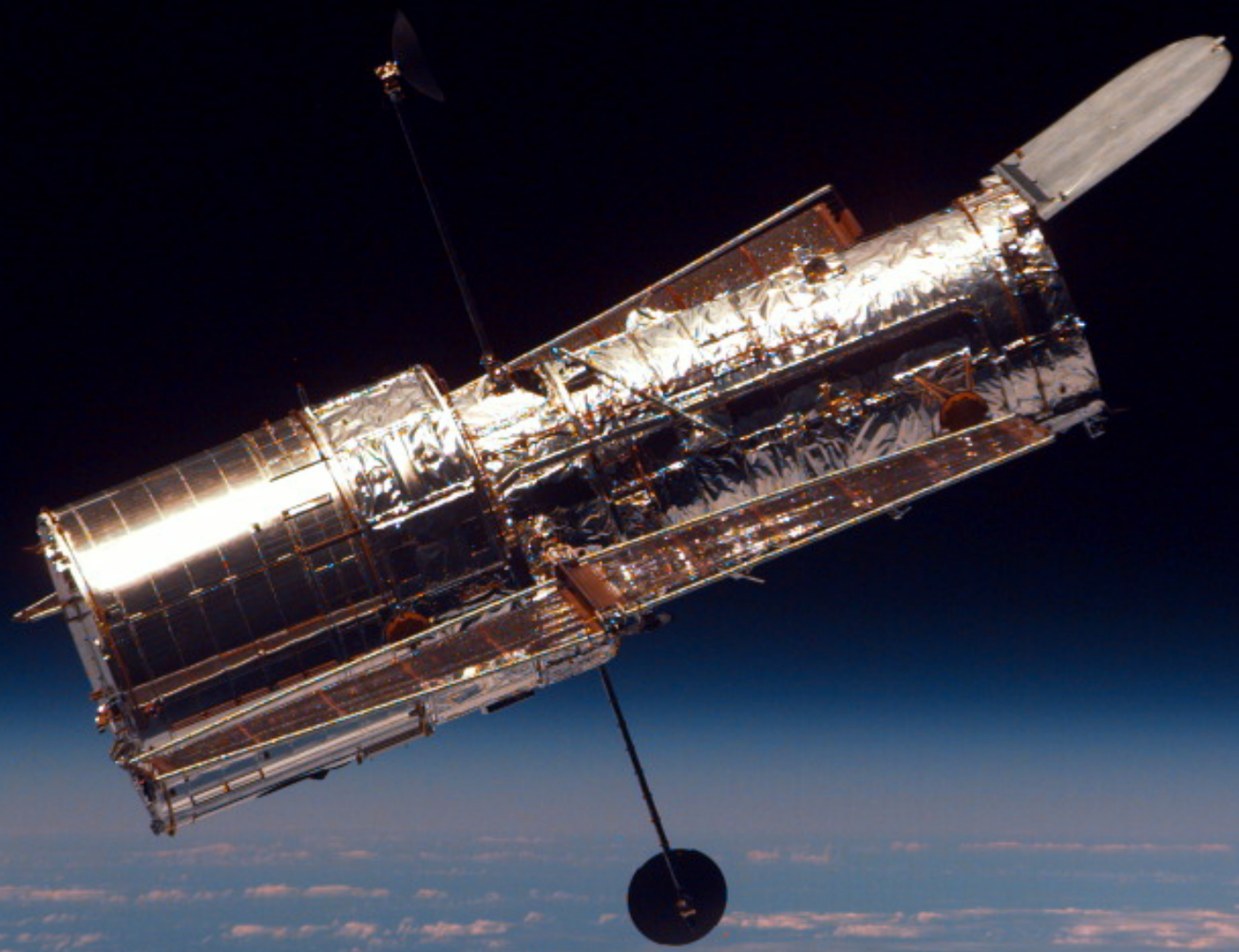
The Dragonfly Telephoto Array

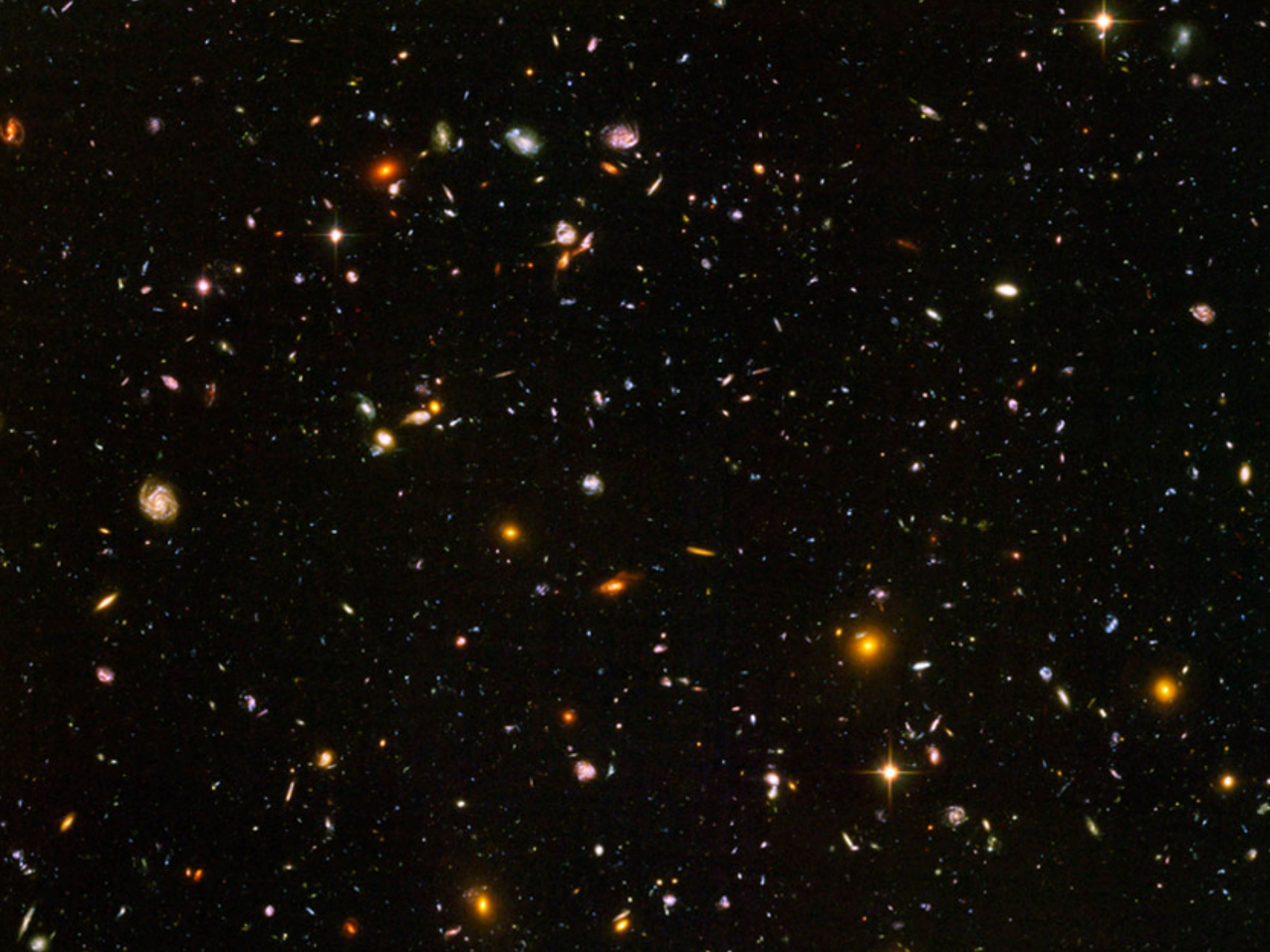


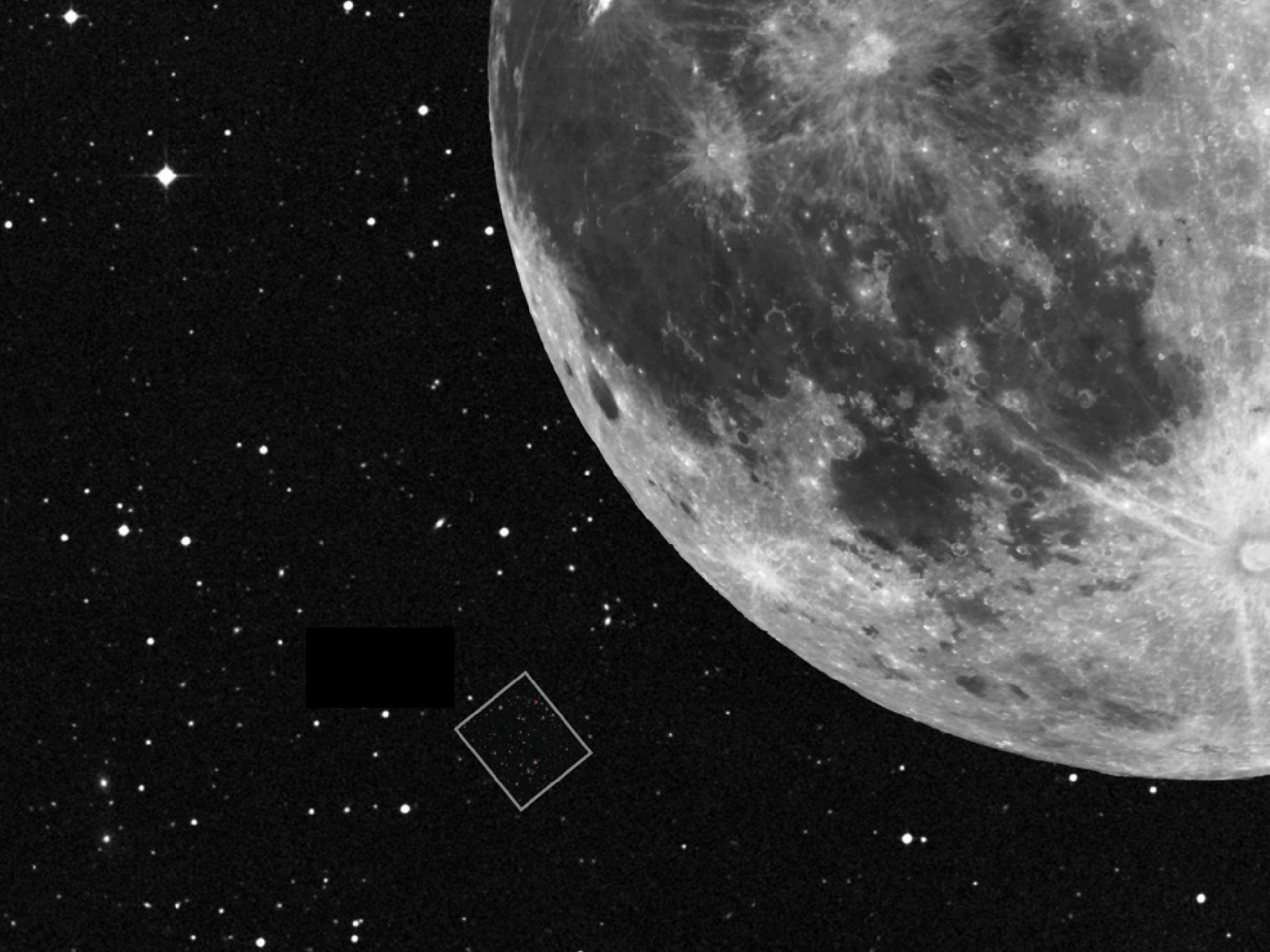


Dragonfly team

- Two PIs, one postdoc, six graduate students

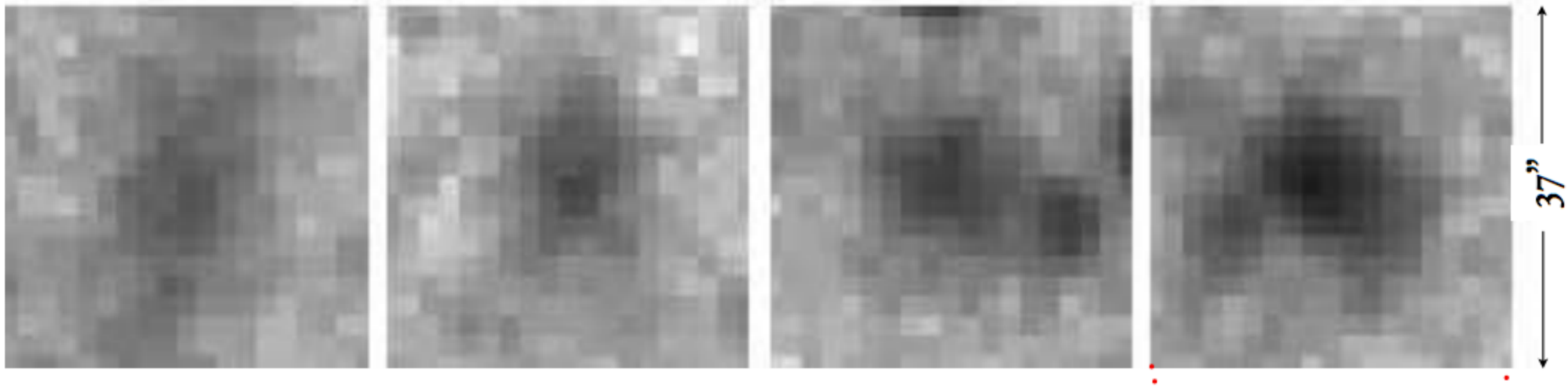






Found new class of “ultra diffuse” galaxies

- Many just-resolved “blobs” in the direction of the Coma galaxy cluster



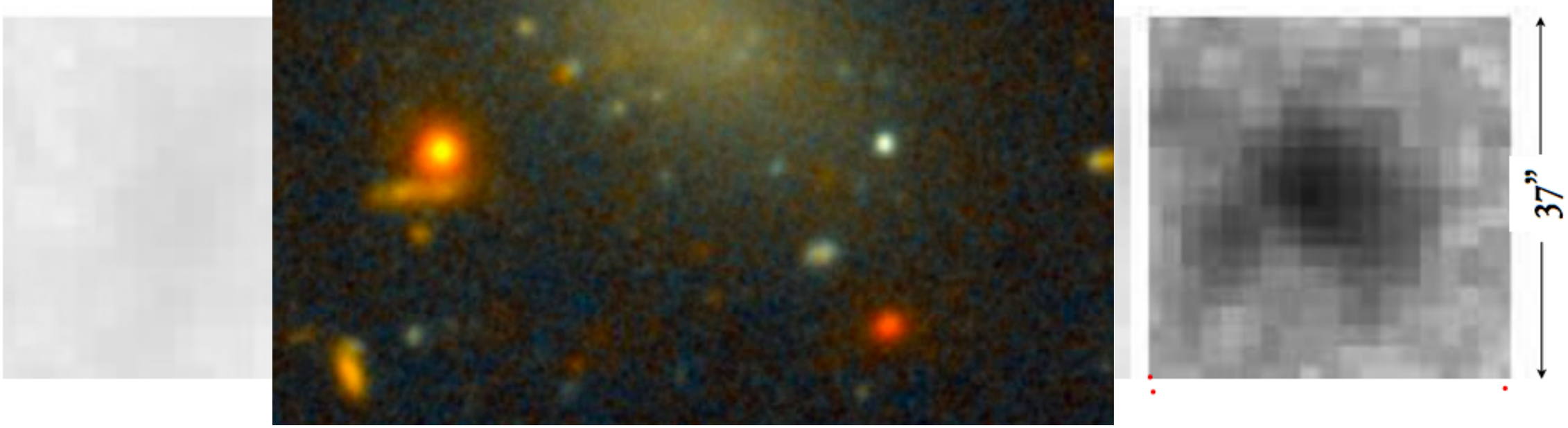
- Follow-up imaging and spectroscopy: turn out to be intrinsically-large, distant galaxies

- Sizes similar to Milky Way, but 100x - 1000x fewer stars

van Dokkum et al 2015

Found new [redacted] xies

- Many just-res[redacted] galaxy cluster



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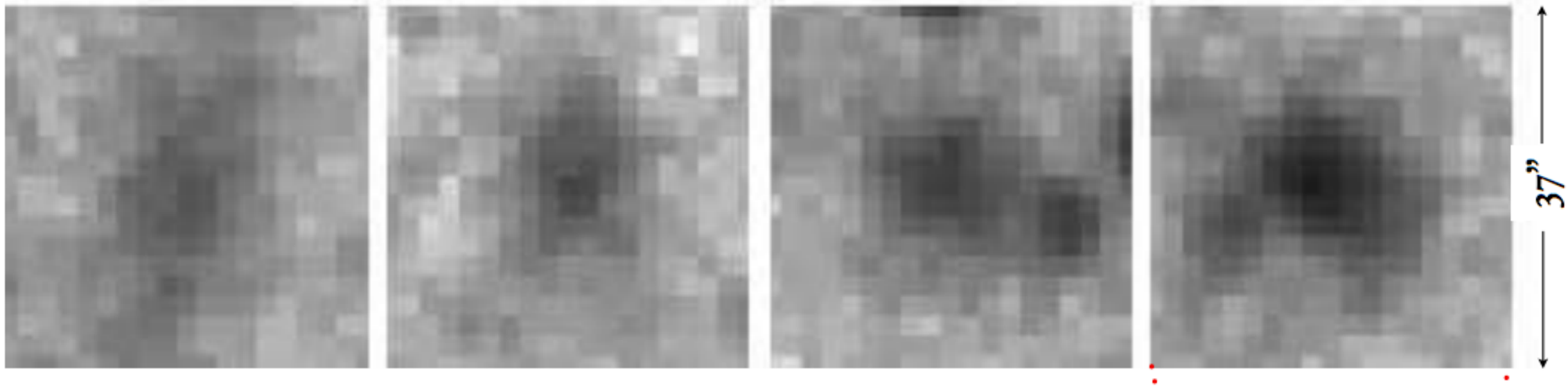

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van Dokkum et al 2015

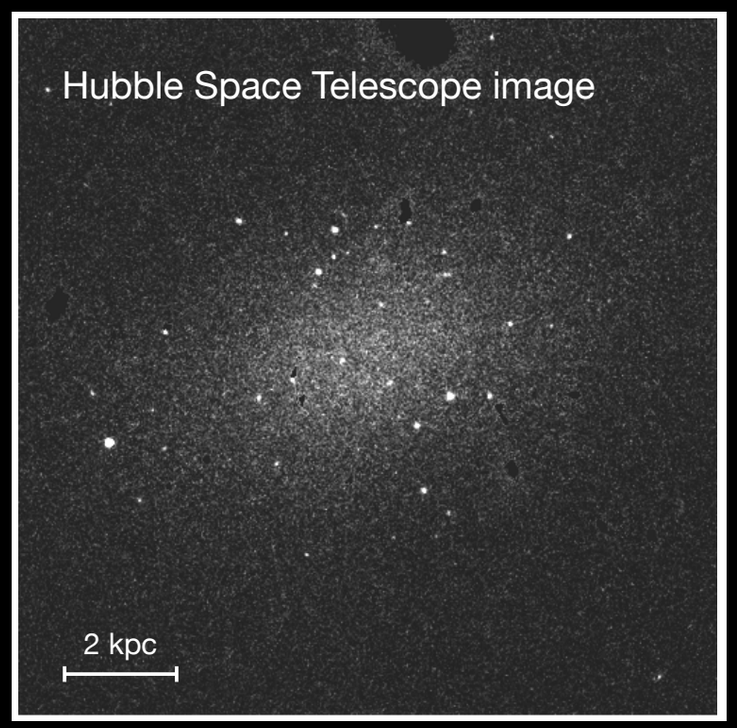
dwarf elliptical
galaxy

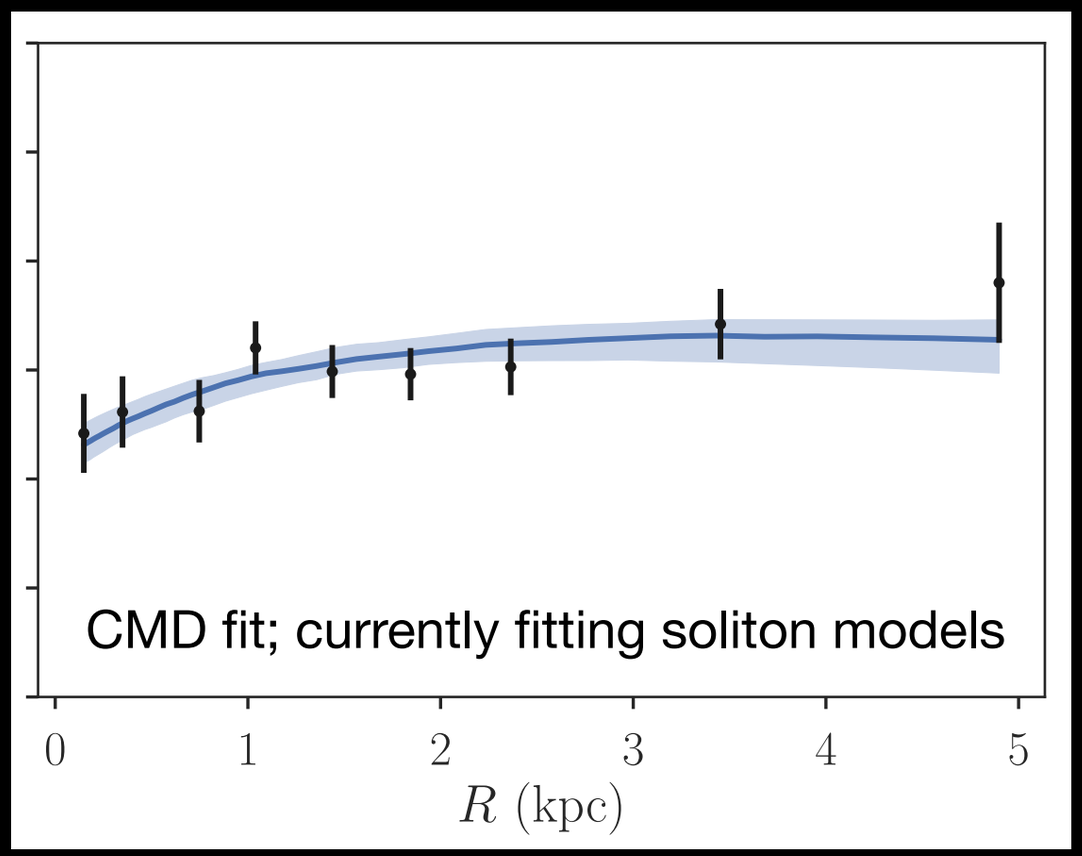
ultra-diffuse galaxy

Andromeda
galaxy

Found new class of “ultra diffuse” galaxies

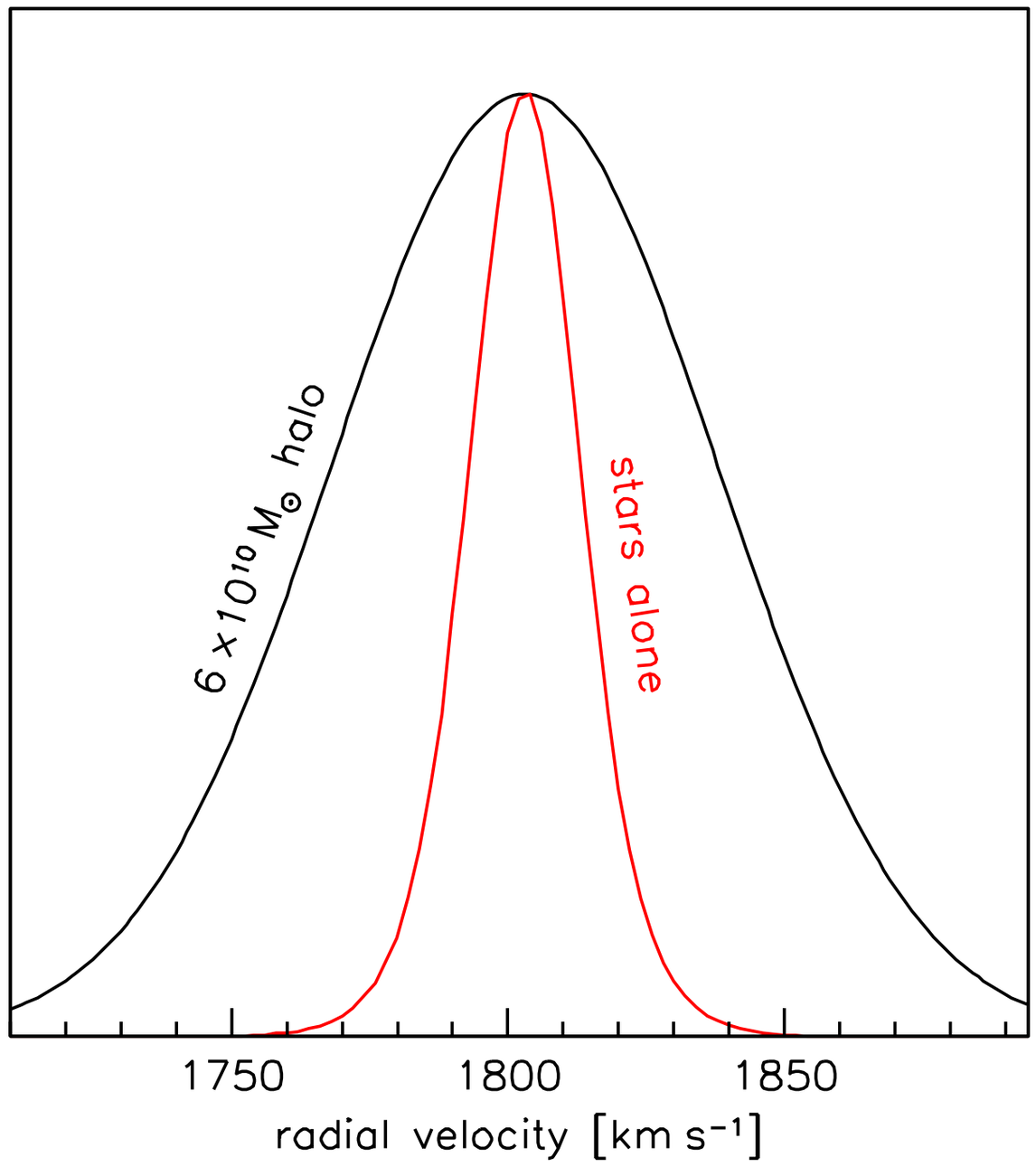
- Ubiquitous: since 2015 discovery, 1000s found by many groups
- Measure masses from extremely deep spectroscopy with Keck telescopes -> gives velocities of stars and/or star clusters
- Dragonfly 44: $r_{1/2}$=4.5 kpc; >90% dark matter even in the center





Surprising find this Spring: NGC1052-DF2

Velocities of globular clusters



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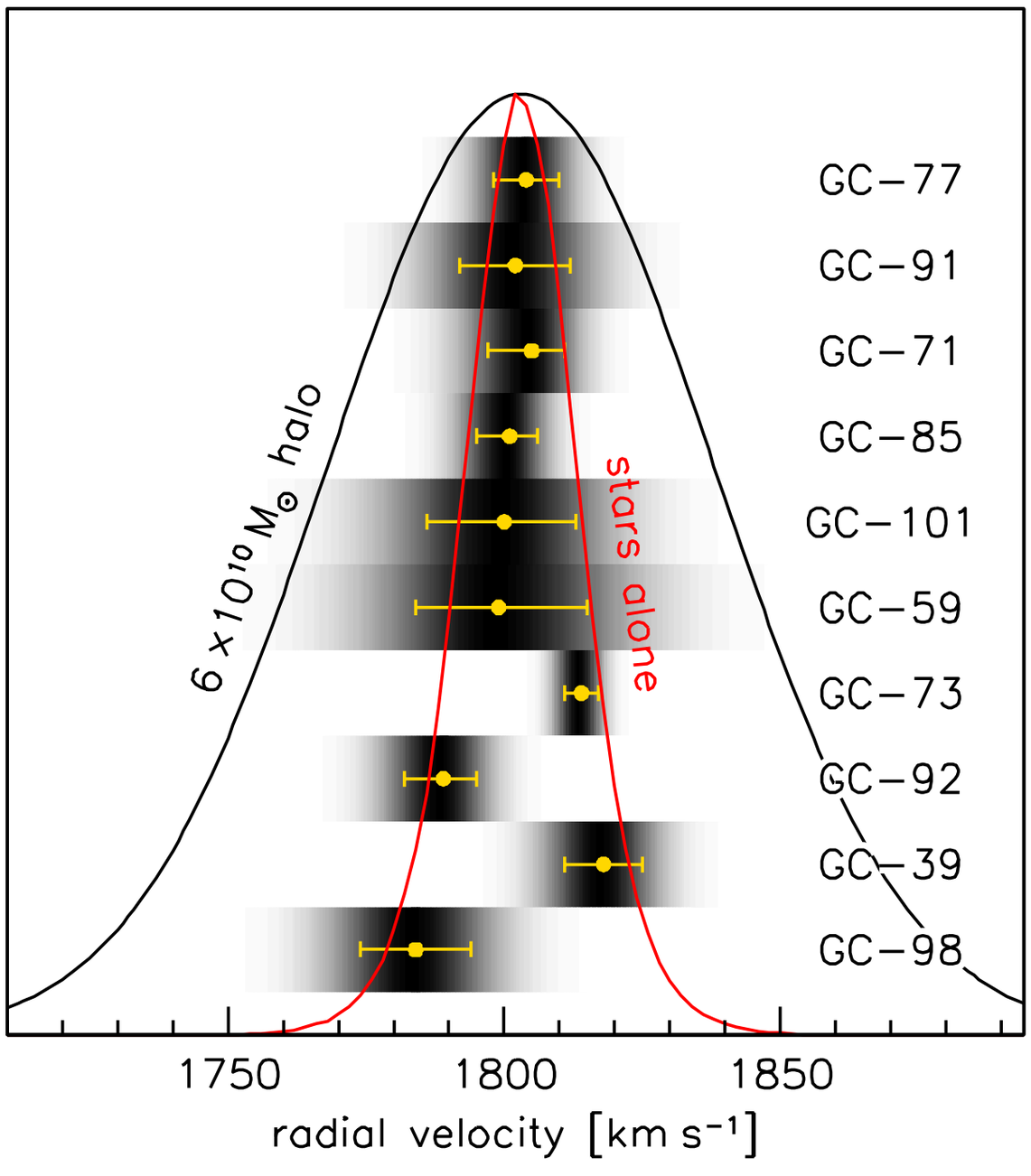
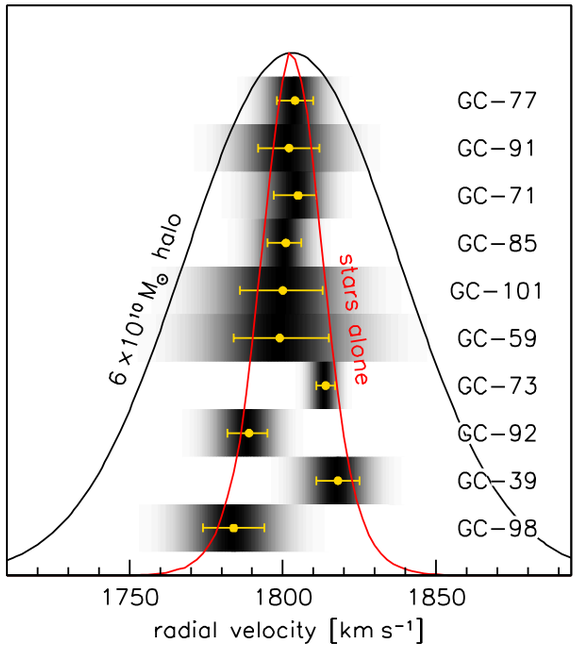
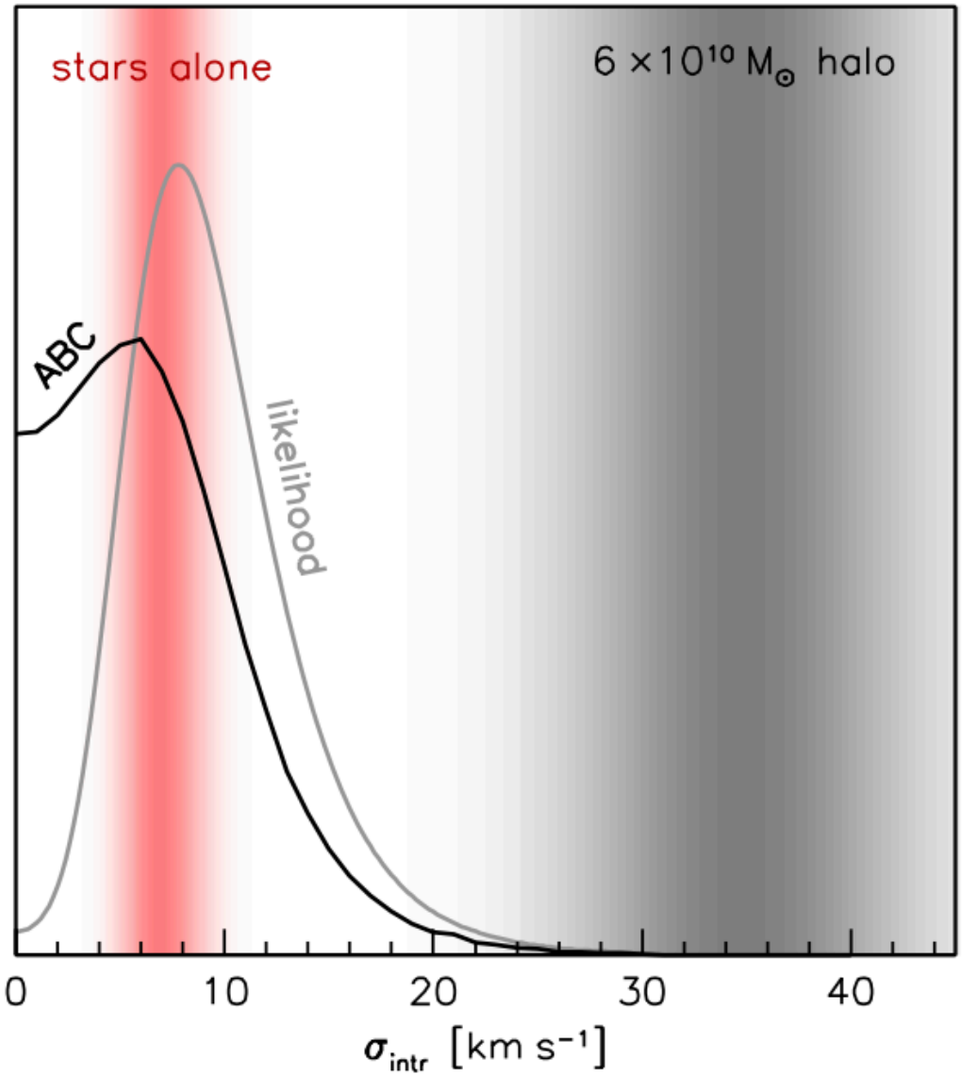


Velocities of globular clusters

- Surprisingly low velocity dispersion of globular cluster system

  van Dokkum et al 2018ab, Martin et al 2018





ABC:

$$\sigma_{\rm intr} = 5.6^{+5.2}_{-3.8}\,{\rm km/s}$$

likelihood:

$$\sigma_{\rm intr} = 7.8^{+5.2}_{-2.2}\,{\rm km/s}$$

stars only:

$$\sigma_{\rm stars} = 7.0^{+1.6}_{-1.3}\,{\rm km/s}$$

Galaxy NGC 1052-DF2

Illustration of Milky Way Galaxy

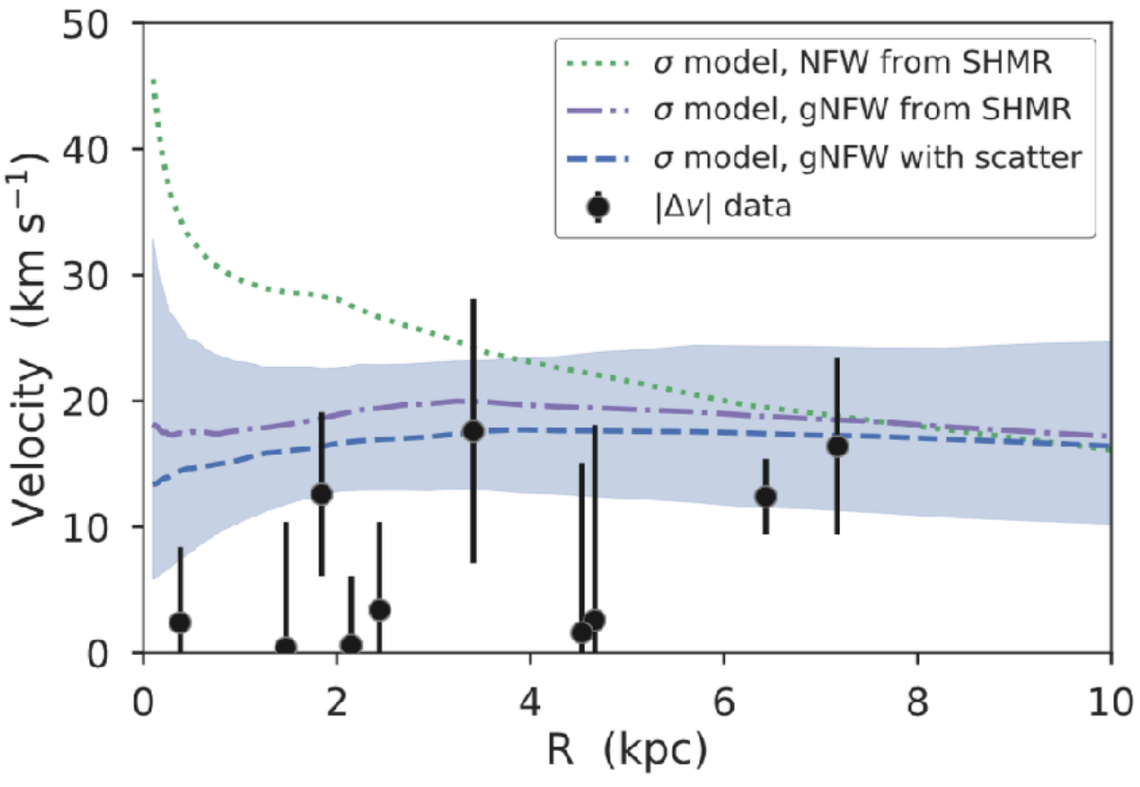
σ @ 8 kpc ~ 7 km/s

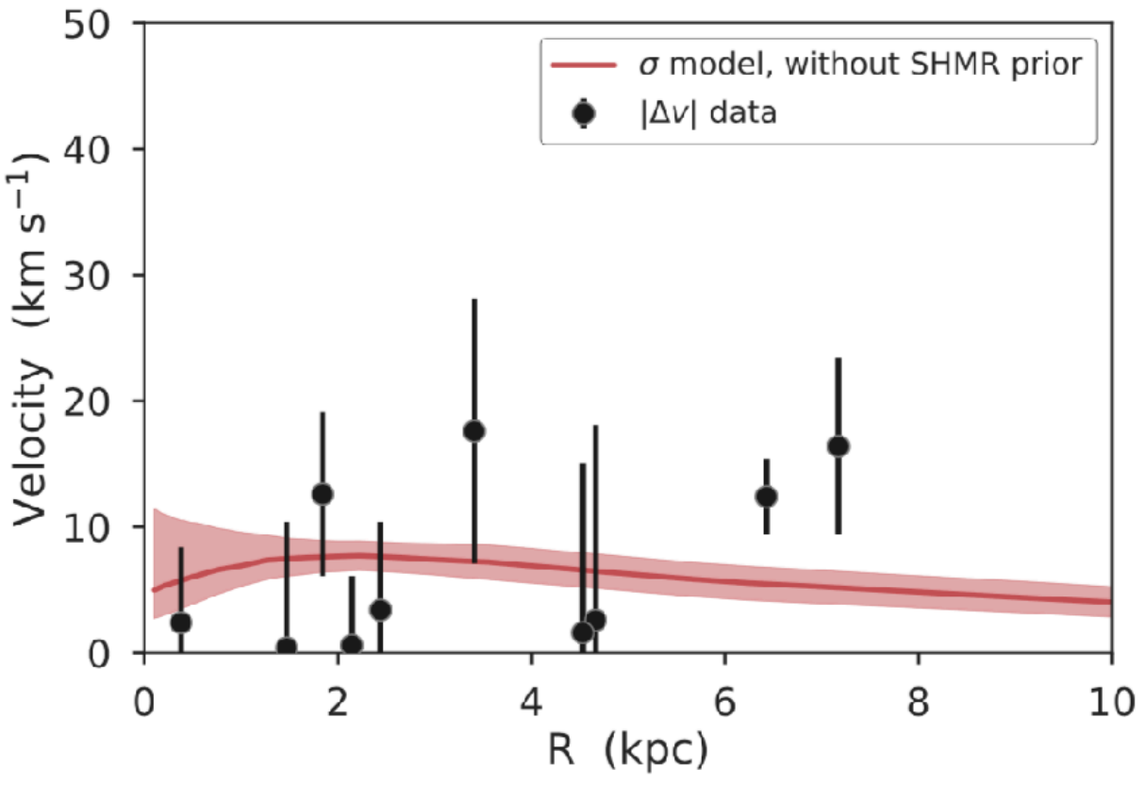
v @ 8 kpc ~ 200 km/s

Mass

- Constraints from generative Jeans model assuming generalized NFW profile, using individual GCs as information in a Bayesian framework

  Wasserman et al 2018





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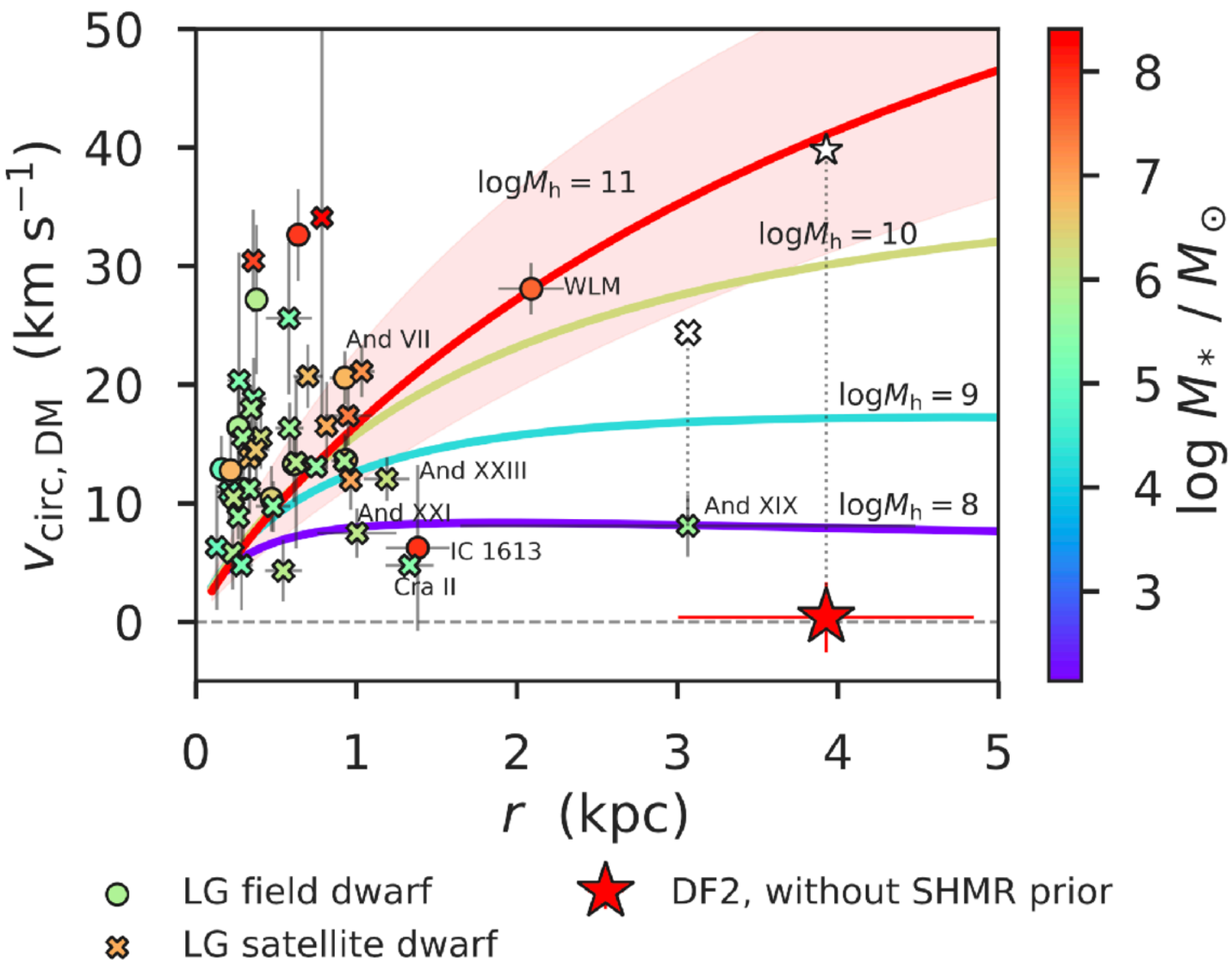
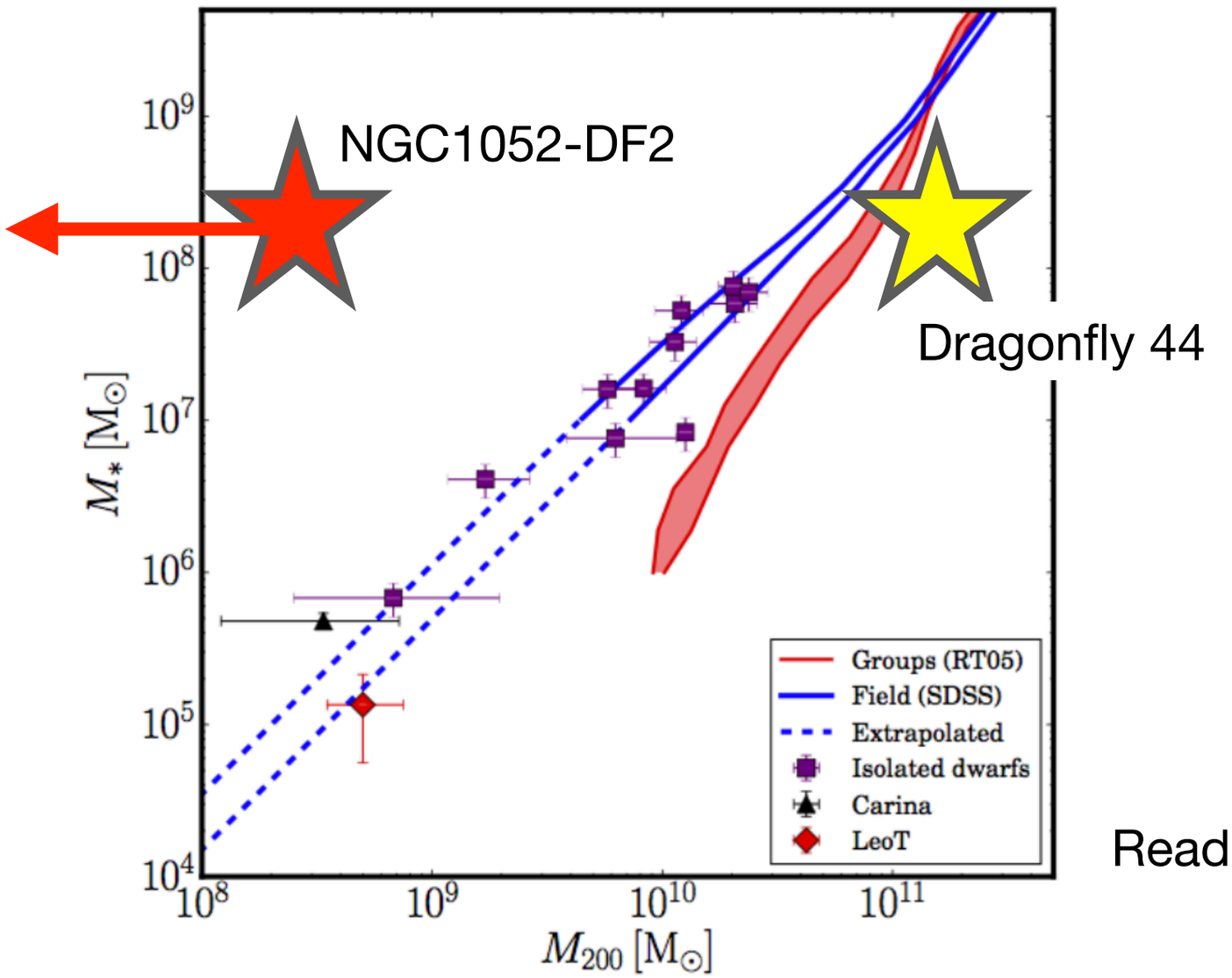


The SMHM relation

- Dragonfly 44, NGC1052-DF2 suggest very large scatter at low masses - may be expected in CMD, not in alternative gravity



Read et al 2017

Summary

- Dragonfly* has opened up the area of searching and characterizing faint, diffuse light in the night sky
- Luckily, the Universe is cooperating: this parameter space turns out to be interesting and we are finding large, diffuse galaxies that provide new information on the distribution of dark matter in the universe
- Still early days: most results based on 8-10 lens array (rather then current 48 lens version), and follow-up work is just beginning

* Dragonfly is not alone in this: there have been huge improvements in analyzing data from conventional telescopes, too, in the past 5 years or so. But Dragonfly is the awesomest.

- Latest: hardware for gas detection