Shedding Light on the Dark Universe with Extremely Large Telescopes

The view from Los Angeles

Tommaso Treu

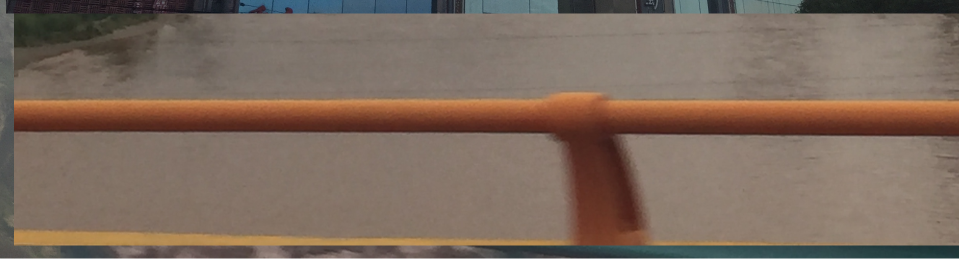
Aims of the Dark Universe series

1)What are the **most promising observations** that will be enabled by giant telescopes? What capabilities are required?

2) What are they key **synergies** between giant telescopes and other facilities? What are the areas and topics where a concerted effort will yield far superior results than the sum of all parts?

3) What theoretical work is needed in preparation for first light? What are the limitations in our understanding that need to be overcome? What calculations are required in order to make **testable predictions** and interpret the results of future astronomical observations?

First Conference; Lanzhou China



Second Conference; Los Angeles USA

First key point

- Simulations of the outcomes of particular studies are increasingly viable and necessary. The resources allocated are now substantial, warranting an investment not only in simulating the actual observations themselves, but also of the analysis which is becoming increasingly sophisticated.

Webster

Second key point

- Tension between different measurements of H0
  - Riess (2016) $H0 = 73.24 \pm 1.24\ km\ /s/Mpc$ (HST)
  - Planck (2015) $H0 = 66.93 \pm 0.62\ km\ /s/Mpc$ (Ade+ 2015)
  - HOLiCOW $H0 = 72.8 \pm 2.4\ km\ /s/Mpc$ (Bonvin+ 2017)

- Also tension with measurement of growth from weak lensing cf Planck
- And BAO measurement of H(z)
- Tension between high and low redshift measurements of H
- Note: recently LIGO published a value of H0 neatly covering both these values $H0 = 70.0$+12.0-8.0 $km\ /s/Mpc$ (Abbott+2017)

Webster

Third key point

- Statistical uncertainty will be substantially reduced
- Do we understand the systematic uncertainty with each measurement?
- Do we have a consistent set of metrics to compare and contrast techniques?

Webster

ELTs and Instrumentation

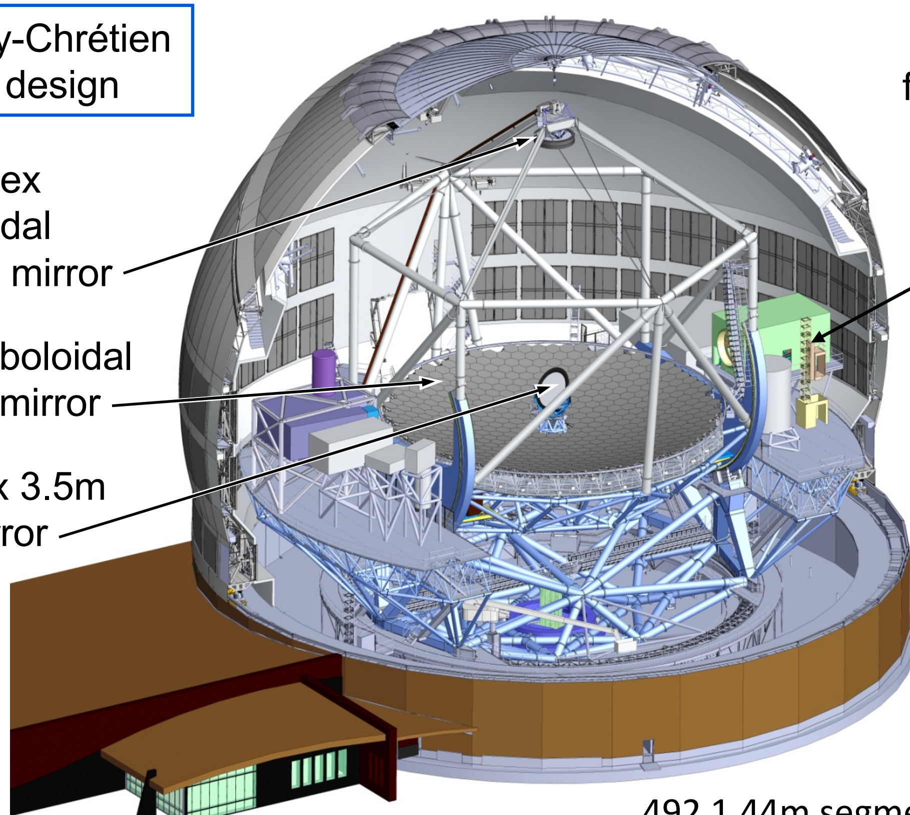
Telescope Concept Overview

Ritchey-Chrétien optical design

3.1m convex hyperboloidal secondary mirror

30m hyperboloidal f/1 primary mirror

Flat 2.5m x 3.5m tertiary mirror



f/15 final focal ratio

Science instruments mounted on Nasmyth platforms

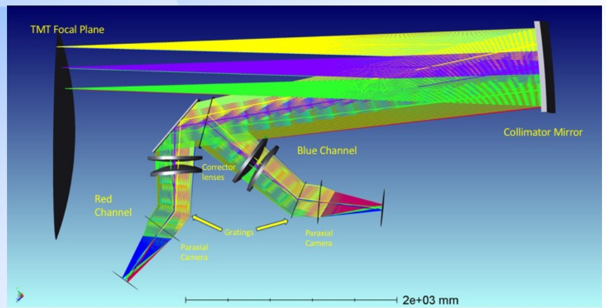
20 arcmin field of view 2.62 m diameter

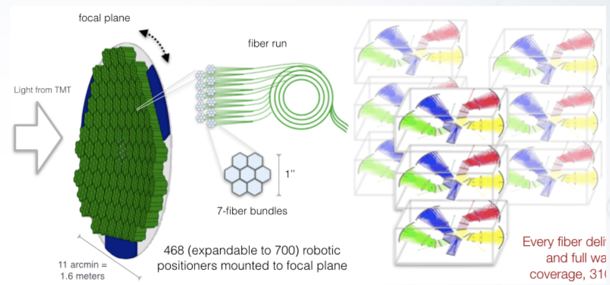
492 1.44m segments (50mm thick)

Bolte

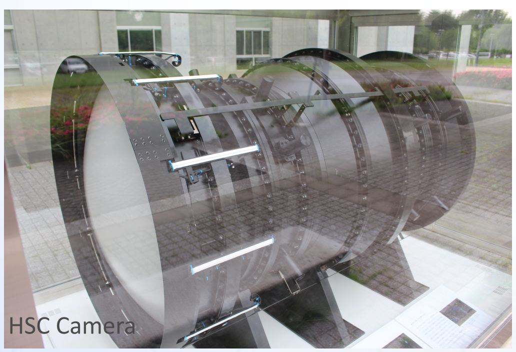
WFOS at a Crossroads…

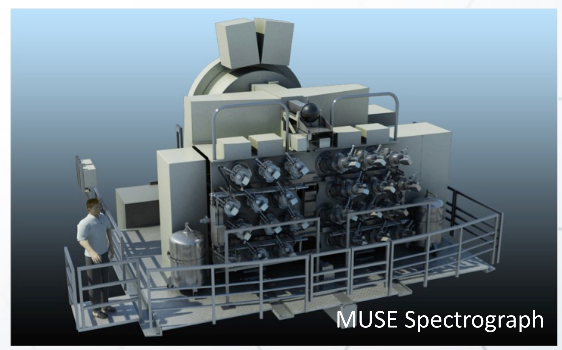
Slitmask-WFOS or… Fiber-WFOS





Monolithic vs. Modular





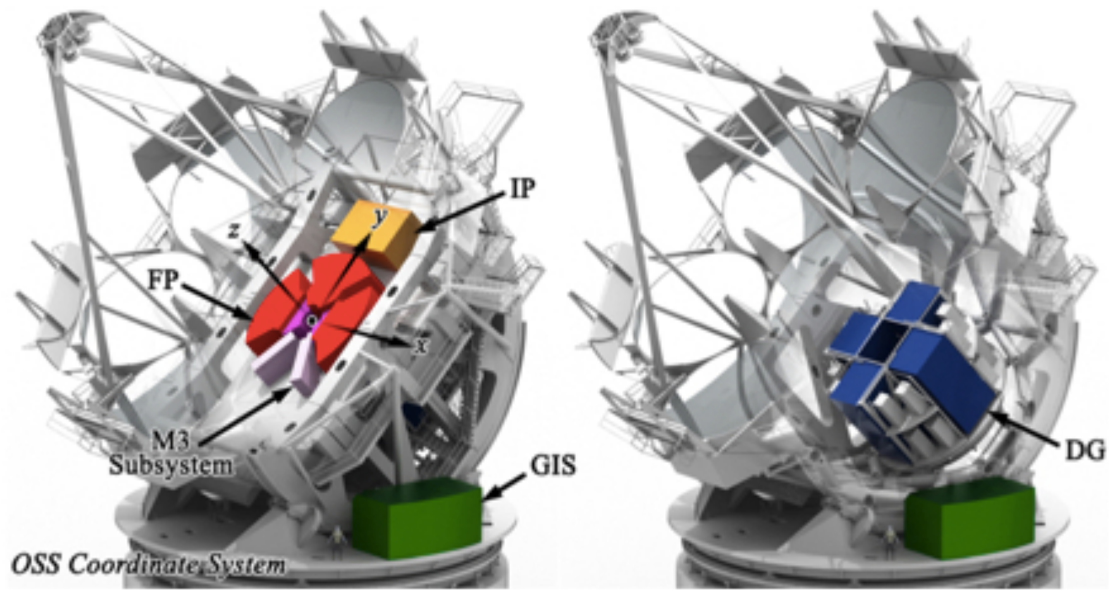
Bundy

x

Fiber-WFOS and Dark Energy

- LSST Photo-z training
- Kinematic Weak Lensing

Bundy



Up to 10 instruments available at any given time

Zaritsky

First Generation Instrument Suite

Instrument	Description	λ Range (µm)	Resolution	AO Modes	Field of View
G-CLEF	Optical High-Resolution High-Stability Spectrograph	0.35 – 1.0	20,000–100,000	NS, GLAO, NGSAO	7 x 0.23" pack, or 1.2" fiber
GMACS	Wide-Field Optical Multi-Object Spectrograph	0.36 – 1.0	1,500–4,000	NS, GLAO	43 $arcmin^2$
GMTIFS	Near-IR IFU Spectrograph & Imager	0.9 – 2.5	5,000–10,000	LTAO, NGSAO	10 or 400 $arcsec^2$
GMTNIRS	Near- to Mid-IR High-resolution Spectrograph	1.15 – 5.3	50,000 (JHK) 100,000 (LM)	NGSAO, LTAO	1.2" long-slit
MANIFEST	Facility Robotic Fiber System	0.36 – 1.0	—	NS, GLAO	20 arcmin diam

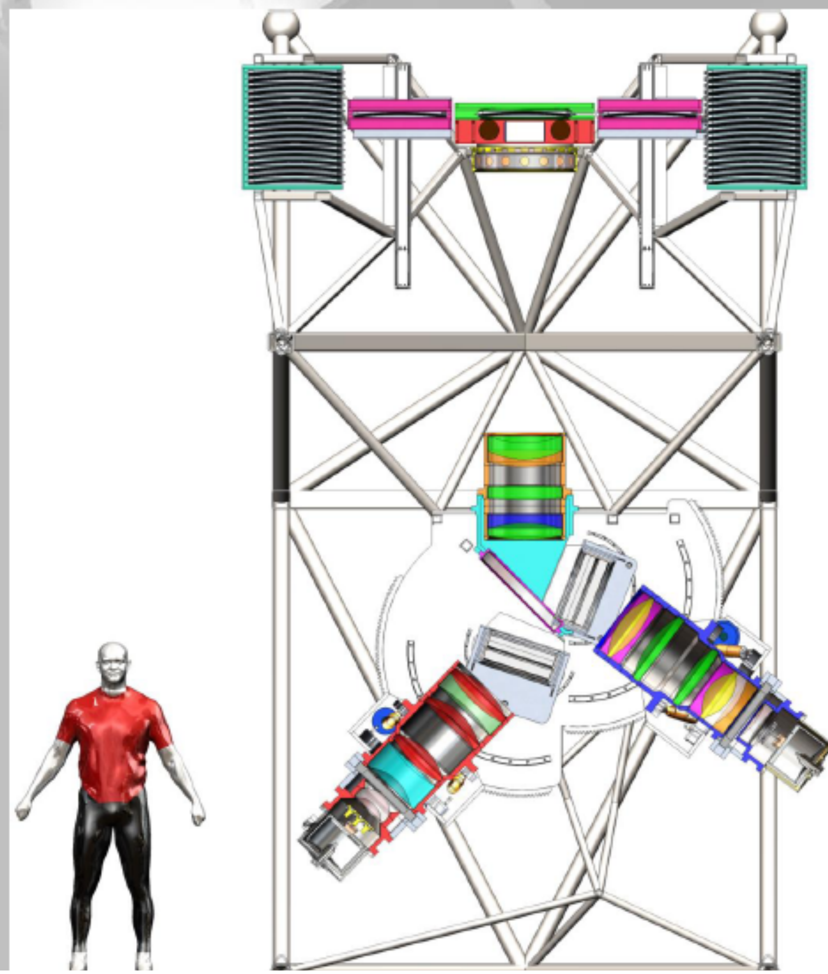
GIANT MAGELLAN TELESCOPE

Munnerlyn Astronomical Instrumentation Lab
Texas A&M University

GMACS design

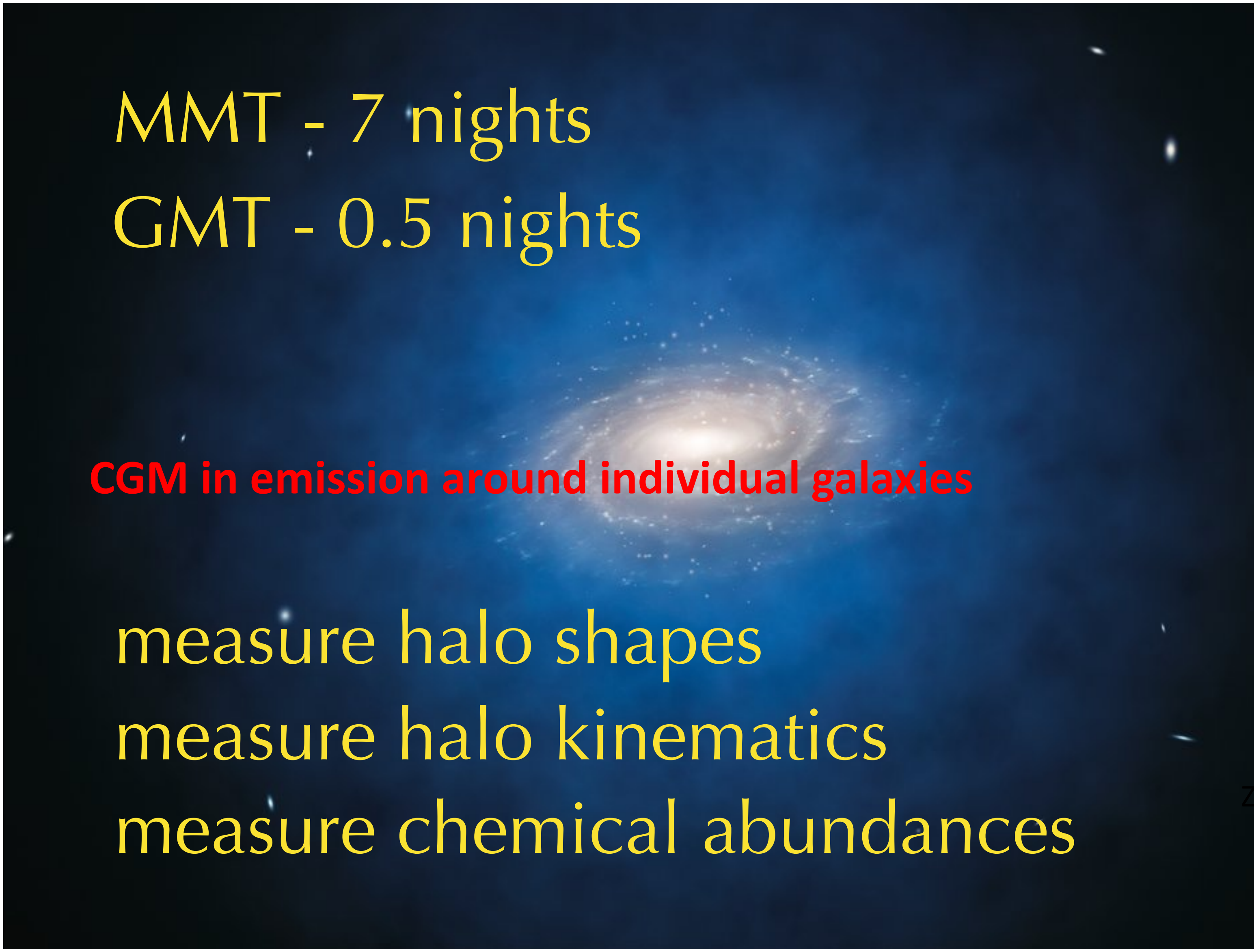
Many more details in 2016 (and soon 2018) SPIE papers:

instrumentation.tamu.edu



Science Case	constraints
Time-domain science	High rel. precision/repeatability/efficiency; large simultaneous wavelength coverage
Brown dwarf/exoplanet atmospheres (weather)	5' FOV, blueward of JWST wavelength coverage. High stability for transit spectroscopy.
Star/Star Cluster ages	<2 Å resolution at Li 6708Å for age measurements; blue coverage (Ca HK)
YSO accretion rates	simultaneous coverage of Balmer lines/break (365-656 nm)
Dwarf Galaxy dynamics	Coverage of CaT (850 nm, R~5000); 3 km/s velocity precision, high stability. 20' FOV preferable
Stellar Abundances	R~5000, blue/red wavelength coverage (370-540 nm; CaT 850 nm)
Redshift surveys (LSST, DES follow-up)	High multiplexing, slitlength requirement: source density will be ~50-60 arcmin^{-2}. FOV as large as possible. Large simultaneous wavelength coverage to improve efficiency.
Galaxy assembly, IGM/CGM studies	R~3000 and redder wavelength coverage for absorption line studies of z > 1 galaxies.
Properties of Galaxies during Reionization	Very red coverage (>900 nm for Ly-α at z > 6.5), higher resolution and high multiplexing/FOV helpful (~0.5-1 source/arcmin^2)

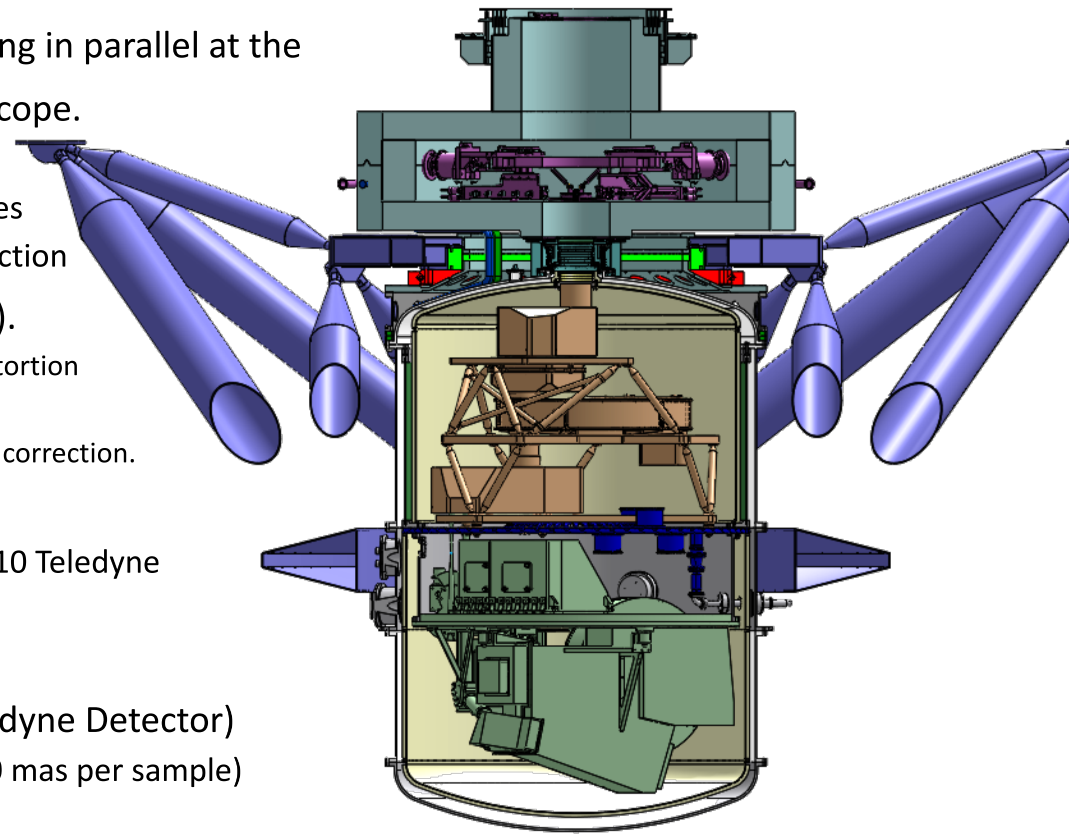
Marshall


MMT - 7 nights
GMT - 0.5 nights
CGM in emission around individual galaxies
measure halo shapes
measure halo kinematics
measure chemical abundances

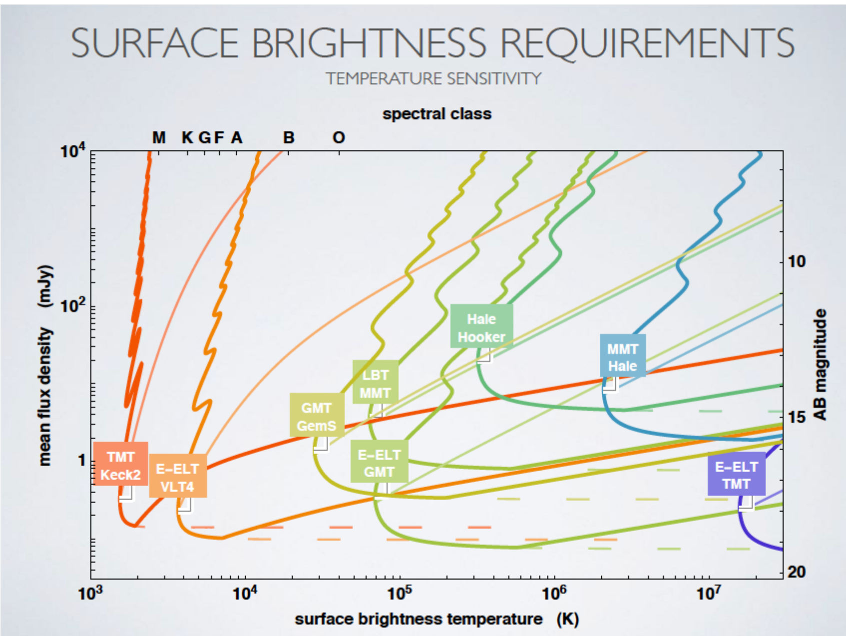
Zaritsky

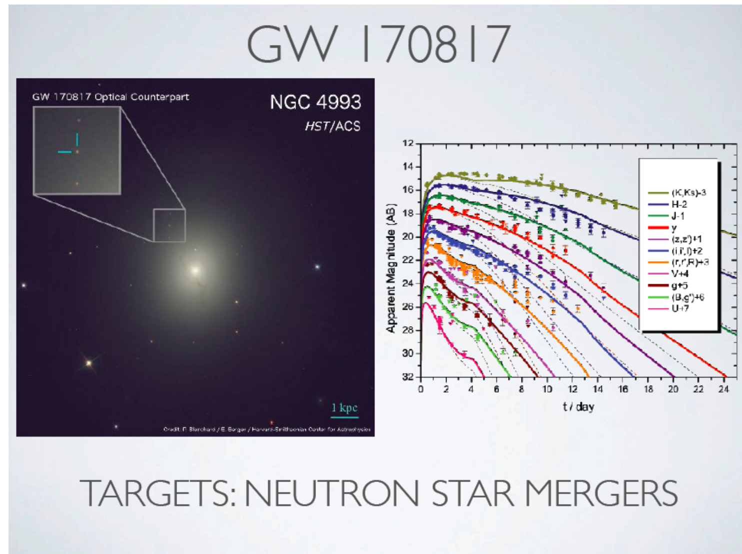
IRIS Capabilities

- First Light Imager and Spectrograph working in parallel at the diffraction limit of the Thirty Meter Telescope.
  - Wavelength Range 0.84-2.4 microns
  - RMS Wavefront Error < 40 nm in fine scales
  - High Order Atmospheric Dispersion Correction
- On-Instrument wavefront sensors (OIWFS).
  - Three sensors to measure tip/tilt, focus and distortion across field.
  - Near infrared sensors to gain from NFIRAOS AO correction.
- "Wide-Field" Imager (60+ filters)
  - 34 arcsec field of view (2x2 grid of H4RG-10 Teledyne Detectors)
  - 4 mas plate scale (Nyquist @ 1.15 μm)
- Integral Field Spectrograph (H4RG-15 Teledyne Detector)
  - IFS with Four Plate Scales (4, 9, 25 and 50 mas per sample)
    - Up to 14,378 individual, simultaneous spectra.
  - Spectral Resolutions of 4000, 8000 and few exotic modes (14 gratings)



Interferometry between ELTs!





Stebbins

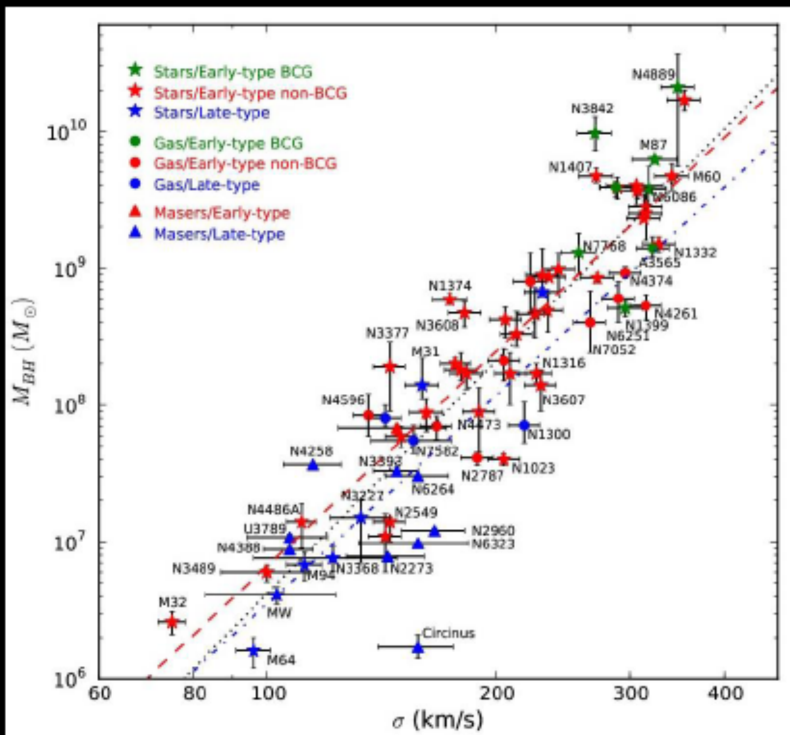
Black holes and Testing Gravity

Galactic center (Ghez)

- Individual orbits can be used to test GR in new regime
- Key requirements
    - AO performance
    - PSF quality

Black Hole Masses

TMT will be able to resolve the radius of influence of the black hole in a typical Seyfert galaxy harbouring a MBH~10^7 Msun out to a distance of ~50Mpc

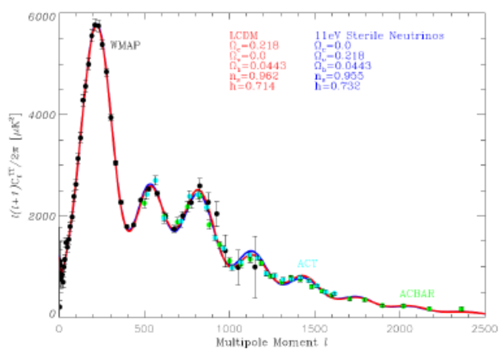


Muller-Sanchez

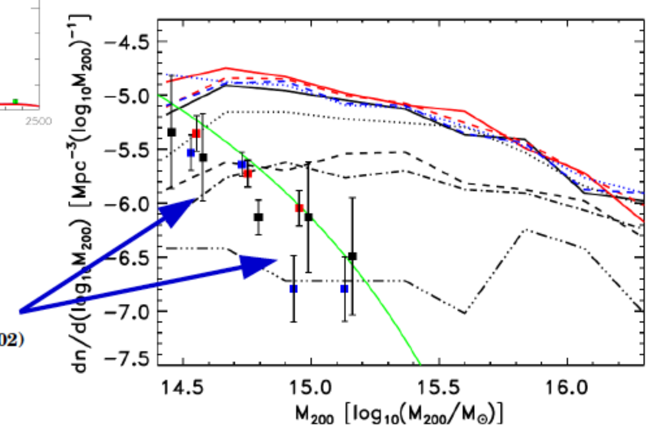
McConell & Ma 2013

Other tests of gravity

The case of MOND with sterile neutrinos



Angus and Diaferio (2011)



Angus et al. (2013)

Dark Matter

Allowed Particle Dark Matter Models
- All produces **same** large-scale structure -

factor of ~10^{33} in mass & >10^{20} in cross section

Cold (WIMP)

Mass ~ 100 GeV

Self-interaction ~ 0

Warm (sterile neutrino)

Mass ~ keV

Self-interaction ~ 0

Self-Interacting

$\sigma/m \sim cm^2/g$

(~nucleon scattering)

Ultra-light Scalar Field

Mass ~ 10^{-22} eV

Bullock

“Cracks” in CDM

- Cusp vs core (Simon, Bonaca, Kaplinghat)
- Substructure (missing satellites + too big to fail) (Nierenberg, Birrer, Gilman, Pace)
- Concentration (More)

The SIDM solution to the small scale puzzles

Particle dark matter with a large elastic self-scattering cross section explains the diverse inner rotation curves.

Require $\sigma/m \sim$ few barns/GeV

Kaplinghat

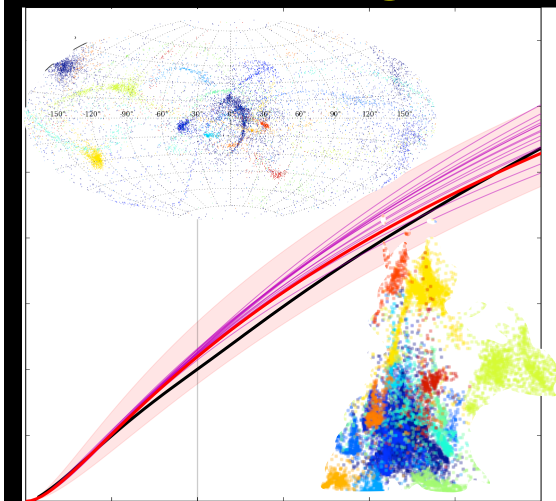
Dwarfs as tests of the dark universe

- Number counts (Bullock)
- Masses (Simon)
- Mass density profiles (Simon)
- Direct detection (Pace)
- Densities (Kaplinghat)
- ELTs will provide crucial line of sight velocities and proper motions (Kallivayalil)
  - Will the spectrographs have enough spectral resolution/fov?
  - Will the images have sufficient stability/fov?

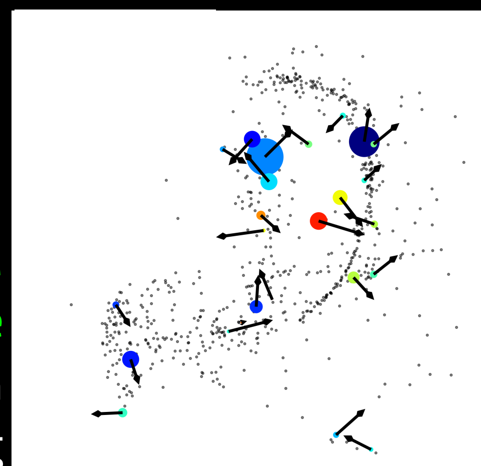
Streams as a test of MW mass and substructure

- Bonaca
- Sanderson
- ELTs crucial for radial velocity of distant streams?

Constraining dark matter models with stellar halos

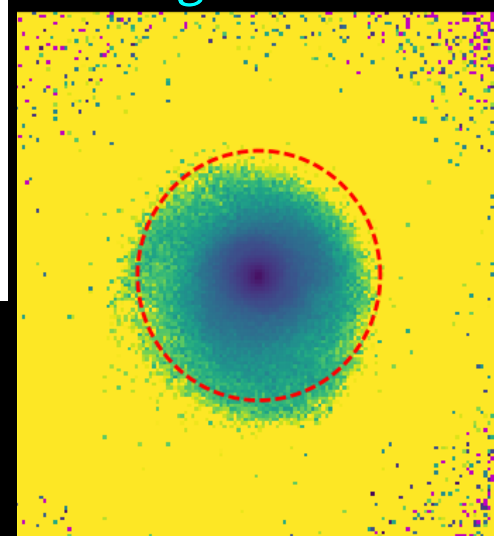


Mass and accretion history of the MW from its tidal streams



Limits on DM substructure from tidal stream scattering

Mass and structure in stellar halos of galaxies



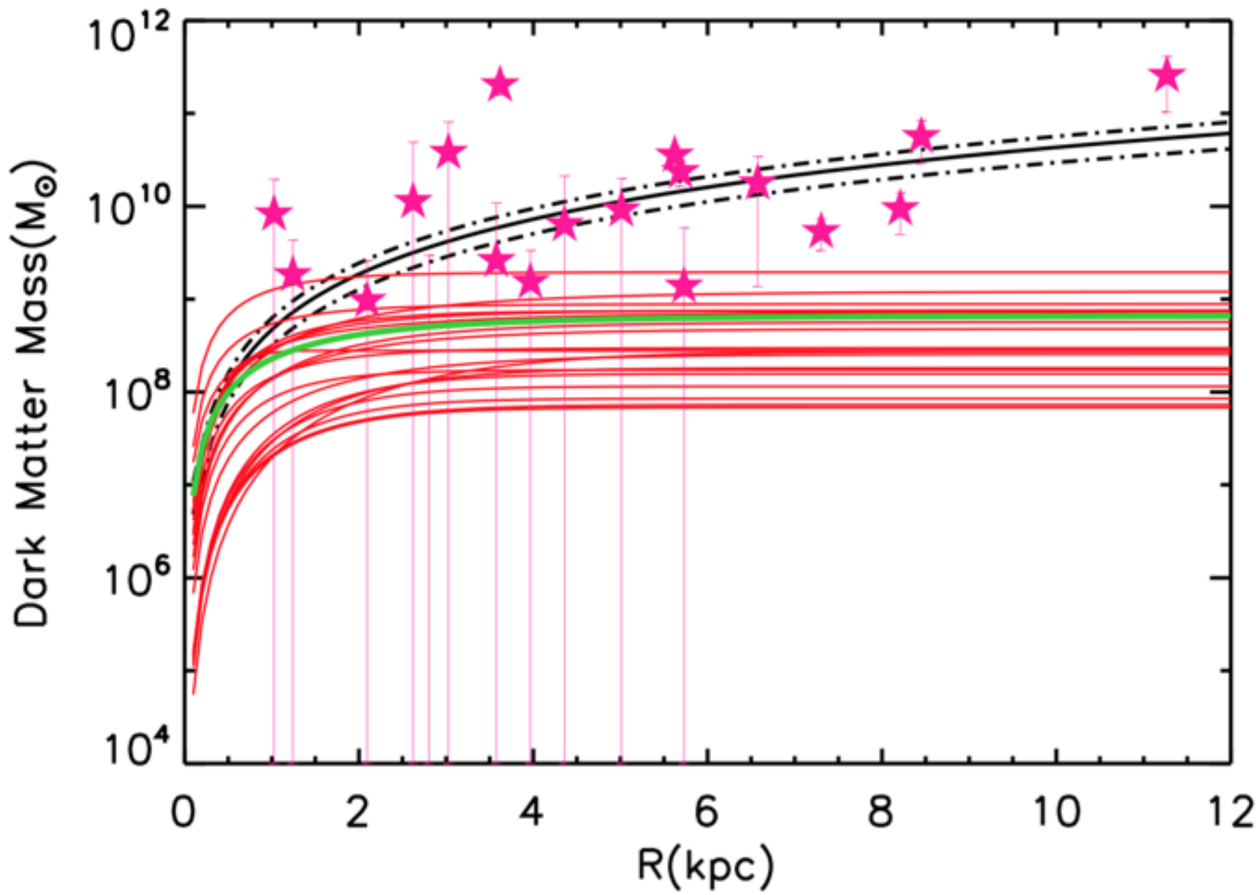
dark matter ↔ galaxy formation

Other phase space constraints

- Pawlowski
- Again, ELTs will give velocities, especially for satellites of galaxies other then the MW
- ELTs well matched to 100Mpc targets?

Target (distance)	Milky Way (~100 kpc)	Andromeda (~800 kpc)	Centaurus A (~4 Mpc)	Local Volume (~10 Mpc)	(~ 100 Mpc)
Angular size of viral volume (r_{vir}~ 250 kpc)	all-sky	18º	4º	1.4º	9’
5% distance uncertainty	± 5 kpc	± 40 kpc	± 200 kpc	~ 500 kpc	~ 5 Mpc
Positions	3D	3D	~3D	2D	2D
Kinematics	3D LoS + PM	1D - 3D LoS (+ PM?)	1D LoS	1D LoS	1D LoS
Angular size of dwarf (r_h ~ 250 pc)	9’	1’	0.2’	5”	0.5”

Dark matter halos of dEs from GC satellite tracers

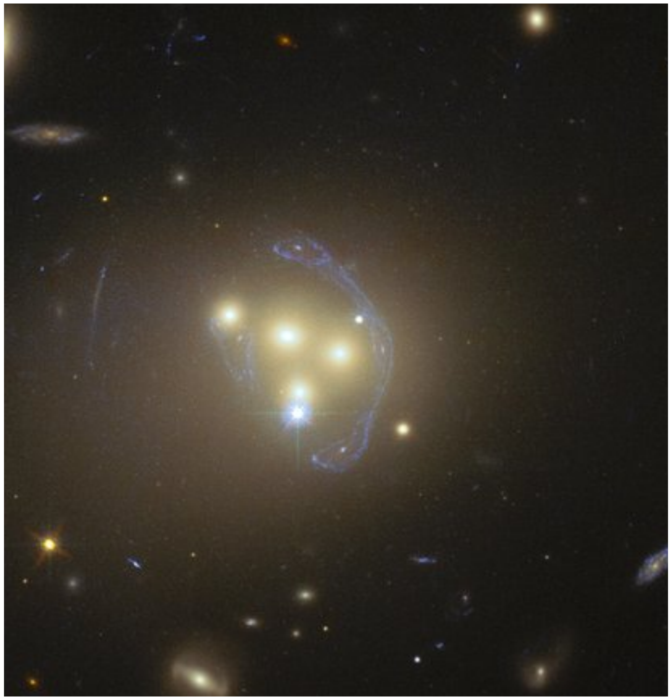


Toloba et al. (2018, in press – arXiv:1803.09768); Peng et al. (2018, in prep.)

GuathaKurtha

Clusters of galaxies

- Can we measure their central densities without kinematics?

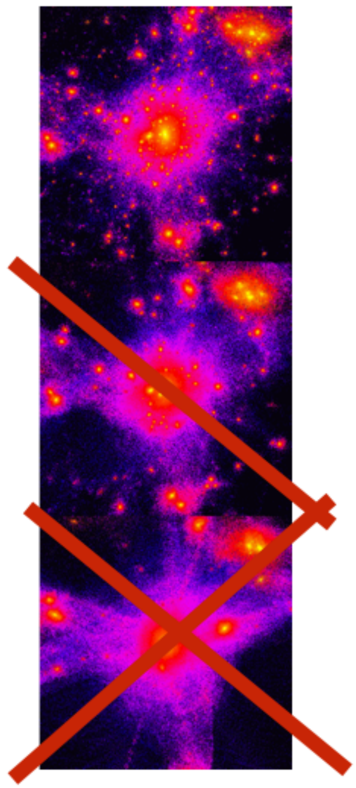


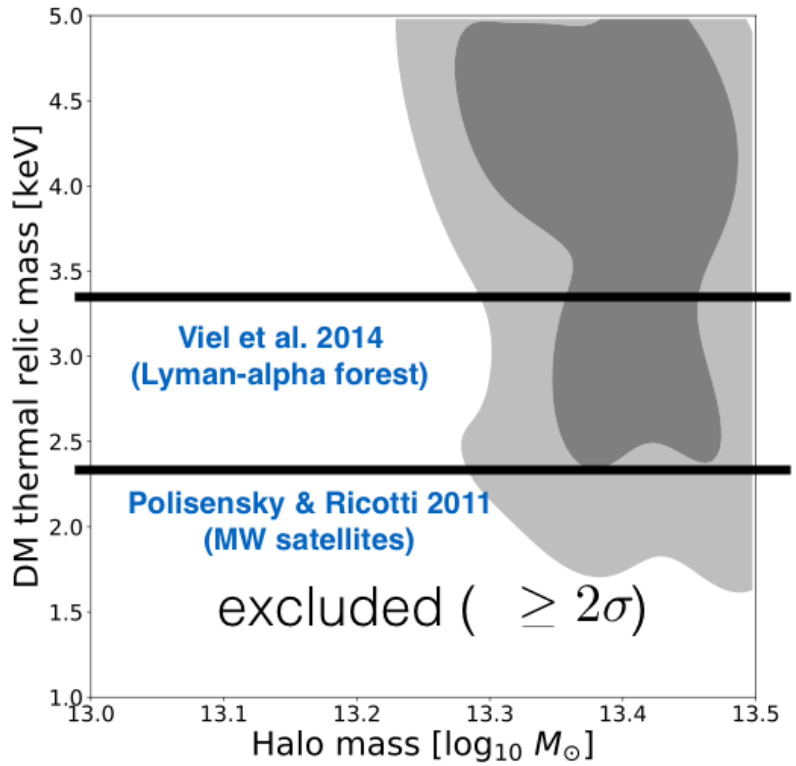
Kaplinghat

Substructure lensing

- Galaxy scale lenses: Nierenberg, Birrer, Gilman, McKean
- Transients behind clusters: Dai, Venumadhav

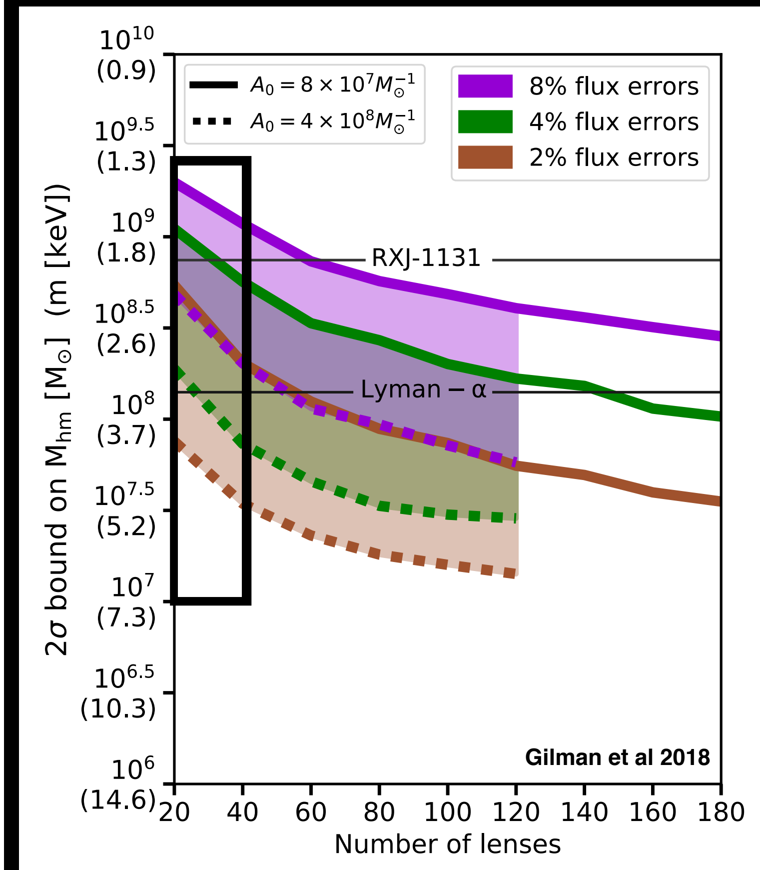
Dark Matter thermal relic mass constraints from lensing substructure

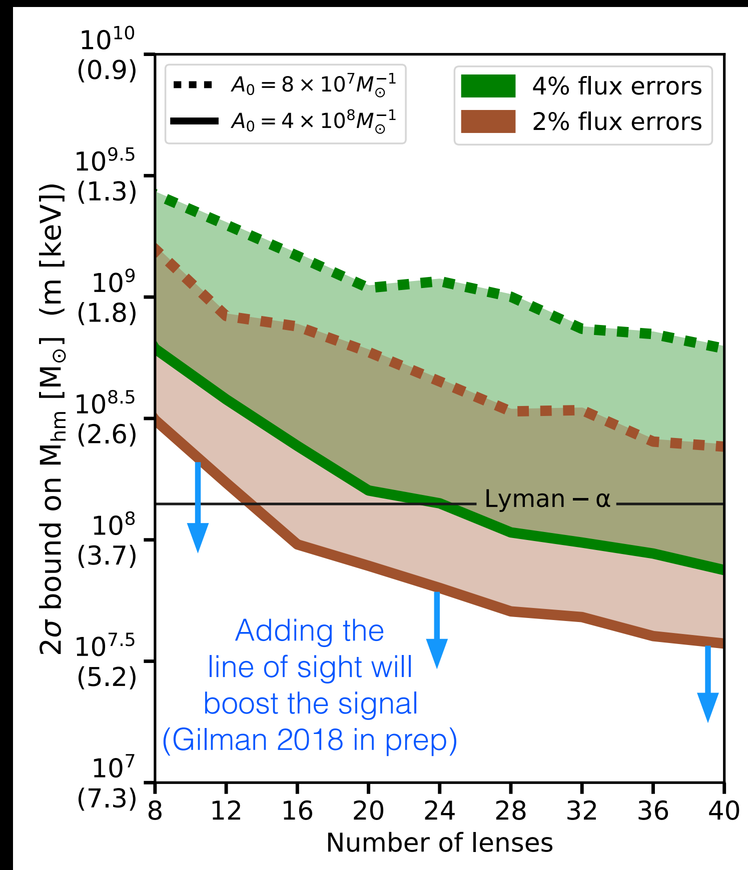




Birrer+ 2017

The Future…

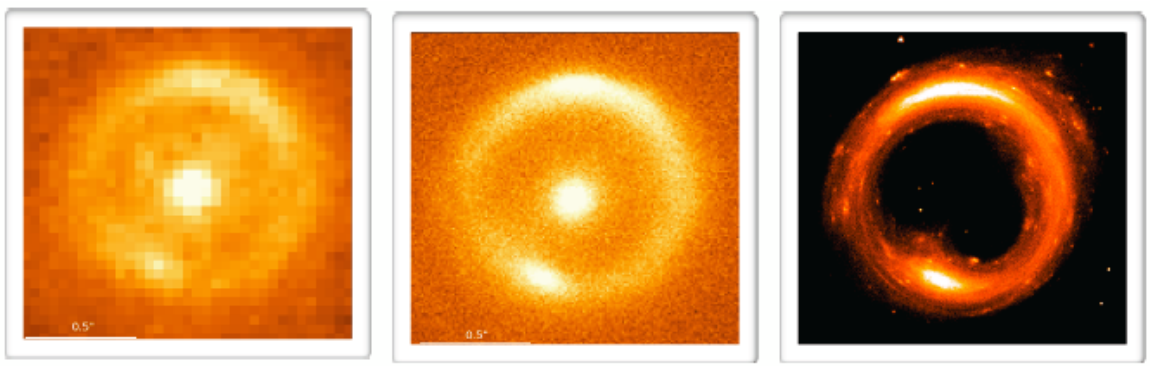




Gilman

ELTs and strong lensing: a heavenly match

- Resolution, sensitivity, and FOV of first generation instruments are perfect for galaxy-scale lensing
- With both flux ratio anomalies and gravitational imaging we should be able to probe subhalos down to Mvir~10^7, an untested regime, where the differences between CDM and WDM are huge. Confirm/rule out particle dark matter.



HST	Keck AO	E-ELT
10^9 M_{sun}	10^8 M_{sun}	?

Simulation courtesy of Simona Vegetti

Nierenberg
See also Birrer, Gilman, McKean

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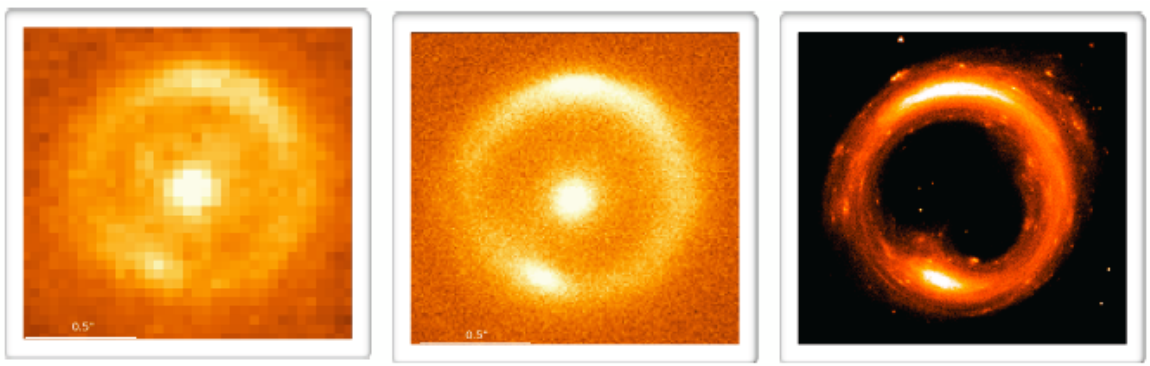


HST | Keck AO | E-ELT

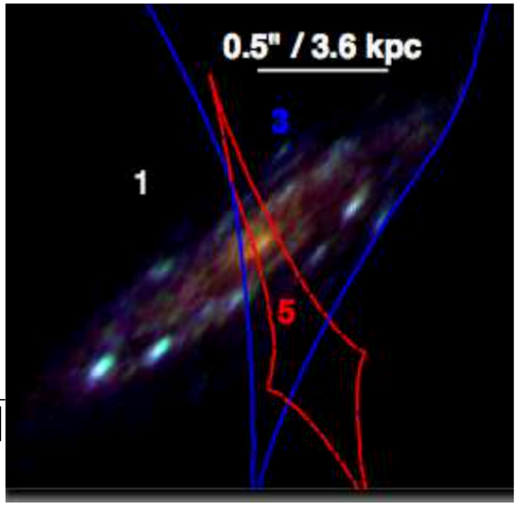
10^9 M_{sun} | 10^8 M_{sun} | ?

Simulation courtesy of Simona Vegetti

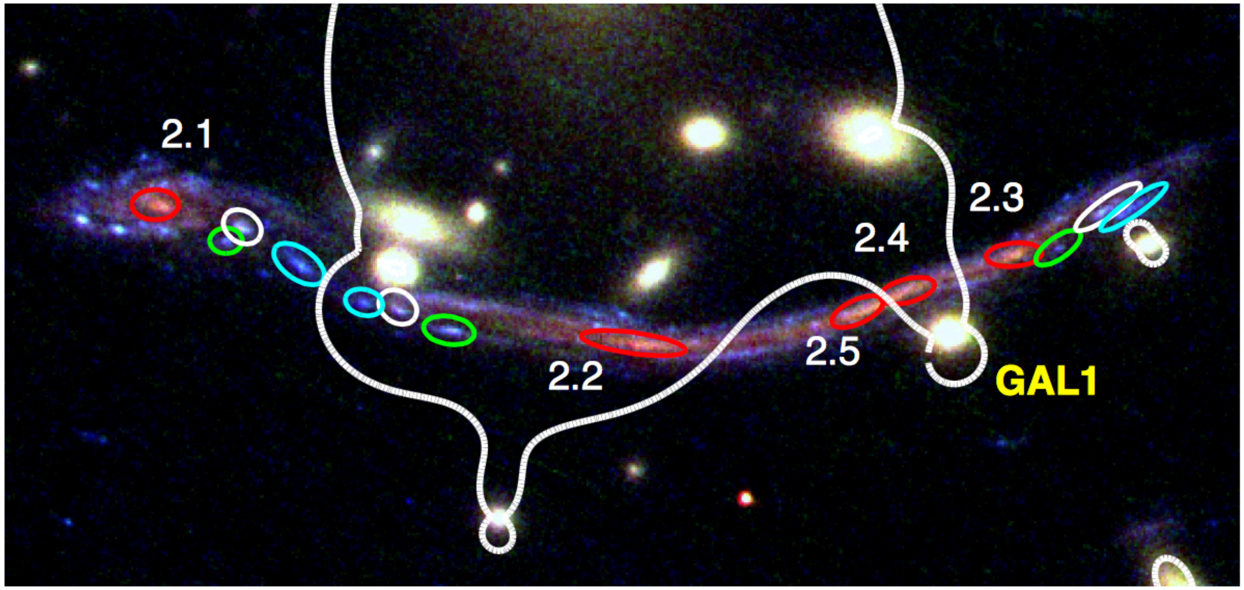
Nierenberg
See also Birrer, Gilman, McKean

What systems are the most promising?

- Source galaxy at low redshift
- Active star formation
- Wide giant arc favorable
- Near critical convergence
- Shear has small derivative $\mu = \frac{1}{|2\,(1-\kappa_0)\,\boldsymbol{d}\cdot\boldsymbol{x}|}$



The "Dragon" of Abell 370 Richard+ 2009



Dai, Venumadhav

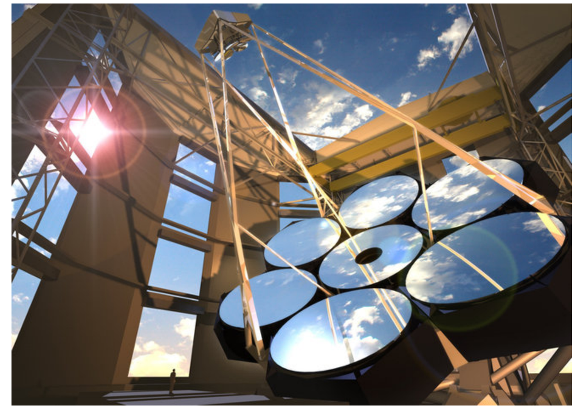
Promise of future ELTs

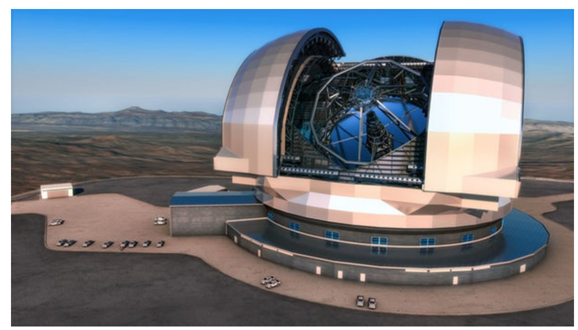
- ❑ Caustic crossing sources are faint, even with huge lensing amplifications. Faster photon collecting rate is good.

- ❑ Smaller diffraction-limited PSF extremely beneficial for detecting point sources.

- ❑ Higher angular resolution crucial for detecting astrometric distortions from subhalos.

- ❑ Red/white super-giants very bright in J,H,K bands. These are very important and powerful bands for ELTs aided with AO.

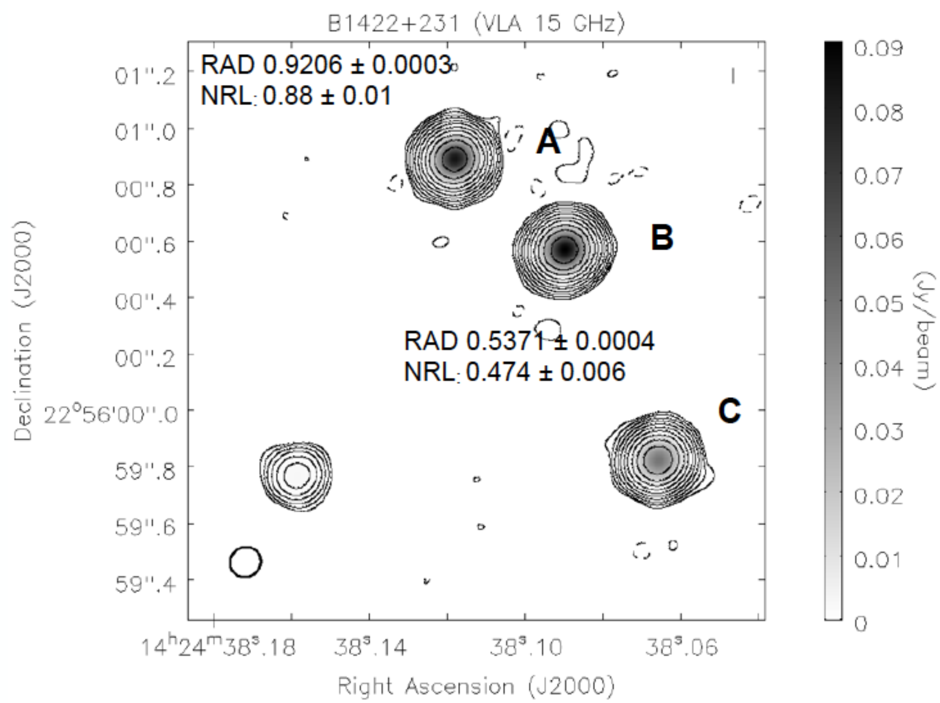




Dai, Venumadhav

Combine RADIO and ELTs! Mid-IR with ELTs?

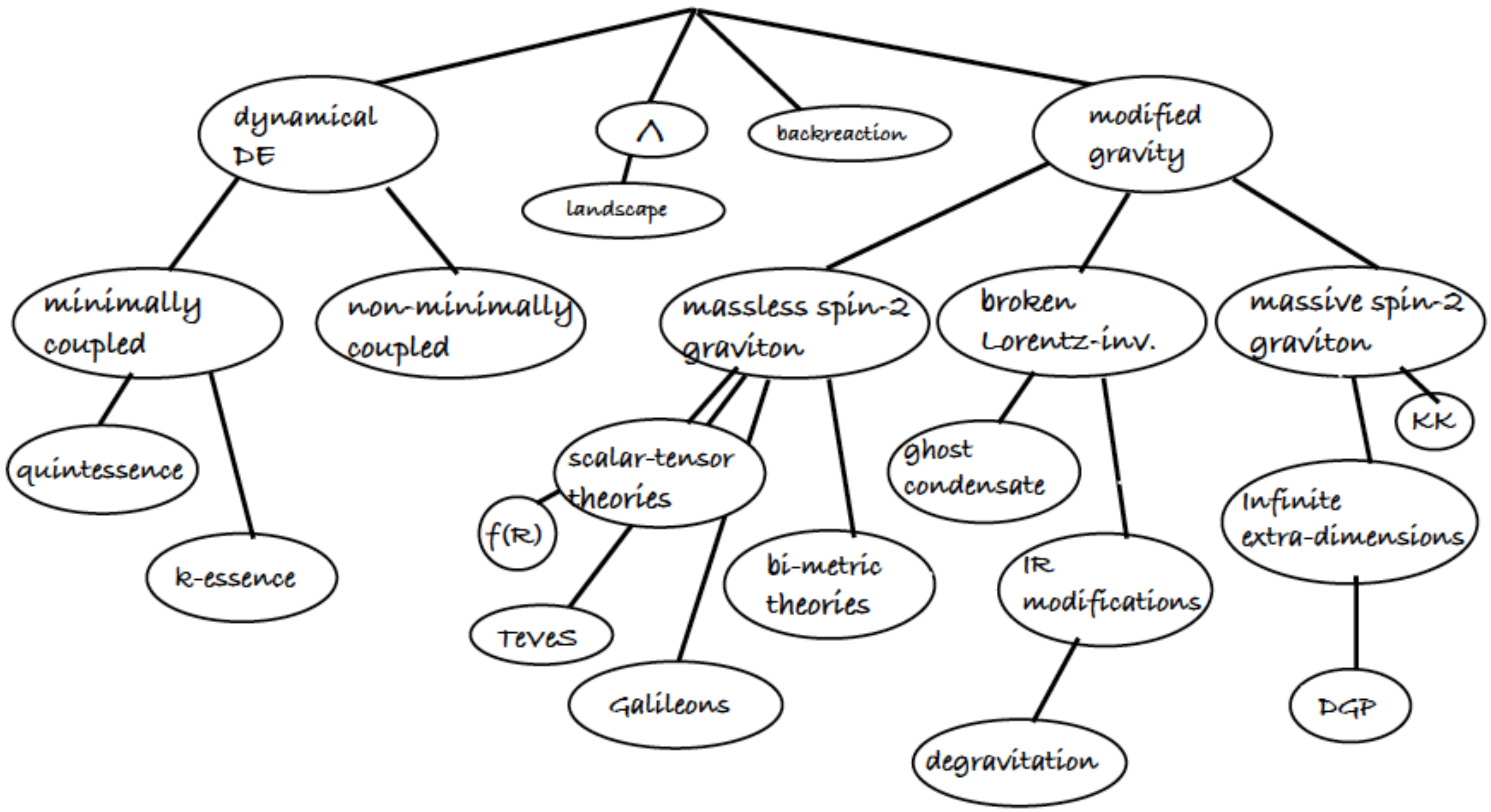
Multiple probes — radio / mm / NLR



McKean

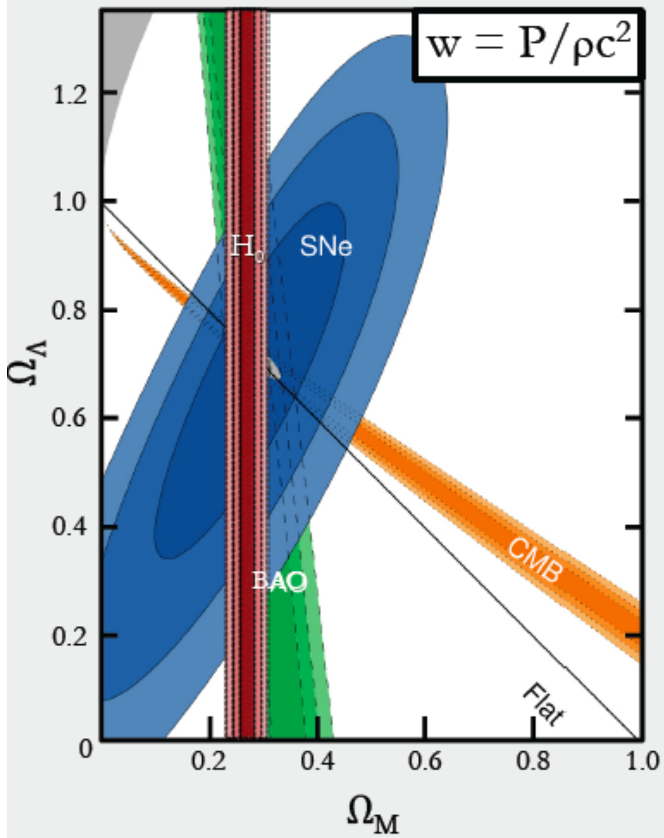
Dark Energy

The theoretical gravitational landscape

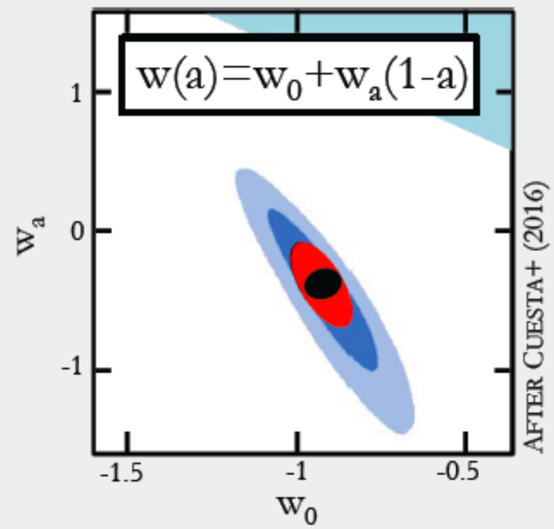


Silvestri

MOTIVATION: WHAT IS THE NATURE OF DARK ENERGY?



SUZUKI+ (2012); RIESS, MACRI+ (2016)

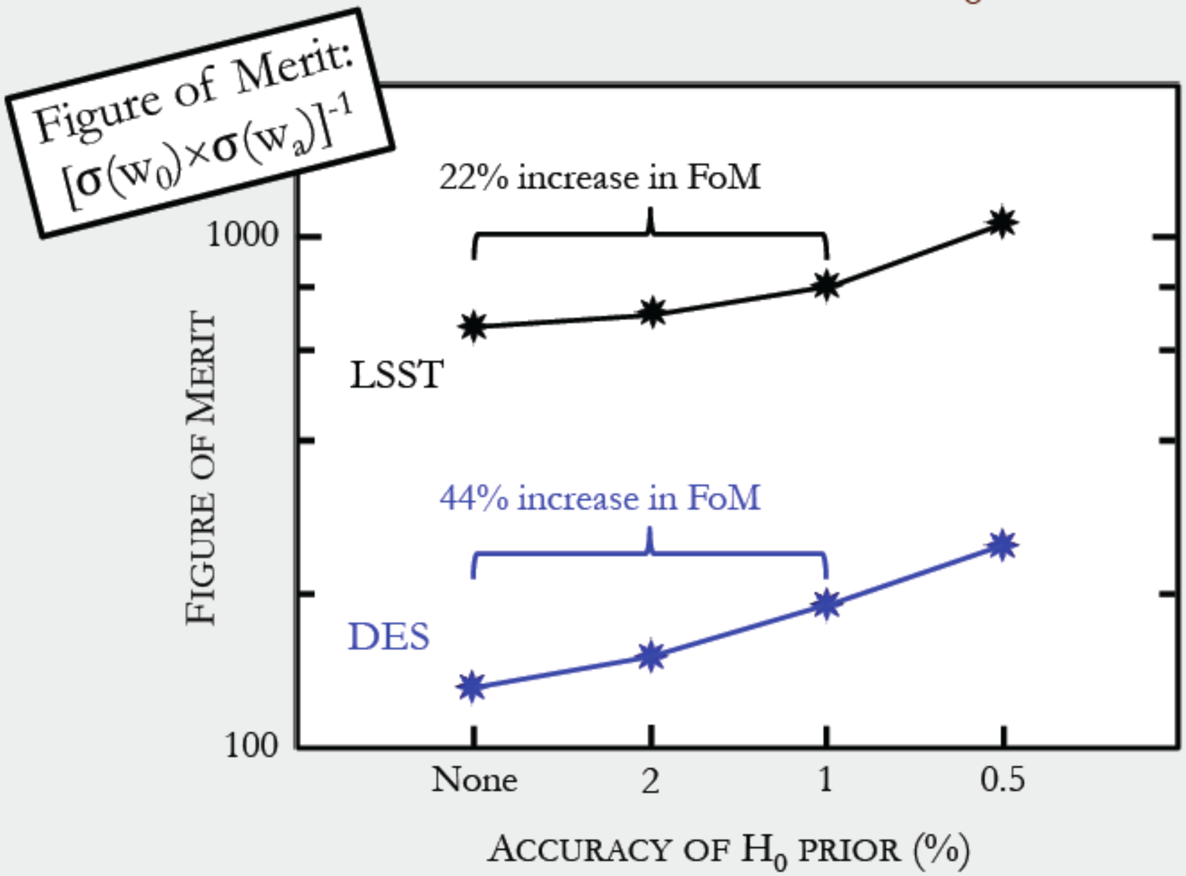


Coupled with additional priors (such as H_0)

- C16: w_0 ±0.18; w_a ±0.6
- DES: w_0 ±0.08; w_a ±0.3
- LSST: w_0 ±0.05; w_a ±0.1

Macri

Motivation for further improvement in H_0



Based on Weinberg+ (2012)

Macri

The Landscape in mid-2020s

- ✓ Gaia
  - ~9,000 Galactic Cepheids; P-L zeropoint to 0.3-0.6%
- ✓ JWST
  - Could detect Cepheids to D~50 Mpc, but time-consuming…
- ➢ LSST
  - Miras in ~200 galaxies within D~15 Mpc
- TMT
  - First light!

TMT OBSERVATIONS

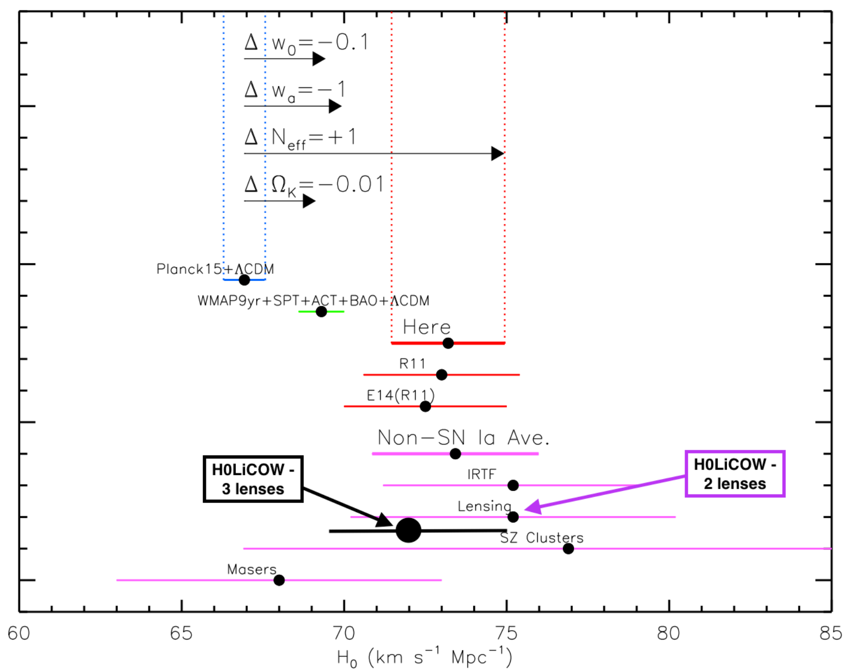
- TMT+IRIS improves over JWST+NIRCam
  - ~9× finer sampling, ~5× better resolution
    → greatly reduce impact of crowding & blending
- FoV considerably smaller…
  - 34" vs 123"
- But much larger aperture!
  - 5, 15 min to SNR~10 for P=20d Cepheid @ 50 Mpc in J&K
  - 1, 2 hr for same object @ 100 Mpc

Photometric Accuracy <5%!

Macri

The Motivation

Fassnacht

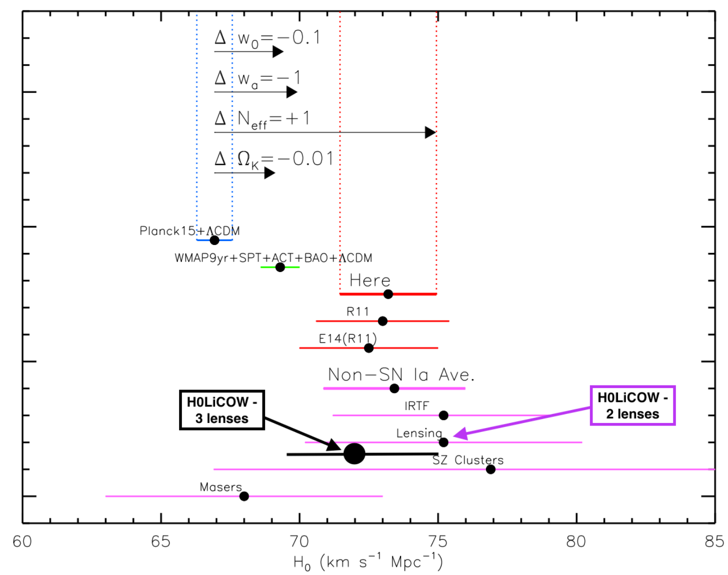


Riess et al. 2016

- H_0 measurements in combination with CMB parameters are a powerful probe of dark energy
- CMB analysis assumes flat ΛCDM ("standard model")
- Indications of new physics will come from combination of CMB and lower-z probes
- Tension between CMB and distance ladder / SN ("Here" in figure)
- Need independent techniques to test for unknown systematics

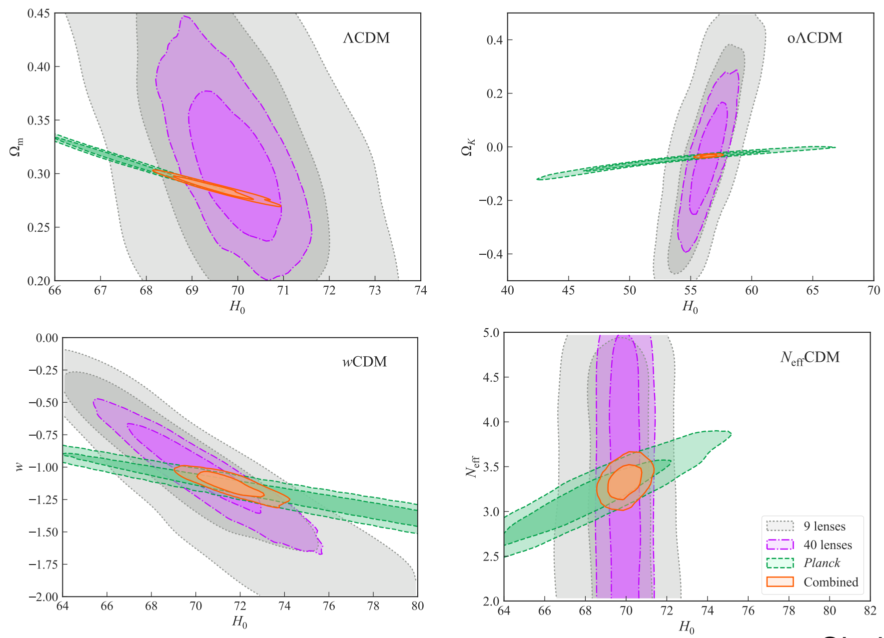
TDSL Cosmology in ELT Era

- Current 3-lens H0licow sample already gives better than 4% precision on H_0
- With ELTs, advances in modeling and analysis, and larger sample sizes, we can aim for ~1% precision (or better?) on H_0
- This will really test the standard ΛCDM model, in an independent fashion from other distance-scale techniques



TDSL Cosmology in ELT Era

Lensing constraints are complimentary to Planck in most combination of cosmologies and parameters.



Shajib et al. '18

X

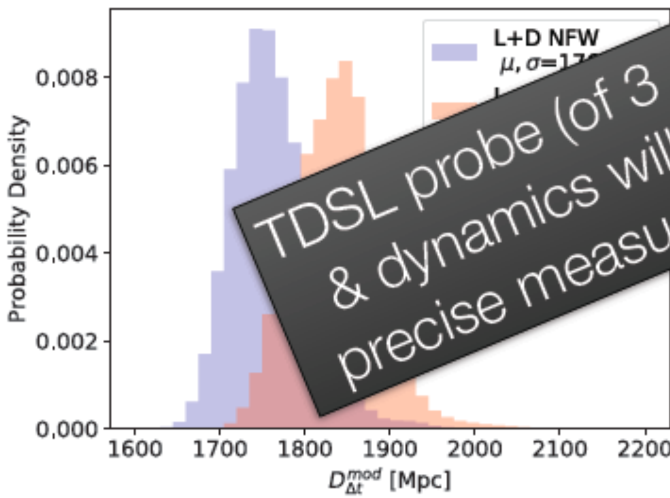
Time-delay distances in the era of JWST

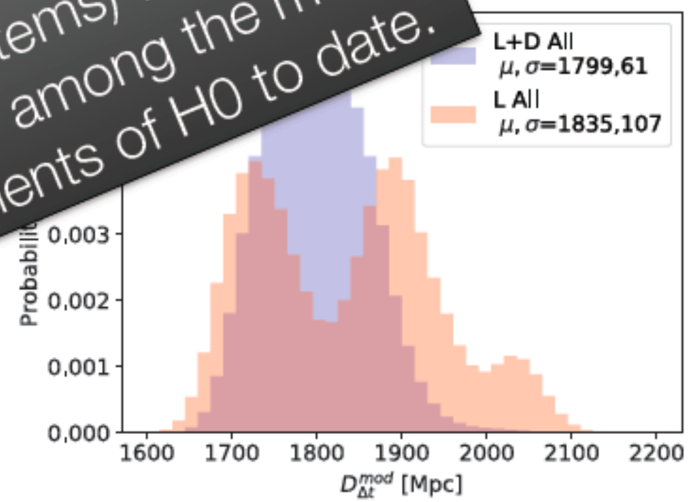
Lensing & Dynamics - Closing the gap

- IFU Stellar kinematics reconcile time-delay distances.

- Feasible observations with next generation of telescopes reduce the time-delay error budget of a single lens to <

TDSL probe (of 3 systems) with lensing & dynamics will be among the most precise measurements of H0 to date.





Yıldırım & Suyu, in prep.

Cluster cosmology

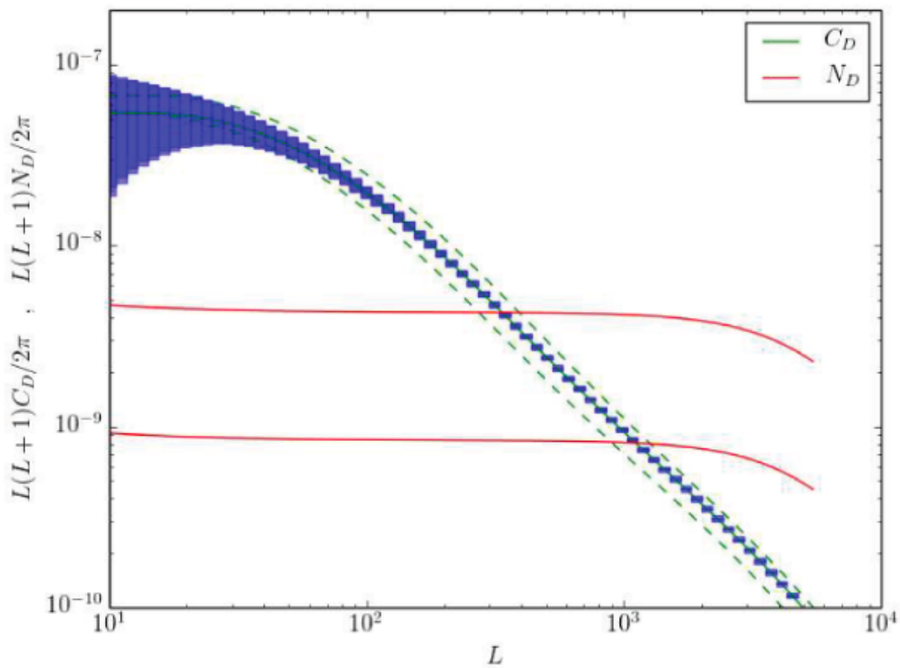
- exciting time for cluster cosmology!
- multiple surveys in 2020s: optical, SZ, X-rays
- need to measure mass-observable relation: mean relation + shape and size of scatter
- relative mass calibration: low-scatter mass proxies
- absolute mass calibration: weak lensing, LSST +Euclid/WFIRST
- potential ELT contributions:
  - spec-z training samples
  - confirmation / spec-z of high-redshift clusters
- unique applications:
  - kinematic weak lensing: reduce weak lensing noise
  - shear ratio test:

- ELT key capability: wide-field, high-multiplexing multi-object spectroscopy

Von der Linden

Lya lensing

TMT P(k) prediction



0.3 % error in σ_8

Croft

Overarching questions

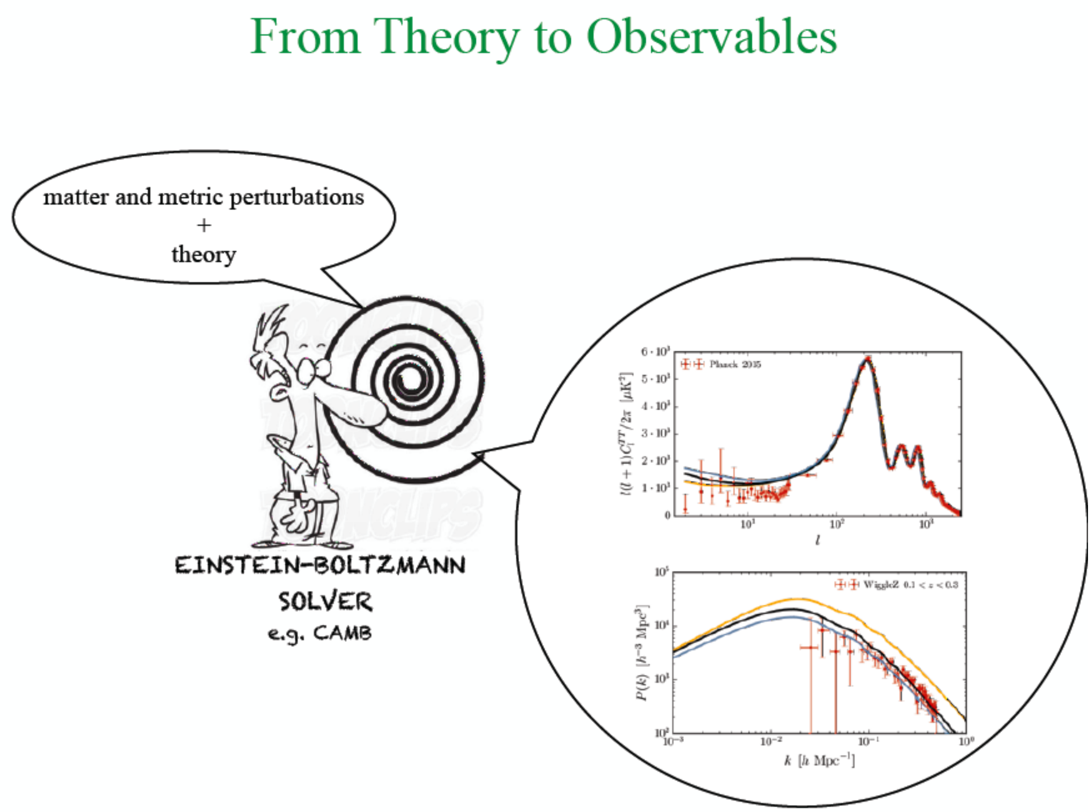
Operational considerations that impact science

- Instruments are expensive
  - Can we trade time across telescopes to avoid/minimize duplication?
- How do we ensure calibration and stability for long periods of time (e.g. proper motion, Sandage test)
- How best do we make use of time?
  - Large vs small programs
  - "Piggy back" programs (e.g. Sanderson)
  - Experiment vs PI driven
  - Give your spectra to Croft!

With great data comes great complexity (Joseph and spiderman)

- ELTs are going to be providing amazing data
- In order to take advantage of them we need to
  - Control systematics
    - PSF reconstruction for AO data (Fassnacht et al.)
    - PSF stability for precision photometry (few percent %)
  - Develop advanced analysis tools
  - End-to-end simulations (forward modeling; e.g. Birrer)
  - Sufficiently accurate theoretical predictions to compare to
    - Theory lags behind observations (Bullock/Diaferio/Silvestri)

We need theorists!



How do we do that for TMT?

Silvestri

The world will be awash with imaging! We need ELTs for spectroscopy and high resolution follow-up

- Photo-z calibration (Newman)
- Radial Velocity and proper motions of stars from WFIRST/LSST (Wang/Kallivayalil)
- Astrometry/PSF stability

WFIRST and GSMTs

- **WFIRST will:**
  - **Survey large sky areas and discover exceptionally interesting objects**
  - Map stellar populations in nearby galaxies in detail
  - Obtain coronagraphic imaging & low-resolution spectra for exoplanets
- **GSMTs will provide** NIR diffraction-limited angular resolution (λ/D = 12.5x smaller than WFIRST)
  - Inner working angle for exoplanet imaging
  - Morphology from the Solar System to the Epoch of Reionization
  - **Crowded field imaging and spectroscopy**
- GSMTs offer huge primary collecting area
  - **Faint-object spectroscopy**
  - **High-resolution spectroscopy**
  - Fast time-resolved observations

SKA and GSMTs

- McKean

I look forward to hearing the view from Trieste!

http://indico.ictp.it/event/8320/