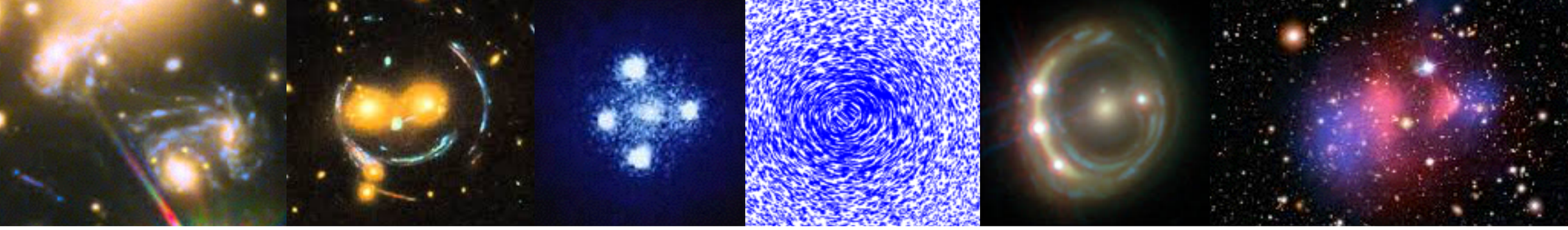


PHY-765 SS19 Gravitational Lensing Week 14

The Future of Gravitational Lensing

Kasper B. Schmidt
Leibniz-Institut für Astrophysik Potsdam (AIP)

Last week - what did we learn?

$$\boldsymbol{\delta}(\boldsymbol{x},t) \equiv \frac{\rho_m(\boldsymbol{x},t) - \bar{\rho}_m(t)}{\bar{\rho}(t)}$$

- Lensing of diffuse source by diffuse lens
- Cosmic Shear:
  - The lensing effects (shearing) of the cosmic web
- The density contrast, $\delta(\boldsymbol{x},t)$ is correlated to the gravitational potential, and hence lensing shear (γ) and convergence (κ)

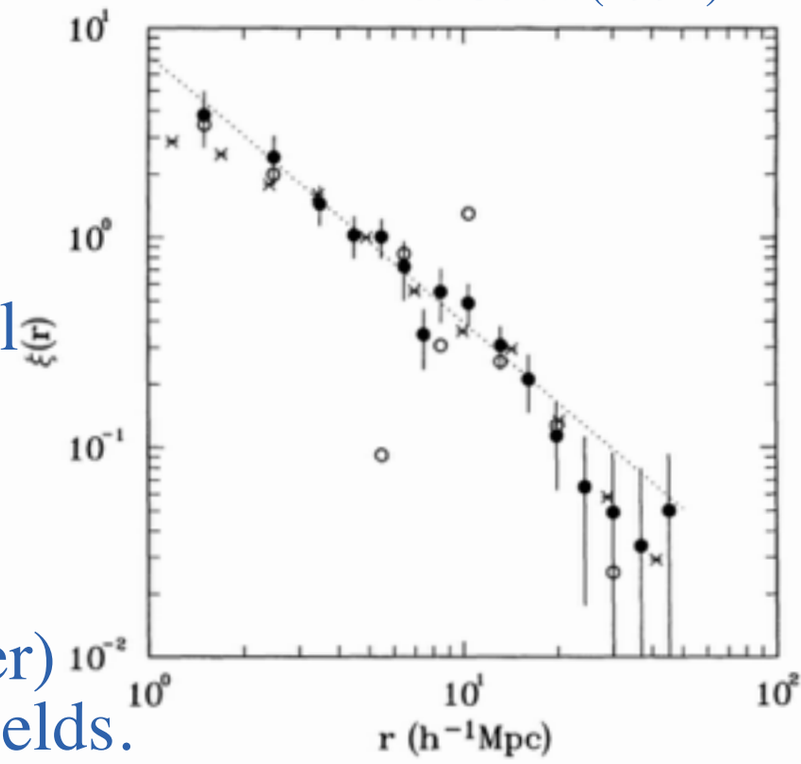
$$\boldsymbol{\delta}(\boldsymbol{x},t) \leftrightarrow \Phi(\boldsymbol{x},t) \leftrightarrow \psi(\boldsymbol{\theta}) \leftrightarrow \kappa \quad \gamma_1 \quad \gamma_2$$

- The correlation function (real) and power spectrum (Fourier) provide information on 2nd order statistics of the density fields.

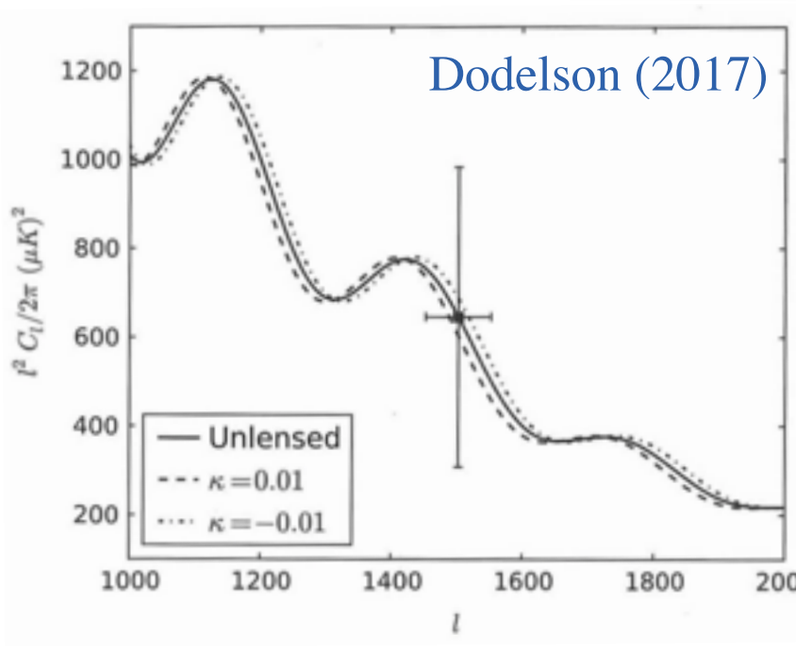
- Statistical analysis of the density fluctuations can be coupled to cosmological parameters (LSS) and lensing (κ)

- CMB provides diffuse source to study observable universe
  - T fluctuation power spectrum (baryon oscillations)
  - M fluctuations power spectrum (lensing potential)

Martinez & Coles (1994)



Dodelson (2017)



The aim of today

- Provide an (incomplete) overview of current, upcoming and future programs and facilities from a GL point-of-view, including:
  - HST
  - OGLE/MicroFUN
  - Gaia
  - SDSS
  - DES
  - LSST
  - JWST
  - WFIRST
  - ELTs

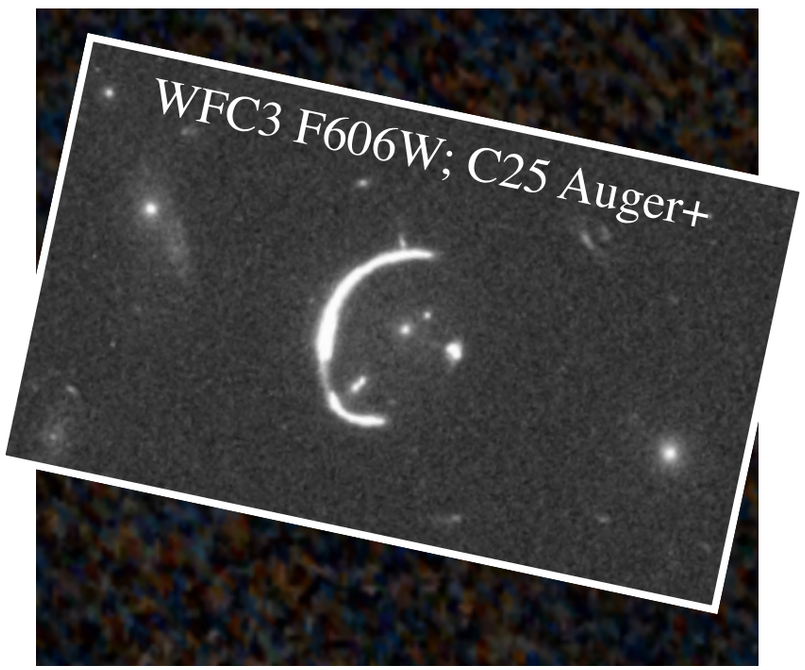
Lensing Aspects Focused on in PHY-765 GL

- Star-Star lensing - Microlensing — **SS**
- Exoplanet searches - Microlensing — **Exo**
- Cluster Lensing - Strong and Weak lensing — **CL**
- QSO lensing - Strong lensing — **QL**
- Galaxy-Galaxy lensing - Strong lensing — **GG**
- Wide field shearing - Weak lensing — **WF**
- Power spectrum and correlation function studies - Weak lensing — **PS**

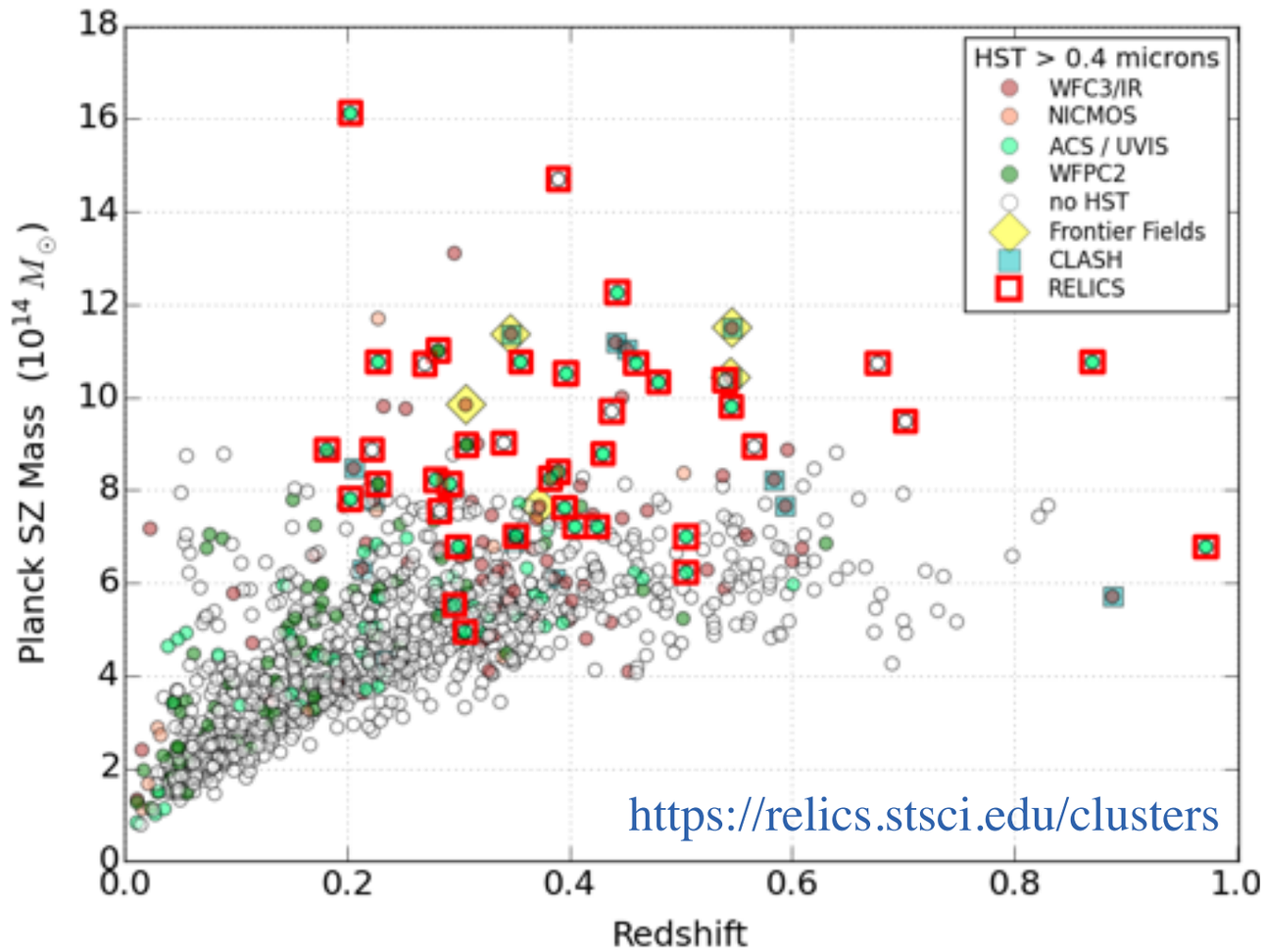
Hubble Space Telescope (HST)

- Focus in the past 5-10 years: Cluster lenses and individual lenses
- Continued follow-up of ground-based candidates and individual systems
- GL currently ~5% (cycle 26) to 10% (cycle 27) of accepted proposals
- REionization Cluster Lensing Survey (RELICS)
  - 41 galaxy clusters; HST observations finished 2017 + 1000 hours w. Spitzer

☑ CL
☑ QL
☑ GG
☐ SS
☐ Exo
☐ WF
☐ PS



Pan-STARRS color img. via
http://cdsportal.u-strasbg.fr

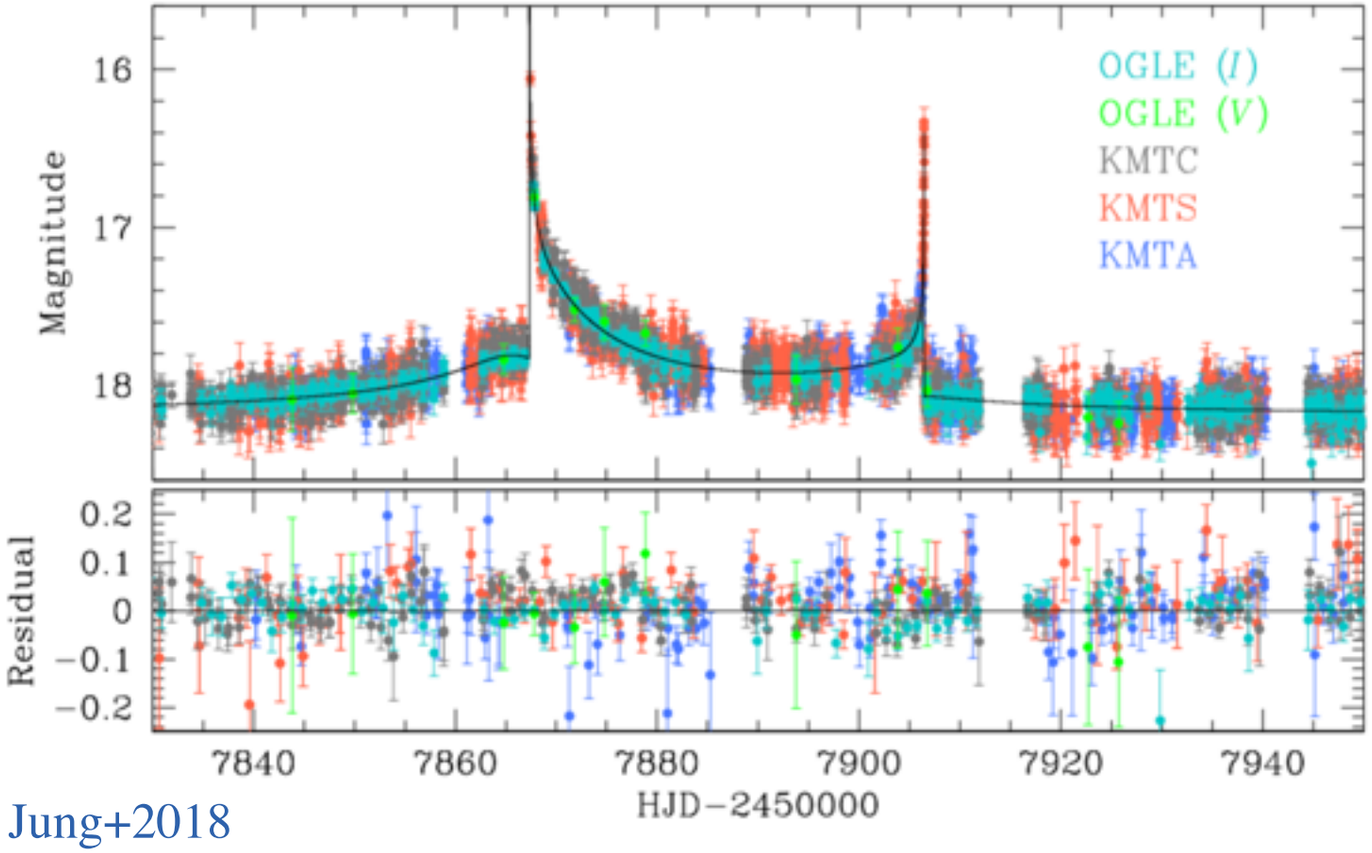


https://relics.stsci.edu/clusters

OGLE & MicroFUN

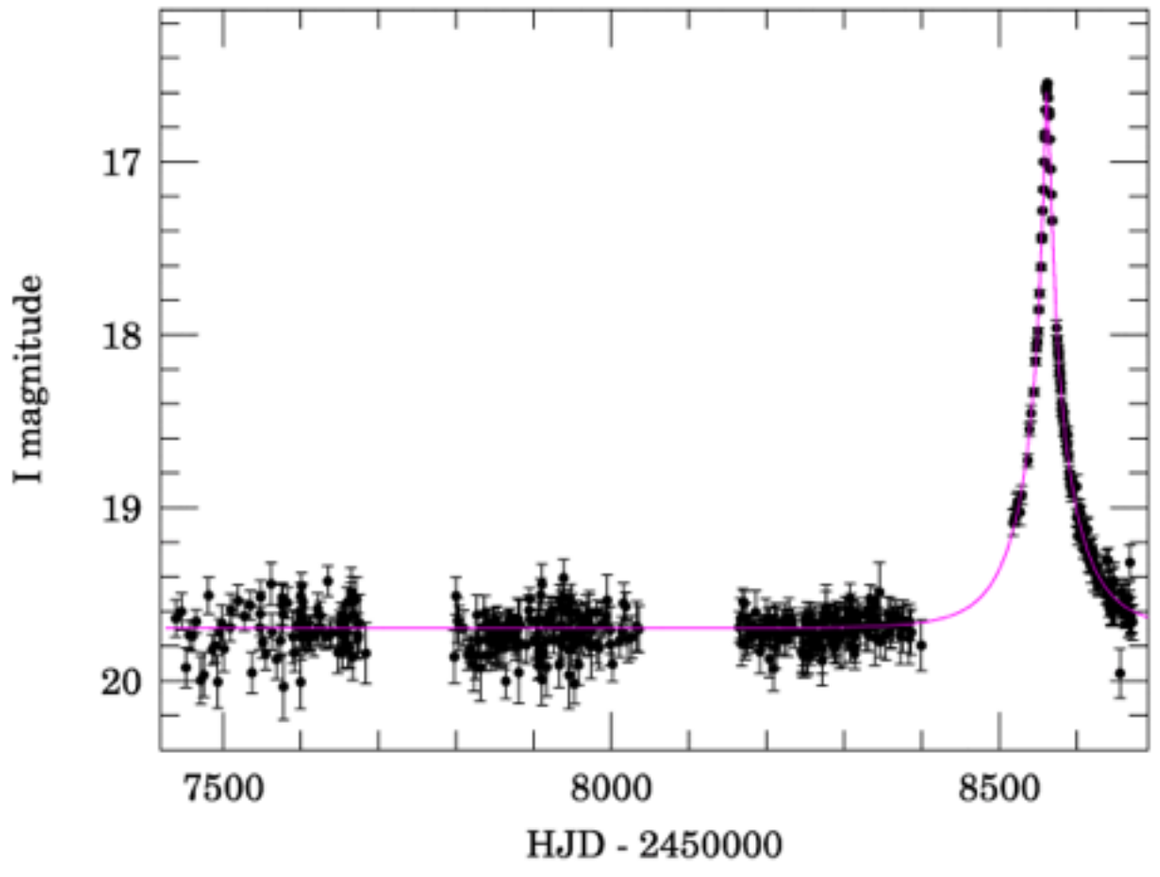
- OGLE-IV (Week 8/9) still producing results
- Microlensing Follow-Up Network (Ohio State University):
  - Members/Telescopes: South Korea, North America, Australia, New Zealand, South Africa, South Pacific, Europe, Israel, Brazil

☐ CL
☐ QL
☐ GG
☑ SS
☑ Exo
☐ WF
☐ PS



Jung+2018

OGLE-2019-BLG-0170



http://ogle.astrouw.edu.pl/ogle/ogle4/ews/2019/blg-0170

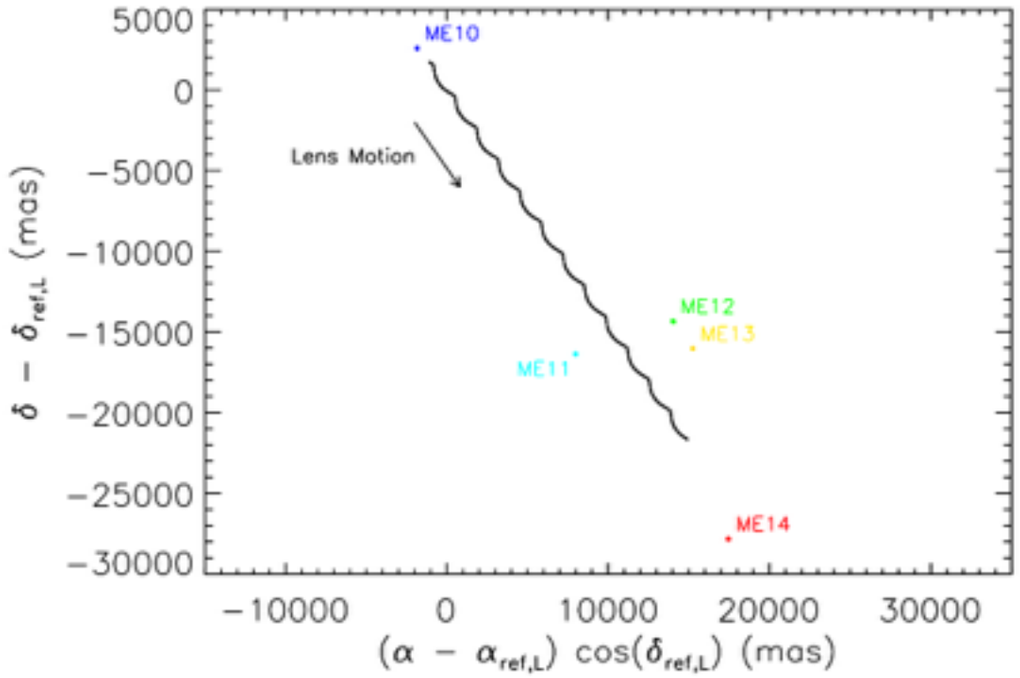
OGLE & MicroFUN

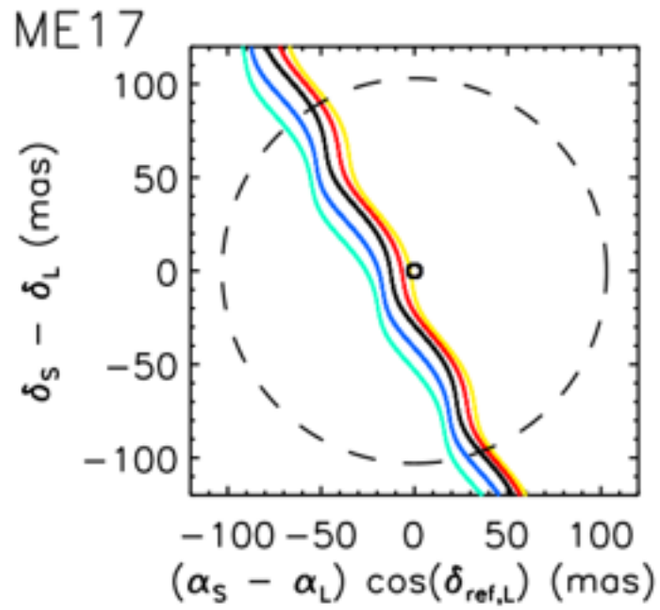
CL
QL
GG

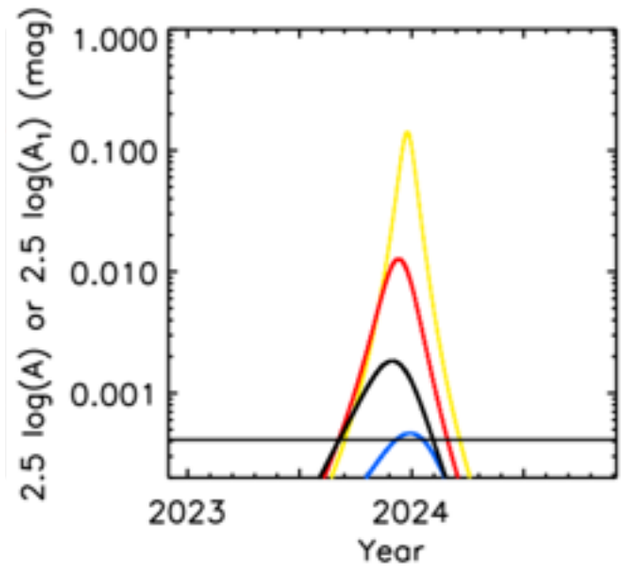
CL
QL ✓
GG
SS (✓)
Exo (✓)
WF
PS

Gaia (Week 7)

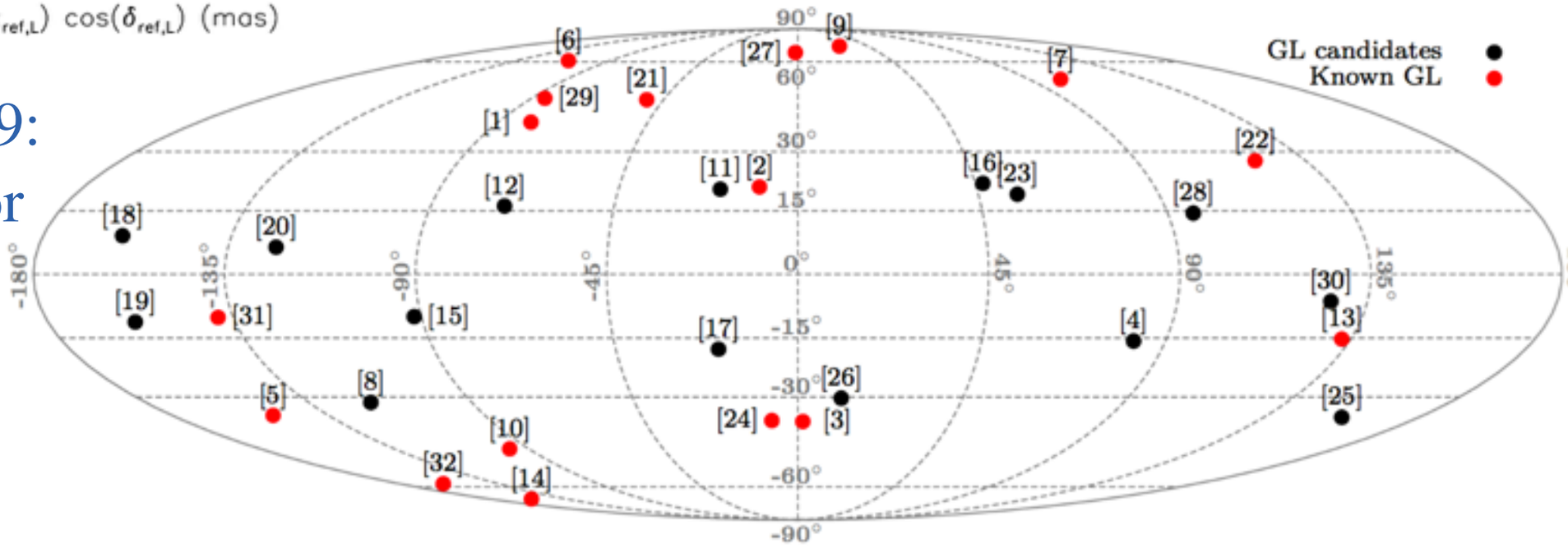
- Recording of motions and positions of >10^9 stars in the Milky Way
- Bramich+18 microlensing event predictions (2014-2026) based on DR2





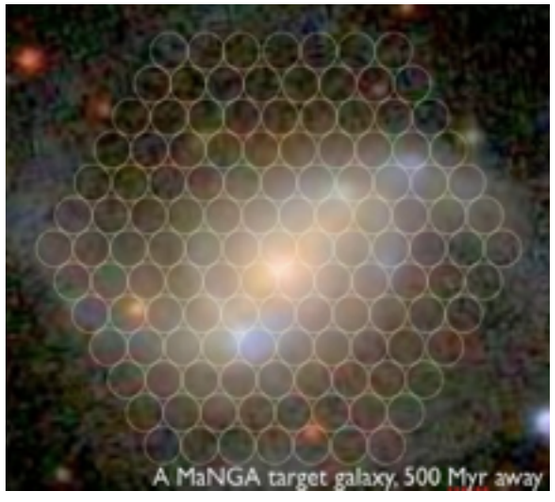


- Delchambre+19: Blind search for lensed systems in Gaia DR2



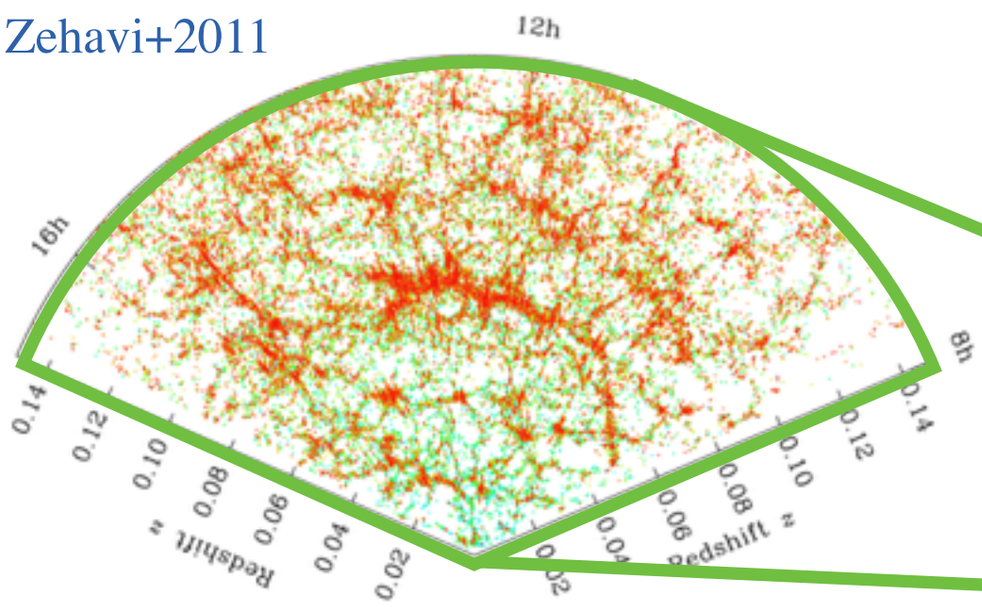
SDSS-IV (Week 7)

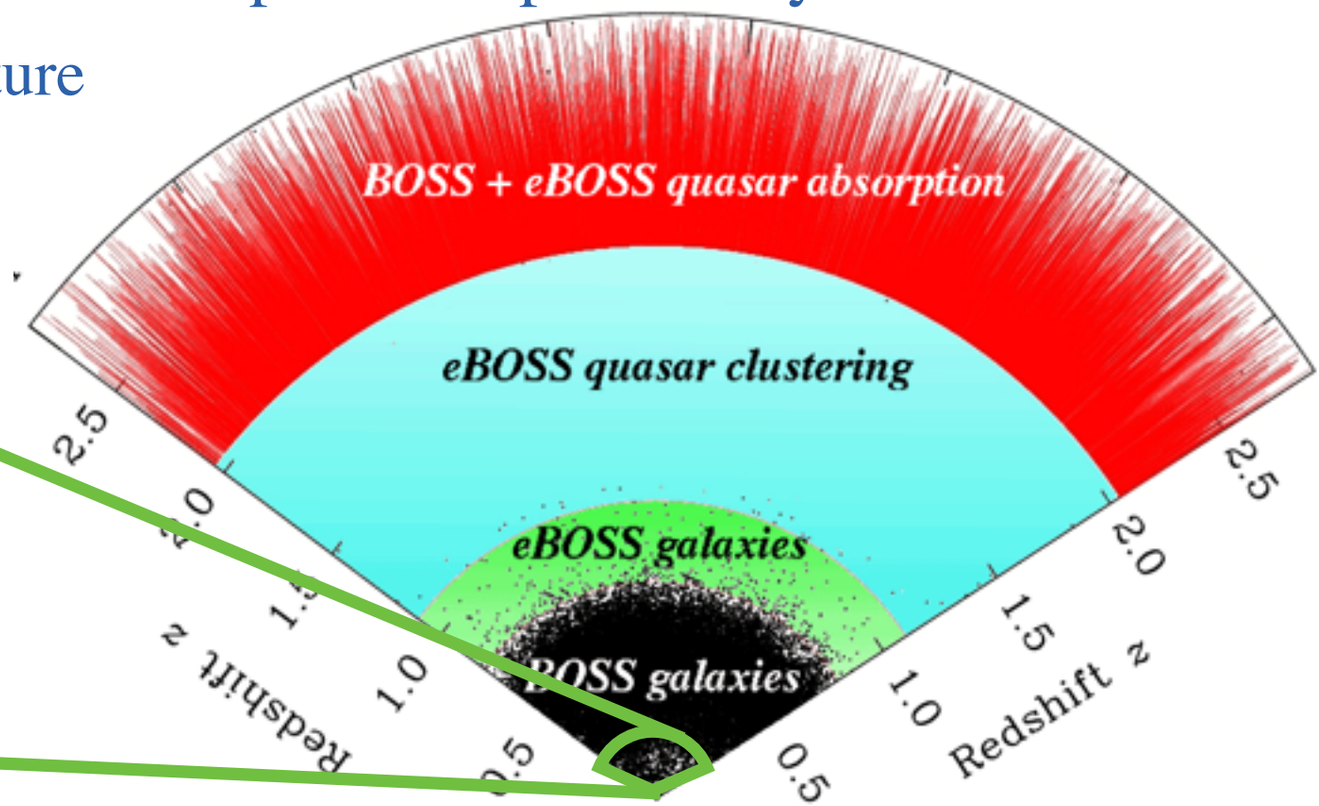
- Imaging survey of >10000 deg^2 in ugriz with spectroscopic campaigns
- SDSS-IV (2014-2020) focuses on:
  - APOGEE-2: APO Galaxy Evolution Experiment 2
    - Spec. of stars in the Milky Way (stellar "archeology")
  - MaNGA: Mapping Nearby Galaxies at APO
    - Talbot+18 present galaxy lenses in MaNGA
  - eBOSS: The Extended Baryon Oscillation Spectroscopic Survey
    - Spec. mapping of large scale structure



☑ CL
☑ QL
☑ GG
☐ SS
☐ Exo
☑ WF
☑ PS

Zehavi+2011





Week 13

https://www.sdss.org/surveys/eboss/

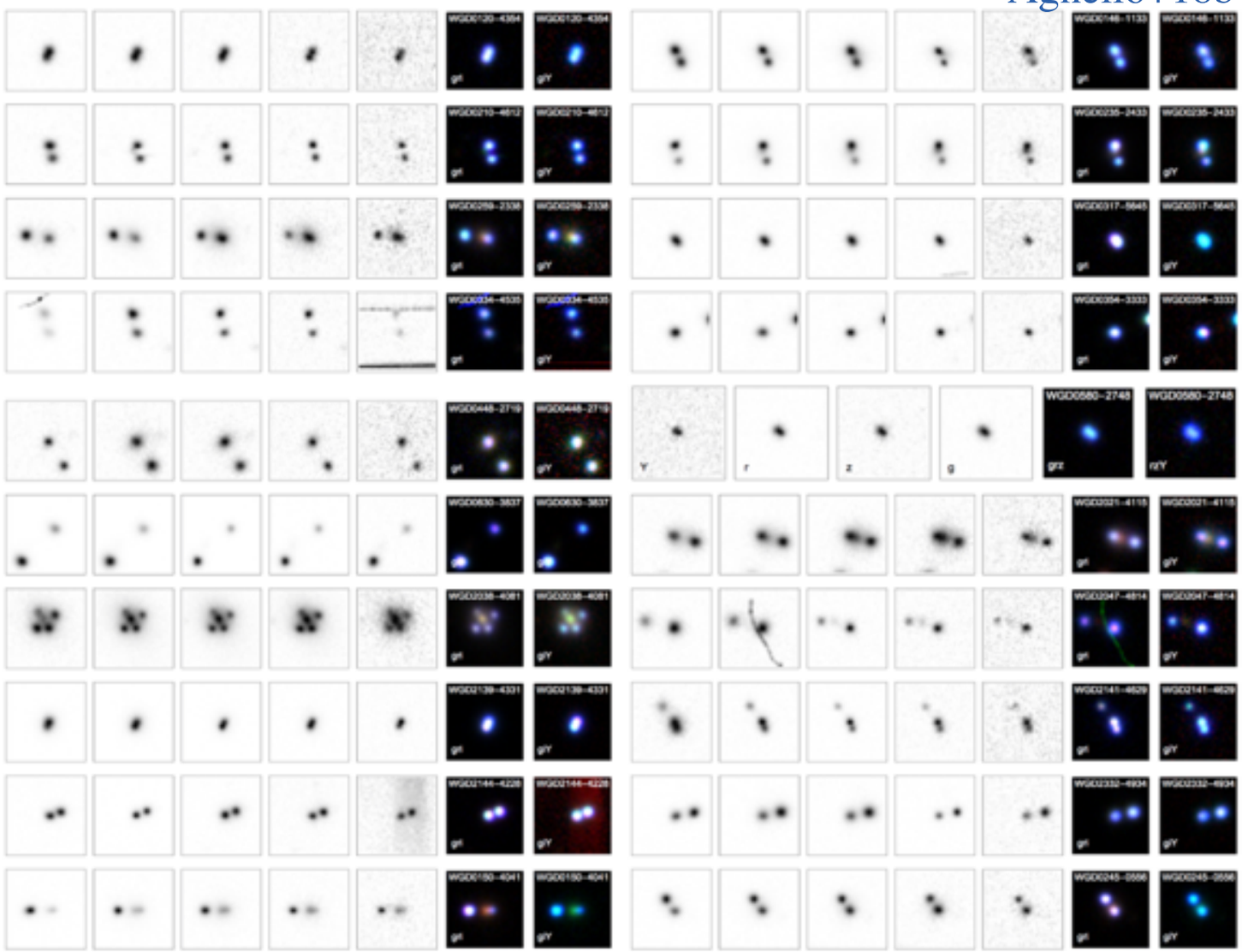
The Dark Energy Survey (Week 7)

- ☑ CL
- ☑ QL
- ☑ GG
- ☐ SS
- ☐ Exo
- ☐ WF
- ☐ PS

- DES (2013-2018) and STRIDES
  - Agnello+15,18a (QSO lenses), Nord+16 (clusters),
- Combining large datasets from multiple surveys to improve selections
  - Agnello+18b presents first results from a combined DES & Gaia search

Agnello+18a

Agnello+18b



Predicting numbers of QSO lenses (Week 7)

- Oguri & Marshall (2010) aimed at predicting number of lenses
- Focus on multi-epoch data (potentially enabling time-delay measurements)
- Assume lens galaxies are ellipticals with SIE surface mass density (κ)
- They formulate the lensing rate (probability) as an integral over $d\theta$ and dz
- Integrating over source L, survey V and dz provides estimate for N_{lenses}

	QSO (detected)		QSO (measured)	
Survey	$N_{non\text{-}lens}$	N_{lens}	$N_{non\text{-}lens}$	N_{lens}
SDSS-II	1.18×10^5	26.3 (15 per cent)	3.82×10^4	7.6 (18 per cent)
SNLS	9.23×10^3	3.2 (12 per cent)	3.45×10^3	1.1 (13 per cent)
PS1/3π	7.52×10^6	1963 (16 per cent)	–	–
PS1/MDS	9.55×10^4	30.3 (13 per cent)	3.49×10^4	9.9 (14 per cent)
DES/wide	3.68×10^6	1146 (14 per cent)	–	–
DES/deep	1.26×10^4	4.4 (12 per cent)	6.05×10^3	2.0 (13 per cent)
HSC/wide	1.76×10^6	614 (13 per cent)	–	–
HSC/deep	7.96×10^4	29.7 (12 per cent)	4.30×10^4	15.3 (13 per cent)
JDEM/SNAP	5.00×10^4	21.8 (12 per cent)	5.00×10^4	21.8 (12 per cent)
LSST	2.35×10^7	8191 (13 per cent)	9.97×10^6	3150 (14 per cent)

(…) = percentage quads

Oguri & Marshall+10

Large Synoptic Survey Telescope (LSST)

- 8.4 meter photometric survey telescope of half the sky
- To be operational from 2022 at Cerro-Pachon in Chile

CL
QL
GG
SS
Exo
WF
PS

Large Synoptic Survey Telescope (LSST)

- [x] CL
- [x] QL
- [x] GG
- [(x)] SS
- [ ] Exo
- [x] WF
- [ ] PS

- 8.4 meter photometric survey telescope of half the sky
- To be operational from 2022 at Cerro-Pachon in Chile
- 10 years survey of sky through ugrizy in 3.5 degrees wide FoV
- Impact on all (imaging) aspects of lensing:
  - Time-domain for ≳day variations
  - Galaxy lensing discoveries
  - QSO lensing
  - Wide-field weak lensing
- Complements SDSS surveys in the north

LSST Science book (2009)

Single-visit depths (point sources; 5σ)	u: 23.9 g: 25.0 r: 24.7 i: 24.0 z: 23.3 y: 22.1 AB mag
Baseline number of visits over 10 years	u: 70 g: 100 r: 230 i: 230 z: 200 y: 200
Coadded depths (point sources; 5σ)	u: 26.3 g: 27.5 r: 27.7 i: 27.0 z: 26.2 y: 24.9 AB mag

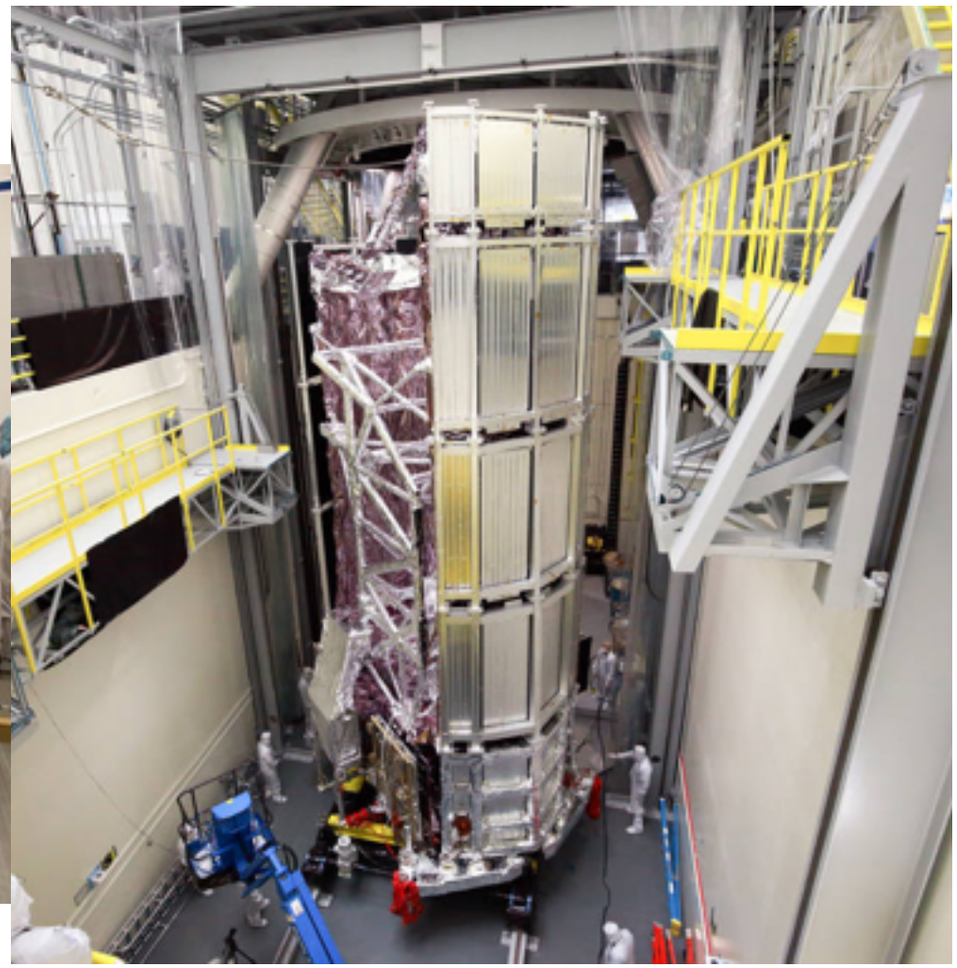
James Webb Space Telescope (JWST)

- 6.5 meter NIR (0.6-28.5 μm) space-based (L2) telescope

CL
QL
GG
SS
Exo
WF
PS

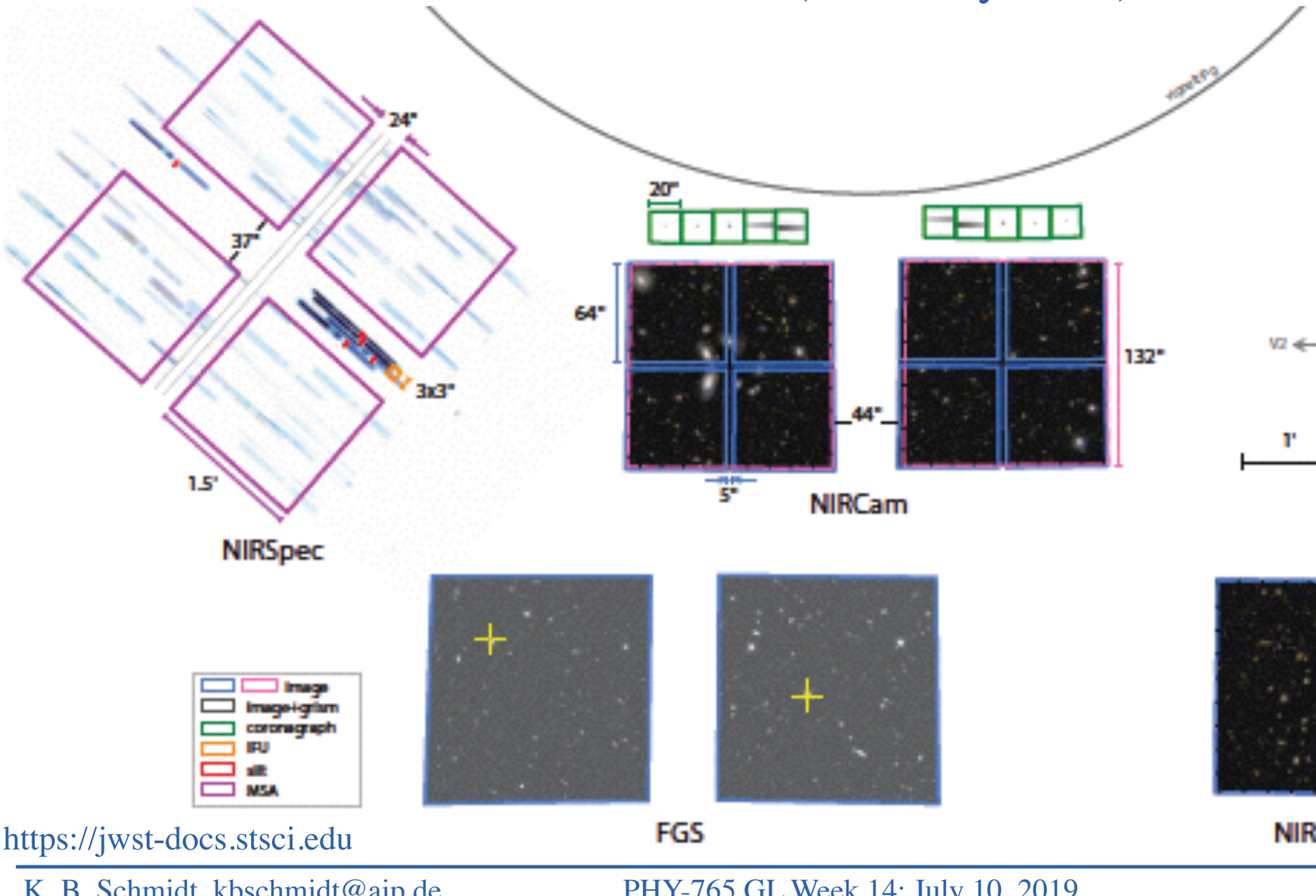
Oct. 2017: Mirror and instruments passed vacuum testing

May 2019: Emergence of spacecraft element (bus and sunshield) from vacuum chamber after succesfull tests



James Webb Space Telescope (JWST)

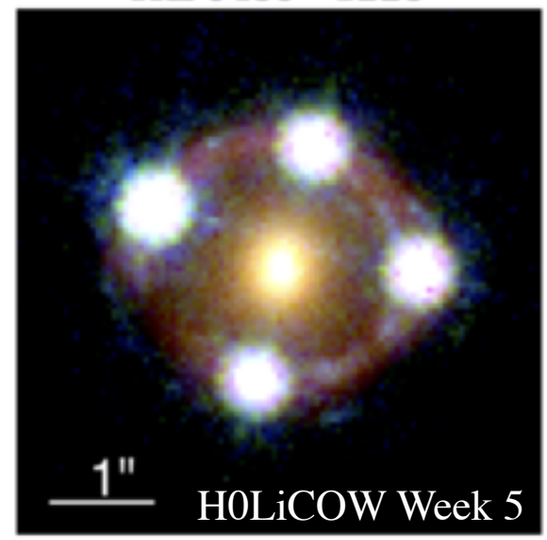
- 6.5 meter NIR (0.6-28.5 μm) space-based (L2) telescope
- Includes both imaging and spectroscopic capabilities
- Current launch date: March 2021 (as of July 2019)



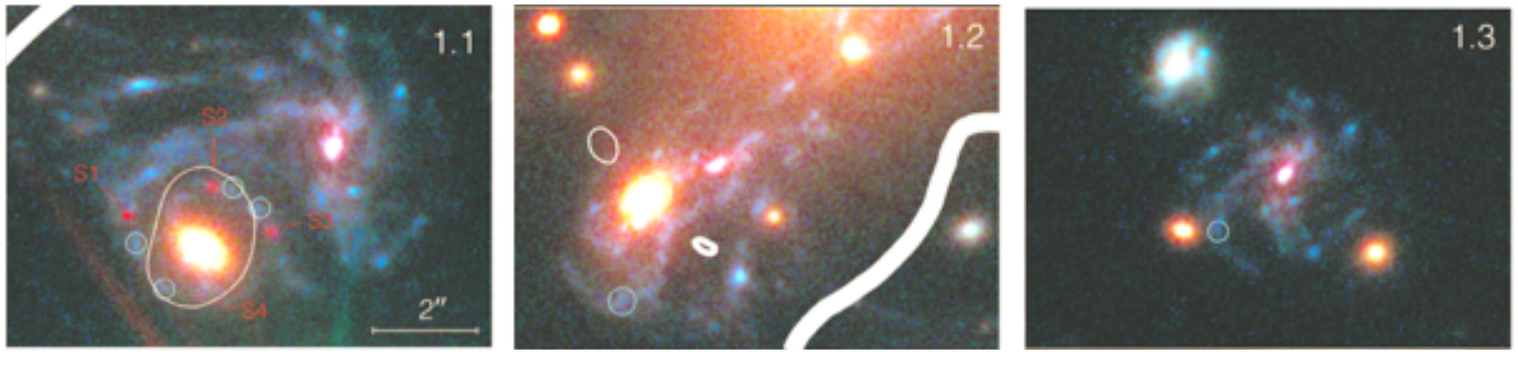
https://jwst-docs.stsci.edu

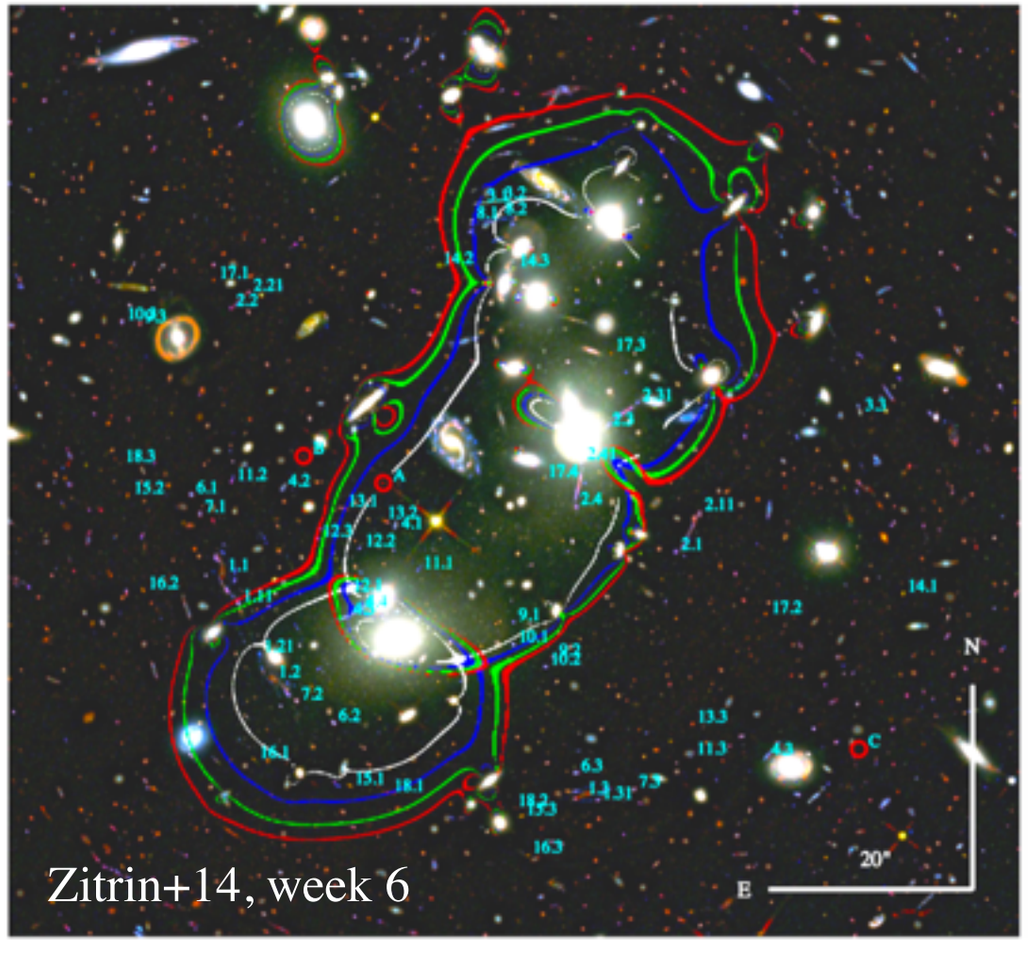
James Webb Space Telescope (JWST)

- GTO-1198: Host Galaxies of Strongly Lensed Quasars
  - Imaging with NIRCam and spectroscopy with NIRSpec
- GTO-1199: Metallicity study of MACS1149
  - Spectroscopy with NIRISS and NIRSpec
- GTO-1208: The CAnadian NIRISS Unbiased Cluster Survey (CANUCS)
  - Imaging with NIRCam and spectroscopy with NIRISS and NIRSpec
- ERS-1324:: Studying galaxy cluster A2744
  - Imaging with NIRCam and spectroscopy with NIRISS and NIRSpec



SN Refsdal host (behind MACS1149); week 4 & 5

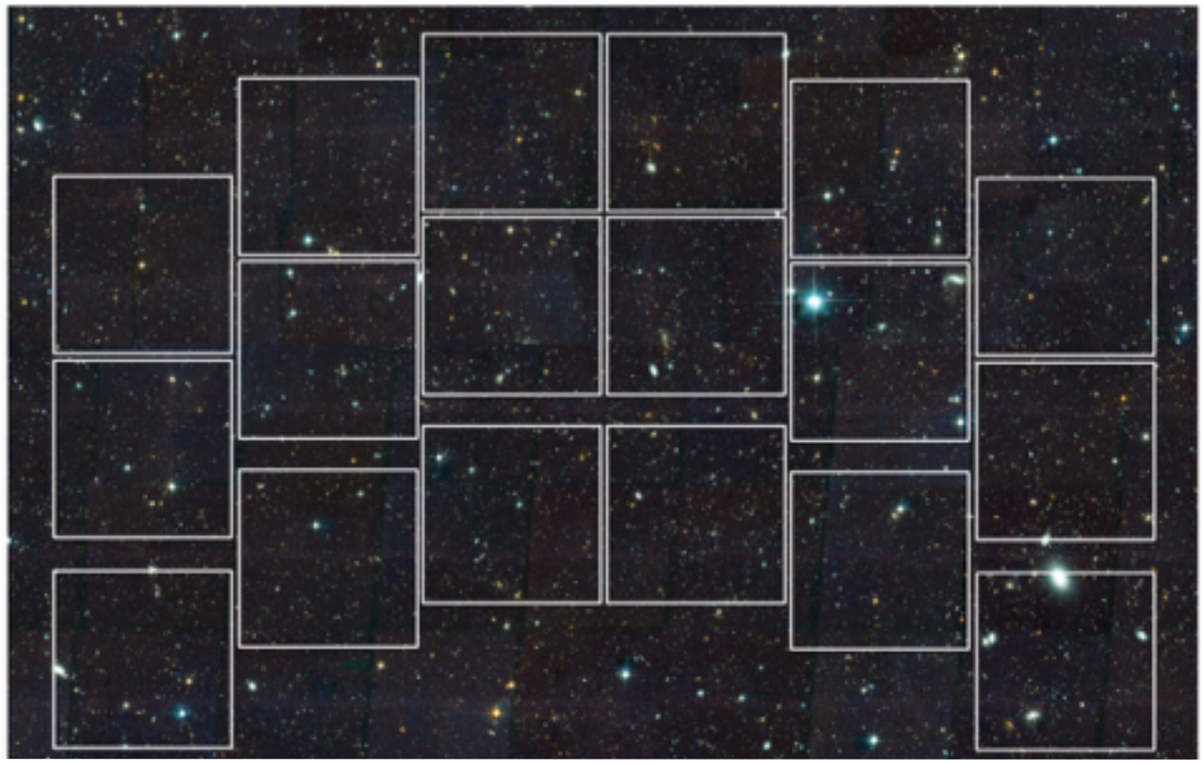




Wide Field IR Survey Telescope

- WFIRST is a 2.4 meter NIR (0.8-2.0μm) space-based (L2) telescope
- Current launch plan: mid-2020s
- Survey telescope (FoV=0.28deg^2) producing time-series of HST-like data

CL
QL
GG
SS
Exo
WF
PS

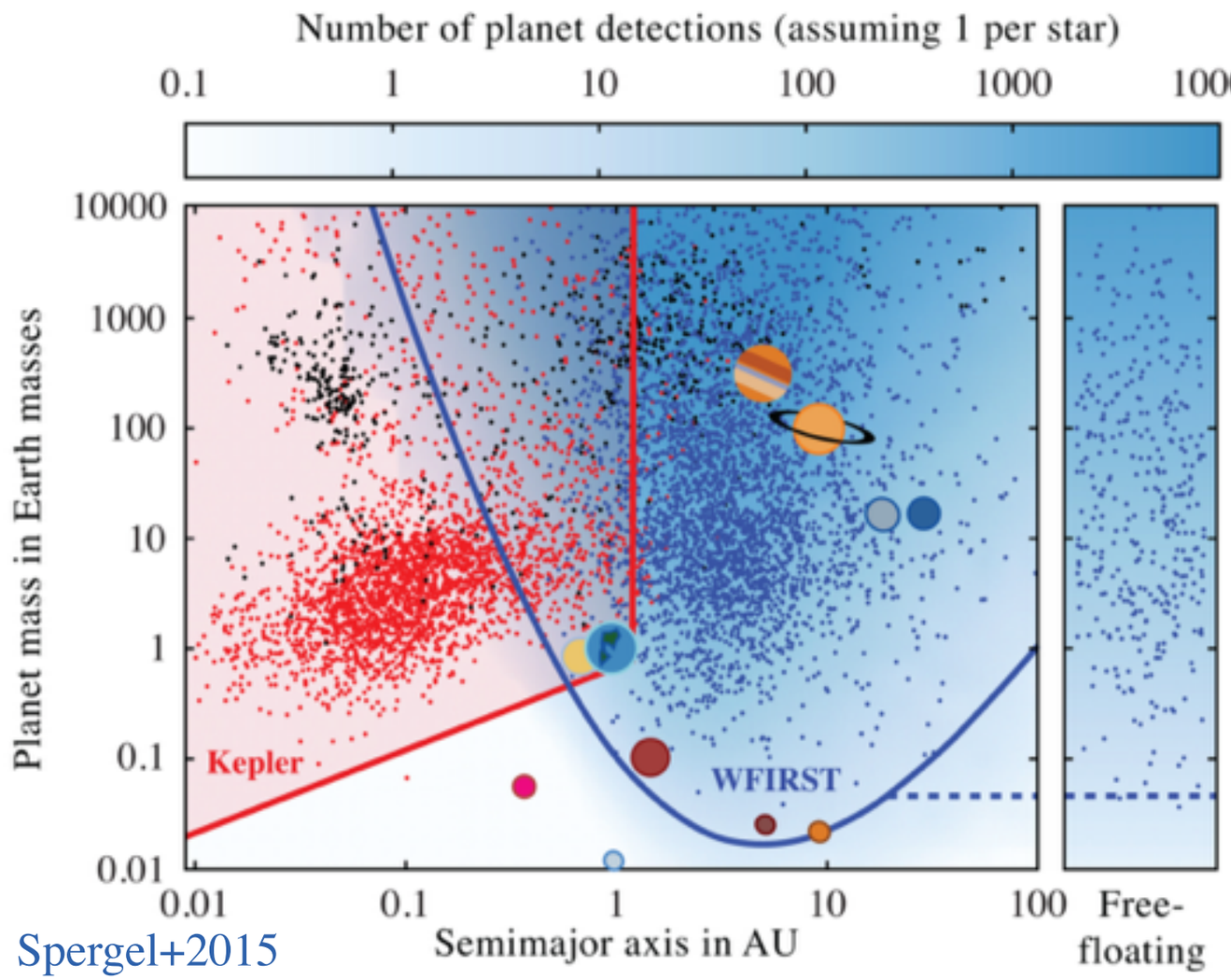


Spergel+2015

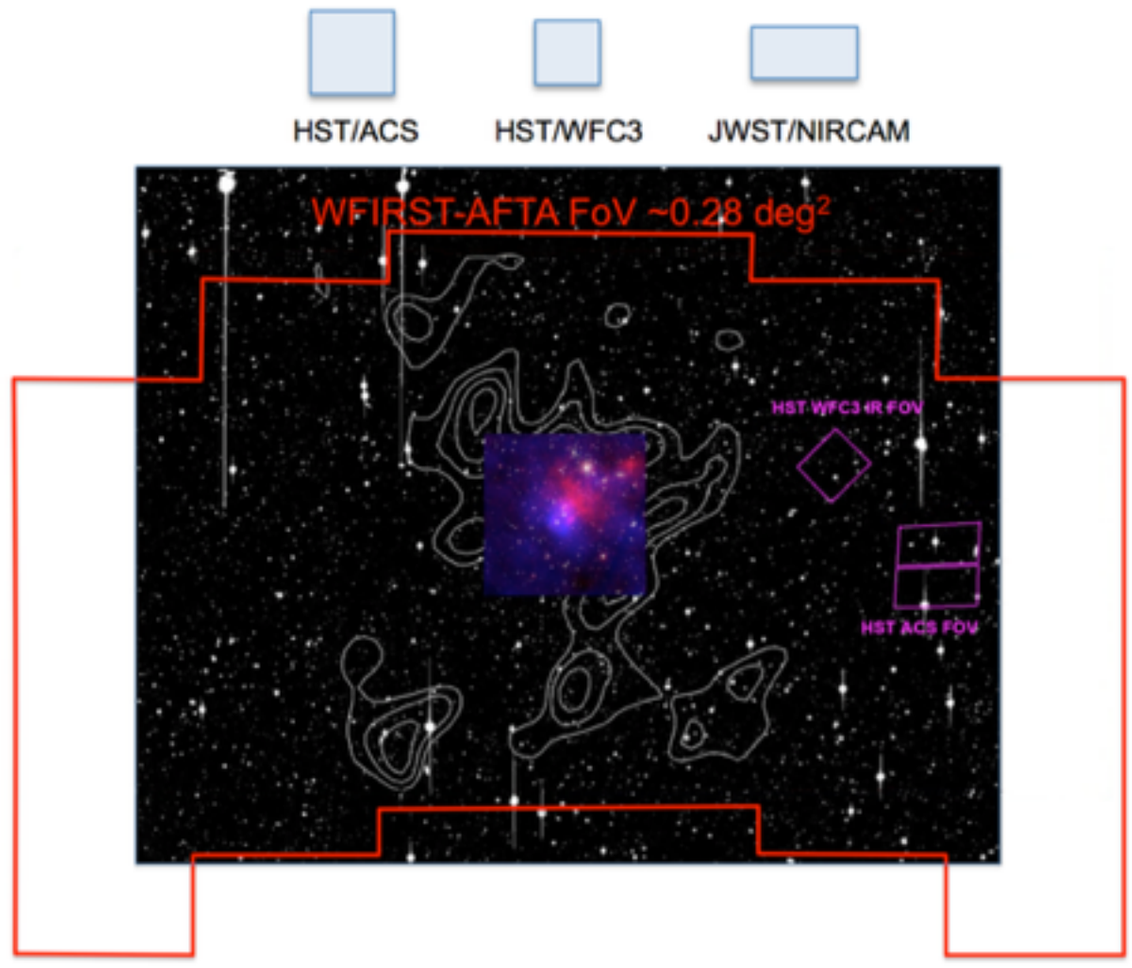
Wide Field IR Survey Telescope

- WFIRST is a 2.4 meter NIR (0.8-2.0μm) space-based (L2) telescope
- Current launch plan: mid-2020s
- Survey telescope (FoV=0.28deg^2) producing time-series of HST-like data
- Exoplanet microlensing searches is a key science driver

☑ CL
☑ QL
☑ GG
☑ SS
☑ Exo
☑ WF
☐ PS



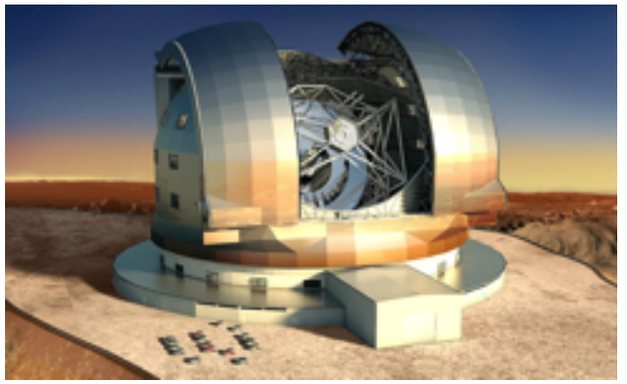
Spergel+2015



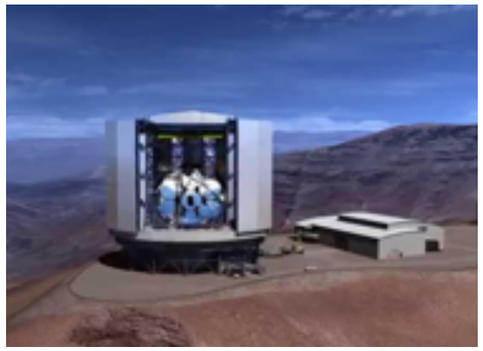
Spergel+2015

Extremely Large Telescopes (ELTs)

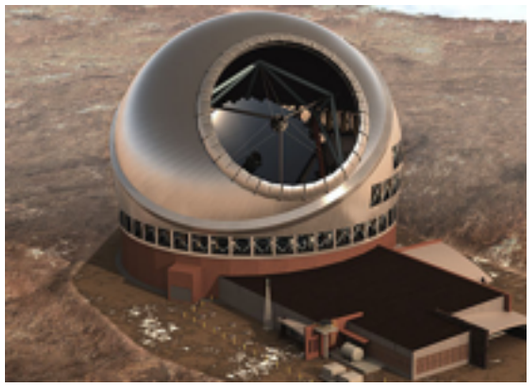
- Ground-based astronomy is slowly moving from 10m-class to ELTs
- Three main contesters currently underway:
- The ESO Extremely Large Telescope (E-ELT) → 2024
  - Optical-IR imaging and spectroscopy; changing instruments
  - 40 meter segmented mirror on telescope to be build in Chile
  - Partners: ESO member countries



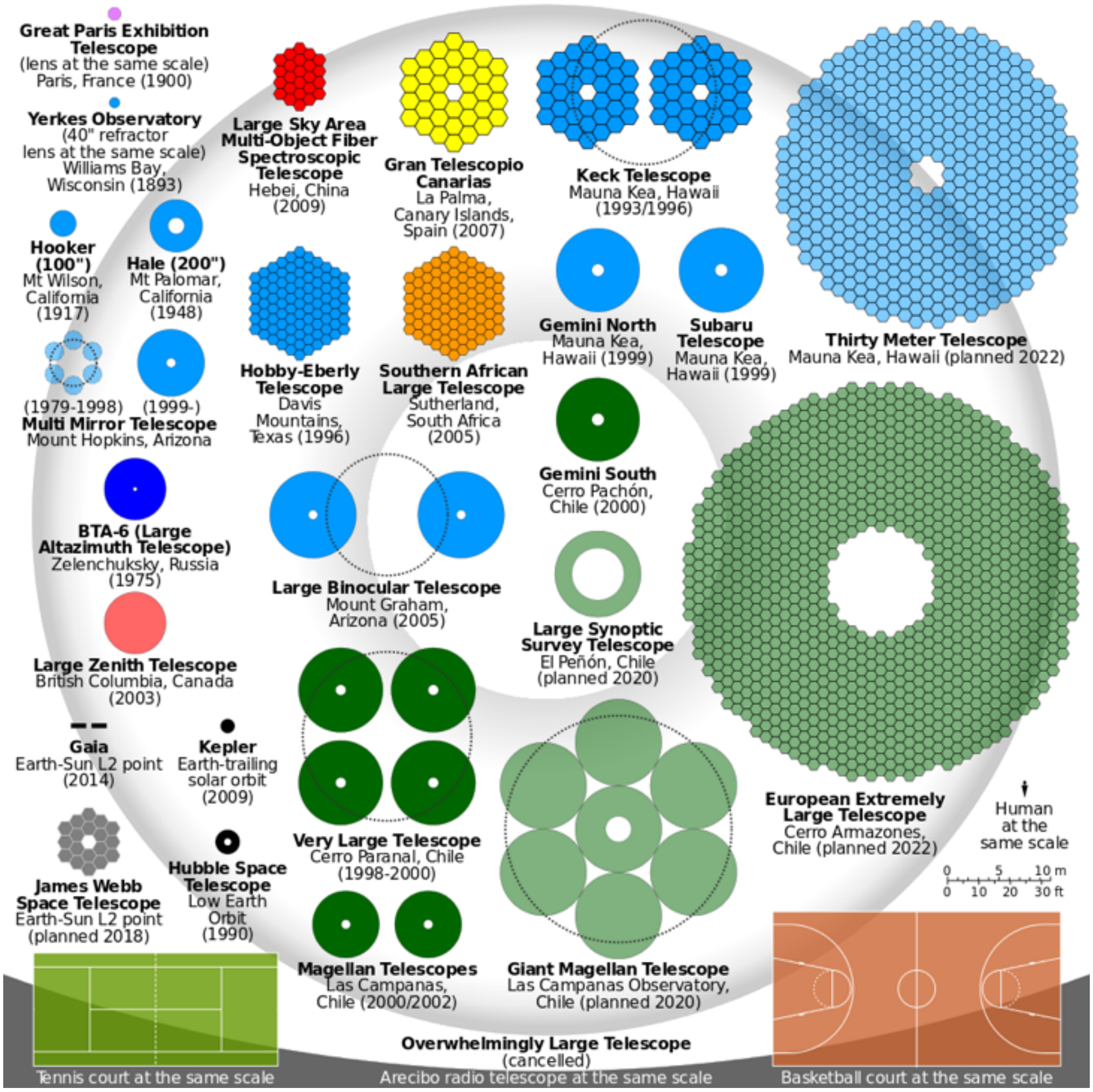
- The Giant Magellan Telescope (GMT) → 2025
  - Optical-IR imaging and spectroscopy; changing instruments
  - 7 × 8.4 meter segmented mirror on telescope to be build in Chile
  - Partners: Arizona, Carnegie, Sao Paolo, Texas A&M, Harvard, KASI, etc.



- The Thirty Meter Telescope (TMT) → 2027
  - 0.3-28 μm imaging and spectroscopy; changing instruments
  - 30 meter segmented mirror to be build in Hawaii (or La Palma)
  - Partners: Caltech, UC, NAO of Japan, Canada, and India



- ☑ CL
- ☑ QL
- ☑ GG
- ☑ SS
- ☑ Exo
- ☑ WF
- ☐ PS


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor lens at the same scale)
Williams Bay, Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Overwhelmingly Large Telescope
(cancelled)
Arecibo radio telescope at the same scale
Tennis court at the same scale
Basketball court at the same scale

So in summary…

- Cluster Lensing - Strong and Weak lensing ☑ **CL**
- QSO lensing - Strong lensing ☑ **QL**
- Galaxy-Galaxy lensing - Strong lensing ☑ **GG**
- Star-Star lensing - Microlensing ☑ **SS**
- Exoplanet searches - Microlensing ☑ **Exo**
- Wide field shearing - Weak lensing ☑ **WF**
- Power spectrum and correlation function studies - Weak lensing ☑ **PS**

The Future of Gravitational Lensing Is Bright!