Cosmic Origins Science Enabled by the Coronagraph Instrument on NASA's WFIRST/AFTA Mission

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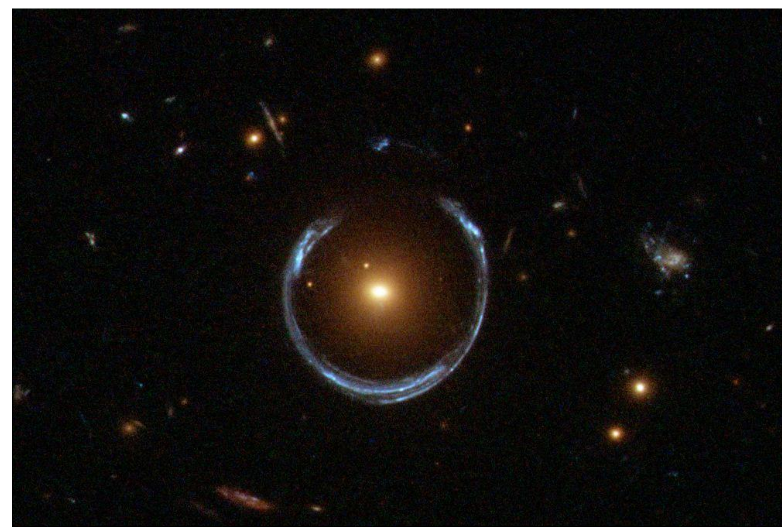
Seyfert Galaxy Markarian 817



Horseshoe Einstein Ring LRG 3-757

Summary and conclusions

1. Many examples of important Cosmic Origins Science will be enabled. Investigations involving Quasars, Super Massive Black Holes and Gravitational Lenses may receive great benefits.
2. The AFTA coronagraph will be a very powerful instrument with its planned baseline capabilities . A few additional features would also be useful. The feasibility of implementation could be considered during Pre-Phase A studies.
3. COR science targets and their measurement requirements will differ in important respects from the host stars of exoplanets.
   – Many investigations will not require maximum contrast being implemented for exoplanet science. Efficient ways to achieve less extreme contrast would be valuable.
   – Not all targets will be point sources. Effective means of suppressing the glare of slightly extended objects would be useful.
   – The central objects will usually be fainter than the exoplanet host stars.
   – Narrow-band filters would enhance observations of nebular emission features.
   – An Integral Field Spectrograph is a very powerful tool. Spectral resolution suitable for velocities of 100 km s^{-1} would be a very useful diagnostic.
4. Some of the most important objects of interest to COR are rare, in some cases with only a handful currently known. Surveys with the Wide Field Imager will discover many new examples.

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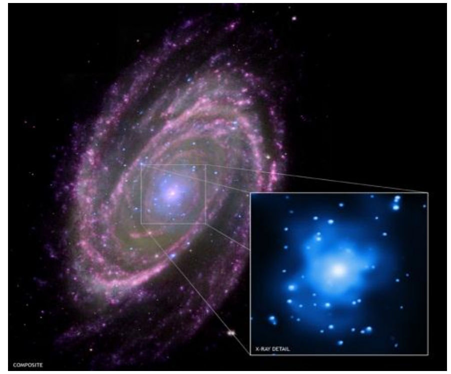
Potential COR Coronagraphic Investigations

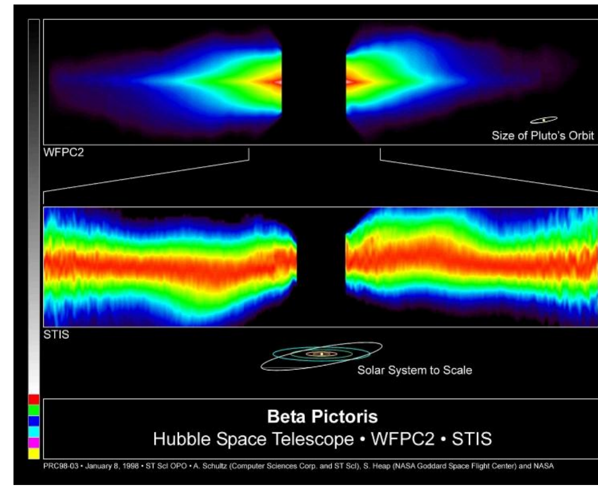
- Quasars & AGN
  - Host galaxies
  - Central black holes
  - Accretion disks
  - Bulges, spiral arms etc.
  - Mergers
  - Jets
- Young stars
  - Accretion disks
  - Outflows, jets
  - Protoplanetary disks
- Evolved Stars
  - Debris disks
  - Ejectae, symmetries
  - LBVs - η Carinae
  - WR stars
  - Interactions with ISM



Galaxy M81 V ~ 6.9

Cat’s Eye Nebula
Central star V $\approx$ 9.8

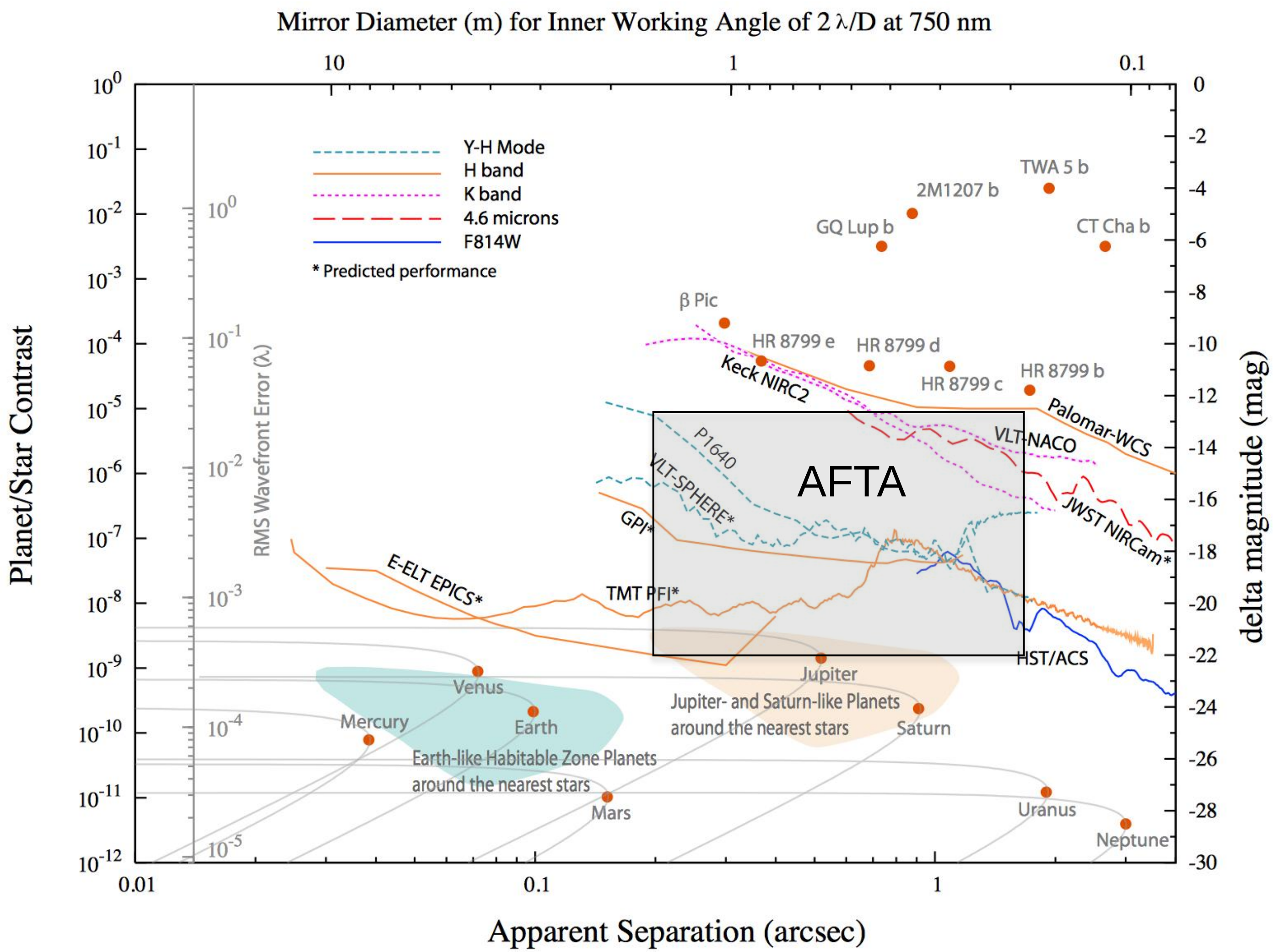
Interesting structures and processes may be hidden by a bright central object.



β Pic V $\approx$ 3.9

Evolving Red Supergiant V838 Mon
V ~ 6.9 to 15.7

AFTA will explore a unique region of parameter space for a space observatory



Adapted from Mawet et al. 2012, Optical, Infrared, and Millimeter Wave Proceedings of the SPIE, Volume 8442, id. 844204

Baseline capabilities will be particularly useful for COR science.

- Diffraction-limited angular resolution of a 2.4m telescope is better than 40 mas at the shortest wavelengths. Spatial sampling finer than 20 mas per pixel for both direct imaging and spectroscopy.
- Ability to observe full annular region around central object, either with annular format of HLC or sequence of separate masks in OMC
- Wide spectral bands allow multi-color photometry
- Polarization capability
- IFS with spectral resolution R $\sim$70
- Range of contrasts, 10^{-9} not usually required for COR investigations
- “Straight through” mode with wider FOV
- Detector characteristics, low read noise, high dynamic range, bin pixels
- Observing strategies, roll, dither etc.
- Image post-processing techniques to enhance low contrast features

The expected performance will accommodate the characteristics of COR science targets

- Temporal stability will enable observations of faint targets
  - Initial setup of Deformable Mirrors requires bright stars to minimize speckles
  - Slew from setup star to COR science target
  - Contrast is expected to be maintained for several hours
- Contrast will be only modestly degraded for targets that are not point sources
  - All light from within the Inner Working Angle will be suppressed
  - Contrast will degrade by approximately a factor 2 for each 0.1 arc sec beyond the IWA
- It may not be necessary to engage the jitter-suppression for many COR investigations
  - Jitter suppression uses light from the object being blocked to control the Fast Steering Mirror. Many COR targets will be too faint to enable this process.
  - Contrast may be sufficient for the COR investigations even without the FSM.

Additional capabilities could be useful

- Narrow-band filters, Hα, He, [O III], [N II], S etc. for nebular detection and diagnostics at zero redshift
- IFS with greater instantaneous wavelength coverage and higher spectral resolution, R = 3000 (ΔV = 100 km s^{-1})
- Efficient means of providing contrasts of 10^{-6} to 10^{-7} when maximum contrast is not needed
- Efficient means to provide contrasts of 10^{-6} when central bright object is not a point source.

The host galaxies of quasars will be revealed

Supermassive black holes in centers of most galaxies

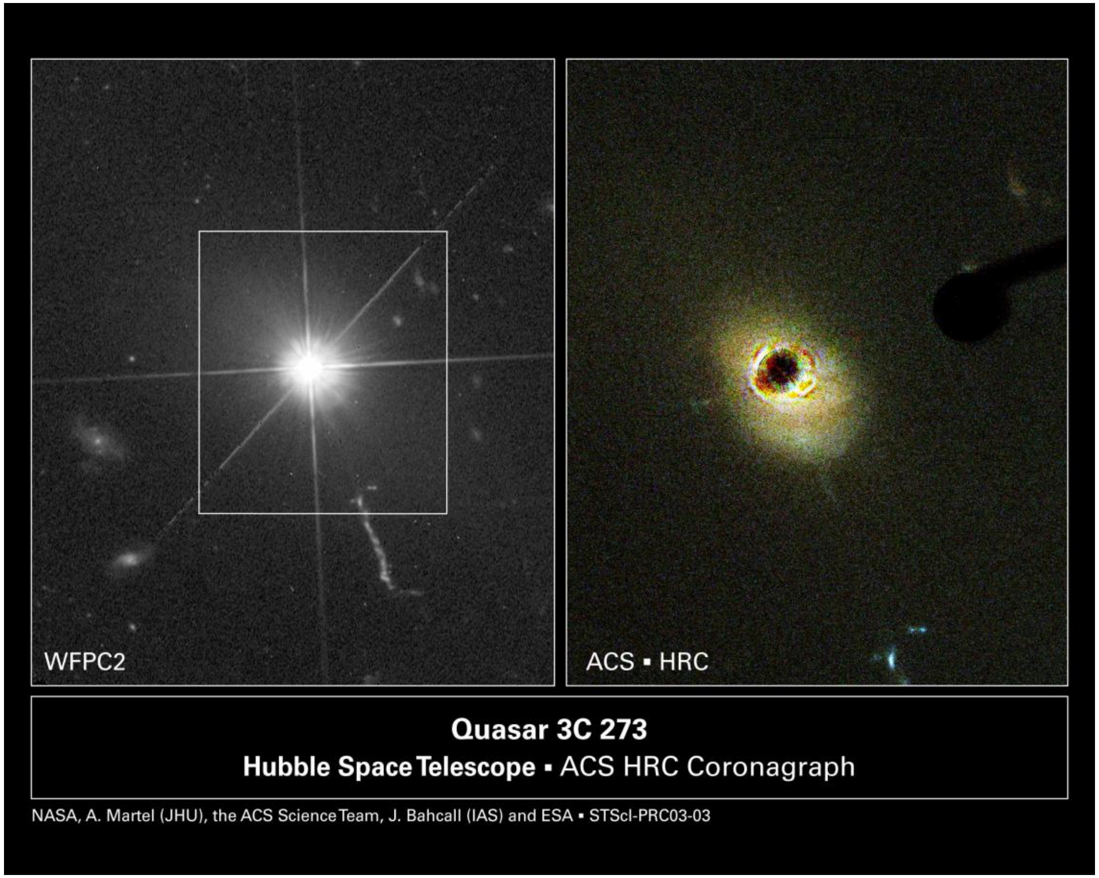
Galaxies are small and faint at redshifts of peak activity

Limited success at detecting and characterizing galaxies, even with HST, even with nearest and brightest quasars.

Nearly point source quasar well suited to coronagraph

Broad band imaging will maximize sensitivity, measures colors, reveal morphology, star formation regions

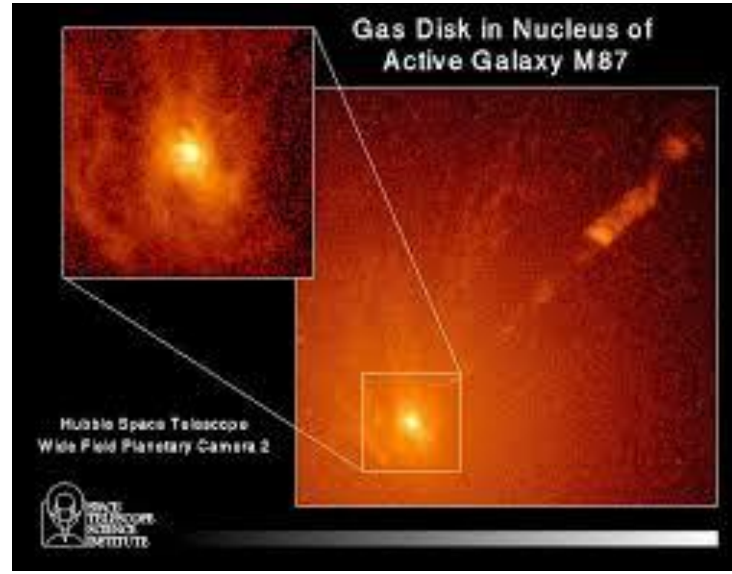
IFS spectroscopy can indicate signs of star formation, bulges



The nearest Quasar 3C 273, z = 0.158, m ≈ 12.9

The core regions of AGN have accretion disks, and the origins of jets

Galaxy Virgo A = M87
Nucleus m ~ 9.6



Unobscured, high luminosity, actively accreting SMBH

Supermassive black hole having profound effects on surrounding galaxy

Traces of tidal tails of mergers?

Root of jets or bi-conical outflows

Accretion disks, torus

Intense star formation regions

Winds

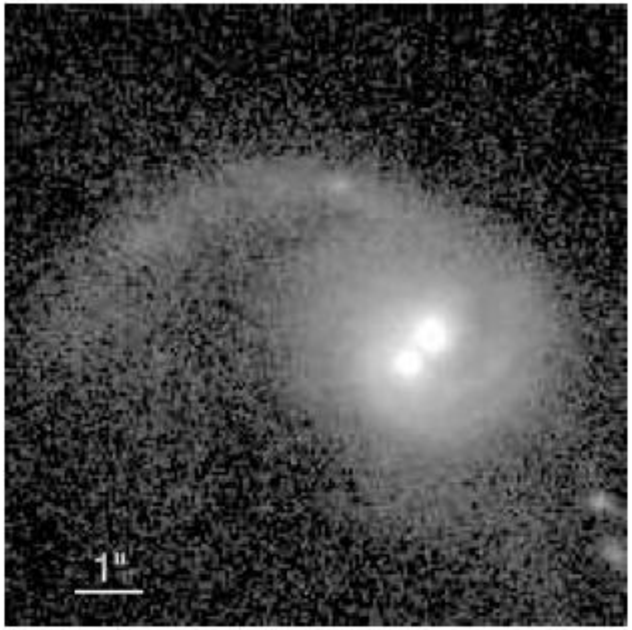
Probably not point source. Contrast will not be maximum. That's OK

Multi-spectral images

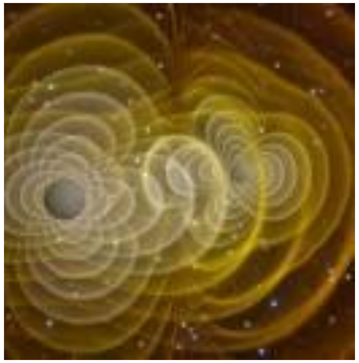
Velocities few hundred km s^{-1}

MRK 817 m ≈ 14

Dual Nuclei AGN may be merging galaxies, or future merging SMBH

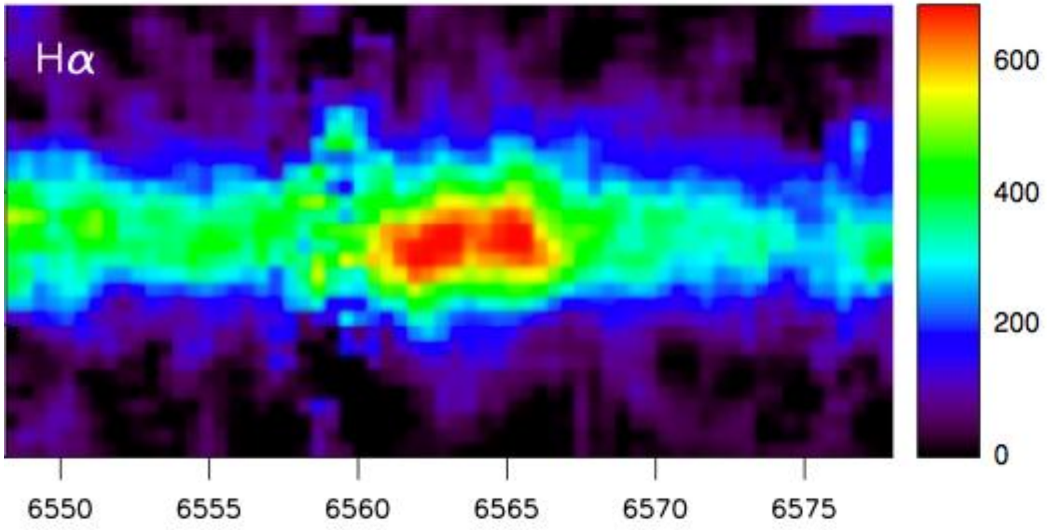


MK 739 m ~ 14.8



Visualization of gravitational waves emanating from merging black holes

- Recognized cases have nuclei separated by few tenths arc sec or more, and similar brightness.
- Suppression of apparently single nucleus could reveal fainter and/or closer second object.
- Broad band imaging with bright source suppressed could reveal vestiges of tidal interactions during merging.
- IFS could study double-peaked nebular emission lines, Hα, [O III], [N II] etc.
- ΔV few hundred km s^{-1} typical
- May inform understanding of SMBH merging for future GW detection missions (LISA)



The location of intergalactic matter that forms absorption lines in the spectra of Quasars is now poorly known

Gas clouds along line of sight to quasar

>50% of matter outside of galaxies

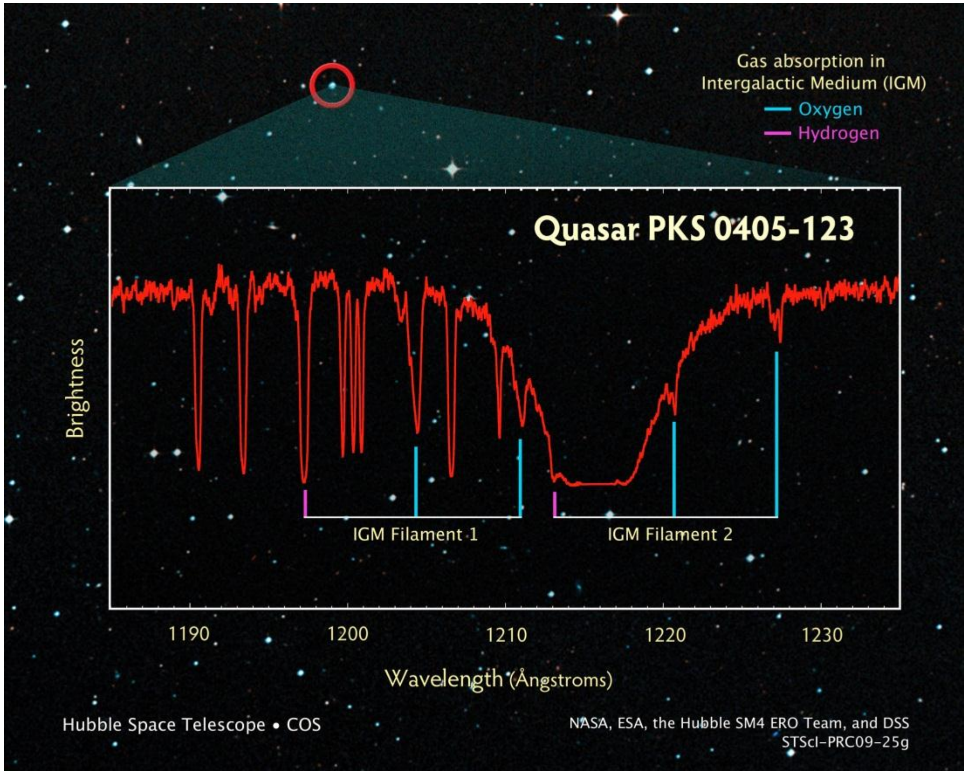
Cosmic Web?, filaments?

Complex structures and cycles of flow into filaments, into and out of galaxies

Few or no detections of source of gas producing absorption

Deep, broadband images with quasar light suppressed

Quasar effectively a point source. Well suited to coronagraph



PKS 0405-123 z = 0.573, V $\approx$ 14.8

Einstein Rings are gravitationally-lensed images of very distant galaxies

Lensed galaxies are at various distances, redshifts.

Multiple lensed galaxies

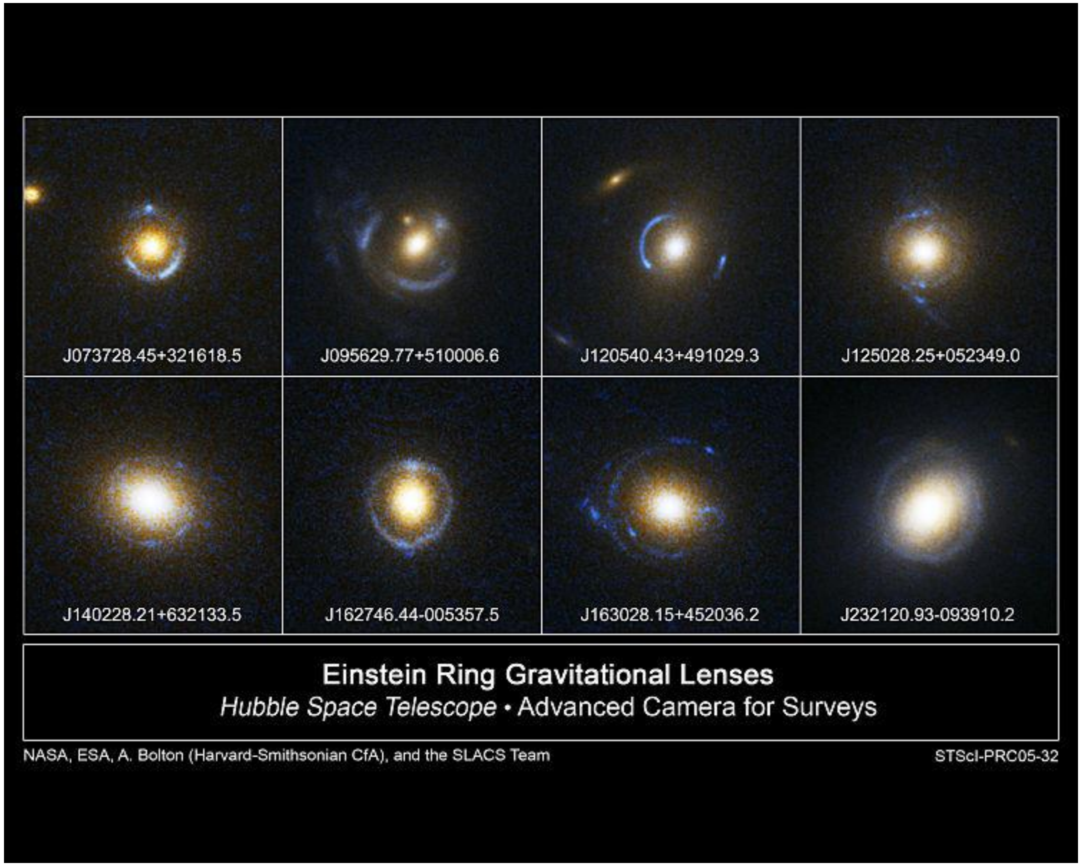
Well suited to broad band filter imaging.

Star formation regions in lensed galaxies

IFS spectra of knots in lensed galaxies

Mass distribution, including DM, in foreground lensing galaxy

Lensing galaxy is not a point source. Need an efficient way to suppress light from slightly extended object.



Brightest lensing galaxies m ~15 to 17