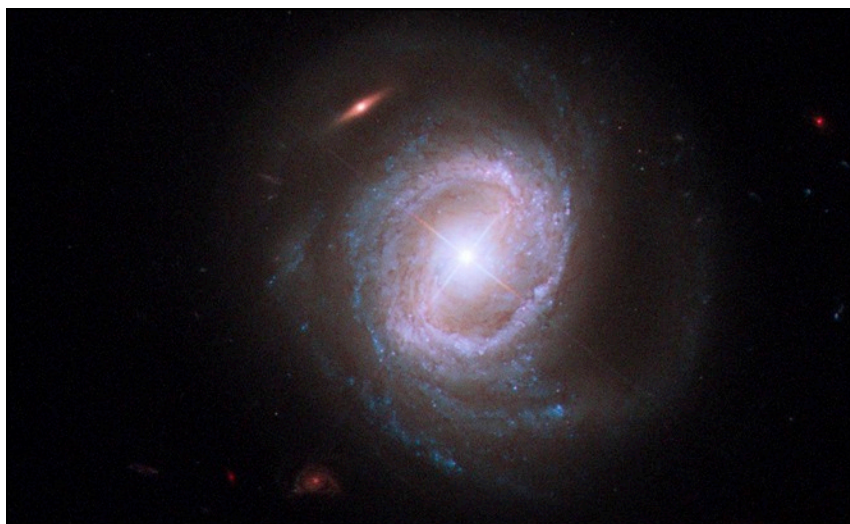
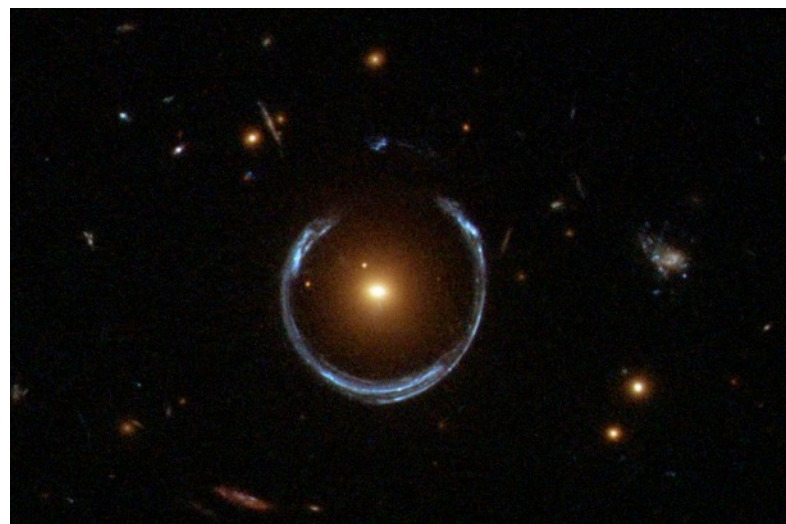


Cosmic Origins Science Enabled by the Coronagraph Instrument on NASA's WFIRST/AFTA Mission

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January 2015



Seyfert Galaxy Markarian 817



Horseshoe Einstein Ring LRG 3-757

Summary and conclusions

1. Many examples of important Cosmic Origins (COR) Science will be enabled. Investigations involving Quasars, Super Massive Black Holes and Gravitational Lenses may benefit greatly.
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 equivalent to 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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SAG 6 Charter

The Wide-Field Infrared Survey Telescope (WFIRST) is the highest priority large space mission recommended by the 2010 Decadal Survey of Astronomy and Astrophysics. It is designed to perform wide-field imaging and slitless spectroscopic surveys of the visible to near-infrared sky. The Astrophysics Focused Telescope Assets (AFTA) study design of the mission makes use of an existing 2.4 m telescope to enhance light collecting and imaging performance. The main instrument is a wide-field multi-filter imager with infrared grism spectroscopy. It also features a small-field low-resolution integral field spectrograph. A coronagraph instrument is part of the study and has a primary science focus of direct imaging and spectroscopy of gas-giant exoplanets and debris disks.

The WFIRST-AFTA Science Definition Team solicits community input for potential WFIRST-AFTA coronagraphic science investigations related to NASA's Cosmic Origins (COR) or Physics of the Cosmos (PCOS) themes. Such science investigations may further enhance the science case for the AFTA-study design that includes the coronagraph. While not a primary driver for coronagraph design, science investigations other than exoplanet and debris disk studies may provide helpful insight for future design choices.

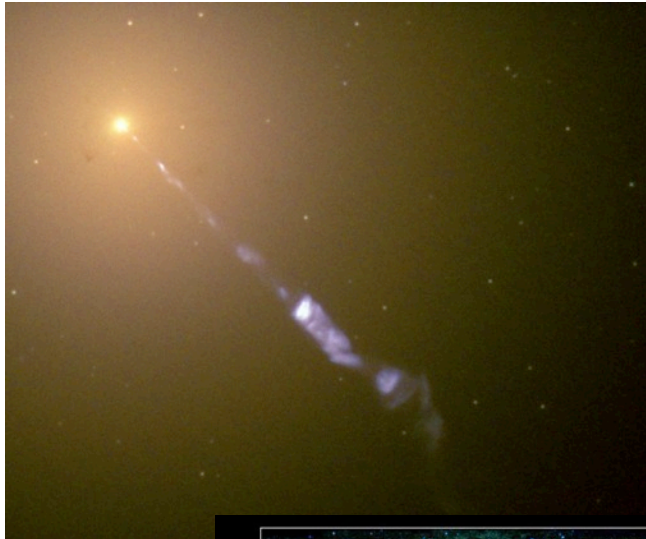
Response to Charter

- We have used information about the design parameters and expected performance that was available in the fall of 2014. We recognize that these are subject to change as the design matures.
- We have identified examples of scientific questions that were outstanding at the time of this study and that could benefit from a space-based coronagraph. Some may be addressed by ground or other space-based observatories before WFIRST/AFTA flies.
- We have indicated how potential COR investigations may differ from the exoplanet objectives for which the coronagraph is being designed. We indicate how the planned capabilities could be used, and where different or additional capabilities could be beneficial. These are not requirements to be imposed on the design, but options to be considered during Pre-Phase A studies.
- Drafts of this report were reviewed with colleagues at GSFC, JPL and STScI.
- A near-final draft was submitted to the NAC Astrophysics Subcommittee in November 2014.

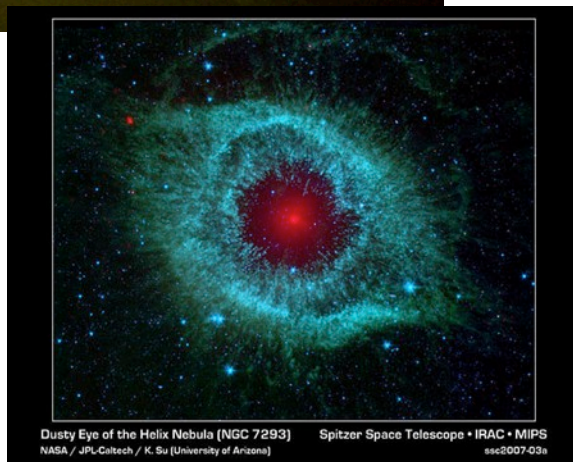
COR science maps directly into the objectives of:

2010 Astrophysics Decadal Survey

2013 30-Year Roadmap



Supermassive black holes
Galaxy formation
Galaxy evolution
Starbirth
Protoplanetary systems
Stellar evolution



Potential COR Coronagraphic Investigations

- Quasars and 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



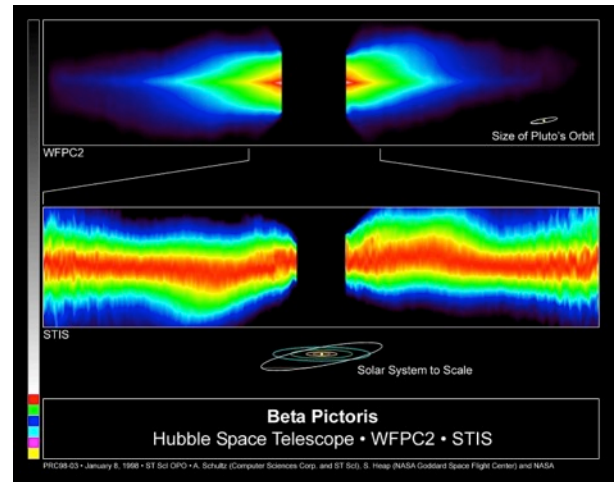
Galaxy M81 $V \sim 6.9$



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

Evolving Red Supergiant V838 Mon
 $V \sim 6.9$ to 15.7

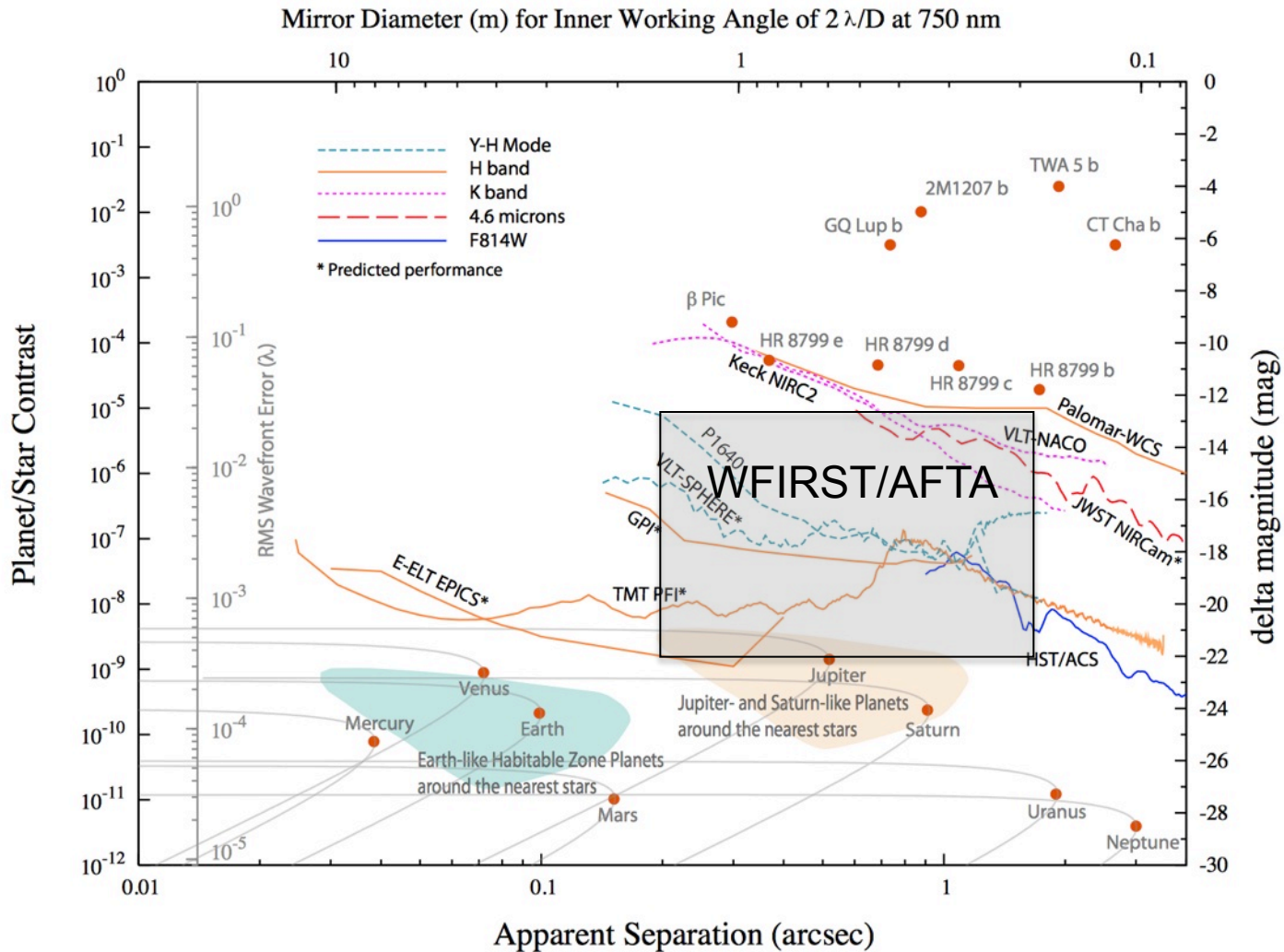
Interesting structures and processes may be hidden by a bright central object.



β Pic $V \approx 3.9$



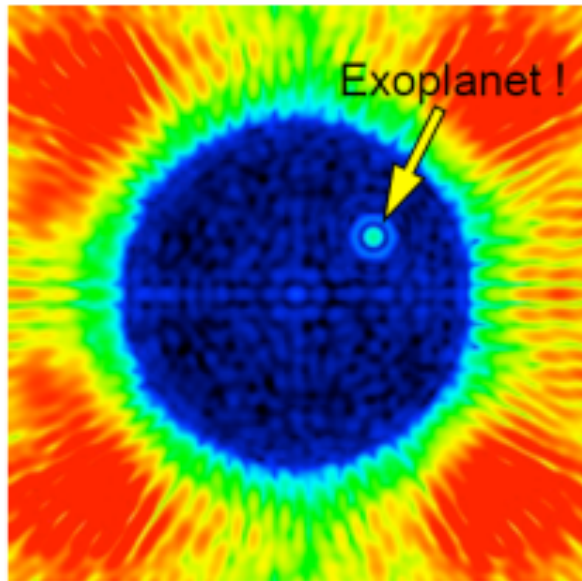
WFIRST/AFTA will explore a unique region of parameter space for a space observatory



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

Imaging with the AFTA Coronagraph

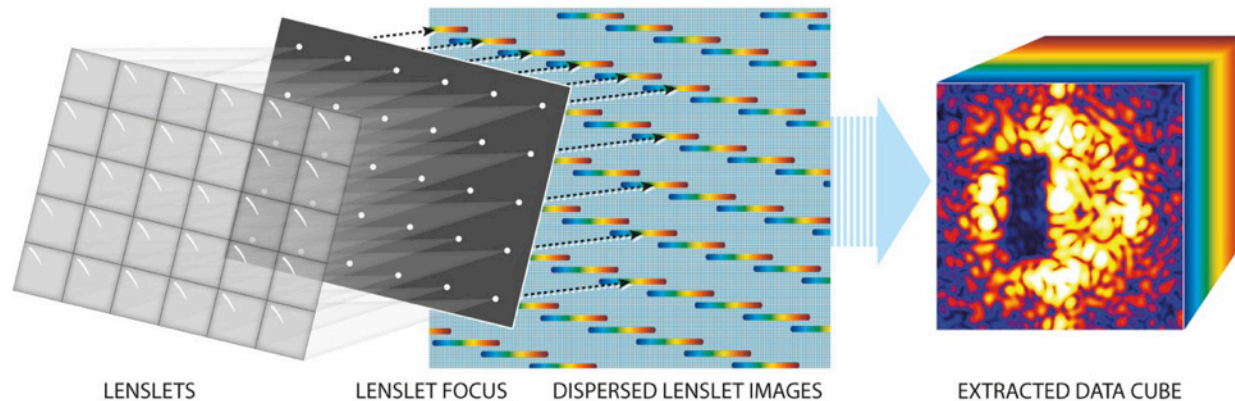
**Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot (primary)
Phase-Induced Amplitude Apodization (backup)**



Note: The following Coronagraph parameters were the design values as of September 2014. They are subject to change as the design matures.

- 430 – 980nm spectral coverage
- 5 bands 10% width each, broad band photometry
 - $\lambda_c = 450, 550, 650, 800, 950\text{nm}$
- IWA Central 100 – 250 mas radius occulted
- OWA 0.75 – 1.8 arc sec radius of darkest zone
- Contrast $\sim 10^{-9}$ best with careful setup
- Contrast $10^{-5} - 10^{-8}$ with less effort
- Shape of dark zone
 - SPC: 2 “bow tie” regions, 4 – 12 λ/D , 60° sectors
 - HLC: Annular region, 4 – 10 λ/D ,
- “Straight through” mode also possible
- Detector format 1K x 1K
- Full FOV = 17 arc seconds on a side

Integral Field Spectroscopy with the AFTA Coronagraph



Note: The following Integral Field Spectrograph (IFS) parameters were the design values as of September 2014. They are subject to change as the design matures.

- 600 – 980nm spectral range
- 4 spectral bands 20% bandwidth each
- R ~70 spectra dispersed over 24 pixels
- 76 X 76 element lenslet array with 174 μ m pitch (5776 samples)
- 17 mas per lenslet spatial sample
- 1.3 arc sec diameter FOV
- 1K X 1K detector format

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
- Integral Field Spectrograph (IFS) with spectral resolution $R \sim 70$
- Range of contrasts, 10^{-9} not usually required for COR investigations
- “Straight through” mode with wider field-of-view (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 (IWA) 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 (FSM). 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

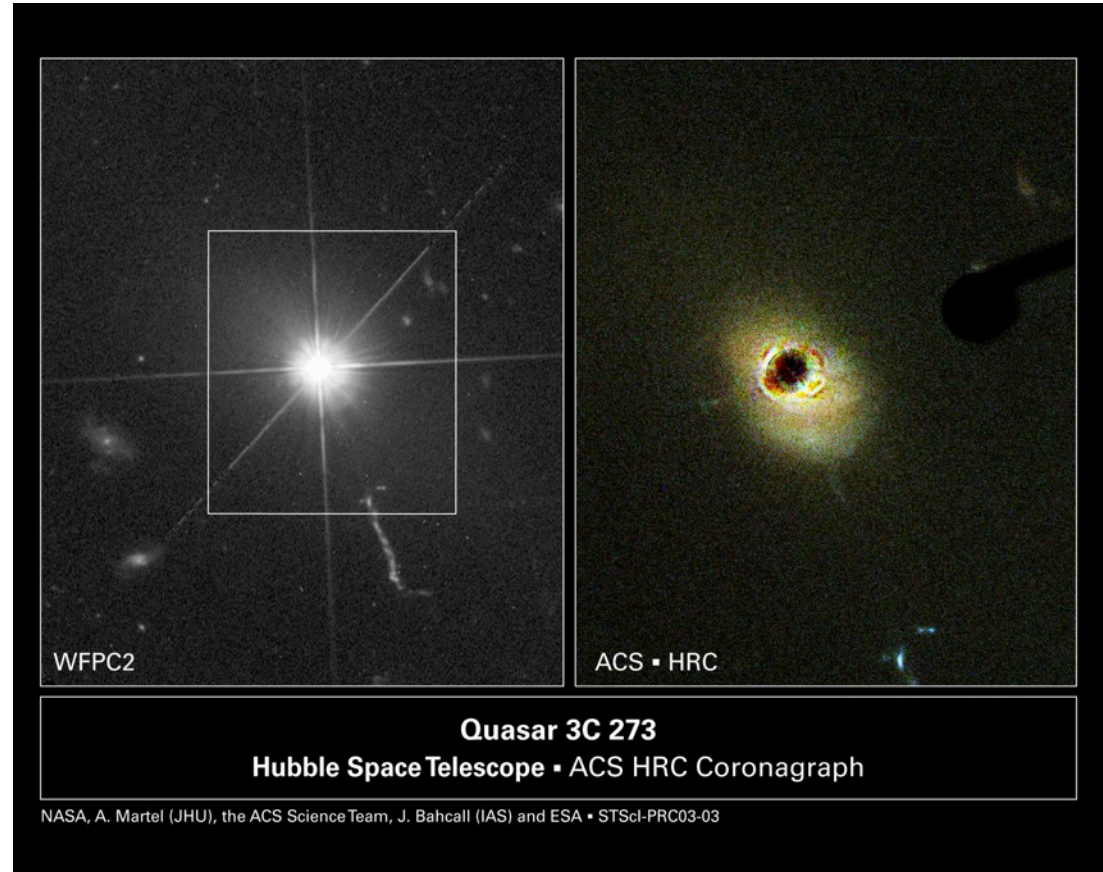
- Narrow-band filters, $H\alpha$, He, [O III], [N II], S II, etc. for nebular detection and diagnostics at zero redshift
- IFS with greater instantaneous wavelength coverage and higher spectral resolution, $R = \lambda/\Delta\lambda = 3000$ ($\Delta V = 100 \text{ km s}^{-1}$)
- Efficient means of providing 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

Clear documentation will be helpful as the design matures

- Illustrations of shape and geometry of FOV
 - For both direct imaging and integral field spectroscopy
 - For the different coronagraph designs
 - As functions of wavelength
 - For the chosen detectors and plate scales
 - Restrictions (if any) on orientation, “roll-angle”
- Location of IFS μ -lens array in FOV
- Contrast that can be expected for slightly extended targets or those too faint to engage the FSM jitter-suppression process
- Change in contrast over a larger FOV, especially outside the nominal dark hole
- Availability and use of “straight-through” mode with no coronagraph mask. Can spectral filters still be used?
- What polarization capabilities are planned?

The host galaxies of quasars will be revealed

- Supermassive black holes (SMBH) 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
- IF spectroscopy can indicate signs of star formation, bulges

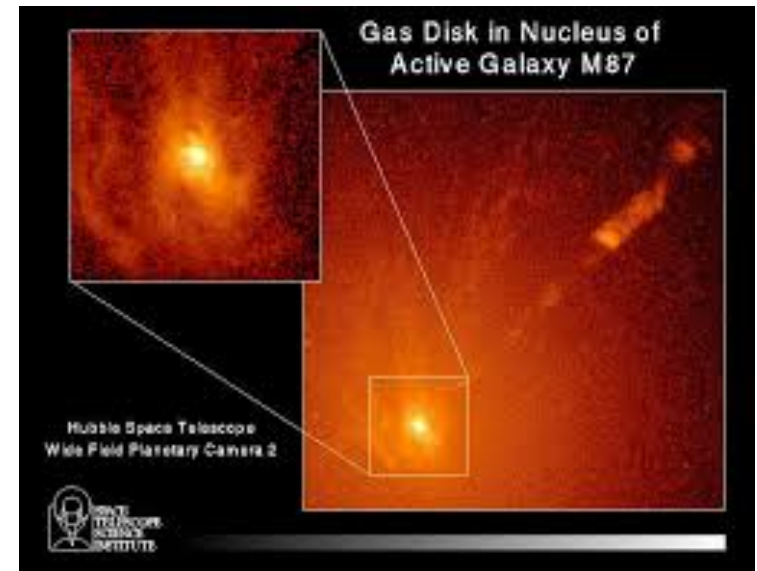


The nearest Quasar 3C 273, $z = 0.158$, $m \approx 12.9$

The core regions of AGN have accretion disks and jets

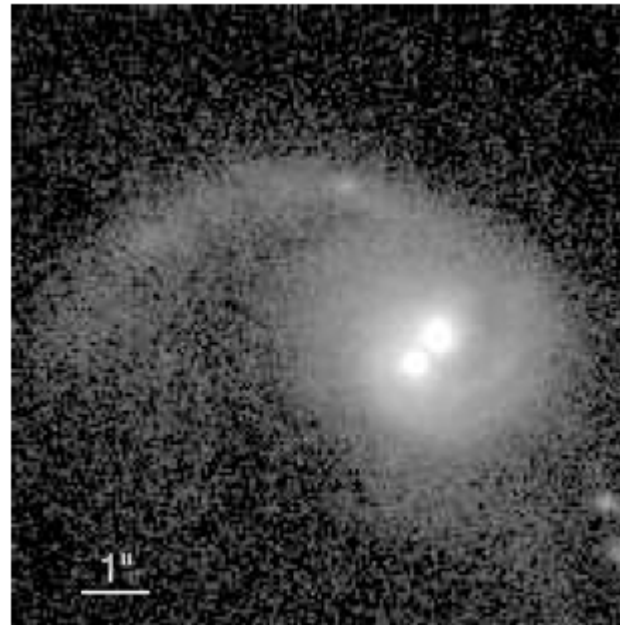
- Unobscured, high luminosity, actively accreting SMBH
- Supermassive black hole having profound effects on surrounding galaxy
- Traces of tidal tails of mergers?
- Root of jets or bi-conical outflows
- Accretion disks, torus
- Intense star formation regions
- Winds
- Probably not point source, so contrast will not be maximum
- Multi-spectral images
- Velocities few hundred km s^{-1}

Galaxy Virgo A = M87
Nucleus $m \sim 9.6$

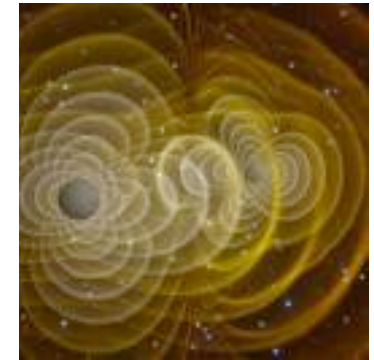


Dual Nuclei AGN may be merging galaxies, or future merging SMBH

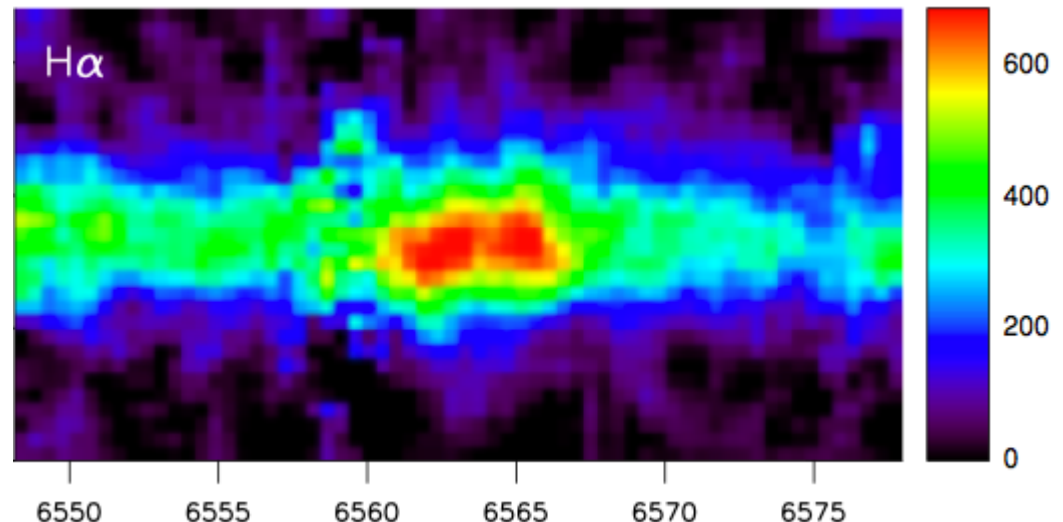
- Recognized cases have nuclei separated by few tenths arc sec or more, and similar brightness
- Suppression of apparently single nucleus could reveal fainter and/or closer second object
- Broad band imaging with bright source suppressed could reveal vestiges of tidal interactions during merging
- IFS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



MK 739 $m \sim 14.8$

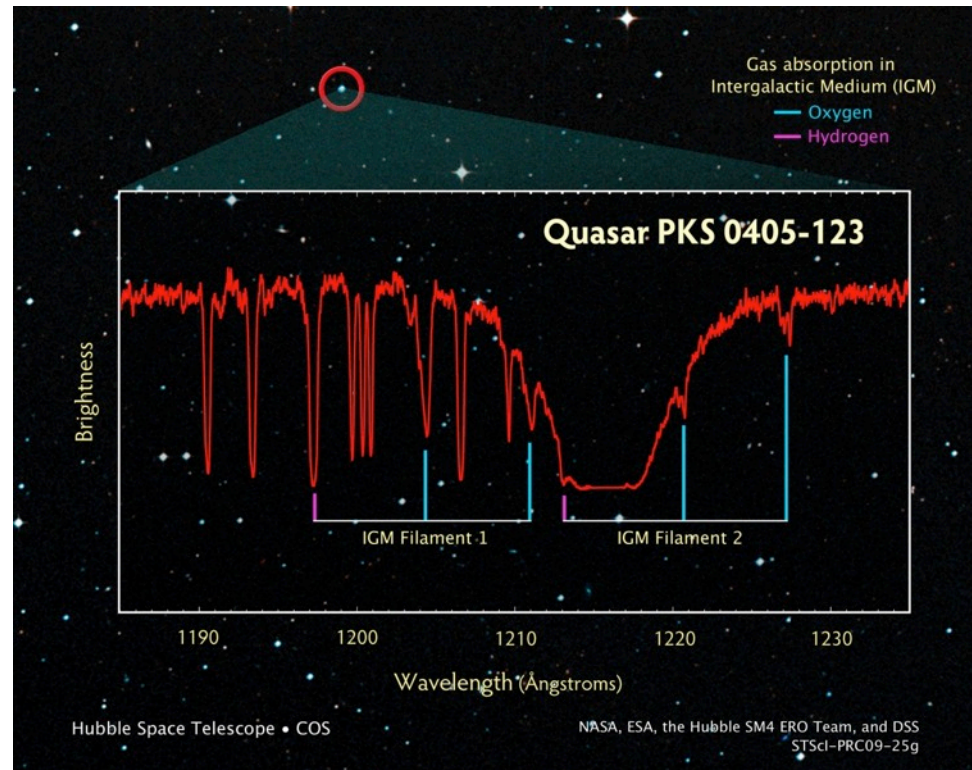


Visualization of gravitational waves emanating from merging black holes



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

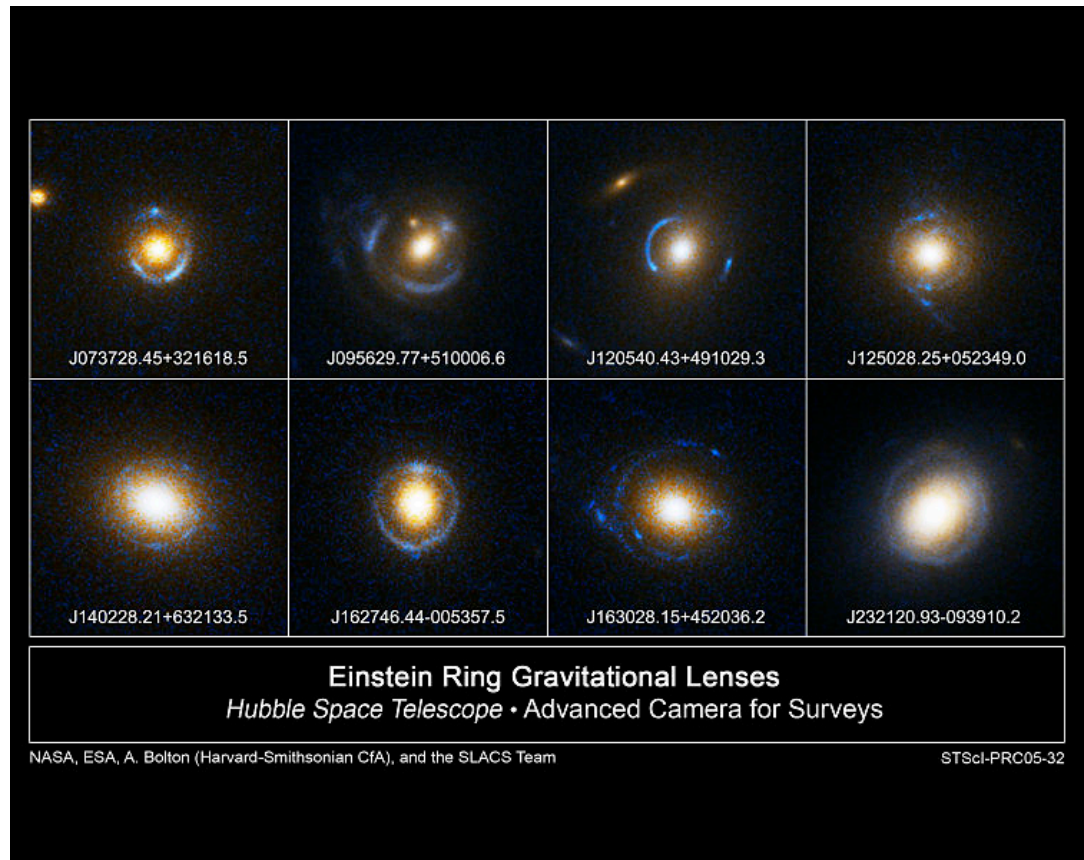
- Gas clouds along line of sight to quasar
- >50% of matter outside of galaxies
- Cosmic Web? Filaments?
- Complex structures and cycles of flow into filaments, into and out of galaxies
- Few or no detections of sources of gas producing absorption
- Deep, broadband images with quasar light suppressed
- 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 dark matter, 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 $m \sim 15$ to 17

Morphology and origin of structures in protoplanetary disks can be studied

- Detect and resolve fainter regions of disks
- Detect possible planet-induced structures such as belts, edges, gaps
- Scattered starlight is polarized
- Included as part of exoplanet goals, but science is relevant to Cosmic Origins theme also

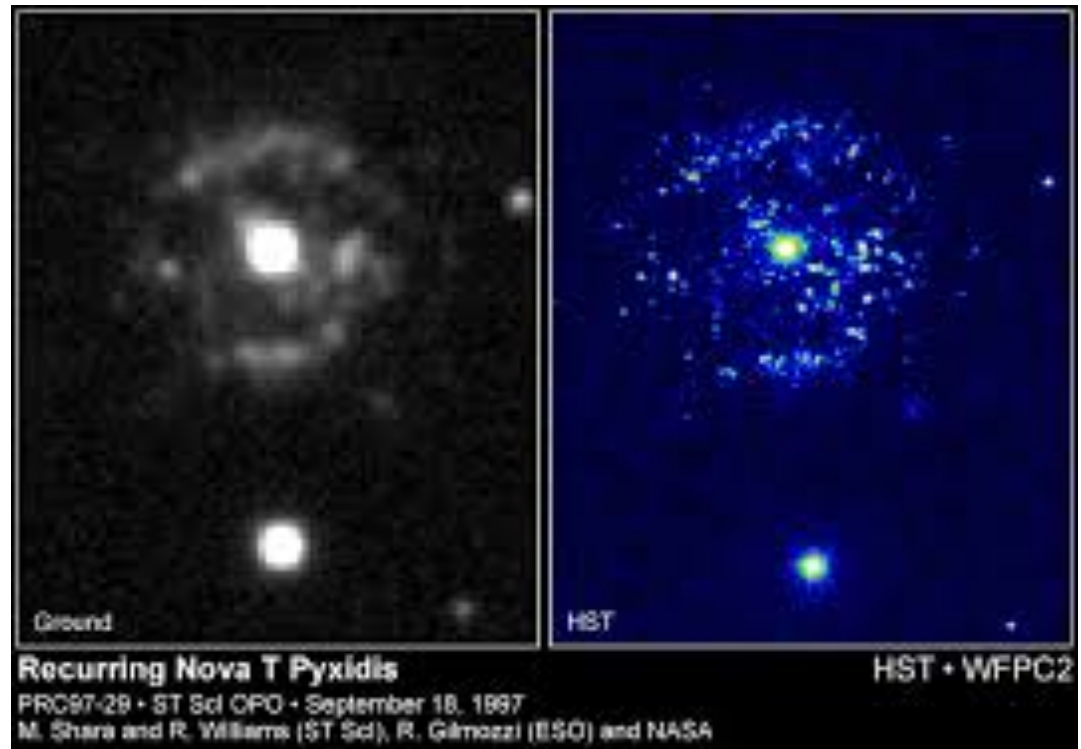


C.A. Grady (NOAO, NASA/GSFC), et al., NASA

AB Aur $V = 7.1$

Ejecta from recurrent novae and other variable stars can be detected and analyzed

- Episodes, outbursts
- Photo-ionization
- Rapid variability
- Time domain
- Proper motions of knots
- Narrow band nebular filters needed



T Pyx $V_{\min} \approx 15.5$, $V_{\max} \approx 6.3$

Summary of ways in which COR applications differ from exoplanet investigations

- In many cases the bright central objects needing to be suppressed are not point sources. They may extend beyond the IWA of the coronagraph.
- The central objects will generally be much fainter than exoplanet host stars.
- Contrasts as deep as 10^{-9} are not needed. The structures of interest may be brighter than exoplanets.
- The structures under study may not be point sources either. They may be spiral arms, tidal tails, star-forming knots, accretion disks, inner regions of jets, etc.
- In many cases the faint structures of interest will emit nebular emission lines, not scattered starlight continua.
- Extragalactic targets will be at a range of redshifts. The wavelengths of their important spectral features will differ from their rest-frame values.
- Spectroscopic diagnostics will require resolution of several hundred km s^{-1} to be of most value.

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