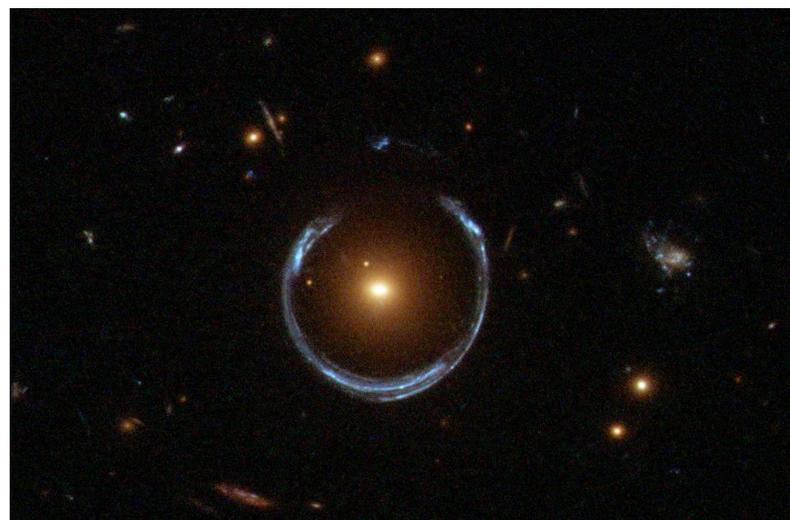


Cosmic Origins Science Enabled by the Coronagraph Instrument on NASA's WFIRST/AFTA Mission

Dennis Ebbets, Ken Sembach, Susan Neff



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.
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.
 - 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.

SAG 6 Contributors

- COPAG EC connection – Dennis Ebbets, Ken Sembach, Susan Neff
- Dominic Benford NASA GSFC
- Jim Breckenridge Cal Tech
- Julia Comerford University of Colorado
- CU CASA colloquium (15 participants)
- Charles Danforth University of Colorado
- Carol Grady Eureka Scientific
- Sally Heap NASA GSFC
- Bruce Macintosh Stanford University
- Marshall Perrin Space Telescope Science Institute
- Ilya Poberezhskiy JPL
- Laurent Pueyo STScI
- Mike Shara AMNH
- Karl Stapelfeldt NASA GSFC
- John Stocke University of Colorado
- Remi Soummer Space Telescope Science Institute
- Wes Traub JPL
- Steve Unwin JPL
- Nadia Zakamska Johns Hopkins University

SAG 6 Charter

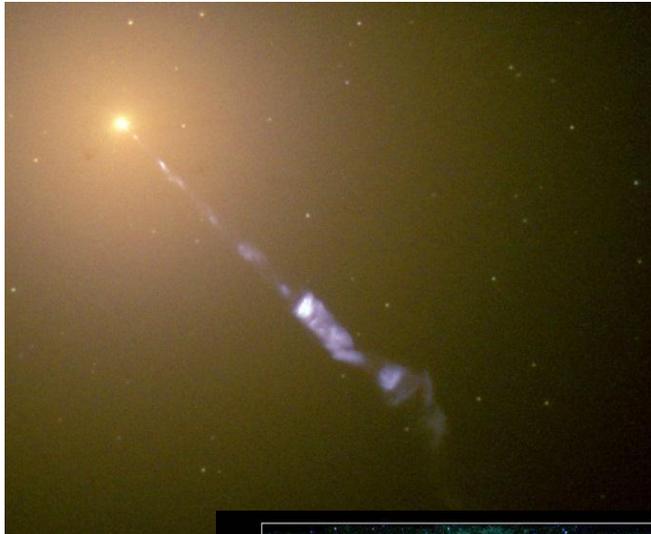
The Wide-Field Infrared Survey Telescope (WFIRST) is the highest priority large space mission recommended by the 2010 Decadal Survey of Astronomy and Astrophysics. It is designed to perform wide-field imaging and slitless spectroscopic surveys of the visible to near-infrared sky. The Astrophysics Focused 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.

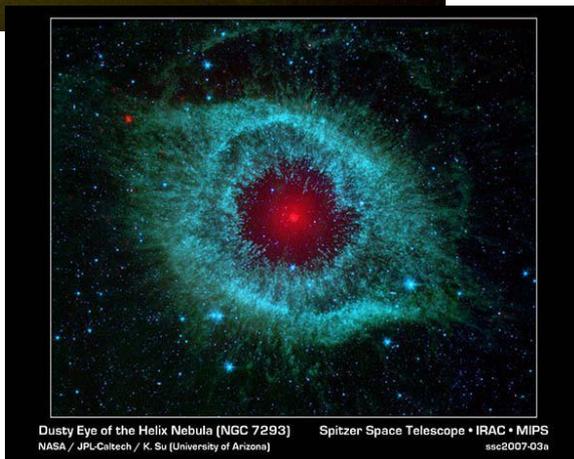
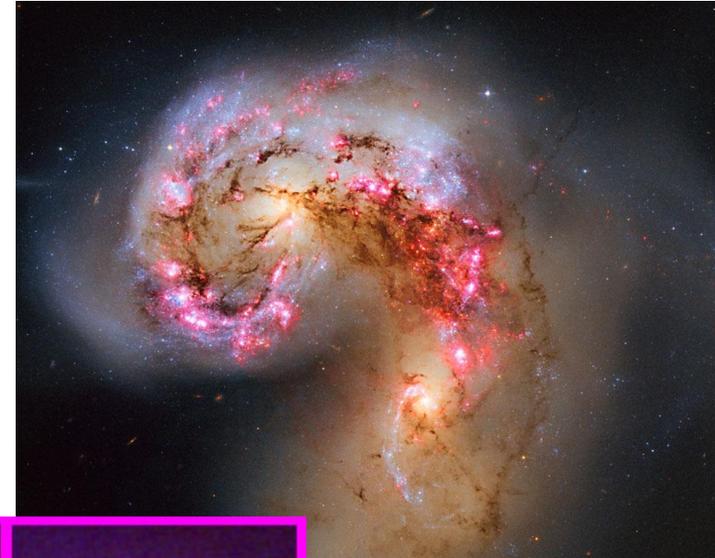
COR science maps directly into the objectives of:

2010 Astrophysics Decadal Survey

2013 30 Year Roadmap

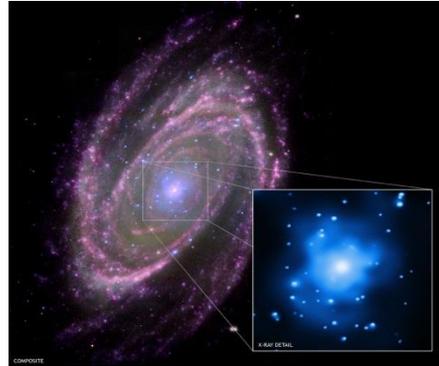


Supermassive Black Holes
Galaxy formation
Galaxy evolution
Starbirth
Protoplanetary systems
Stellar evolution

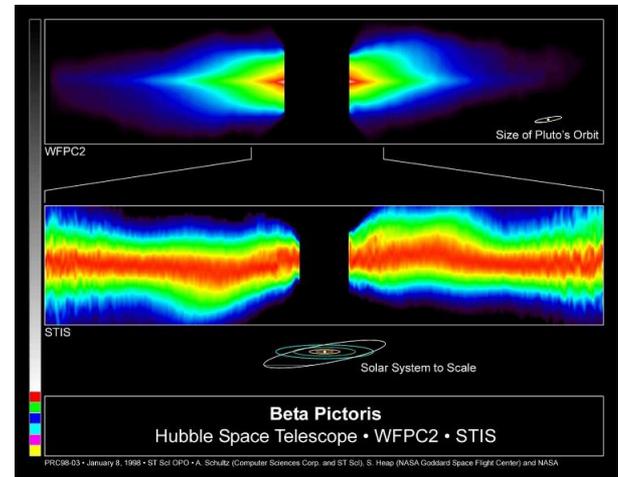


Potential COR Coronagraphic Investigations

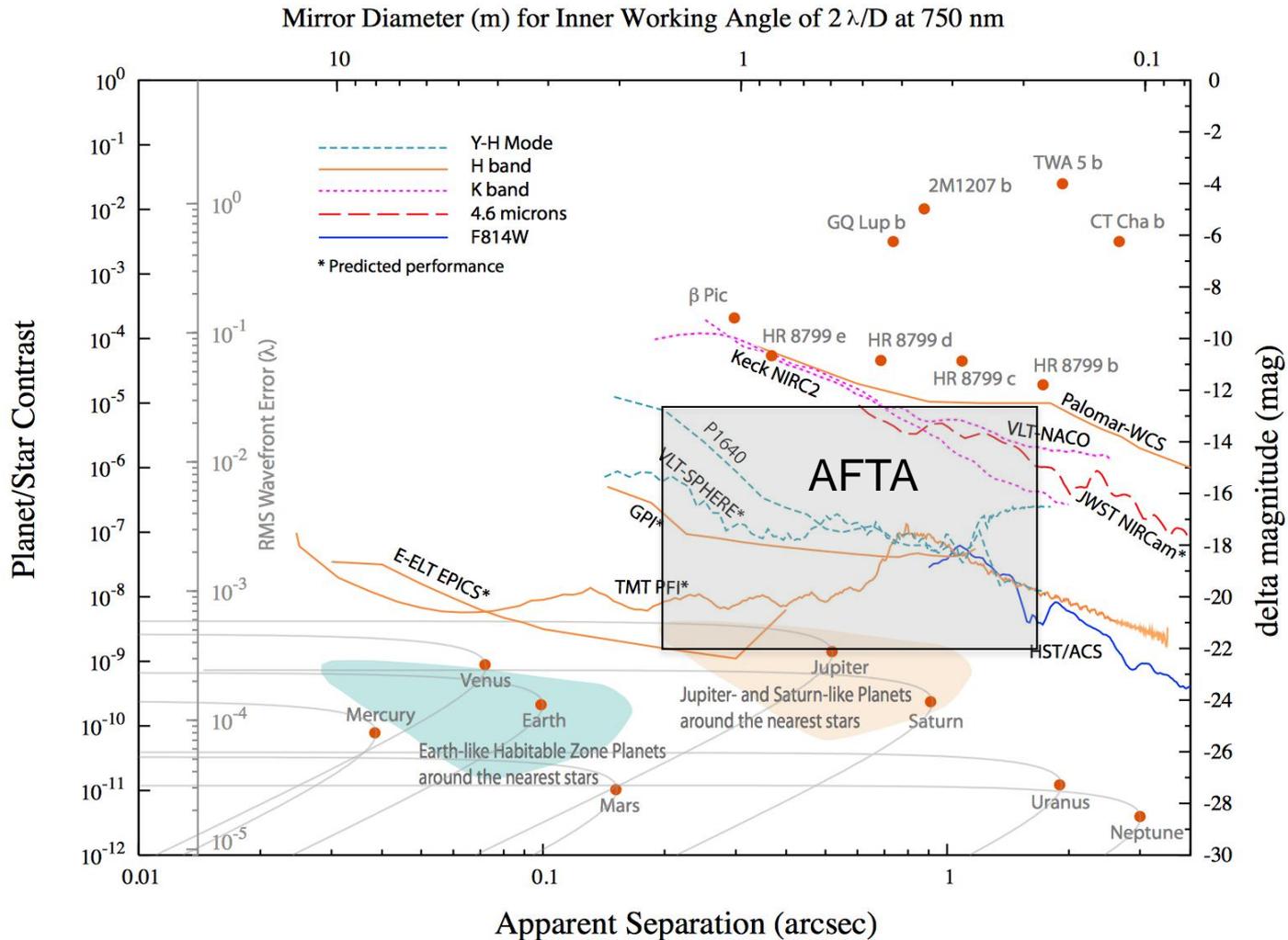
- Quasars & AGN
 - Host galaxies
 - Central black holes
 - Accretion disks
 - Bulges, spiral arms etc.
 - Mergers
 - Jets
- Young stars
 - Accretion disks
 - Outflows, jets
 - Protoplanetary disks
- Evolved Stars
 - Debris disks
 - Ejecta, symmetries
 - LBVs - η Carinae
 - WR stars
 - Interactions with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



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



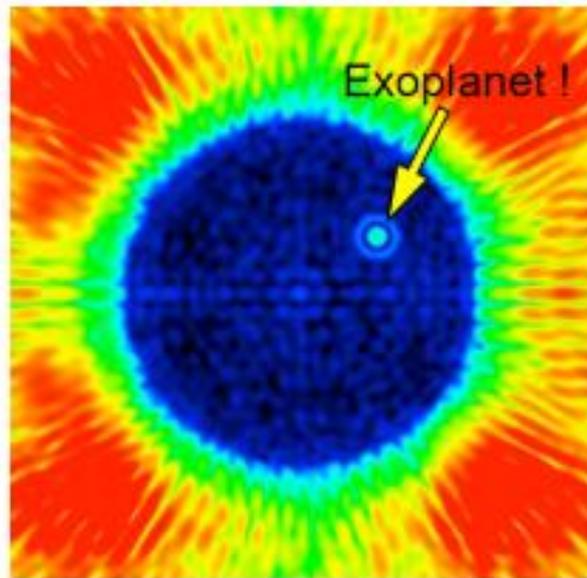
AFTA will explore a unique region of parameter space for a space observatory



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

Imaging with the AFTA Coronagraph

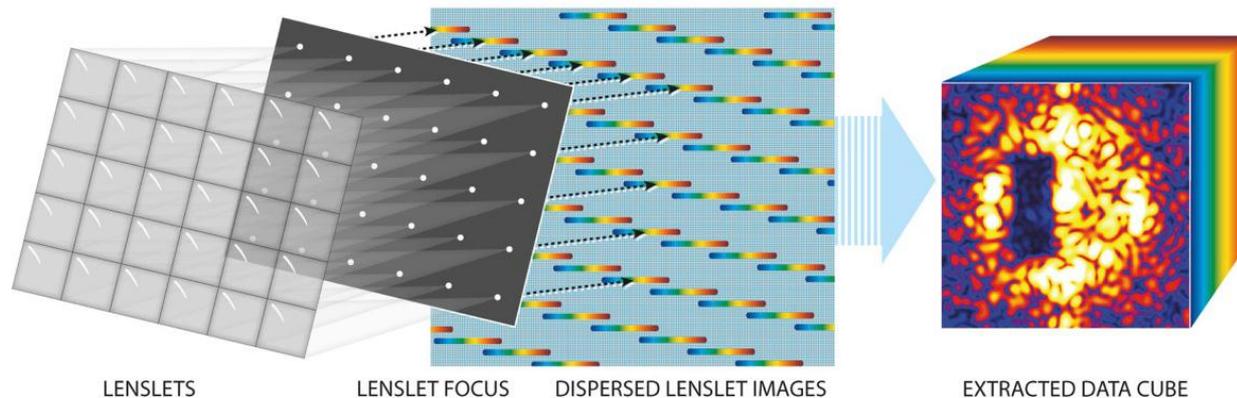
**Occulting Mask Coronagraph = Shaped Pupil + Hybrid Lyot (primary)
Phase-Induced Amplitude Apodization (backup)**



Note: The following 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 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
- 140 X 140 lenslet array with 100 μ m pitch (19600 samples)
- 17 mas per lenslet spatial sample
- 2.38 X 2.38 arc sec FOV covered by 140 x 140 lenslets
- 2K X 2K detector format to capture the spectra

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

Additional capabilities could be useful

- Narrow-band filters, H α , He, [O III], [N II], S etc. for nebular detection & diagnostics at zero redshift
- IFS with greater instantaneous wavelength coverage and higher spectral resolution, $R=3000$ $\Delta V=100$ 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. Image plane occulting spot or bar.

Clear documentation will be helpful as the design matures

- Illustrations of shape and geometry of FOV
 - For both direct imaging and IF spectroscopy
 - For the different coronagraph designs
 - As functions of wavelength
 - For the chosen detectors and plate scales
 - Restrictions, if any, on orientation, “roll-angle”
- 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?
- Location of IFS μ -lens array in FOV.
- What polarization capabilities are planned?

The host galaxies of quasars will be revealed

Supermassive black holes in centers of most galaxies

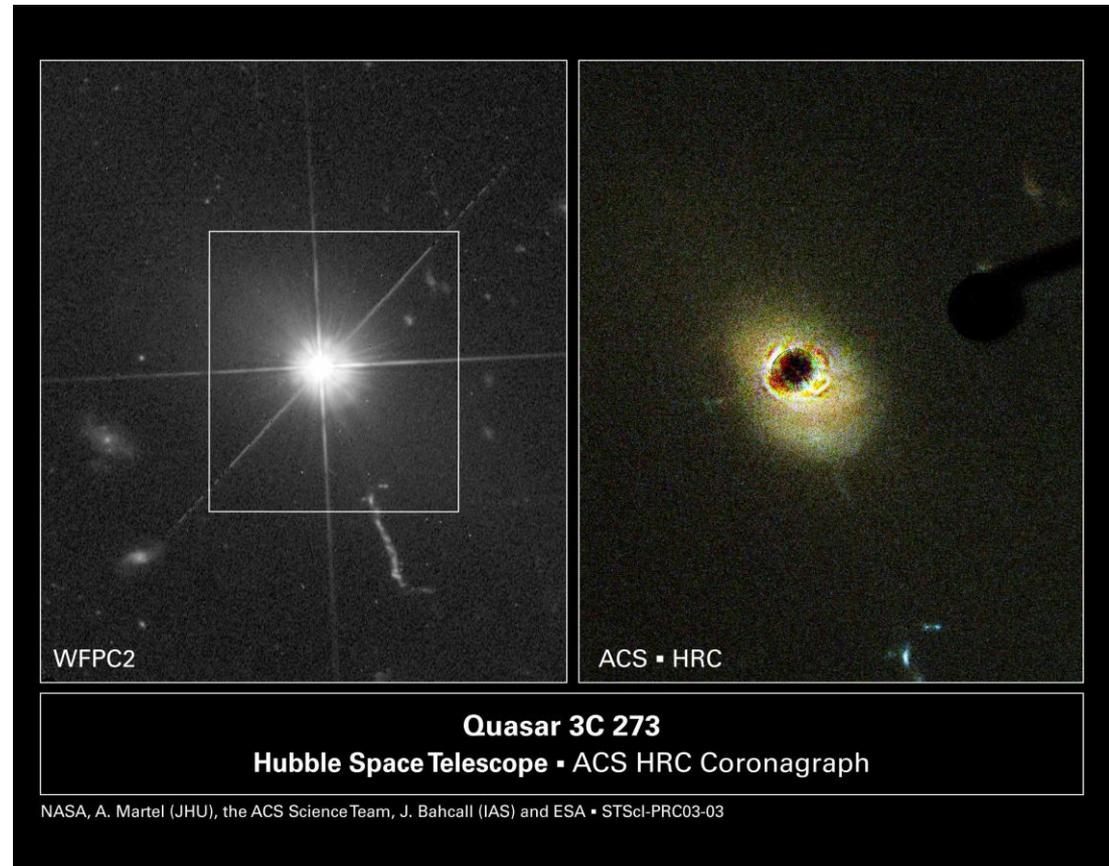
Galaxies are small and faint at redshifts of peak activity

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

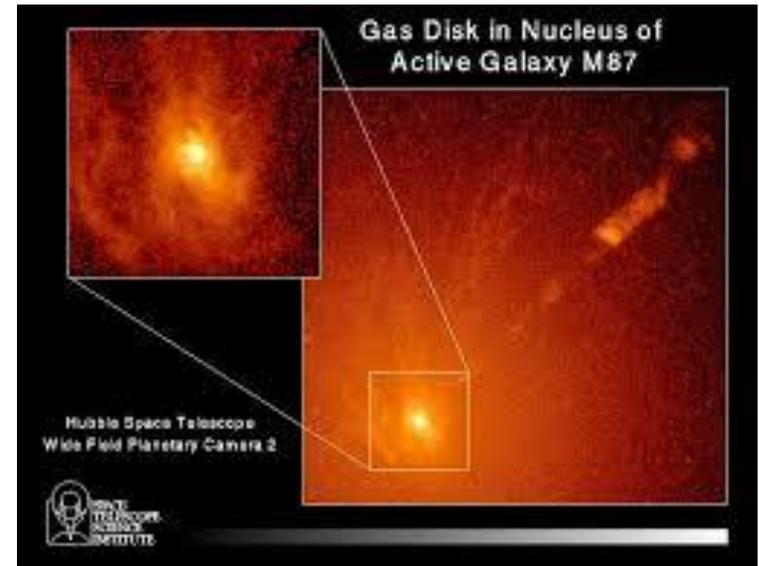
Intense star formation regions

Winds

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

Multi-spectral images

Velocities few hundred km s^{-1}



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.

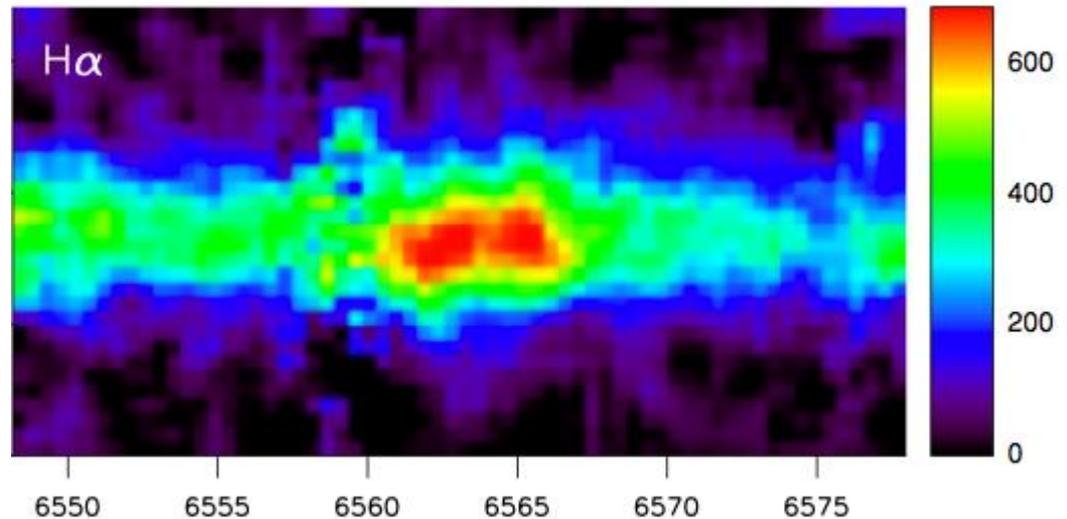
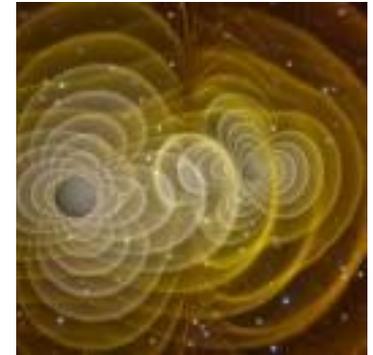
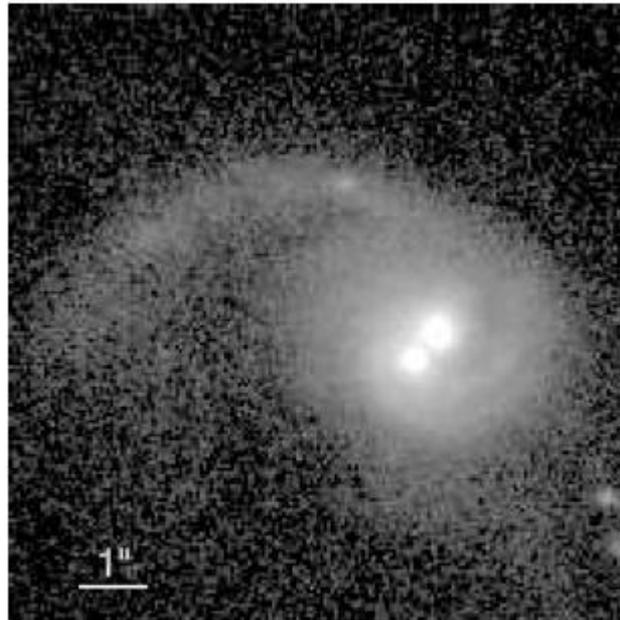
Suppression of apparently single nucleus could reveal fainter and/or closer second object.

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 (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

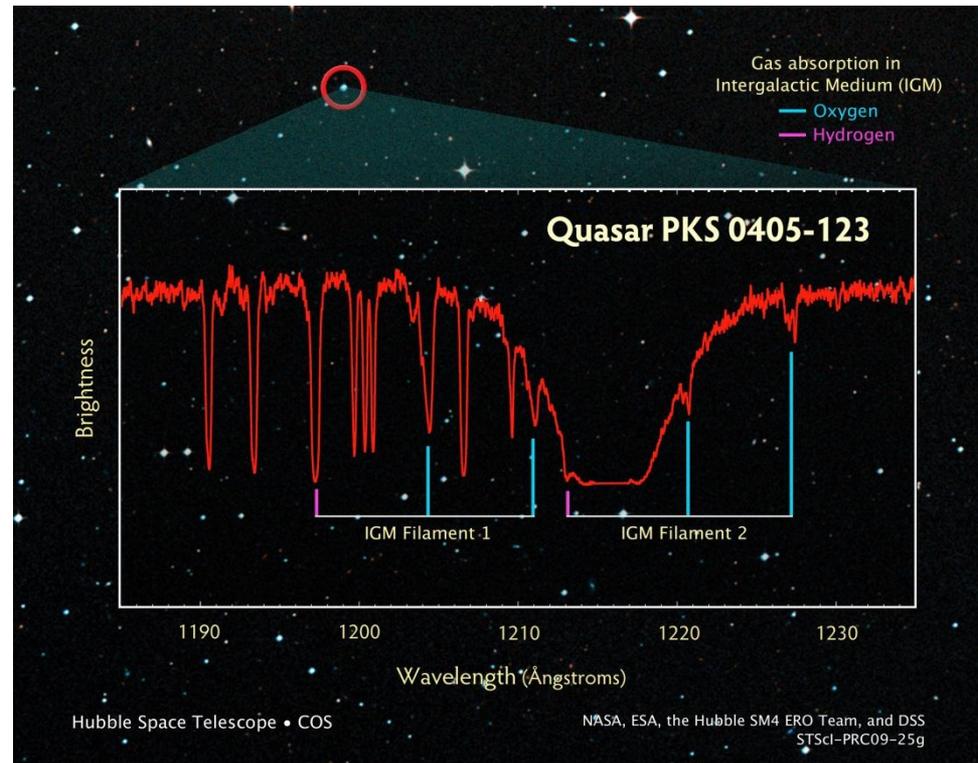
Cosmic Web?, filaments?

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



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.

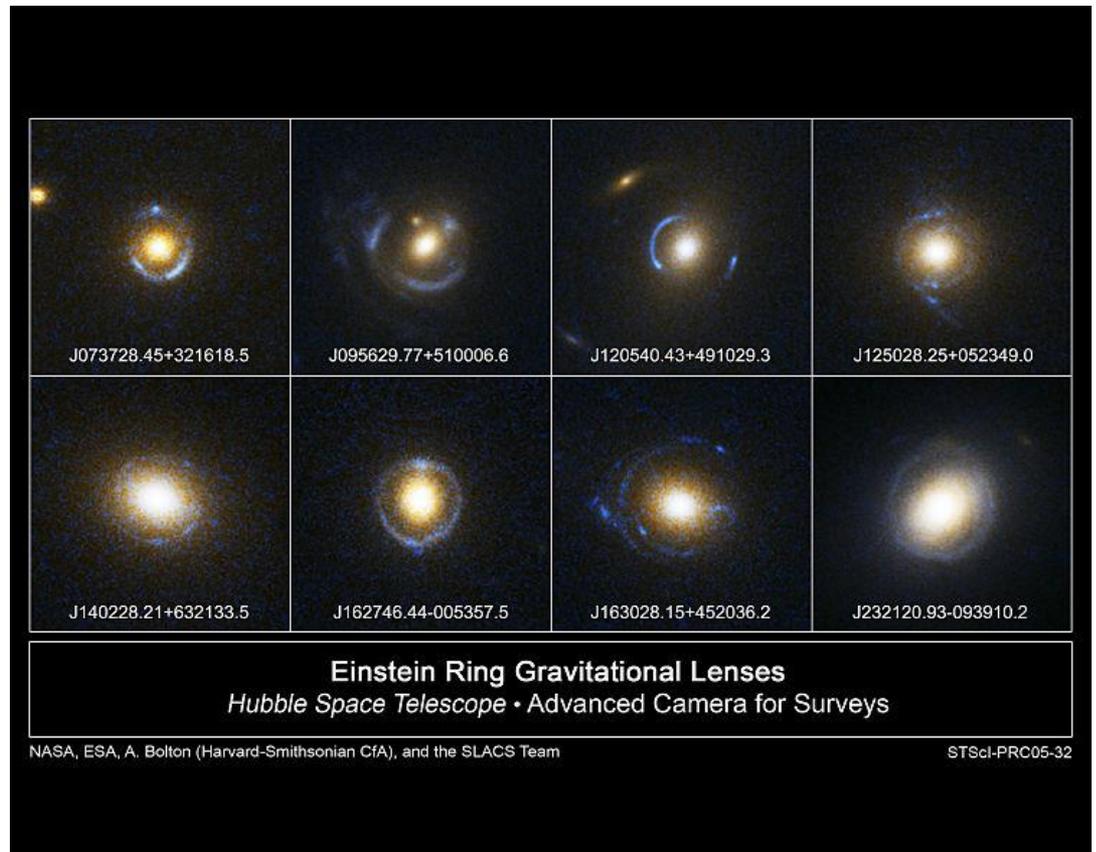
Star formation regions in lensed galaxies

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.



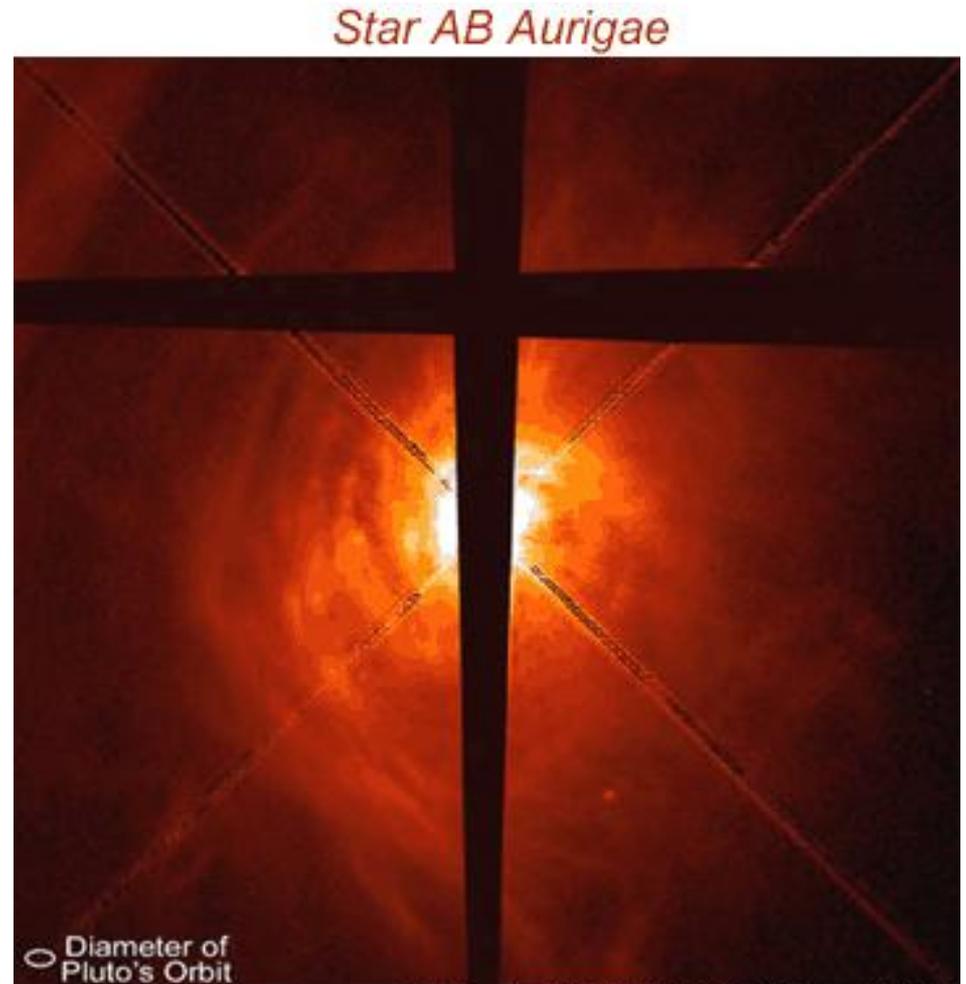
Morphology and origin of structures in protoplanetary disks can be studied

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

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

Episodes, outbursts

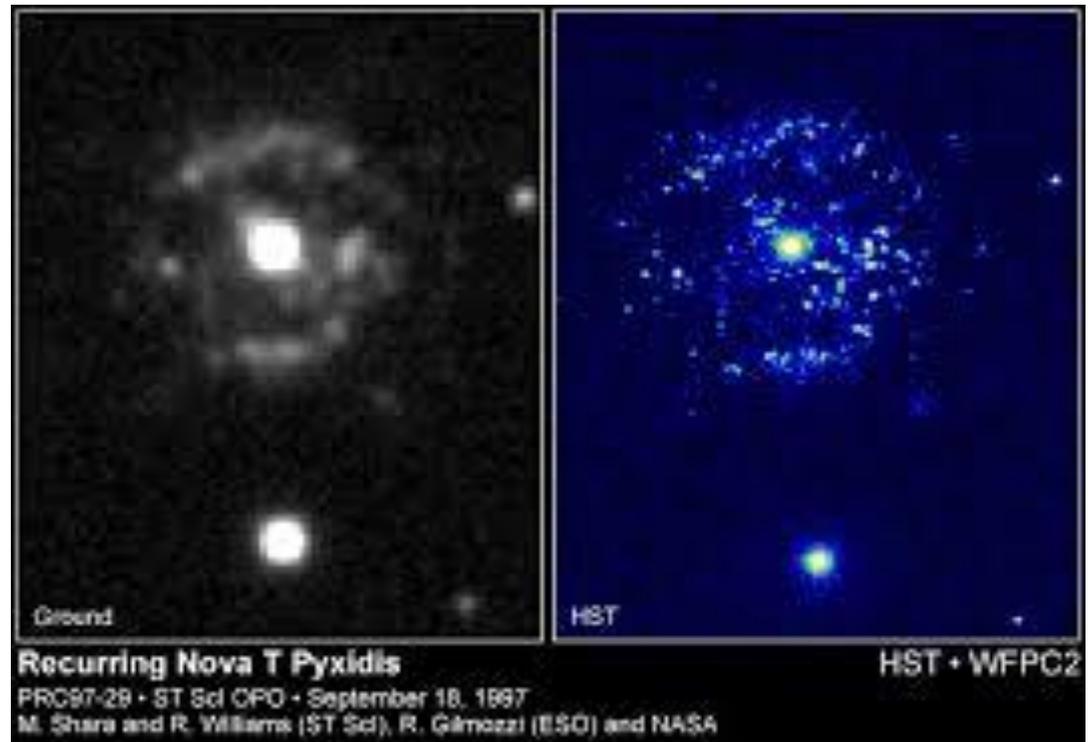
Photo-ionization

Rapid variability

Time domain

Proper motions of knots

Narrow band nebular filters needed



Summary of ways in which COR applications differ from exoplanet investigations

- In many cases the bright central object needing to be suppressed is not a point source.
- Contrasts as deep as 10^{-9} are not needed.
- The central objects will generally be much fainter than exoplanet host stars.
- In many cases the faint structures of interest emit in 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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