A Random Selection of Topics on Interferometry

Extragalactic Science with SIM
Very Deep Visible Nulling Interferometry

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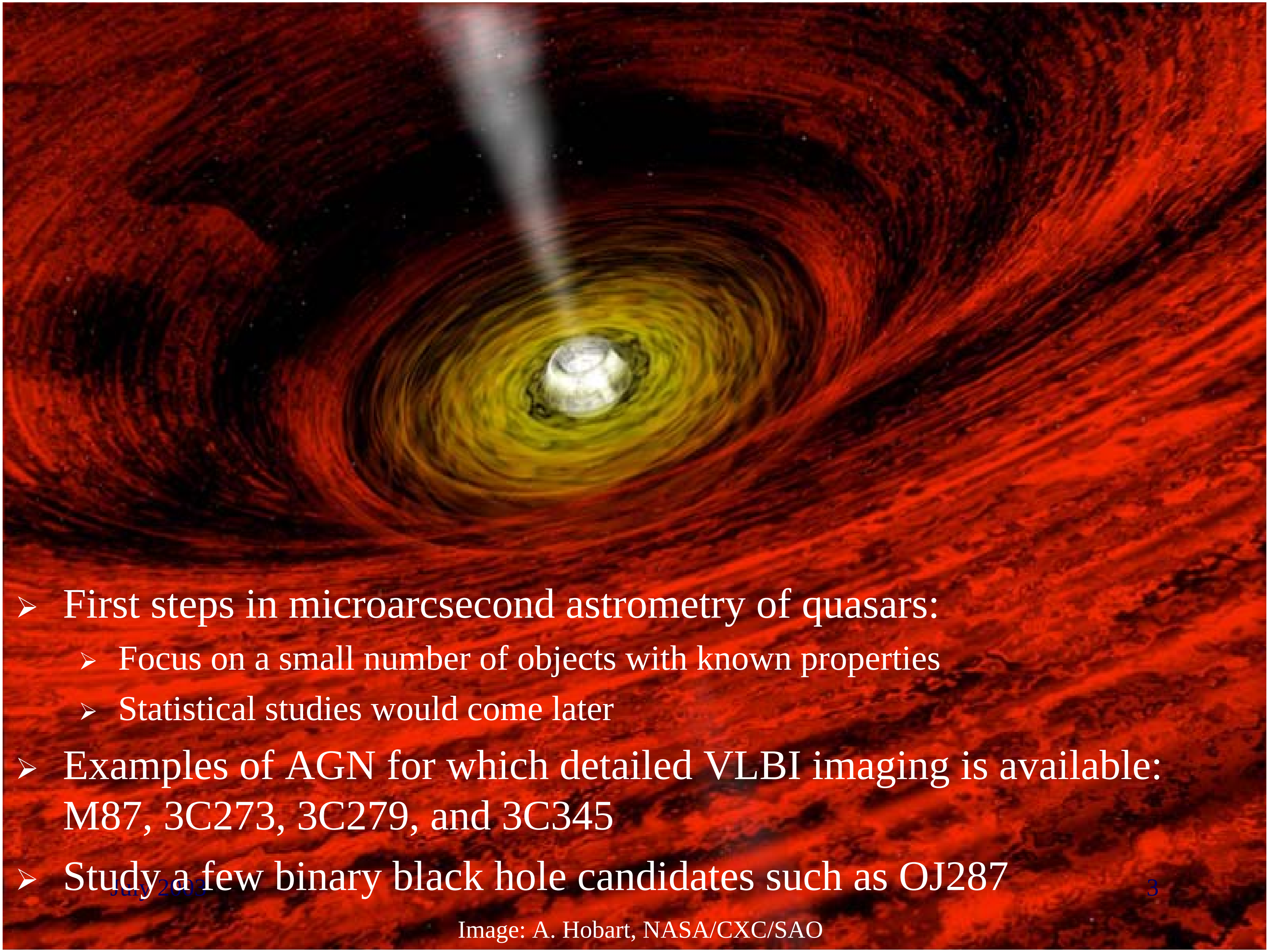
Interferometry Summer School 2003

Understanding the fundamental AGN power source A. Werhle PI

- We are generally comfortable with the basic framework, in which massive black holes power the AGN phenomenon, but:
  - How are galaxy mergers related to the AGN phenomenon?
  - Are binary black holes (resulting from mergers?) common?

- We also think that accretion onto massive black holes fuels the energetic AGN phenomena, but:
  - What are the sizes and geometric relations between the components of the 'core' region: jets, accretion disk, hot corona ?
  - How much do viewing direction and observational selections affect the picture?



- First steps in microarcsecond astrometry of quasars:
  - Focus on a small number of objects with known properties
  - Statistical studies would come later
- Examples of AGN for which detailed VLBI imaging is available: M87, 3C273, 3C279, and 3C345
- Study a few binary black hole candidates such as OJ287

Image: A. Hobart, NASA/CXC/SAO

Three AGN questions which SIM will address:

1. Does the most compact non-thermal optical emission from an AGN come from an accretion disk or from a relativistic jet?
2. Do the cores of galaxies harbor binary supermassive black holes remaining from galaxy mergers ?
3. Does the separation of the radio core and optical photocenter of the quasars used for the reference frame tie change on the timescales of their photometric variability, or is the separation stable ?

Key Project Strategy

The AGN/Reference Frame *SIM Key Projects* have 3% of SIM observing time

- Monthly observations should yield results within the first year of operation
- Observe a few target-rich ‘tiles’, not a statistical sample
- Validate use of AGNs as reference frame objects

SIM will make 3 kinds of AGN measurements

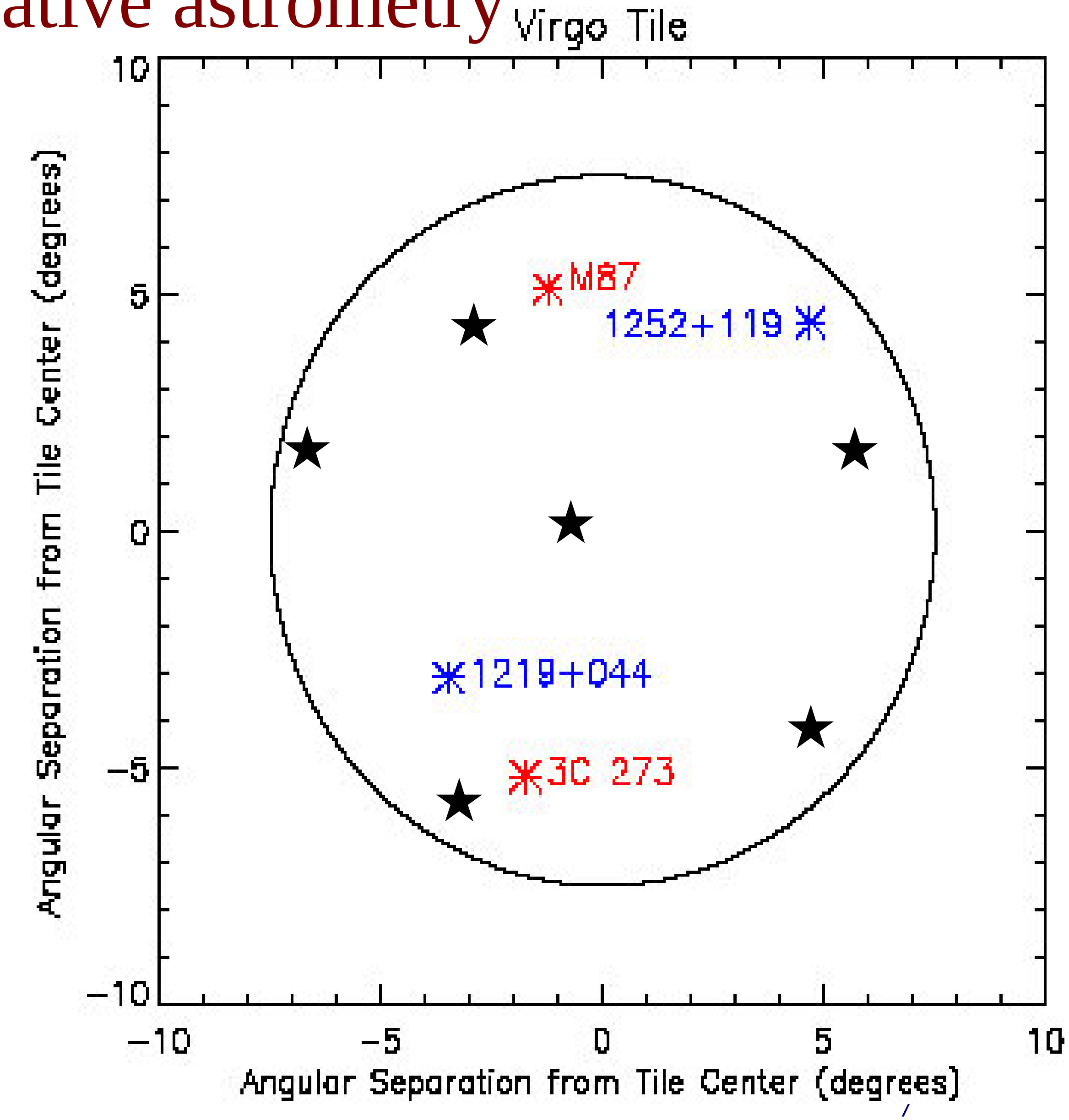
- Relative astrometry between QSO and reference stars (or other QSOs)
  - Narrow-angle observing at ~ few µas (depending on magnitude)
  - Pick selected ‘tiles’ for differential astrometry

- Global astrometry: motion of QSOs relative to global reference frame
  - Frame accuracy is ~ 4 µas
  - Detect QSO motions at about this level
  - Statistical properties of ~50 quasars as part of the grid

- Astrometric shifts as a function of wavelength
  - Directly provide structure information on scales of 10s of µas

Sample ‘tile’ for relative astrometry

- SIM instrument field (‘tile’) is 15□ diameter
- Select tile centers for objects of interest
- ‘Virgo tile’ contains:
    - M87
    - 3C 273
    - Two ICRF quasars
    - 6 - 8 halo K-giants



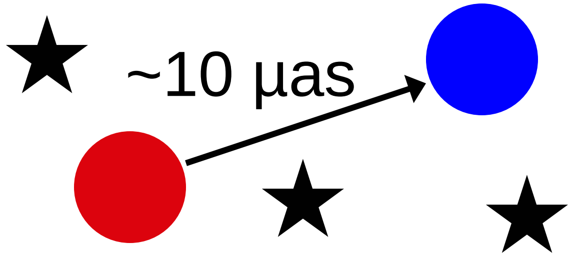
What physical effects would we expect to see with SIM ?

- **Accretion disk** radiates thermal emission with peak in optical-near-UV
  - size: 0.012 pc (=2 lightweeks)
  - ~160 μas diameter at distance of M87
  - *brighter in blue than in red*

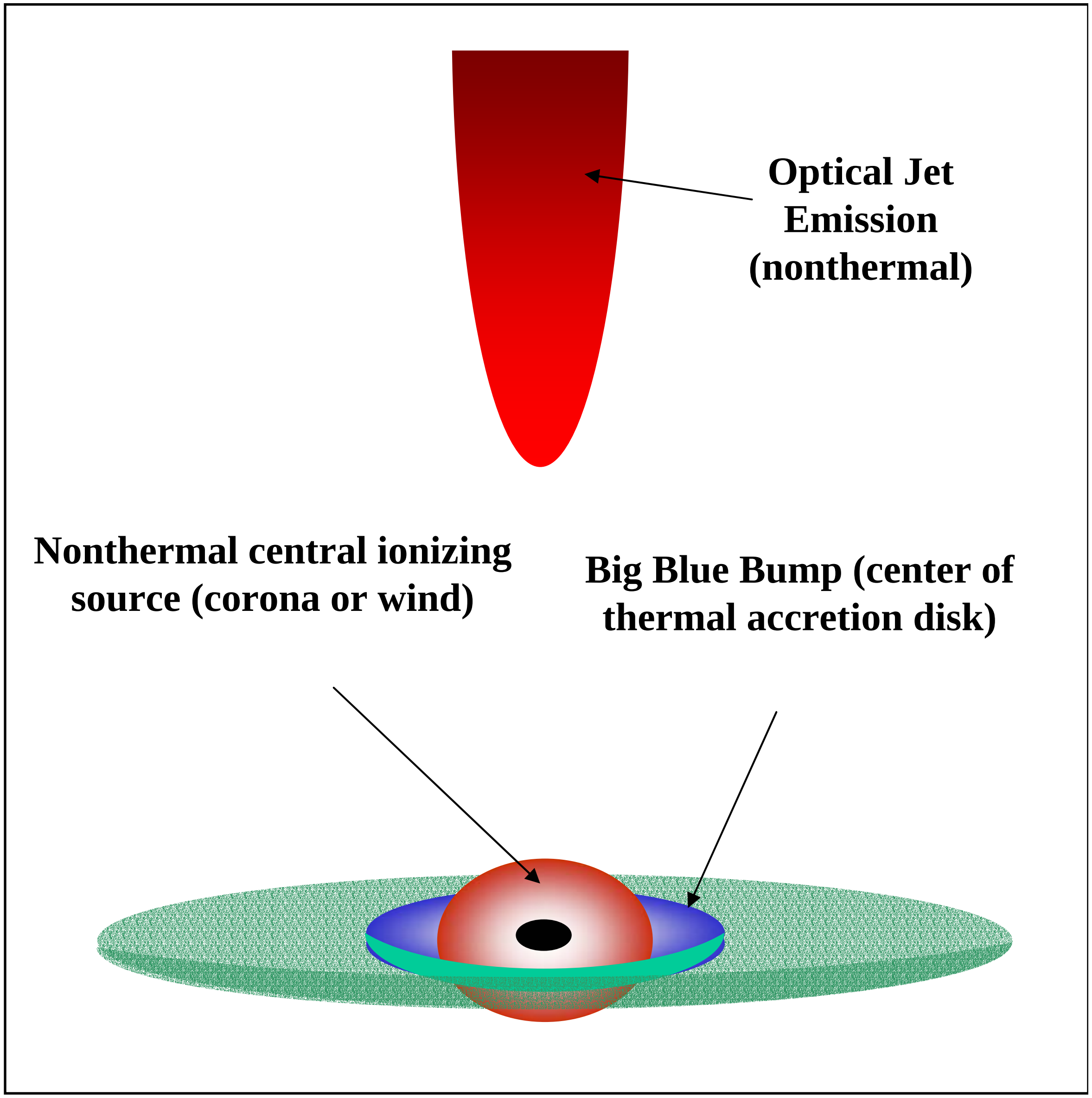
- **Corona** or wind radiates non-thermal emission
  - *brighter in red than in blue*
  - *both red and blue photocenters centered on BH*

- **Relativistic jet** also radiates non-thermal emission.
  - Base of the jets is offset from the core by hundreds of times the diameter of the accretion disk
  - *brighter in red than in blue*
  - *red photocenter offset from blue photocenter in jet direction*

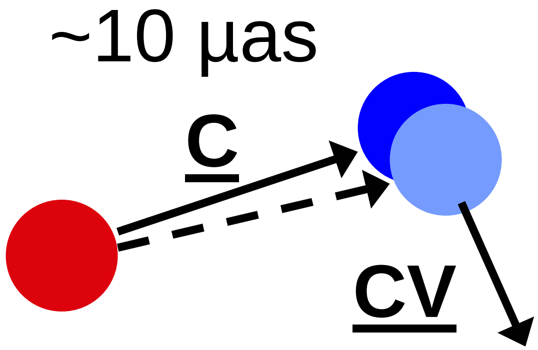
Detecting astrometric variability



- Astrometric signal is a *vector* position shift on the sky
- Shift of ~10 µas should be readily measurable
  - time-variable
  - color-dependent
  - or both



Probing AGN compact emission



Astrometric variability

- SIM measures positions (in 2 orientations) relative to reference stars
- Variability **V** is a vector (in a local frame)

Color shift

- SIM can measure the astrometric shift **C** between red and blue bands
- Color shift does not require use of reference stars
- Variability **CV** in the color shift can also be measured

Color Dependent Differential Astrometry

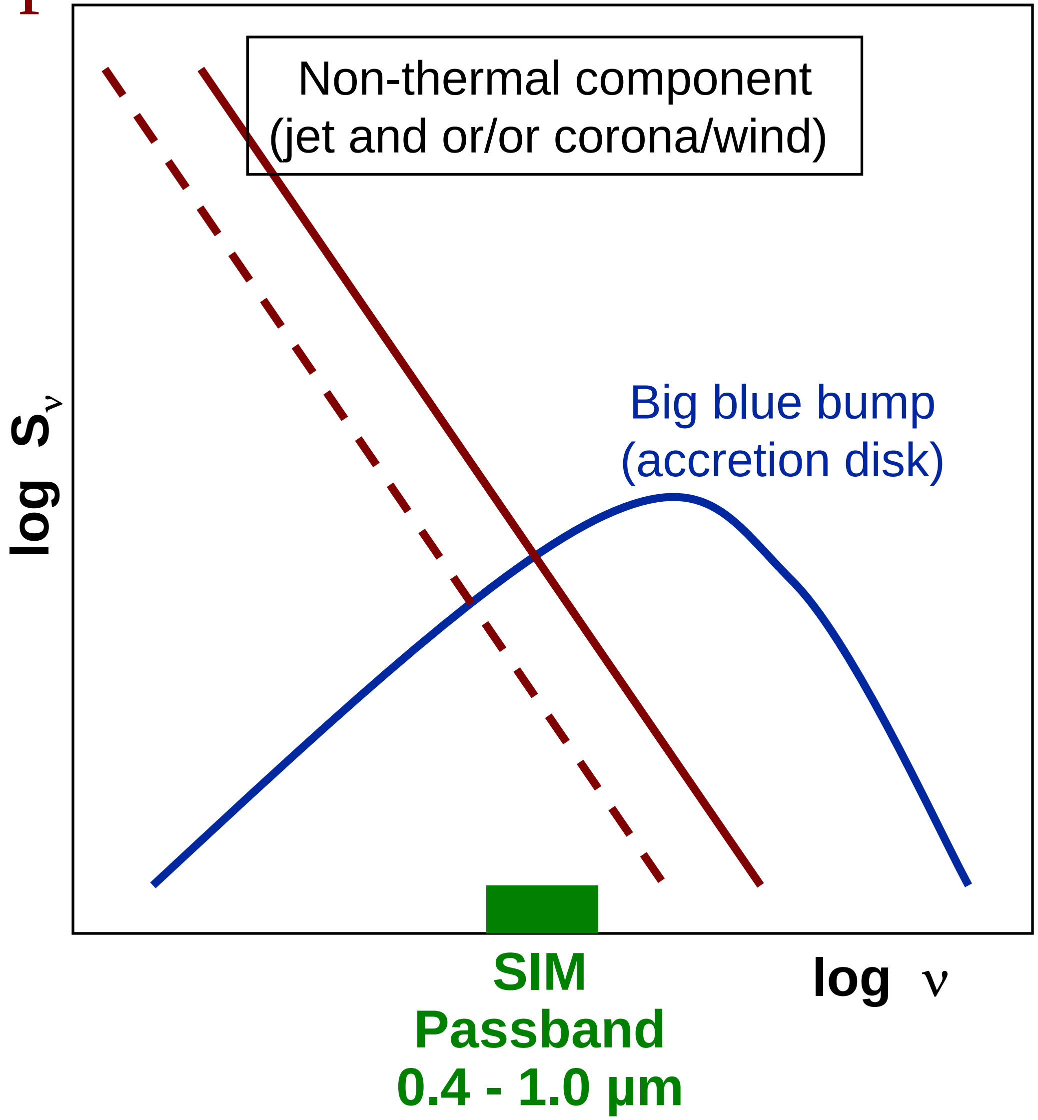
- Measure differential group delay
  - Should be a robust measurement, since it involves only a single target, and does not depend on the absolute value of the group delay
  - Hence, more powerful than group delay itself
  - Same as Keck Interferometer plans for detecting “hot Jupiters”

- Simple experiment: divide the 80 SIM spectral channels into “red” and “blue” groups
  - Average over red and blue groups, find offset from difference in averaged phases
  - Astrometric accuracy reduced by only ~ 4 due to half the photon count and doubling length of white light fringe envelope

- Should be ‘easy’ to detect a shift of 20 μas in a single measurement
  - Shift of 30-100 μas are expected for quasar targets such as 3C 345

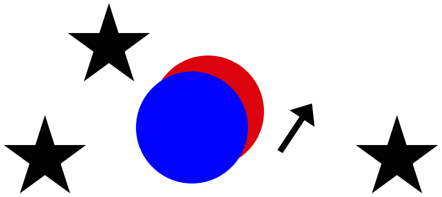
Representative quasar spectrum

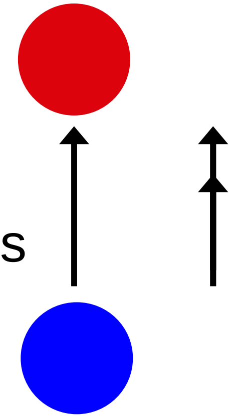
- SIM observes in the optical
- Strongly 'concave' spectrum indicates transition between components



Where does the compact non-thermal emission come from?

Expect no color shift,
(or small shift ~1-5 μas)
with no preferred axis;
no preferred variability direction

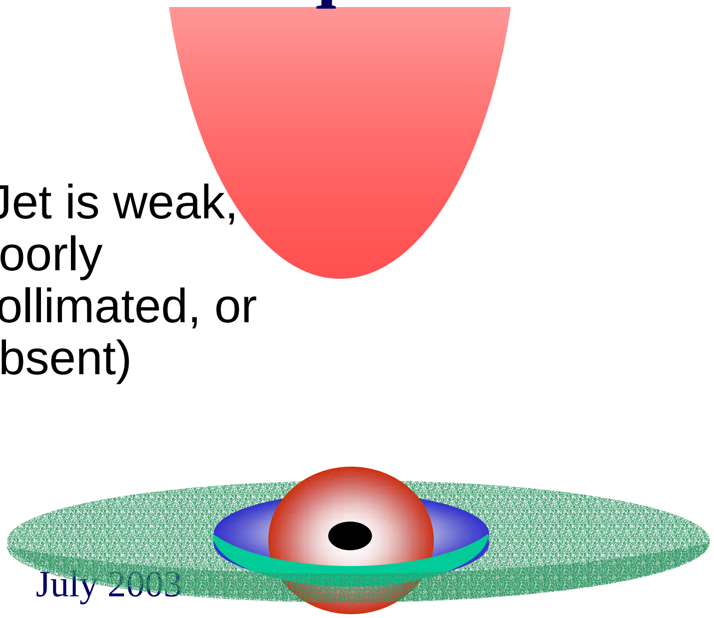




Up to
~100 μas

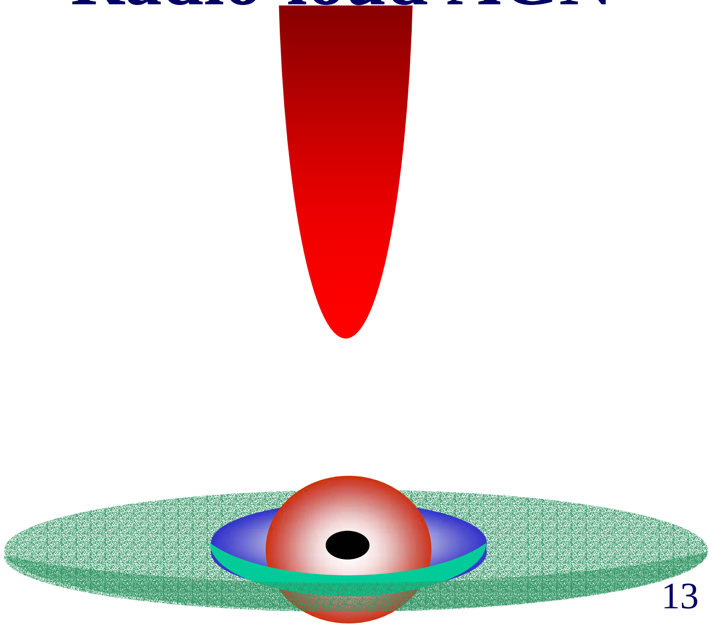
Expected
variability
direction:
along jet

Radio-quiet AGN



(Jet is weak, poorly collimated, or absent)

Radio-loud AGN



Estimating the emission region size

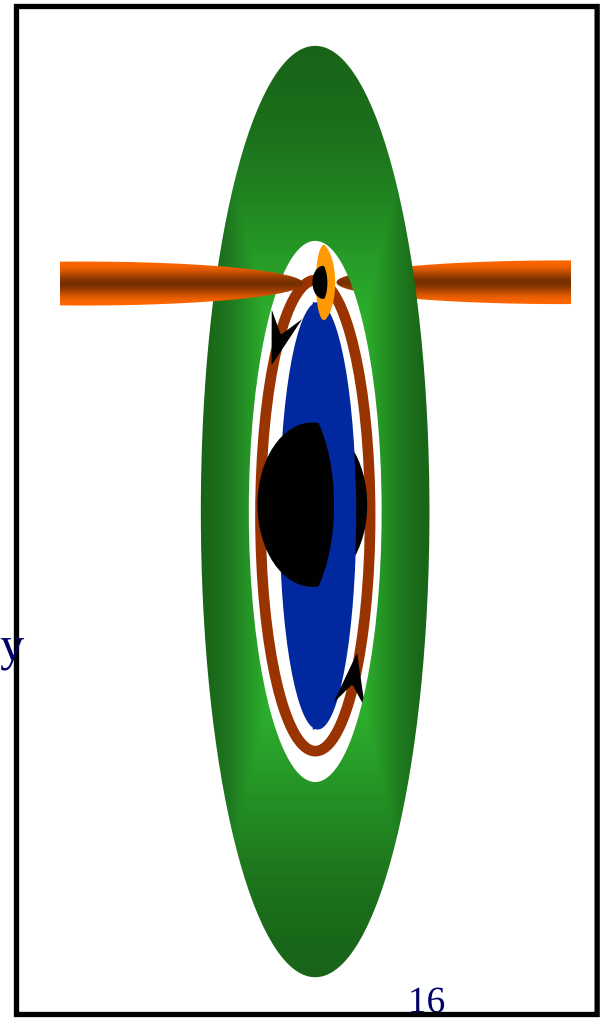
- Accretion disks are small
  - ~ 160 µas (at 15 Mpc - M87)
  - ~ 2 µas (at 3C345 - $z = 0.6$)
- Hot corona region is also small
  - ~ 70 R_s corresponds to ~ 1 µas at $z = 0.6$
- Konigl-type relativistic jet [e.g., Hutter and Mufson 1986]
  - Power-law variation of particle density and magnetic field with radius
  - Spectrum is superposition of emission from all radii
  - Optical-depth variations results in shifts of position with frequency
  - Large size: 100s x size of accretion disk
  - Large shift between radio and optical (>~ 100 µas)

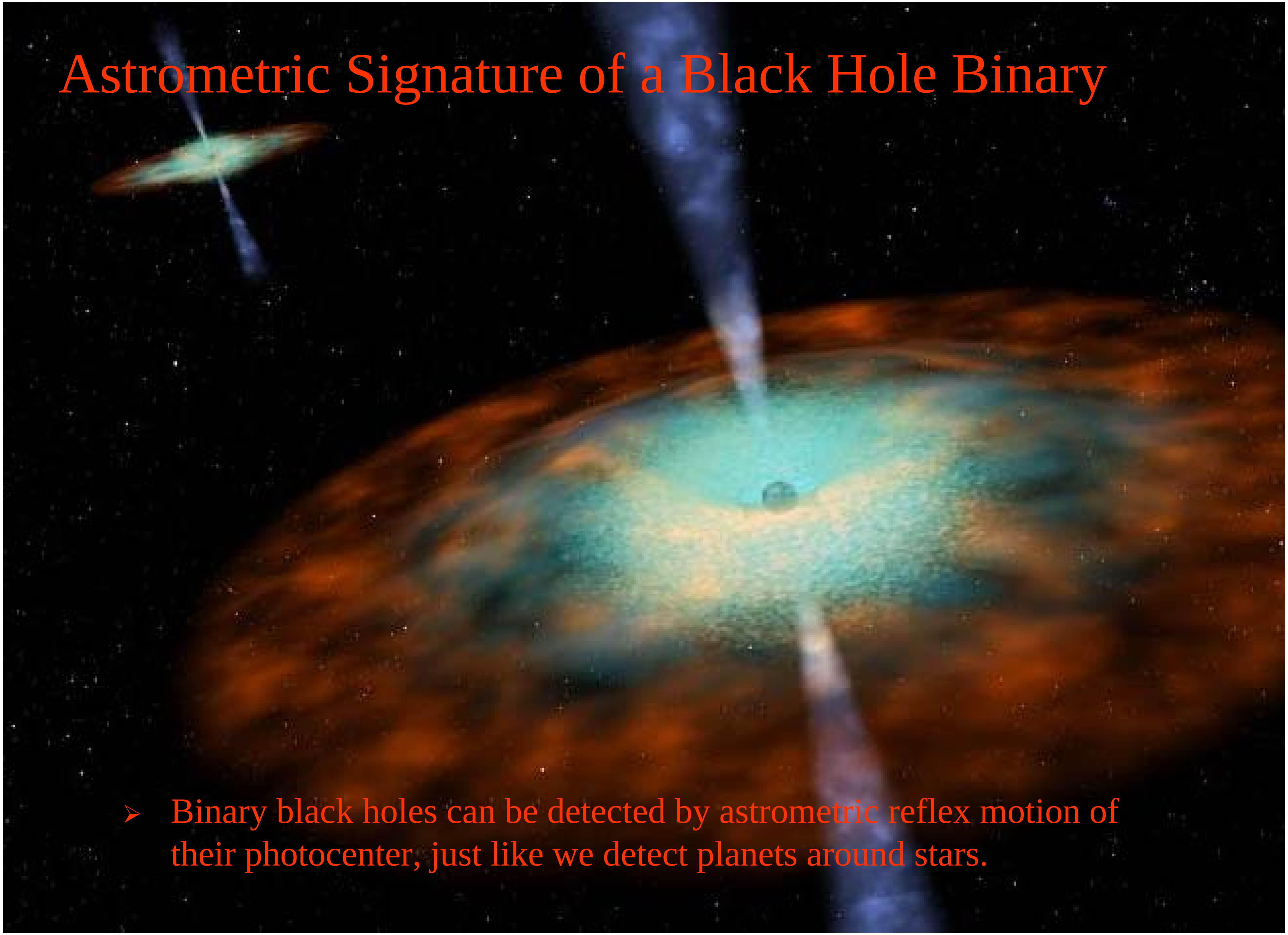
Estimating the magnitude of the jet position shift - (Konigl model)

- **Example: 3C 345** (*z* = 0.6)
  - Offset from BH expected to be ~ 80 µas
  - Photocenter shift from red to blue ~ 20 - 30 µas - in direction of jet
  - Radio peak (22-GHz) offset ~ 100 - 150 µas from BH
- **Example: 1038+528 A,B** (*z* = 0.7, 2.3) [Marcaide & Shapiro 1984]
  - Radio positions shift with (radio) frequency - optical depth effect
    - ~ 0.7 mas shift between 13 and 3.6 cm
  - Extrapolation to optical gives expected shift ~ 0.3 mas
    - Radio positions (ICRF) currently good to 0.3 mas

Astrometric Signature of a Black Hole Binary

- Binary black holes can be detected by astrometric reflex motion of their photocenter, just like we detect planets around stars.
- Size of the effect: an estimate for OJ 287
    - from Lehto & Valtonen (1996)
  - $z = 0.306$
  - P = 12 years
  - Assumed mass ratio ~ 170
  - Semi-major axis ~ 0.06 pc
    - = 22 µas (for $H_0 = 100$)
- Expected motion in 5 years
  - ~ 18 µas and systematic, if emission comes from secondary
  - ~ 0 (or random) if emission comes from primary
- Study statistically for ~ 50 quasars
  - Best candidates are at small redshifts (z <~ 0.5)





Astrometric Signature of a Black Hole Binary

- Binary black holes can be detected by astrometric reflex motion of their photocenter, just like we detect planets around stars.

Reference Frame Tie - two requirements

(1) SIM needs a *non-rotating frame* (for Galactic structure studies)

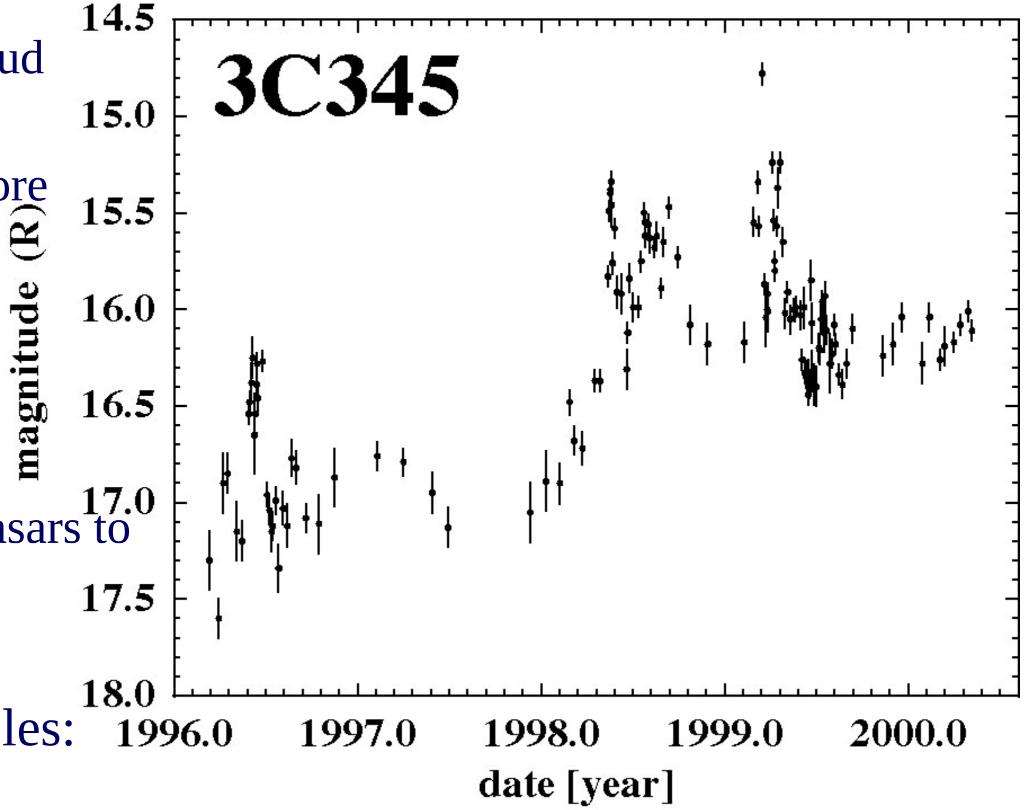
- We don't *have to* select radio-loud quasars
- Maybe radio-quiet quasars are more suitable?

(2) Need to reference to the ICRF

- internationally recognized
- Need radio and optically loud quasars to tie SIM to the ICRF

Could pick two different quasar samples:

- *radio-loud*
- *radio-quiet*
  - not yet a solved problem



- Probably a poor choice for reference frame tie object !

Current and Future Work

- Identify more potential ICRF quasars in “target-rich” tiles such as those centered on M87 or 3C345
- Identify more supermassive binary black-hole candidate systems
- Begin VLBI phase referencing experiments on M87 or other AGN to see if the core is moving with respect to nearby ICRF sources
- Evaluate historical optical variability of ICRF and astrophysically interesting AGN to establish timescale and magnitude of variability
- Coordinate with collaborators on the SIM Key Project led by Ken Johnston to find common targets, especially in the southern hemisphere
- Develop color-dependent differential astrometry techniques with current ground-based optical interferometers

SIM Science Overview

- Planet Finding is a core goal for Origins
  - SIM astrometry complements other methods of planet detection
    - Determines mass, the most fundamental parameter of a planet
    - Is more sensitive than Radial Velocity (3 vs 30 M_{Earth}) with no sin(inclination) ambiguity
  - SIM targets stars within 25 pc that are suitable for follow-up by TPF
- SIM will determine the architecture of solar systems, telling us whether our solar system is rare or common
- At no extra hardware cost, SIM carries out an exciting program of fundamental galactic and extragalactic astrophysics
  - A key parameter for all Milky Way objects observed by HST, Chandra, SIRTF, JWST, GALEX, etc is an accurate distance from the Earth
    - A distance turns a flux into a luminosity or an angular motion into a physical motion
    - SIM turns phenomenology into physics
  - 10 μas wide angle astrometry gives 1% distances to any object in the galaxy and 10% proper motions in the local group of galaxies

SIM Will Make Definitive Planet Census

What We *Don't* Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - Only astrometry measures planet masses unambiguously
- Are there low-mass planets in 'habitable zone' ?

A Deep Search for Earths

- ➢ Are there Earth-like (rocky) planets orbiting the nearest stars?
- ➢ Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- ➢ Sensitivity limit of ~3 M_e at 10 pc requires 1 μas accuracy

A Broad Survey for Planets

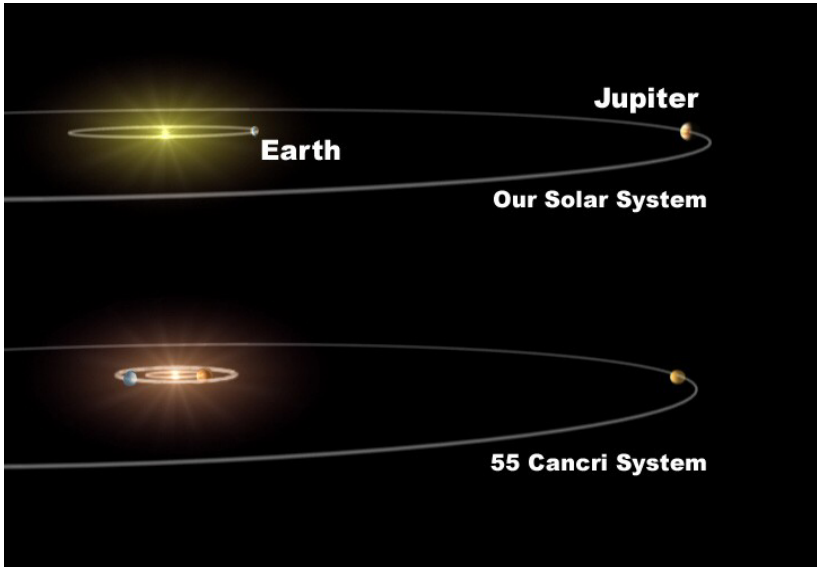
- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2000 stars within ~25 pc at 4 μas accuracy

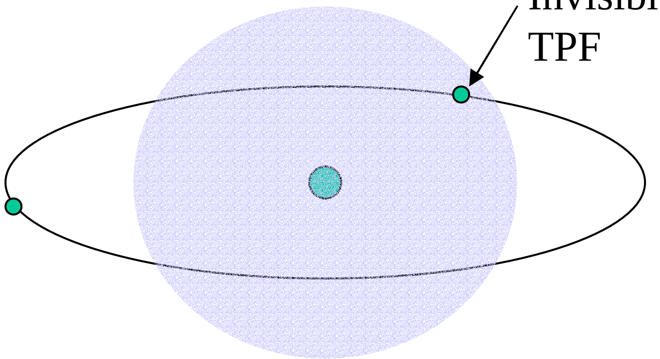
Evolution of Planets

- ➢ How do systems evolve?
- ➢ Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- ➢ Do multiple Jupiters form and only a few (or none) survive?

SIM Complements an Paves The Way for TPF

- SIM will tell TPF what stars are likely to be hospitable to terrestrial planets
  - Presence of Jovian planets in the wrong orbits will preclude stable orbits in the habitable zone
- SIM's orbital information will determine when planets in eccentric/inclined orbits will be at an elongation suitable for direct detection. (avoid false negatives)
- Combination of SIM masses with TPF spectroscopy of hundreds of planets will lead to new era in comparative planetology
- For stars where SIM doesn't detect a planet, and subsequently, TPF does detect a planet, SIM archival data can determine or constrain the mass of that planet with ~0.5 Earth mass accuracy.

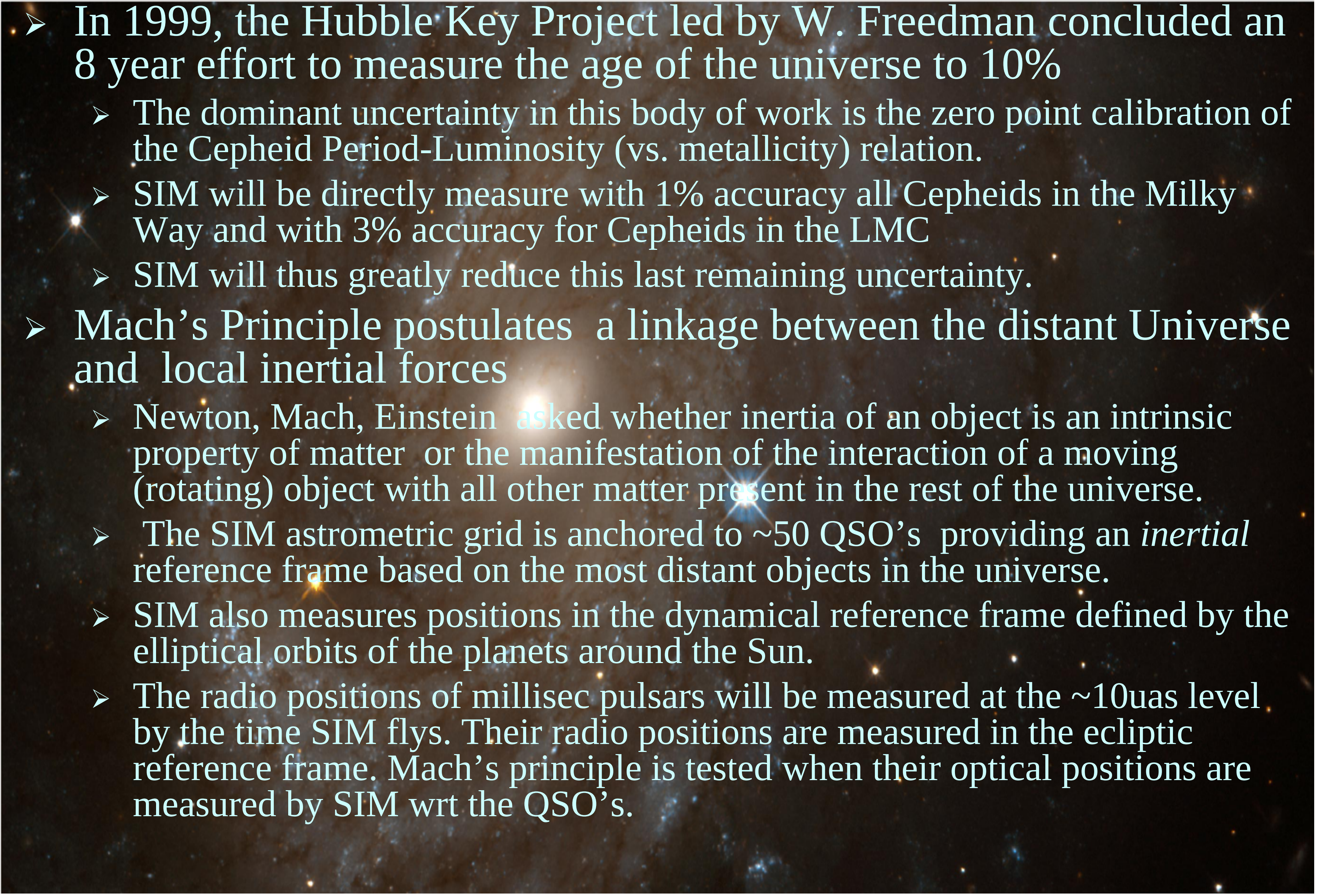




TPF inner working R

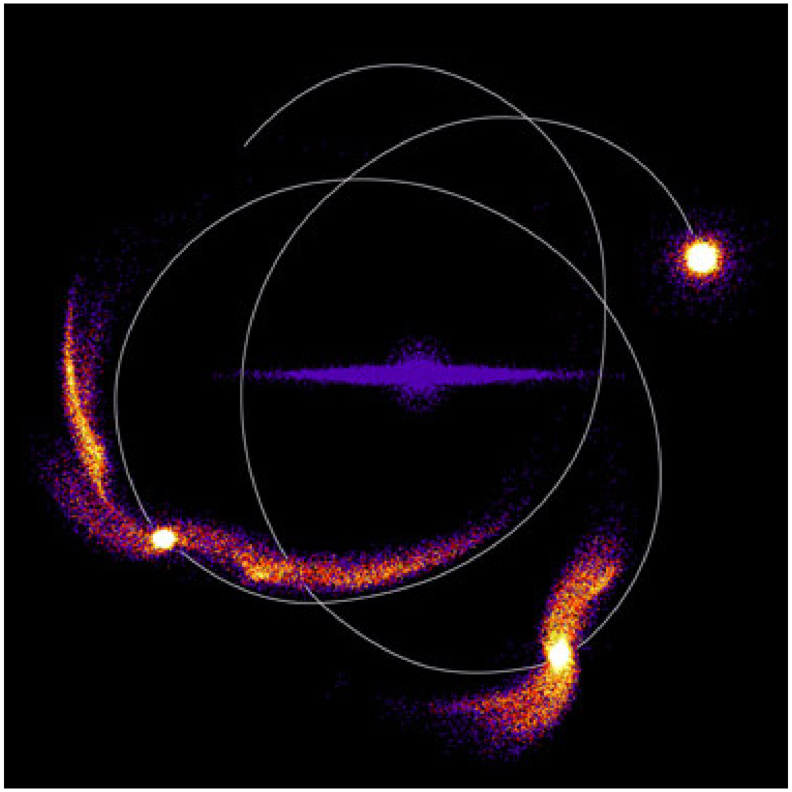
False Positives and
False Negatives.

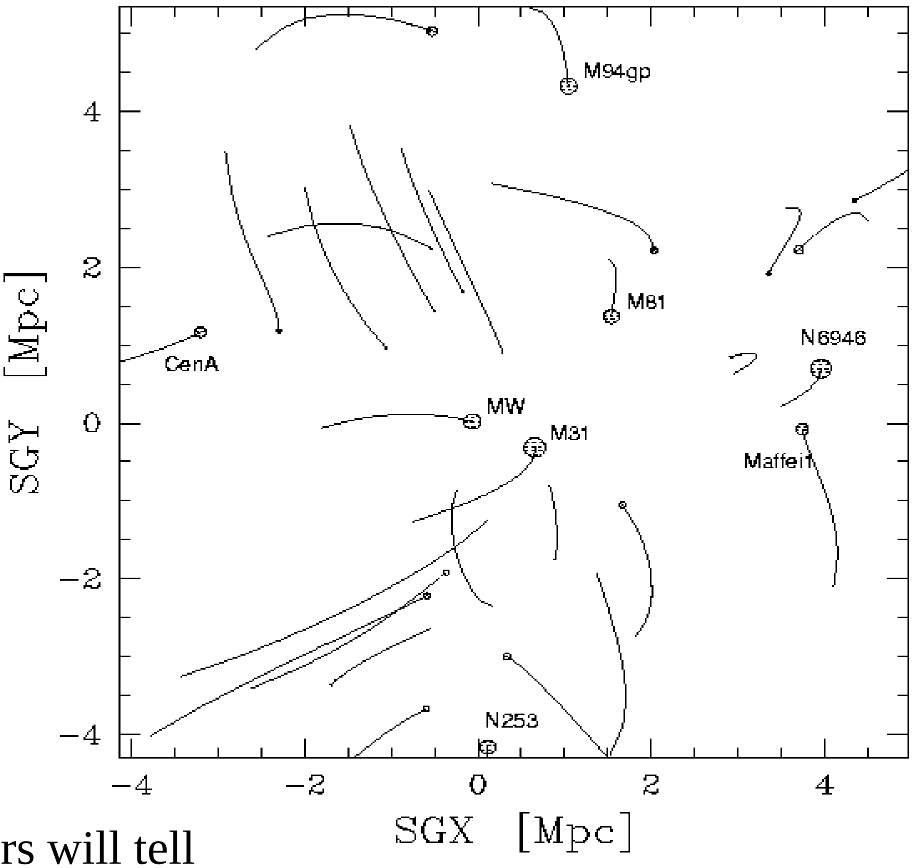
Cosmic Distance Scale and Mach’s Principle



- In 1999, the Hubble Key Project led by W. Freedman concluded an 8 year effort to measure the age of the universe to 10%
  - The dominant uncertainty in this body of work is the zero point calibration of the Cepheid Period-Luminosity (vs. metallicity) relation.
  - SIM will be directly measure with 1% accuracy all Cepheids in the Milky Way and with 3% accuracy for Cepheids in the LMC
  - SIM will thus greatly reduce this last remaining uncertainty.
- Mach’s Principle postulates a linkage between the distant Universe and local inertial forces
  - Newton, Mach, Einstein asked whether inertia of an object is an intrinsic property of matter or the manifestation of the interaction of a moving (rotating) object with all other matter present in the rest of the universe.
  - The SIM astrometric grid is anchored to ~50 QSO’s providing an *inertial* reference frame based on the most distant objects in the universe.
  - SIM also measures positions in the dynamical reference frame defined by the elliptical orbits of the planets around the Sun.
  - The radio positions of millisec pulsars will be measured at the ~10uas level by the time SIM flys. Their radio positions are measured in the ecliptic reference frame. Mach’s principle is tested when their optical positions are measured by SIM wrt the QSO’s.

Dark Matter: In the Disk, in the Halo and Between Galaxies





- SIM observations of the motions of stars will tell us about the distribution of all gravitating mass (light plus dark matter) in the Galaxy
- SIM observations of the motions of dwarf galaxies around our own will determine will determine the mass distribution (light plus dark matter) in the Halo.

SIM will measure the proper motion of ~28 nearby galaxies get the distribution of matter in the local group

V^2 Measurements near V~1

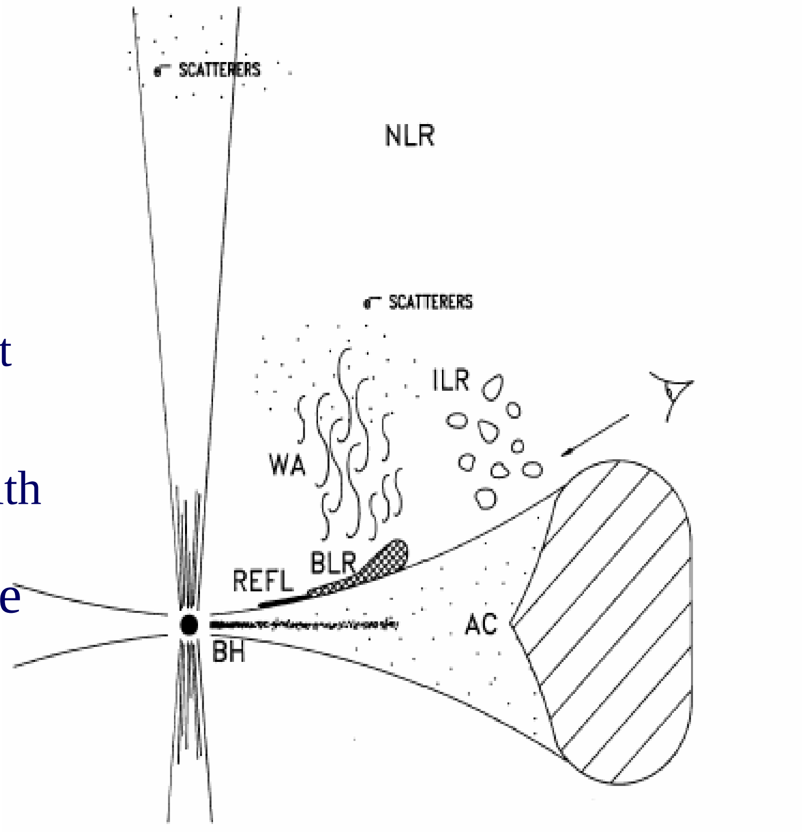
- The space environment makes possible very accurate V^2 measurements. For a mission like SIM, the major limitation is the spacecraft itself.
- Effects that lower V^2
  - Static wavefront error
  - Beam splitter 50/50 (S & P)
  - Tip/tilt static error
  - Non-zero OPD (not important for SIM)
  - Tilt jitter [20 mas (+/- 10%?)]
  - OPD jitter [10 nm (+/- 10%?)]
  - On SIM one might be able to estimate jitter (using the guide interferometers) to better than 10%.
  - 0.12 mas radius disk has 0.998 V^2

Can be Calibrated

~0.2%

AGN Accretion Disks

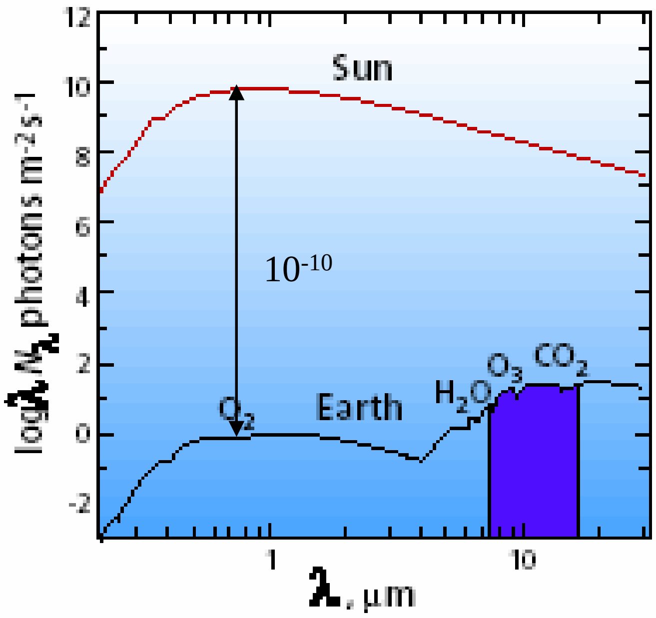
- Even though SIM is no longer optimized for general imaging, SIM has advantages for studying AGN and other very compact objects
  - Accurate visibility measurements in space
  - Wavelength range 0.45~0.9 um.
  - Broad wavelength coverage and 180 deg baseline rotation for improved uv-plane coverage (to measure disk geometry)
  - Spectroscopic imaging to give the apparent diameter of the disk at ~80 temperature zones and a channel centered on OIII emission of the BLR to locate the BLR with respect to the accretion disk
- The brighter AGN's are ~11 mag far above the 20 mag limit for SIM.
  - SIM could probe many AGN's in this manner

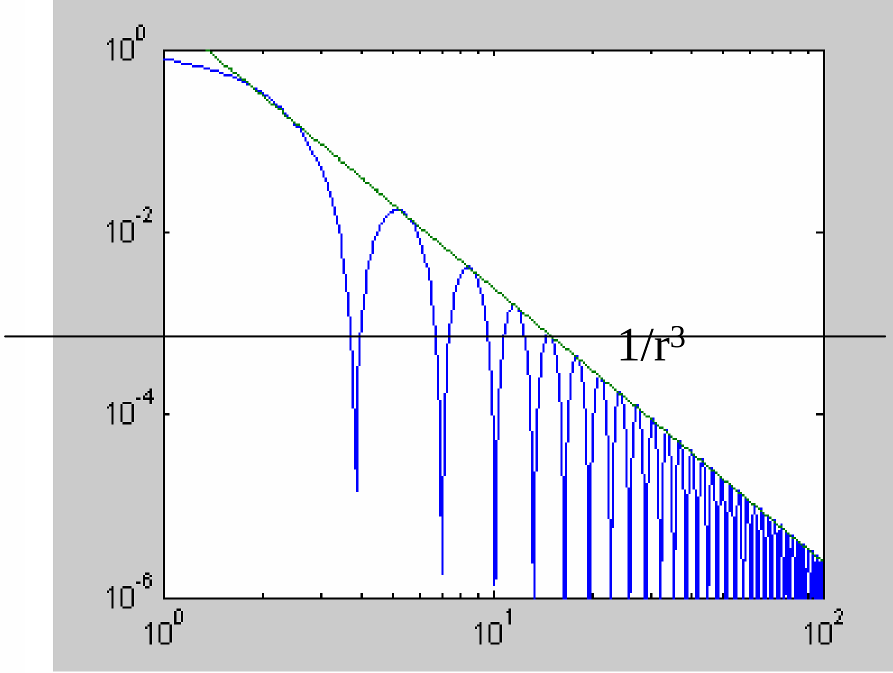


Very Accurate V^2 to Very Deep Nulls

- A small effort aimed at interferometric direct detection of Planets in the visible. (K. Wallace, B. Lane, B. Levine, G. Serabyn, B. Mennesson, M. Shao)
- The technical issues in making very accurate V^2 measurements are very similar (identical?) to obtaining very deep nulls.

TPF Problem



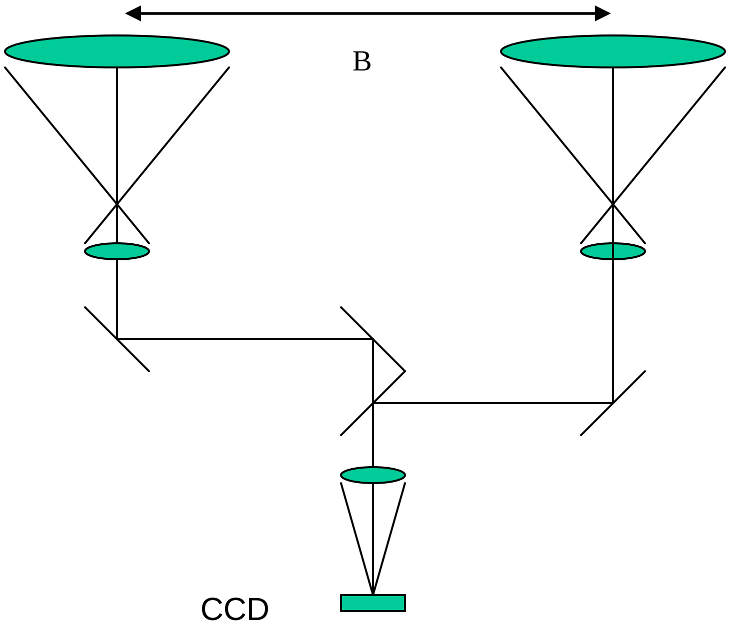

Airy function (log-log)

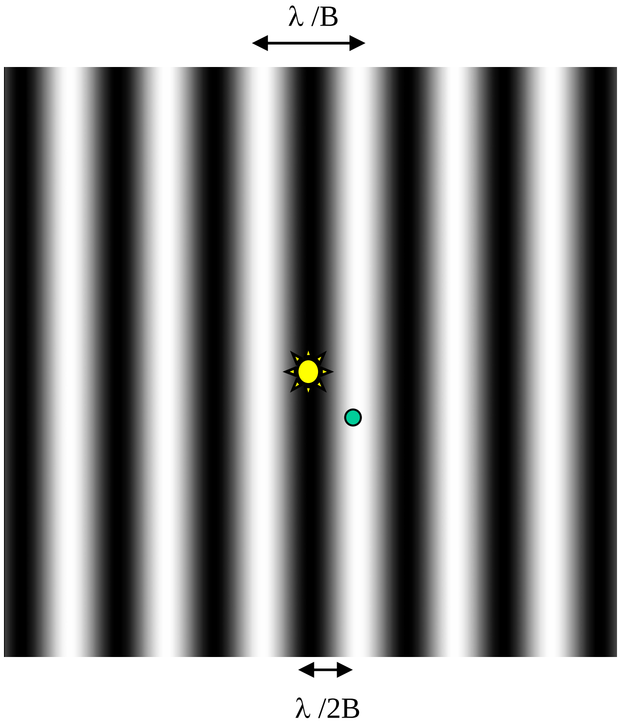
Typically 3~4 airy rings out, a diffraction limited telescope's PSF is down by ~10^{-3}, so one needs to suppress diffracted light by ~ 10^{-7}.

The ability to almost totally suppress diffracted light implies an almost perfect optical system, one with 99.999,99% strehl. (or for an interferometer a system visibility of 99.999,99%)

I Control of Diffracted light, small inner working distance
II Control of scattered light

Nulling Introduction





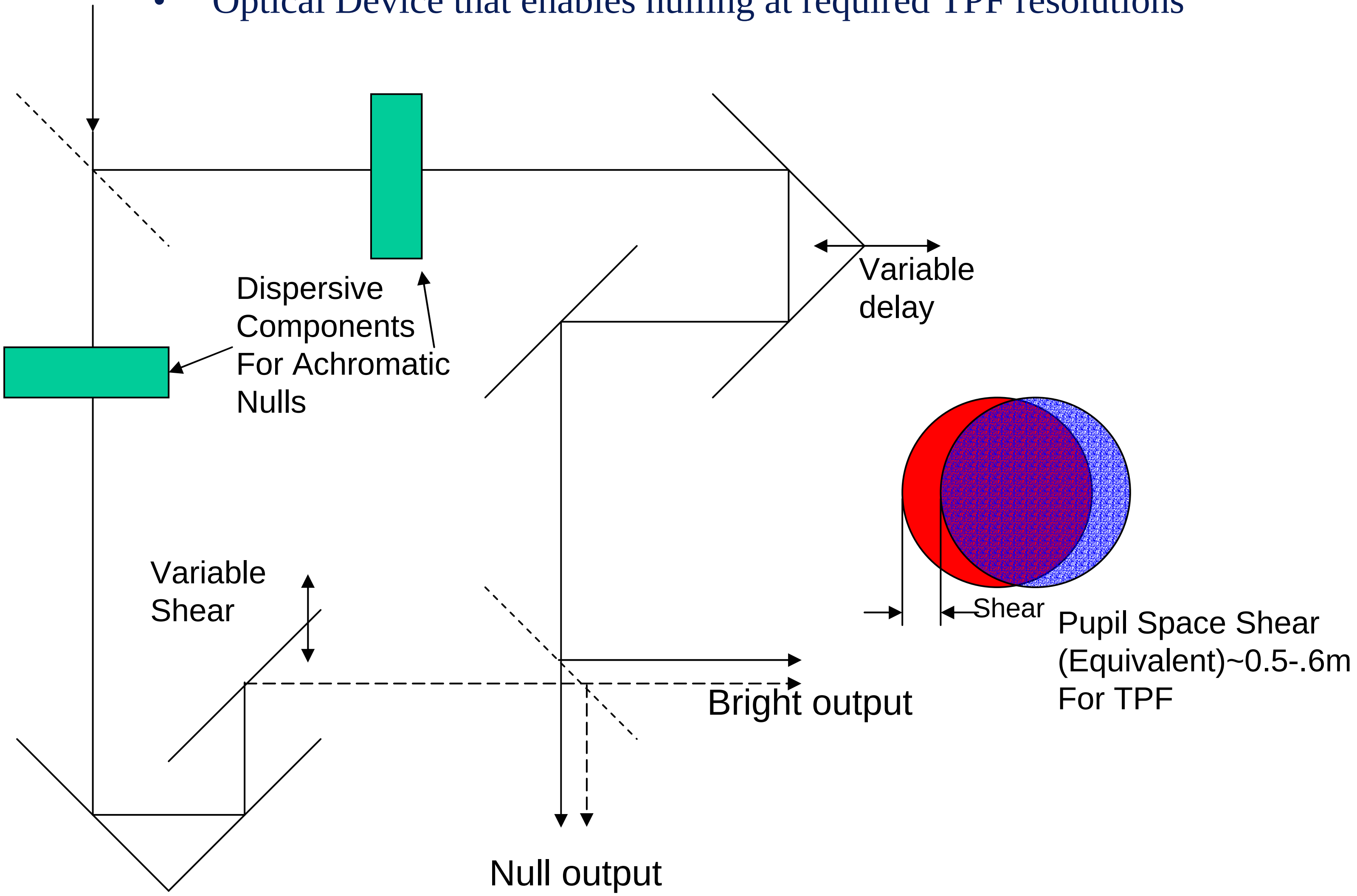
Transmission Pattern of Nuller
On the sky. (Star is at the center)

In a simple 2 element nulling interferometer, we want λ/b to resolve the star-planet separation. In the thermal IR λ ~10um, B >10m

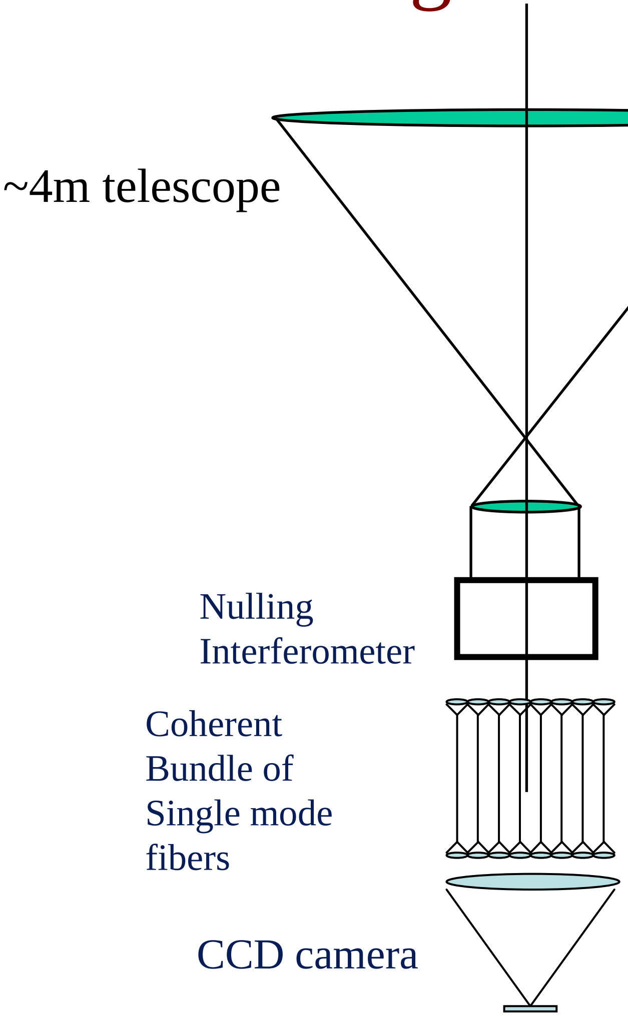
In the visible λ~0.5um, B>50 cm. The baseline is so short, it’s less than the diameter of the telescope needed to collect photons to detect an Earth.

Modified Mach-Zender Interferometer

- Optical Device that enables nulling at required TPF resolutions



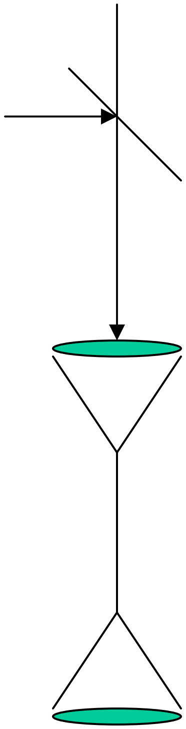
Visible Nulling Coronagraph



Deep nulls (10^{-7}) imply very high system visibility, which is possible only with the use of single mode fibers.

The coherent bundle of single mode fibers is a way to obtain a large imaging field of view, while keeping the advantage of single mode fibers.

High Visibilities (deep nulls) with single mode fibers



At visible λ, 10^{-7} null
Implies $\Delta\phi \sim \lambda/15{,}000$
Intensity match ~0.04%

Without the fiber, the
Two interfering wavefronts
Can only differ by a very
Small 0.5 angstroms rms

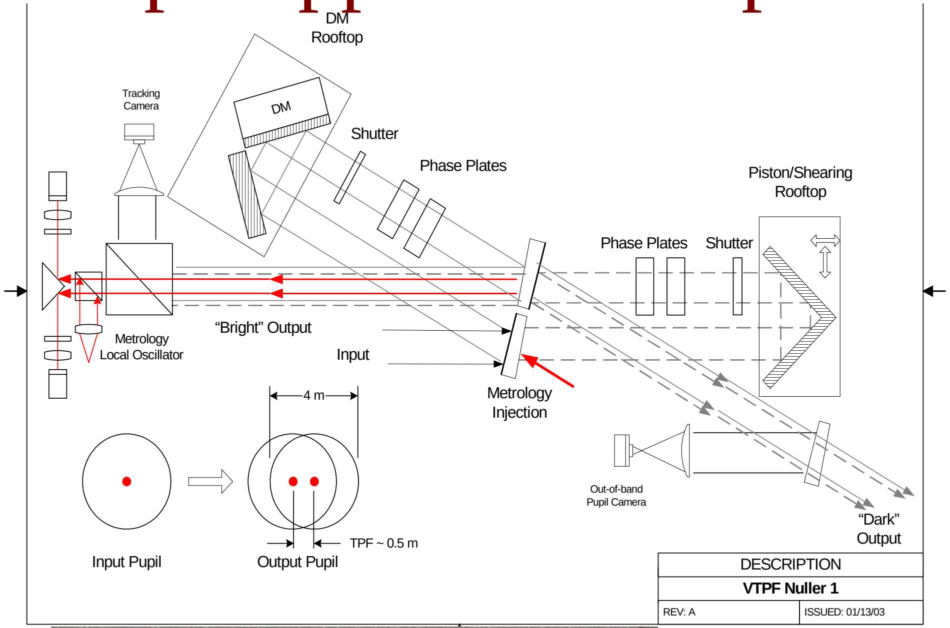
But inside the fiber we
have only two variables
to control, phase/amplitude

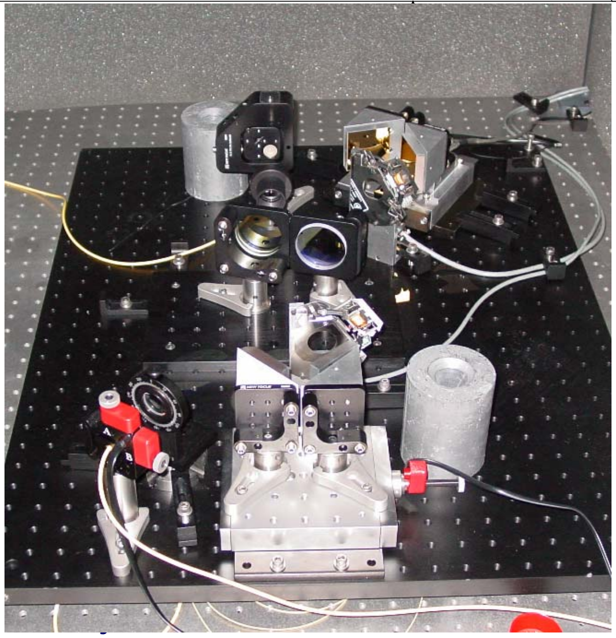
- The nulling interferometer /coronagrah, has a ~ 1000 element deformable mirror, one DM element for each fiber to control phase and amplitude.

- Each fiber has a field of view of λ/d, d is the subaperture dia.
- The field of view of the fiber array is ~ 1000 airy spots (area) 32*32.

- Null leakage: If each fiber has 10^{-7} starlight leakage, then in the image plane (1000 airy spots) the average starlight leakage is ~ 10^{-10}/airy spot

Deep Suppression Experiment





Residual leakage ~7x10^{-9} due to 3~4 angstrom vibration

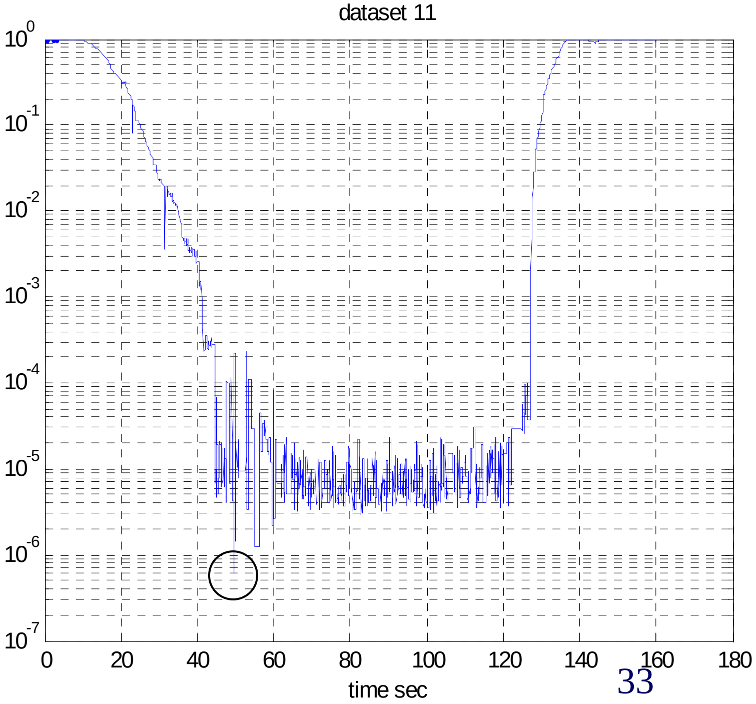
Transient null ~6x10^{-10}/airy spot.

Improvement will need quieter setup and vacuum.

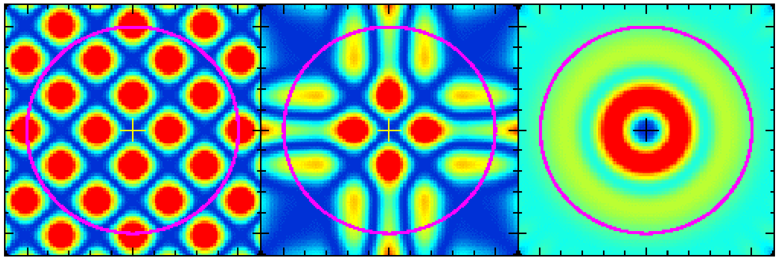
10^{-6}/airy spot

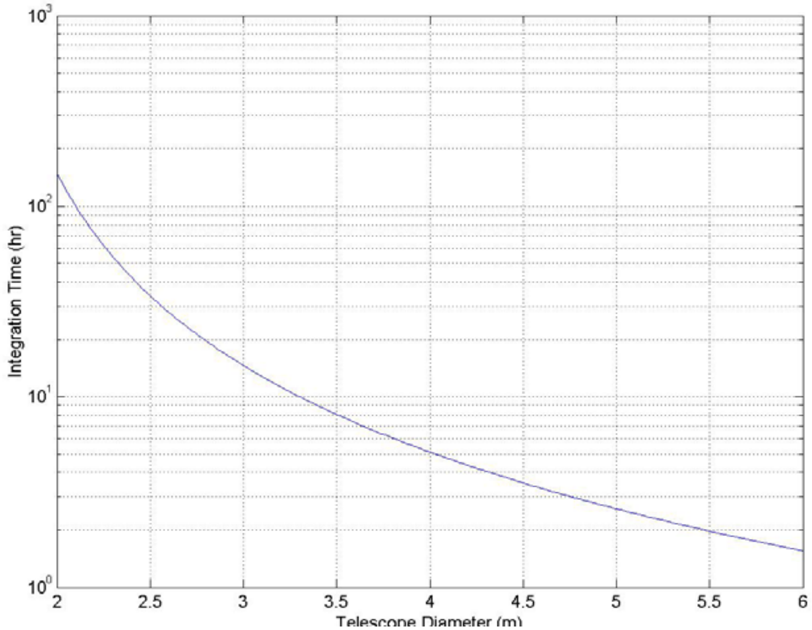
10^{-8}/airy spot

10^{-10}/airy spot



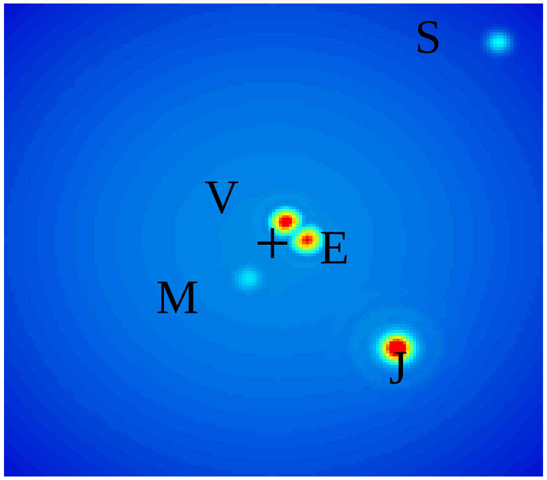
Simulated Image of Solar System





Solar system at 10pc

SNR=5 on Earth in 5.1 hrs
SNR=10 on each of 20 spectral
Channels in 200 hrs



Simulation of 4m nulling interferometer
(60cm shear) image after rotation.

Summary

- Ground based interferometers have traditionally been called stellar interferometers. Because their science focus has been stellar astrophysics. (radio arrays aren't called stellar interferometers)
- As the sensitivity, and accuracy (V^2, astrometry, nulling etc.) of interferometers improve the areas in astrophysics that can benefit from high spatial resolution will grow.
- Large ground based interferometers like Keck-I and VLTI are the first wave of these instruments, and the first generation of space interferometer is "relatively speaking" not that far away.