# Ground-Based IR Astronomy:

## Past Milestones & Future Directions

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# IR Astronomy: The Early Years

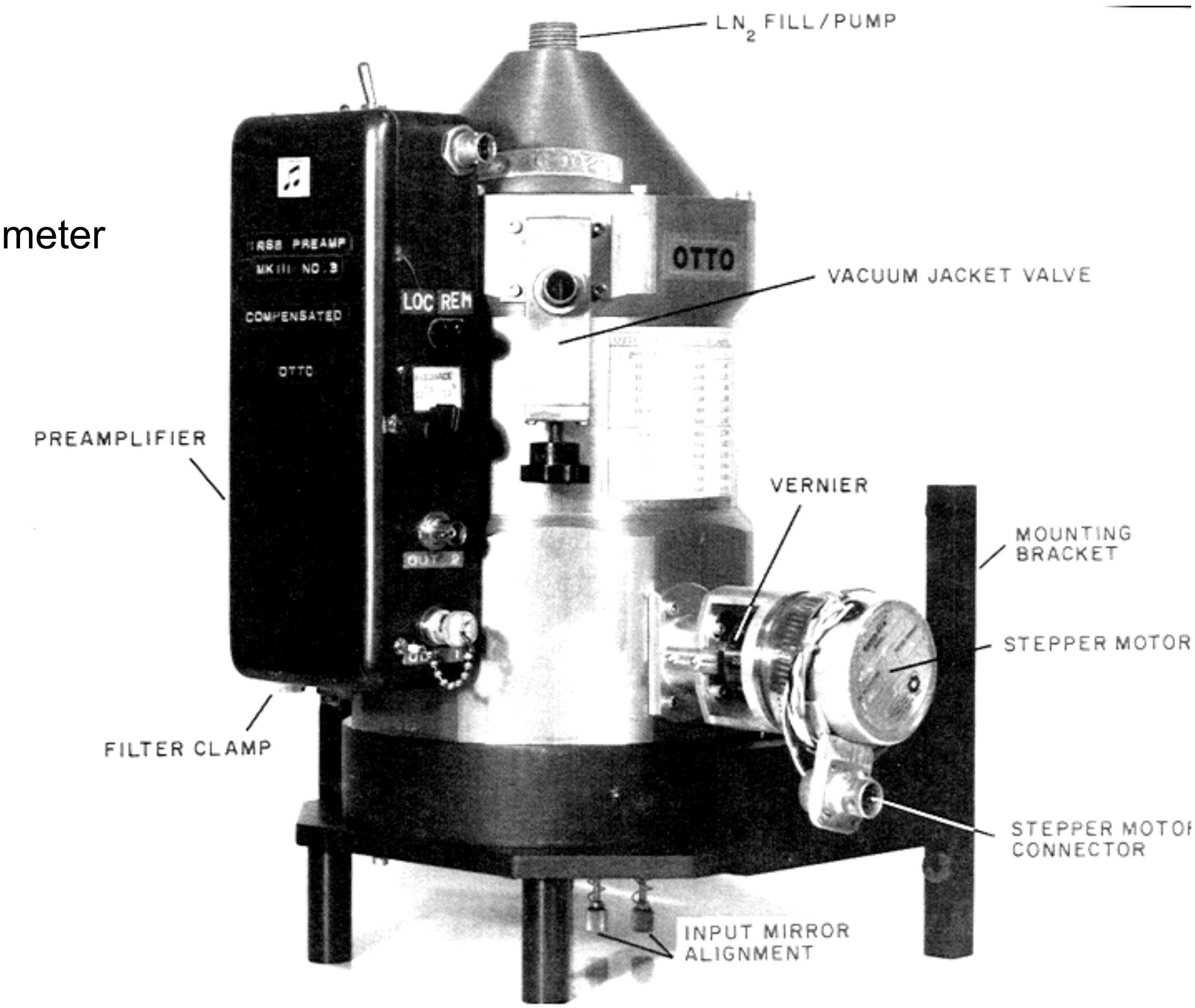
- Initial instruments limited in:
  - Sensitivity
  - Spatial resolution
  - Multiplexing
  - Spectral Resolution

# Sensitivity

- PbS detectors and Ge bolometers
- Moderate size telescopes (1m - 2m)
- Typical limits: K < 8 mag; N < 5

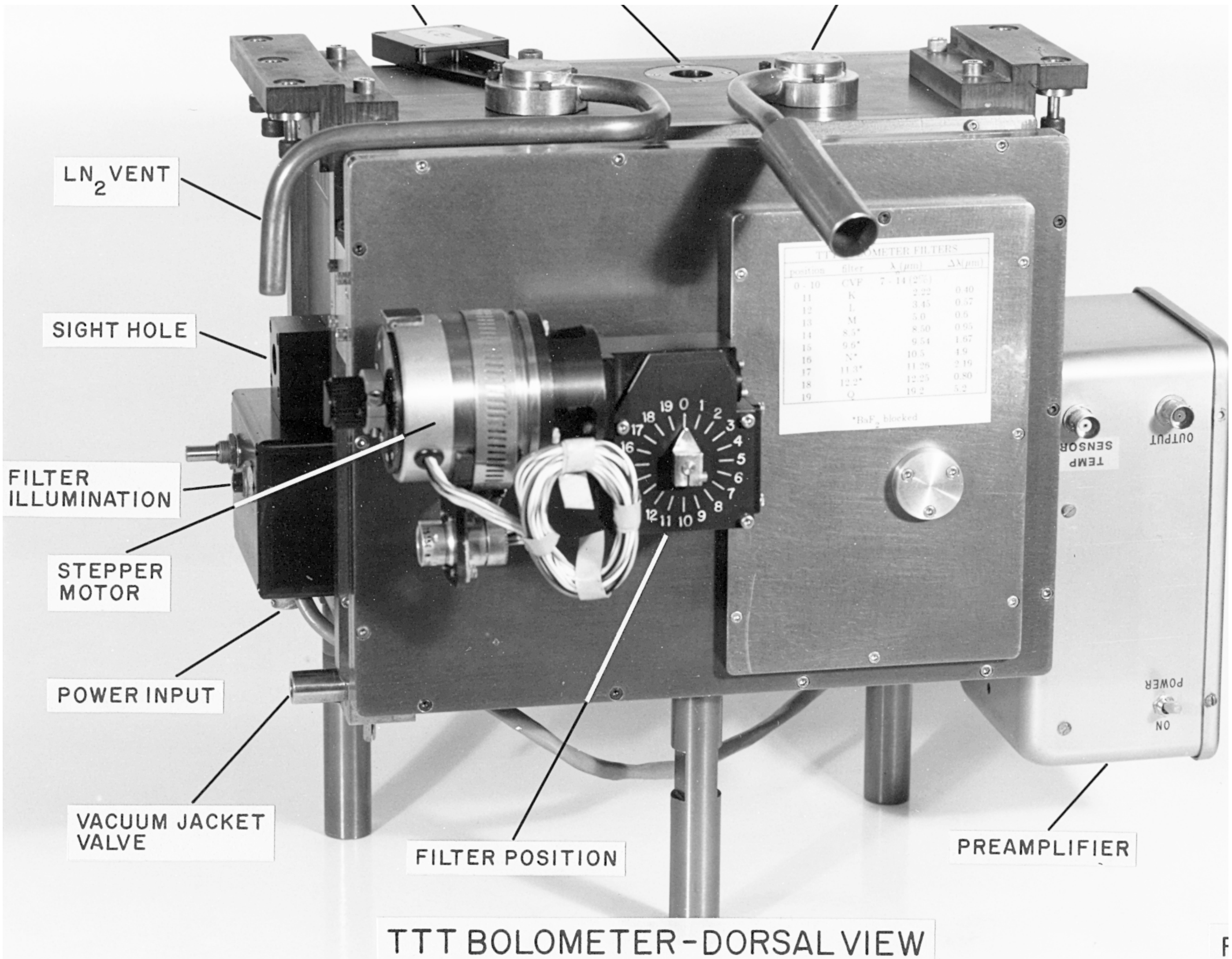
# Early Single Channel Instruments

InSb Photometer



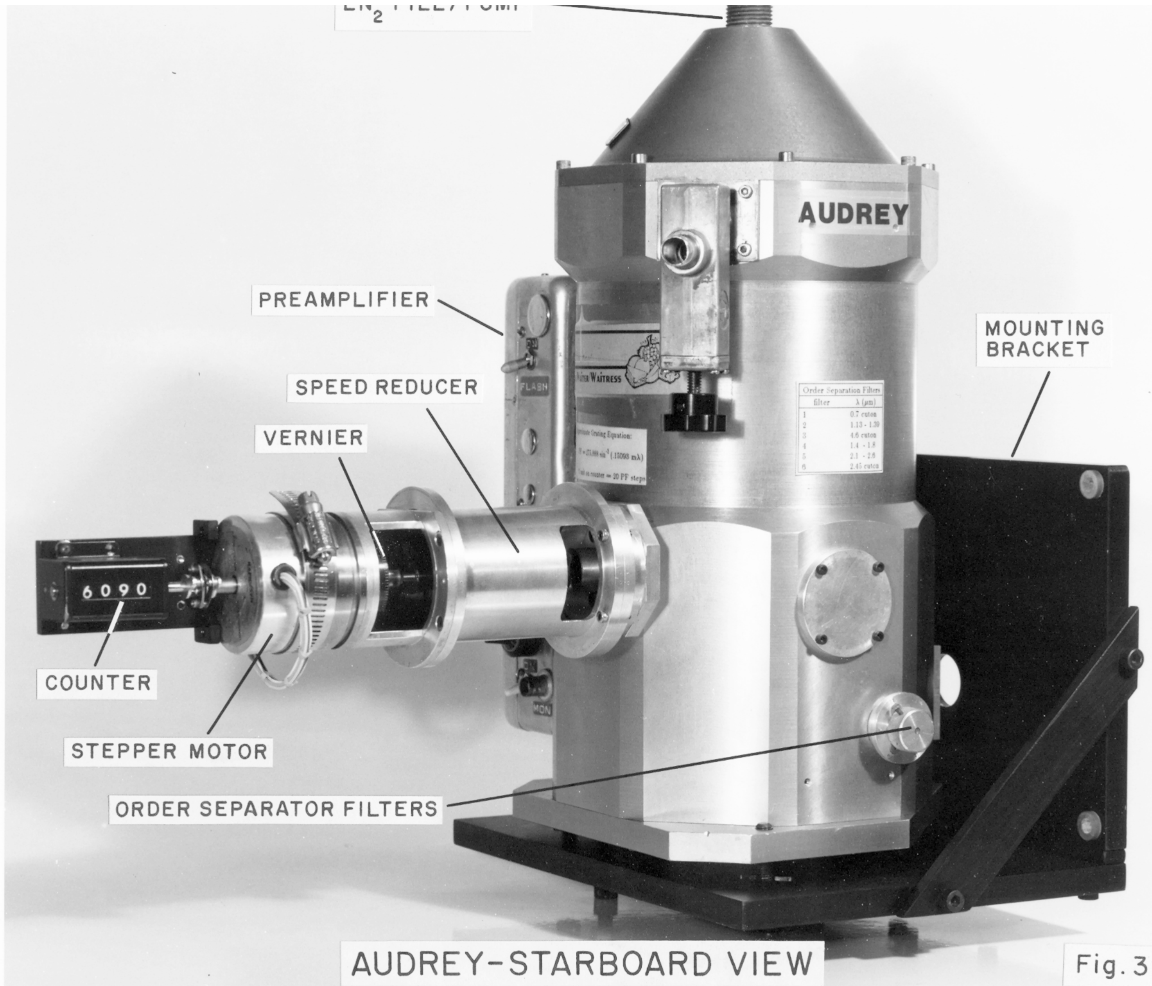

OTTO – QUARTER VIEW

# Early Single Channel Instruments




Ge Bolometer

# Early Single Channel Instruments




Scanning CVF
Spectrometer

# Delicate Adjustments Needed

Susan Kleinmann

# Spatial Resolution

- Limited by seeing, aperture size and/or telescope diffraction limit
- Typical instrument entrance apertures:
  - 3 to 30 arc sec
- IR instruments rarely scheduled on large telescopes

# Typical IR Observing ~1970

# Multiplexing

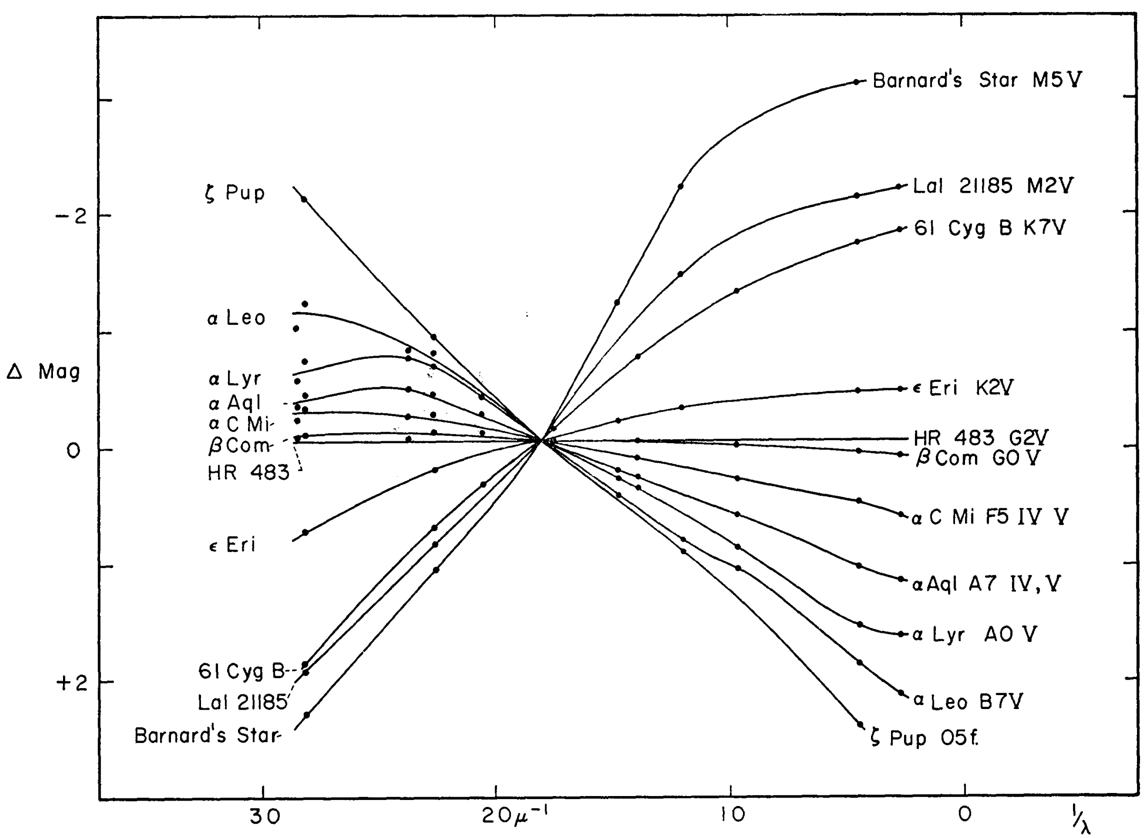
- Early observations typically made with single channel photometers
- Mapping and wide area surveys were ‘challenging’
- Imaging array detectors (InSb; Hg-Cd-Te; Si:As- and Ge-doped Si) became generally available only over the past two decades

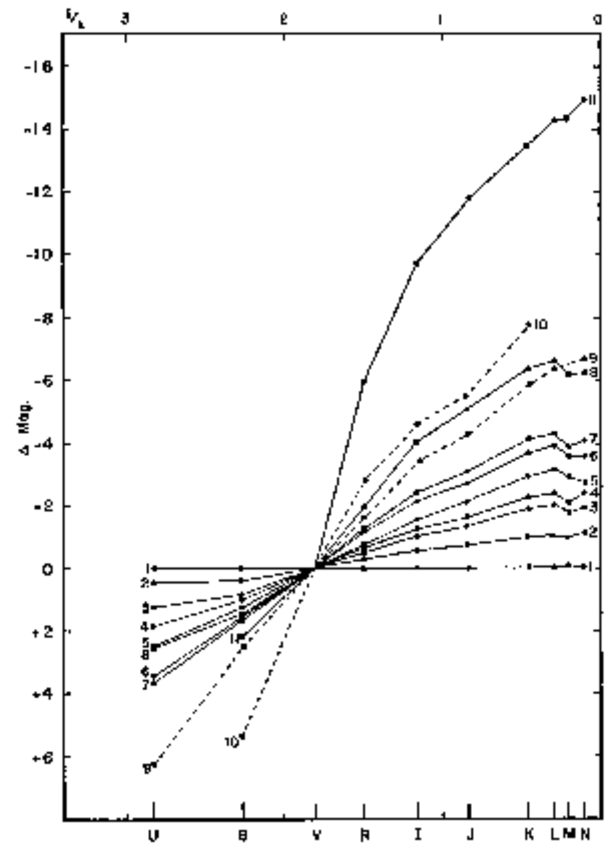
# Spectroscopy/Spectral Resolution

- The availability of single, relatively low sensitivity detectors limited spectroscopy
- Fourier Transform Spectrometers provided an early solution to enabling spectroscopy
- Later, Continuously Variable Filters were used (primarily for R <100 measurements)

# Photometry of Bright Stars

Pioneering work of Johnson; Low



# Photometry of Bright Stars

Pioneering work of Johnson (1962); Low (1964)

GIANT STARS

| Sp (III) | $U-V$ | $B-V$ | $V-R$ | $V-I$ | $V-J$ | $V-K$ | $V-L$ | $V-M$ | $V-N$ | B.C. | $T_e$ (°K) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| G5 | +1.55 | +0.92 | +0.69 | +1.17 | +1.52 | +2.08 | +2.18 | +2.02 | +2.05 | −0.20 | 5010 |
| G8 | +1.64 | +0.95 | +0.70 | +1.18 | +1.56 | +2.16 | +2.27 | +2.09 | +2.12 | −0.21 | 4870 |
| K0 | +1.93 | +1.04 | +0.77 | +1.30 | +1.71 | +2.35 | +2.47 | +2.25 | +2.28 | −0.30 | 4720 |
| K1 | +2.13 | +1.10 | +0.81 | +1.37 | +1.80 | +2.48 | +2.61 | +2.36 | +2.39 | −0.36 | 4580 |
| K2 | +2.32 | +1.16 | +0.84 | +1.42 | +1.87 | +2.59 | +2.73 | +2.45 | +2.48 | −0.42 | 4460 |
| K3 | +2.74 | +1.30 | +0.96 | +1.61 | +2.12 | +2.92 | +3.07 | +2.75 | +2.80 | −0.59 | 4210 |
| K4 | +3.07 | +1.41 | +1.06 | +1.81 | +2.36 | +3.24 | +3.39 | +3.05 | +3.11 | −0.79 | 4010 |
| K5 | +3.34 | +1.54 | +1.20 | +2.10 | +2.71 | +3.67 | +3.83 | +3.47 | +3.54 | −1.08 | 3780 |
| M0 | +3.43 | +1.55 | +1.23 | +2.17 | +2.82 | +3.79 | +3.96 | +3.59 | +3.65 | −1.17 | 3660 |
| M1 | +3.48 | +1.56 | +1.28 | +2.27 | +2.90 | +3.92 | +4.09 | +3.72 | +3.78 | −1.25 | 3600 |
| M2 | +3.51 | +1.59 | +1.34 | +2.44 | +3.08 | +4.11 | +4.29 | +3.91 | +3.97 | −1.41 | 3500 |
| M3 | +3.51 | +1.60 | +1.48 | +2.79 | +3.51 | +4.58 | +4.77 | +4.39 | +4.45 | −1.80 | 3300 |
| M4 | +3.32 | +1.59 | +1.74 | +3.39 | +4.26 | +5.24 | +5.44 | +5.10 | +5.14 | −2.44 | 3100 |
| M5 | +3.00 | +1.55 | +2.18 | +4.14 | +5.04 | +6.06 | +6.31 | +6.00 | +6.00 | −3.23 | 2950 |
| M6 | +2.43 | +1.54 | +2.80 | +5.06 | +5.86 | +7.01 | +7.39 | | | −4.15 | 2800 |

# Photometry of Normal Galaxies

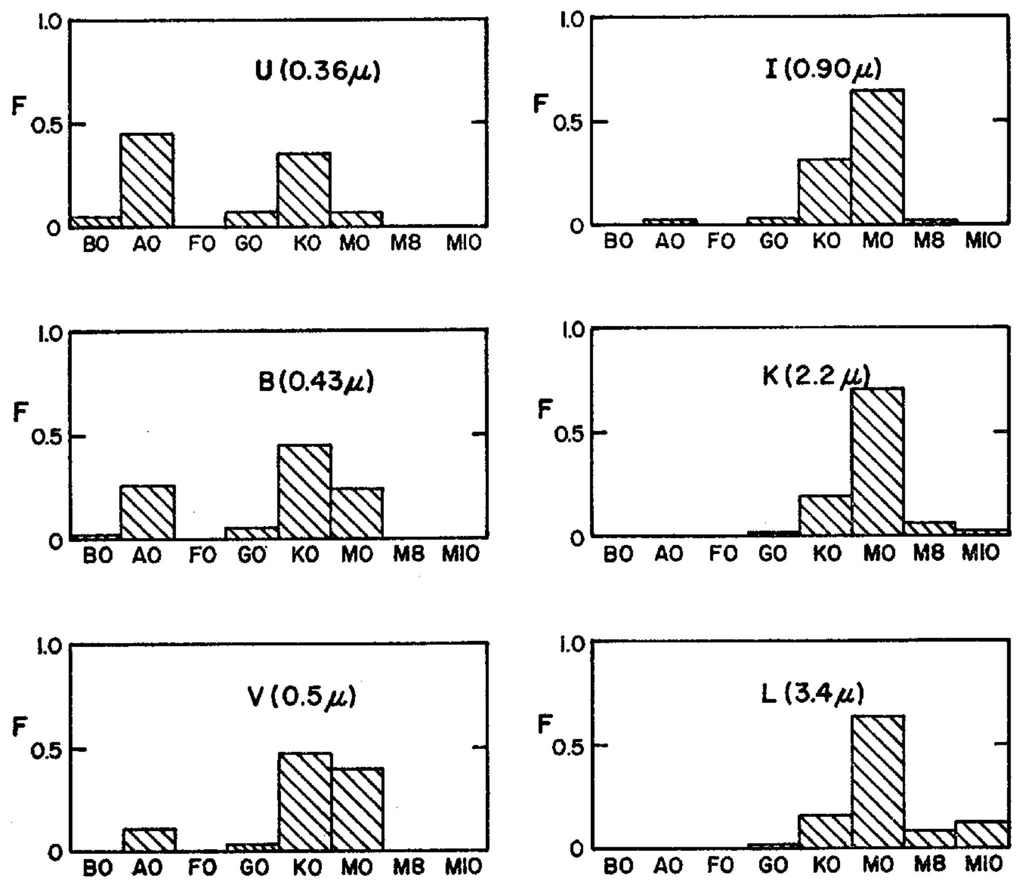
Johnson (1965)

| NGC | $U-V$ | $B-V$ | $V-R$ | $V-I$ | $V-J$ | $V-K$ | $V-L$ |
|---|---|---|---|---|---|---|---|
| 224...... | 1.68 | 1.01 | ....... | 1.68 | 2.29 | 3.22 | 3.18 |
| 3034...... | 1.33 | 0.86 | 0.86 | 1.60 | 2.60 | 3.52 | 3.96 |
| 3368...... | 1.62 | 0.99 | 0.90 | 1.72 | 2.33 | 3.44 | 3.69 |
| 4168...... | 1.44 | 1.01 | 0.86 | 1.50 | 2.48 | 3.02 | 3.04 |
| 4278...... | 1.54 | 1.00 | 1.00 | 1.72 | 1.79 | 3.18 | 3.57 |
| 4486...... | 1.59 | 1.03 | 0.94 | 1.77 | 2.20 | 3.07 | 3.39 |
| 4736...... | 1.38 | 0.90 | 0.84 | 1.58 | 2.11 | 3.01 | 3.37 |
| 5055...... | 1.38 | 0.94 | 1.01 | 1.89 | 2.52 | 3.72 | 3.72 |
| 5846...... | 1.70 | 1.07 | 0.92 | 1.75 | 2.79 | 3.04 | 3.74 |
| 5982...... | 1.53 | 1.00 | 0.82 | 1.54 | 1.54 | 2.71 | 3.87 |

# Photometry of Normal Galaxies

Population Synthesis (Johnson, 1965)

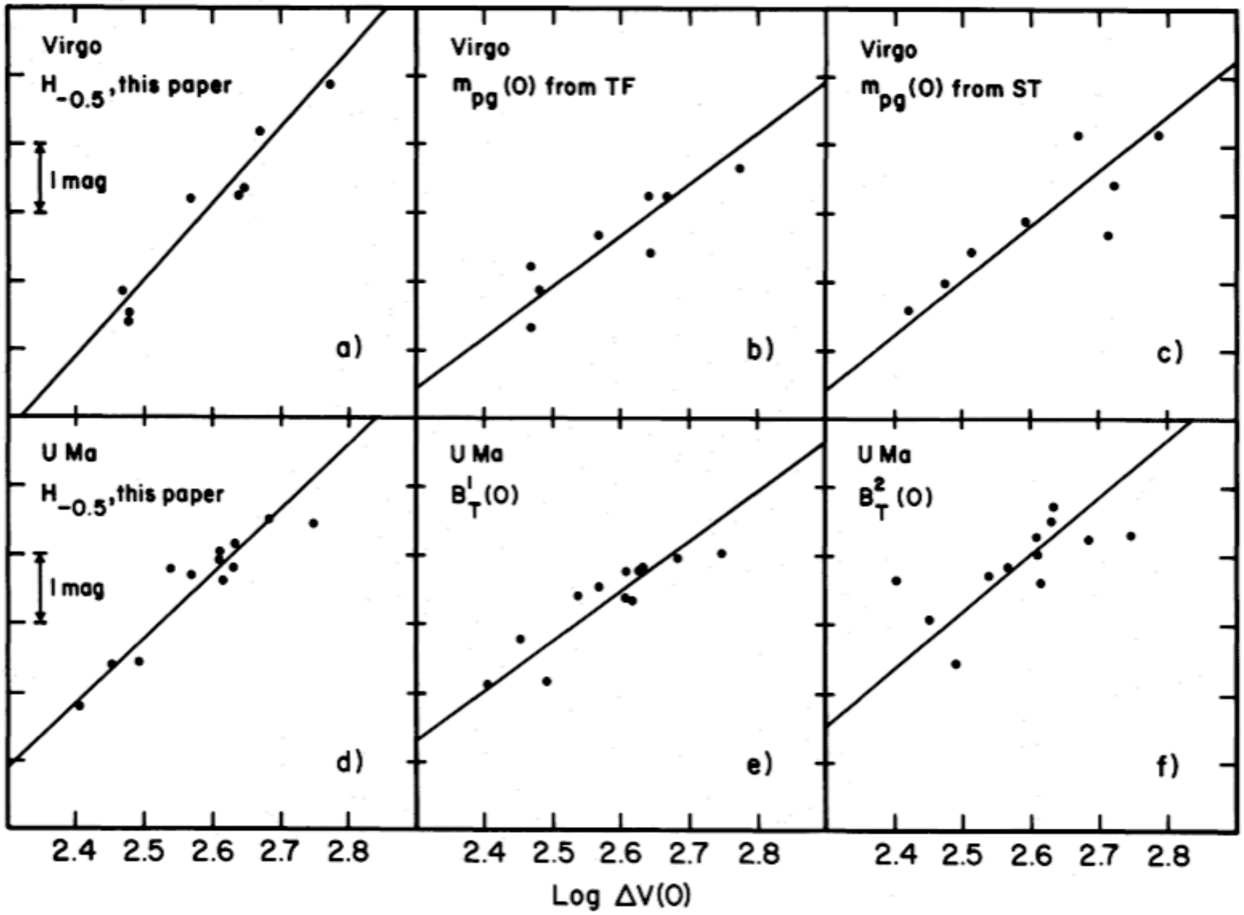
– Concludes that light from K giants dominates near- IR



# Photometry of Normal Galaxies

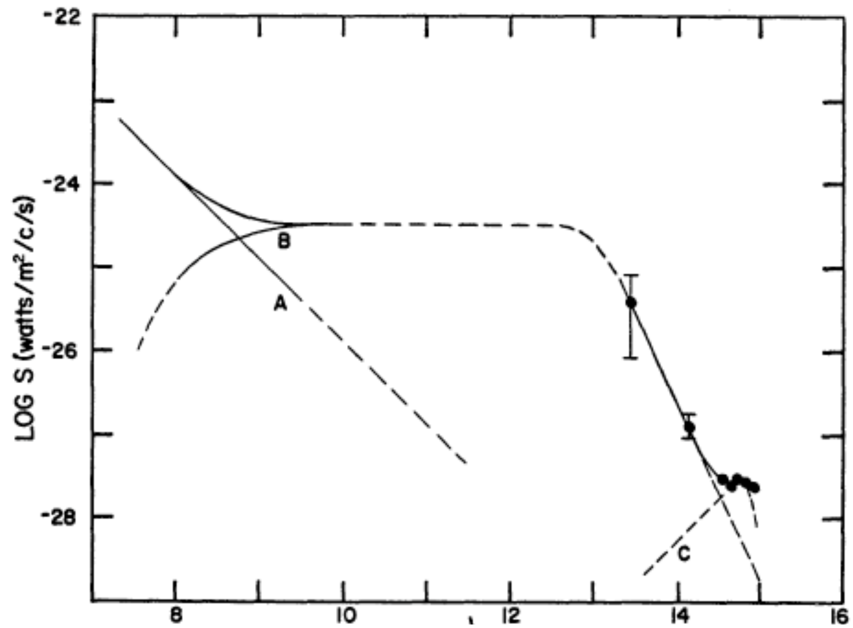
Johnson result leads to Aaronson, Mould & Huchra (1980)

- IR provides basis for studying fundamental plane



# Photometry of AGNs/QSOs

Johnson & Low (1965)




THE OBSERVATIONAL DATA

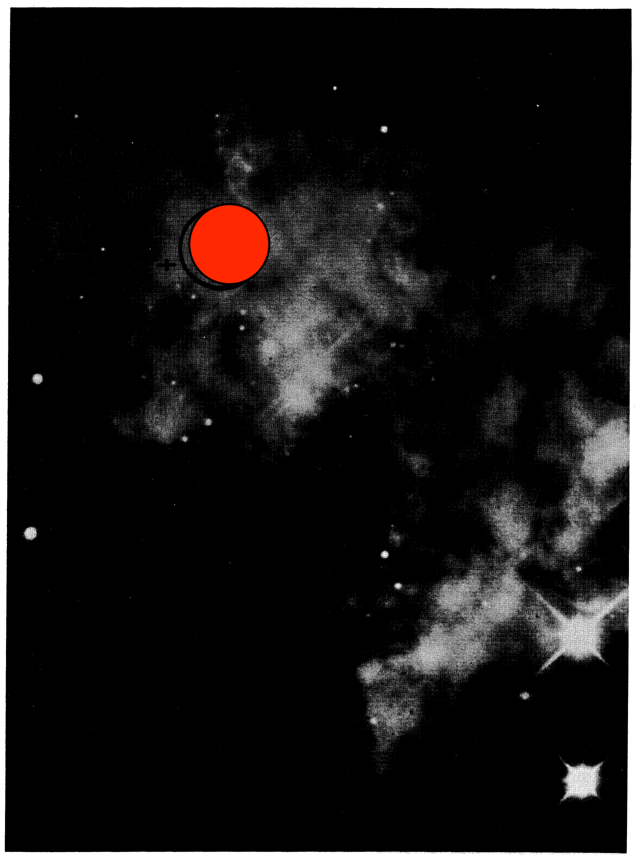
| | $U-V$ | $B-V$ | $V-R$ | $V-I$ | $V-K$ | $V-N$ |
|---|---|---|---|---|---|---|
| 3C 273 | −0 68 | +0 20 | +0 24 | +0 74 | +3 60 | +10 4 |

# Early IR Surveys

- TMSS (Neugebauer & Leighton, 1966)
  - Single PbS detector
  - Mapped Northern hemisphere
  - Limiting magnitude: K ~ 3
  - Nearly 6000 sources detected
  - IR excesses in AGB stars, YSOs discovered

# Early IR Maps: YSOs

## Kleinmann-Low Nebula

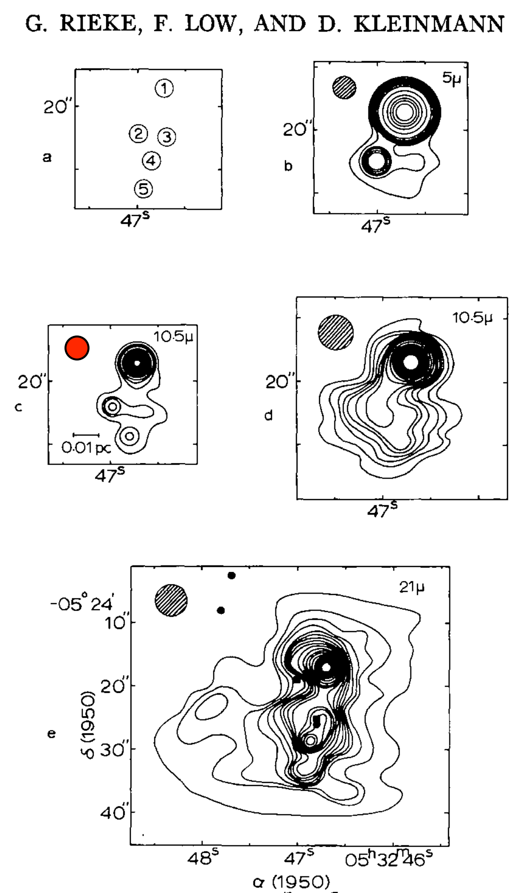


1967

5μ

10μ

20μ

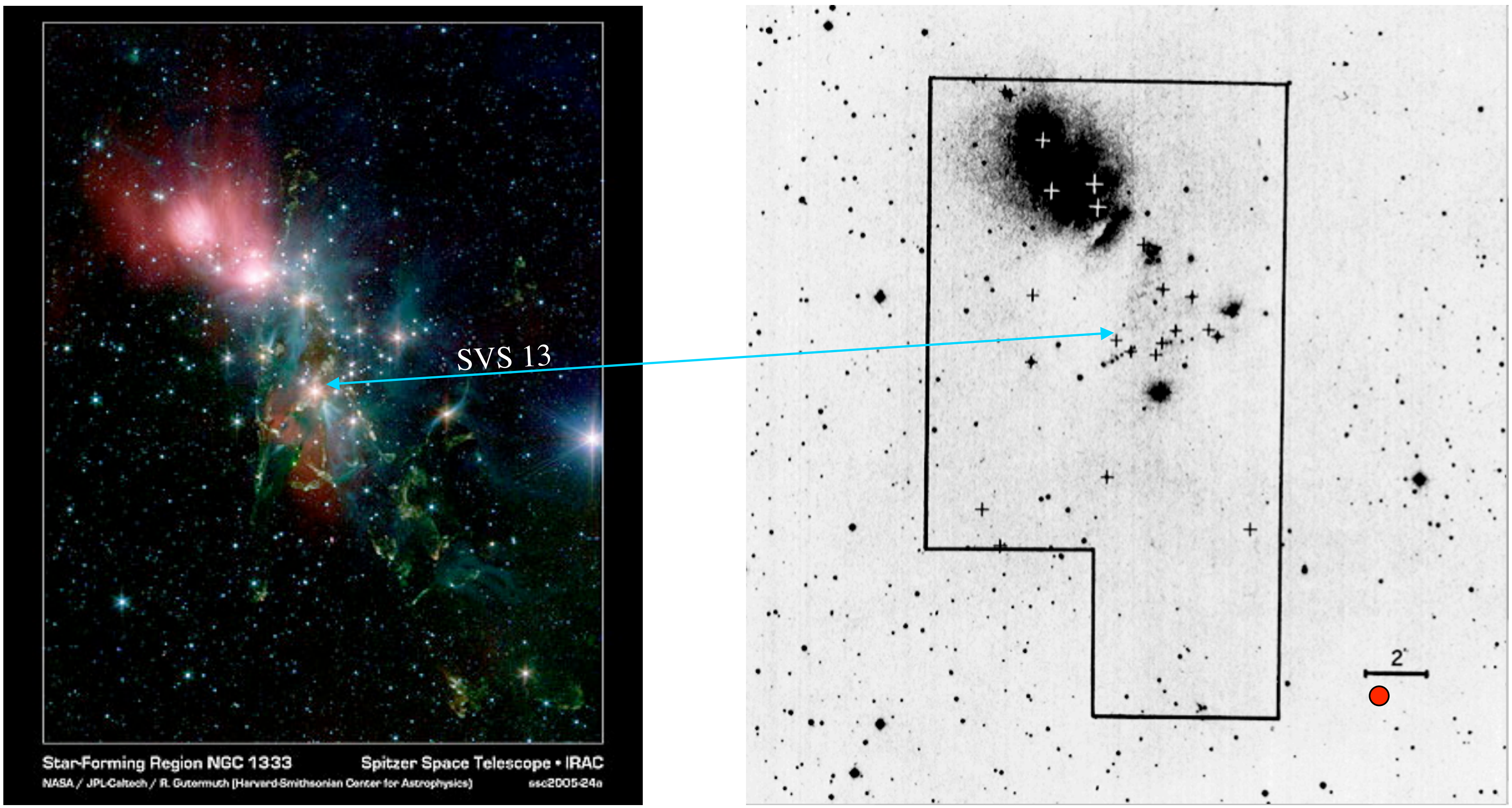



1973

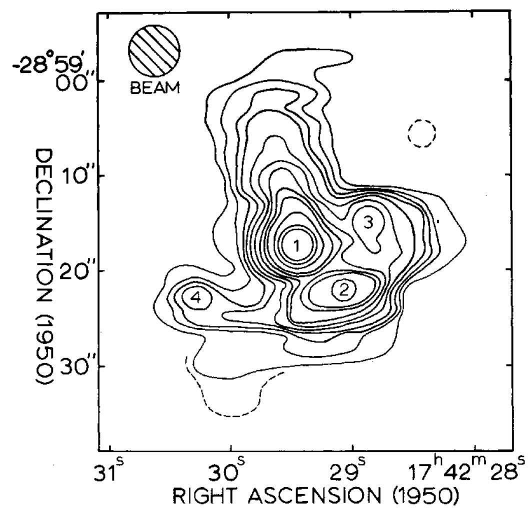
# Early IR Maps: YSOs

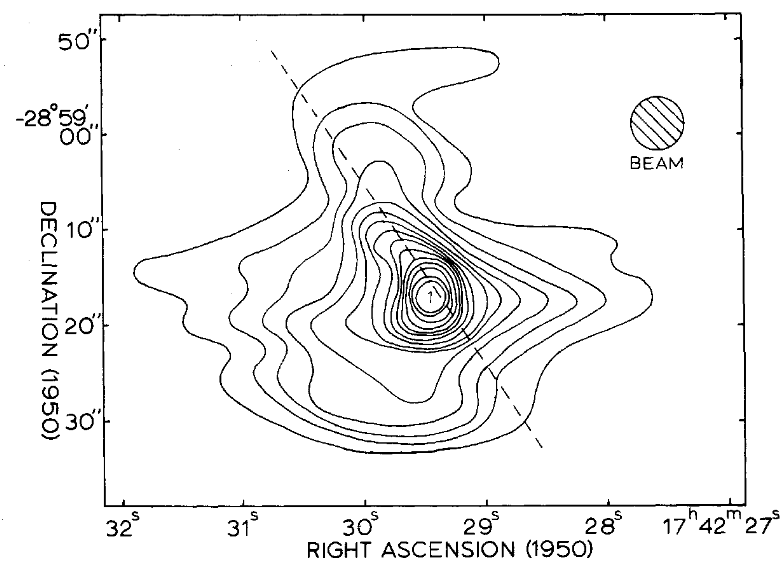
Spitzer Space Telescope 2005

Strom, Vrba, Strom 1976



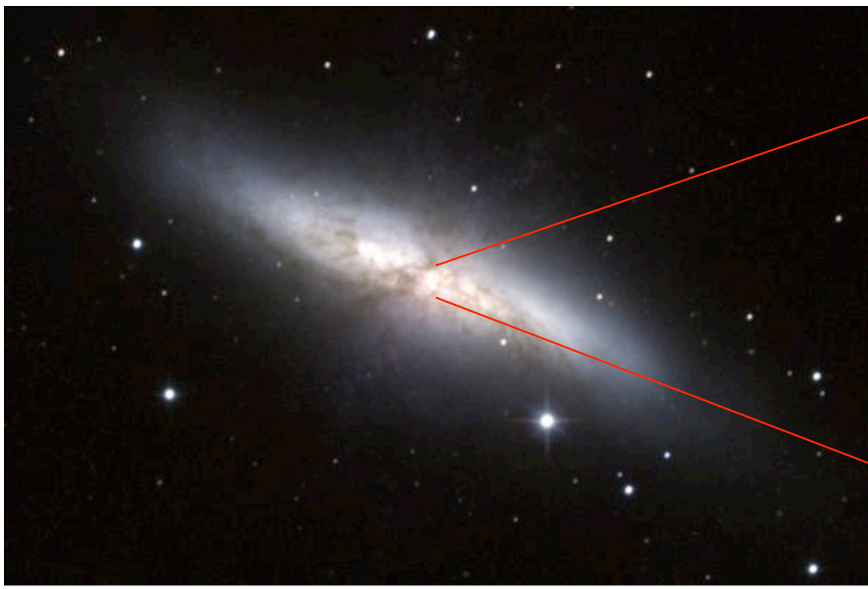
# Early IR Maps: The Galaxy

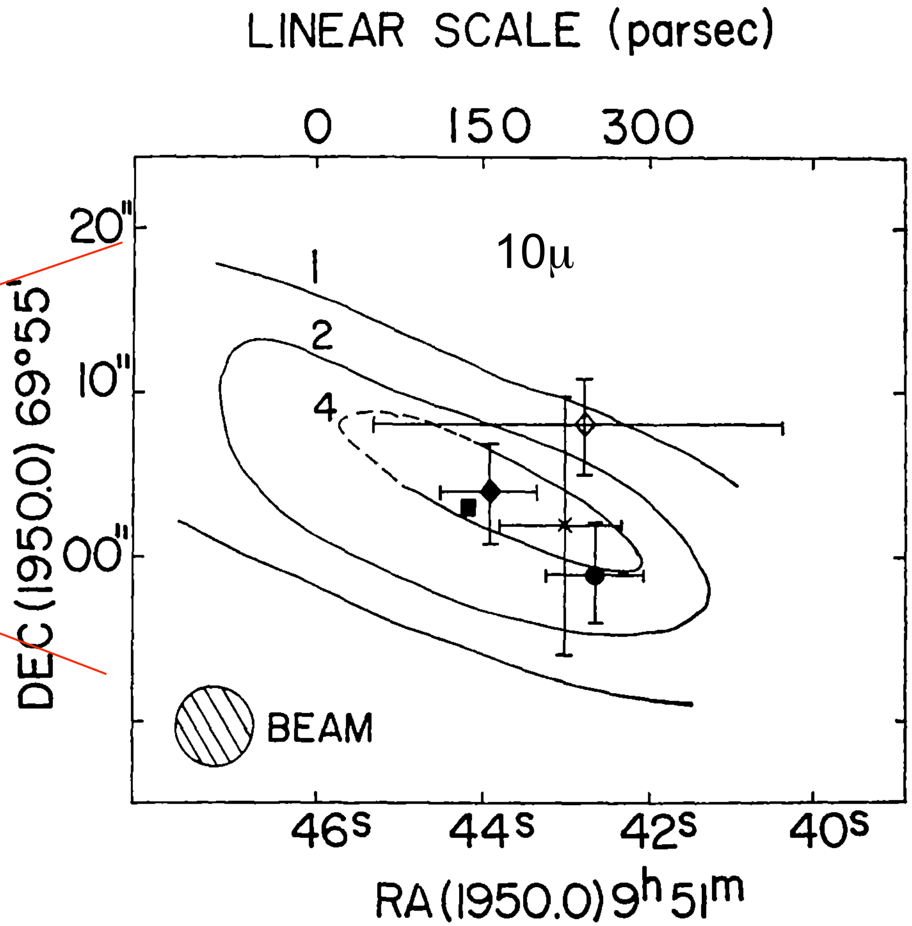



Rieke and Low, 1973

# Early IR Maps: M82






Kleinmann & Low, 1970

# Early IR Spectra

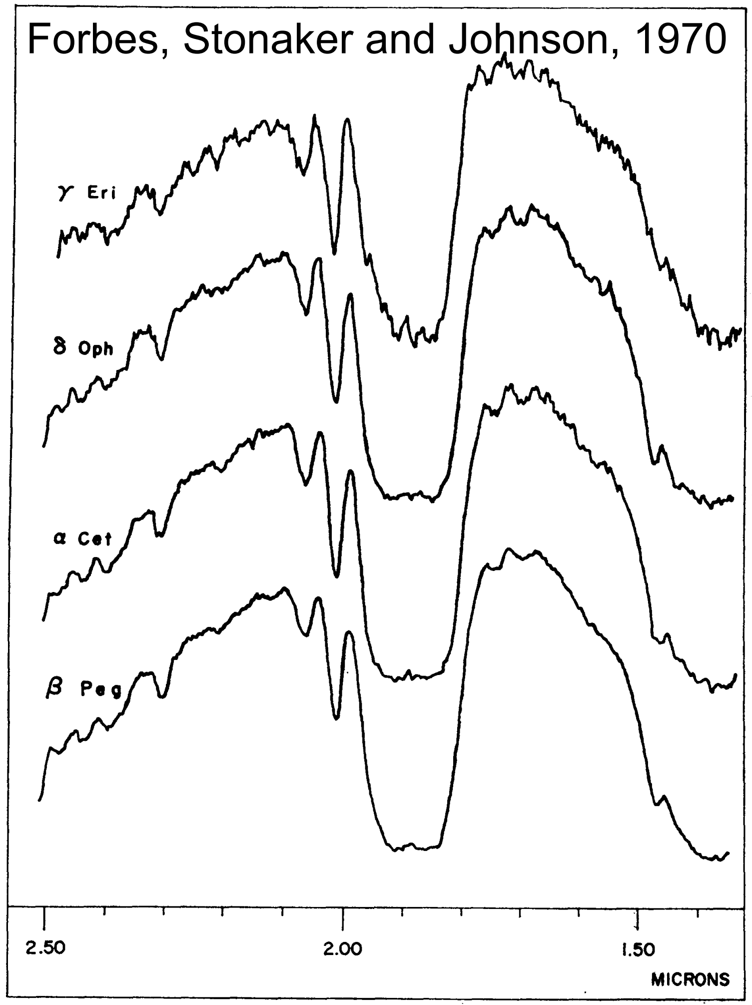
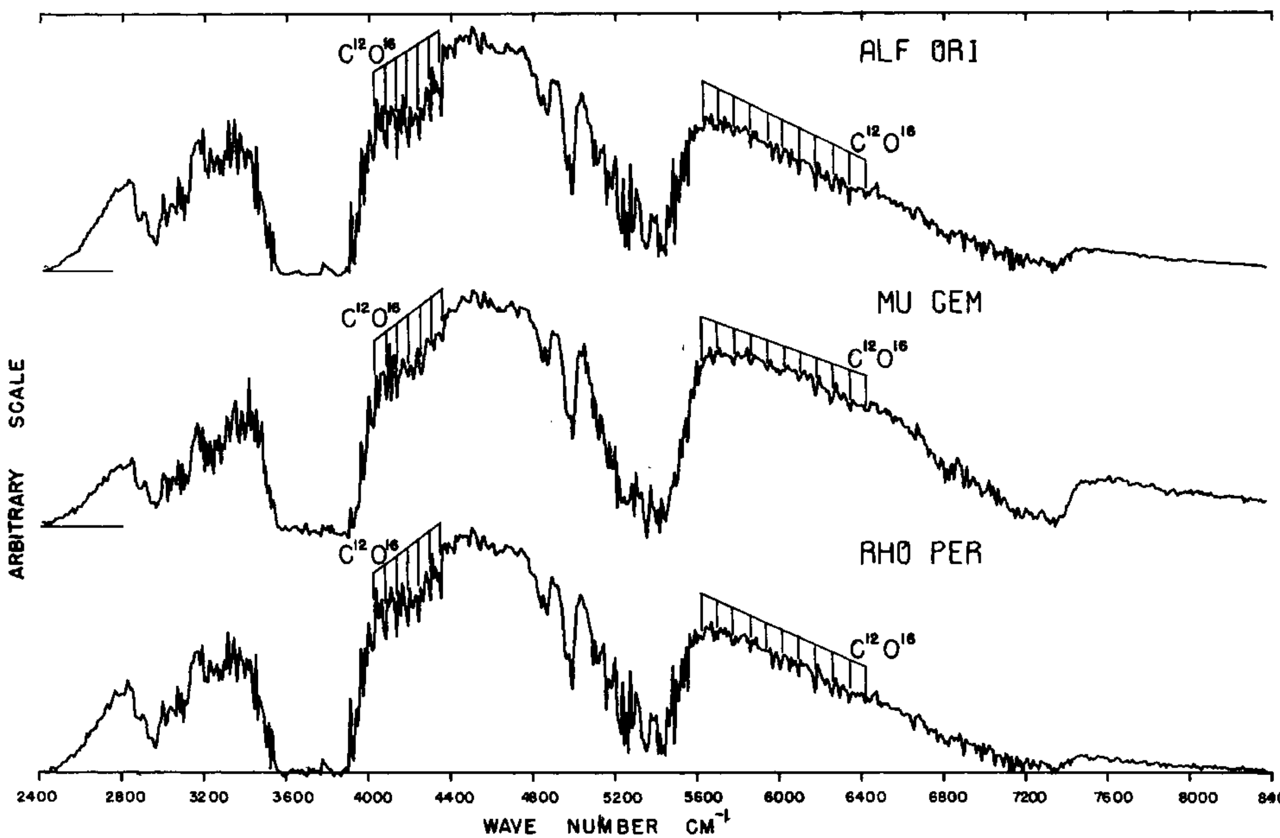



FIG. 3. Normal giant spectra, M1–M2.

CVF + Single Detector
R ~ 100

# Early IR Spectra

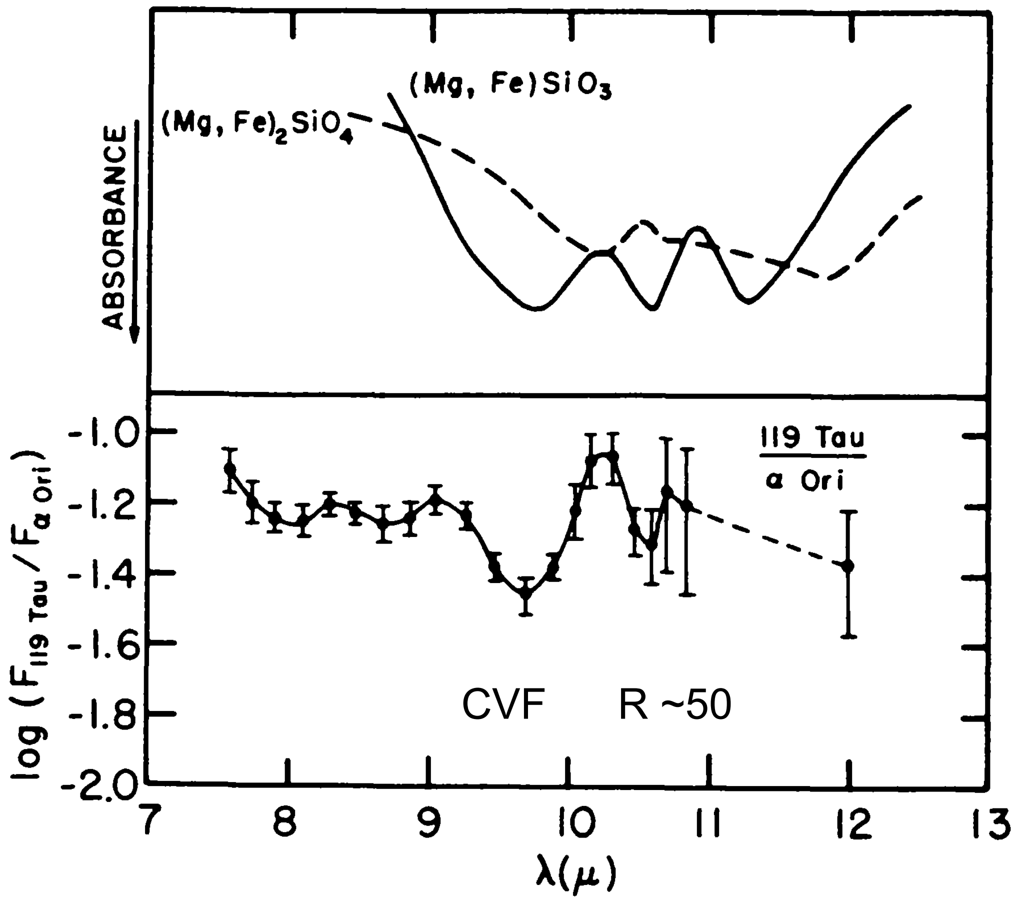
R. Thpmpson et al, 1970




FTS + Single Detector R ~ 500

# Early IR Spectra

Knacke, Gaustad, Gillett & Stein, 1969



# IR Astronomy: The Transition

- By 1975-1980, IR astronomy gradually entered the ‘mainstream’
  - No longer an exotic specialty focused on a few sources
  - Critical to establishing a full picture of cosmic sources

# IR Astronomy: Transition Years

- Specialized, low emissivity telescopes built to exploit IR; increase sensitivity
- Spatial resolution matched to seeing/diffraction limit via use of array detectors
- Array detectors enabled high resolution mapping and surveys
- Spectroscopic measurements exploited larger telescopes, array detectors

# A Maturing Discipline

Large, low emissivity telescopes constructed

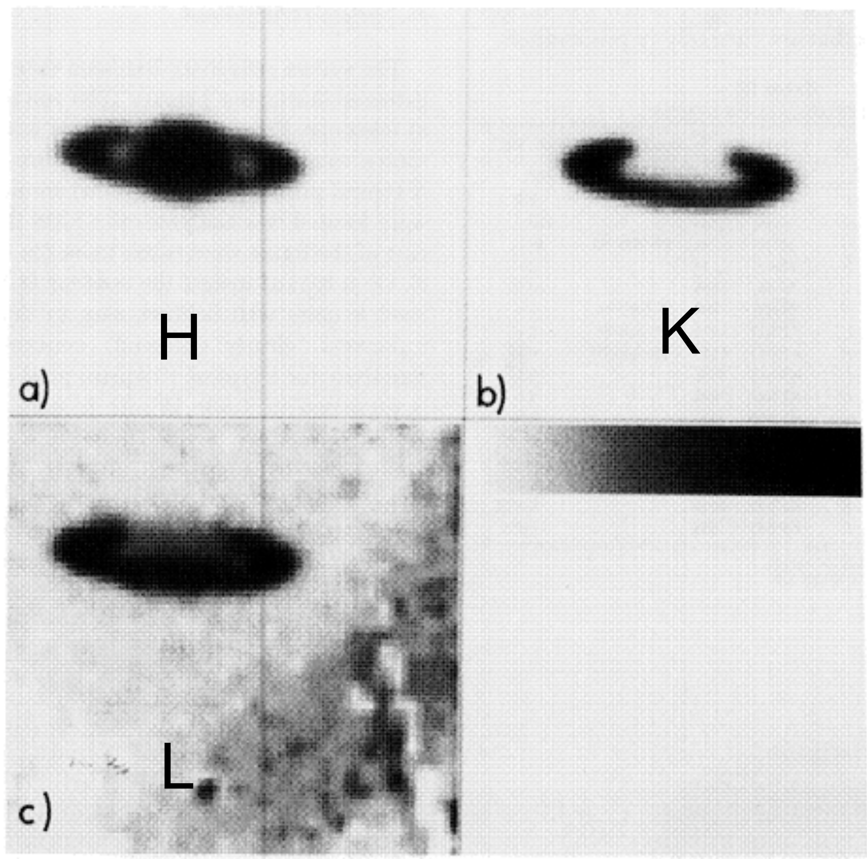
- Increase sensitivity & angular resolution

IRTF 3.0m

UKIRT 3.8m

# A Maturing Discipline

## Multiplexing: IR Arrays developed

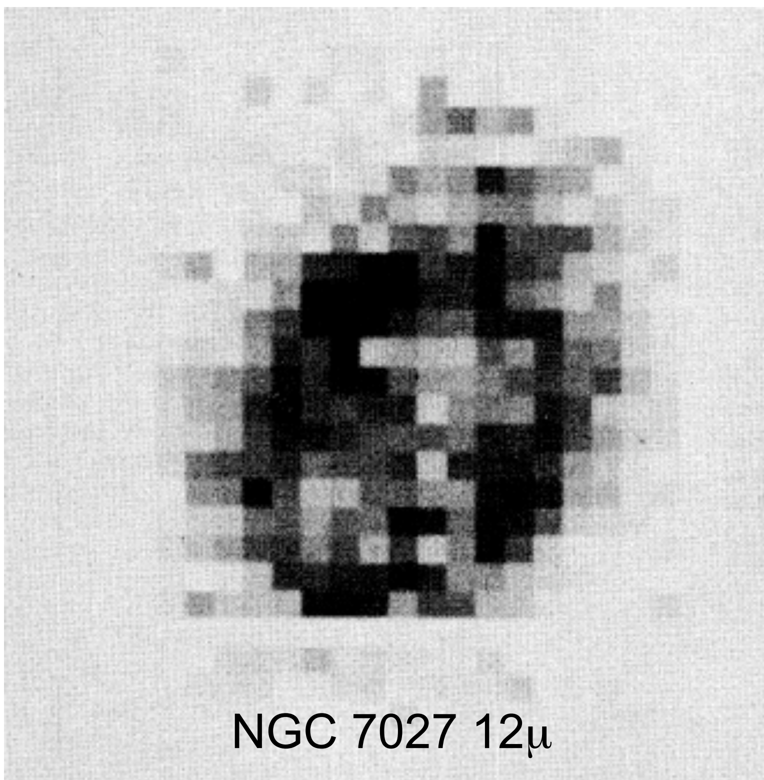



32x32 InSb
Rochester Camera

Forrest et al. 1985

# A Maturing Discipline

## Multiplexing: IR Arrays developed



NGC 7027 12μ

32x32 Si:Bi
NASA 10μ Camera

Arens et al. 1984

# A Maturing Discipline

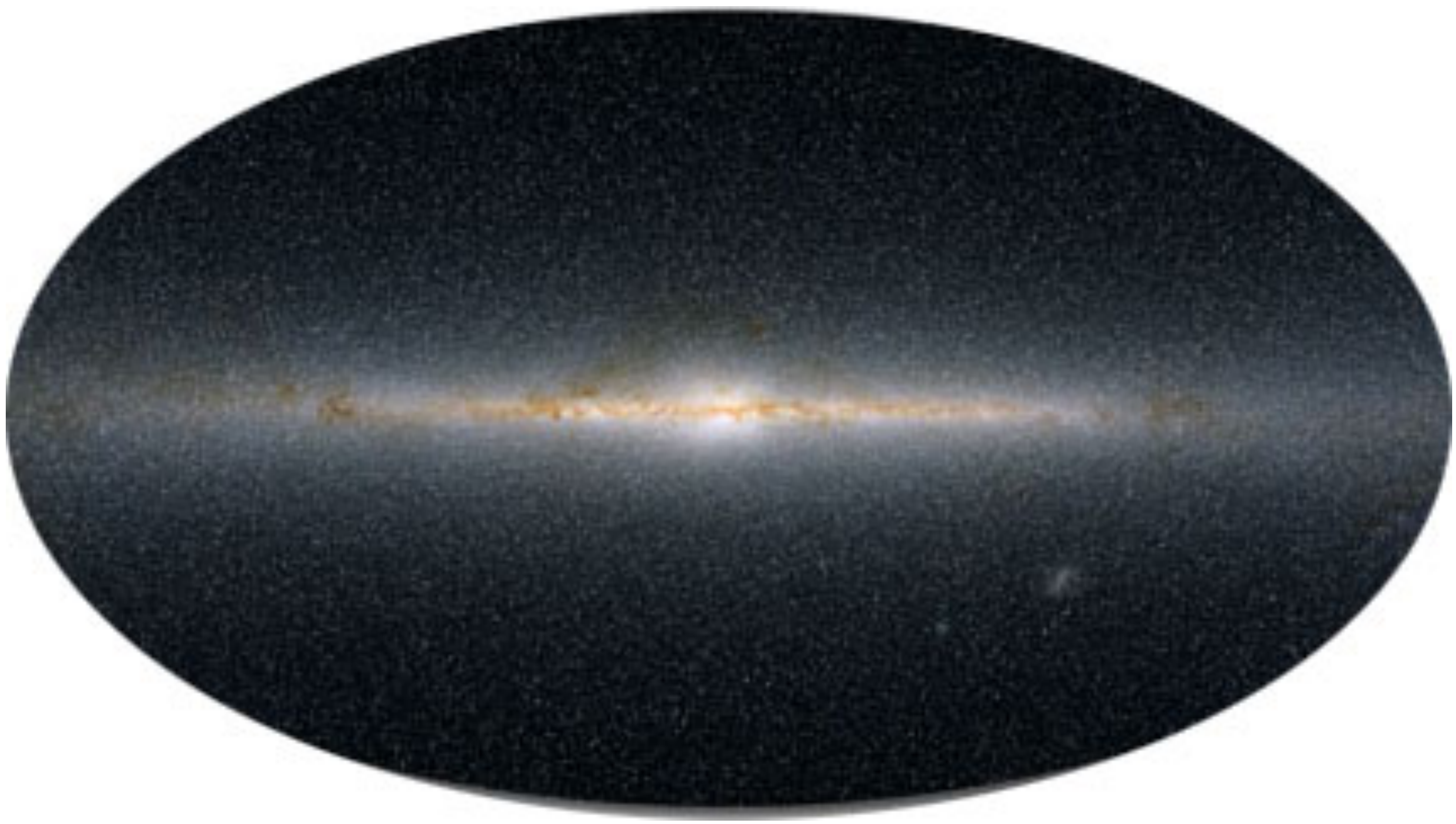
## Multiplexing: IR Arrays developed

NGC 2024
JHKL composite

NOAO SQIID Camera
$256^2$ PtSi

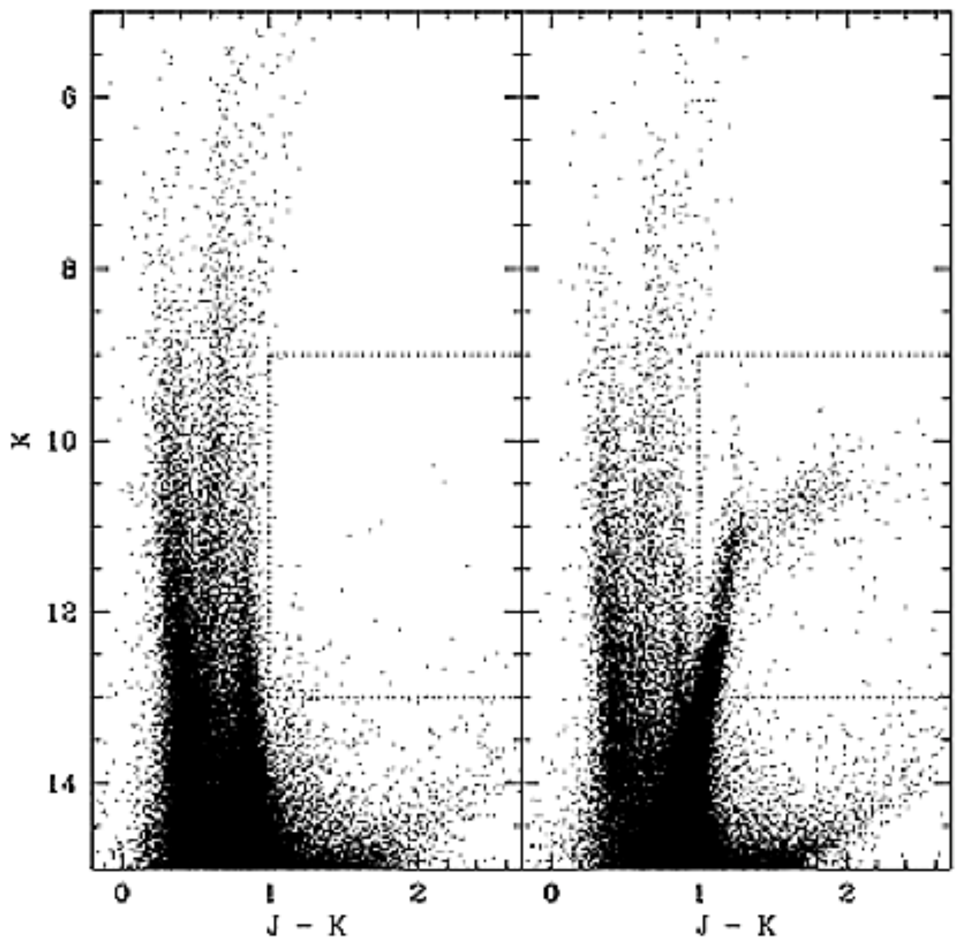
Gatley, Merrill et al (1990)

# A Maturing Discipline



2MASS Survey

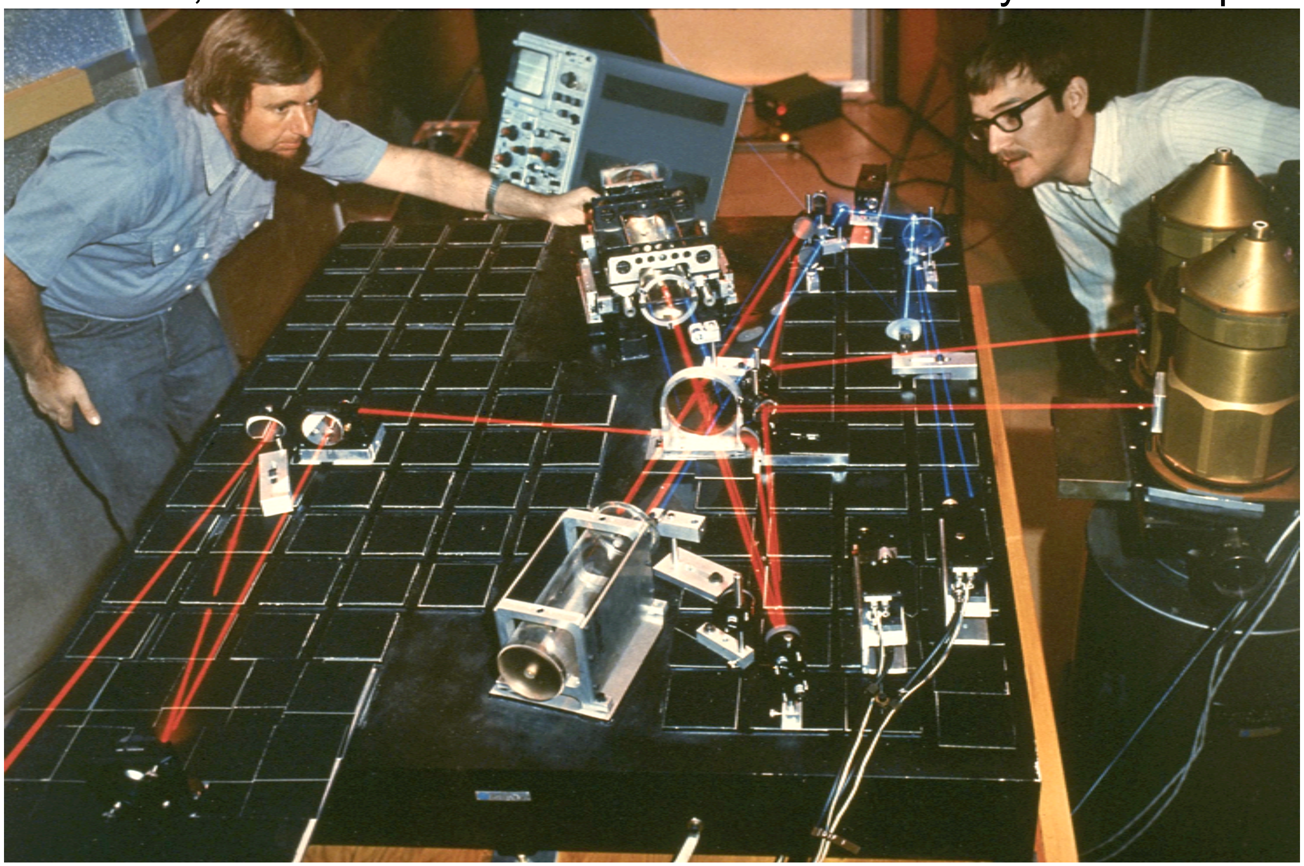
# A Maturing Discipline




Search for Magellanic Stream with 2MASS

# A Maturing Discipline

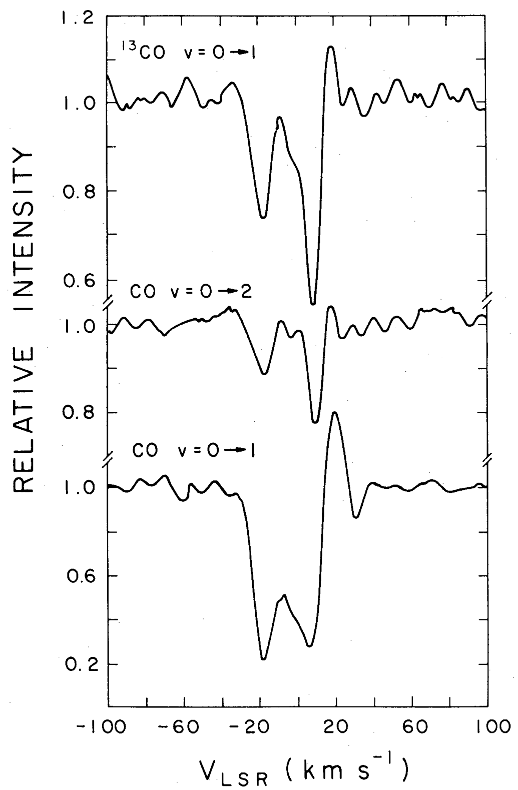
R ~ 50,000 FTS at the Coude focus of the 4m Mayall Telescope



By 1980, major IR instruments were scheduled regularly on large telescopes

# A Maturing Discipline

Use of large telescopes for IR observation enables high resolution spectroscopy



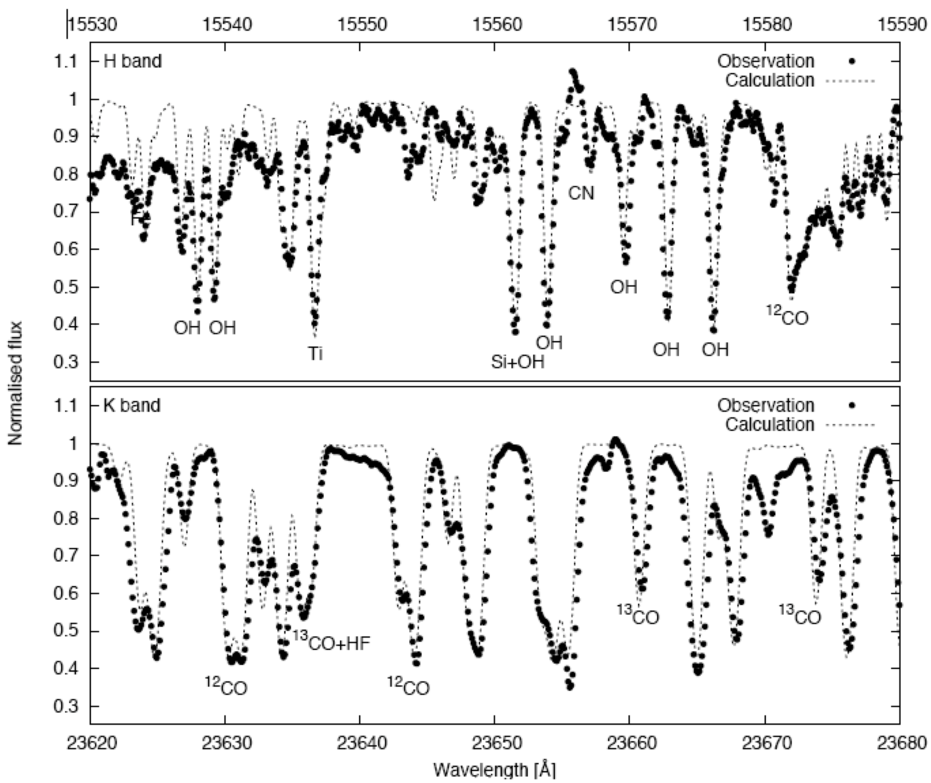

BN Object
Forming High Mass Star

First measurements of inflow and outflow rates in a protostar

FTS (R ~ 50,000)
Scoville et al. 1983

# A Maturing Discipline

Use of large telescopes for IR observations enables high resolution spectroscopy




LMC AGB star

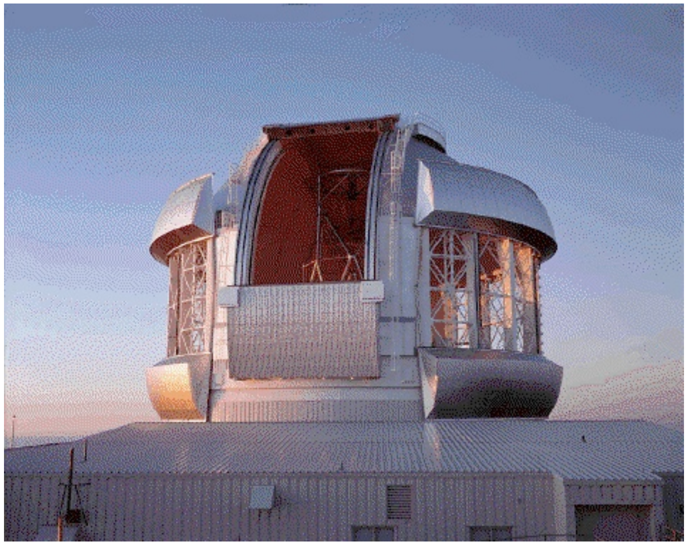
Measuring CNO and isotopic abundances in the LMC

Phoenix (R ~ 50,000)

# Perceived Importance of IR ~1990

- 1990 Bahcall report:
  - The "decade of the infrared"
- Build large IR-optimized ground-based facilities to increase sensitivity; angular resolution
- Build SIRTF(Spitzer)
- Carry out deep, full sky near-IR survey
- Develop technology for future IR facilities:
  - Adaptive optics
  - Design for next generation O/IR telescopes
  - Testbed interferometers

# Decade of the Infrared

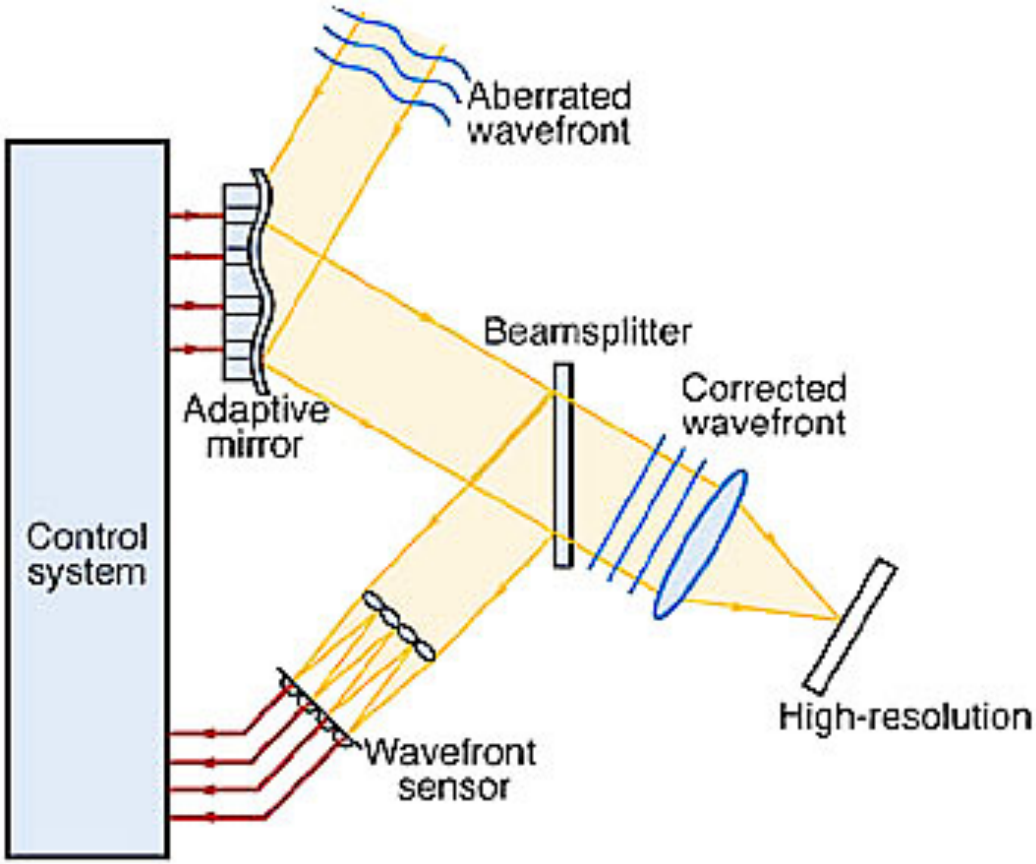


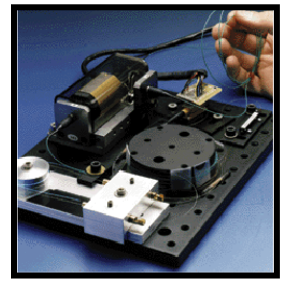
Gemini North 8m

2MASS

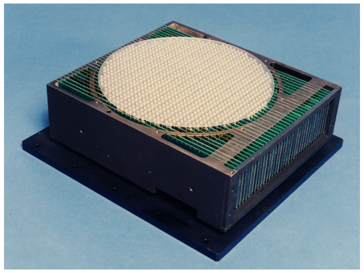
Spitzer Space Telescope

# Decade of the Infrared



Laser Guide Stars



Deformable Mirrors

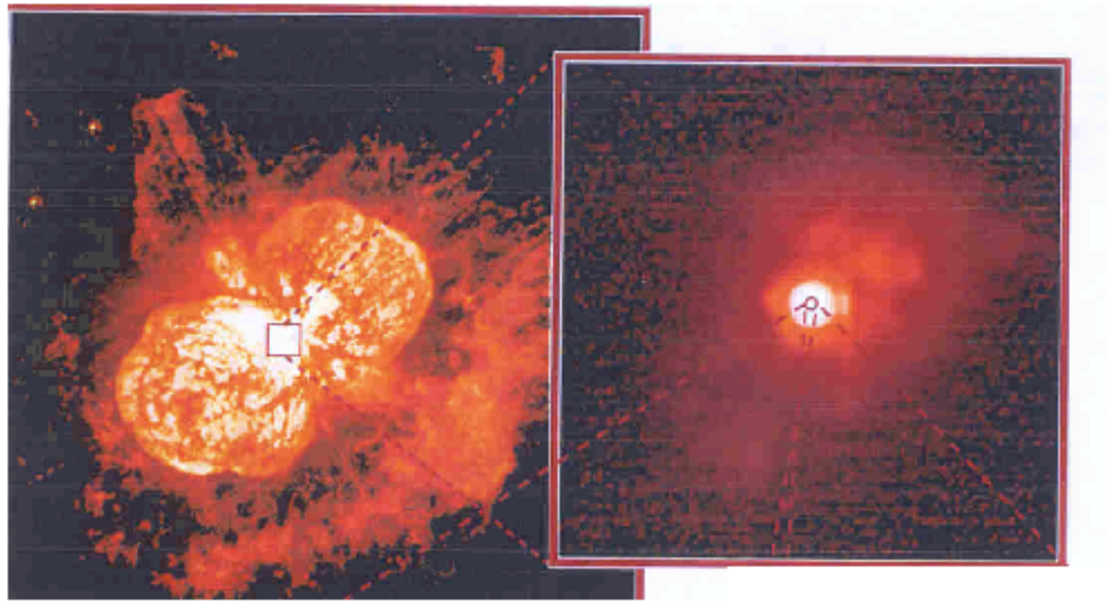
Fast Wavefront Sensors

# Decade of the Infrared

VLTI

WFP2 Optical

VLTI   2μ

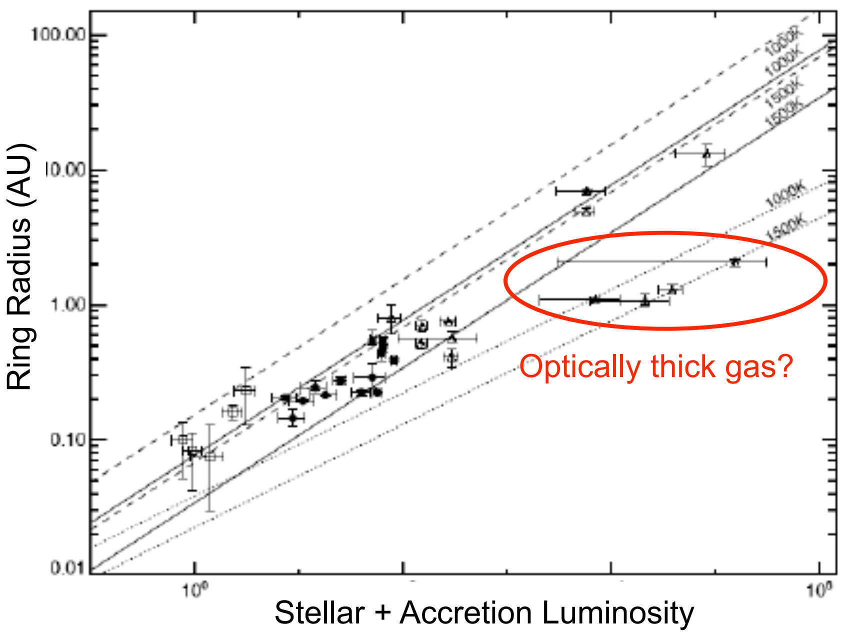


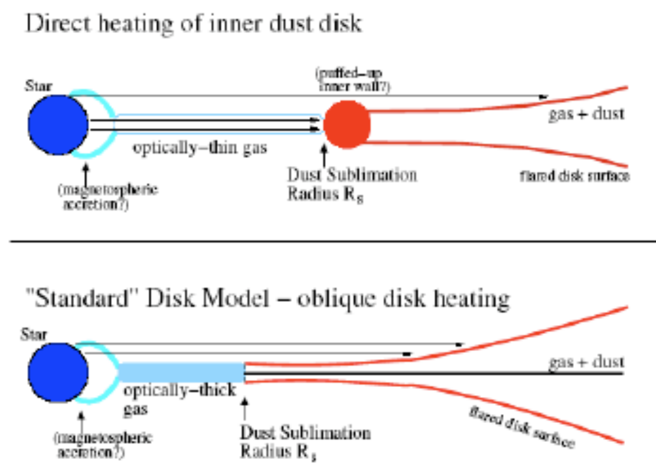
η Car

High angular resolution in the IR with VLTI

# Decade of the Infrared

Probing the inner disks around young stars with IR interferometry



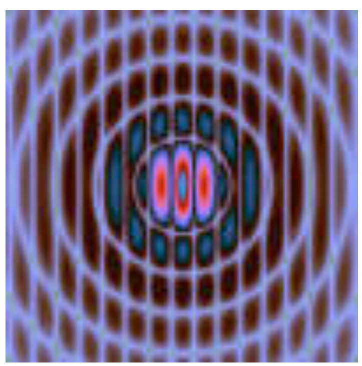

$\tau_{gas} < 1$

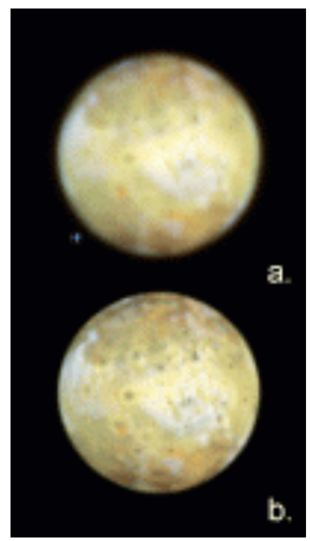
$\tau_{gas} >> 1$

# Decade of the Infrared

LBT

LBT PSF



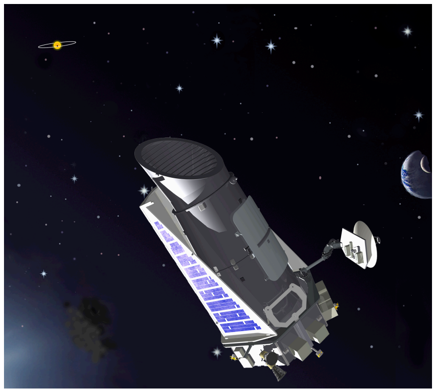



Simulated near-IR images of Io

# Context for the Next Decade

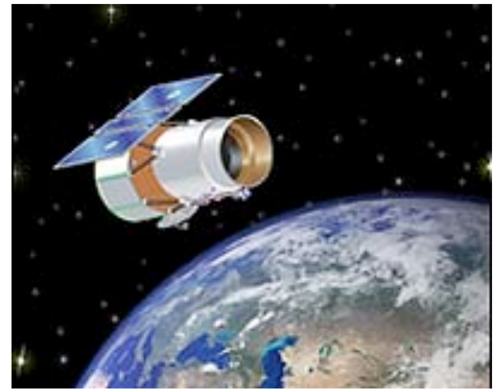
- A variety of facilities (space and ground) that will provide:
  - High sensitivity
  - Moderate-to-high angular resolution
  - Complementary wavelength coverage
- In the context of these powerful facilities, what is the future role of ground-based IR astronomy?

# Context for the Next Decade

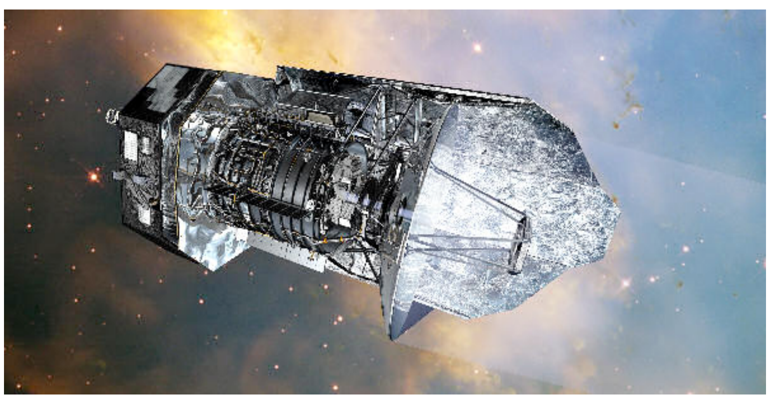


KEPLER

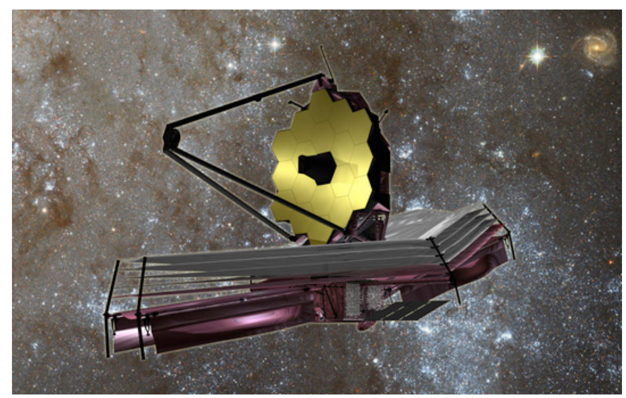
SOFIA



WISE



HERSCHEL



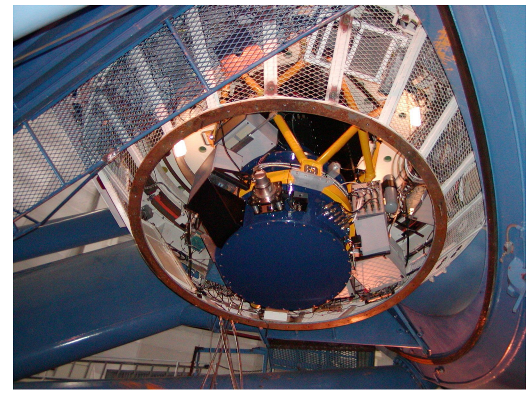
JWST

Rich target list for high resolution imaging and spectroscopy at near- and mid- IR wavelengths

# Context for the Next Decade

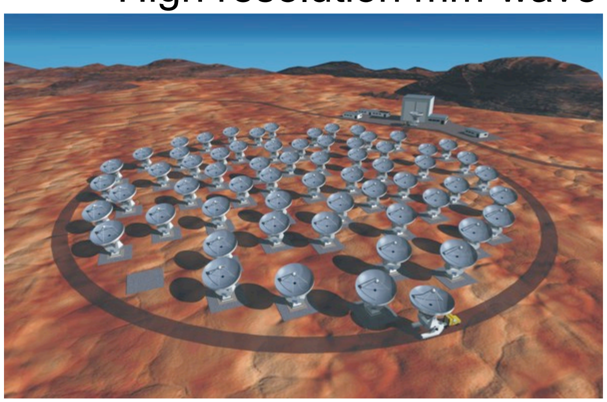
VISTA

Deep surveys requiring followup imaging & spectroscopy

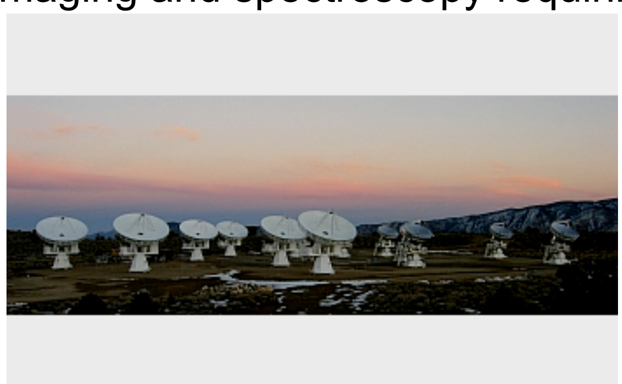


NEWFIRM

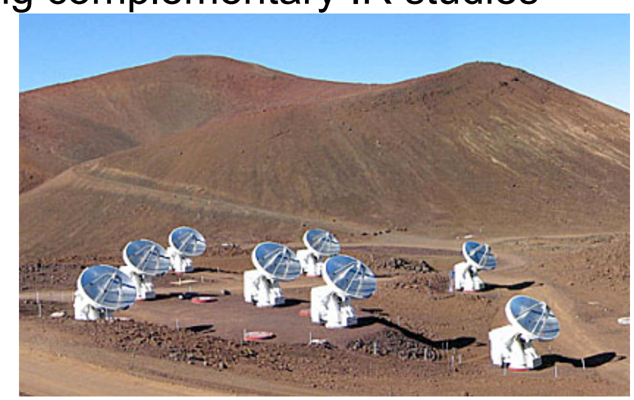
High resolution mm-wave imaging and spectroscopy requiring complementary IR studies



ALMA



CARMA



SMA

# IR Astronomy: The Future

Keys to the future:

- Combine increased aperture & diffraction-limited imaging
- Achieve sensitivity gains ~ $D^4$ (background-limited)
  - Analyze circumstellar disks and protostellar envelopes (R~$10^5$ spectra)
- Reach critical angular resolution thresholds
  - Resolve planets; star-forming regions in z > 3 galaxies
  - Analyze stellar populations in galaxies and crowded regions in MWG
- Combine IFU spectroscopy with high resolution imaging
  - Analyze kinematics, SFR & chemical composition in forming galaxies

# IR Astronomy: The Future

Keys to the future:

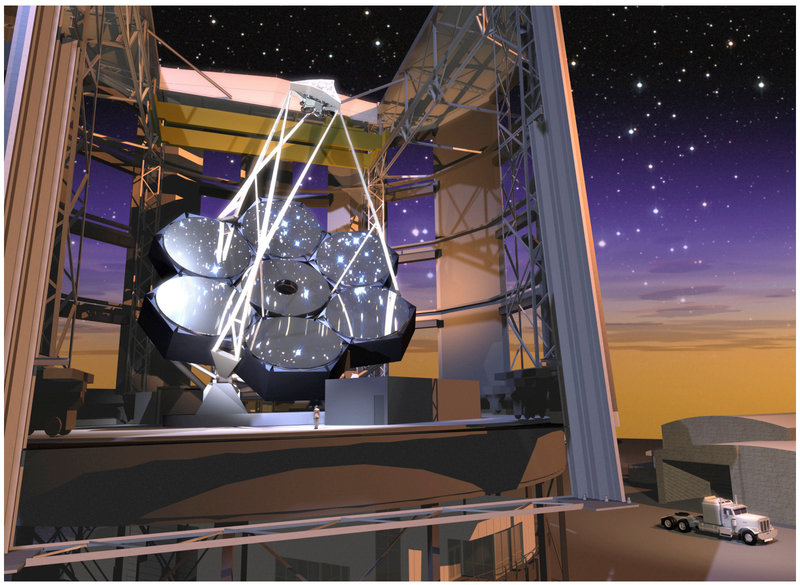
- Diffraction-limited imaging enables dramatic gains for:
  - Imaging and spectroscopy of high contrast scenes
    - Direct imaging and spectroscopy of planets
  - Accurate photometry in crowded fields
    - Extragalctic stellar populations & dense, star-forming regions
  - High angular resolution imaging exceeding the capabilities of JWST at near- & mid-IR wavelengths
    - Forming galaxies (kinematics & composition)

# IR Astronomy: The Future

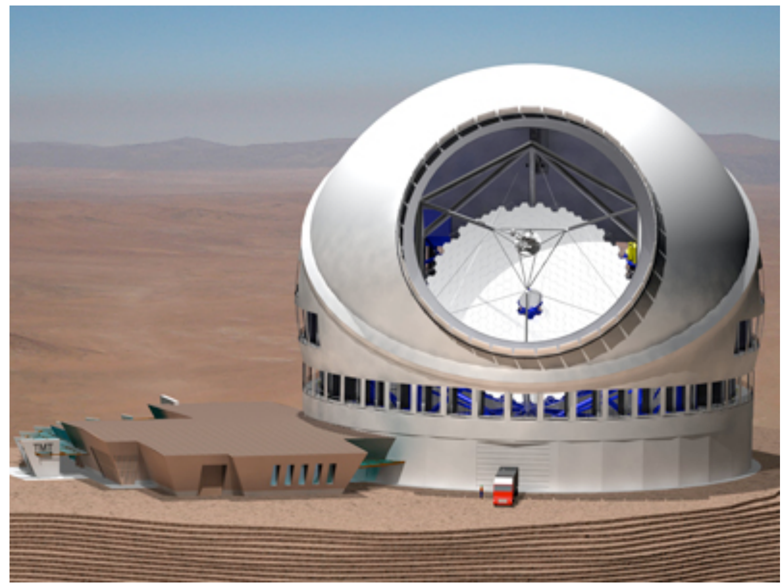
Essential to achieving needed capabilities:

- Large aperture
- Adaptive optics
  - Can in principle provide 7mas images at $\lambda \sim 1\mu$
    - 1 AU at nearest star-forming regions
    - 150 pc at z ~ 3 galaxy
- Current AO technology enables diffraction-limited imaging in the IR but not the optical

# IR Astronomy: the Future

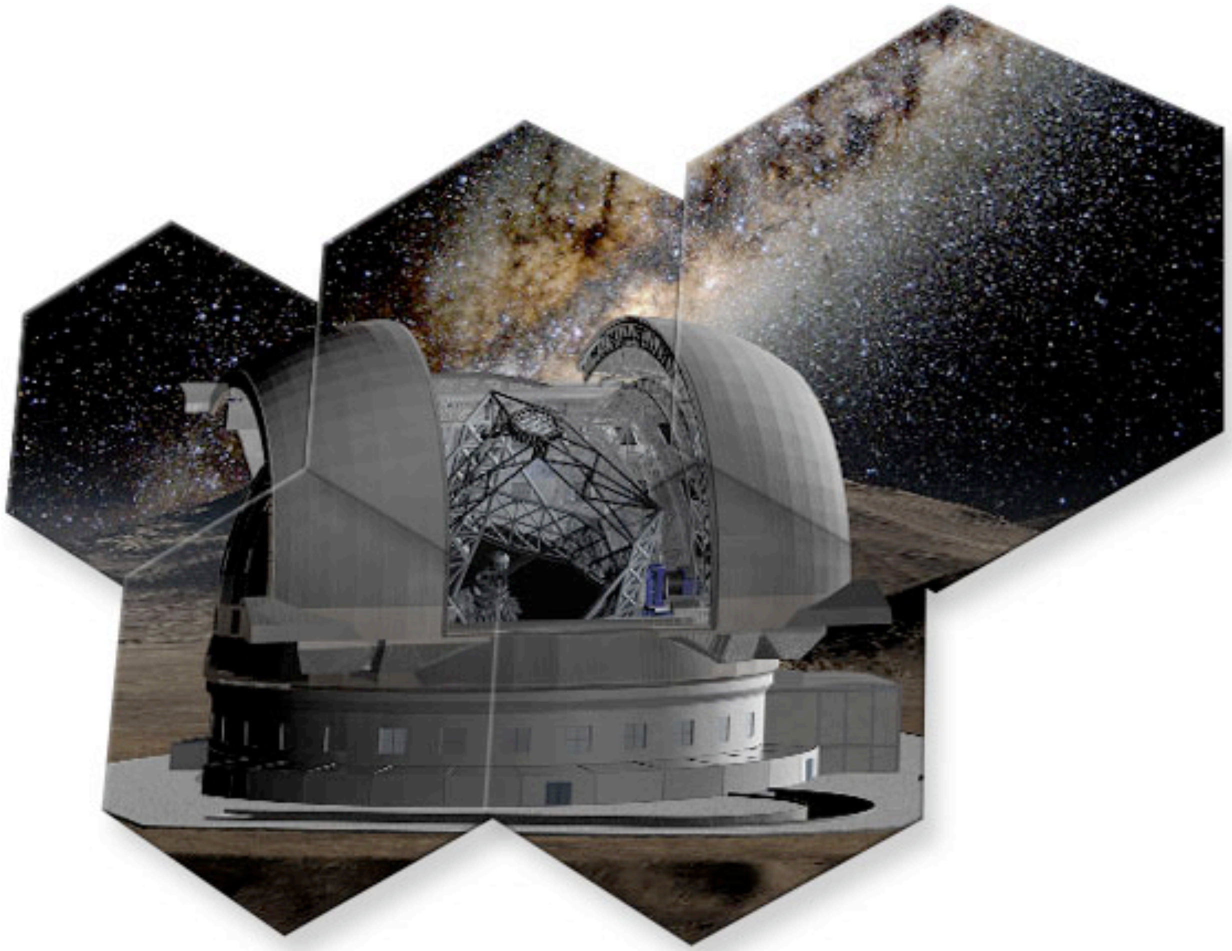


GMT



TMT

# IR Astronomy: The Future

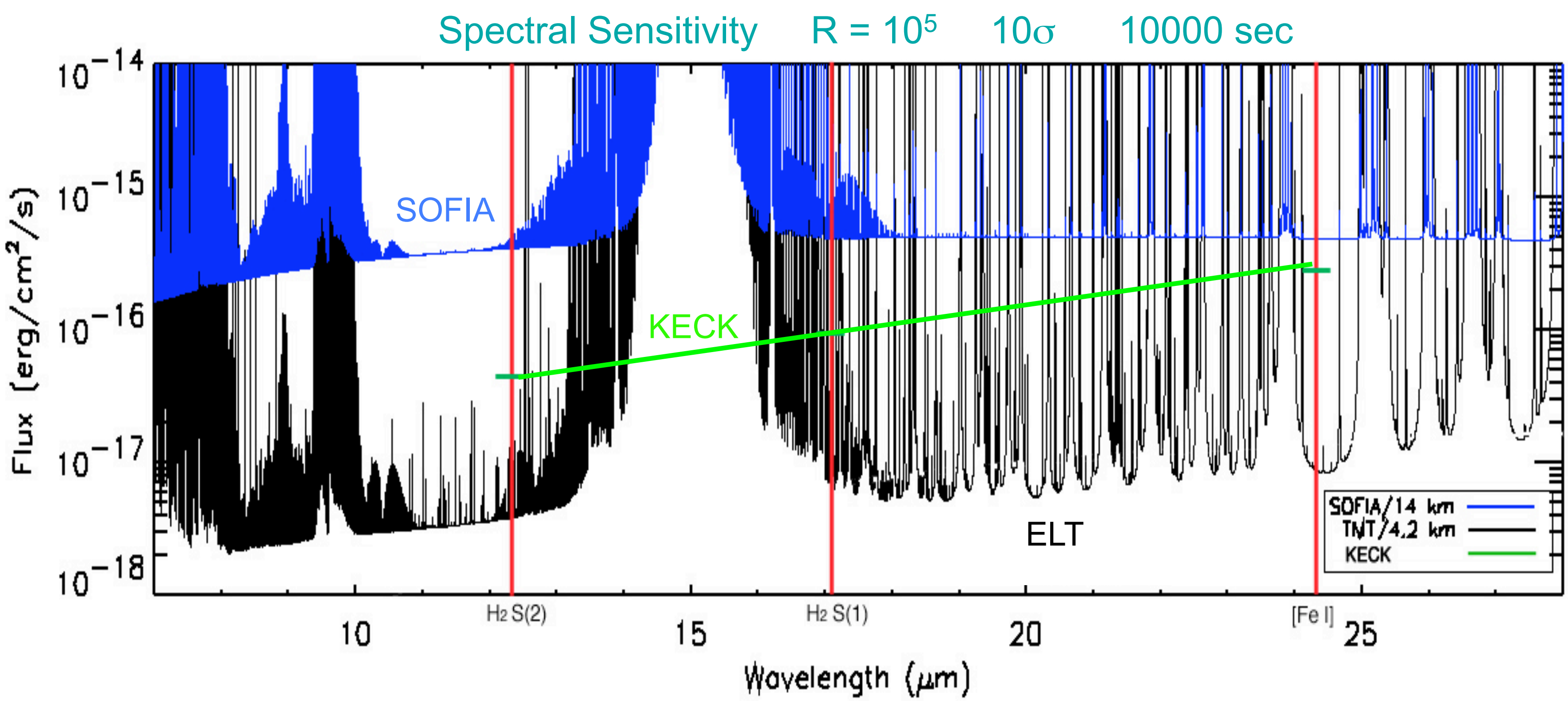


E-ELT

# A Example of $D^4$ Science in the mid-IR

# Mid-IR Spectroscopy & Imaging

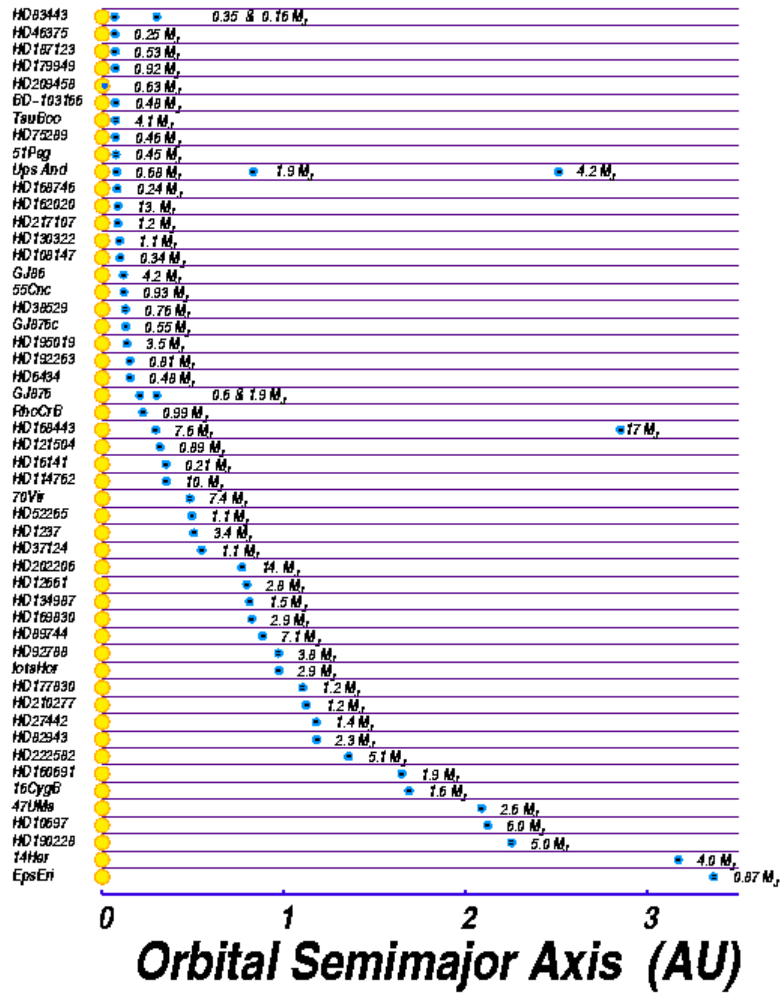
## Potential gains for high resolution spectroscopy



# Probing Planet Formation in YSO Accretion Disks

# The Challenge

What factors account for the diversity of planetary system architectures?



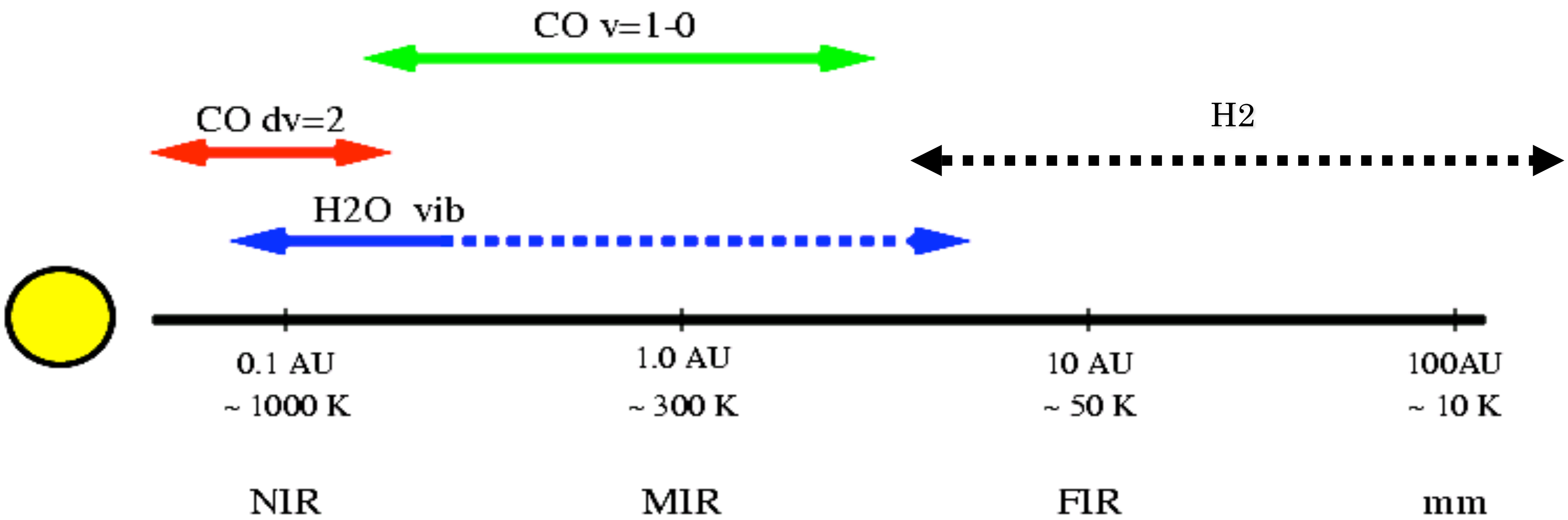
# Mid-IR Study of Accretion Disks

- Goals:
  - Quantify M[r],T[r] and chemistry in circumstellar accretion disks
  - Detect signatures of giant planet formation
- Key Questions:
  - When and where do EGPs form during the accretion phase
  - How much gas is available to build giant planets and where is it?

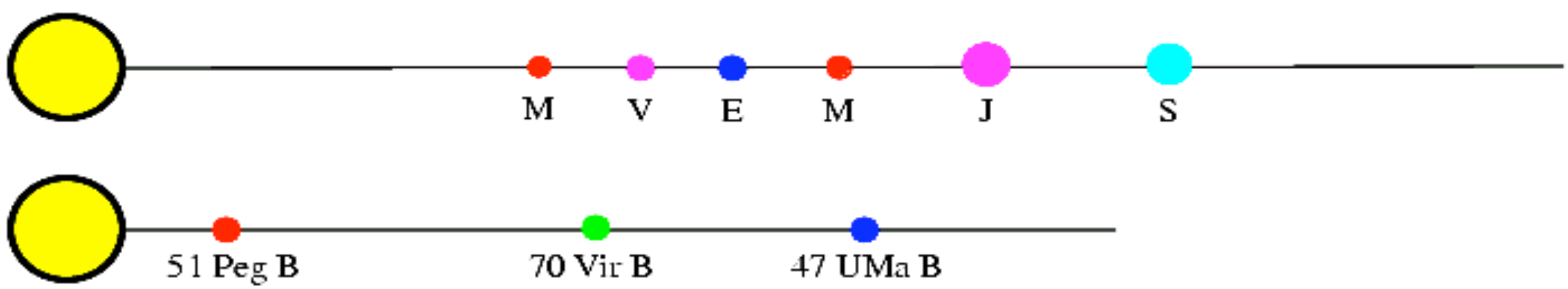
# Key Mid-IR Measurements

- Molecular tracers diagnostic of gas with temperatures from
  - 1500 K (near the disk- stellar magnetosphere boundary) to
  - 30-50 K (near the orbit of Neptune)
- Example molecules:
  - CO, $H_2$, $H_2O$, $C_2H_2$, HCN
- Velocity widths range from
  - ~100 km/sec near the disk-magnetosphere boundary, to
  - ~ 3 km/sec at 100 AU
- Line profiles probe gas distribution
  - High S/N at high spectral resolution critical
  - Targets are unresolved; spectroscopy probes structure on ~ AU scales

# Infrared Diagnostics of Protoplanetary Disks

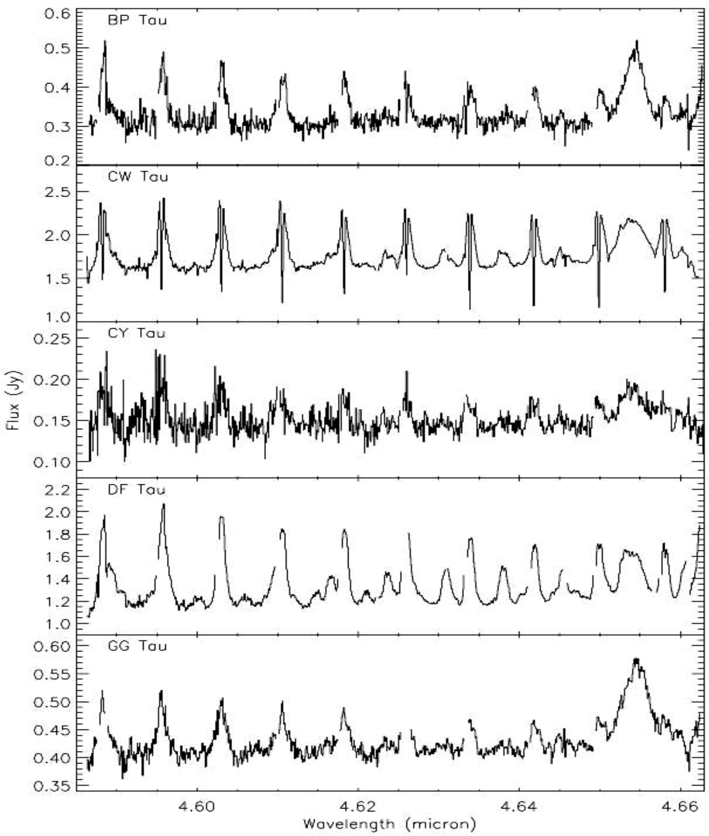



# Planets Around Normal Stars



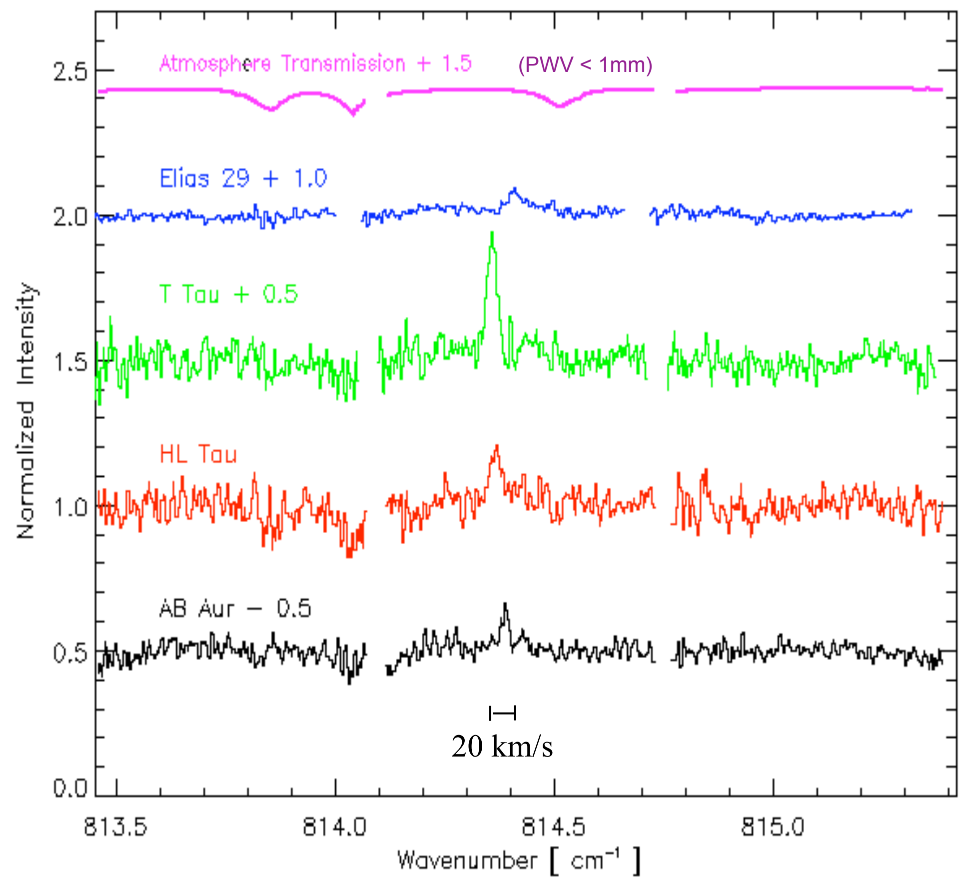
# Circumstellar Accretion Disks: Examples of Gas Diagnostics

CO fundamental (4.6μm)

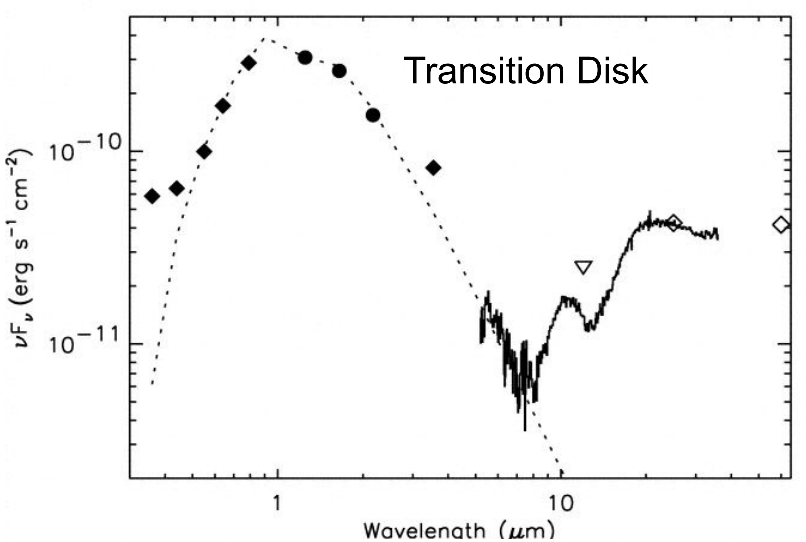


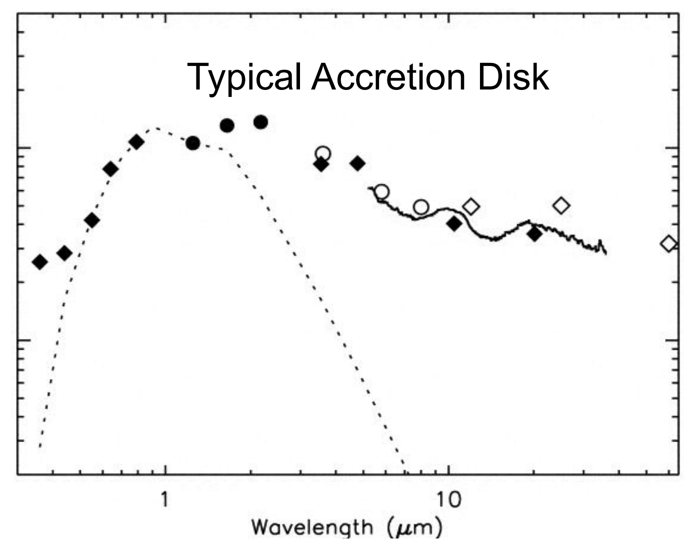

Najita et al. 2003

$H_2$ J=4-2 line (12 μm)



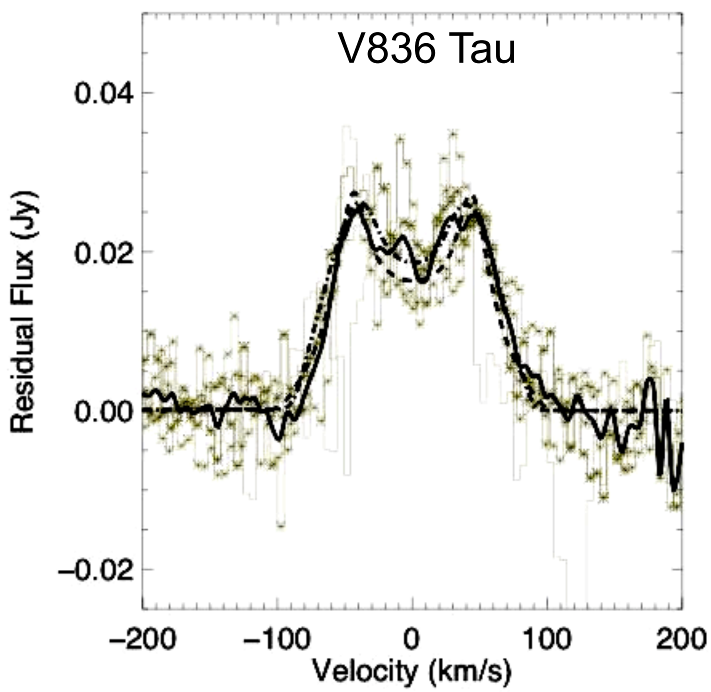
# Searching for Forming Planets



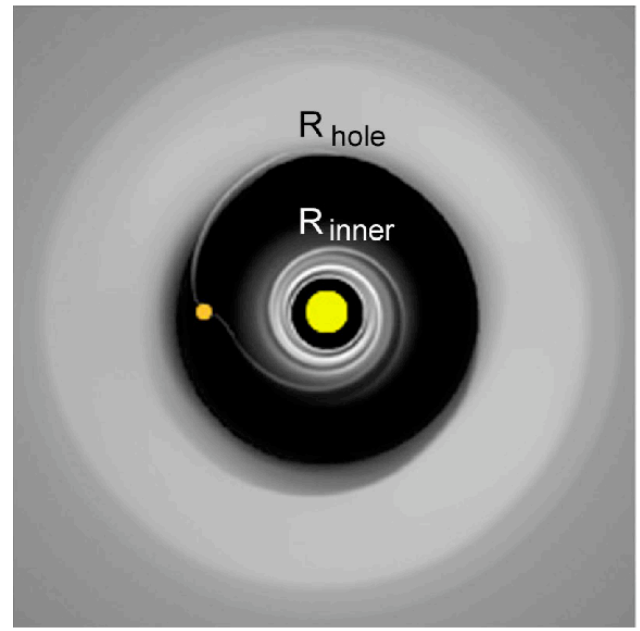



# Searching for Forming Planets

Najita, Crockett & Carr

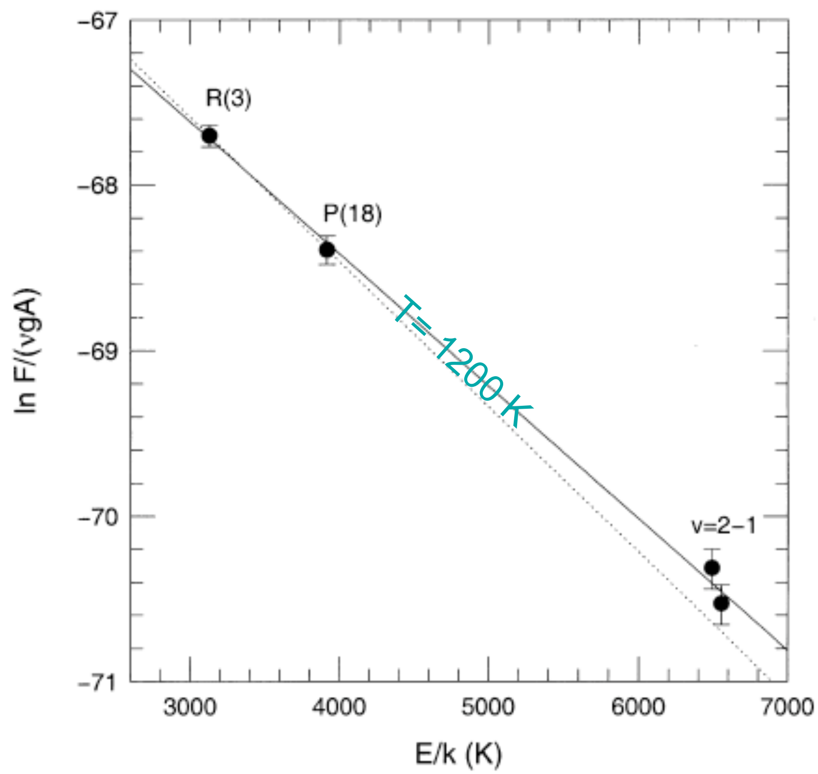



Line profile indicates CO emission from 0.06-0.4 AU




Predicted flow pattern in a disk that has formed a Jovian mass planet

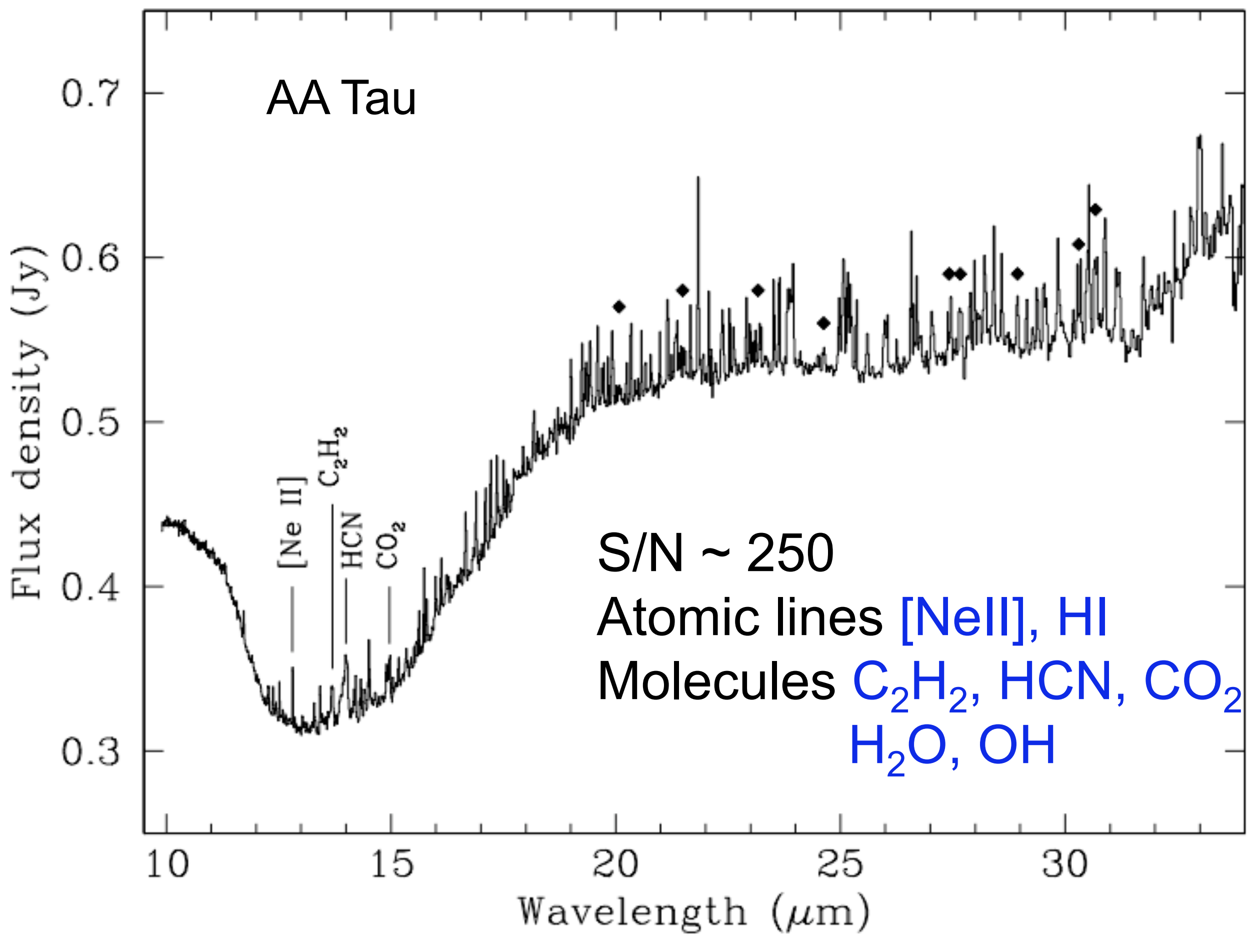
# Diagnosing Disk Physical Parameters



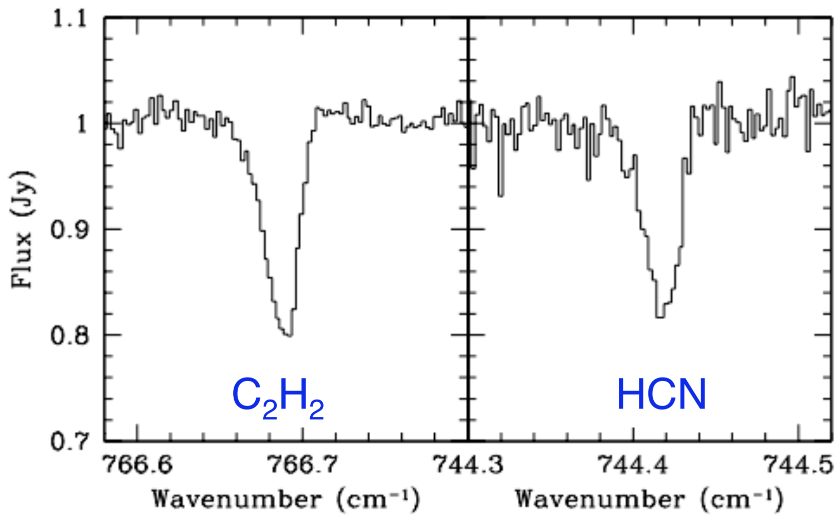

Deriving Excitation Temperature from Multiple CO fundamental Transitions

# Searching for Complex Molecules

Spitzer Observations of a Typical solar-type PMS Star

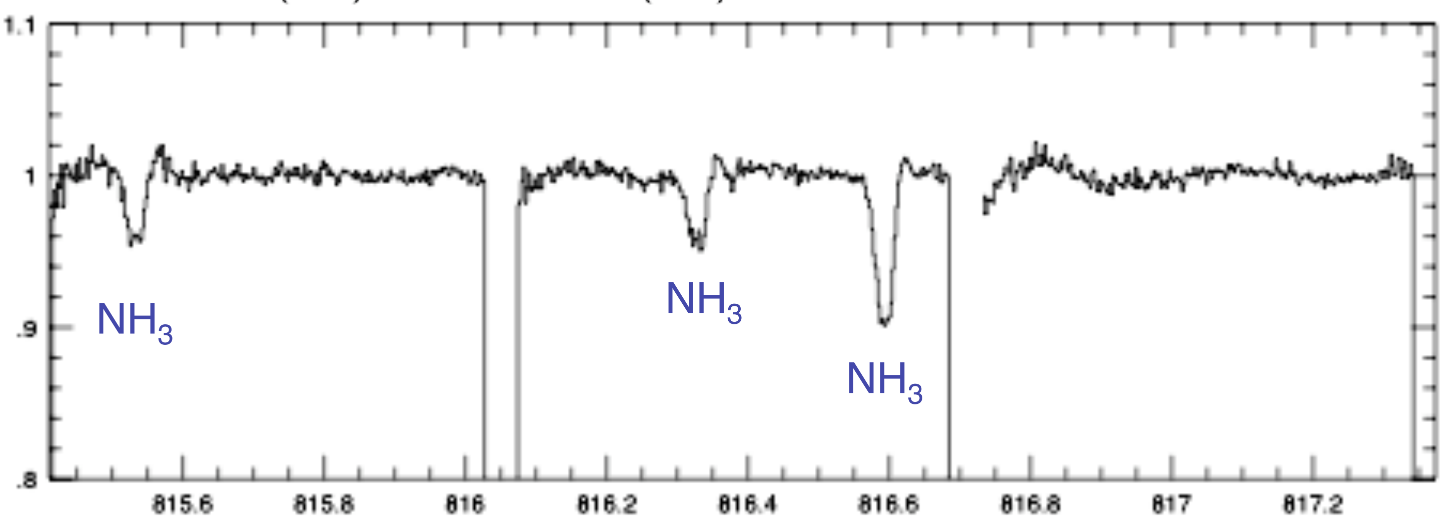


# Searching for Complex Molecules



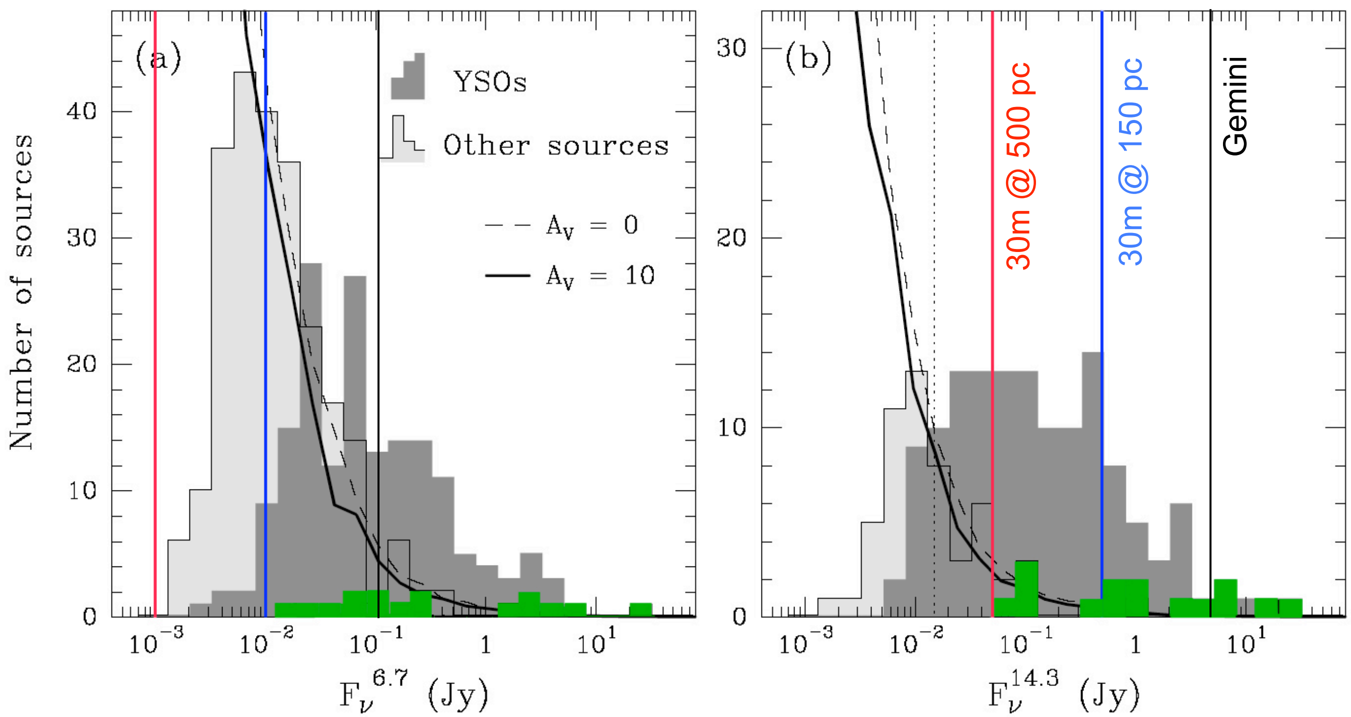

Gemini/TEXES (R=$10^5$)

FWZI ~ 20 km/s



# Potential Targets

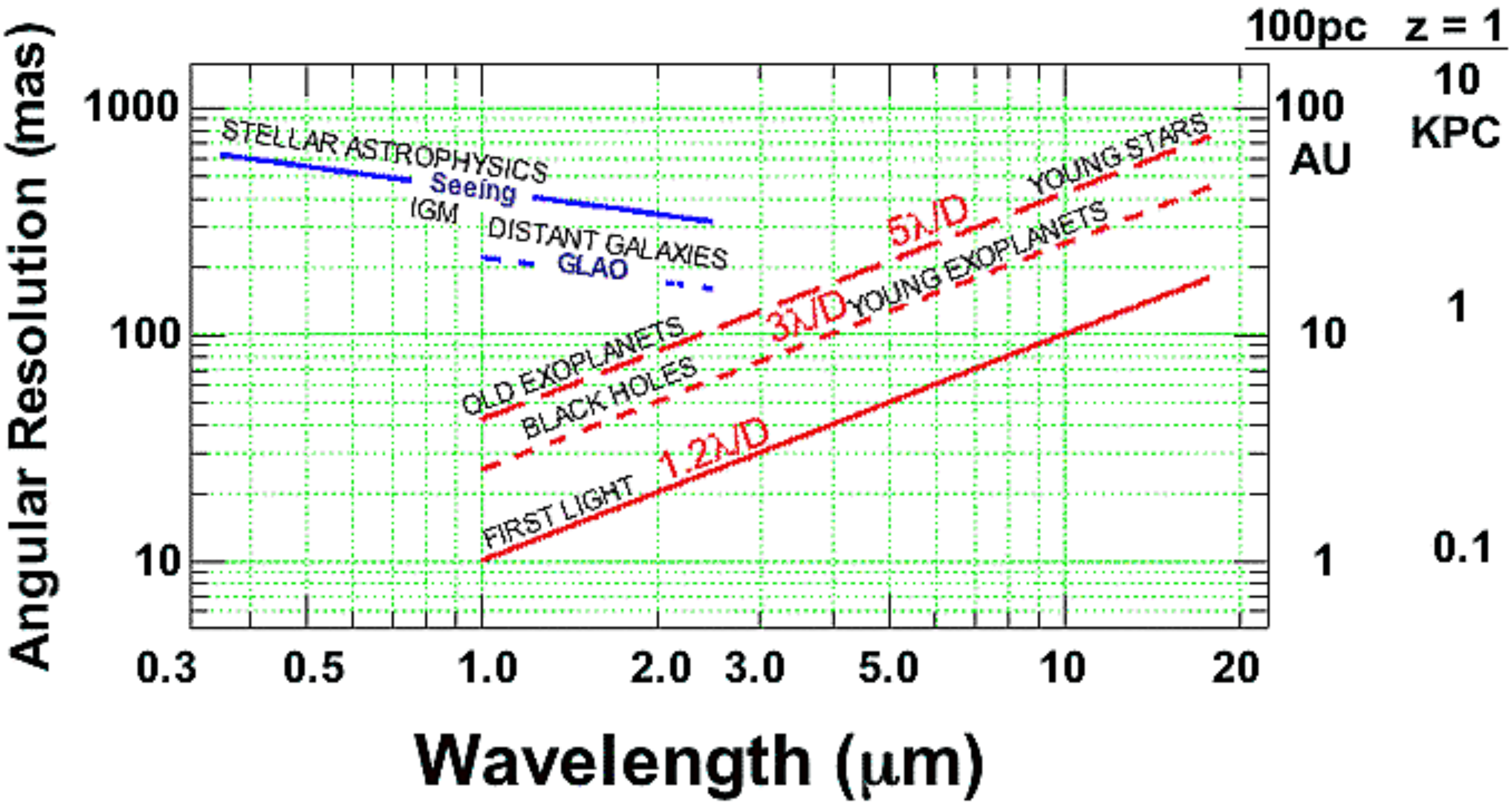
Potential Targets in the Ophiuchus Molecular Complex
(Based on an ISOCAM Survey: Bontemps et al 2001)




Diffraction-Limited ELT Needed to Enable Statistical Studies

# Examples of IR Imaging Science in the ELT era

# Potential of ELTs with AO



# Understanding Galaxy Assembly: Studies of Stellar Population Mixes

# Quantifying Stellar Populations

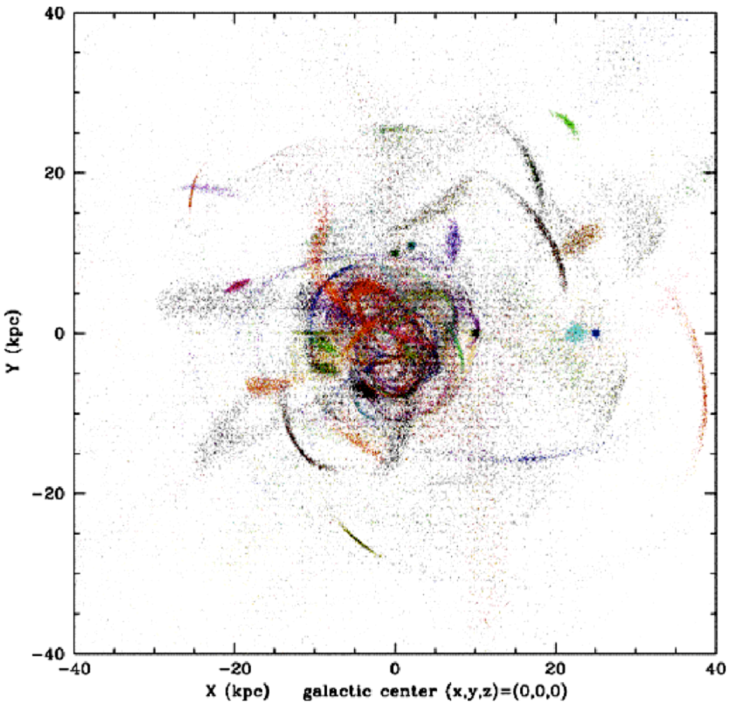
## Key Questions:

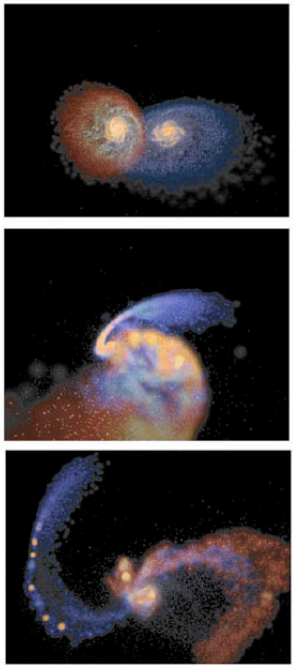
- What is the relationship between bulge and disk formation?
- Can we infer the merger history of elliptical galaxies?

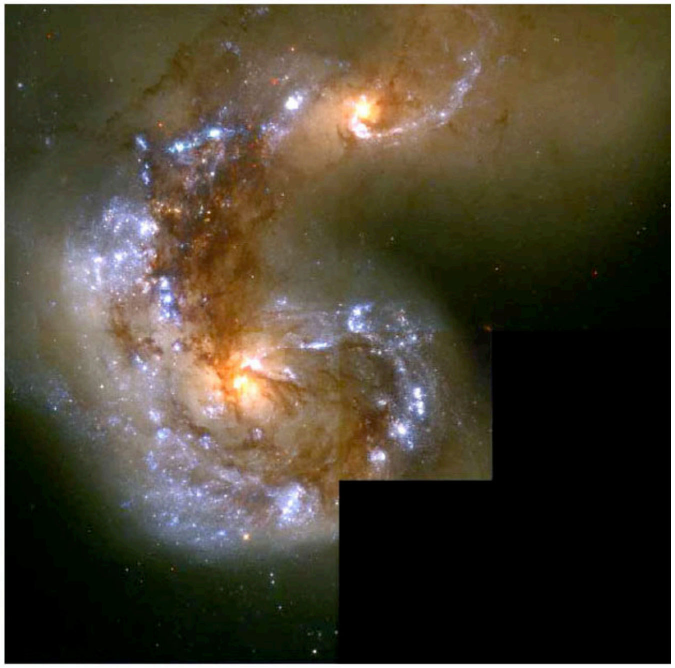
## Key Measurements:

- near-IR photometry of the dominant stellar populations in spiral bulges, spiral disks and portions of elliptical galaxies
  - — enables estimates of age and chemical composition

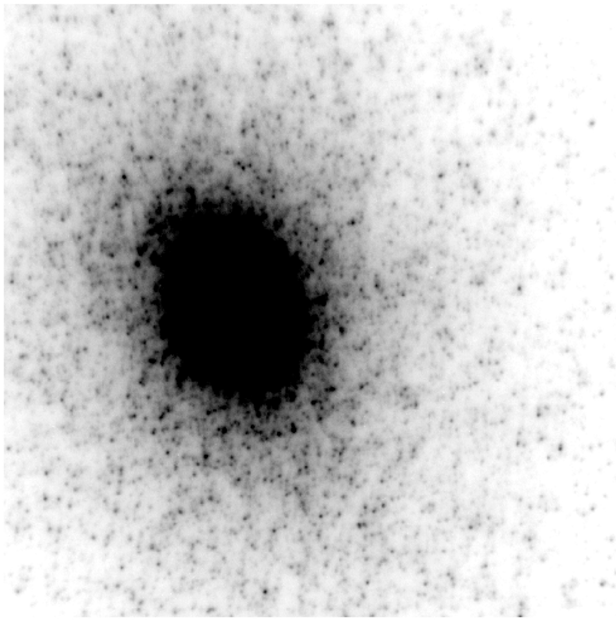
# Current Galaxy Formation Models



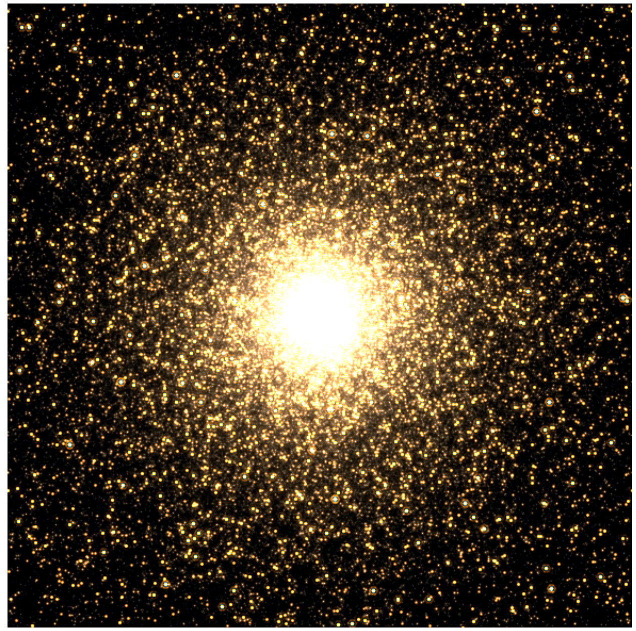





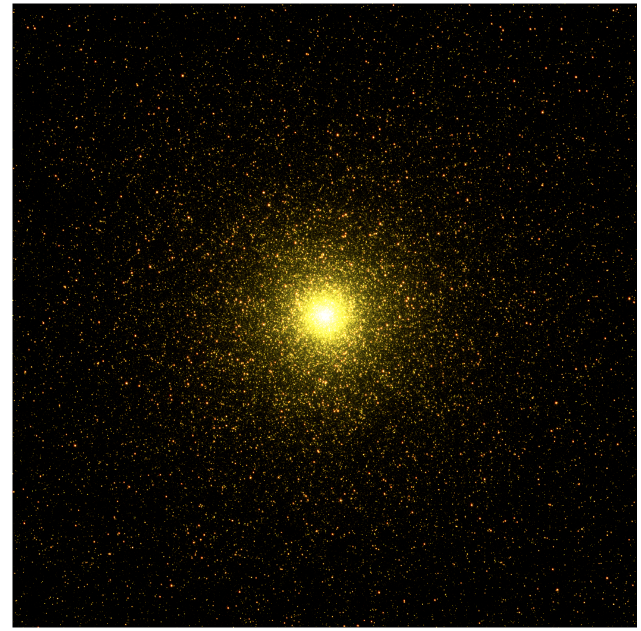
# The Center of M32



Gemini (Davidge et al. 2000)

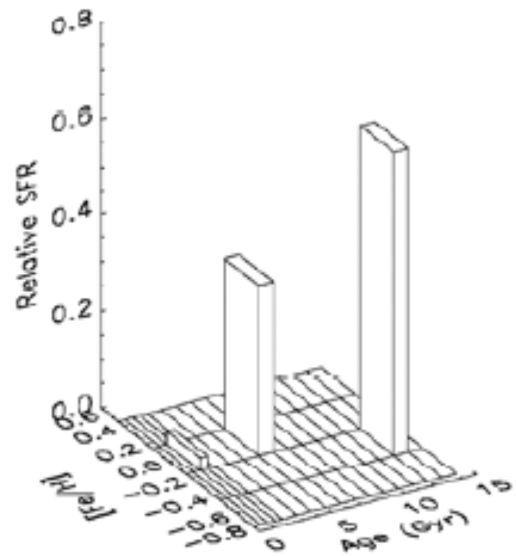


JWST simulation



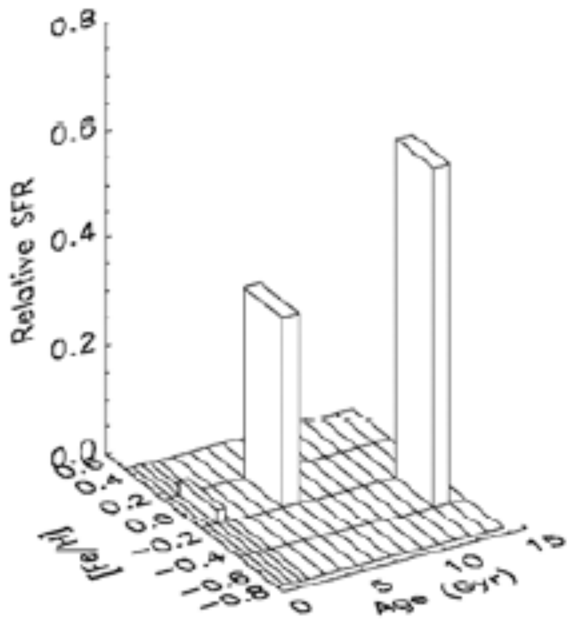
30m simulation

Input age, composition mix

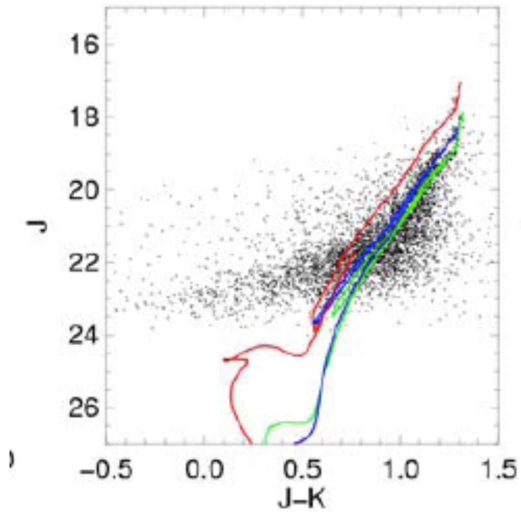


# The Center of M32

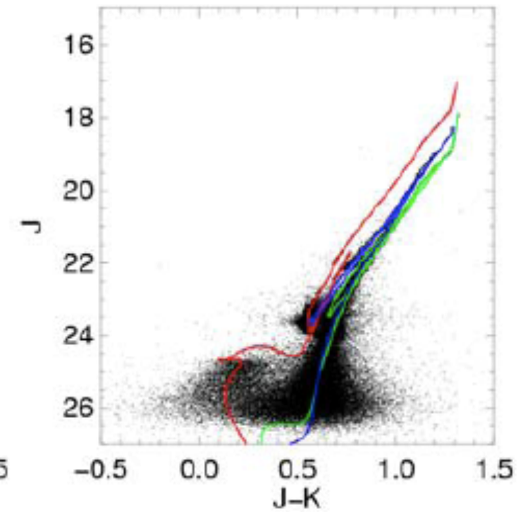
Input age, composition mix



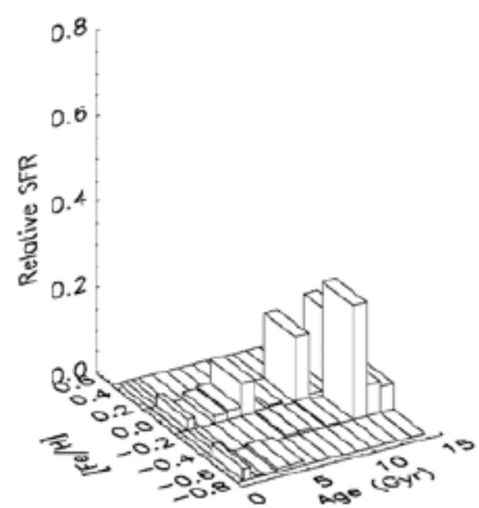

JWST simulation

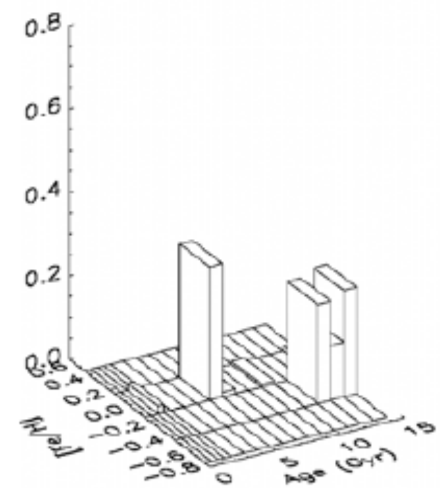



GSMT simulation

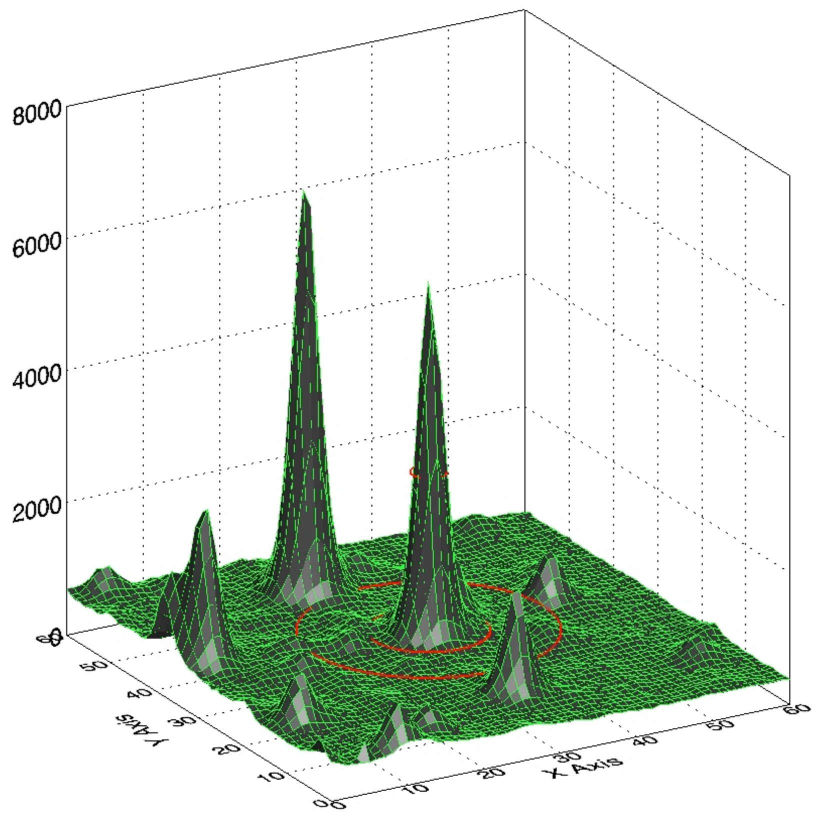



Photometric Accuracy Limited by Crowding



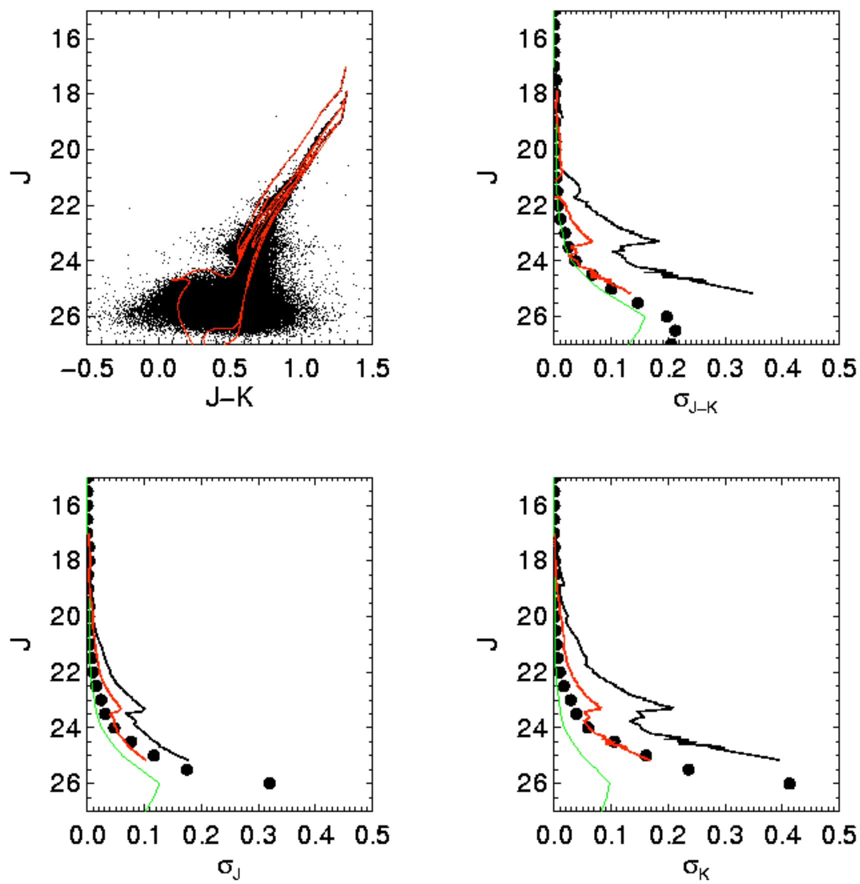
# Crowding Limits Photometric Accuracy




–Crowding introduces photometric error through luminosity fluctuations within a *single* resolution element of the telescope

–Due to the unresolved stellar sources (not sky!) in that element.

# Crowding Limits for a 30m ELT




Limiting luminosity due to crowding ~ (telescope diameter)$^{-2}$

# Probing the Stellar IMF in High Density & Low Metallicity Regions

# Probing the IMF in New Regimes

Goals:

- Quantify the IMF in rich, dense star-forming regions
  - dominant contributor to total stellar content of galaxies
- Understand the relationship between IMF; initial conditions
  - e.g. explore linkage to re core density; thermal + turbulent pressure

Critical to understanding and modeling star-formation in the early universe

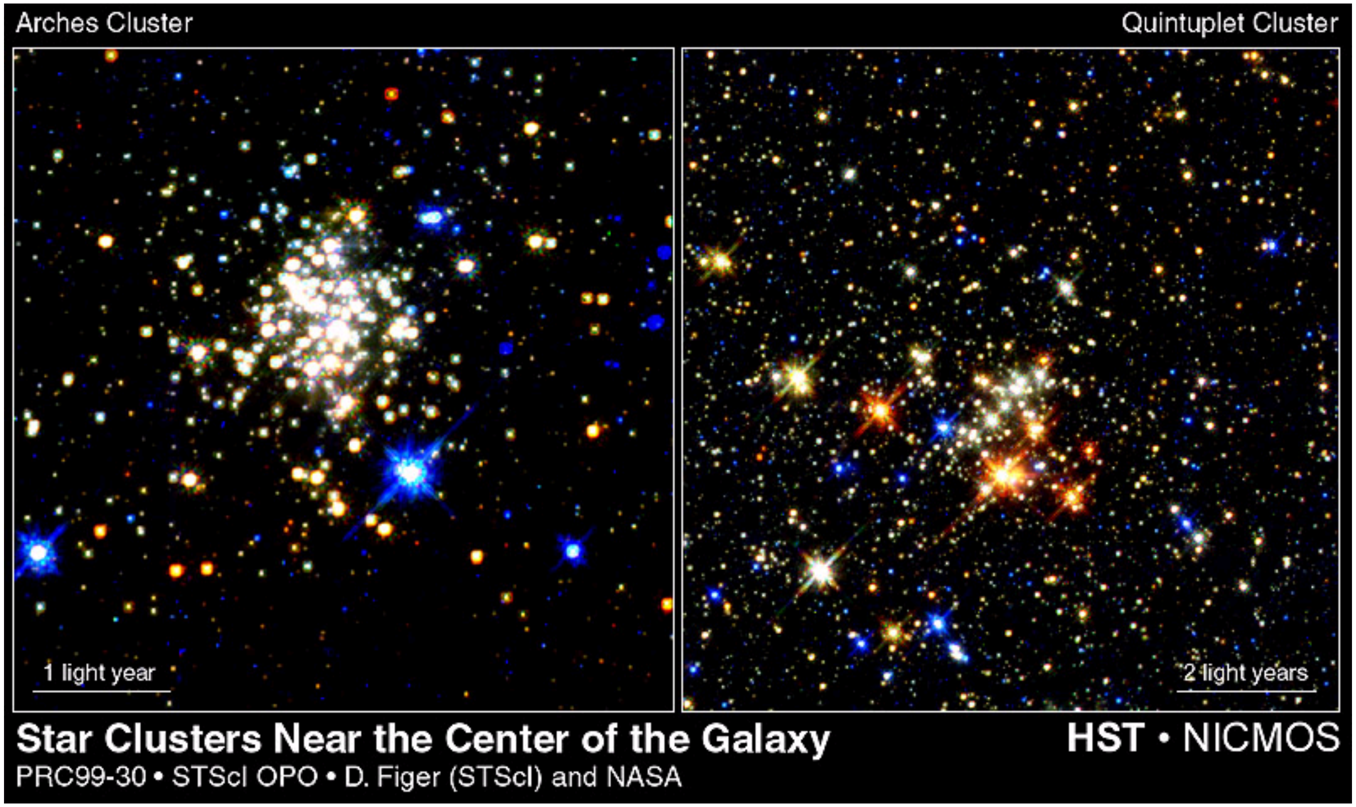
# Measurements Needed

Measurements Needed:

- JHK photometry
  - High quality images (high Strehl ~ 0.7 at K-band)
- IFU spectroscopy at R ~ 1000 provides spectral types
- Spectral types + photometry yield:
  - $N(A_v)$
  - statistical model of N(K)
  - N (M) for assumed age

# Example Targets

Galactic Center Superclusters: d = 10 kpc

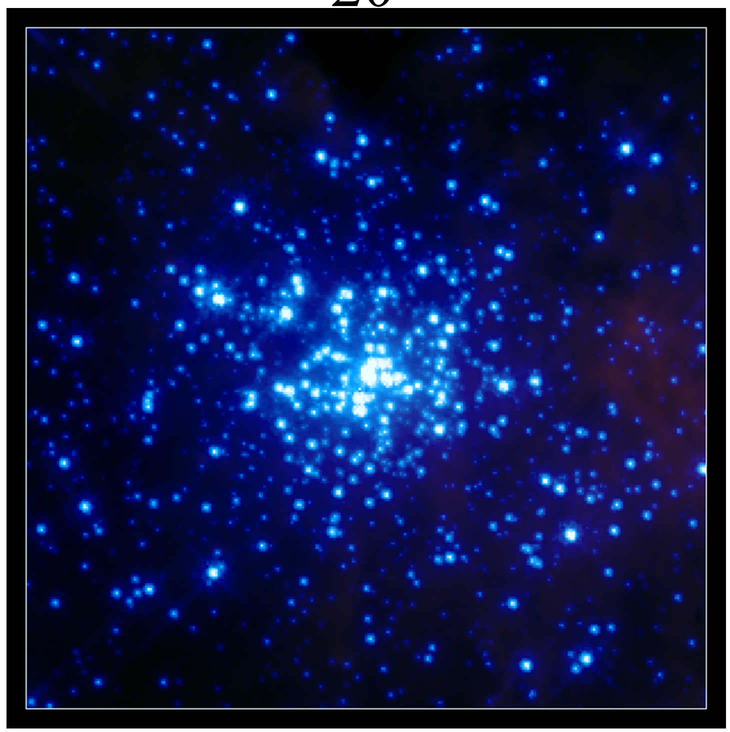



Stellar density ~ 100x Orion Nebula Cluster

# Example Targets

LMC Massive Cluster: d = 200 kpc

20”



R 136

Stellar density ~ 10x Orion Nebula Cluster

# Potential of IR Observations with ELTs

**Key issue is crowding (not photon collection)**

With a ~30m ELT, K-band diffraction limit is 15 mas

- Clusters like R136 can be studied throughout M33 disk
  - Probe IMF for wide range of densities; metallicities
- R136-like clusters can be studied out to M82 (upper end of IMF)

# Simulated Performance

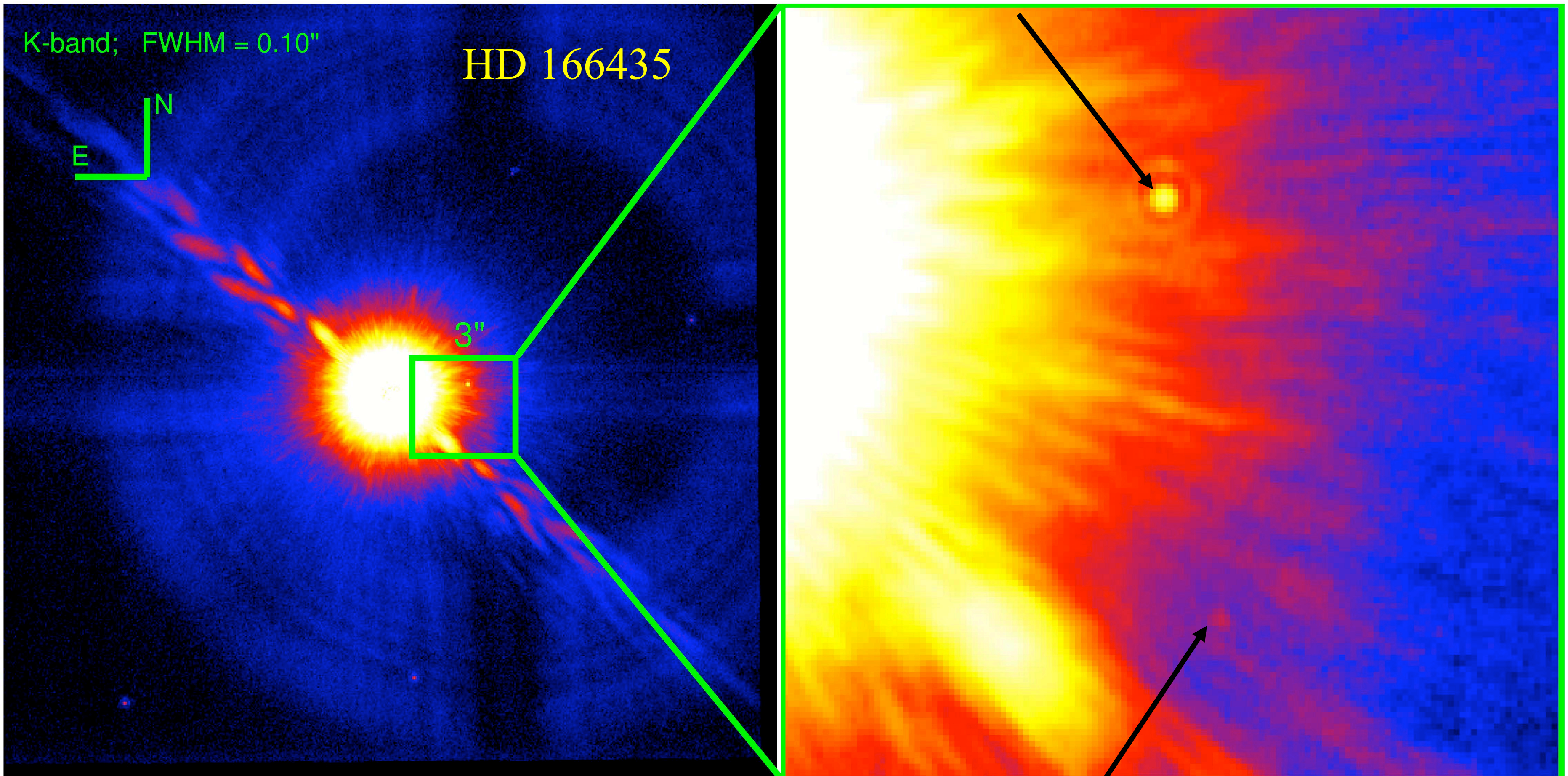
| | Limiting $M_K$ | | | Limiting mass | | | Exposure time | | |
|---|---|---|---|---|---|---|---|---|---|
| | LMC | M33 | M82 | LMC | M33 | M82 | LMC | M33 | M82 |
| $0.5R_{1/2}$ | >9.0 | -7.5 | <-8.0 | ~0.01 | ~150 | >150 | 10000 | 0.01 | <0.2 |
| $R_{1/2}$ | >9.0 | -5.6 | <-8.0 | ~0.01 | 83 | >150 | 10000 | 0.08 | <0.2 |
| $2R_{1/2}$ | >9.0 | -2.2 | -7.8 | ~0.01 | 9.4 | >150 | 10000 | 2.2 | 0.2 |
| $5R_{1/2}$ | >9.0 | 3.0 | -3.9 | ~0.01 | 0.4 | 28 | 10000 | 10000 | 16.6 |

# Results: 8-m

| | Limiting $M_K$ | | | Limiting mass | | | Exposure time | | |
|---|---|---|---|---|---|---|---|---|---|
| | LMC | M33 | M82 | LMC | M33 | M82 | LMC | M33 | M82 |
| $0.5R_{1/2}$ | -2.2 | <-8.0 | <-8.0 | 9.5 | >150 | >150 | 0.1 | 0.1 | <3 |
| $R_{1/2}$ | 6.1 | <-8.0 | <-8.0 | ~0.05 | >150 | >150 | 10000 | 0.1 | <3 |
| $2R_{1/2}$ | 6.1 | -7.3 | <-8.0 | ~0.05 | >150 | >150 | 10000 | 0.2 | <3 |
| $5R_{1/2}$ | 6.1 | -3.0 | <-8.0 | ~0.05 | >150 | >150 | 10000 | 36.6 | <3 |

# Imaging Extrasolar Planets

# Current Capability




6 x 60 sec on-source exposure with coronagraph;

Ks band (2.16µm);

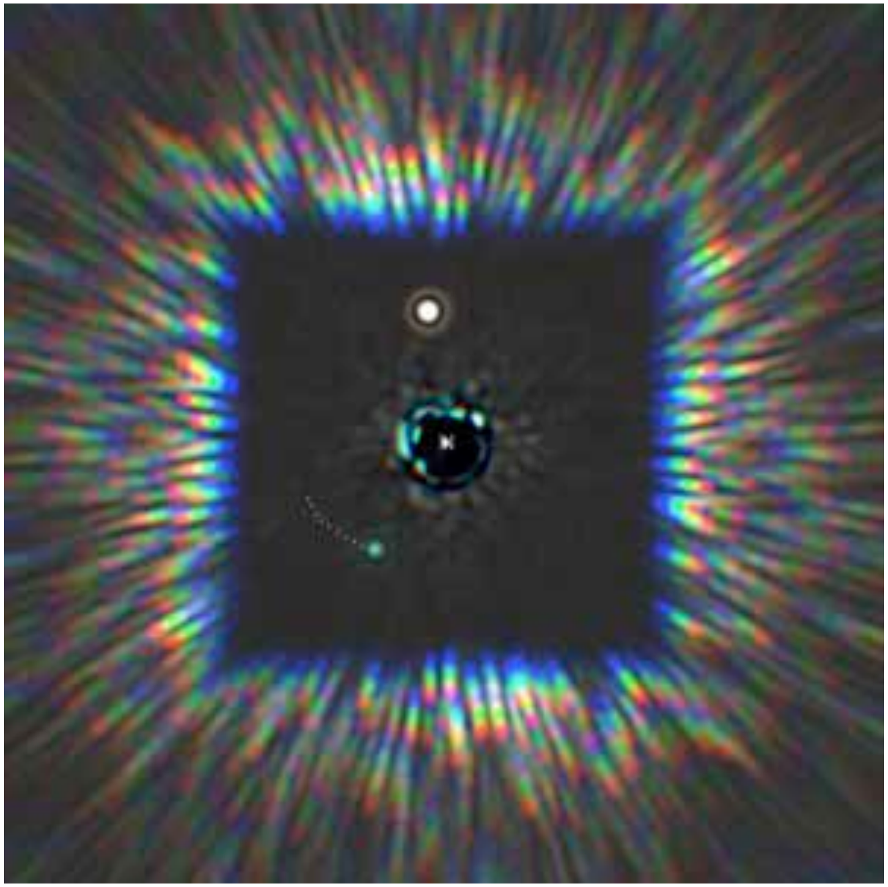
V = 6.9; Strehl > 65%.

ΔK = 13.6 at 3.3″ ($3.6 \times 10^{-6}$)

Slide courtesy of Stan Metchev

# Gemini Planet Imager

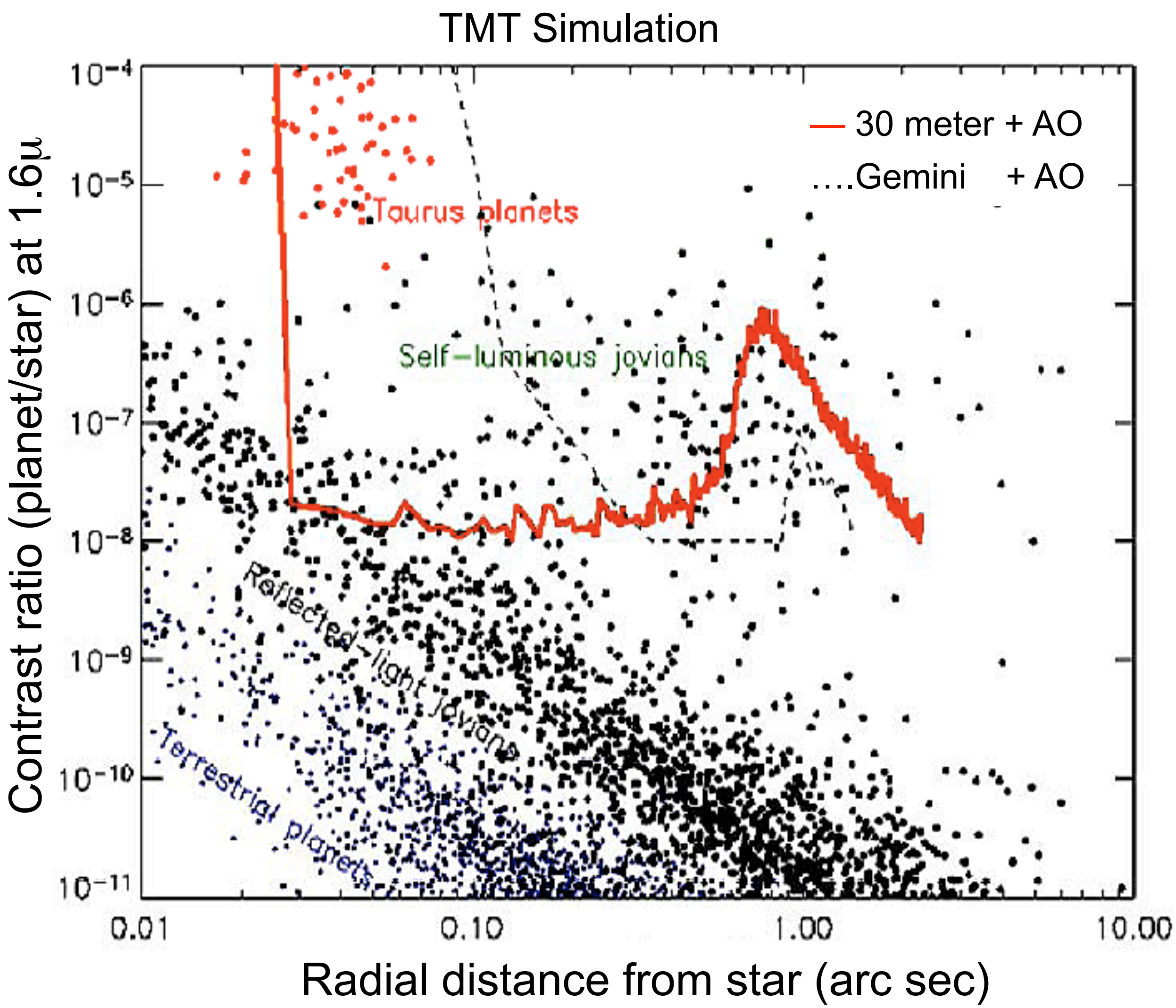
Simulated Perfomance, courtesy James Graham



$10^6$ Contrast Ratio

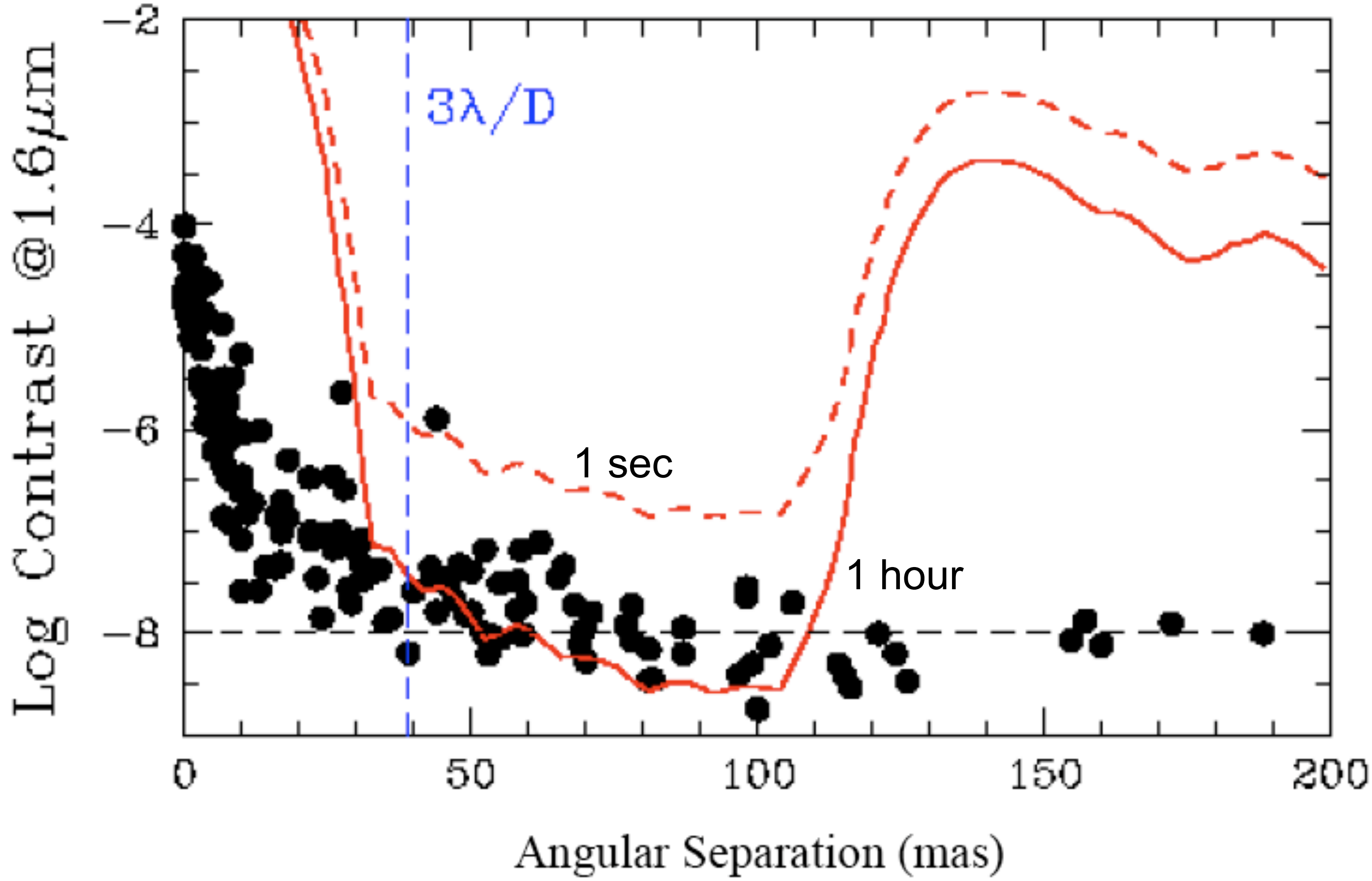
1.6μ

# Imaging Extrasolar Planets

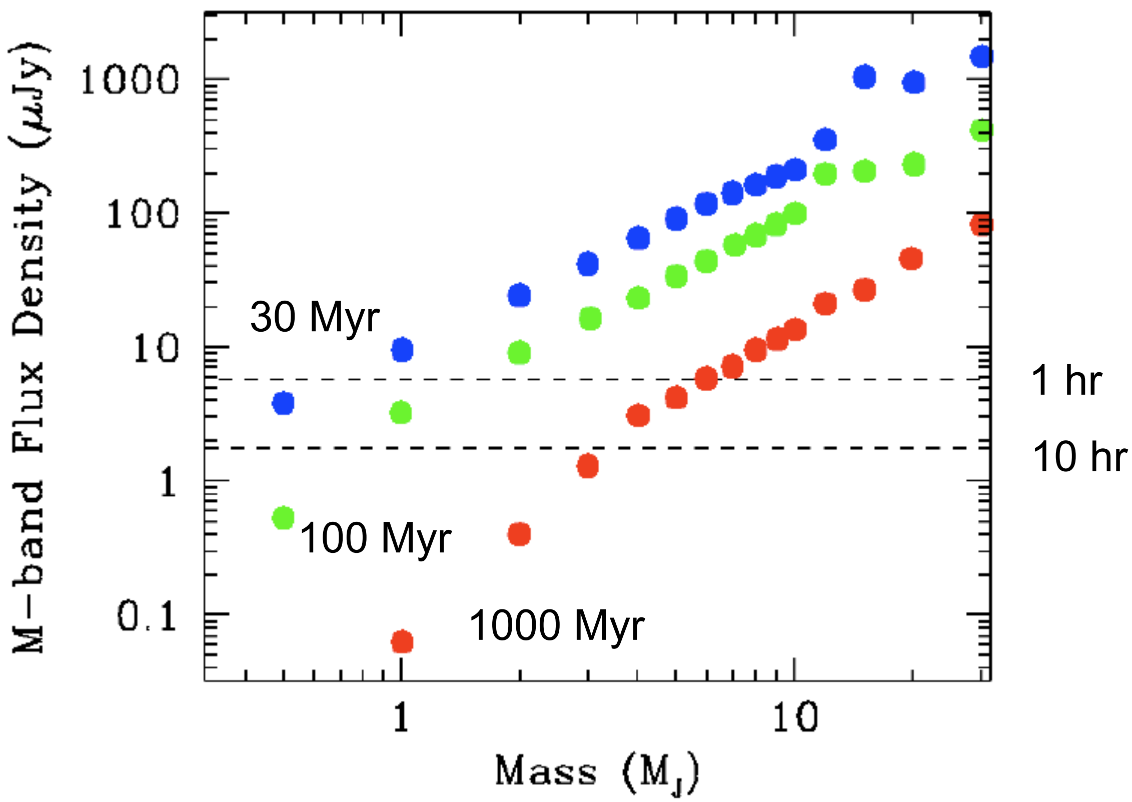


# Imaging Extrasolar Planets

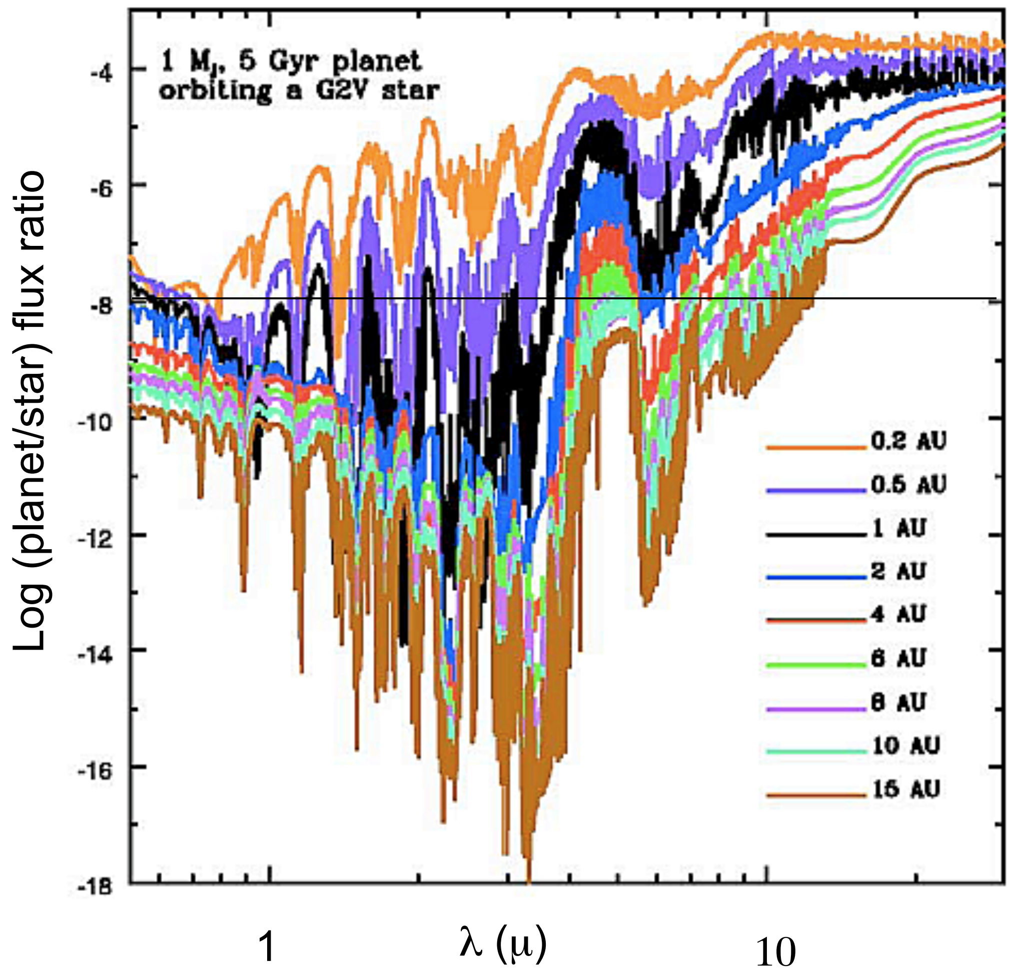
GMT simulation for known Exoplanets



# Imaging Extrasolar Planets: Thermal Infrared



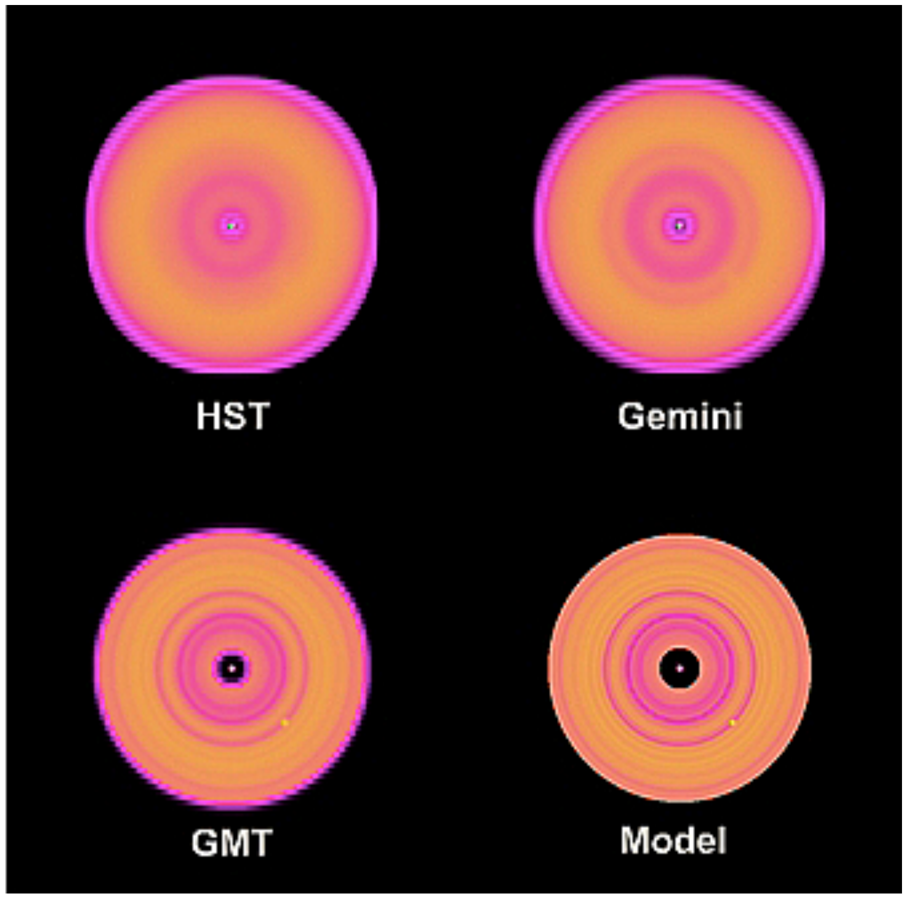
# Determining the Nature of Exoplanet Atmospheres




ExAO spectroscopy of exoplanets

# Detecting Forming Planets

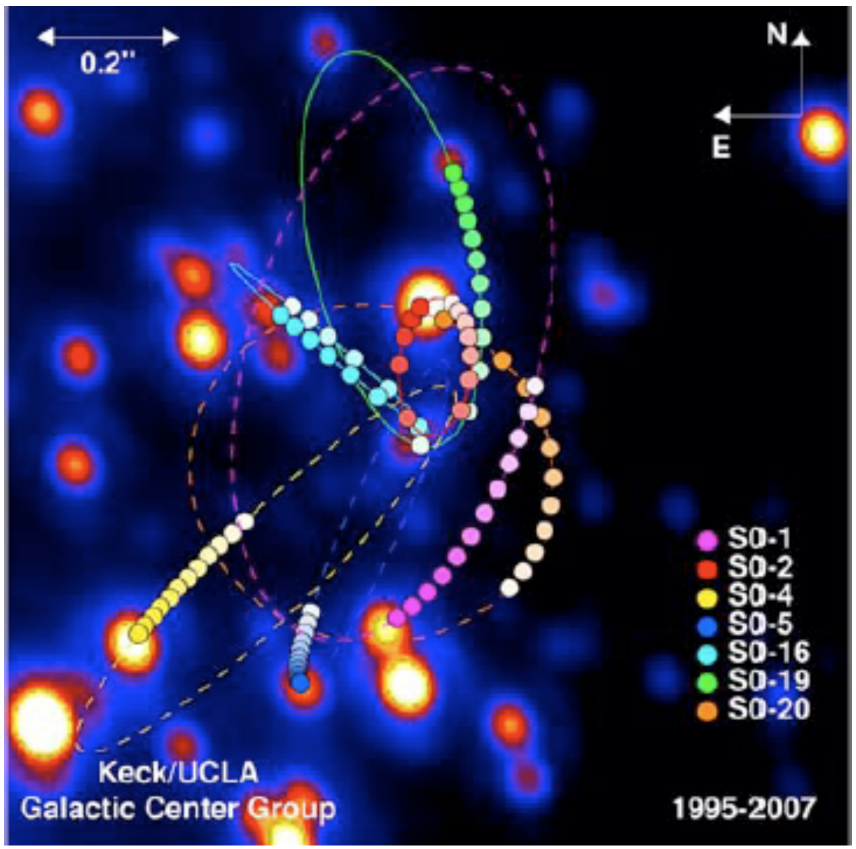
Gap opened by 1 Earth mass planet in CS disk @ 75pc

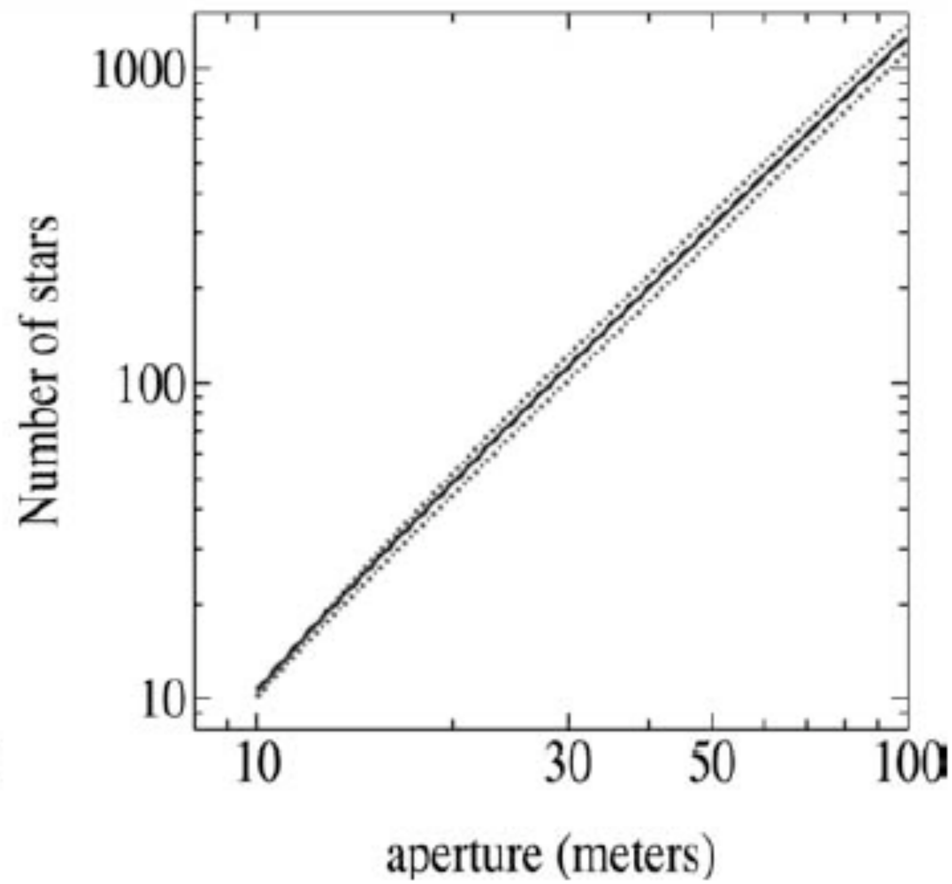



GMT Simulation

# Probing the Central Black hole in the Milky Way Galaxy

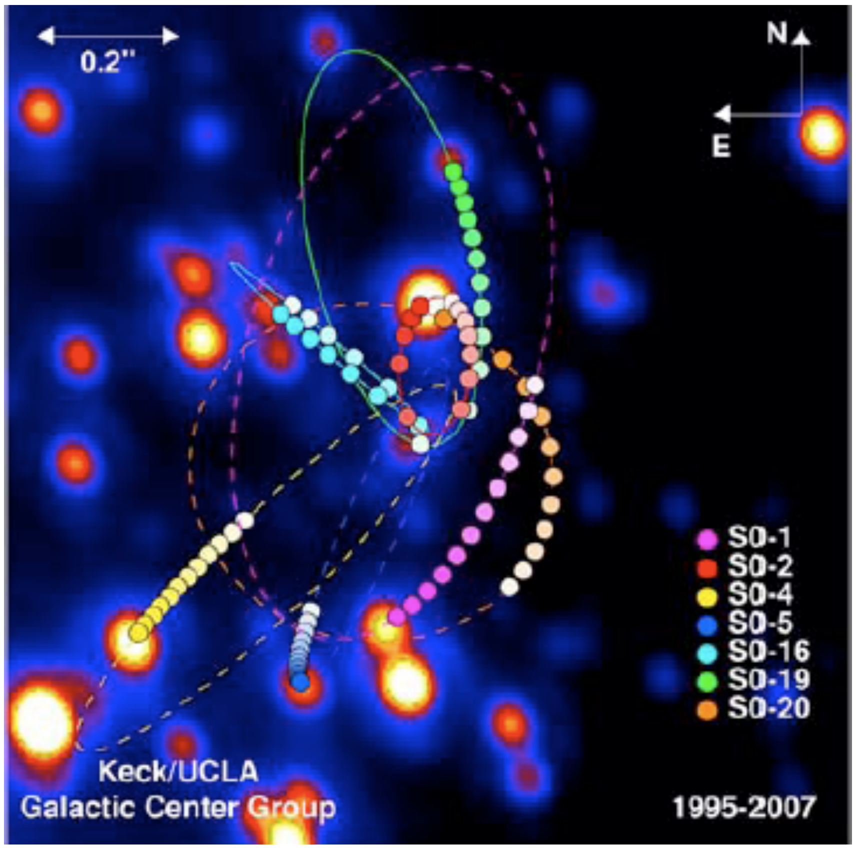
# Proper Motions near the GC




~30m ELT yields positions with 30 μarcsec accuracy

# Proper Motions near the GC



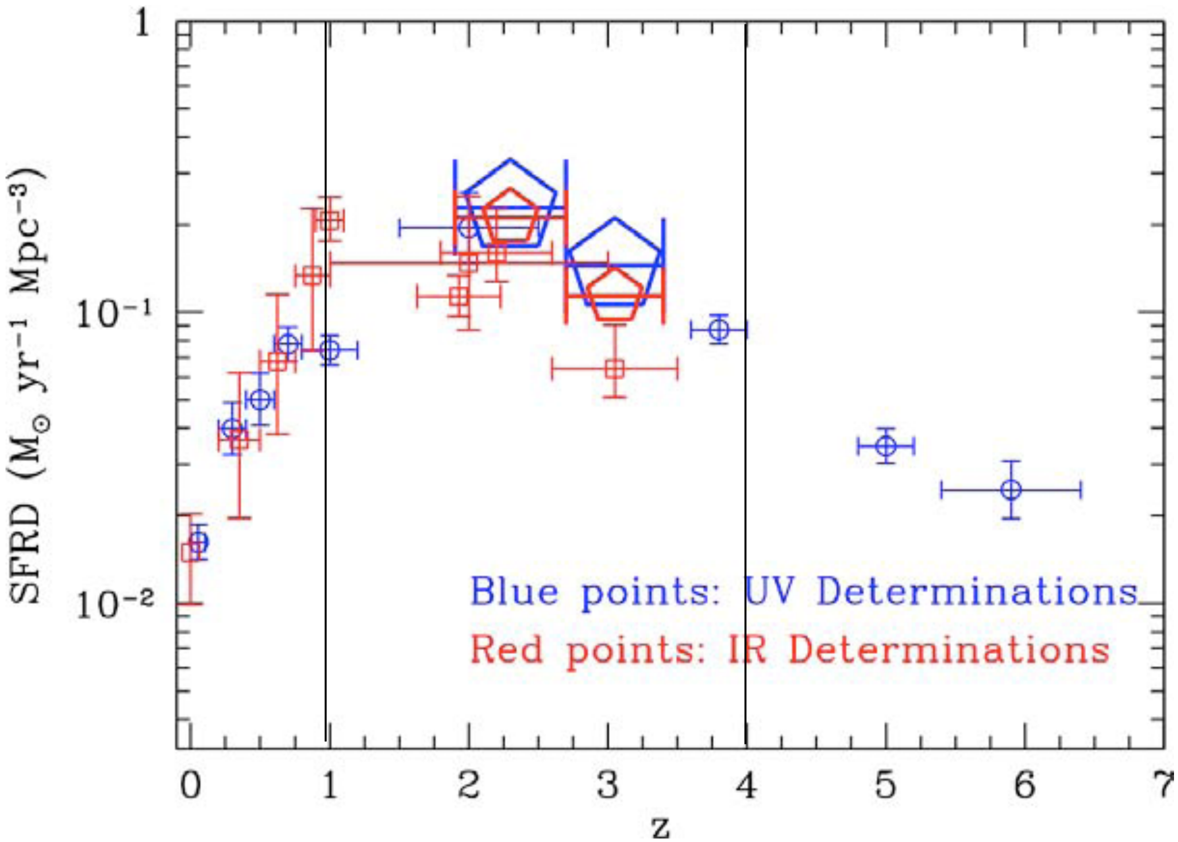

–Determine $M_{BH}$ and $R_C$ to 0.1%

–Determine distribution & shape of extended matter around the BH

–Detect stellar mass black holes from deflections in orbital motions of target stars

# Probing the Epoch of Maximum Star Formation

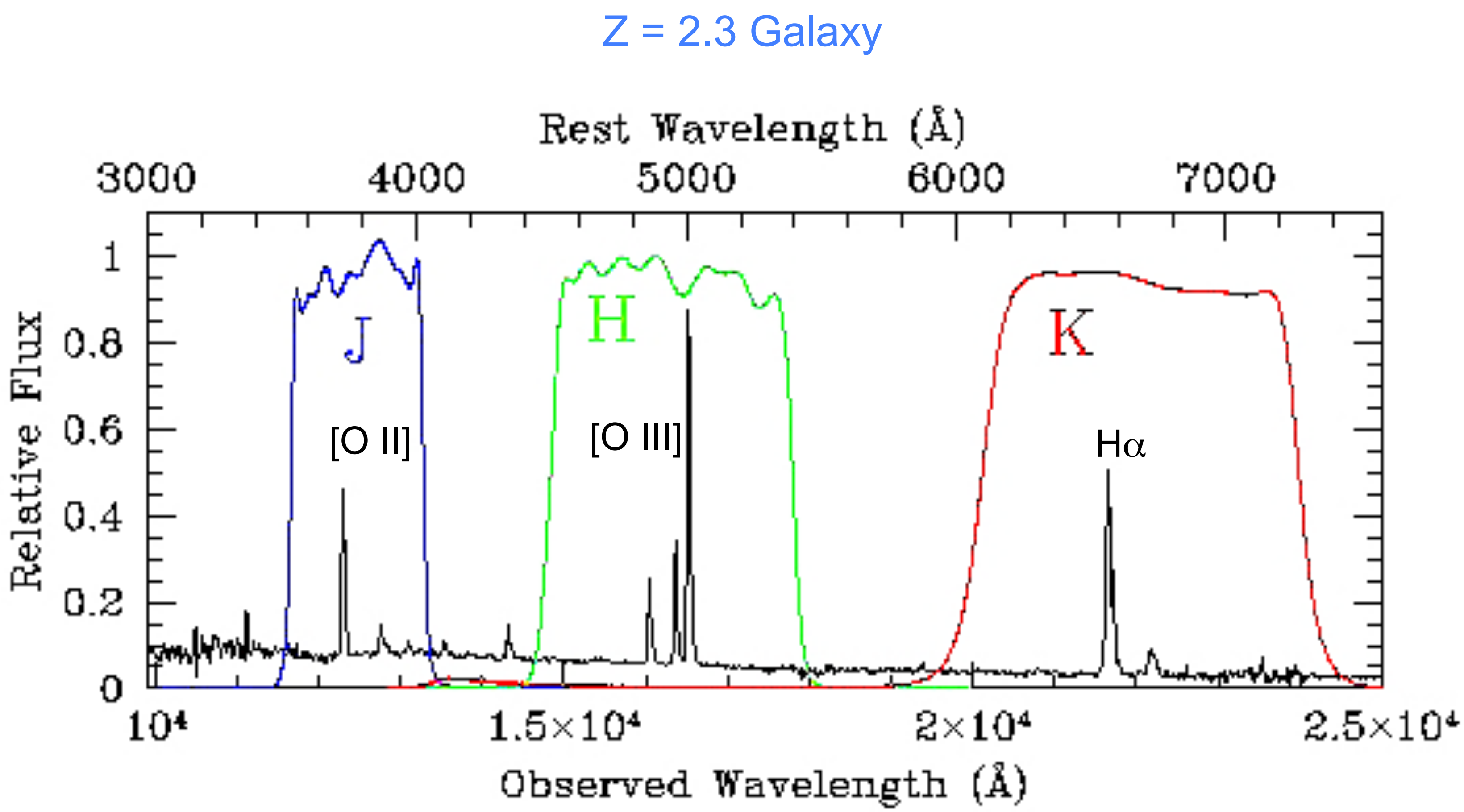
# Star Formation vs z




–ELTs will enable AO-fed IFU spectroscopy

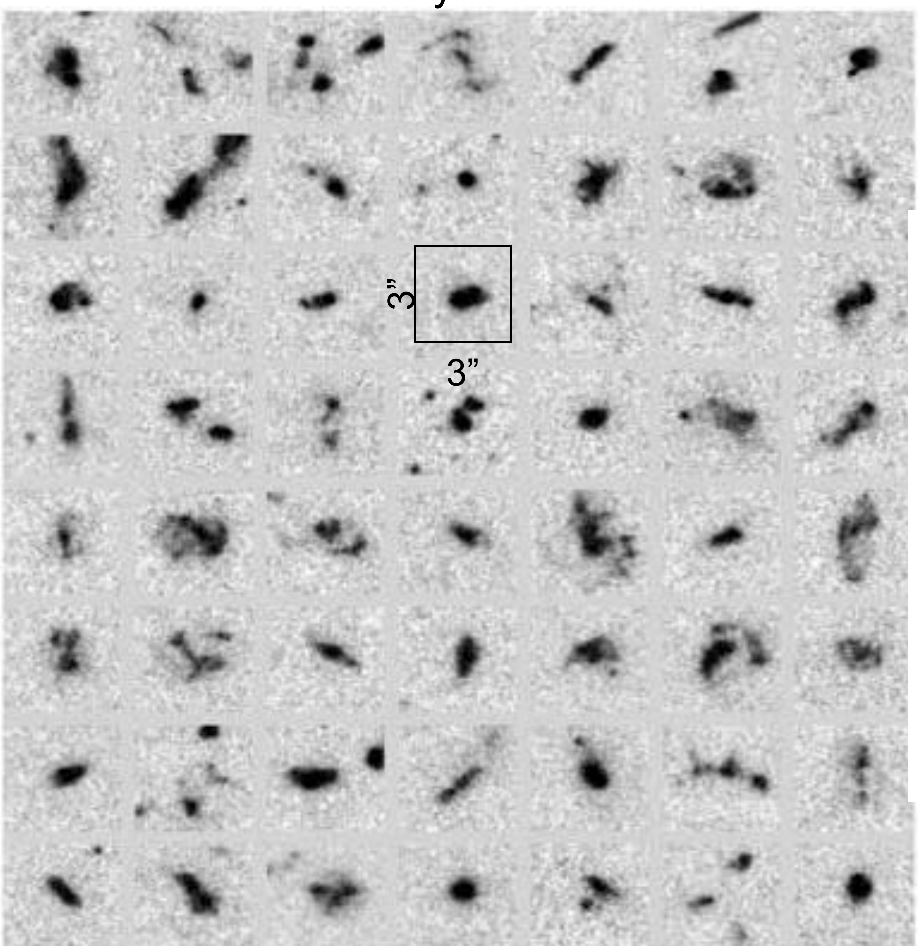
–Probe structure, kinematics and chemistry

# Why the IR is Critical

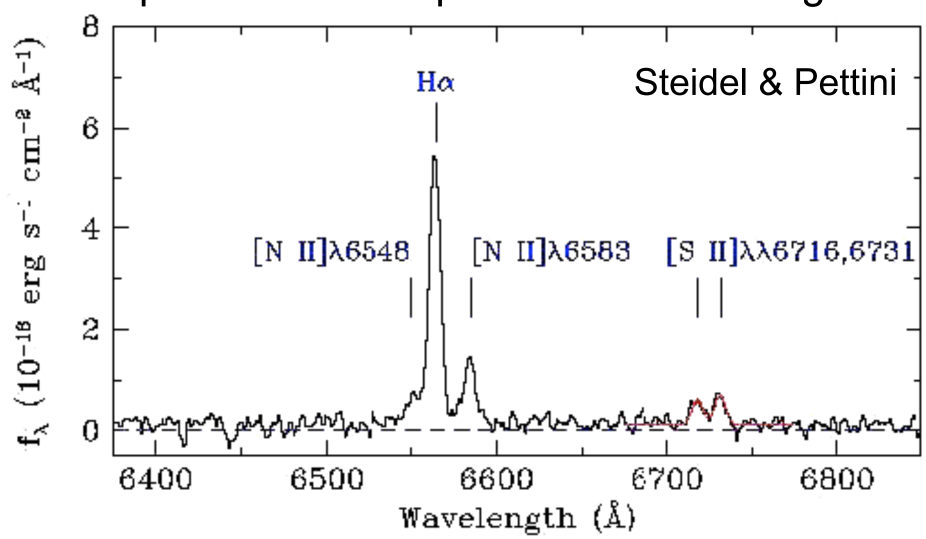


# Examples of Potential Targets

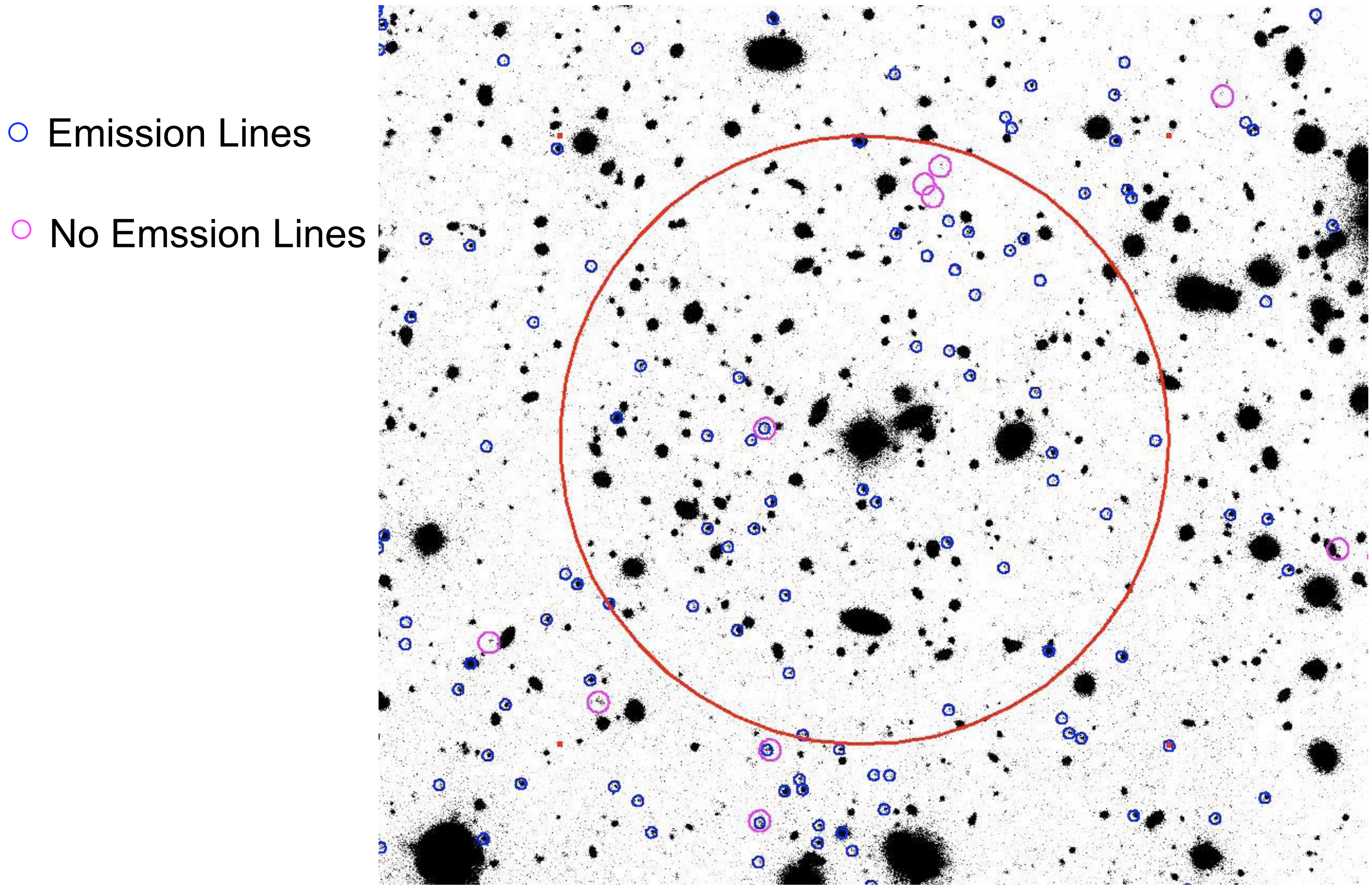
GOODS Survey: z ~ 1.5 Galaxies




Composite K-band spectra of ten z~2.3 galaxies

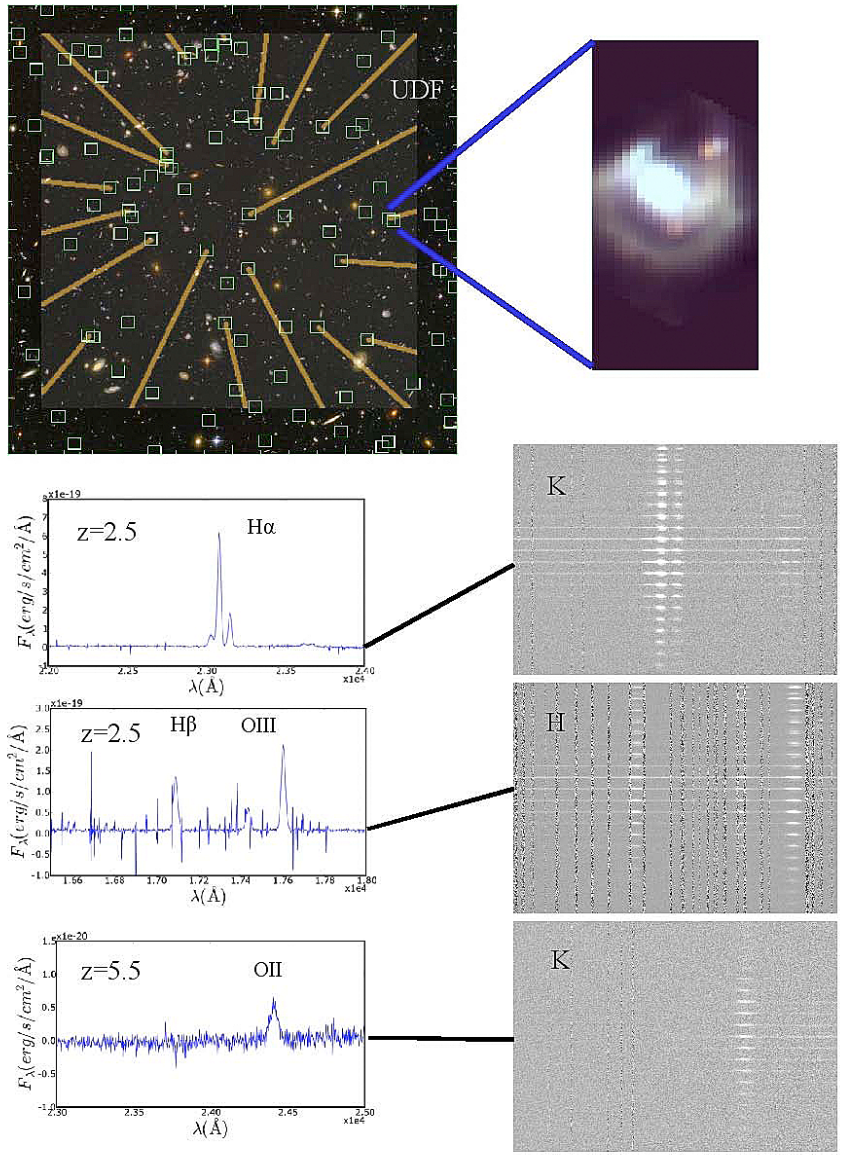


# Target Density at 1.5 < z < 3.5



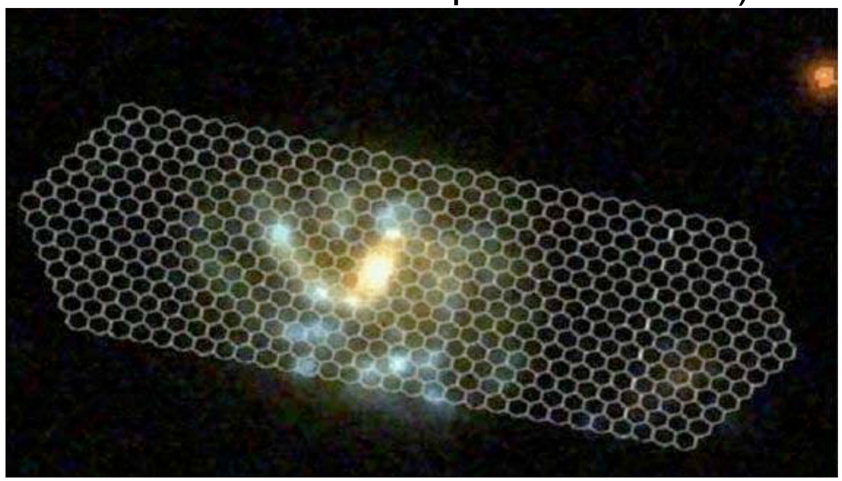

2.3’ AO-corrected Field of View

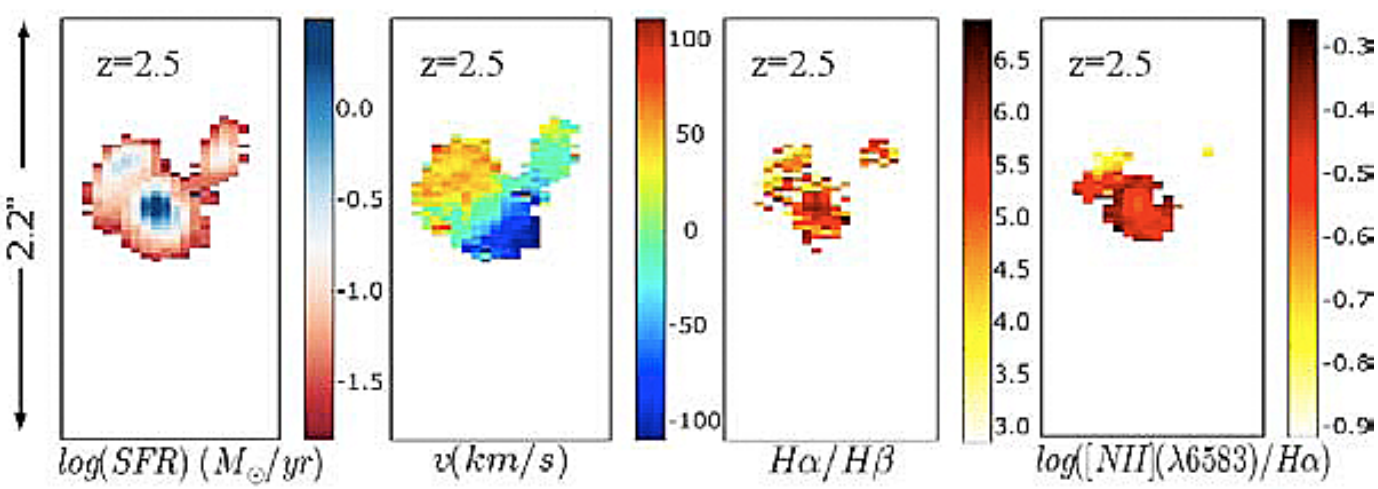
# Simulated Observations



# Quantifying Key Parameters

Cell size ~50-100pc for 1 < z < 5)

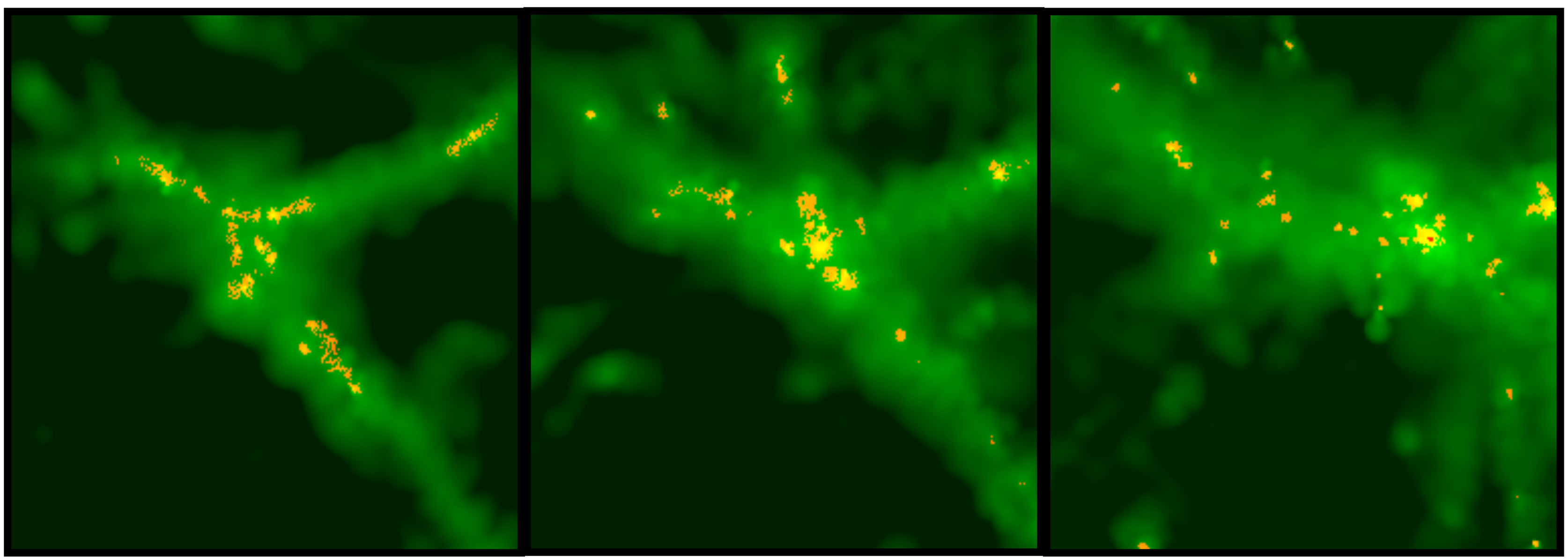




# The Objects Powering Reionization

# The First Stars in the Universe

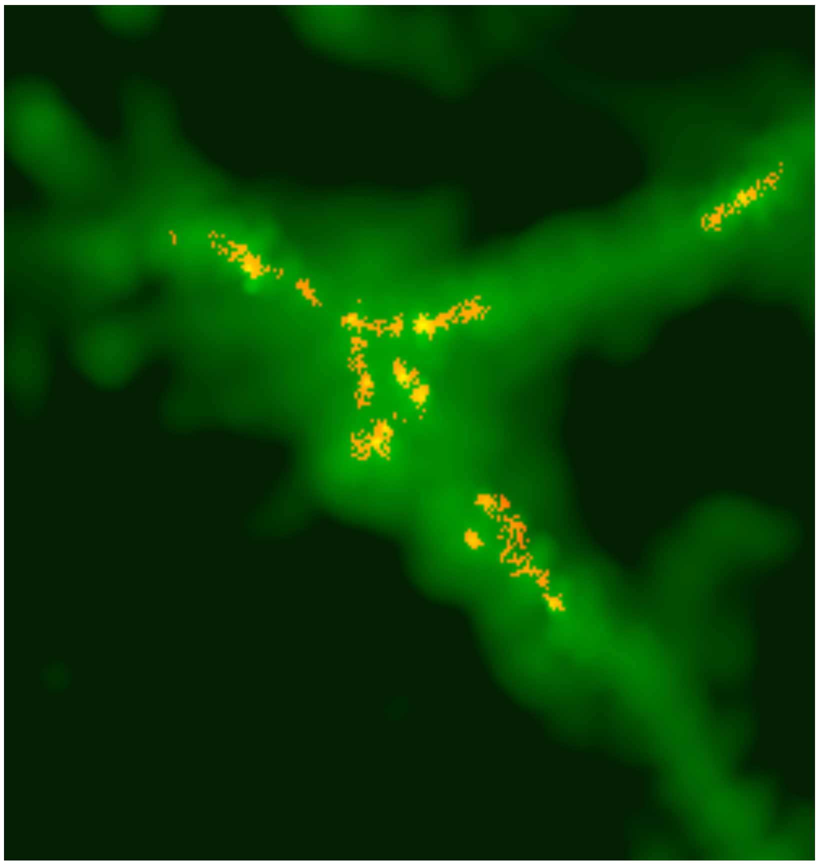
- Hydrodynamic simulations by Davé, Katz, & Weinberg
  – Ly-α cooling radiation (green)
  – Light in Ly-α from forming stars (red, yellow)



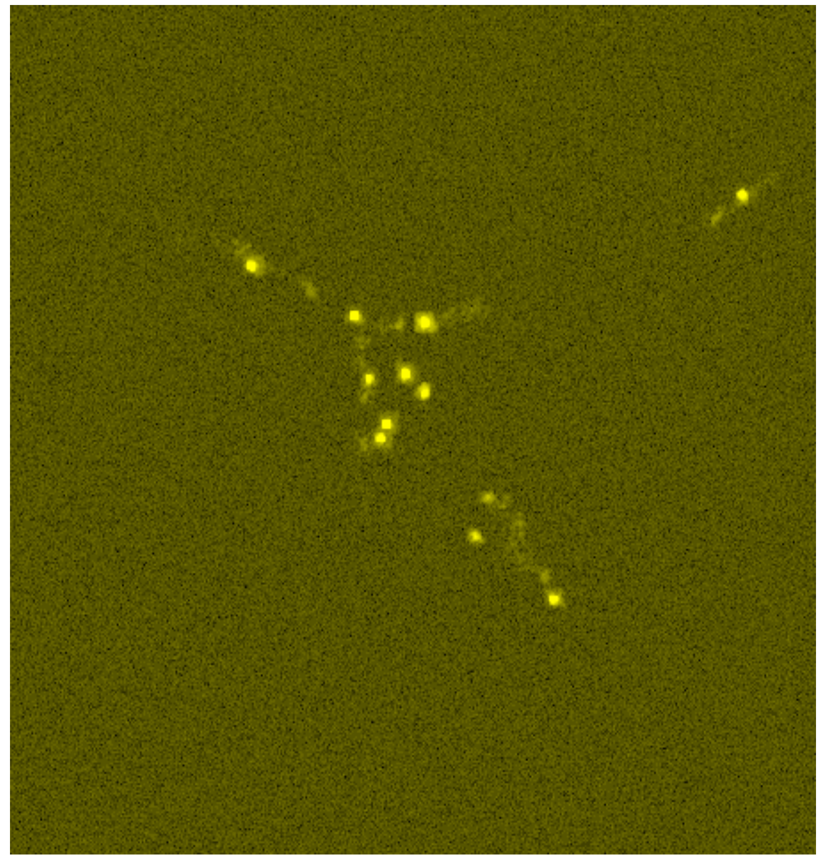
z=10 z=8 z=6

# Observing the First Forming Stars

*1 Mpc*



Dave et al simulation

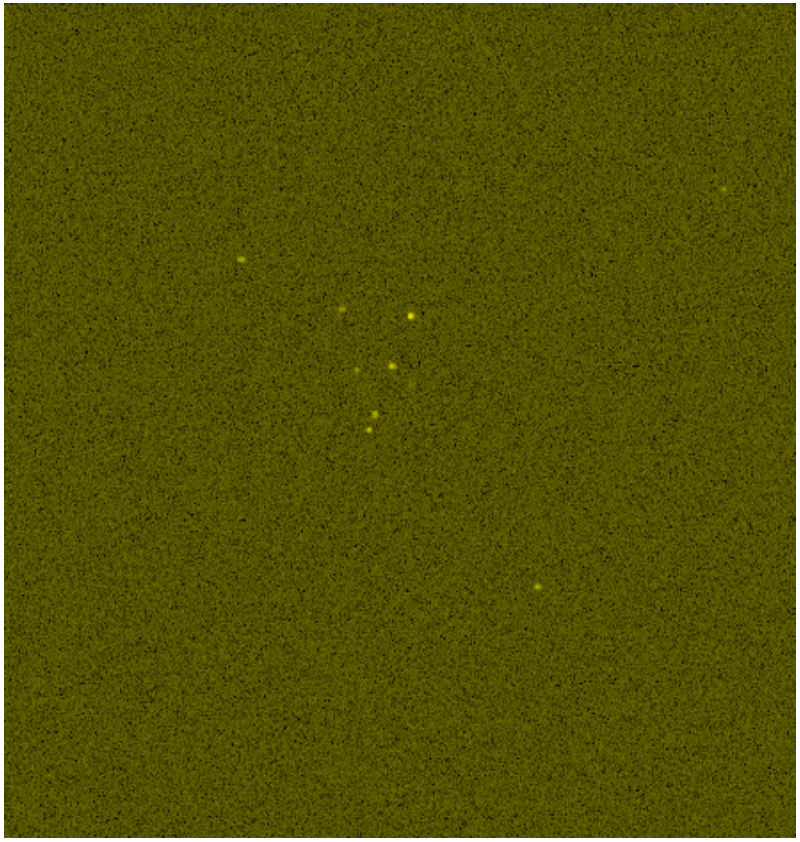


30-m telescope R=3000, $10^5$ sec

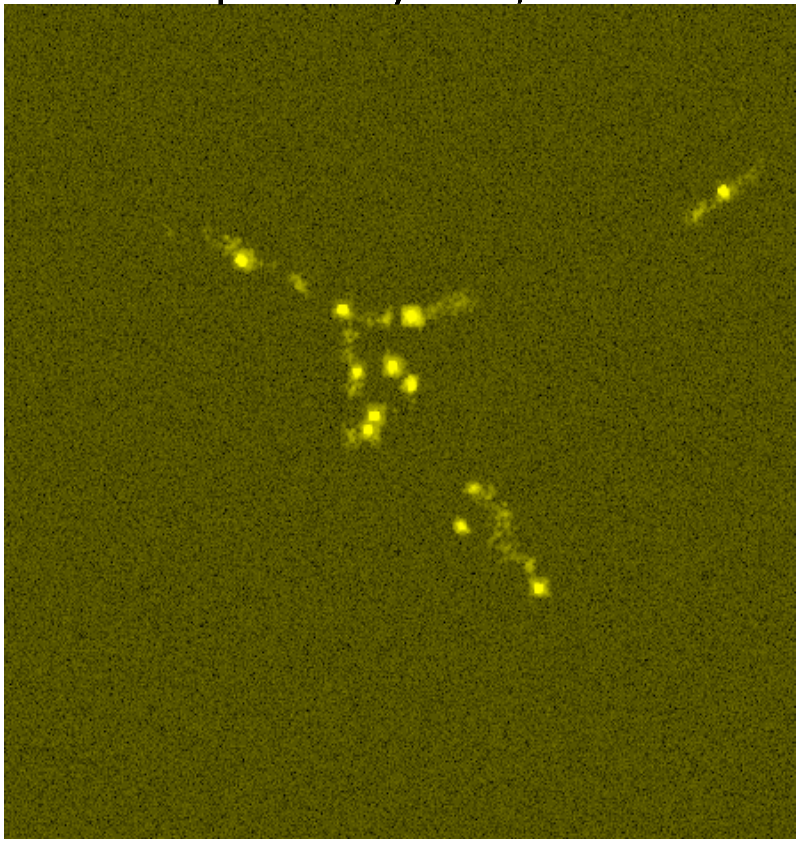
*Barton et al., 2004, ApJ 604, L1*

# A possible IMF diagnostic at z=10

HeII (λ1640 Å)
Standard IMF



HeII (λ1640 Å)
Top-Heavy IMF, Z=0

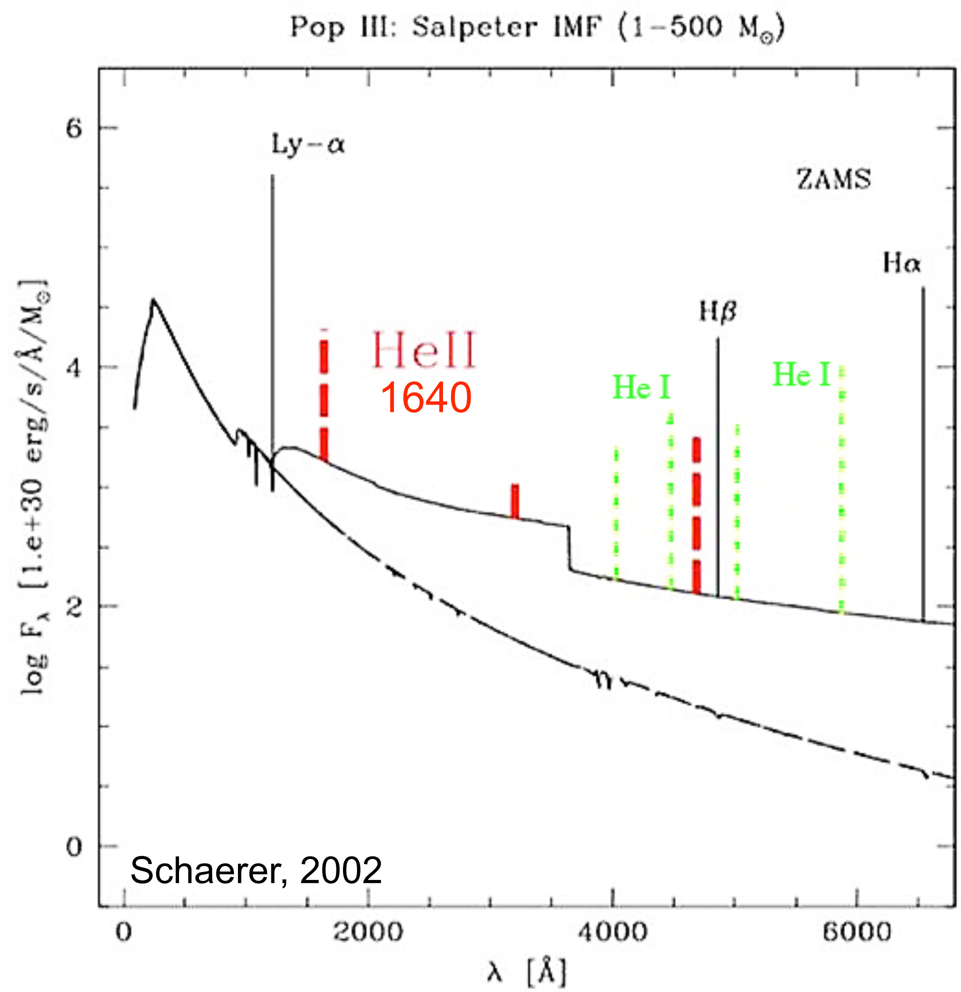


(IMF + stellar models from Bromm, Kudritzki,& Loeb 2001, ApJ 552,464)

# Star formation at $z \geq 7$

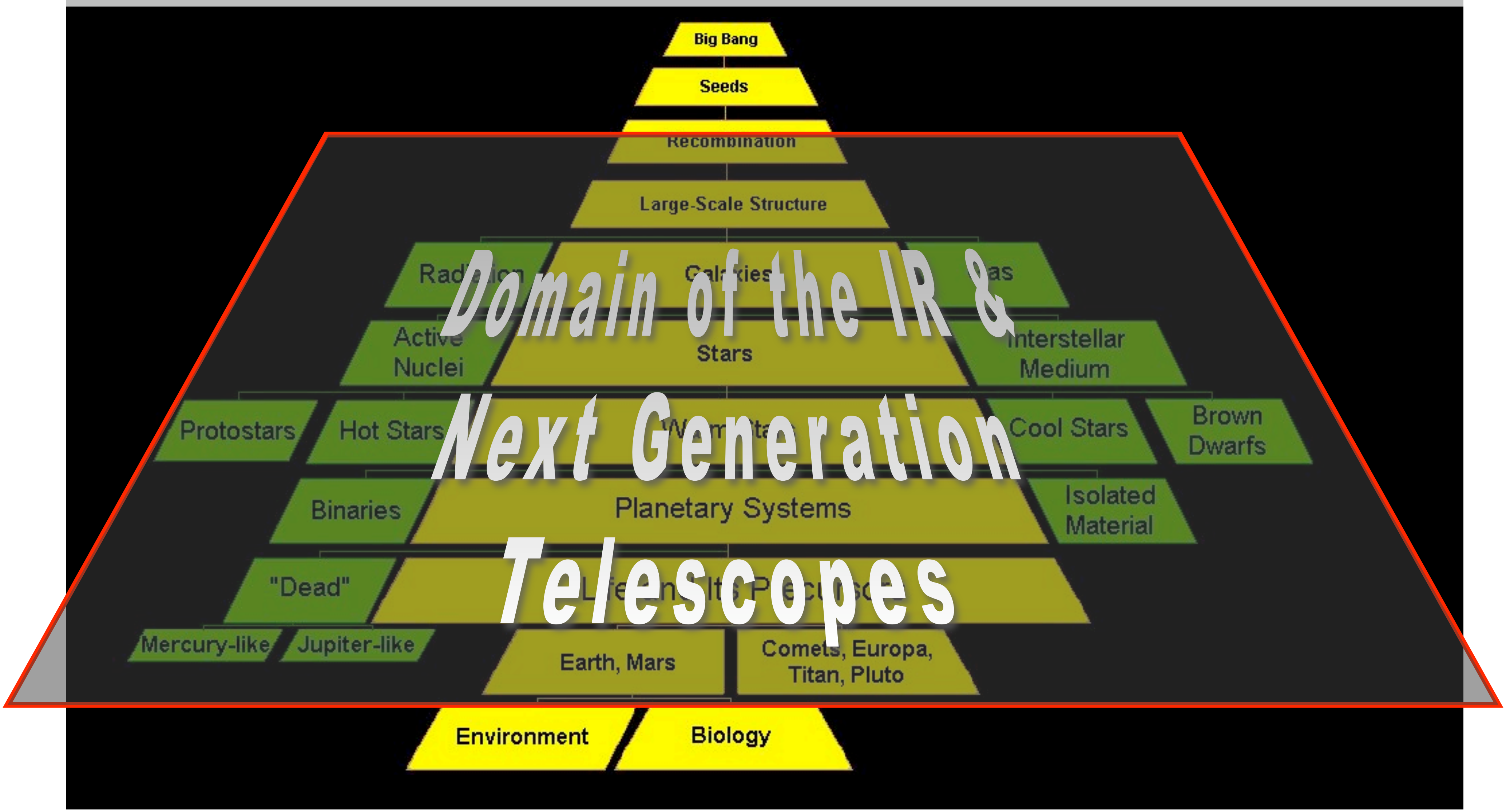
- area of 2’ × 2’ ~ $(5\ \mathrm{Mpc})^3$ at $z = 10$
  - — simulations predict 10s of objects detecable with 30m ELT
  - — Multi-conjugate AO systems can provide this FOV at 2$\mu$
- Several hundred pointings can provide a robust sample
- Follow-up spectroscopy will diagnose SF activity
- AO imaging (scales < 200 pc) will reveal morphology

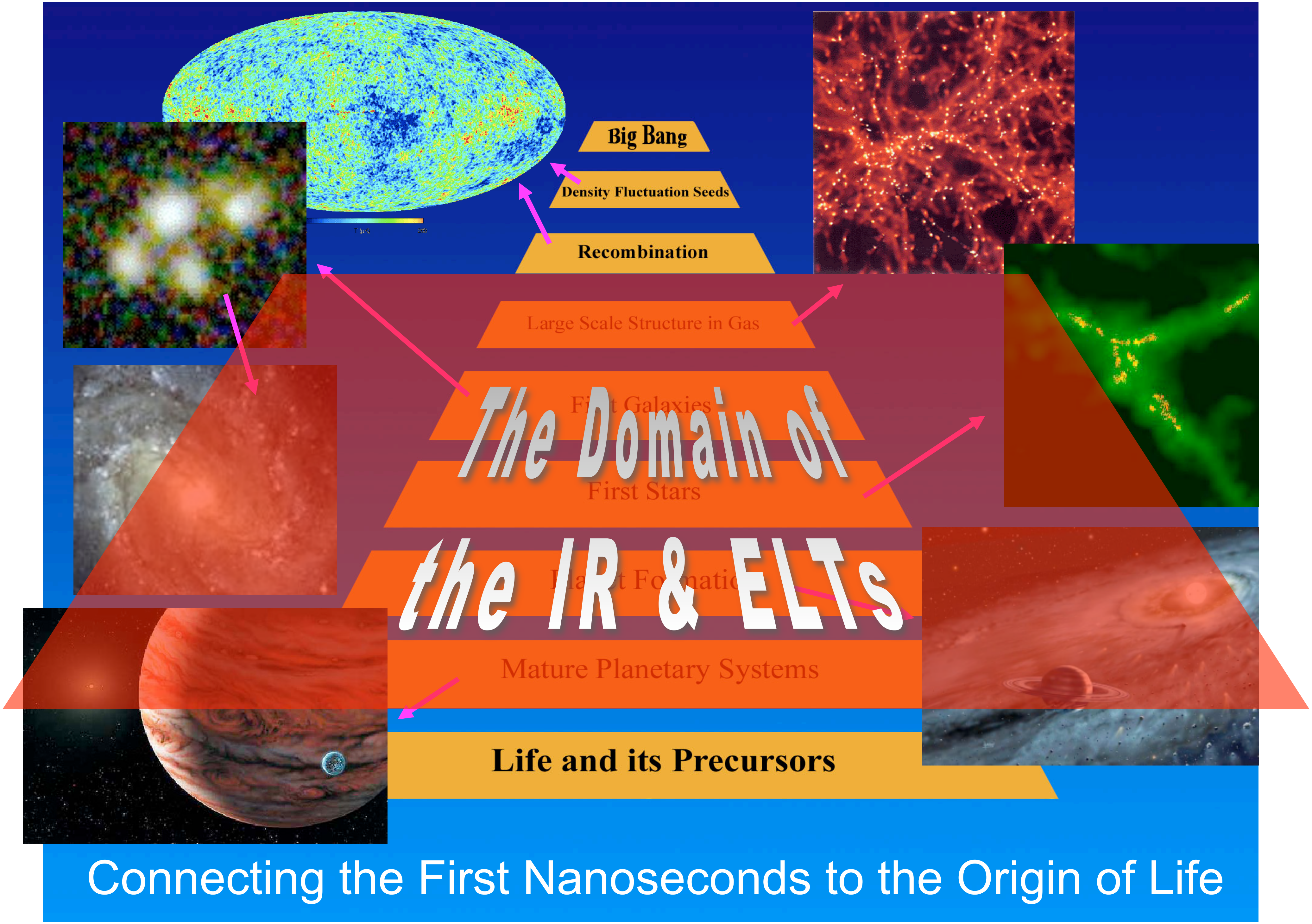
# Simulated Spectrum: z~10 Galaxy



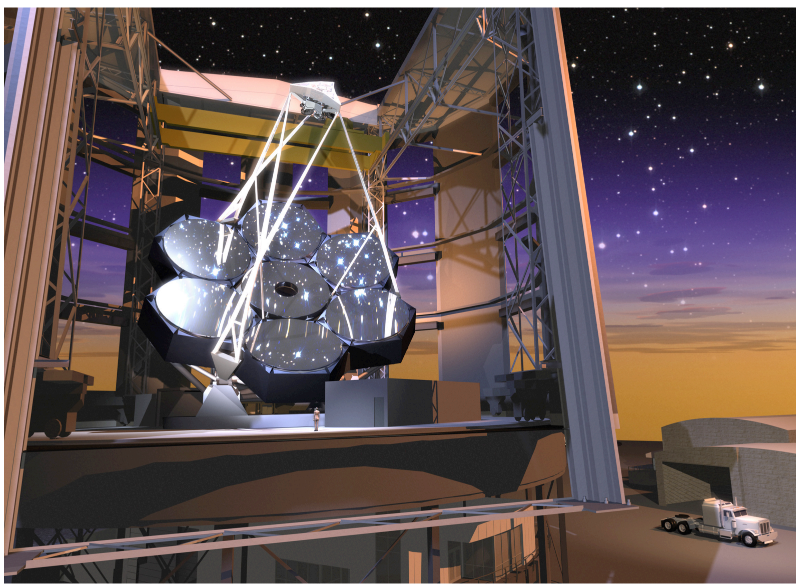
# Scientific Opportunities: The Next Generation

21st Century astronomy is uniquely positioned to study "*the evolution of the universe in order to relate causally the physical conditions during the Big Bang to the development of RNA and DNA*" (R. Giacconi, 1997)



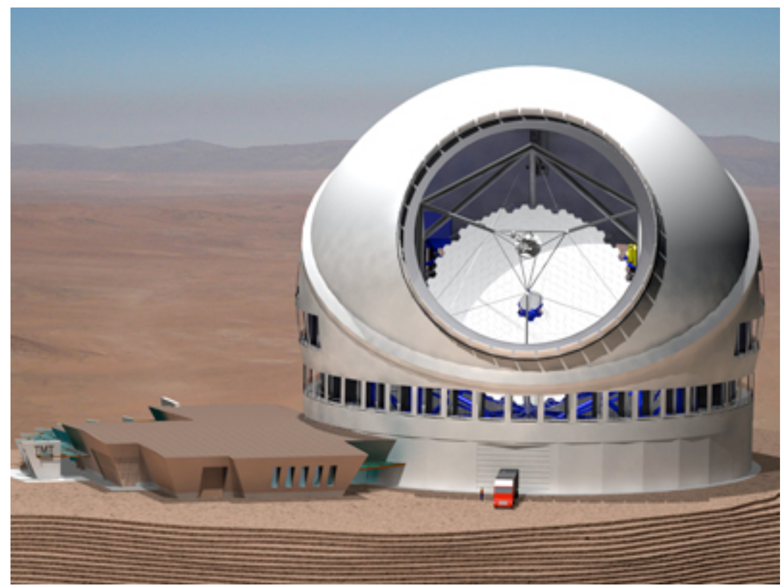

Big Bang
Density Fluctuation Seeds
Recombination
Large Scale Structure in Gas
The Domain of
First Stars
the IR & ELTs
Mature Planetary Systems
Life and its Precursors
Connecting the First Nanoseconds to the Origin of Life

# Message: Make it Happen!



GMT

&



TMT

# Make it Happen!

Use the career & legacy of Giovanni Fazio as a guide:

- Take the lead, even when there's no one behind you!
- Be persistent and patient
- Think of science and the community before self
- Be generous
- Have the courage to involve young people and give them responsibility
- Always be open to new ideas and possibilities

THANK YOU GIOVANNI !