Frontier Science Enabled by a Giant Segmented Mirror Telescope

Rolf-Peter Kudritzki [1] for
the GSMT Science Working Group

[1] Chair, GSMT Science Working Group
Institute for Astronomy, University of Hawaii

http://www.aura-nio.noao.edu/gsmt_swg/SWG_Report/SWG_Report_7.2.03.pdf

Giant Segmented Mirror Telescope

- Top priority of NAS/NRC 2001 decadal survey
  - 30m segmented primary mirror
  - 10x gain in light gathering power (sensitivity)
  - Diffraction limited, Adaptive Optics (AO),
  - 3x gain in angular resolution (image sharpness)
  - Projected costs ~ $ 700 M
  - Private/public/international partnership recommended for funding

Two incarnations of the GSMT

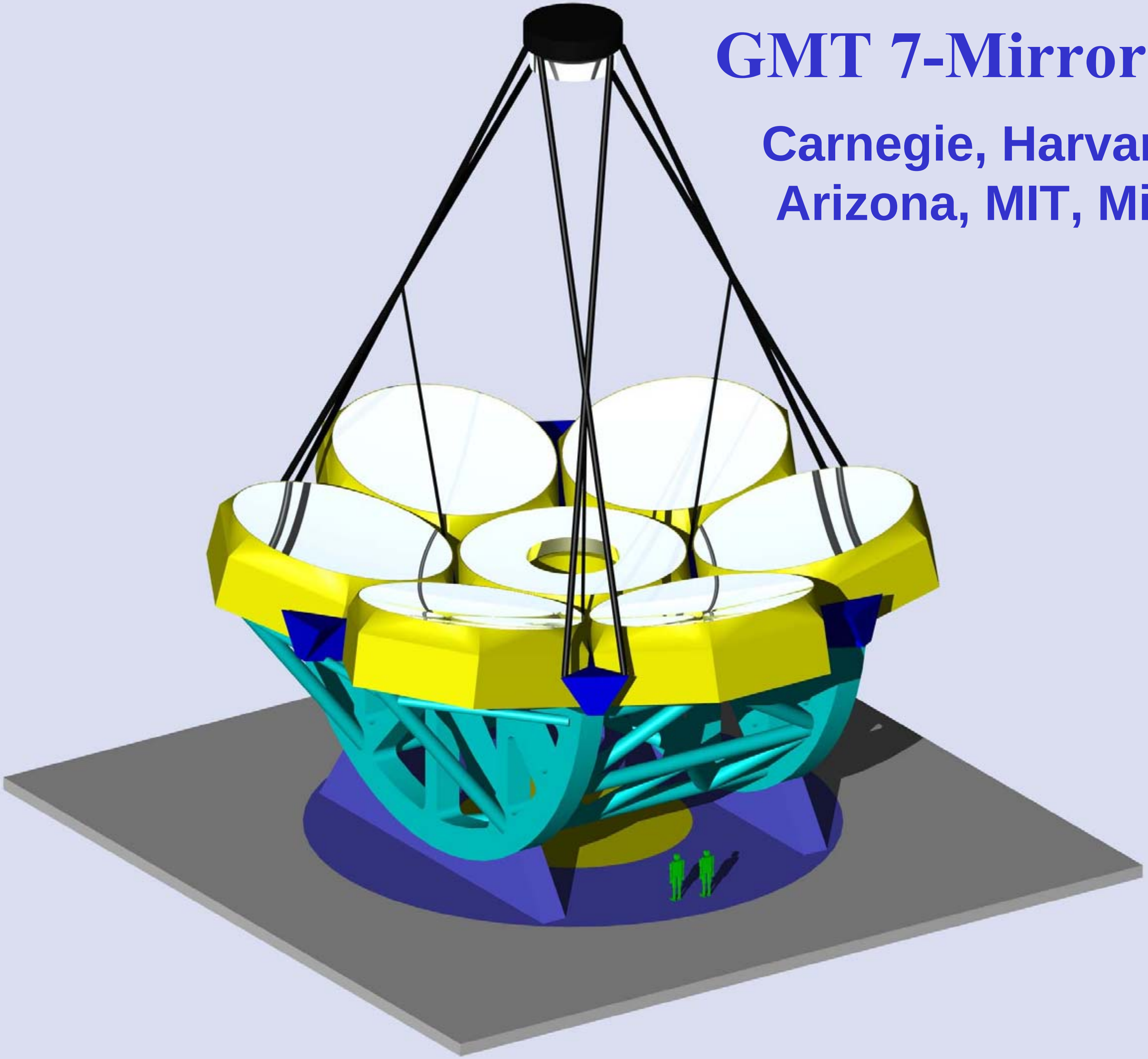
- **TMT – 30m segmented mirror (≈ Keck)**
  UC, Caltech, AURA, ACURA

- **GMT – 20m consisting of seven 8.2m segments**
  spatial resolution ≈ 25m
  Carnegie, Harvard, Arizona, MIT, Michigan

TMT: A partnership of CELT, AURA & ACURA

GMT 7-Mirror Concept

Carnegie, Harvard/Smiths.,
Arizona, MIT, Michigan



GSMT SWG Members

Chair: Rolf-Peter Kudritzki, UH IfA
Vice-Chair: Steve Strom, NOAO

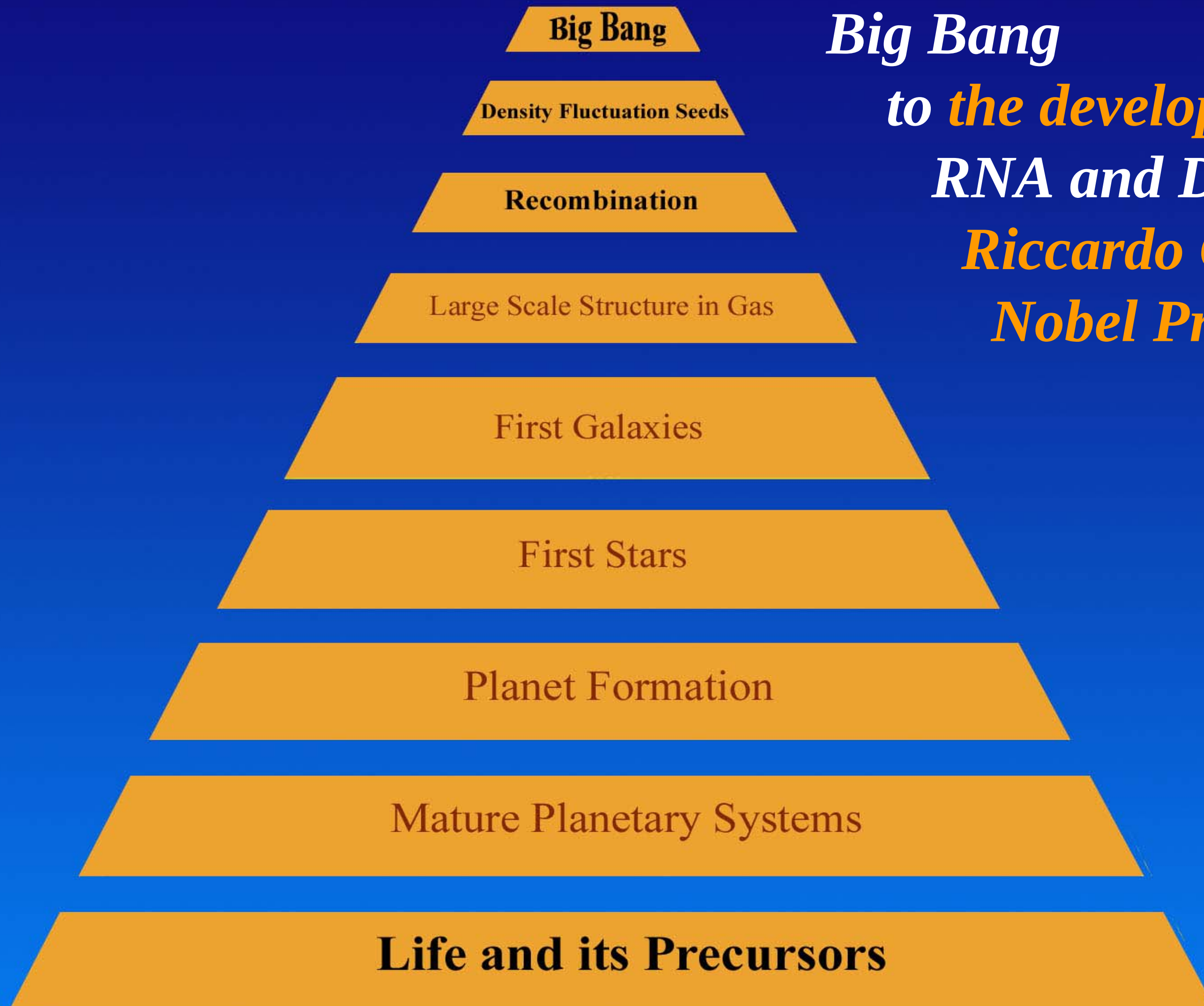
SWG Members:

- Jill Bechtold -- UA
- Mike Bolte -- UCSC
- Ray Carlberg -- U Toronto
- Matthew Colless -- ANU
- Irena Cruz-Gonzales -- UNAM
- Alan Dressler -- OCIW
- Betsy Barton-Gillespie -- UA
- Terry Herter -- Cornell
- Mansanori Iye -- NOAJ
- Paul Ho -- CfA
- Jonathan Lunine -- UA LPL
- Claire Max -- UCSC
- Chris McKee -- UCB
- Francois Rigaut -- Gemini
- Doug Simons -- Gemini
- Chuck Steidel -- Caltech
- Kim Venn -- Macalester

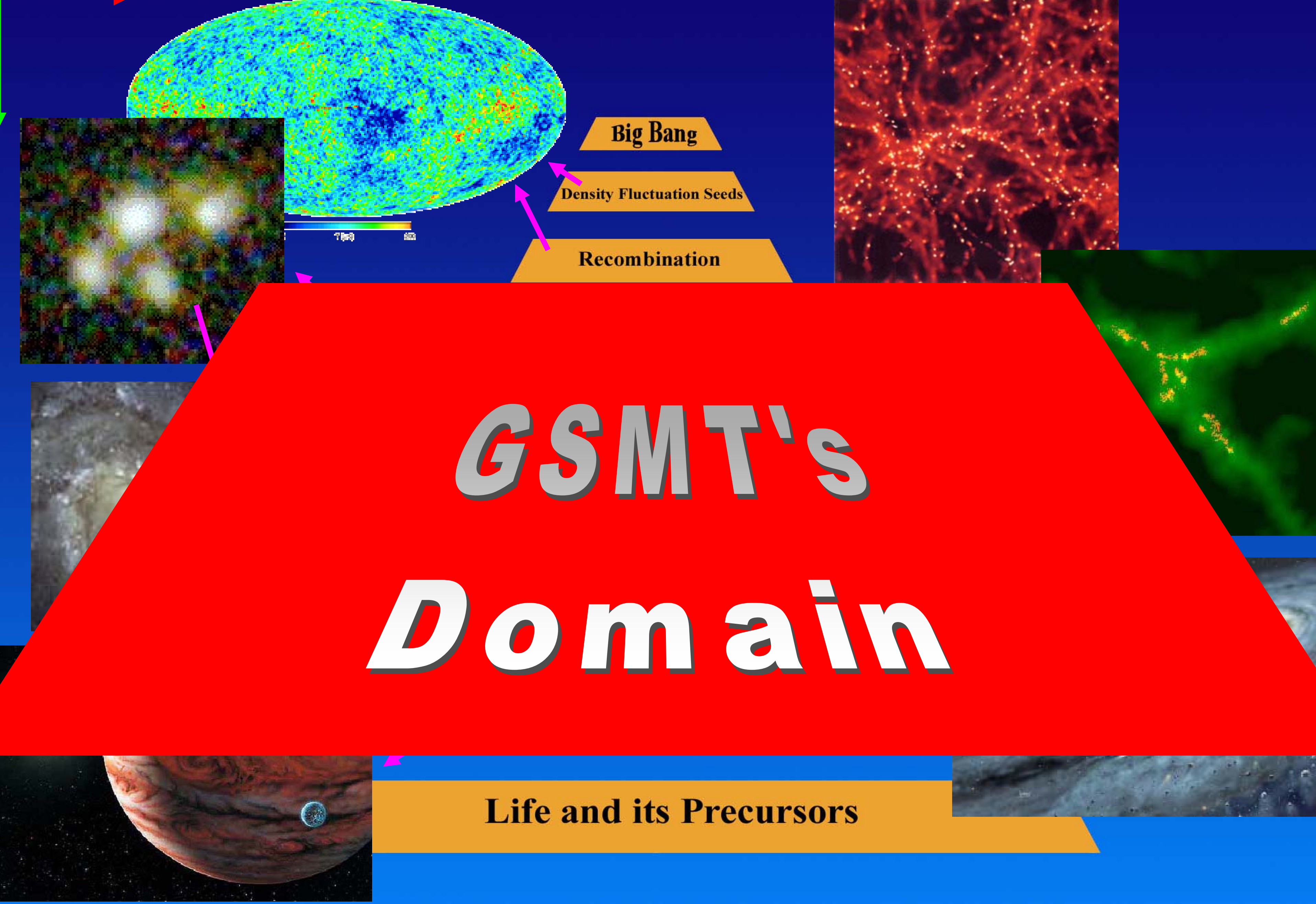
http://www.aura-nio.noao.edu/gsmt_swg/

“21st century astronomy is uniquely positioned to study the evolution of the universe in order to relate causally the physical conditions of the Big Bang to the development of RNA and DNA”

Riccardo Giacconi
Nobel Prize, 2002



Connecting the First Nanoseconds to the Origin of Life



Connecting the First Nanoseconds to the Origin of Life

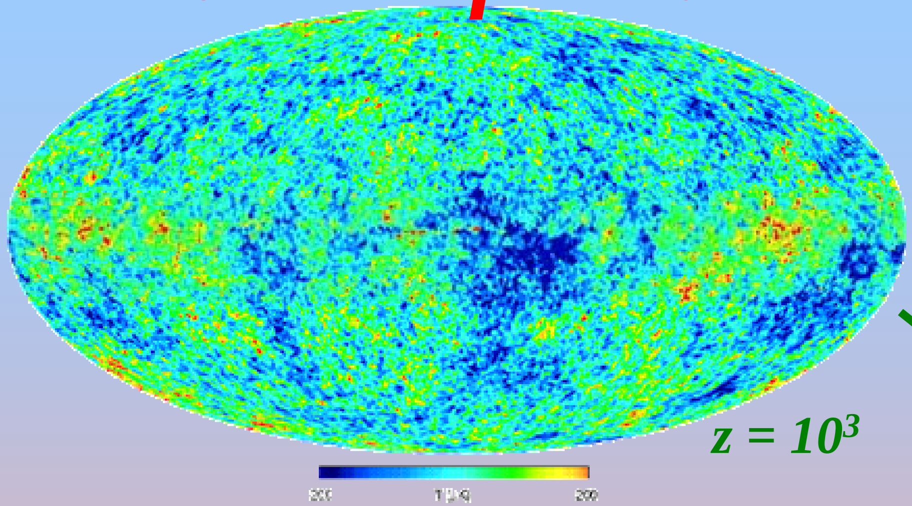
Science Enabled by GSMT

- **3-D map of galaxies and IGM over $2.5 < z < 4.5$**
  - Redshift survey of 10^6 galaxies in 3×10^8 Mpc^3 co-moving volume
  - High resolution spectra of IGM absorption spectra
    - Determine 3-dimensional distribution of gas and galaxies
    - Track evolution of metal abundance & relate to galactic activity
- **Star formation at $z > 7$**
  - Deep near-IR imaging with MCAO
    - Detect Lyman break galaxies or Ly-α emitters
    - Follow up spectroscopy to disentangle physical properties
- **Observing the galaxy assembly process**
  - Integral field unit spectra of pre-galactic fragments at $2.5 < z < 4.5$
  - MCAO imaging and spectroscopy of nearby galaxies
    - Determine age and stellar kinematics; measure mass directly
    - Quantify star formation activity and chemical composition
    - Disentangle populations; age and distribution of chemical composition of merger remnants distributed in nearby galaxy halos

Science Enabled by GSMT

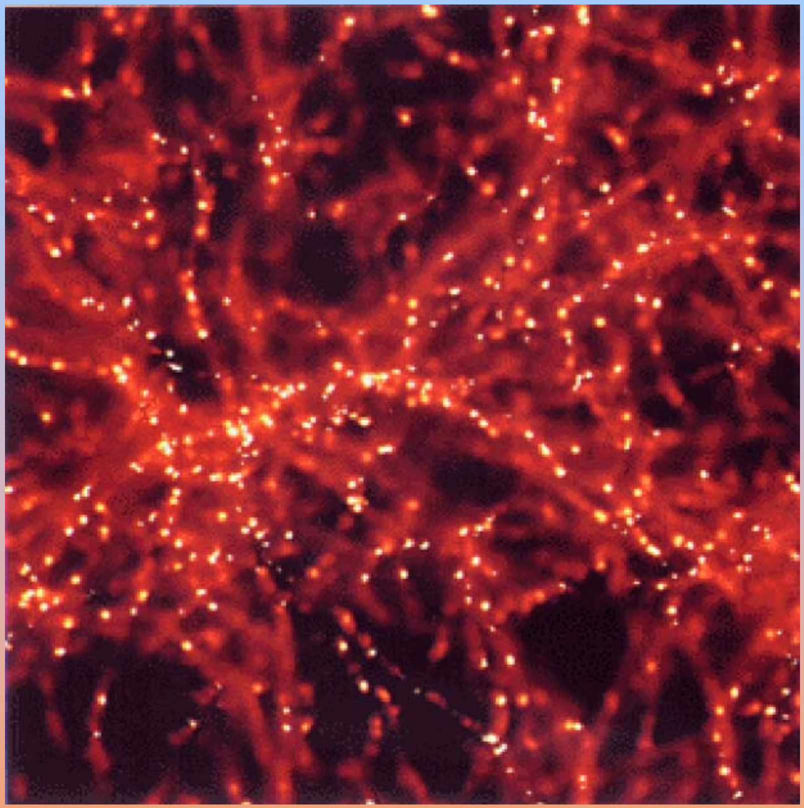
- **Understanding where and when planets form**
  - Ultra-high resolution mid-IR spectra of ~1000 accreting PMS stars
    - Physics of proto-planetary disks
    - Infer planetary architectures via observation of “gaps” in disks
- **Detecting and characterizing mature planets**
  - Extreme AO coronography; spectroscopy of giant extra-solar planets out to 70 pc
  - Physical properties of planets, chemical composition

Evolution of the universe - theoretical scenario

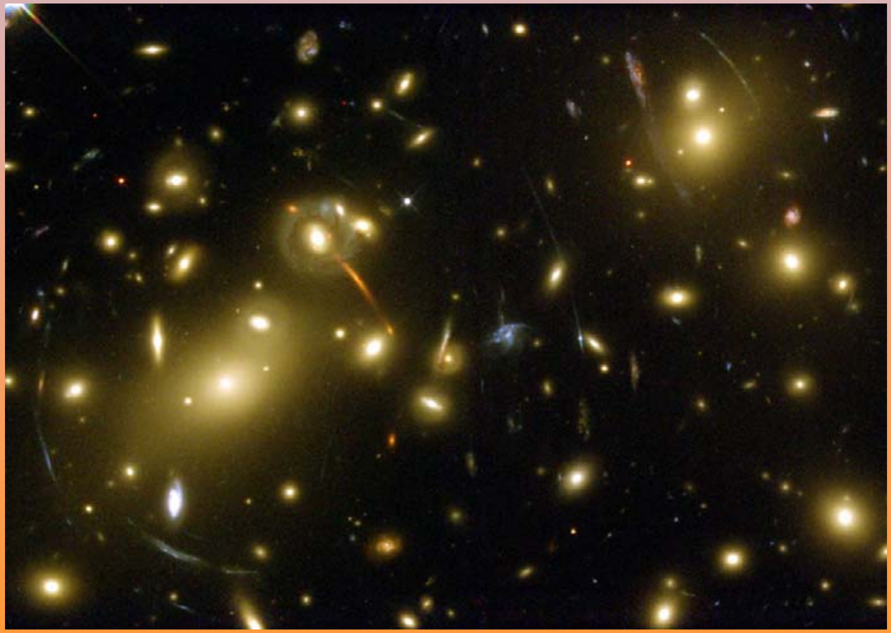


***z* = 10^3**

***z* = 3.5**



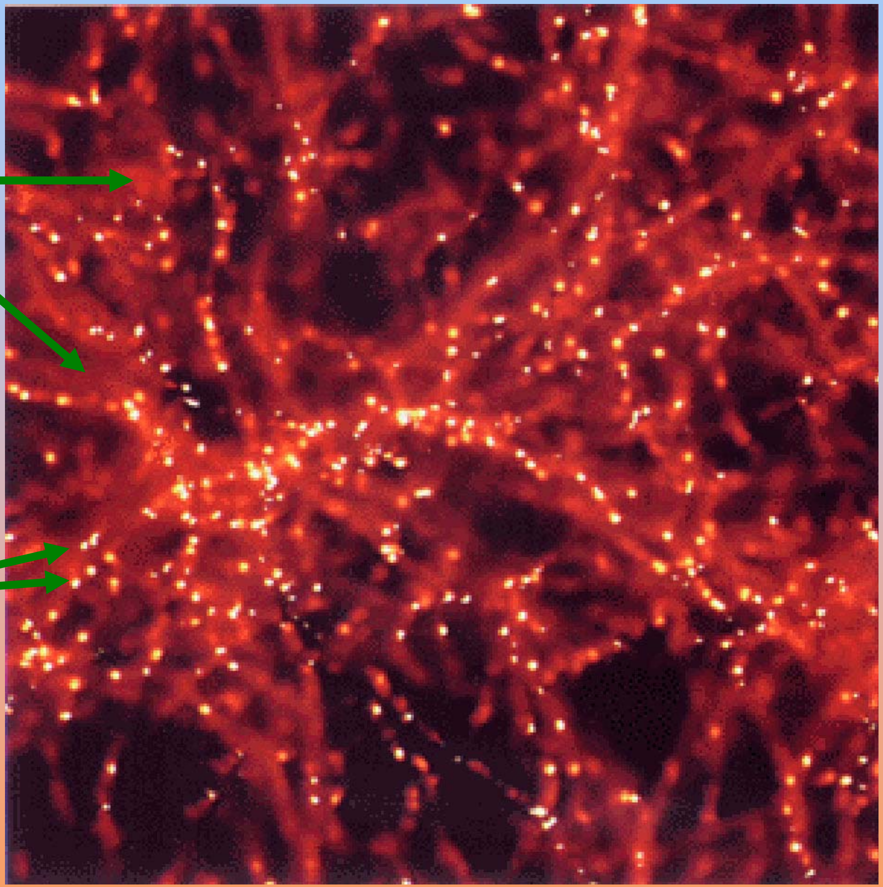
***z* = 0.5**



Numerical simulation (L. Hernquist) showing the cosmic web of intergalactic gas and dense proto-galactic clumps

Predicted cosmic web of intergalactic gas and galaxies at z = 3.5

Intergalactic gas



High density clumps concentrated by dark matter → galaxies

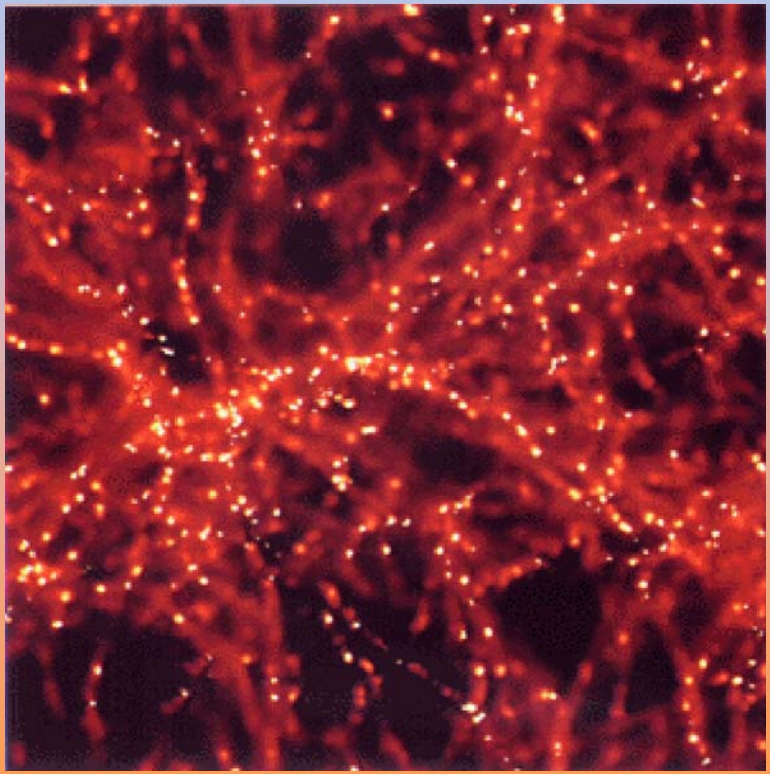
Structure depends strongly on nature of dark matter dark energy

We need to observe 3D-structure of cosmic web at z = 3.5

GSMT will have the power to reveal the 3D-structure and physics of the cosmic web!!

Tomography of the universe at 12 billion lyr

Survey 5º × 5º ~ 600Mpc × 600 Mpc × 900Mpc @ $2.5 < z < 4.5$



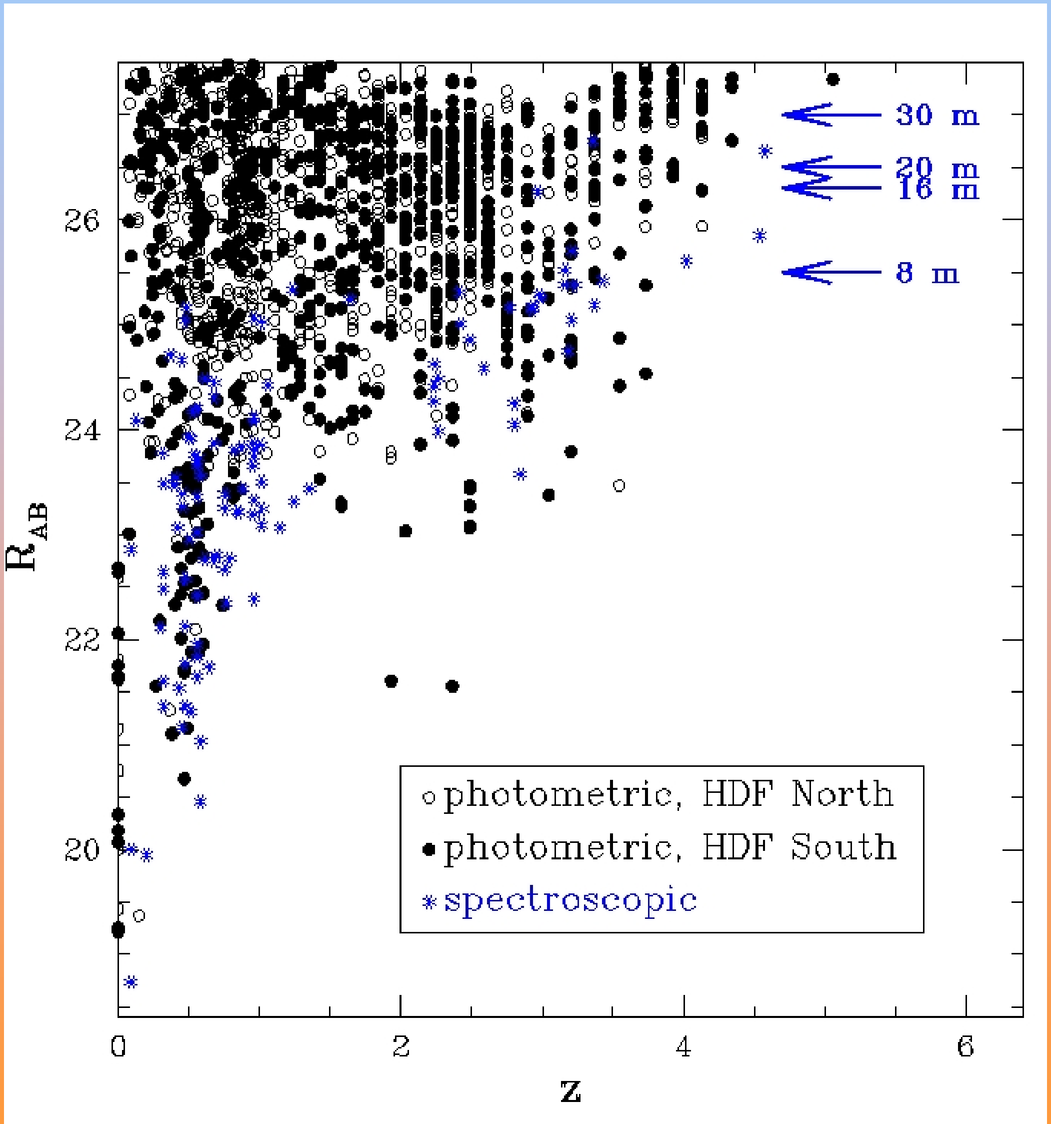
10^6 galaxies down to $m_R = 26.5$
low resolution spectra
→ redshifts, 3D-distribution,
distribution of dark matter

10^4 galaxies down to $m_R = 24.0$
as background sources
to probe intergalactic gas
high resolution spectra
→3D-distribution and chemical
composition of gas

Only GSMT can take spectra of these faint objects !!!

Sensitivity is vital for a survey down the luminosity function

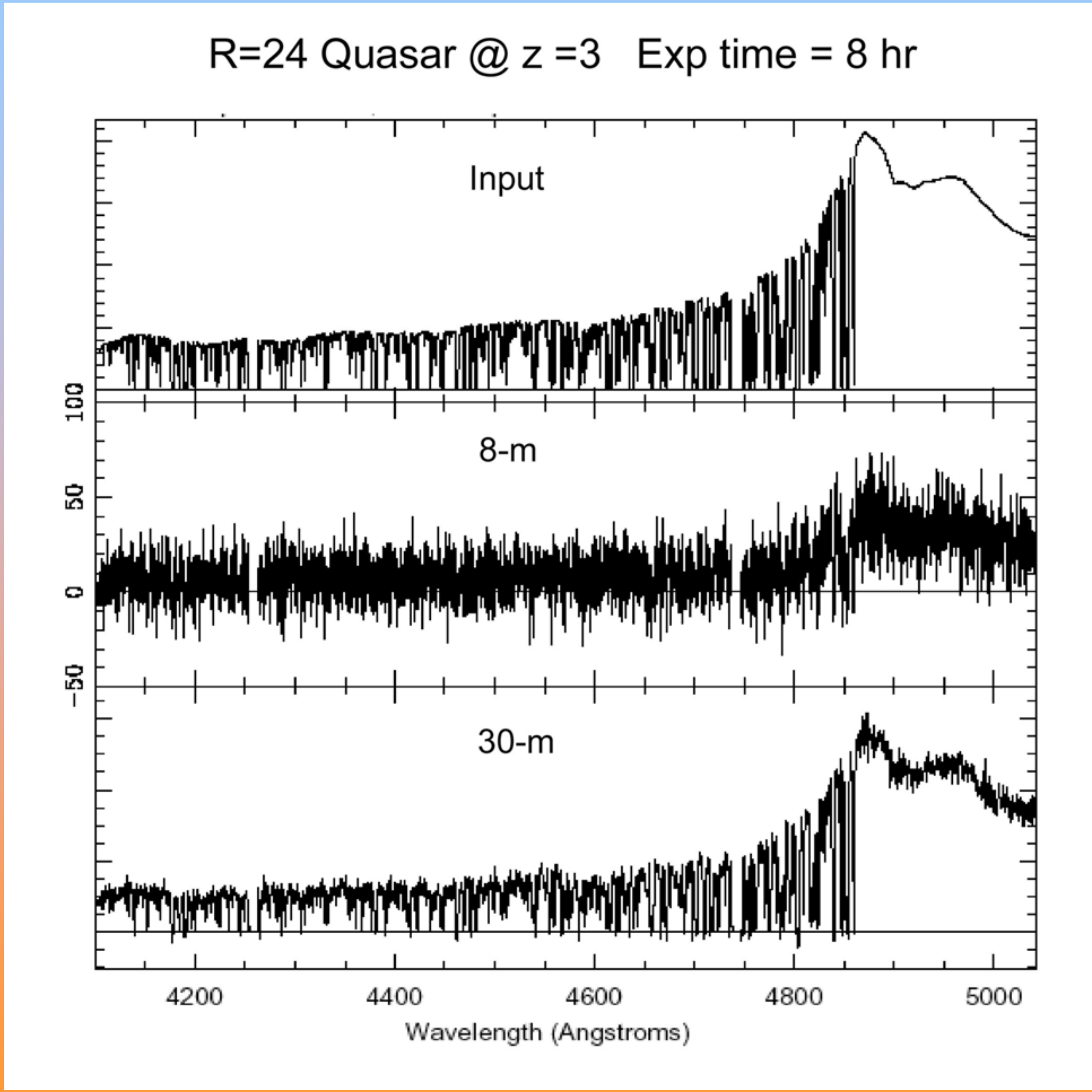
RAB



PHOTOMETRIC REDSHIFT

- **S/N=3 limits**
- **t_{exp} = 10^4 s**
- **FWHM = 0.5”**

The power of GSMT



Intrinsic spectrum of faint quasar with "forest" of intergalactic gas absorption lines

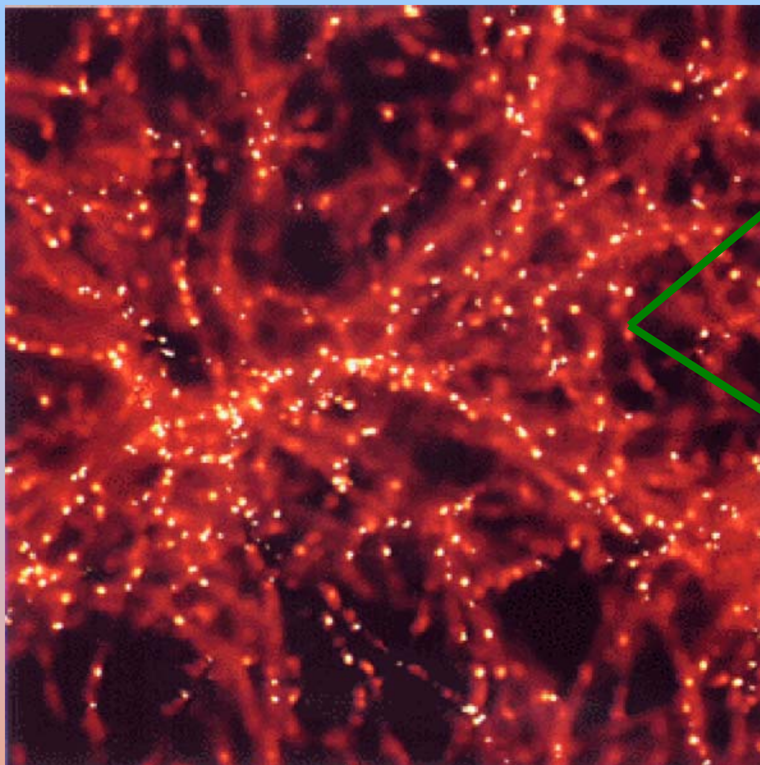
All night exposure with 8m-telescope

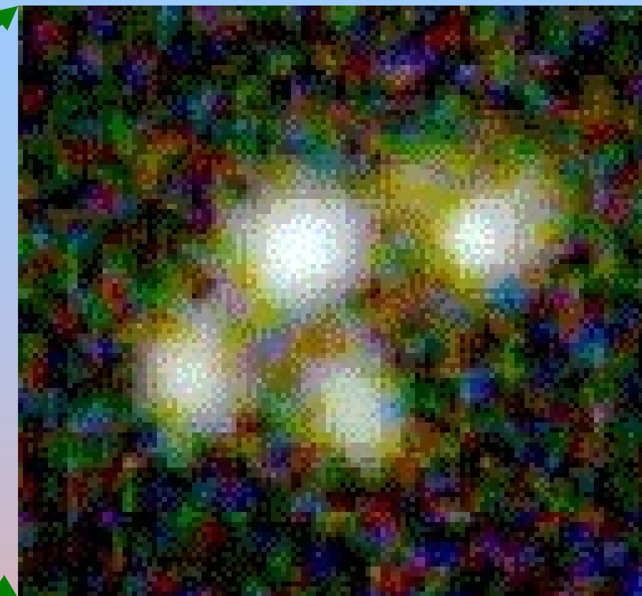
All night exposure with GSMT

(J. Bechthold)

Tomography of universe at 2.5 < z < 4.5

- **Goals:**
  - **Survey 5º × 5º ~ 600Mpc × 600 Mpc × 900Mpc @ z ~ 3.5**
  - **Link emerging distribution of IGM/ galaxies to CMB and distribution of dark matter**
  - **Determine metal abundances of IGM/galaxies**
- **Measurements:**
  - **Spectra for 10^6 galaxies (R ~ 2000, S/N ~ 5), $m_R \leq 26.5$**
  - **Spectra of 10^4 galaxies/QSOs (R ~20000, S/N ~30), $m_R \leq 24$**
- **Key requirements:**
  - **15-20' FOV;MOS ~ 2000/20 multiplex (low/high res)**
- **Time to complete study with GSMT: 500 nights**





z = 3 galaxy from Hubble Deep Field

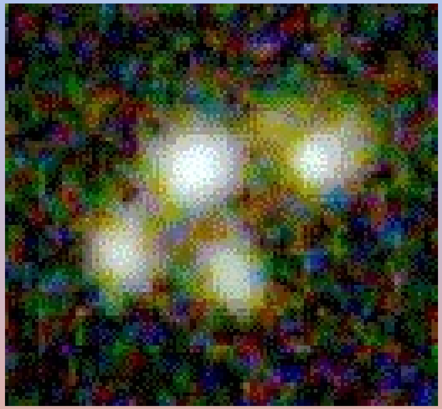
How do galaxies form and evolve ?

Goal: test/constrain hierarchical assembly theory
intrinsic properties of primeval galaxies
how did they transform to the galaxies today?

Problem: the typical primeval galaxies are very faint → GSMT !!!

A galaxy survey at z = 3.5

Survey 5º × 5º ~ 600Mpc × 600 Mpc × 900Mpc @ $2.5 < z < 4.5$



10^6 galaxies down to $m_R = 26.5$
low resolution spectra → z, star formation rate

10^5 galaxies down to $m_R = 25.5$
low resolution spectra with high signal →
chemical composition, initial mass function

10^3 galaxies down to $m_R = 25.0$
High resolution spectra + MCAO
→ internal galaxy kinematics on scales of 100pc
→ masses, merging dynamics etc.

Only GSMT can take spectra of these faint objects !!!

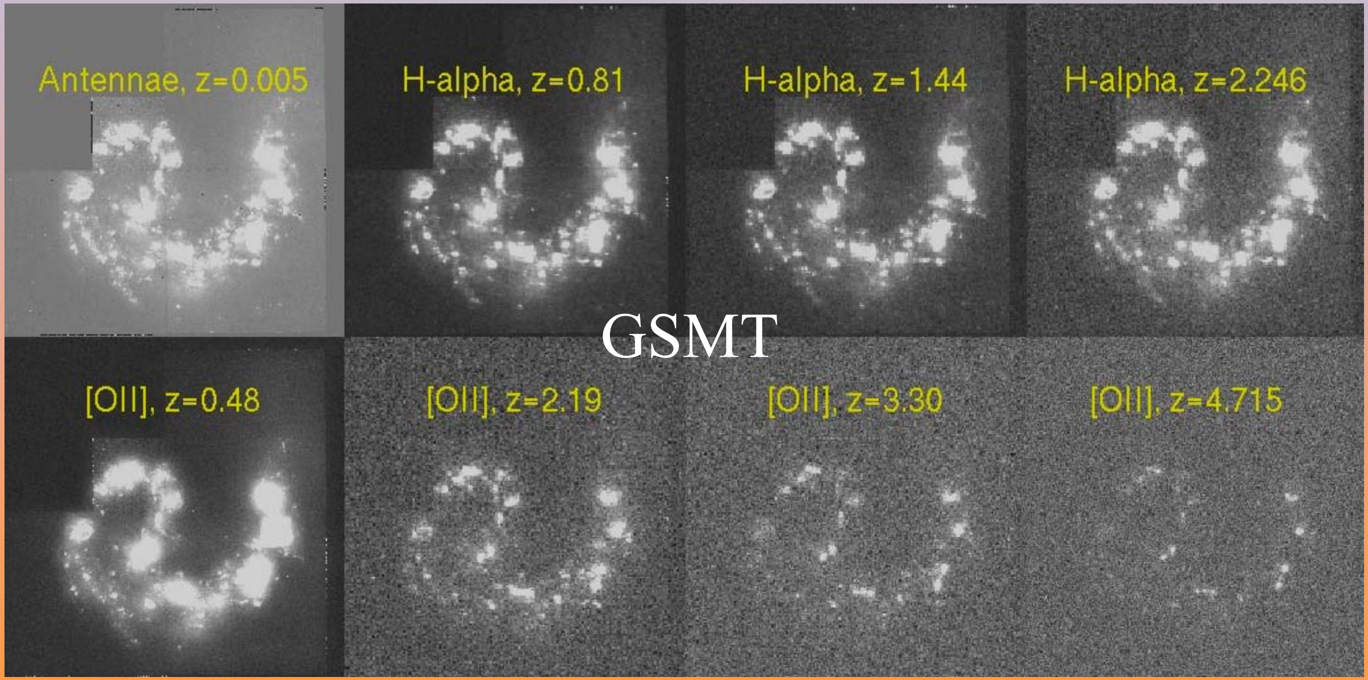
Formation of giant galaxies

Hydro-simulation
(C. Mihos, L. Hernquist)

“Antennae” galaxy – two galaxies merging
(HST, B. Whitmore)

GSMT narrow-band imaging of starbursts

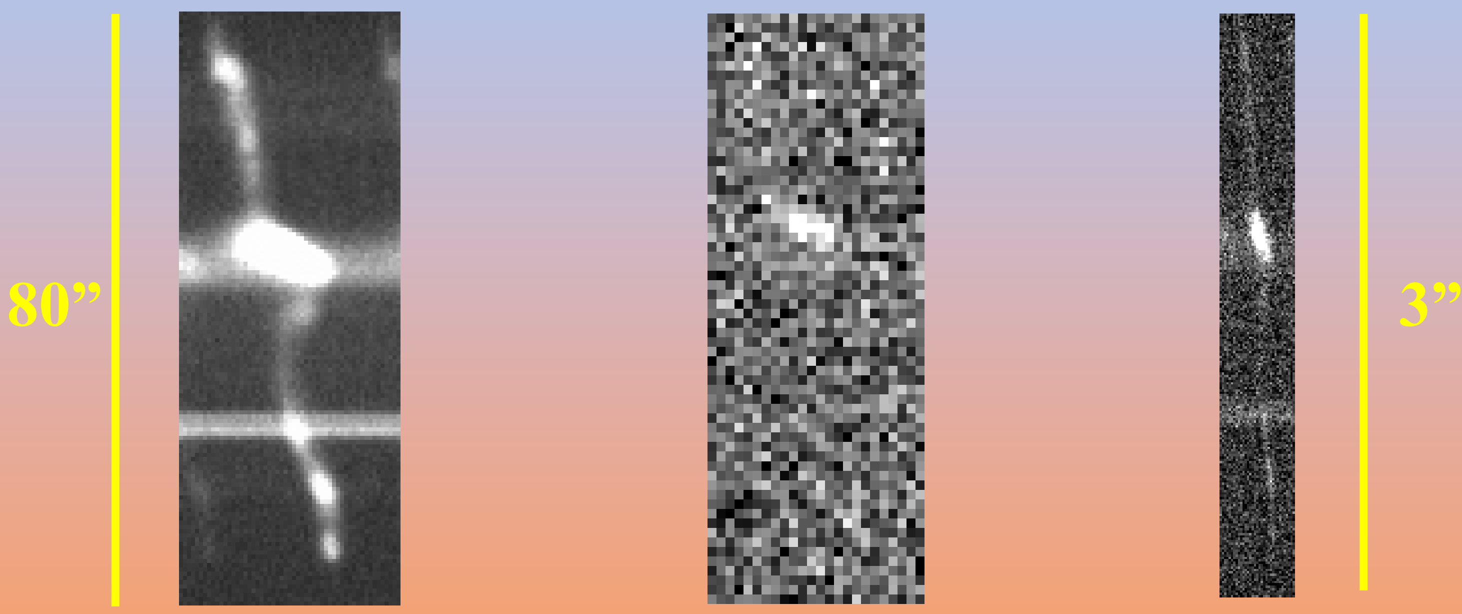
Simulated monochromatic images of the ‘Antennae’
(local starburst galaxy: 10^5 seconds integration time)
Courtesy: E. Barton-Gillespie



2”

Galaxy Kinematics with GSMT

Hα in typical spiral galaxy: 10^5 sec exposure



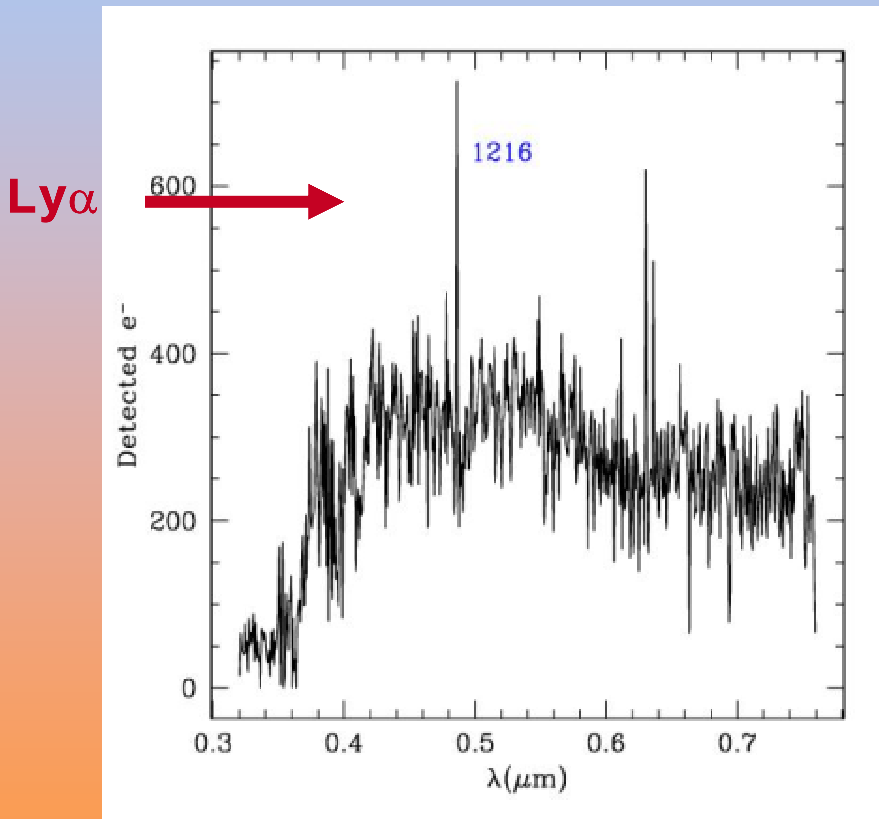
z=0.01

z=1.5
8m

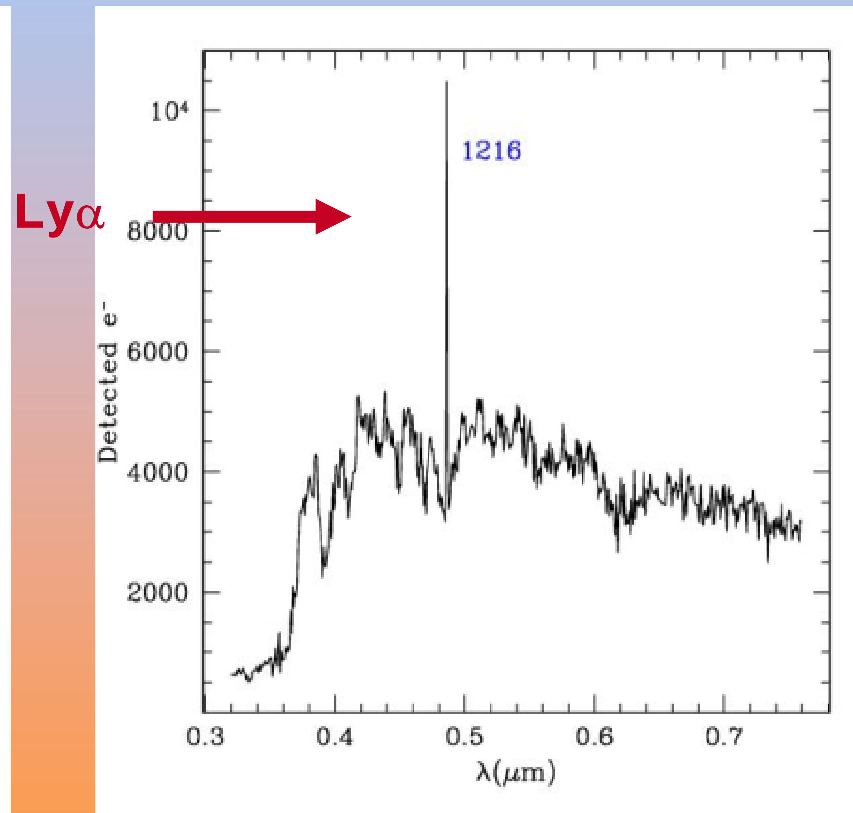
z=1.5
30m

Intrinsic UV Spectra

Rest-frame UV, 6 hours, R=6000, $m_{0.64\mu m,AB}=24.5$



8 meter



30 meter

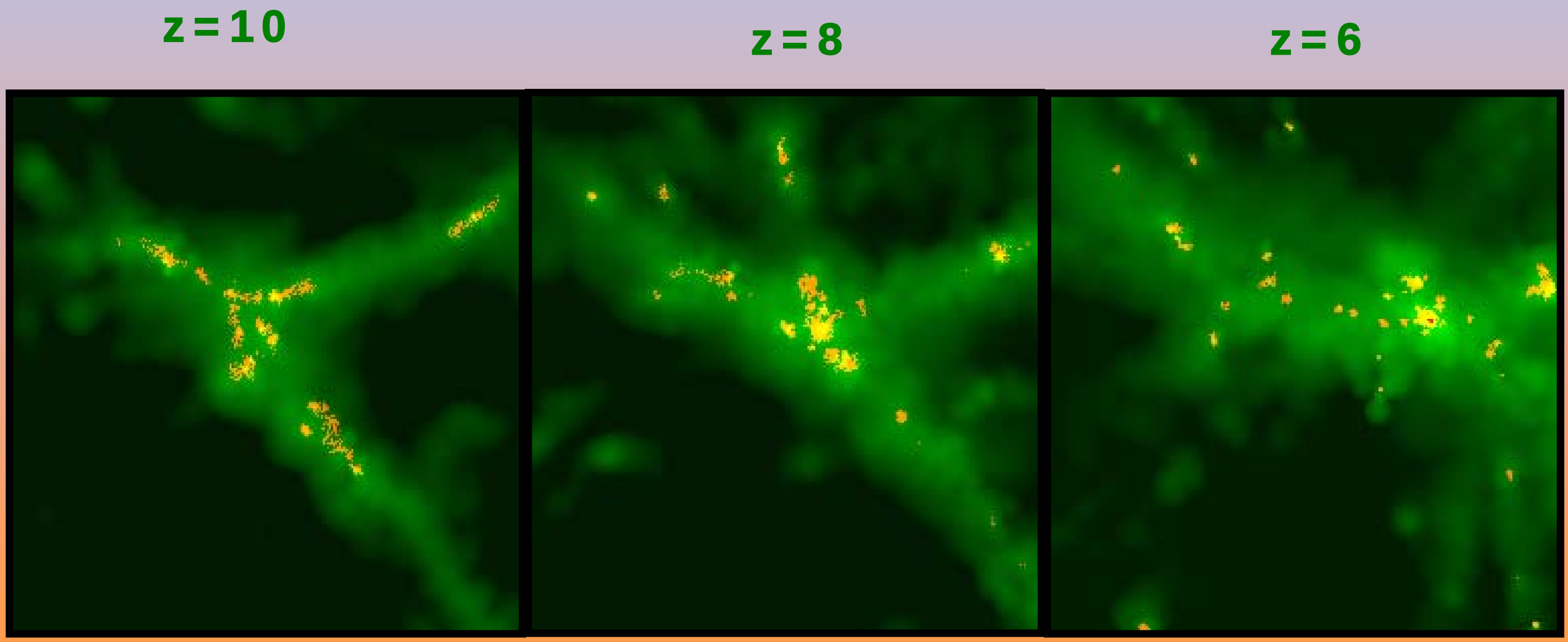
The Survey at $2.5 \leq z \leq 4.5$

- 10^6 galaxies in 5°×5° area down to $m_R = 26.5$
  MOS (1000) spectroscopy (R ~ 2000), t_{exp} ~ 2h
  → z, SFR
- 10^5 galaxies down to $m_R = 25.5$, (10^3 in 15'×15')
  MOS (1000) spectroscopy (R ~ 2000), t_{exp} ~ 4h
  → (S/N) ~ 20, metallicities, IMF
- 10^3 galaxies down to $m_R = 25.0$ (100 in 10'×10')
  → internal kinematics with resolution ≤ 1kpc
  some 250 galaxies with ≤ 100pc (MCAO)

requires 150 nights in addition to large scale structure survey

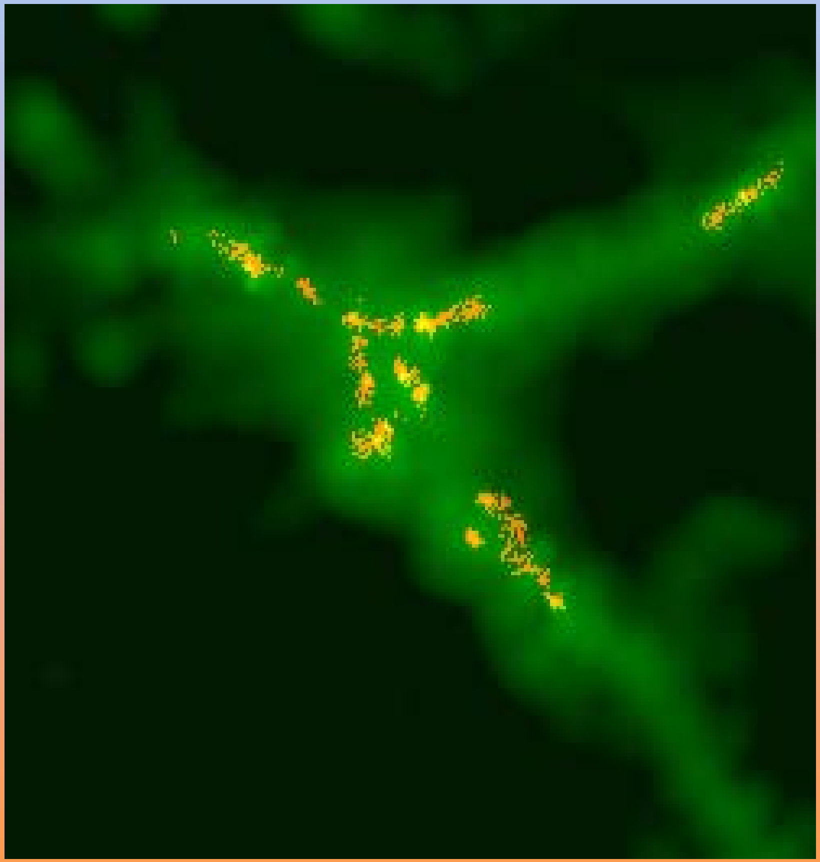
The first stars in the universe - clues from hydrodynamic simulations

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

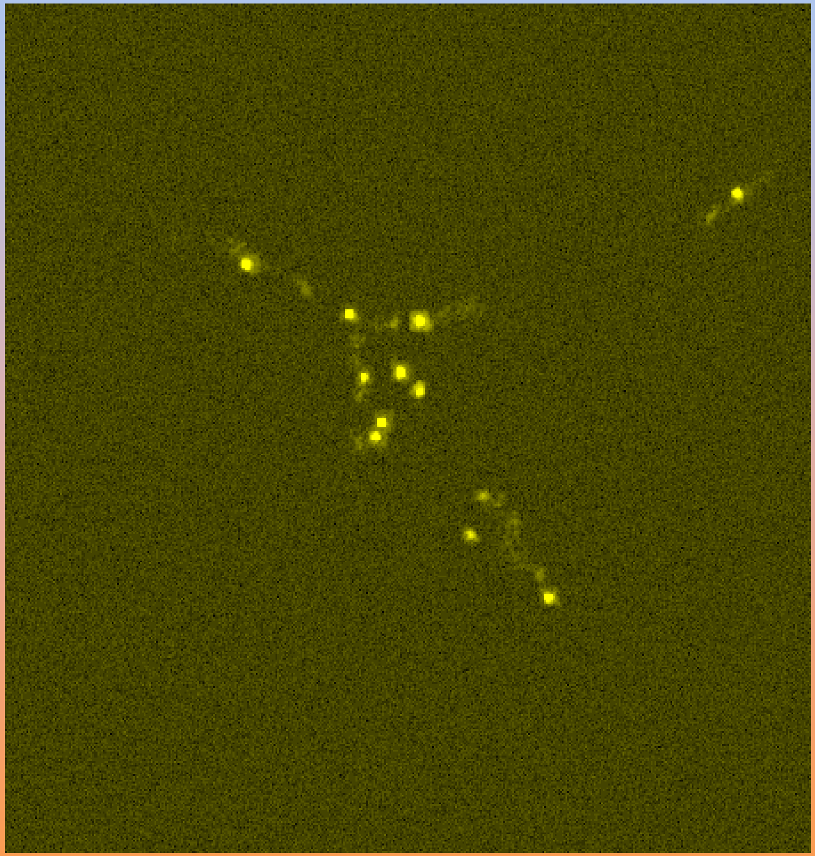


Stars forming at z=10!

1 Mpc (comoving)



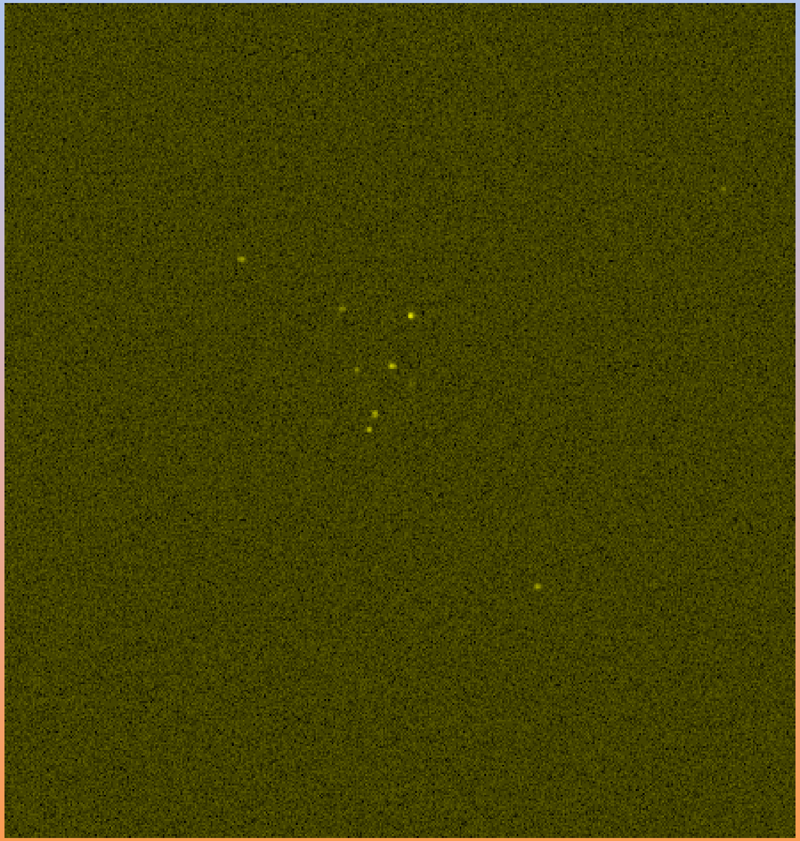
Simulation



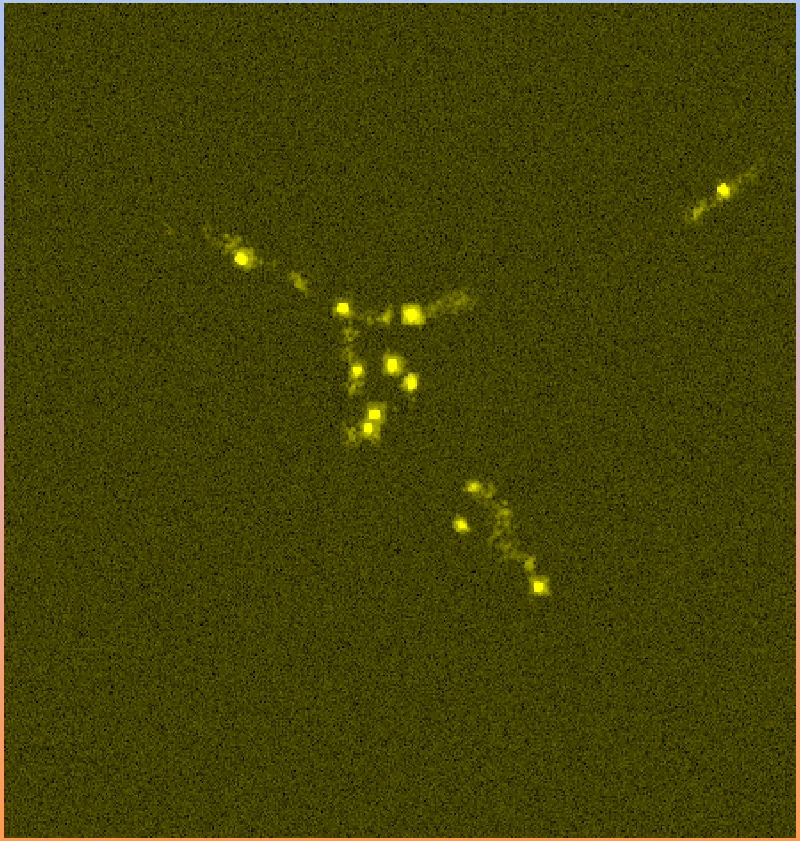
As observed through 30-meter telescope R=3000, 10^5 seconds, Barton et al., 2004, ApJ 604, L1

A possible IMF diagnostic at z=10

HeII (λ1640 Å)
Standard IMF



HeII (λ1640 Å)
Top-Heavy IMF, zero metallicity



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

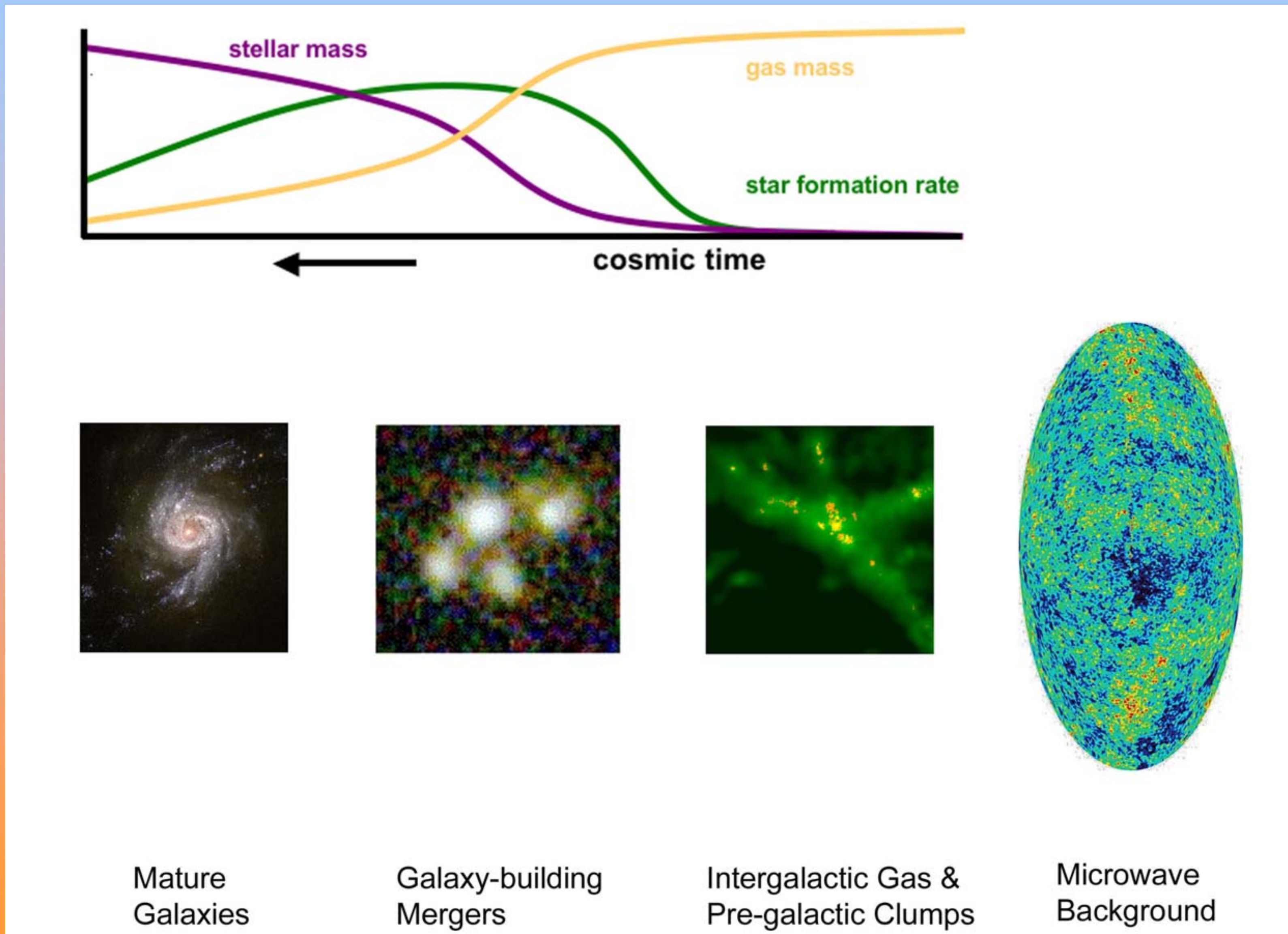
Star formation at z ≥ 7

- area of 2’ × 2’ ~ (5 Mpc)^3 at z = 10

  → simulations predict several tens of objects detectable with GSMT
- 2’ × 5’ FoV → fair sampling of very early universe with up to 400 pointings
- imaging (MCAO, GLAO) and
- follow-up spectroscopy (R ~ 3000, multiplex 100-600)
- Morphological studies on scales < 100 pc with AO

→ 100 nights with GSMT

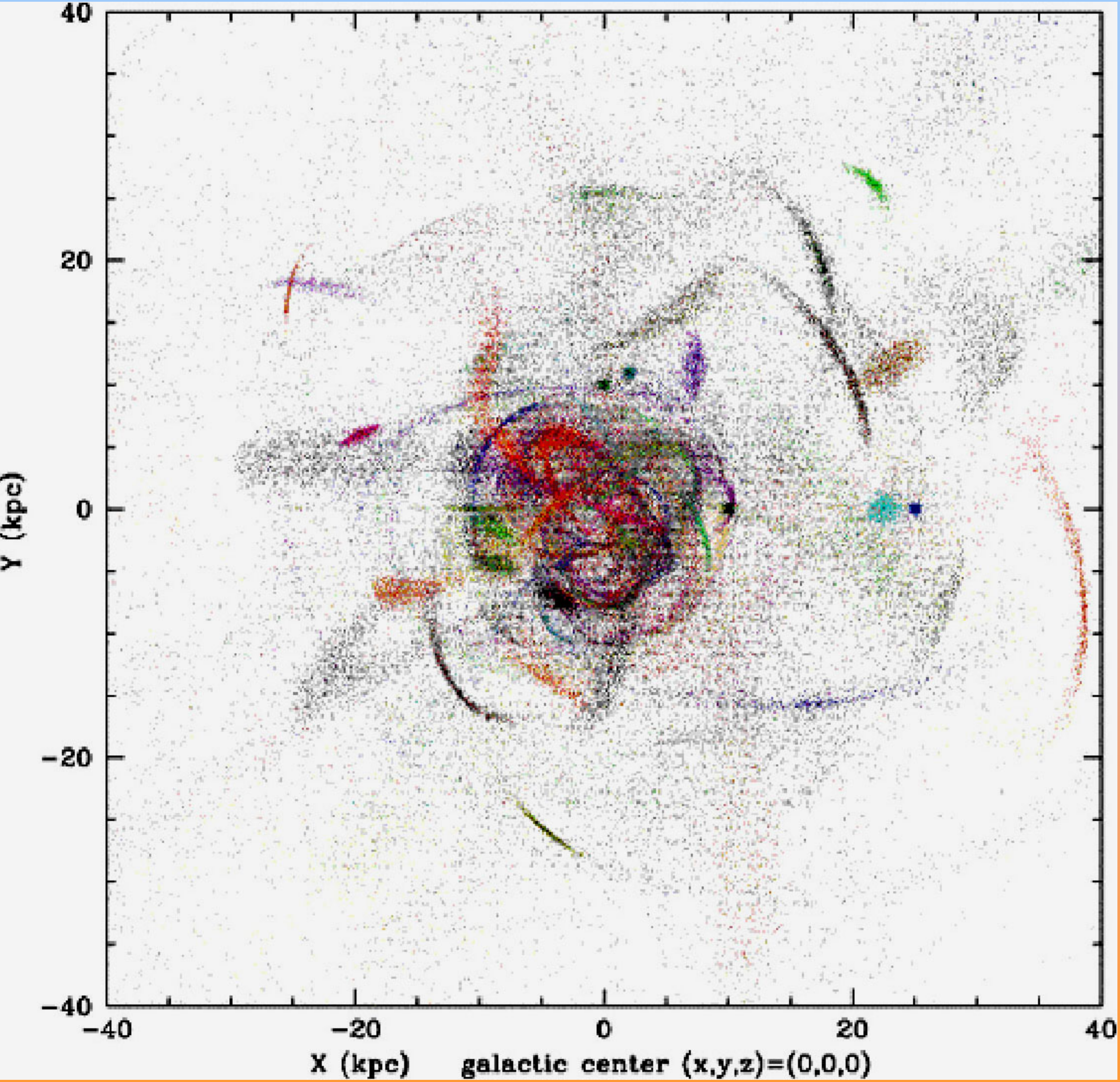
Connecting the Distant & Local Universe



Formation of giant galaxies

Hydro-simulation *"Antennae" galaxy – two galaxies merging*

The halos of Milky Way-like galaxies



Simulation depicting streams of dynamically and chemically distinct stars (color coded)

Remnants of multiple past merger events

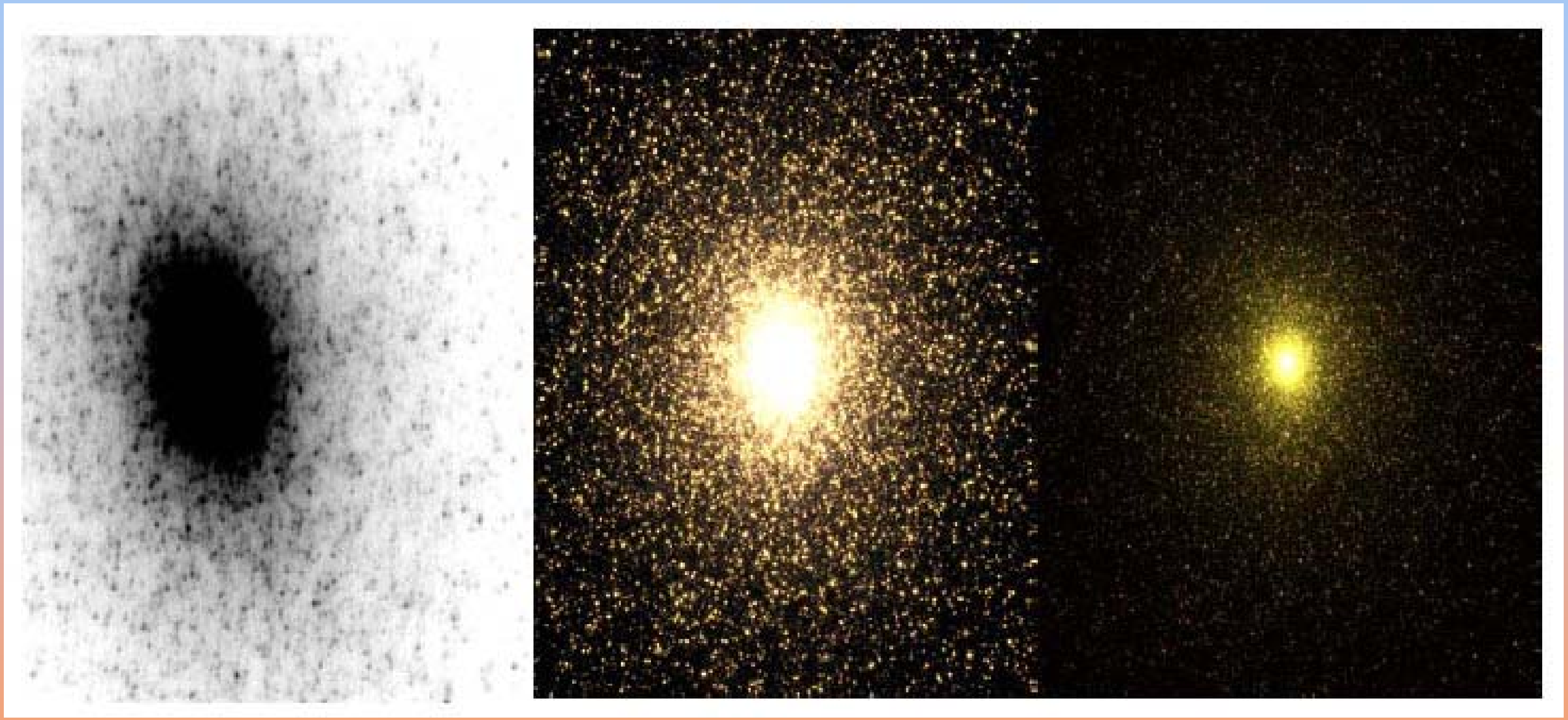
Spectroscopy with GSMT will provide complete genealogical record and nucleosynthesis history together with dynamics

(P. Harding)

The different stellar populations in galaxies

- **Goals:**
  - Quantify ages; [Fe/H], [α/H], [s,r/H], ; for stars in nearby galaxies spanning all types
  - Use 'archaelogical record' to understand the assembly process
  - Quantify IMF in different environments
- **Measurements:**
  - CMDs for selected areas in local group galaxies
  - Spectroscopy (R ~ 1500 → kinematics, ~ 40000 → nucleosynthesis)
- **Key requirements:**
  - MCAO delivering 2' FOV; MCAO-fed NIR spectrograph
- **Time to complete study with GSMT: 150 nights**

M32

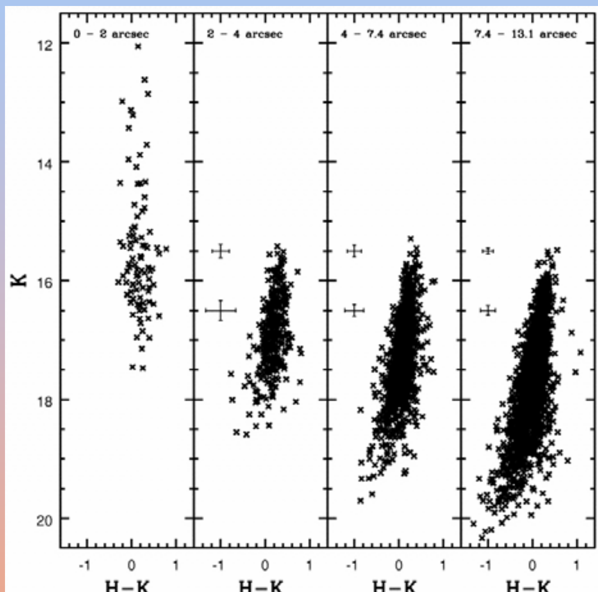


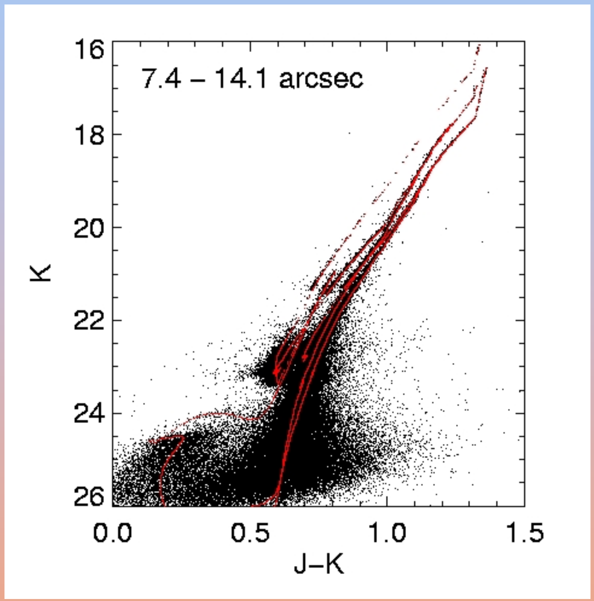
Gemini North Hokupa'a AO (IfA)	same region JWST simulation	same region GSMT simulation

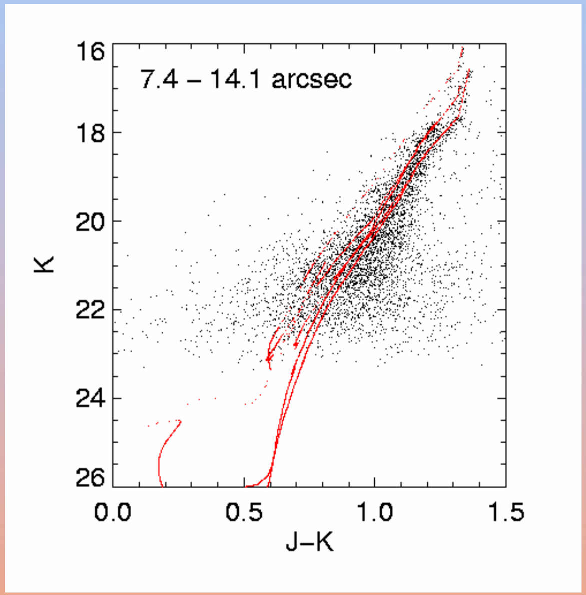
K. Olson, F. Rigaut, B. Ellerblok

Stellar Populations in Galaxies

20”







M 32 (Gemini/Hokupaa) **GSMT with MCAO** **JWST**

Population: 10% 1 Gyr, [Fe/H]=0; 45% 5 Gyr, [Fe/H]=0; 45% 10 Gyr, [Fe/H]=-0.3

Simulations from K. Olsen and F. Rigaut

Assumptions for MCAO simulations

	J	K
FWHM	0.009	0.015 arcsec
Strehl	0.2	0.6

PSF includes effects of

- **limited number of actuators in deformable mirrors**
- **optical effects of the primary mirror segments (tilt, de-phasing)**
- **limited temporal sampling of wave fronts**
- **limited spatial resolution of wave front sensors**

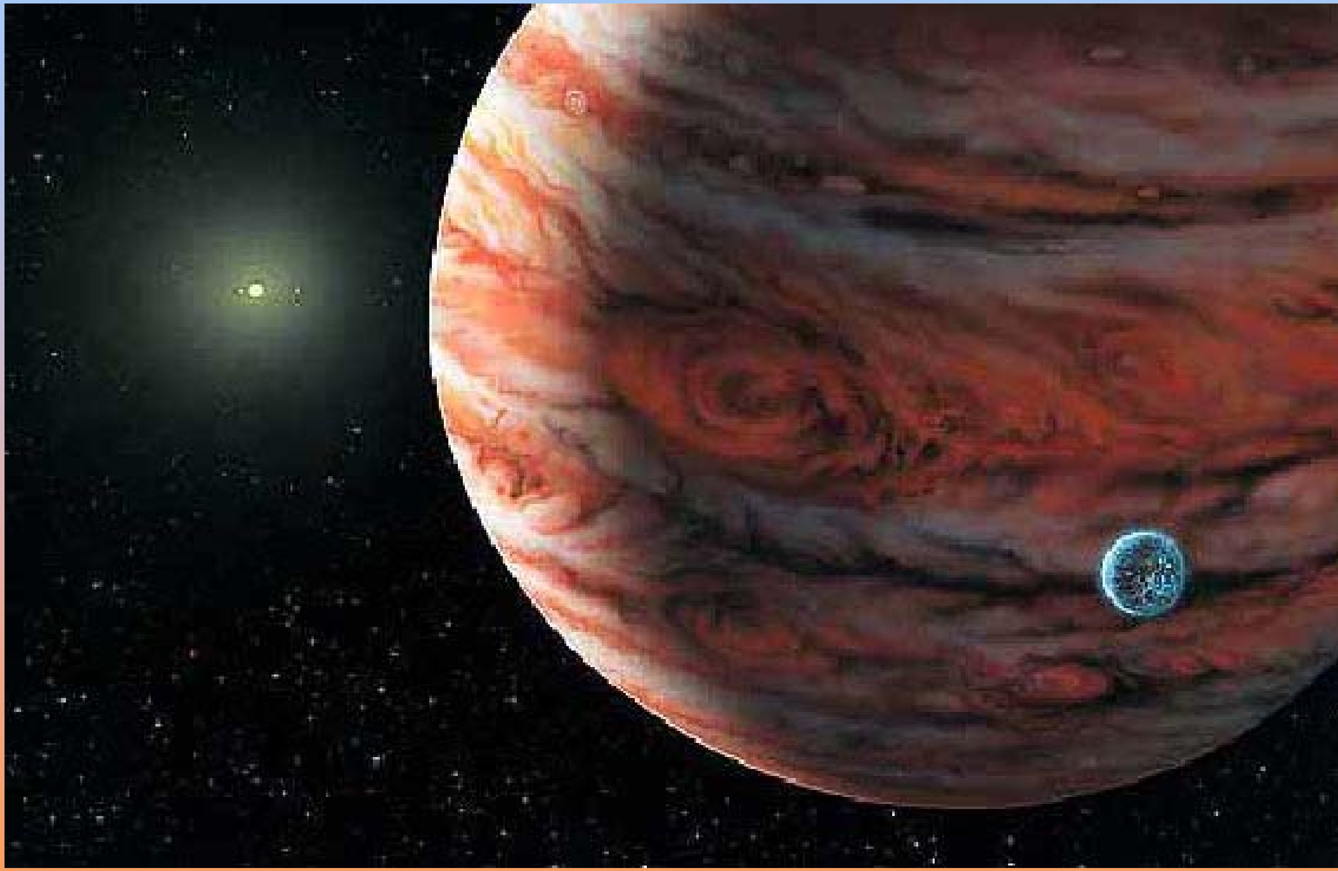
no PSF variations with time and position included

Exploring other solar systems

More than 100 planets around other stars detected so far ("indirect" technique- very small periodic spectral line shifts indicate orbital motion)

Most planetary systems vastly different from Solar System

No direct images of other planetary systems so far



Artist conception of planetary system orbiting around 55 Cancri using results of radial velocity Keck observations

Planets around other stars

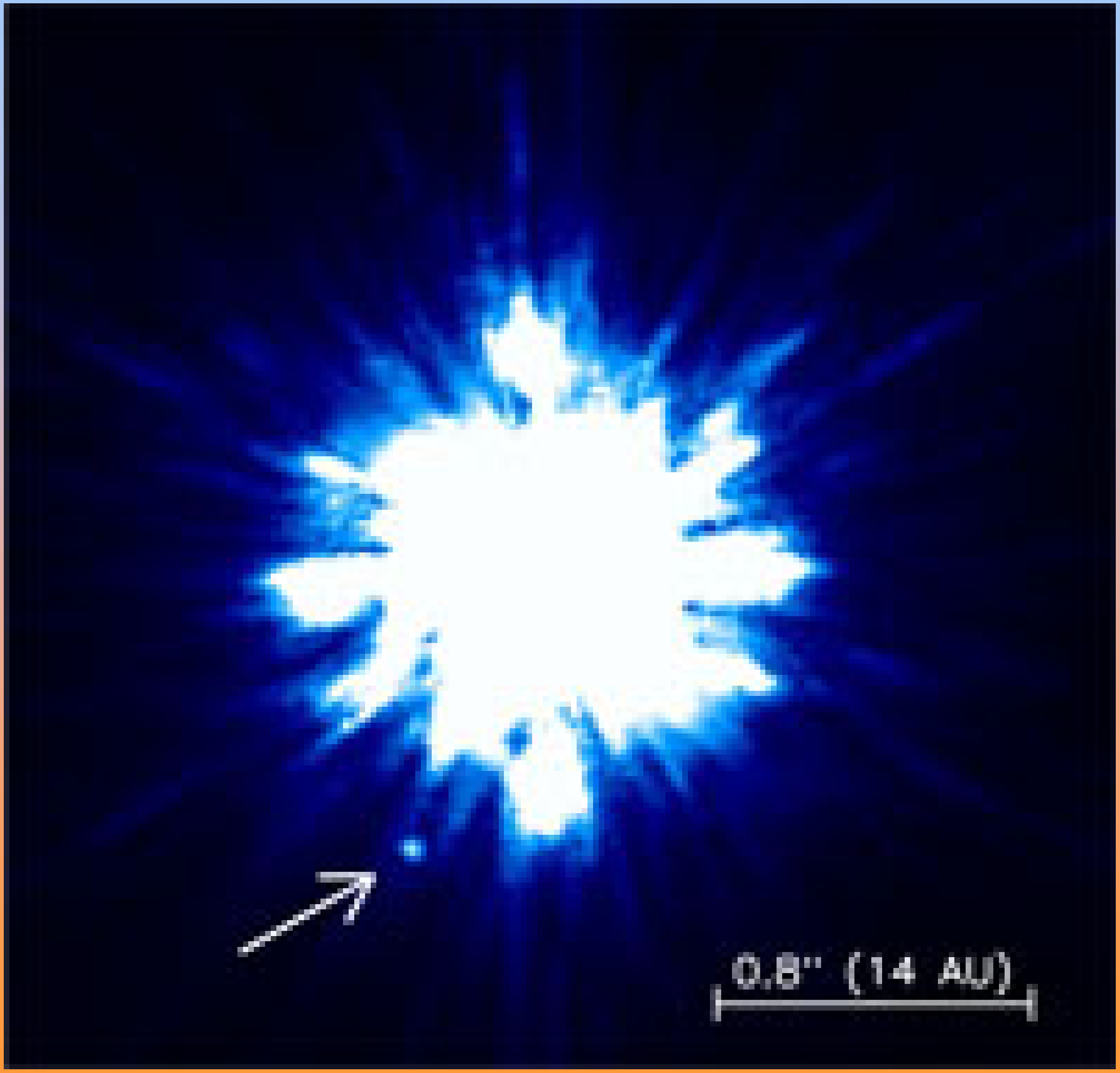
"Brown Dwarf" orbiting a star at same distance as Saturn from sun

Gemini/Keck AO detection by Michael Liu (IfA), 2002

Problem: Planets much fainter than Brown Dwarfs

→30m telescope needed !!

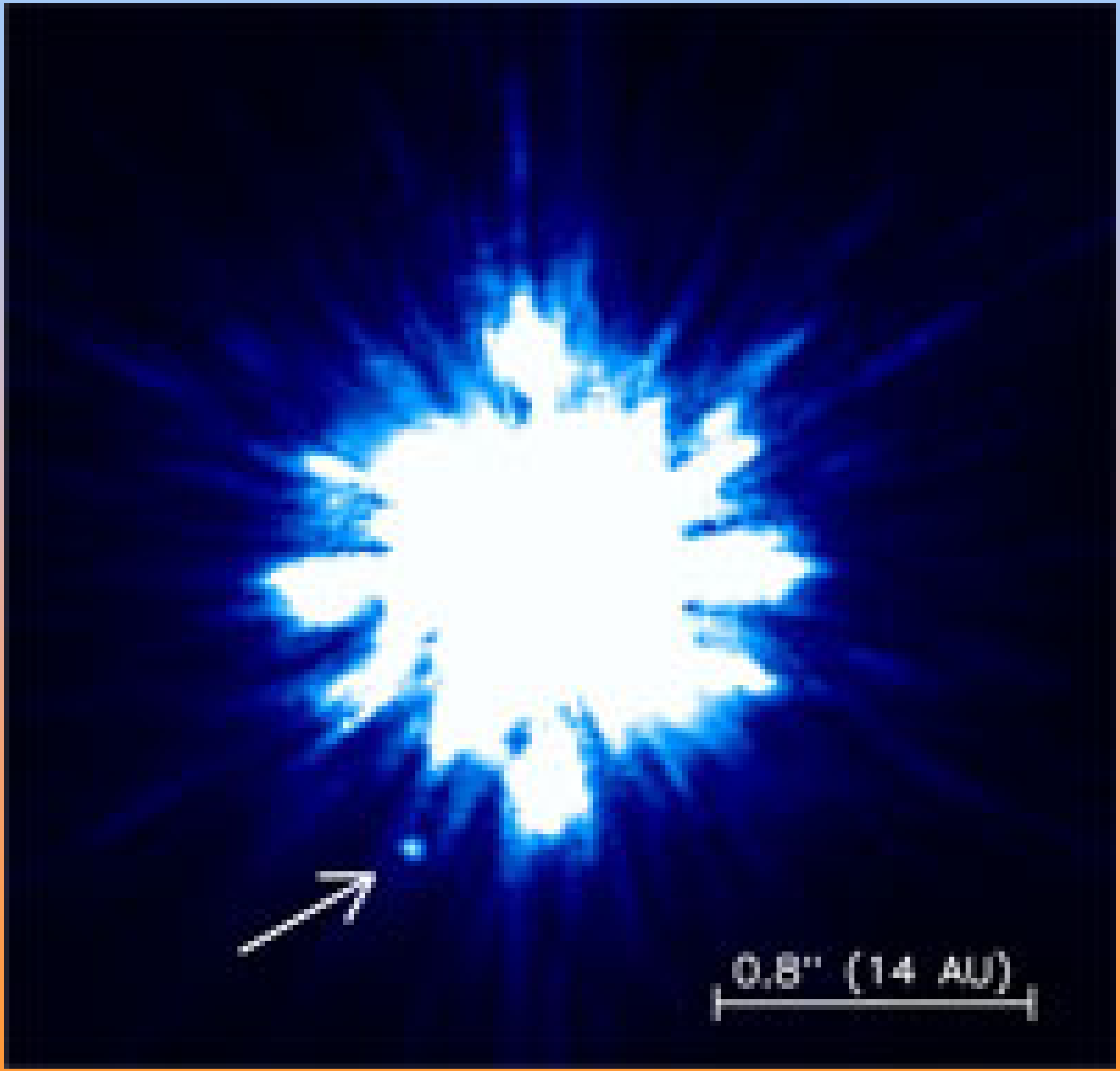
→ GSMT !!



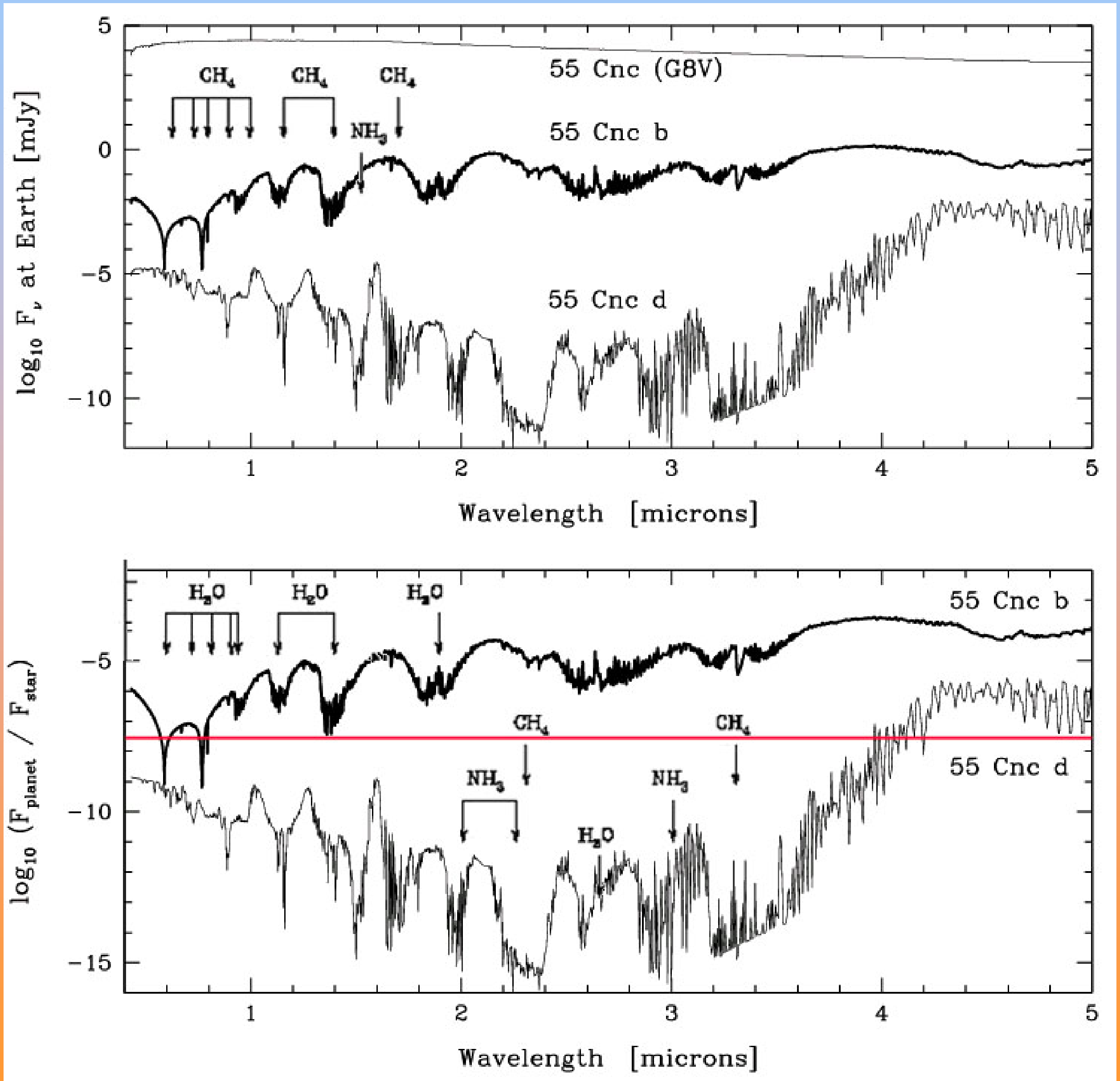
The power of GSMT

GSMT will allow
for the first time

- To image giant planets surrounding many hundred stars out to distances as great as 200 light years (coronography + AO)
- To determine masses and radii by imaging and spectroscopy
- To analyze their atmospheric structure and chemical composition by spectroscopy



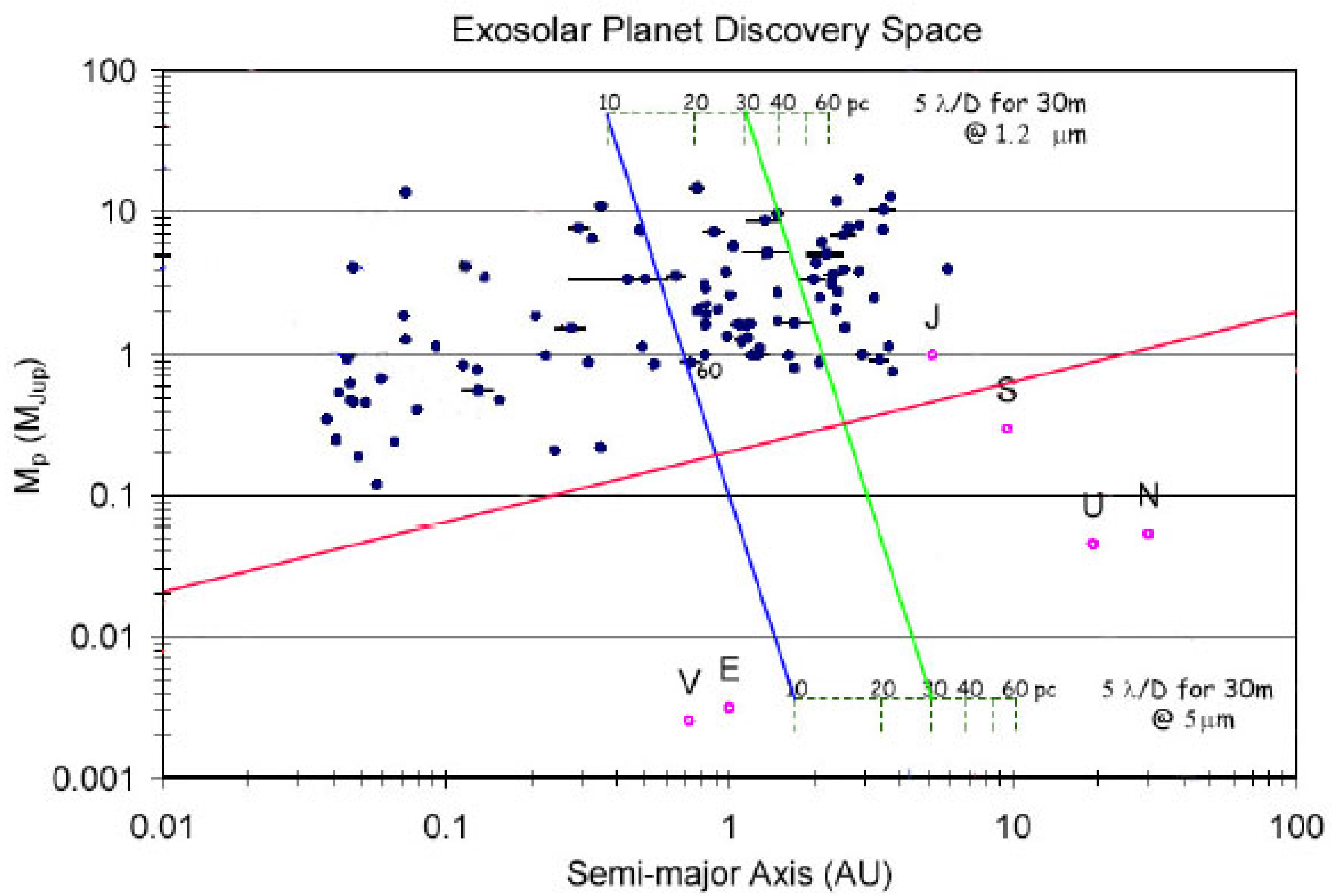
55 Cancri – physical characterization by spectroscopy



GSMT →
Detection of 55 CnC b/c
Chemical composition of Atmosphere of 55 CnC b

Sudarsky, Burrows & Hubeny, 2003

GSMT discovery space



The physics of giant exo-planets

Goal: Image and characterize exo-planets

- Mass, radius, albedo
- Atmospheric structure
- Chemistry → physics of giant planet formation
  →repercussion for formation of terrestrial planets, life on terrestrial planets
- Rotation
- "Weather"

Measurements: R~ 10 photometry & R ~ 200 spectra

- Near-infrared (reflected light)
- Mid-infrared (thermal emission)

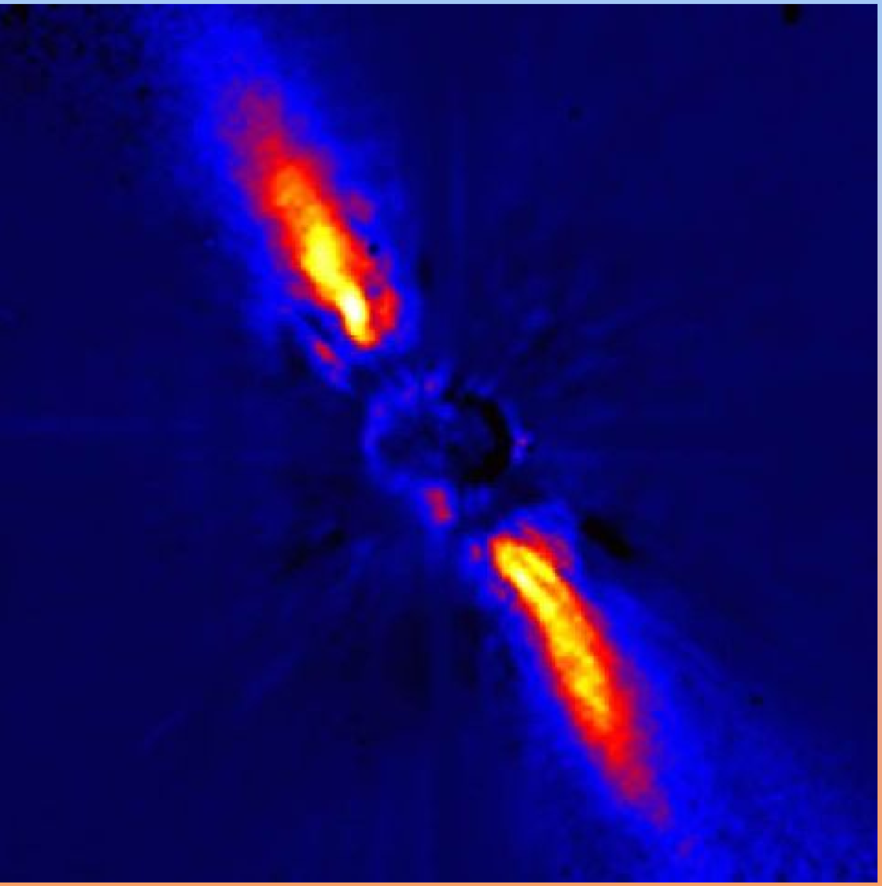
Role of GSMT: Enable measurements via

- High sensitivity
- High angular resolution

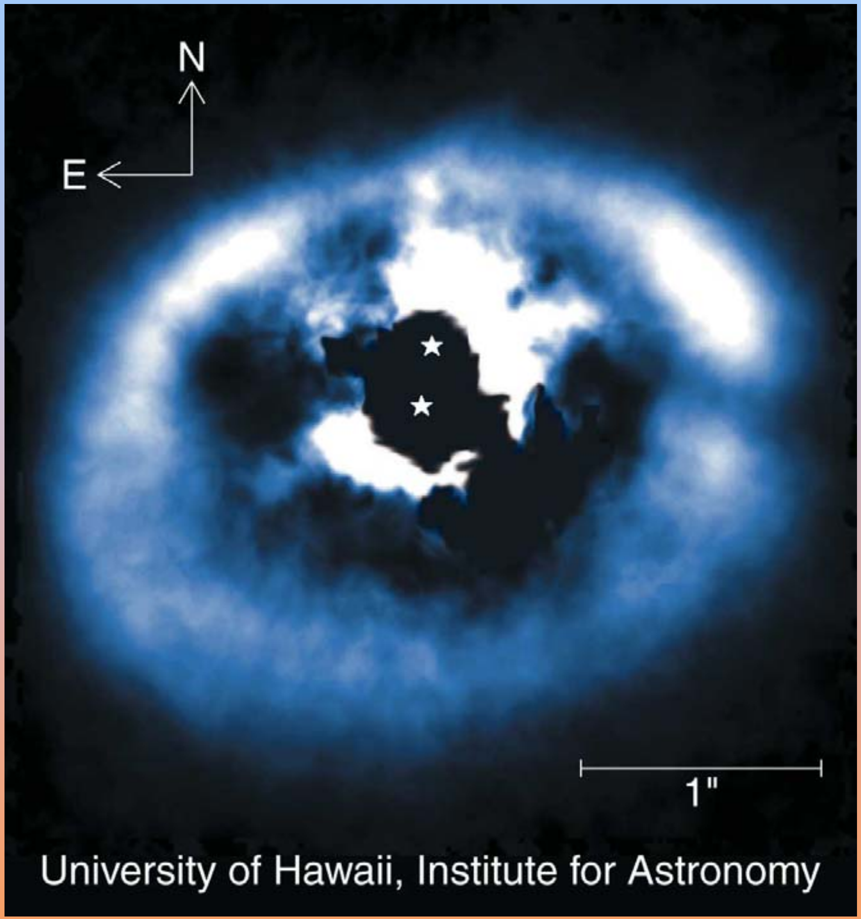
Exploring the process of planet formation

Artist conception of a proto-planetary disk
with young planets and asteroids

Proto-planetary disks around stars

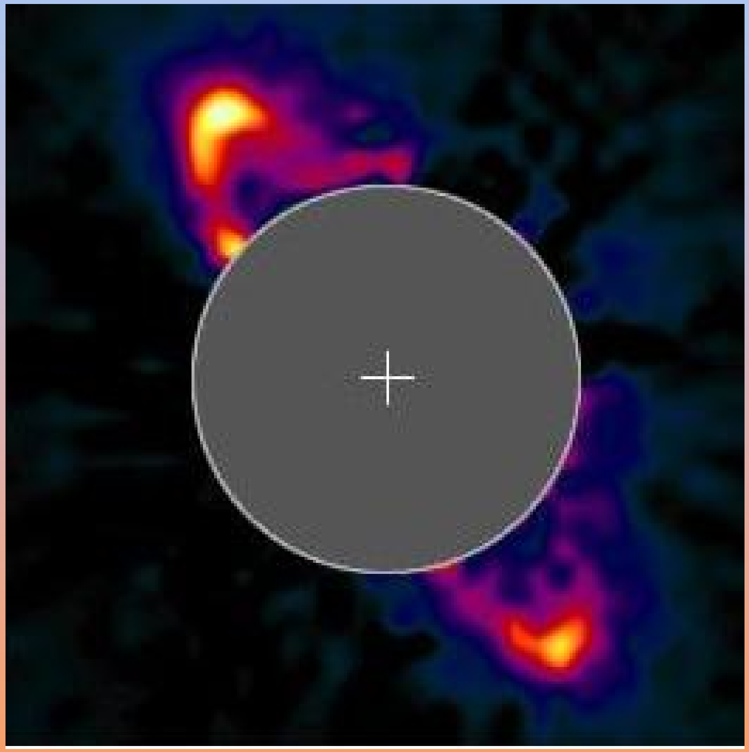


β *Pic (ESO VLT)*



GG Tau, Gemini (Hokupaa)
Potter et al., 2002

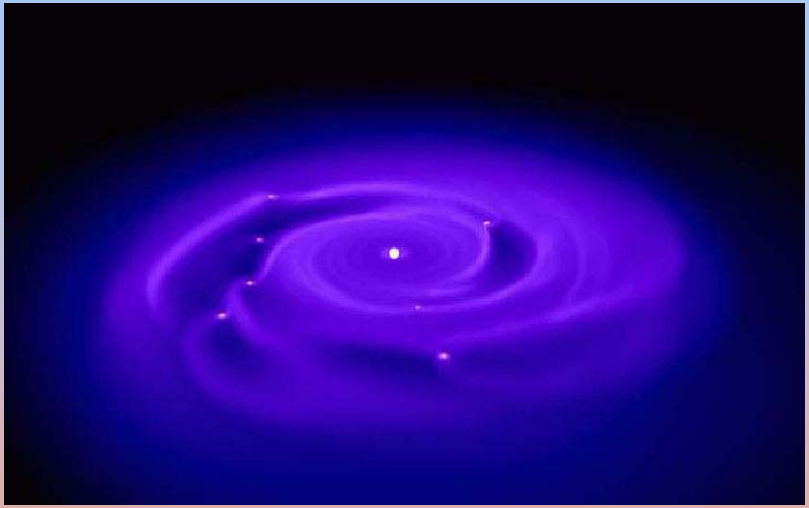
Proto-planetary disks around stars



HST, NICMOS

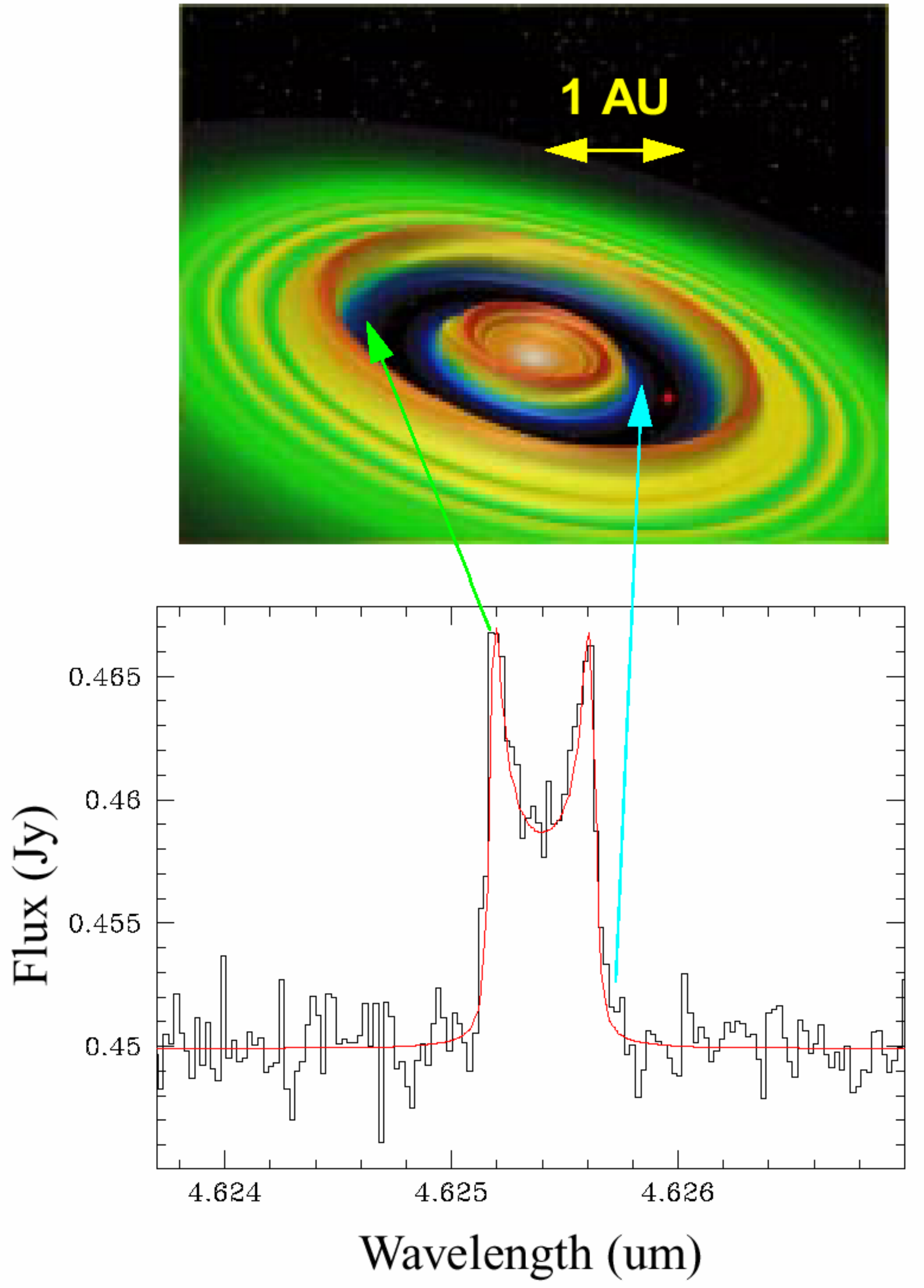
Formation of planets in proto-planetary disks

Goals:



- AO imaging and IR spectroscopy of thousands of disks around nearby young stars
- characterize physics of disks, T(r), ρ(r)
- detect giant planets directly
- detect giant planets indirectly from gravitational "gaps" in disks
- characterize planets from properties of disks (location, widths)

Probing Planet Formation with High Resolution Infrared Spectroscopy



Simulated 8 hr exposure of mid-IR CO fundamental spectral line profile emitted by gas in gap produced by giant planet

width of line → location in disk
Width of line peaks → width of gap
→ mass of planets

Origins of Planetary Systems

- **Goals:**
  - Understand where and when planets form
  - Physical nature of proto-planetary disks (T(r), ρ(r), Σ(r))
  - Observation of ‘gaps’ to constrain formation and physics of giant planets
- **Measurements:**
  - Spectra of some 10^3 accreting PMS stars (R~10^5; $\lambda \sim 5\mu$) in SF regions
- **Key requirements:**
  - On axis, high Strehl AO; low emissivity
  - Exploit near-diffraction-limited mid-IR performance
- **Time to complete study with GSMT:**
  - 1 year

Complete information about SWG →

http://www.aura-nio.noao.edu/gsmt_swg/

This science report →

http://www.aura-nio.noao.edu/gsmt_swg/
SWG_Report/SWG_Report_7.2.03.pdf