Multi-wavelength observations -- a short introduction

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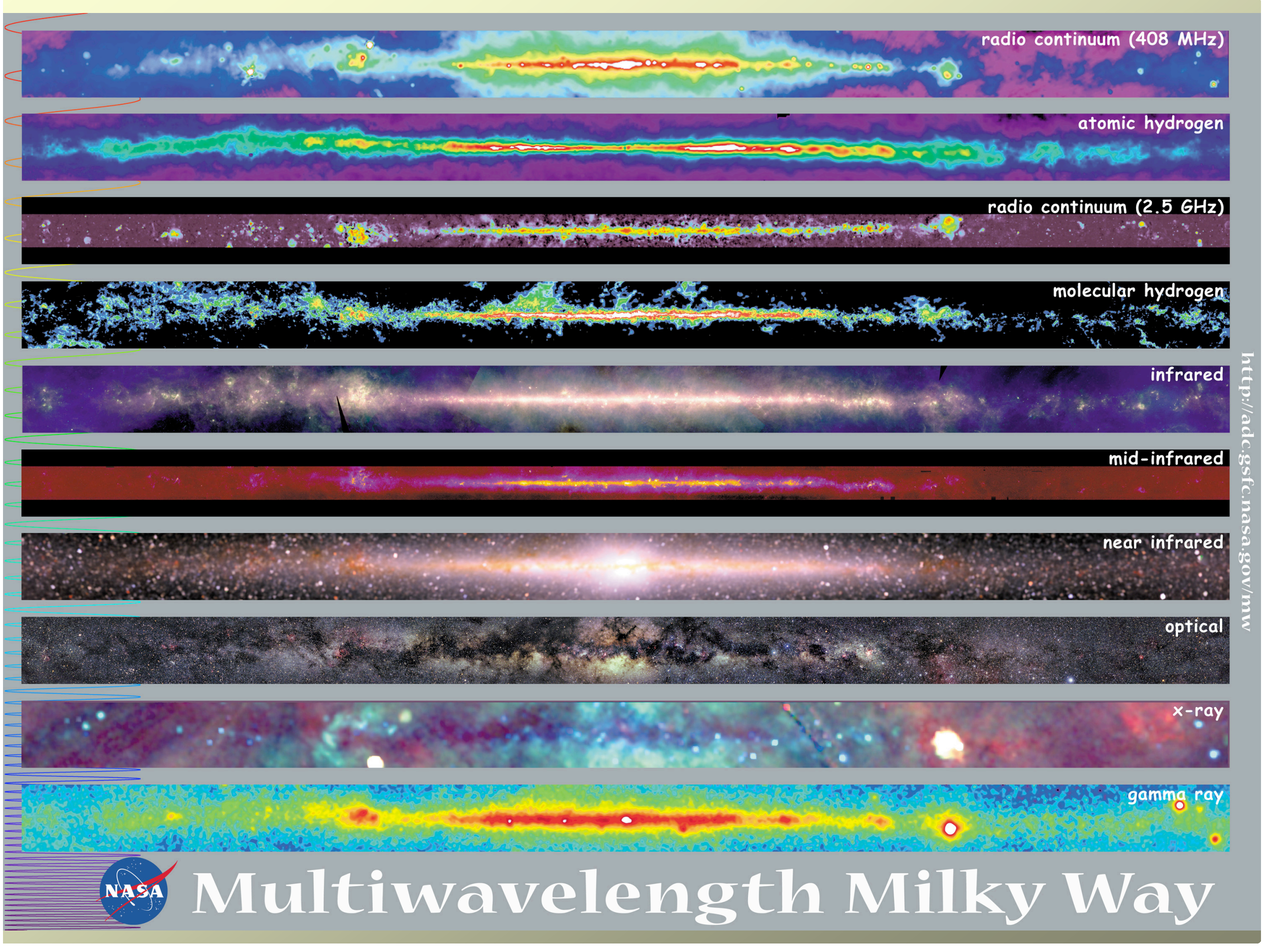
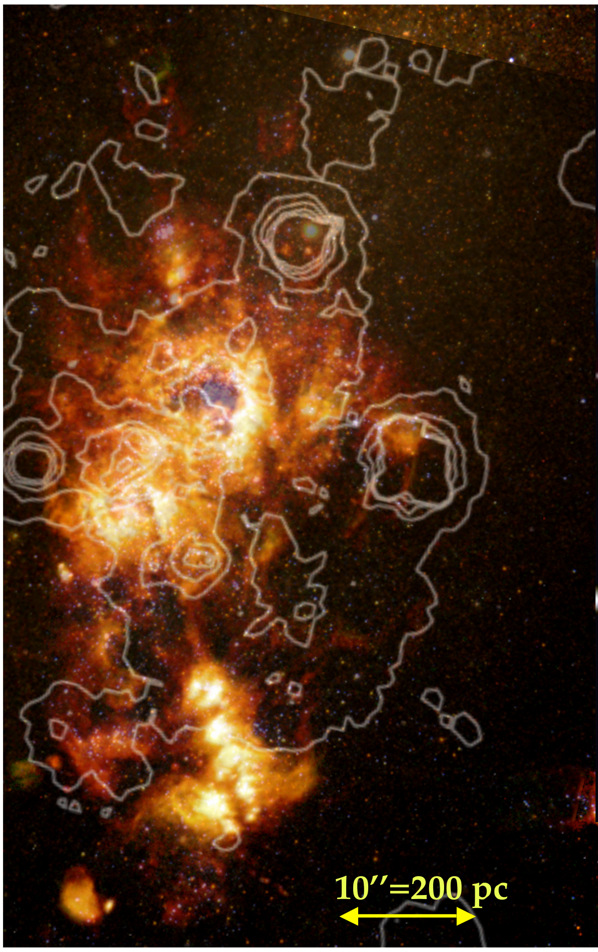
Why? What for? How? Basics, overview…

- Introduction
- Instruments, techniques, detectors
- Atmosphere
- X-rays
- UV
- **Visible - near-IR**
- **IR**
- radio



Orion

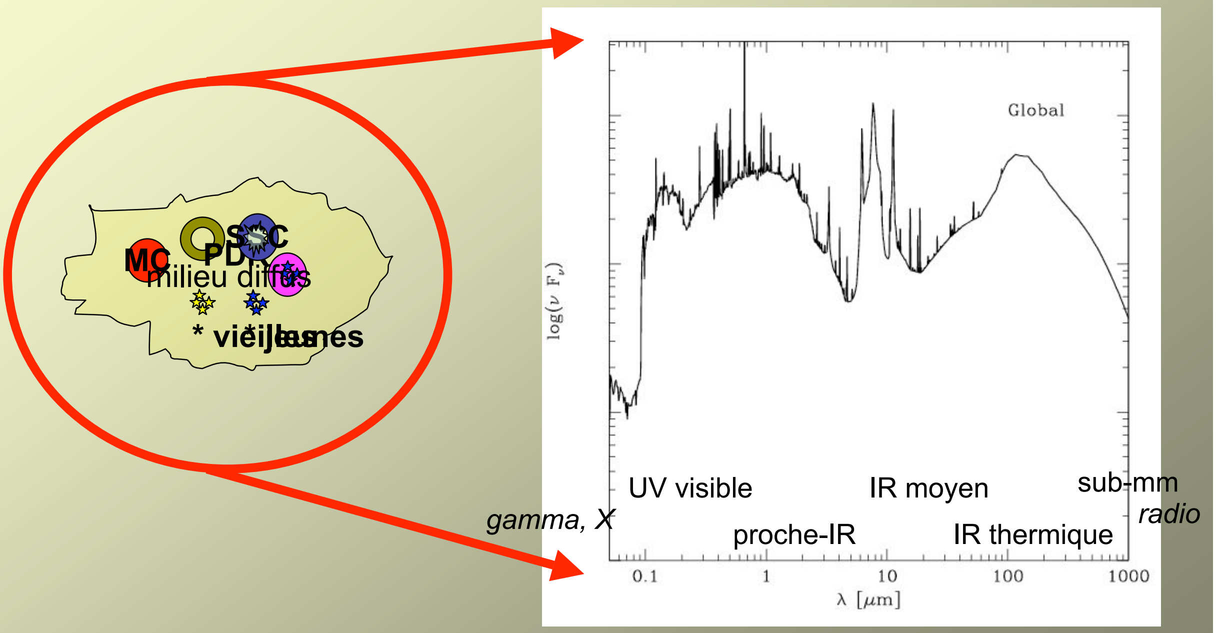


Vents galactiques,
supervents

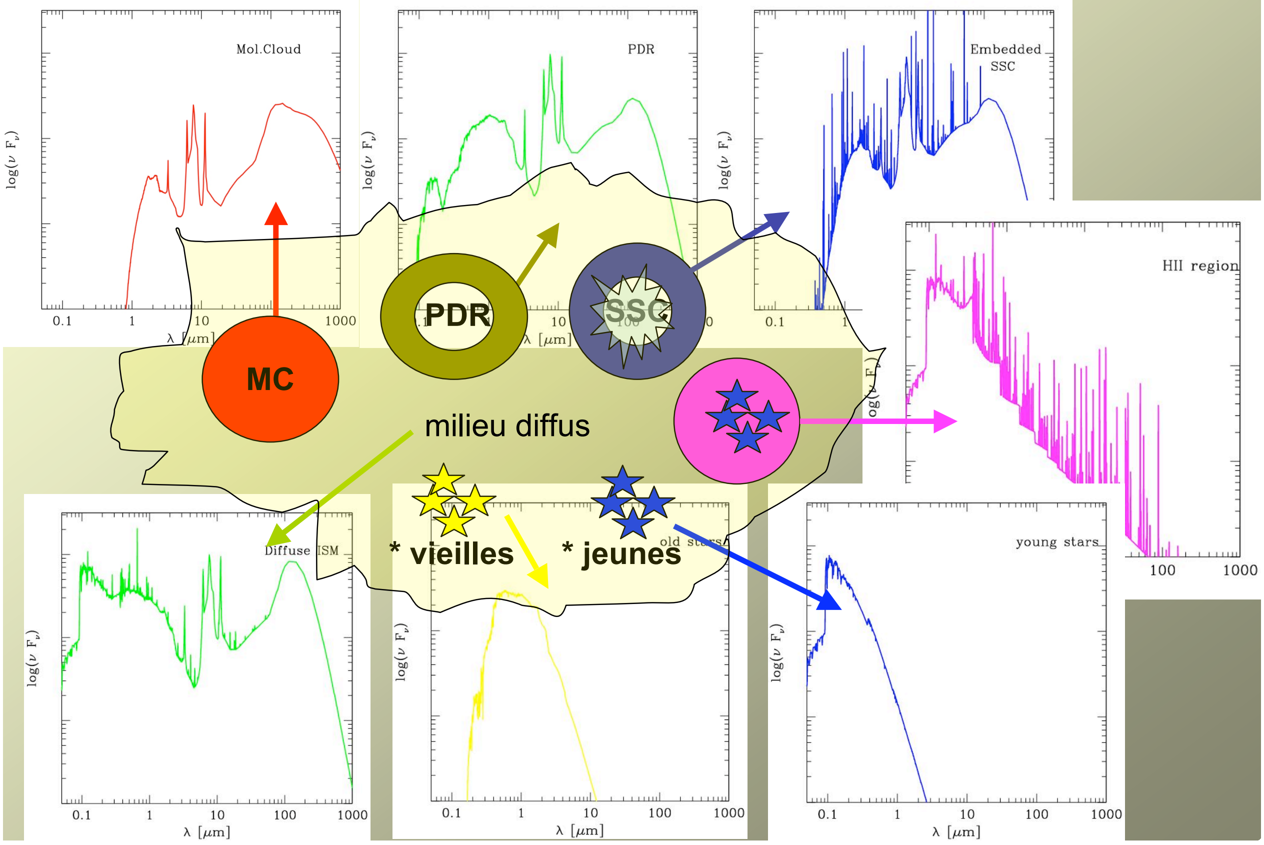
Observation / modélisation multi-longueur d'onde des galaxies

Observations intégrées (galaxie lointaine) vs résolues (proche)

Spectre intégré/global



Observation / modélisation multi-longueur d'onde des galaxies

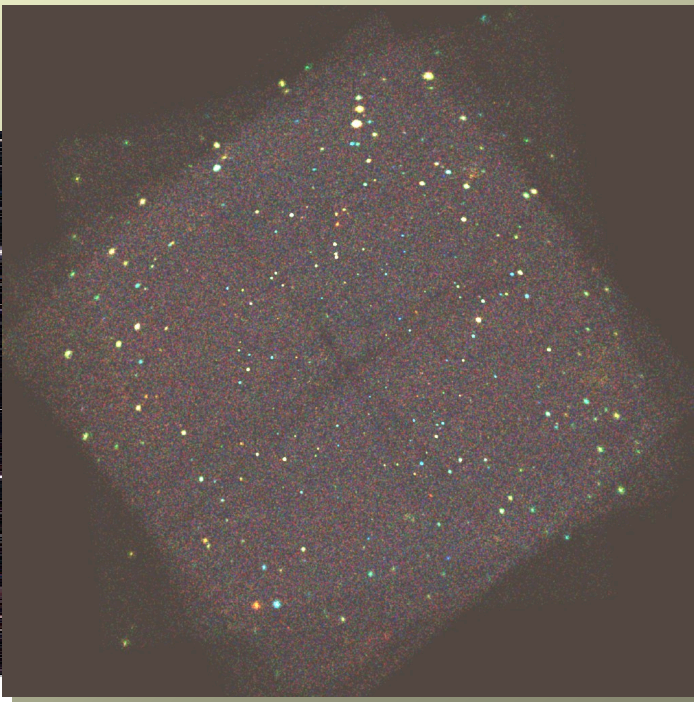


Visible versus X-rays

Chandra Deep Field South - color composite, 940 ksec

Chandra Deep Field South (CDF-S)
(MPG/ESO 2.2-m + WFI)

ESO PR Photo 02a/03 (10 January 2003)



Type of Radiation	Wavelength range (nm)	Frequency range (Hz)	Typical Sources	Temperature of radiating object	Examples of telescopes
Radio	$> 1 \times 10^3$	$< 3 \times 10^{11}$	Interstellar medium, cool gas, electrons	<10	VLA, ATCA… ALMA
IR	10^3 - 10^6	3×10^{11} - 4×10^{14}	cool clouds of dust and gas, planets	10 - 10^3	SCUBA, Spitzer, Herschel,… JWST
Visible	400 -700	4×10^{14} - 7.5×10^{14}	exterior of stars	10^3 - 10^5	VLT, HST,…
UV	20 - 400	7.5×10^{14} - 3×10^{16}	supernova remnants, very hot stars	10^5 - 10^6	HST, FUSE
X-ray	0.01 - 20	3×10^{16} - 3×10^{19}	supernova remnants, gas in clusters of galaxies, stellar corona	10^6 - 10^8	Chandra, XMM, …
Gamma-ray	<0.01 nm	$> 3 \times 10^{19}$	hypernova, accretion disks around black holes	$>10^8$	INTEGRAL, GLAST, HESS,…

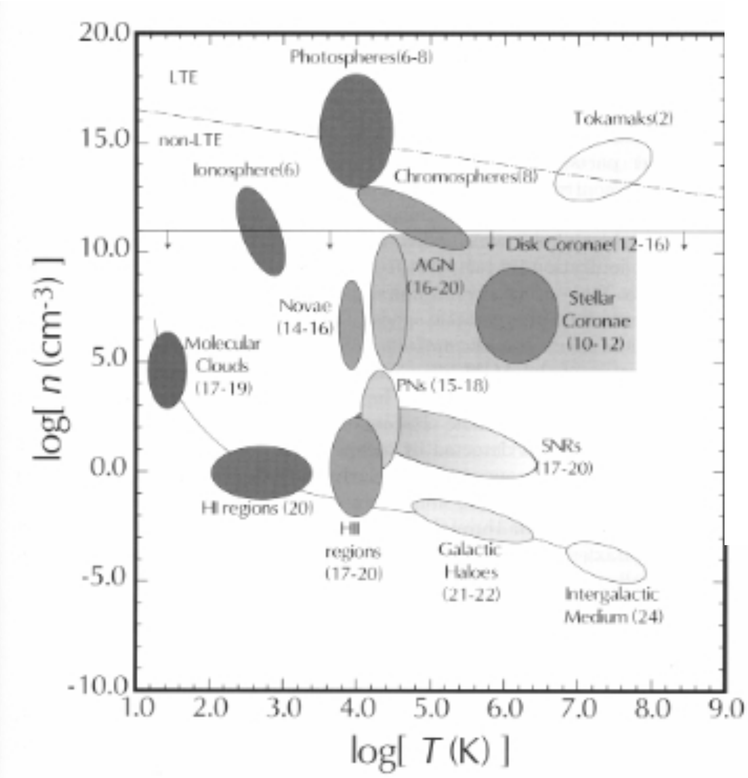
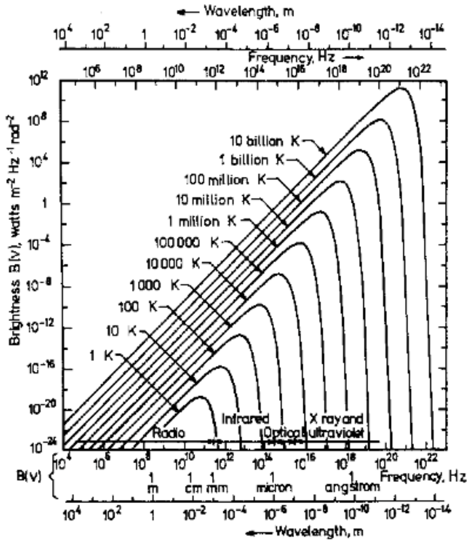
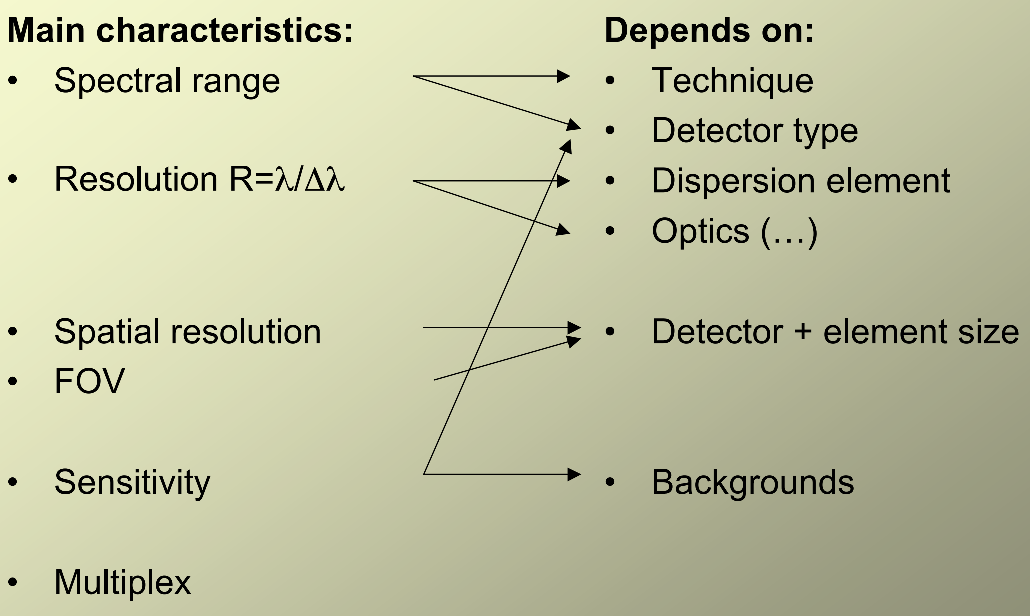


Fig. 1.2. Densities and characteristic sizes of diffuse astrophysical plasmas in the universe. For each class of objects, the characteristic size in log(cm) is given. The approximate boundary between plasmas in LTE and non-LTE plasmas is marked as a dash-dot line. The diffuse universe lies approximately below the horizontal line marked with arrows. The thin solid curve connects the dominant phases of galactic and intergalactic diffuse media.



Conditions (n,T) in astrophysical plasmas (from Dopita & Sutherland)

Instruments



Main characteristics:

- Spectral range → Technique, Detector type
- Resolution R=λ/Δλ → Dispersion element, Optics (…)
- Spatial resolution → Detector + element size
- FOV → Detector + element size
- Sensitivity → Detector type, Backgrounds
- Multiplex

Depends on:

- Technique
- Detector type
- Dispersion element
- Optics (…)
- Detector + element size
- Backgrounds

Techniques & detectors

Techniques:

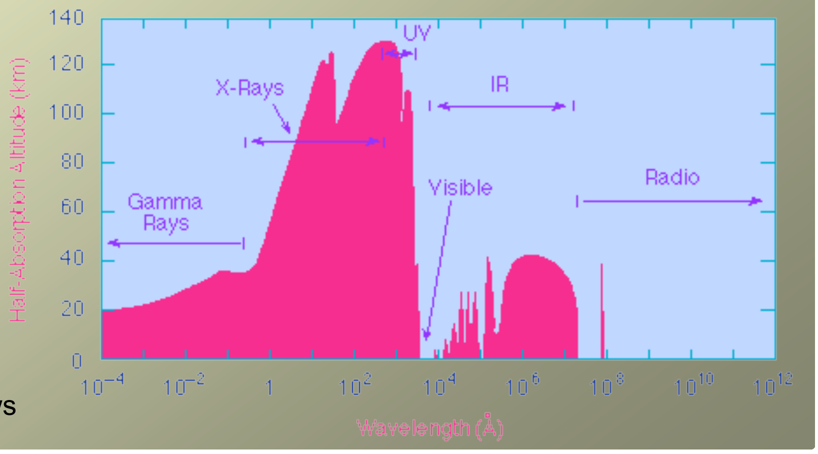
- ***Imaging:*** direct, coded masks, aperture synthesis,…
- ***Spectroscopy:*** slit, fiber, IFU, slitless
  Dispersion elements: grism, grating, FTS,…
- ***Interferometry***

Detectors:

- ***High energy:*** scintillators, proportional counter, spark chambers. CCDs, …
- ***UV:*** Multi-Anode Microchannel Array (MAMA), Microchannel Plates (MCPs), CCDs
- ***Visible***: CCD (Charge Coupled Device)
- ***Near-IR***: other solid-state detectors (fast readout)
- ***IR:*** bolometers
- ***mm-radio:*** « receivers » - many types!

Atmosphere: effects

- Opacity --> limited « windows » from the ground
- Scattering --> daylight!
- Emission --> continuum + lines
- Turbulence --> image degradation + phase fluctuations
- Ionisation --> alters propagation of radio waves



Atmospheric windows

Atmosphere: opacity

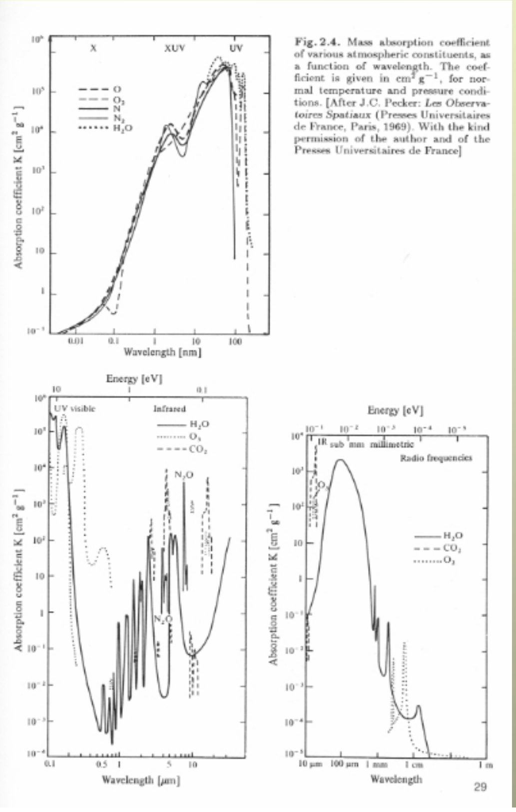


Fig. 2.4. Mass absorption coefficient of various atmospheric constituents, as a function of wavelength. The coefficient is given in $cm^2 g^{-1}$, for normal temperature and pressure conditions. [After J.C. Pecker: *Les Observatoires Spatiaux* (Presses Universitaires de France, Paris, 1969). With the kind permission of the author and of the Presses Universitaires de France]

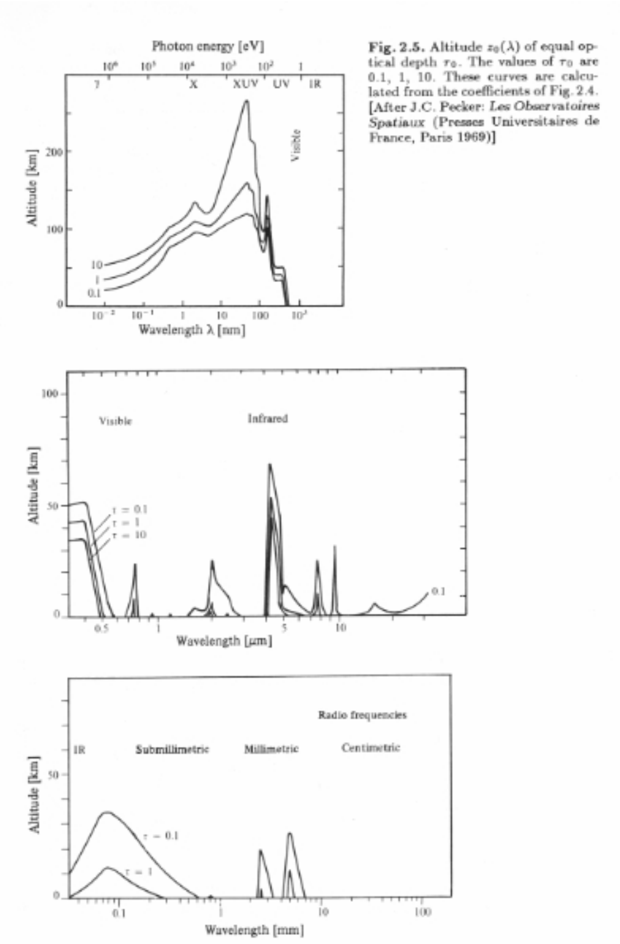
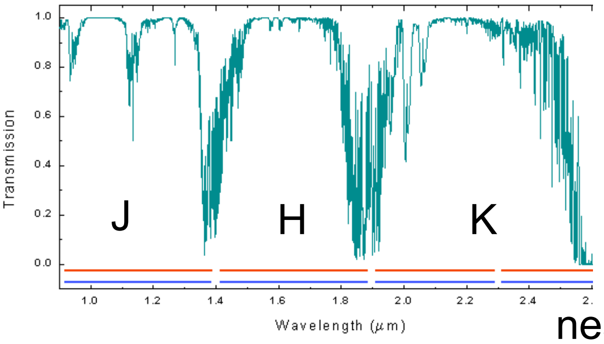
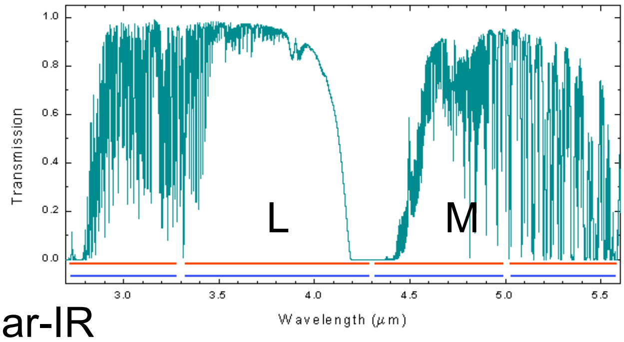


Fig. 2.5. Altitude $z_0(\lambda)$ of equal optical depth τ_0. The values of τ_0 are 0.1, 1, 10. These curves are calculated from the coefficients of Fig. 2.4. [After J.C. Pecker: *Les Observatoires Spatiaux* (Presses Universitaires de France, Paris 1969)]

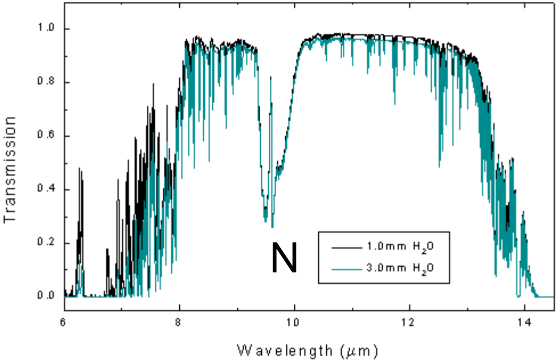
Atmosphere: transmission

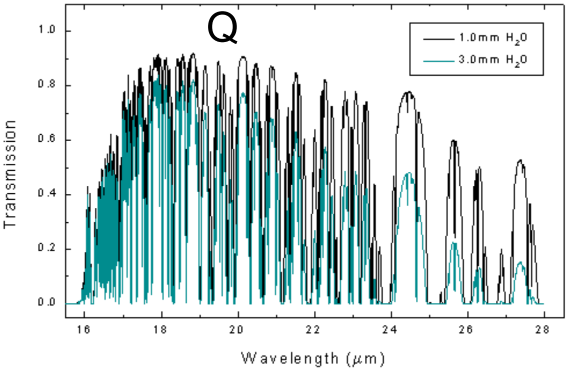




near-IR

mid-IR





Atmosphere: emission

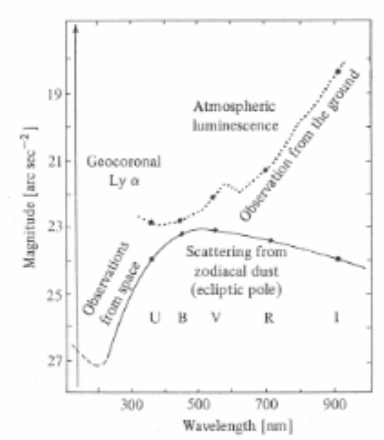
- **Airglow** (e.g. NaI, OI, O2,OH, H): resonant, fluorescent, and chemoluminescent processes in upper atmosphere - due to solar radiation
- Aurorae - due to solar wind
- **thermal emission**: sky (+ telescope, dome…)
- **zodiacal light**: reflection of sunlight on the interplanetary dust cloud (strong on ecliptic)

- Sunlight, moonlight
- light pollution

Other « backgrounds »:

- unresolved stars and galaxies

Typically: sky (mag/arcsec2) J=16, H=14, K=13



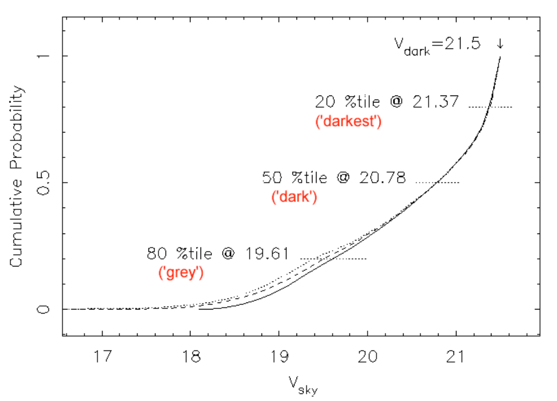
Atmosphere: emission

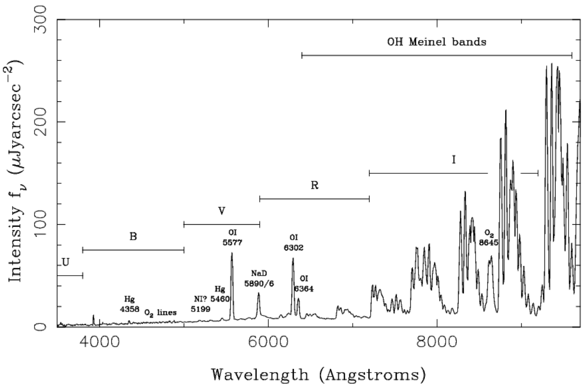
- Airglow
- zodiacal light

Atmosphere: emission

- **Optical sky background** - variable: depends on moon angular separation, lunar phase, ecliptic latitude, zenith angle, and phase of the solar cycle

- No problem for imaging down to ~20-21 mag (in V)
- No problem for spectroscopy with sufficient resolution
- Sky subtraction necessary for faint objects





Atmosphere: emission

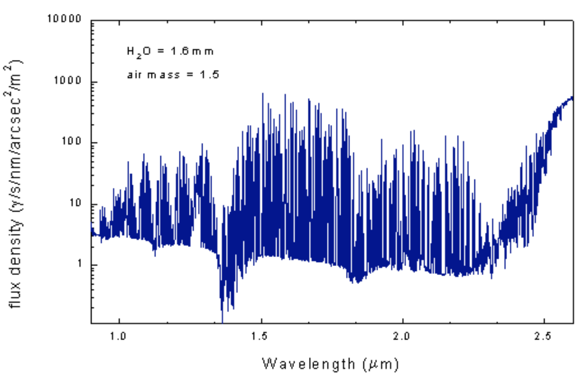
Near-IR sky background

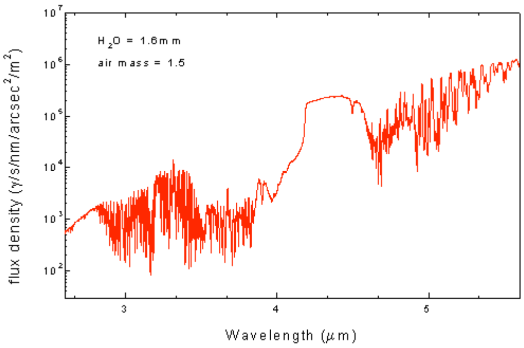
- Dominated by OH (hydroxil) lines
- Variations on timescales of **~5-15 min** with amplitude of 5-10% (stronger during twilight)
- Sky subtraction mandatory!
- Spectroscopy: high sensitivity obs possible with R>~3000-4000!

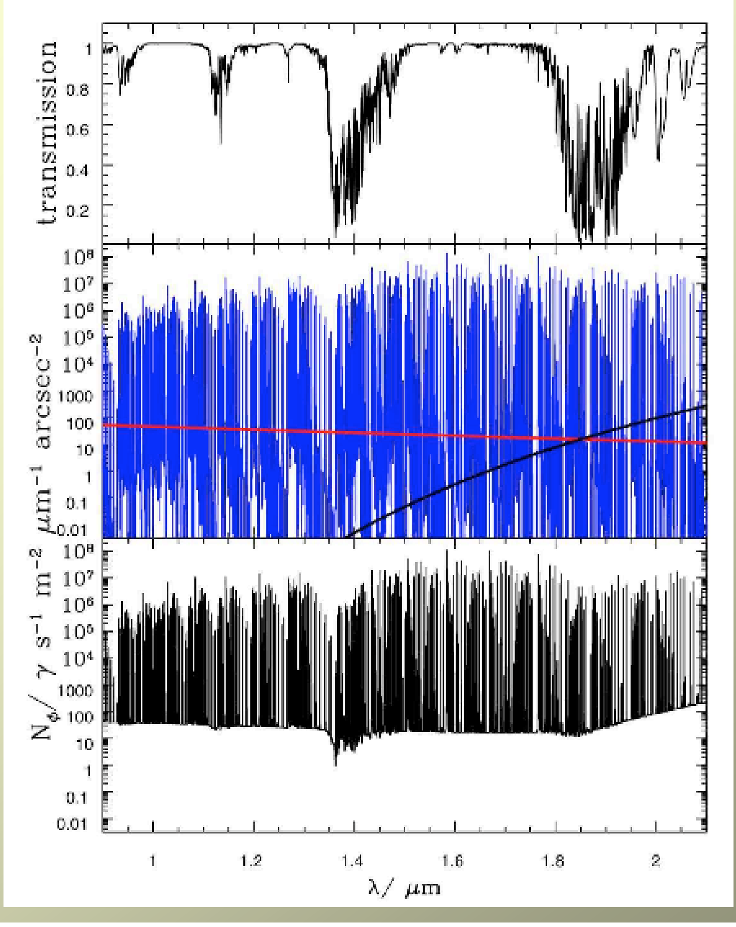
Beyond ~3 micron

- Background dominated by thermal emission (~273-280 K)
- Strength varies with atmospheric water vapour content and air mass

Typically: sky (mag/arcsec2)
J=15.5, H=13.8, Ks=12.9







OH lines
thermal emission
zodiacal light

X- and gamma-rays --> cf. Marc Audard

Peculiarities:

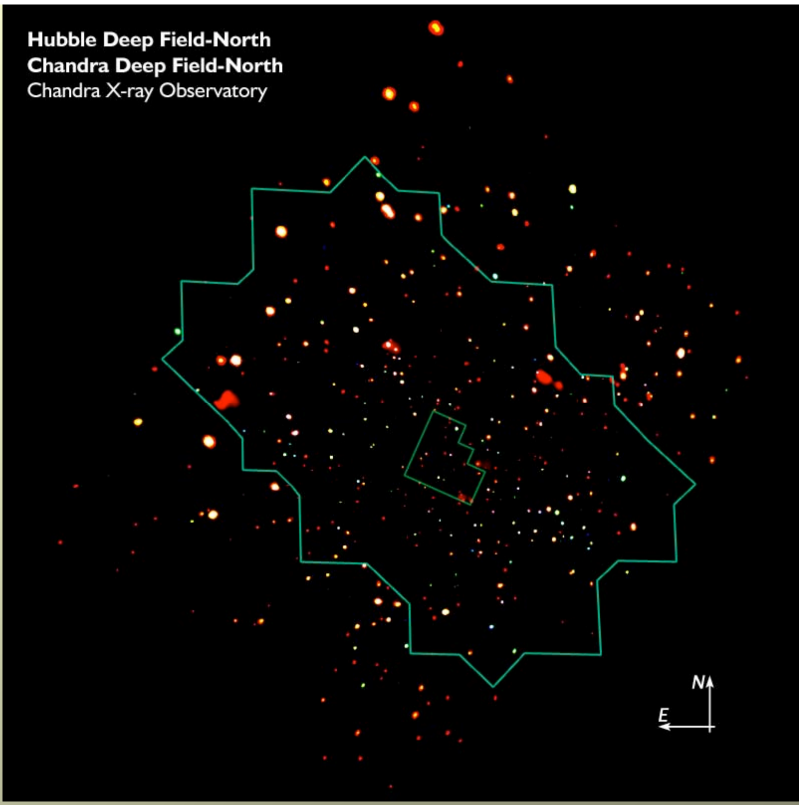
- Normal focussing not possible
  → optics: diffraction, coded masks…
  but focussing via grazing incidence telescope

* High background (cosmic rays…)
  → Shields
  → Anti-coincidence detectors
  → …

Examples:

- Chandra: high spatial resolution, high spectral resolution
- XMM/Newton: high sensitivity
- INTEGRAL, …

X-rays

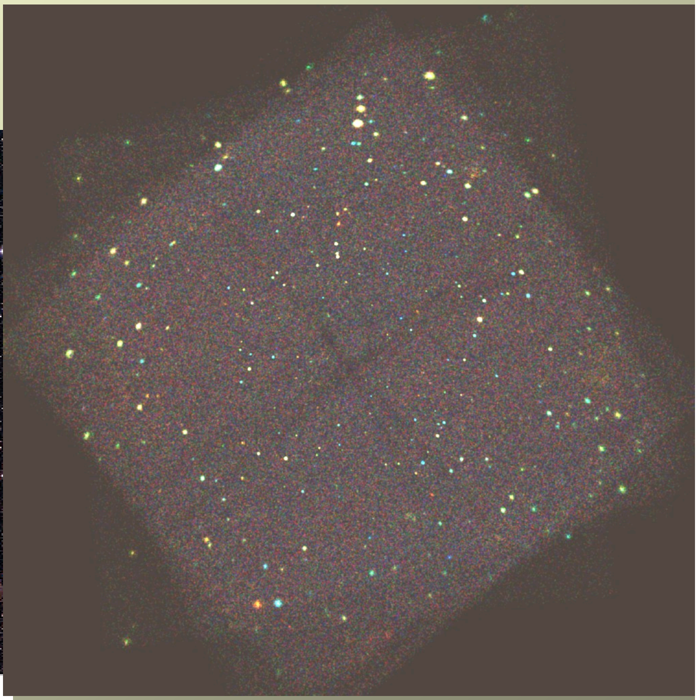


Chandra Deep Field-North survey; this is the deepest 0.5-8.0 keV survey ever made, and nearly 600 X-ray sources are detected. The survey is comprised of 2 Ms of Chandra ACIS-I exposure covering 448 sq. arcmin.

X-rays

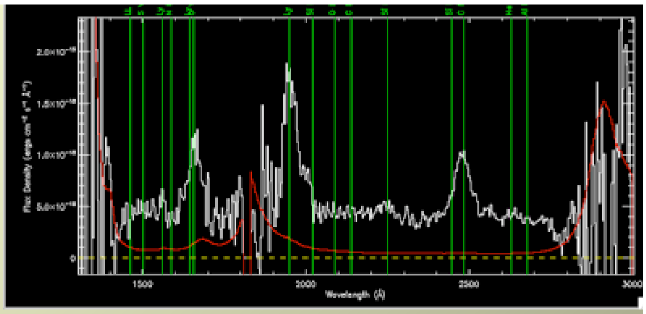
Chandra Deep Field South - color composite, 940 ksec

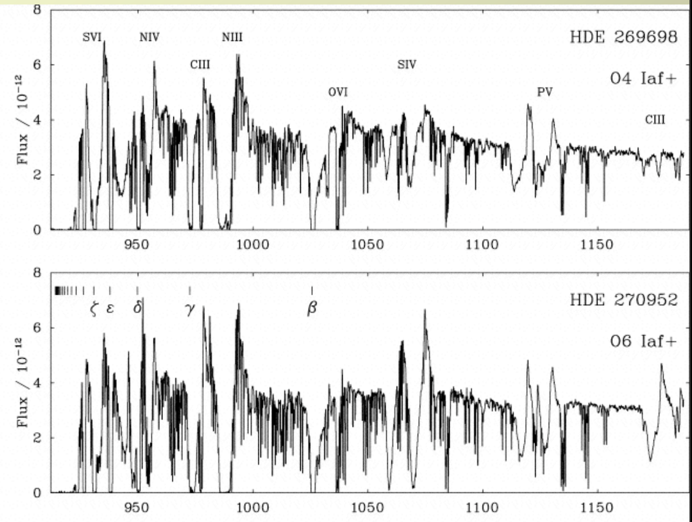
Chandra Deep Field South (CDF-S)
(MPG/ESO 2.2-m + WFI)
ESO PR Photo 02a/03 (10 January 2003)
©European Southern Observatory

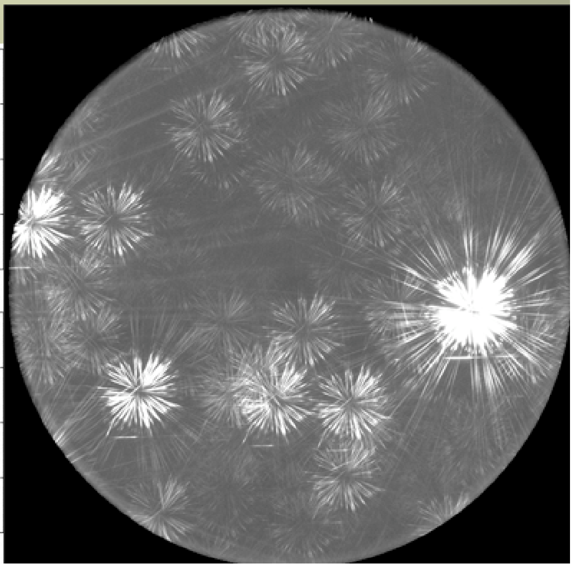


UV

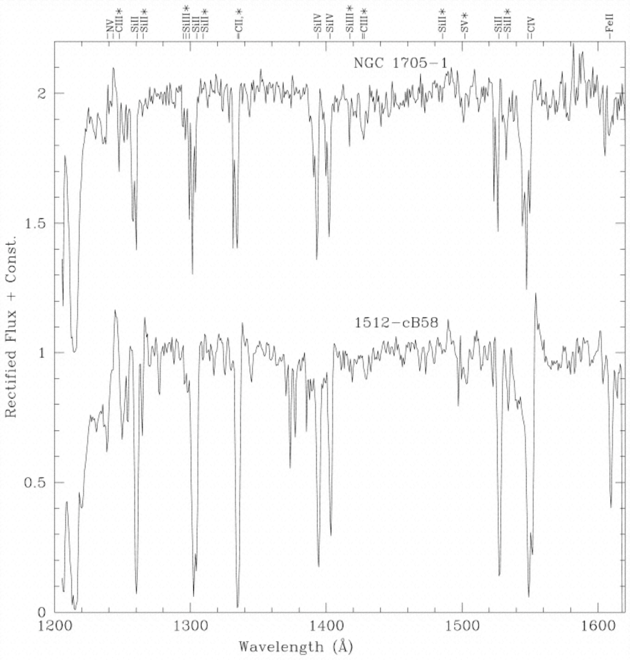
- ~900 - 4000 Ang
- Imaging and spectroscopy
- IUE, HUT, HST, FUSE, GALEX…







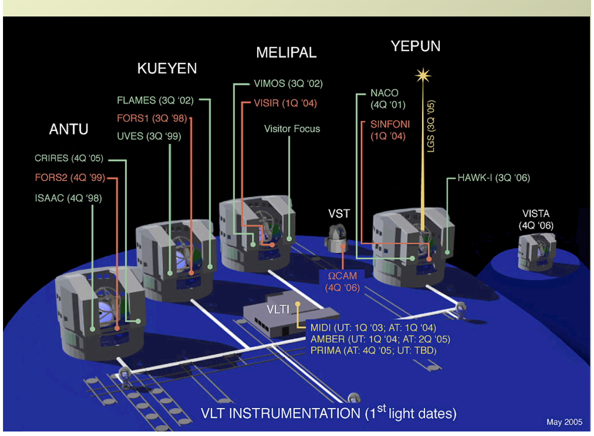
UV

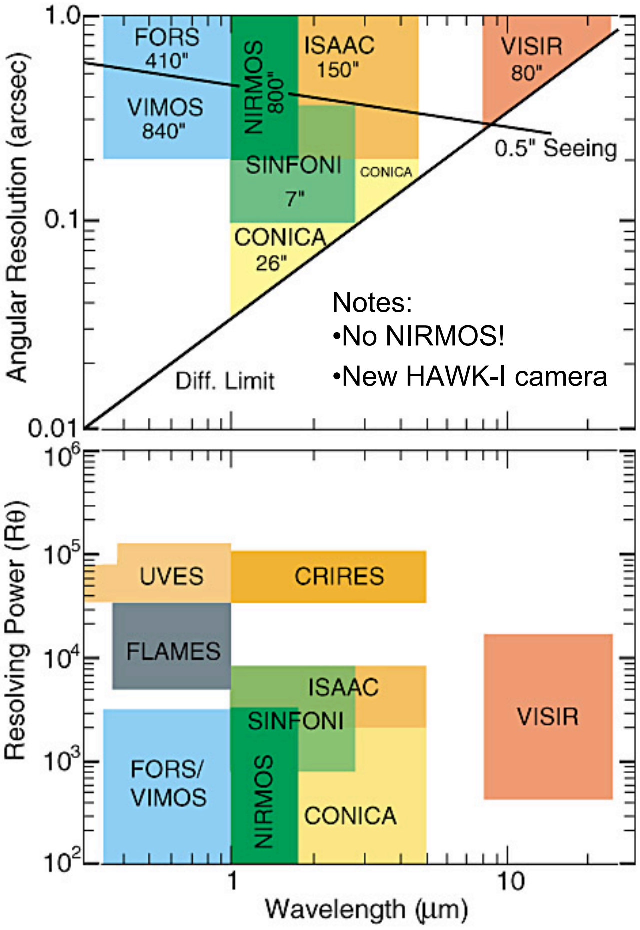


UV spectroscopy: nearby galaxies as templates for high-z observations

ESO VLT instruments: (optical - near-IR - mid-IR)

* spectral coverage
* spatial coverage
* also important: FOV, multiplex!

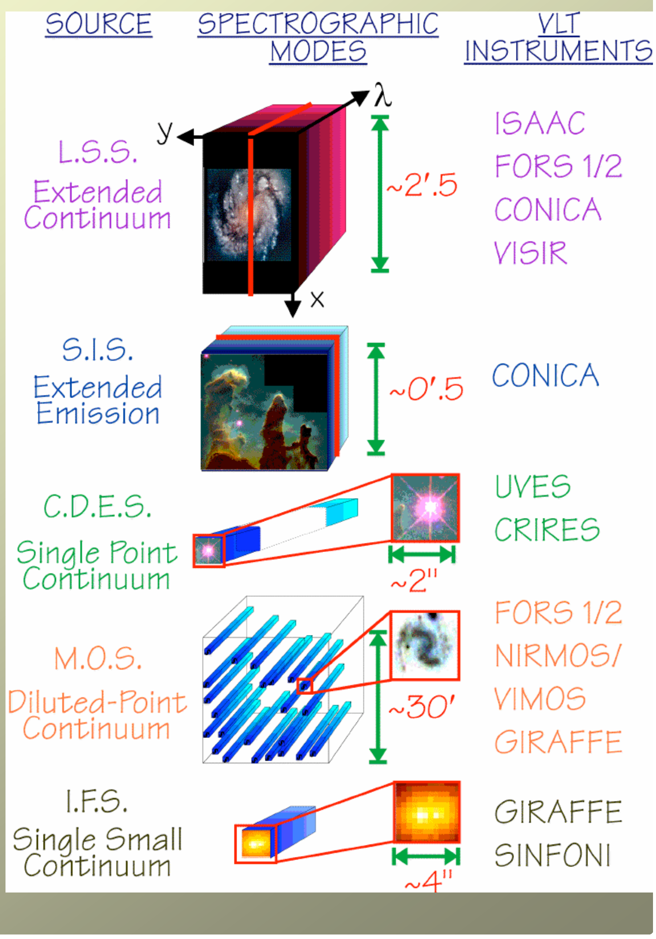




Notes:
- No NIRMOS!
- New HAWK-I camera

ESO instruments:
spectroscopic modes

- Long Slit Spectroscopy
- Scanning Imaging Spectrographs
- Cross dispersed echelle spectrograph
- Multi-object spectrographs
- Integral Field Spectroscopy



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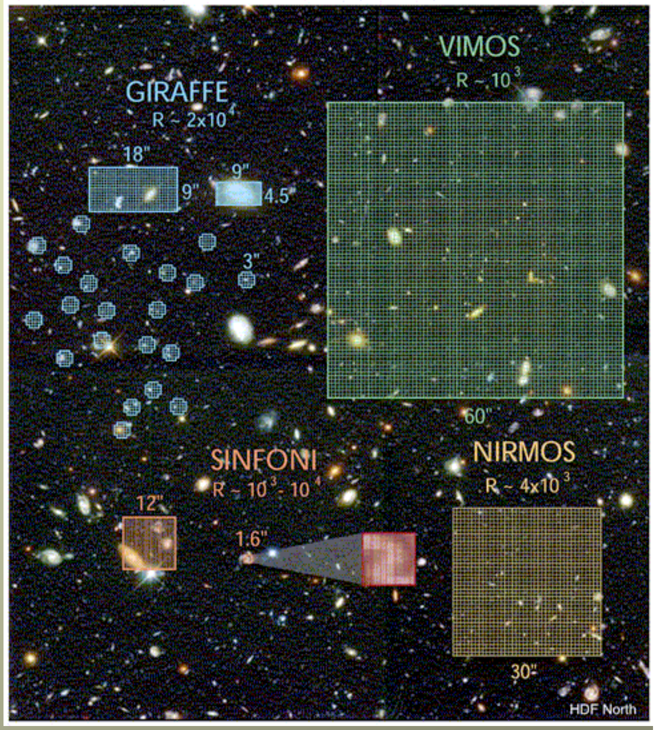

ESO instruments:
VLT 2nd generation instruments

- **X-shooter** (wide-band [UV to near infrared] point source spectrometer) - offered now (P84)!

- **KMOS** (a cryogenic infrared multi-object spectrometer) is in the pre-design phase

- **MUSE** (a huge "3-dimensional" spectroscopic explorer) is in the pre-design phase

- **SPHERE** (a high contrast exoplanet searcher) is in the pre-design phase

Visible - near-IR

- **Def.**: visible ~ 300- (700) 1000 nm; near-IR ~ (0.7) 1 - 5 micron
- **Detectors**:
  * CCD (with Si): to ~1 micron
  * IR: HgCdTe (Mercury-Cadmium-Telluride) or InSb (Indium Antimonide)
  -- good QE (~50%), but high read-out and dark currents (however <<sky emission for imaging)
- **Near-IR - challenges**:
  * detector sensitivity lower
  * arrays smaller than CCDs
  * dominated by sky emission (sky lines+)
  * strong thermal emission --> cryogenic instrument mandatory at >1.6 micron
- **Near-IR - advantages:** adaptive optics…!
  - Improves spatial resolution
  - Improves sensitivity for spectroscopy of unresolved sources

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near-IR observations

Dominated by sky emission (sky lines+)
Sky (mag/arcsec2): J=15.5, H=13.8, Ks=12.9
==> ~insensitive to moon (--> often bright time, but not z, Y bands)
==> short exposures to avoid saturation
==> accurate flat fielding and sky subtraction are crucial!

Sky subtraction:
- use sky and target frames taken close in time
- better: shift and add technique
for imaging and spectroscopy

near-IR observations

Shift and add (« dithering ») - principle:

1. Take set of exposures at position A. Add up and save.
2. Shift pointing by few arcsec (following raster/dither pattern)
3. Take next set of exposure… etc.

4. compute median image = perfect sky flat!
5. Flat field individual images
6. Align individual images (*) and add them up --> final image

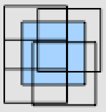
Extended objects or crowded fields: take sky flat outside field using same procedure

(*) Alignment requires enough exposures to detect bright objects!

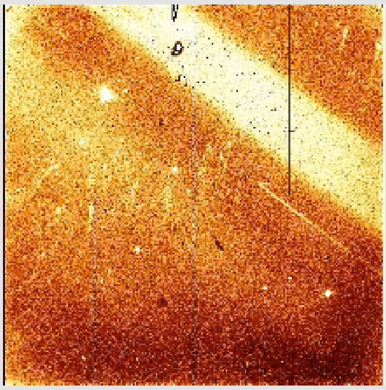
Also: elimination of images with bad seeing etc…

Background subtraction

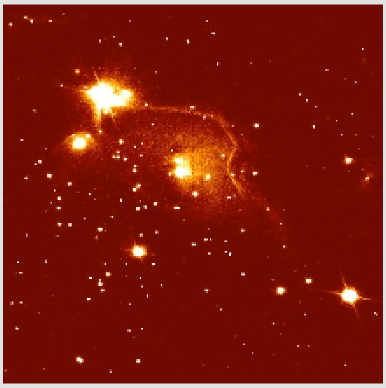
- High and variable background radiation: chopping & nodding/dithering strategies
- Frequent and rapid readouts



5-point dither



Raw NOTCam K image frame 10 5



V361 Cep, K, 300s in total, 6 times on target with frame 5 10, sky subtracted using off-sky fields, flat fielded using differential twilight flats

S1 T S2

For extended emission do beam-switching between Target and Sky:

T – S1 – T – S2 – T - S1 ...

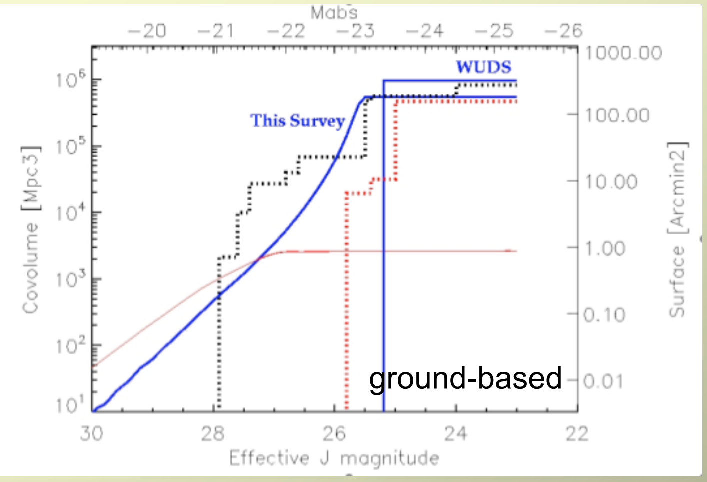
and small-step dither on each position T,S1,S2

Readout time:NOTCam (3.6s) SIRCA(0.04s),

Observing with IR arrays

PROBLEMS	SOLUTIONS
• Non-uniform QE	• Flat field calibration
• High background level	• Dithering & many reads
- point sources	- small step (10-15”)
- extended sources	- field offsets
• Non-linearity	• Stay within linear range
• Memory effects	• Do not saturate
• Bad pixels	• Mask or filter by dithering
• Cosmic rays	• Filter out by shift and add
• Hot rows	• Subtract out well
• Amplifier glow	• Subtracts out well
• Dark current	• Subtracts out with sky

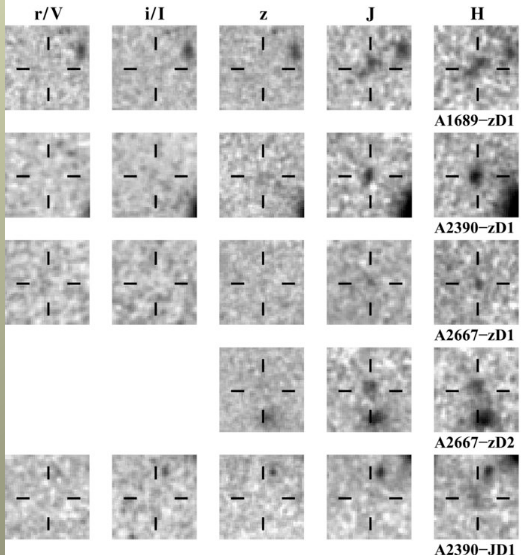
Ultra-deep near-IR observations



With lensing NICMOS/HST

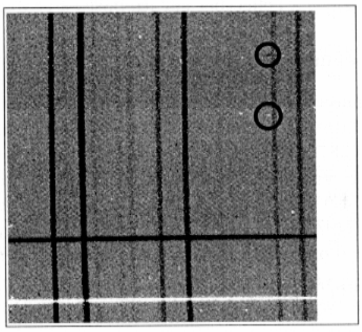
Depths reached:
~25-28 in JH

The most distant galaxies known: z~7-9

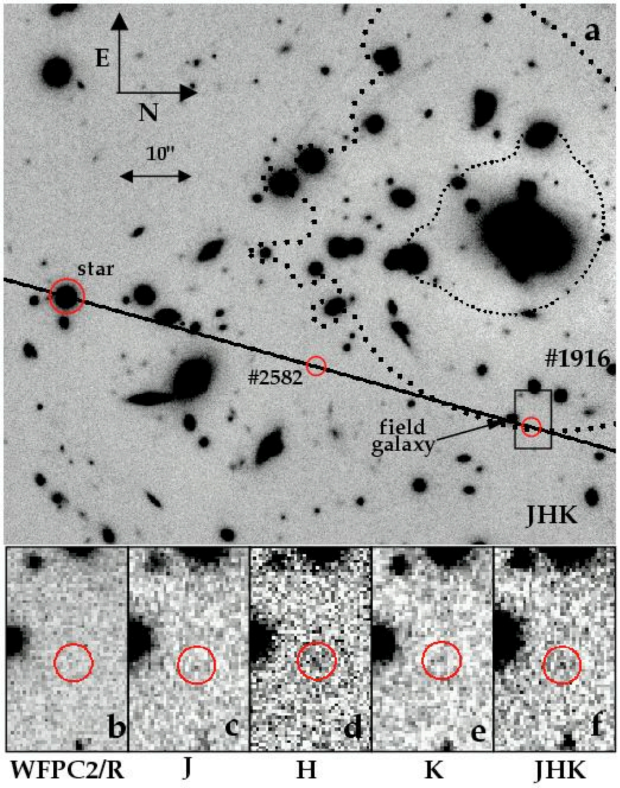


Current « trends »: wide field cameras!

Ultra-deep near-IR spectroscopy



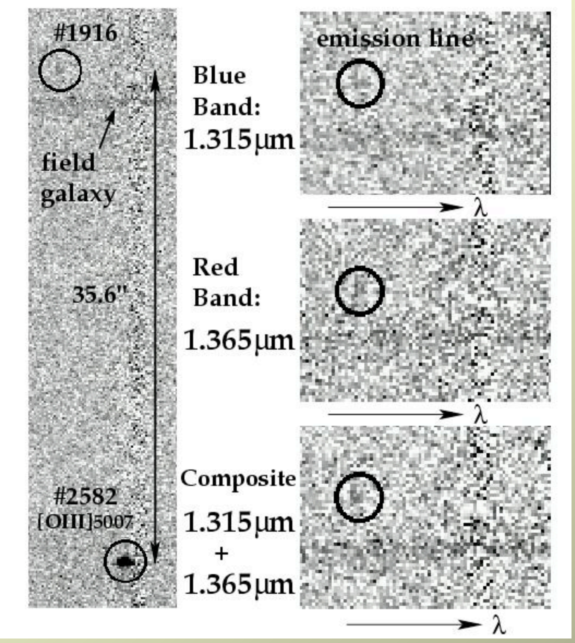
g. 4.31: Soustraction des clichés par paires : on voit apparaître deux traces (positive
l'objet de réference et de la source (raies d'émission encerclées), dues à la translat
la fente entre les positions A et B.

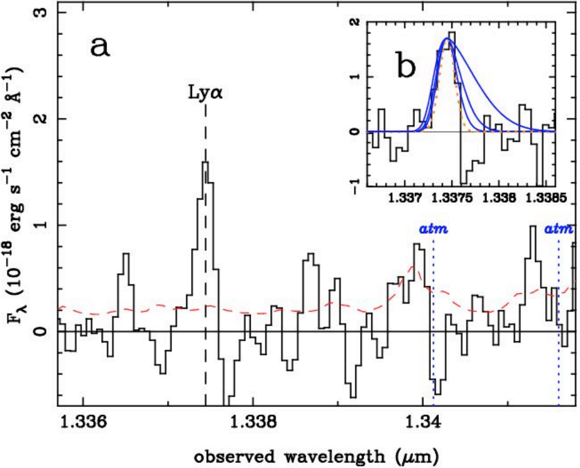


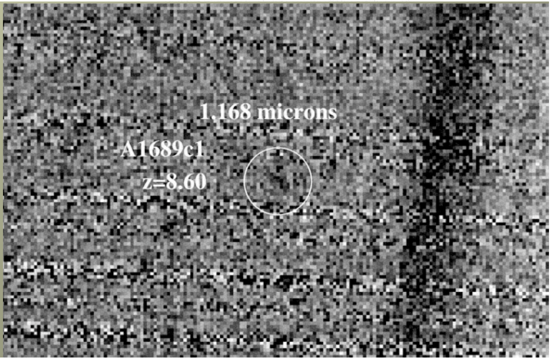
sky subtraction
* long slit: ABBA dither pattern

Wavelength calibration
* often using sky lines

Ultra-deep near-IR spectroscopy







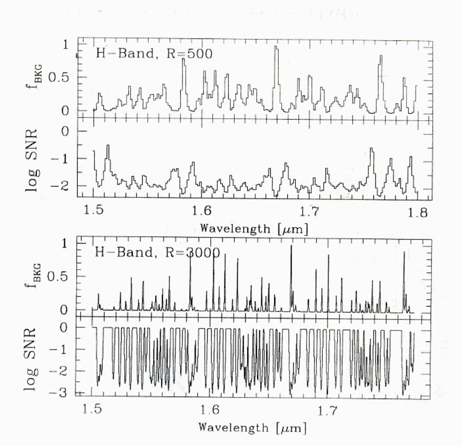
Pelló et al. (2004), Stark et al. (2008)

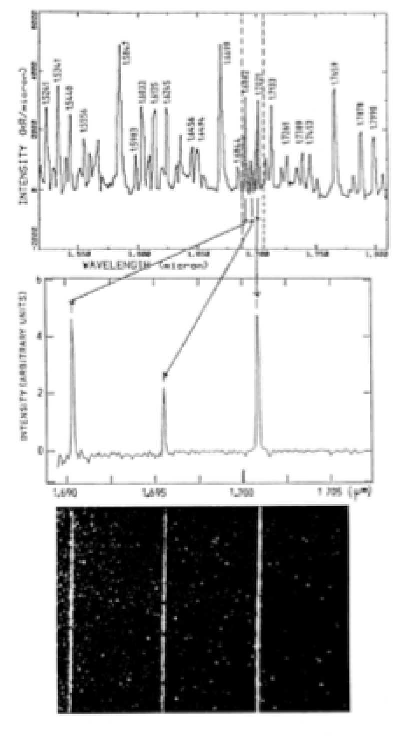
Flux limits: ~4e-18 erg/cm2/s,
typically few 1.e-17

near-IR observations

Sky emission: how to reduce it ?

- → go to space. **Beyond >~1.6-1.8 micron space observations imperative to reach faintest sensitivities!!**
- → Spectral resolution! -- See between the sky lines





R=16500, Maihara et al. (1993)

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near-IR obs

Sky emission: how to reduce it ?

- → Suppress OH lines (e.g. with filters in optics) -

Currently: ~150 lines suppressed in J+H band --> **sky reduced by 4 mags!**

Very promising for imaging!

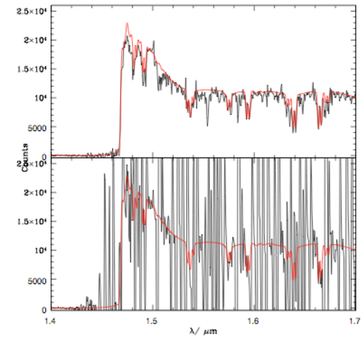
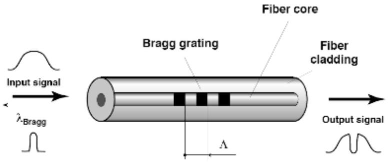


Figure 20. A simulated spectrum of an $H = 24.6$ Vega mag, $z = 11$ QSO as observed by the system described in § 5.3.1 with a 30m telescope. The exposure time was 70hr, and the spectral resolution was $R = 1000$. The top panel shows a system with FBGs and the bottom panel shows an identical system without FBGs. The red lines indicate the true object spectrum.

Ellis & Bland-Hawthorn (2008)

Fibre Bragg Gratings

- Optical fibres with periodicity in refractive index
- Fresnel reflections at each boundary
- Small *but* in phase with each other
- Strong reflection at a single wavelength



Broad band FBG

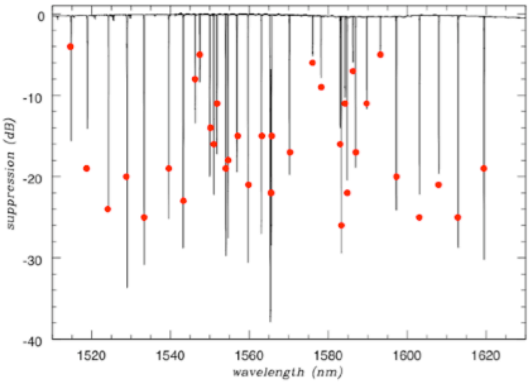
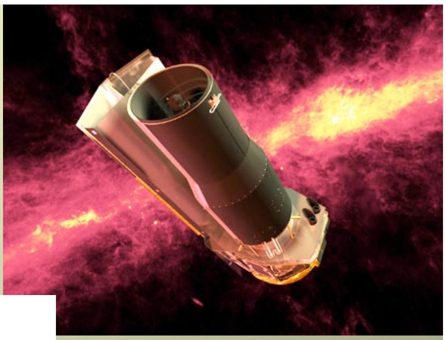


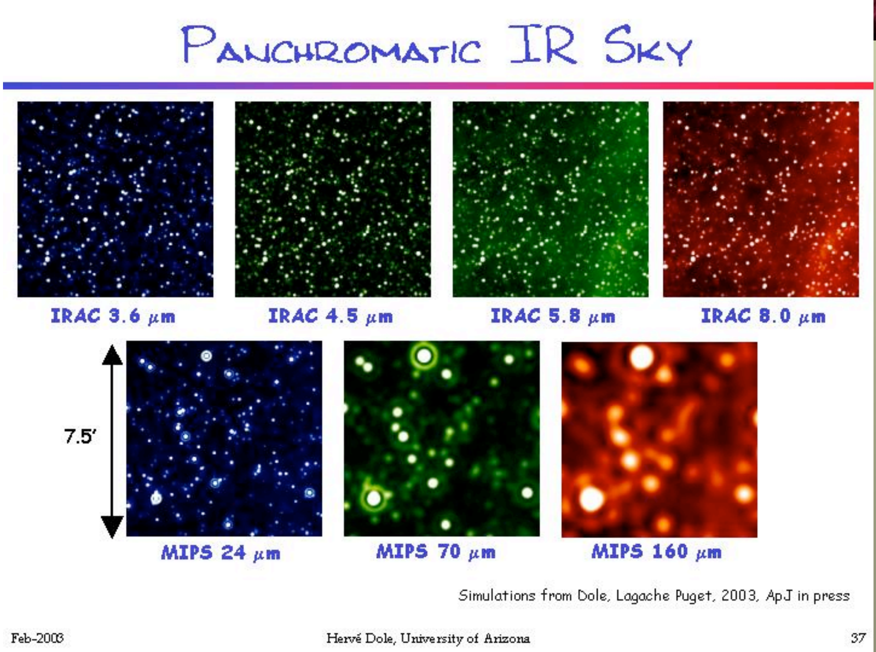
Fig. 4. First broadband FBG from our initial attempt at an

Space near-IR observations

SPITZER:

- ***imaging from 3.6 to 160 micron***
- ***spectroscopy***





PANCHROMATIC IR SKY

IRAC 3.6 μm

IRAC 4.5 μm

IRAC 5.8 μm

IRAC 8.0 μm

7.5′

MIPS 24 μm

MIPS 70 μm

MIPS 160 μm

Simulations from Dole, Lagache Puget, 2003, ApJ in press

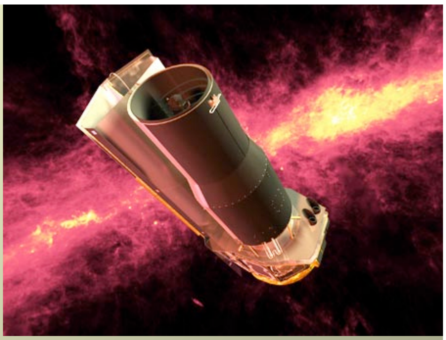
Feb-2003 Hervé Dole, University of Arizona 37

Space near-IR observations

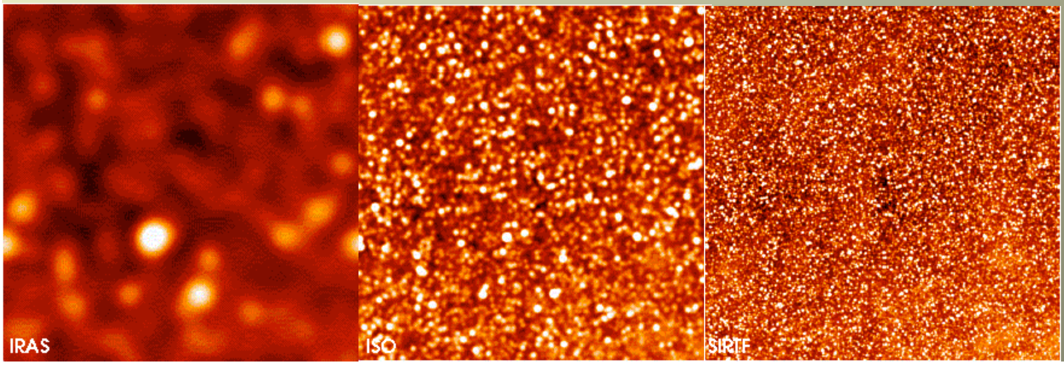
- **Zodiacal background dominates**
- **Difficulty:** confusion limit due to spatial resolution (overlapping images of faint galaxies)

Importance of confusion increases with wavelength

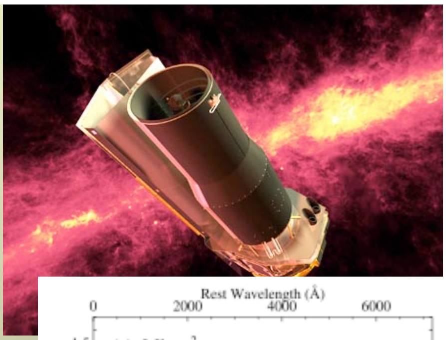
No problem if source position known



Resolution: ~70 40 15 arcsec at 70 micron



Space near-IR observations



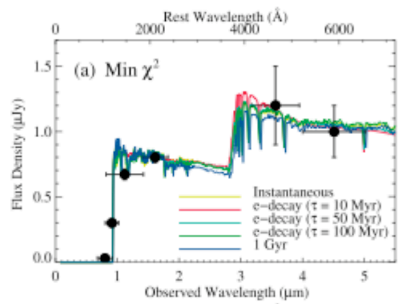
Detection of several z~6-7 galaxies

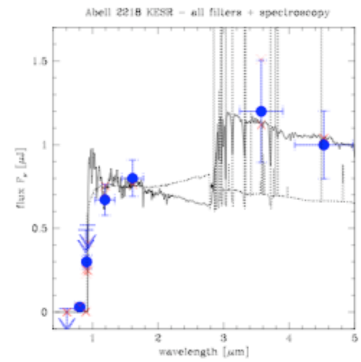
1 muJy = 23.9 mag

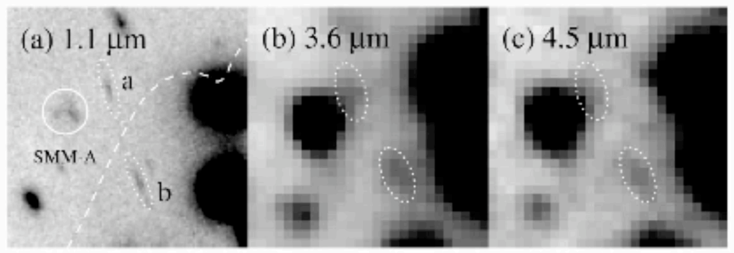
→ **stellar masses**

→ Ages up to 400-700 Myr!

→ z_form up to 10-11







mid-IR observations (chop+nod)

Sky background dominated by thermal emission (sky + telescope)

- **Chopping**: secondary, high frequency (optical path differences though…)
- **Nodding**: telescope « dips » every 2-4 min

« On » source:

signal1 = source + skyA

signal2 = skyB

« Off » source:

signal3 = skyA

signal4 = source + skyB

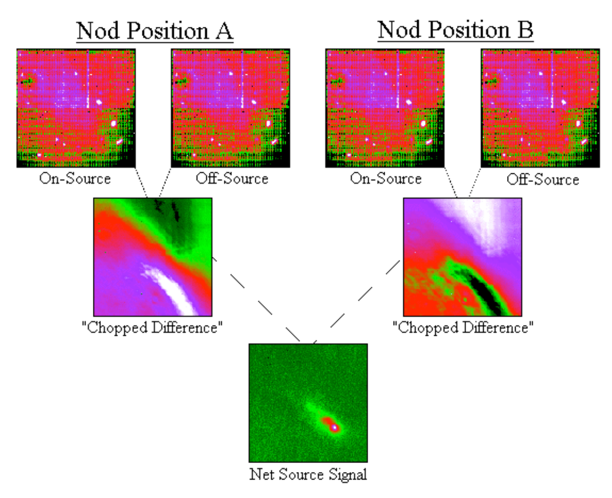
Then compute:

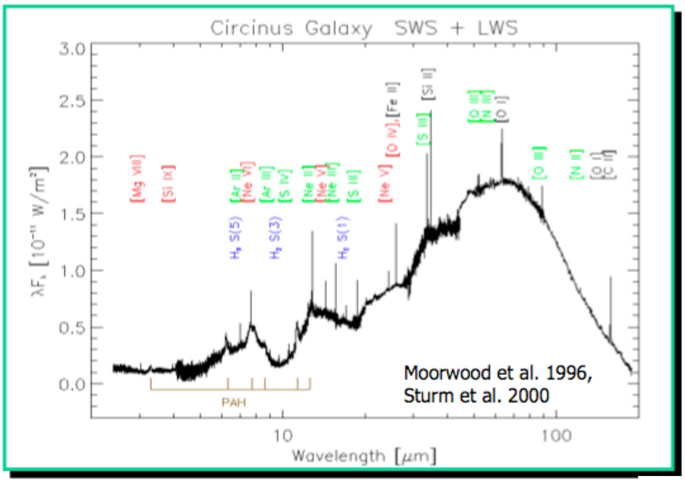
(signal1- signal2) + (signal4-signal3)

= ((source + skyA) - skyB) + ((source + skyB) - skyA)

= 2*source

Complications: extended sources, crowded fields…

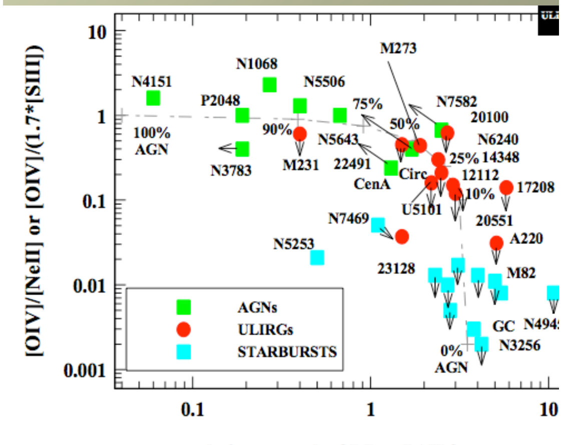




mid-IR observations

E.g. galaxy spectrum

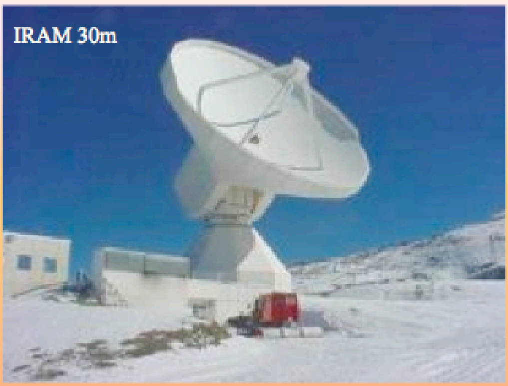
Starburst - AGN diagnostics



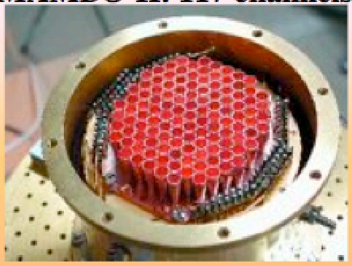
Genzel et al. ApJ 498,579 (1998)

IR to mm observations (imaging)

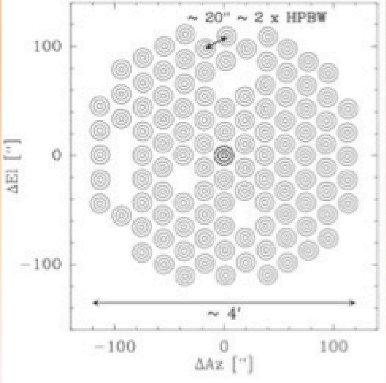
Bolometer observations at the 30m telescope



MAMBO-II: 117 channels



Beam configuration of MAMBO-I



MAMBO-I: 37 channels

rms
sensitivity/channel
~
30 mJy in 1 sec

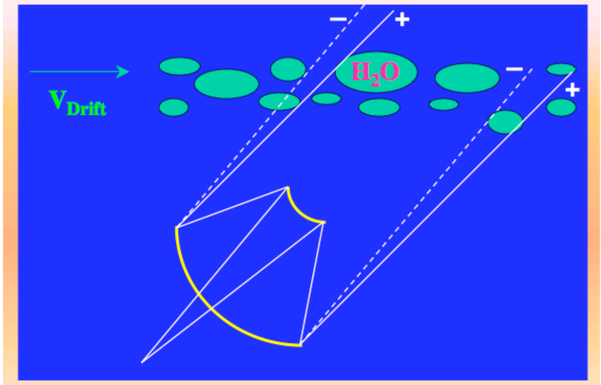
E. Kreysa et al. MPIfR Bonn

IR to mm observations (imaging)

Same basic principles as for mid-IR (chop + nod)

→ **beam switching:** dual beam obtained using « wobbler »
→ **« Scans »** (e.g. on-the-fly (OTF) maps) to cover wide field

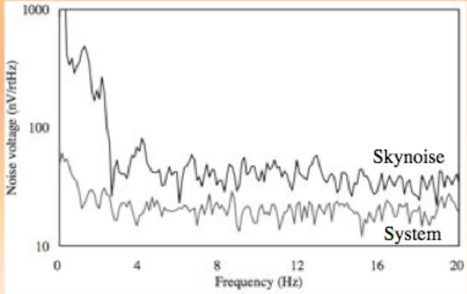
Schematic Model of Skynoise



Classical method of subtracting atmospheric emission:
Beam switching between two positions « + » and « - »

Most atmospheric fluctuations are broad band --> much more problematic for continuum than for line observations

Typical Noise Spectra



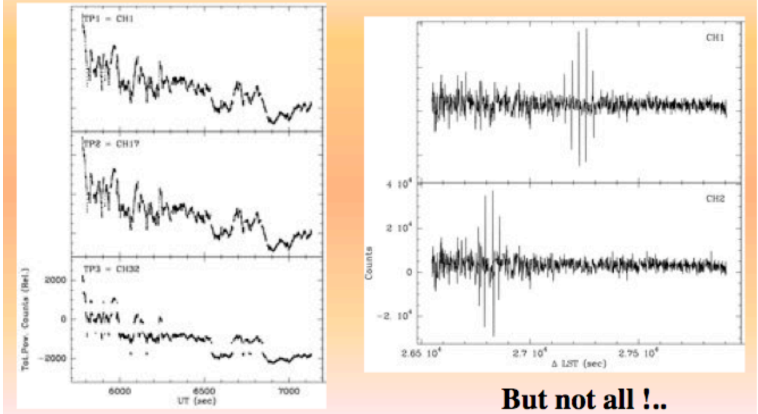
Most fluctuations @ low frequency (< 2 Hz)

IR to mm observations (imaging)

Beam switching (Wobbling) @ 2 Hz cancels most atmospheric fluctuations …

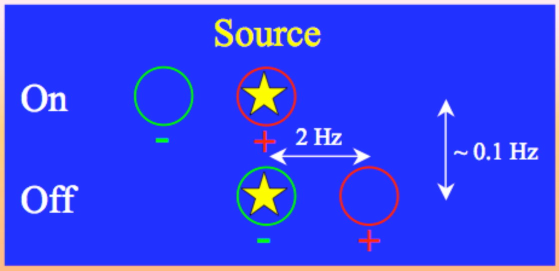
Total Power

Switched Power



But not all !..

On-Off Mode: Wobbling and Nodding

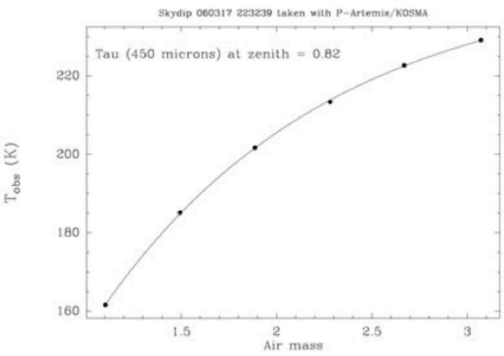


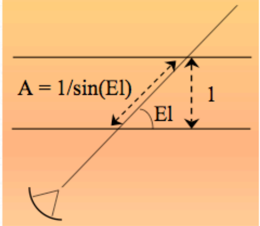
Wobbler Throw
~
30'' - 120''

IR to mm observations (imaging)

Calibrating the atmospheric opacity with skydips

Total power measurements of the sky emission at a series of elevations (= air masses)





$$T_{\rm obs} = F_{\rm eff}\, T_{\rm atm}\,(1 - e^{-\tau_{\rm atm} A}) + (1 - F_{\rm eff})\, T_{\rm cab}$$

$$\sim T_{\rm atm}\, \tau_{\rm atm}\, A$$

Absolute Calibration (Counts --> Jy)

Primary calibrators: Planets (e.g. Mars, Uranus)

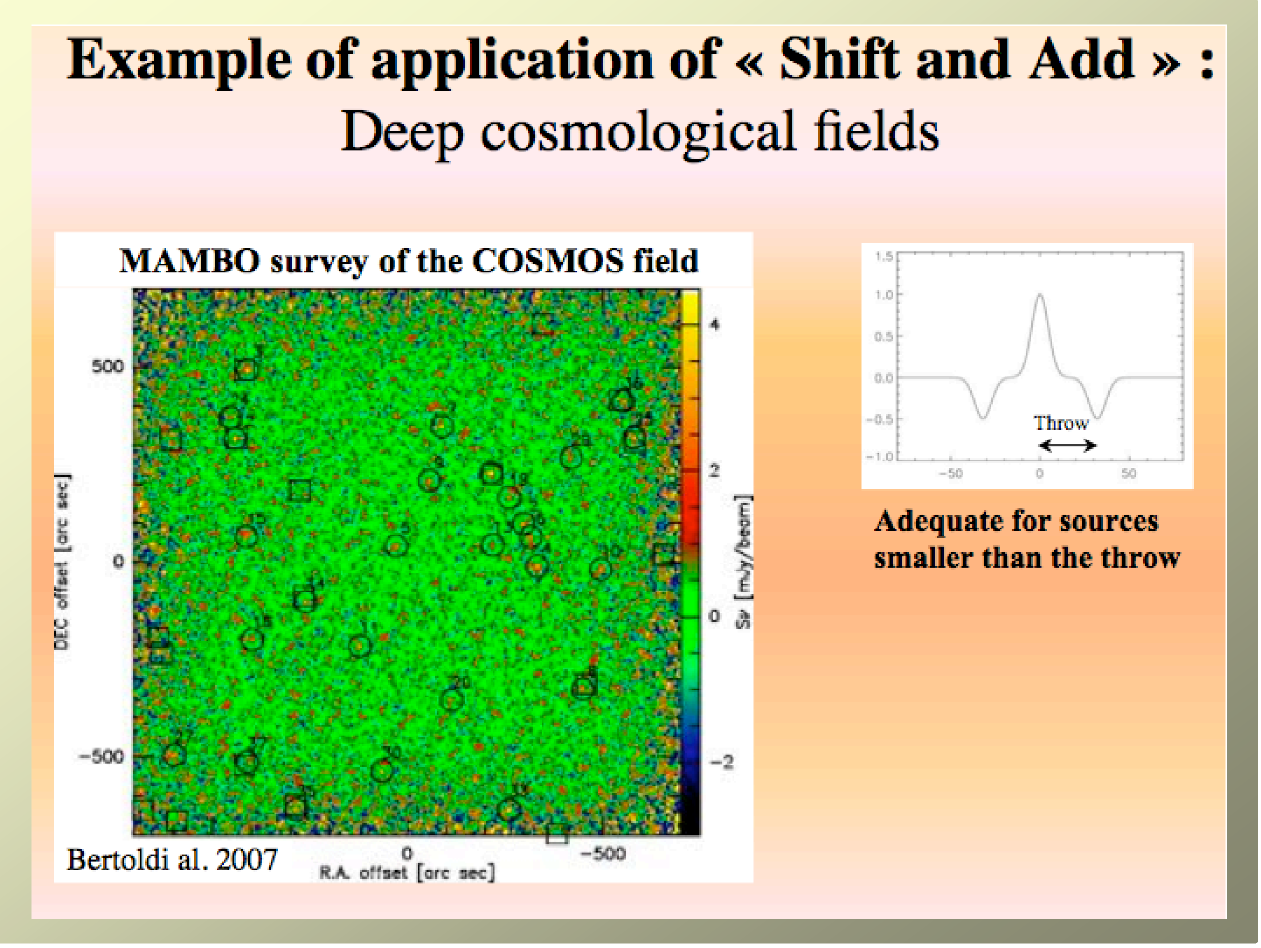
- ➢ Known disk temperature (e.g. 205 K for Mars)
- ➢ Known flux density as a function of epoch

$$\mathrm{Counts}_{\rm CAL} = G \times \mathrm{Flux}_{\rm CAL} \times \exp(-\tau_{\rm atm}\, A)$$

IR to mm observations (imaging)

Typical Bolometer Observing Session

- Skydip to measure the atmospheric opacity (every ~ 2hr ; Check also Taumeter on a regular basis)
- Pointing/Focus/On-Off on strong secondary calibrator or planet
- Pointing on pointing source close to object of interest
- OTF map(s) or series of ON-OFFs on object of interest (should not take longer than ~ 1hr)
- Pointing (every ~ 1hr or before observing a new target)
- Skydip …

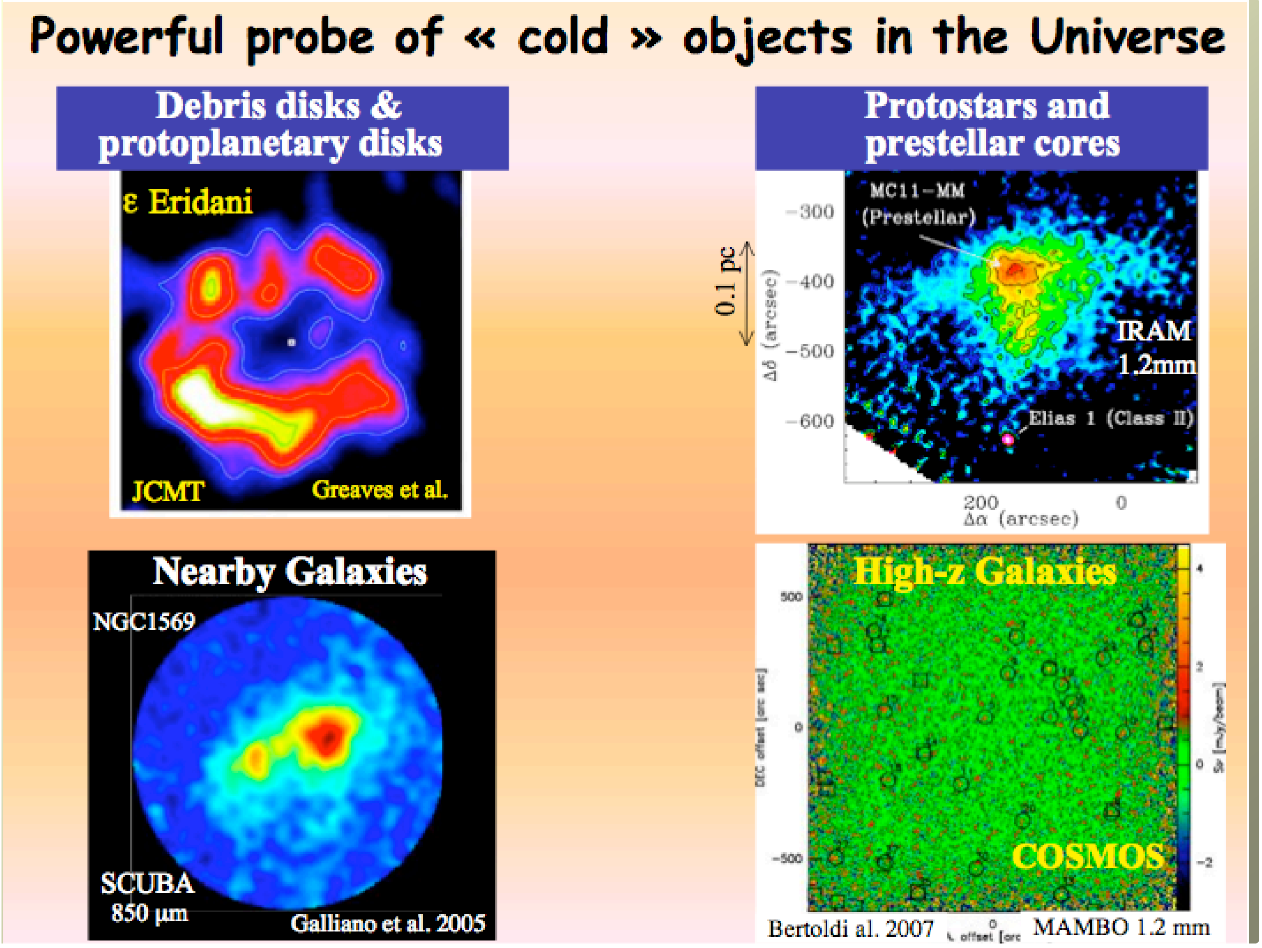


Example of application of « Shift and Add » :
Deep cosmological fields

MAMBO survey of the COSMOS field

Bertoldi al. 2007

Adequate for sources smaller than the throw



Powerful probe of « cold » objects in the Universe

Debris disks & protoplanetary disks

ε Eridani

JCMT Greaves et al.

Nearby Galaxies

NGC1569

SCUBA 850 µm Galliano et al. 2005

Protostars and prestellar cores

High-z Galaxies

COSMOS

Bertoldi al. 2007 MAMBO 1.2 mm

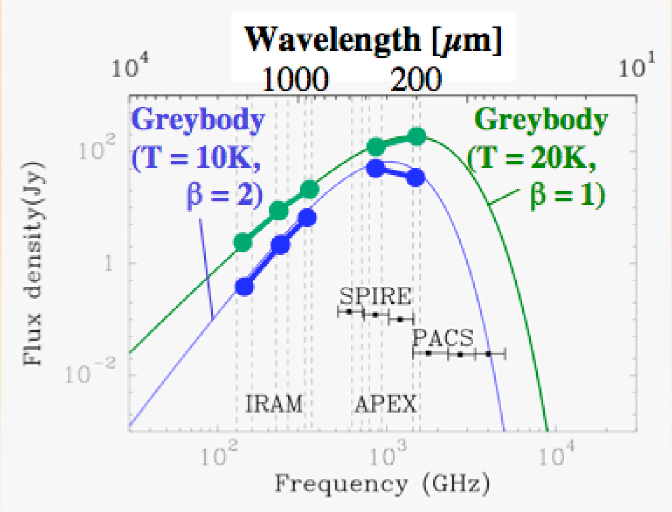
Thermal Emission from Cold Dust ($T_d \sim$ 5-50 K)

- **Optically thin emission at (sub)mm wavelengths**

-- > Direct mass/column density estimates :

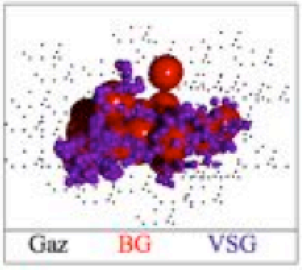
$$M = \frac{S_\nu \, d^2}{B_\nu(T_d)\, \kappa_d}$$

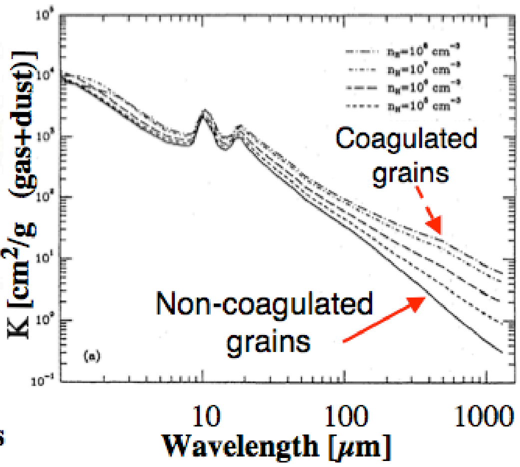
- **$\lambda \sim$ 100–500 µm : good diagnostic of the dust temperature (T_d)**
- **$\lambda \sim$ 0.8–2 mm : good tracer of the mass & opacity ($\kappa_d \sim \lambda^{-\beta}$)**



Dust Opacity: $\kappa_d(\lambda)$

grain-grain Coagulation





Ossenkopf & Henning 1994, Stepnik et al. 2003

Recommended dust opacities:

- **$\kappa_{1.2mm}$ = 0.002 cm^2/g diffuse ISM**
- **$\kappa_{1.2mm}$ = 0.005 cm^2/g prestellar cores**
- **$\kappa_{1.2mm}$ = 0.01 cm^2/g protostellar cores**
- **$\kappa_{1.2mm}$ = 0.02 cm^2/g circumstellar disks**

Column Density Estimates

Optical depth: $\tau_{1.2\mathrm{mm}} = \kappa_{1.2\mathrm{mm}}\,\Sigma$ **where** $\Sigma = \mu\, m_H\, N_{H2}$
mass column density

If $\kappa_{1.2\mathrm{mm}} = 0.01\ \mathrm{cm^2/g}$, $\tau_{1.2\mathrm{mm}} = 1$ **for** $\Sigma = 100\ \mathrm{g/cm^2}$ **or** $N_{H2} \sim 3\mathrm{x}10^{25}\ \mathrm{cm^{-2}}$
($A_V \sim 30000$)

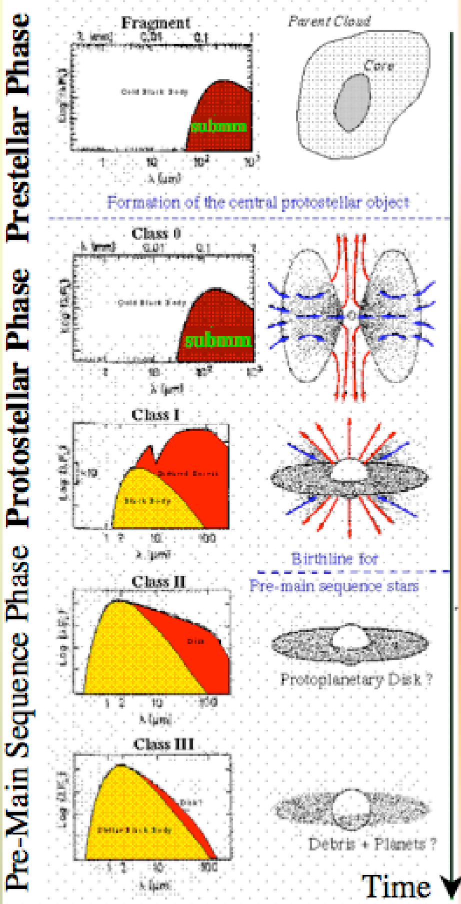
--> 1.2mm dust continuum emission is optically thin in most situations

Uniform T_{dust}: $S_{1.2\mathrm{mm}}^{\mathrm{beam}} = B_{1.2}(\mathrm{T_{dust}})\,(1-e^{-\tau_{1.2\mathrm{mm}}})\,\Omega_{\mathrm{beam}} \approx B_{1.2}(\mathrm{T_{dust}})\,\kappa_{1.2\mathrm{mm}}\,\Sigma\,\Omega_{\mathrm{beam}}$

$$< N_{\mathrm{H2}} >_{\mathrm{beam}} = S_{1.2\mathrm{mm}}^{\mathrm{beam}} / [\Omega_{\mathrm{beam}}\, \mu\, \mathrm{m_H}\, \kappa_{1.2\mathrm{mm}}\, B_{1.2}(\mathrm{T_{dust}})]$$

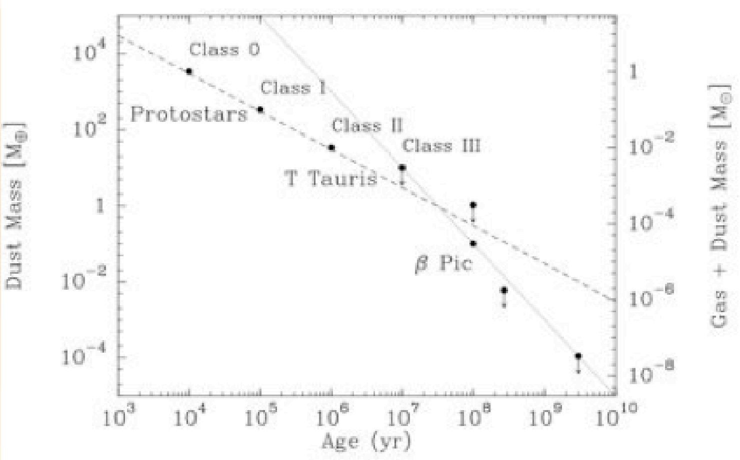
Rayleigh-Jeans approximation for $B_{1.2}(T_{dust})$

$$\boxed{< N_{\mathrm{H2}} >_{\mathrm{beam}} \approx 1.7 \times 10^{22}\ \mathrm{cm^{-2}} \times \left(\frac{S_{1.2\mathrm{mm}}^{\mathrm{beam}}}{10\ \mathrm{mJy/11''\text{-}beam}}\right) \times \left(\frac{\mathrm{T_{dust}}}{10\ \mathrm{K}}\right)^{-1} \times \left(\frac{\kappa_{1.2\mathrm{mm}}}{0.005\,\mathrm{cm^2\,g^{-1}}}\right)^{-1}}$$



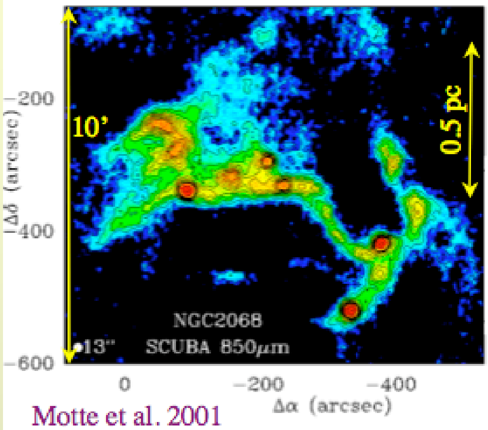
Lada (1987) + André (1994, 2002)

Evolutionary sequence for the formation of solar-type stars


Circumstellar Mass vs. Time

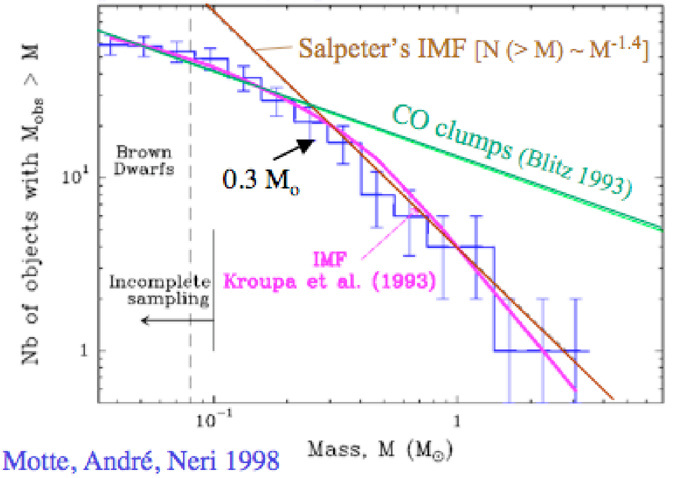
Probing the link between the prestellar core mass function (CMF) and the IMF

NGC2068 at 850 μm



Motte et al. 2001

Mass Spectrum of ρ Oph Prestellar Condensations



Motte, André, Neri 1998

➜ The IMF is at least partly determined by pre-collapse cloud fragmentation (~ 0.1 - 5 M$_O$)

- **Limitations:** Small-number statistics, incompleteness at low-mass end (?) + assume constant dust properties

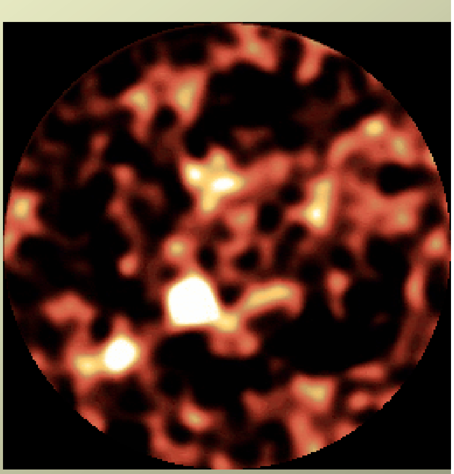
➜ *Herschel* & ALMA needed to confirm/extend conclusions toward lower/higher masses

See also: Testi & Sargent 1998;
Johnstone et al. 2001;
Stanke et al. 2006; Alves et al. 2007

And for massive cores:
Beuther & Schilke 2004

SCUBA galaxies

- New population of dusty, high-z galaxies
- Selected at sub-mm
- Identification difficult, often thanks to radio
- Average redshift z~2.5



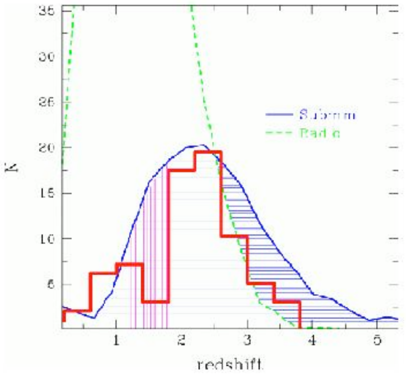
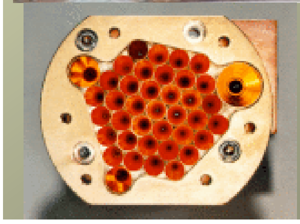
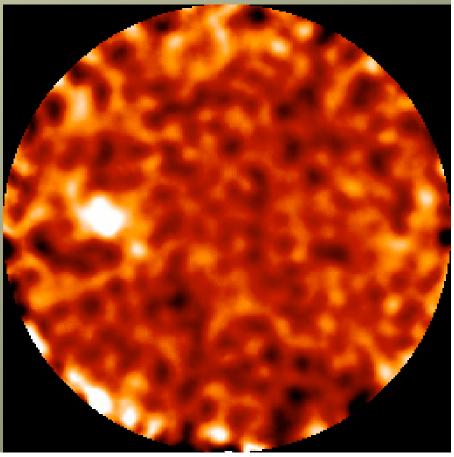
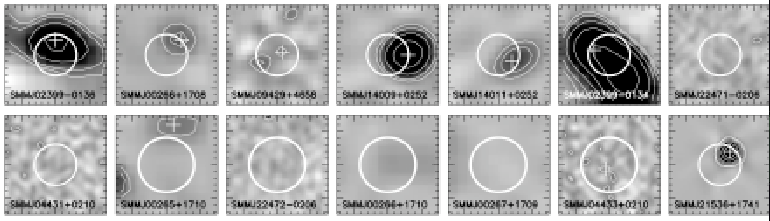


FIG. 4.— The redshift distribution of our submm galaxy sample (red histogram). To interpret the likely effects of the sample selection on this distribution, we plot predicted model

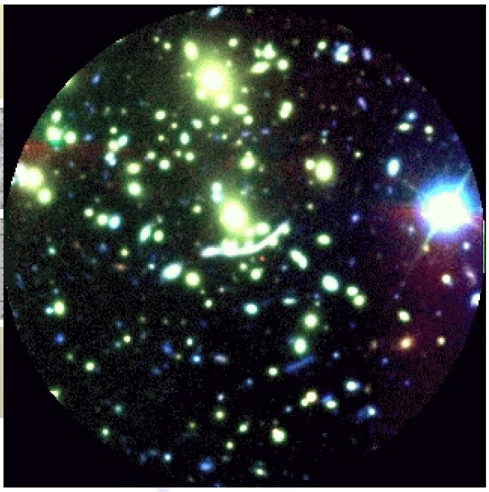


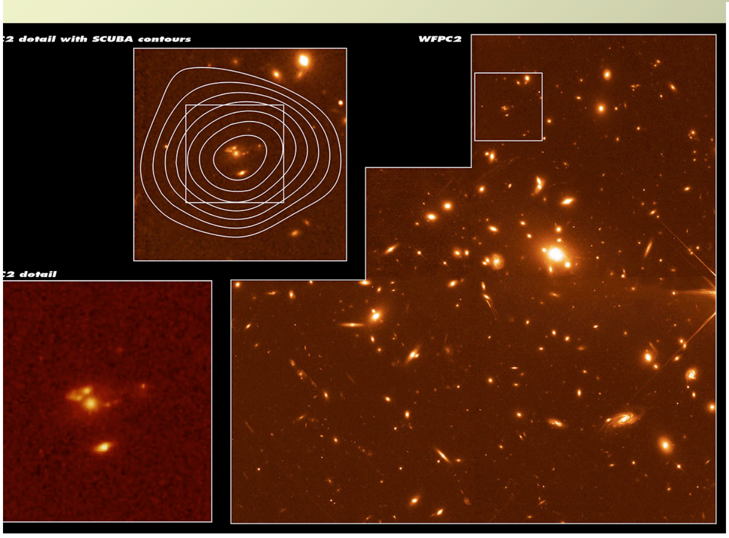


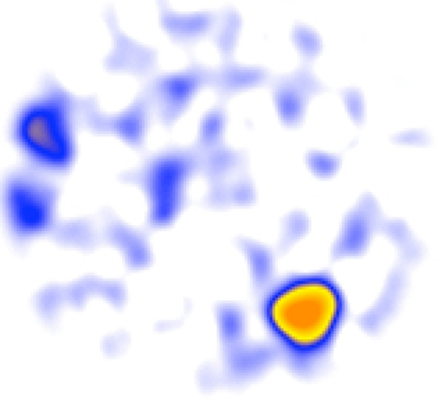
SCUBA galaxies



- Identification thanks to radio or HST imaging

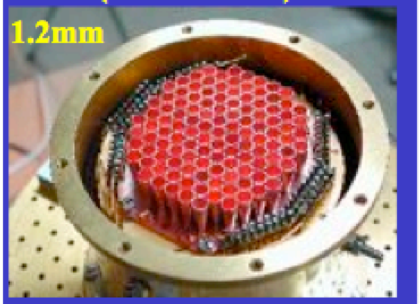




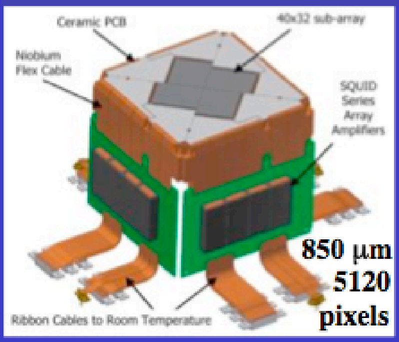


Bolometers for FIR to mm continuum imaging

MAMBO @ IRAM 30m
(117 elements)

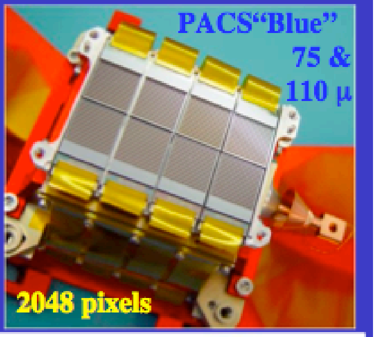


SCUBA-2 @ JCMT

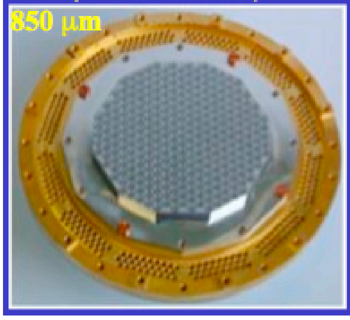


And in the near future…

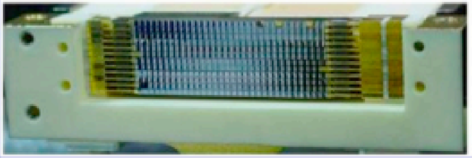
PACS on HERSCHEL

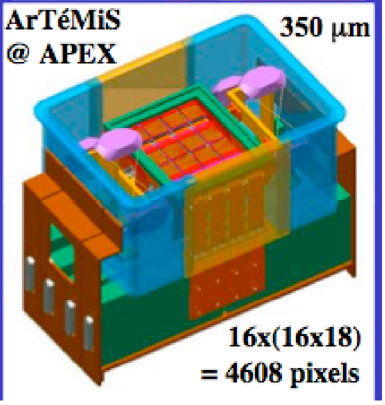


LABOCA @ APEX
(295 elements)



SHARC-2 @ CSO
(384 elements @ 350 µm)

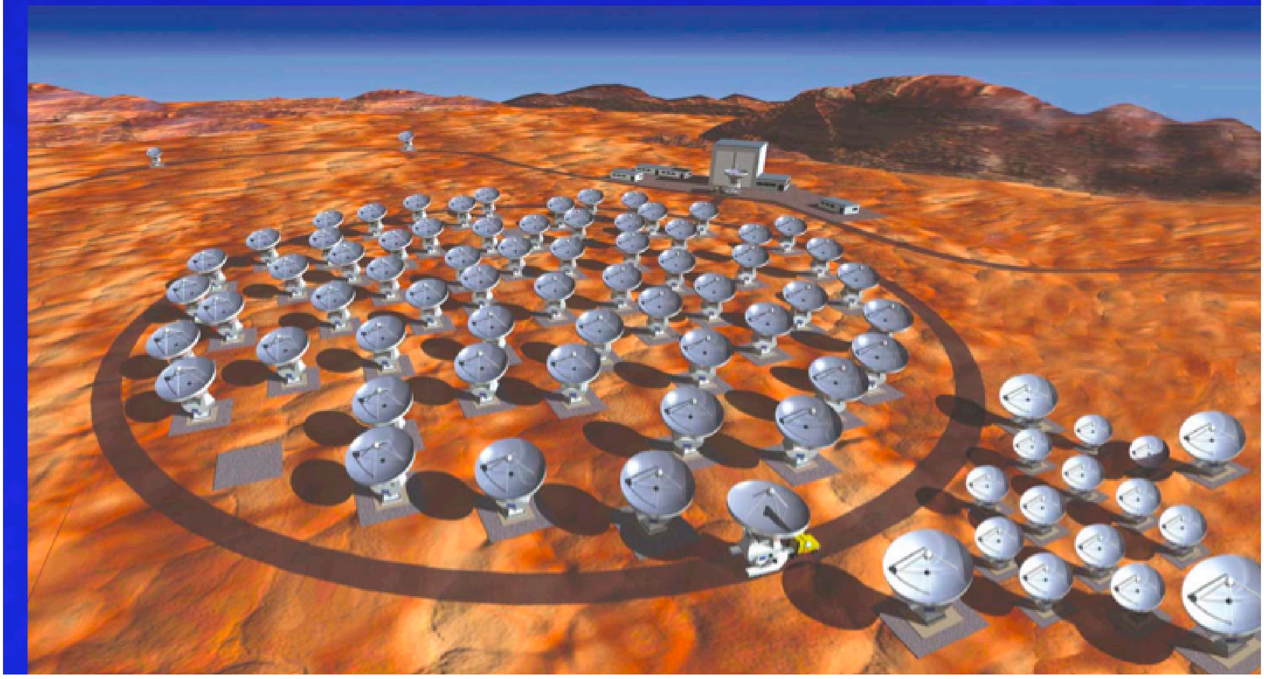




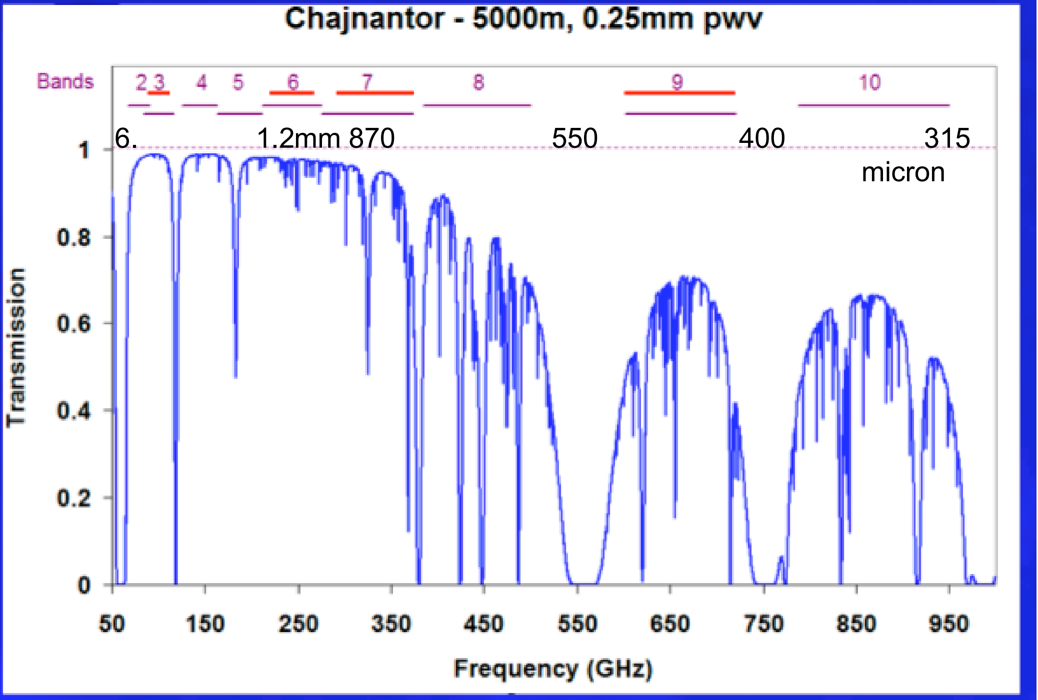
Comparative performance of some current and future bolometer-array instruments

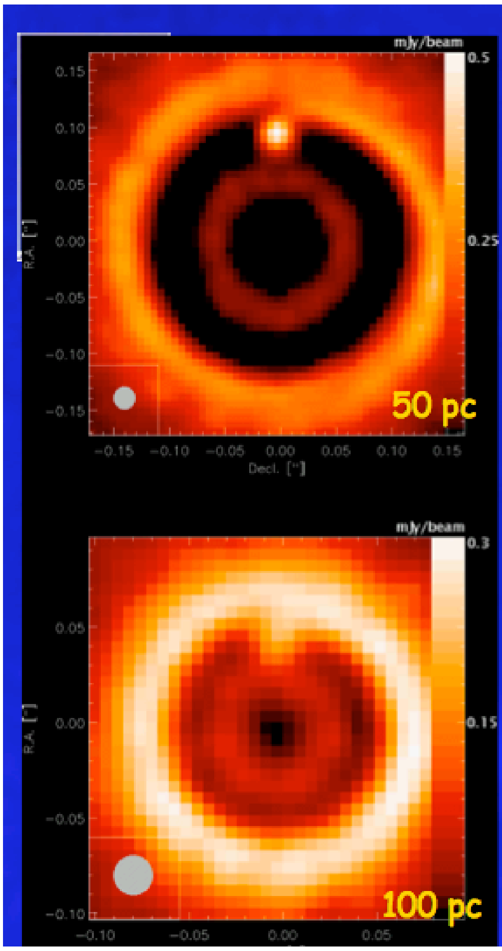
Instrument	Wavelength (μm)	Field of view (arcmin^2)	Beam (arcsec)	Per pixel NEFD (mJy, 1σ, 1s)	Relative imaging speed
Herschel-SPIRE	**250**	**4 x 8**	**17.5**	**32**	**3x10^4**
ArTéMiS / 12m APEX	200 350 450	1.8 x 1.8 3.2 x 3.2 4.1 x 4.1	4.2 7.3 9.4	(410*) 430 400	(4) 46 90
SCUBA-2	450	8 x 8	7.5	600	40
SHARC-2	350	0.9 x 2.5	8.5	1000	1
LABOCA	870	11.4'	18.2	50	50
MAMBO-2	1200	4'	11	30	1

ALMA + ACA



Atmospheric Opacity





ALMA Key Science 1:

Planetary regions, nearby disks

$M_{planet} / M_{star} = 0.5\ M_{Jup} / 1\ M_{sun}$

Orbital radius: 5 AU

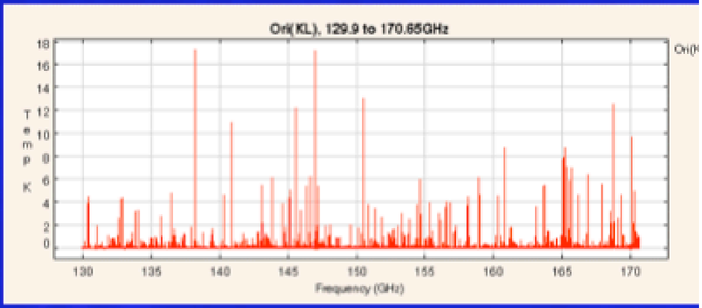
Disk mass as in the circumstellar disk around the Butterfly Star in Taurus

(ALMA: 10km, t_{int}=8h, 30° phase noise)
Wolf & D'Angelo (2005)

ALMA Key Science 2:
Astrochemistry


Orion Nebula
Subaru Telescope, National Astronomical Observatory of Japan
CISCO (J, K' & H2 (v=1-0 S(1))
January 28, 1999

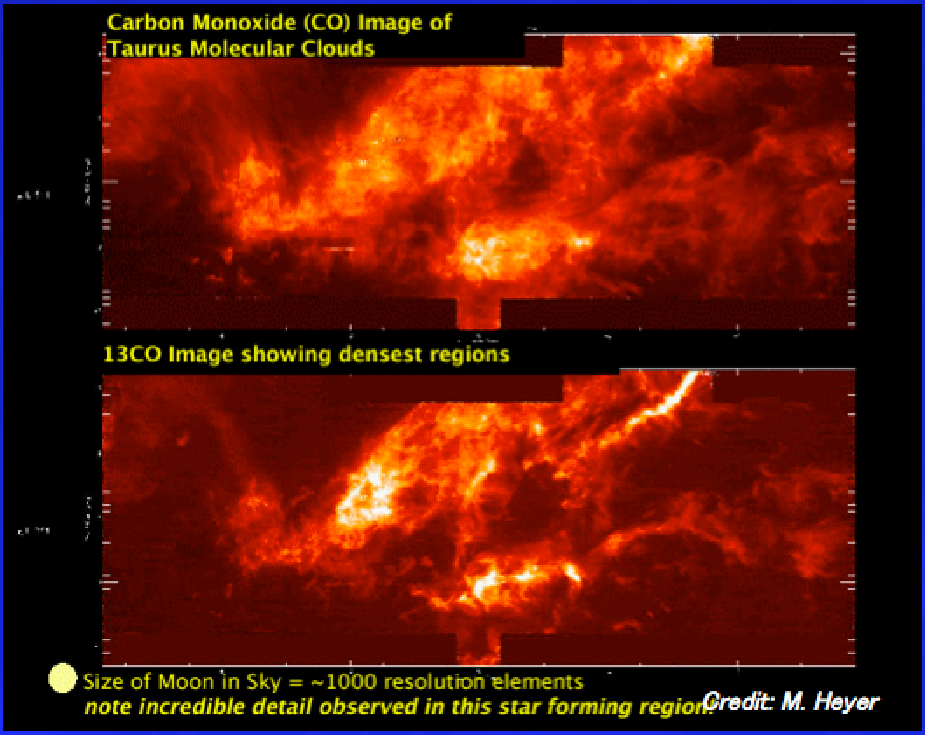
Spectrum courtesy B. Turner (



- Millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.

- Most of the observed transitions of the 125 known interstellar molecules lie in the mm/submm spectral region—here some 17,000 lines are seen in a small portion of the spectrum at 2mm.

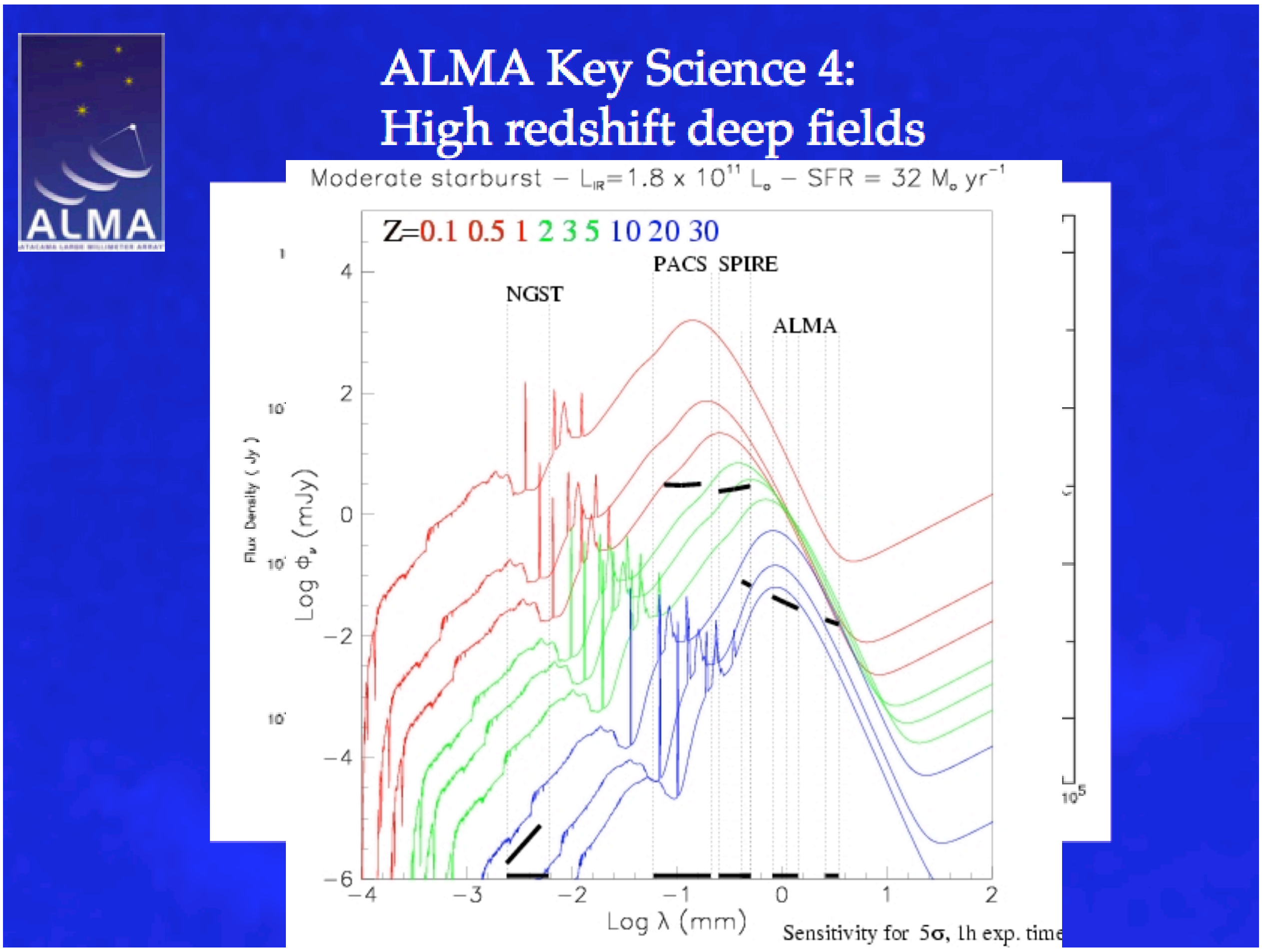
ALMA Key Science 3:
Interstellar Medium


Carbon Monoxide (CO) Image of Taurus Molecular Clouds

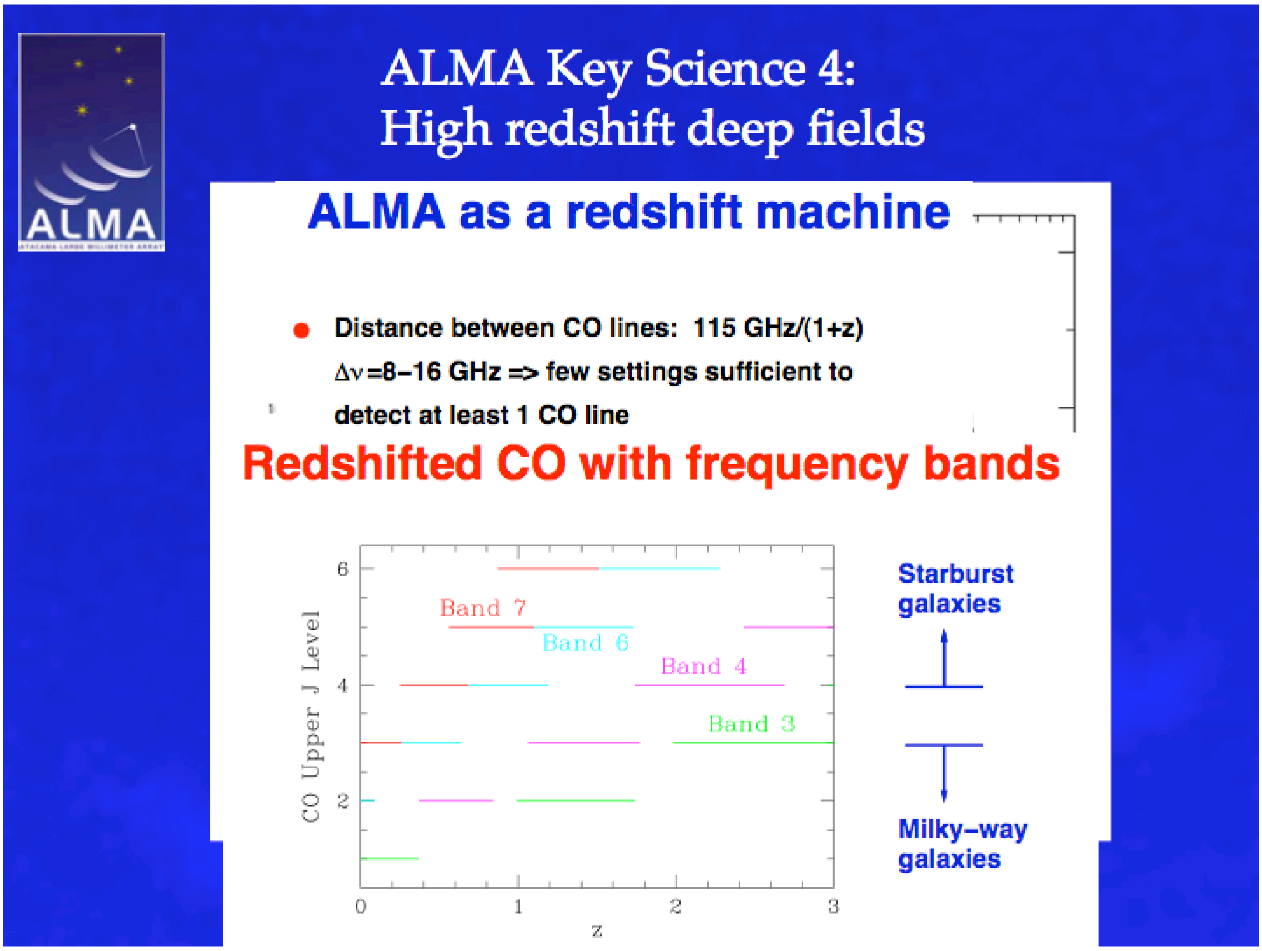
13CO Image showing densest regions

Size of Moon in Sky = ~1000 resolution elements
note incredible detail observed in this star forming region

Credit: M. Heyer



ALMA Key Science 4: High redshift deep fields



ALMA Key Science 4: High redshift deep fields

ALMA as a redshift machine

- Distance between CO lines: 115 GHz/(1+z) Δν=8–16 GHz => few settings sufficient to detect at least 1 CO line

Redshifted CO with frequency bands