Galaxy evolution from the galaxies' perspective: from gas to stars and back again

Reinhard Genzel, MPE & UCB

Lecture 1

- gas & star formation in local disk galaxies
- discourse on observational capabilities, from UV to radio

Lecture 2

- starbursts, mergers & ULIRGs
- star forming galaxies at the peak of the galaxy formation epoch
- galaxy kinematics: disks and mergers

Lecture 3

- galaxy kinematics: disks and mergers
- gas at the peak of the galaxy formation epoch
- observations of stellar and AGN feedback
- disk evolution
- metallicity and metallicity gradients

observational strategies for studying galaxy formation/evolution

- multi-band look-back imaging surveys →large samples, but 'cheap' proxies
- local stellar archaeology
- detailed, spatially resolved in situ observations → small representative samples because 'expensive'
- pathology

Hanny's Vorwerp

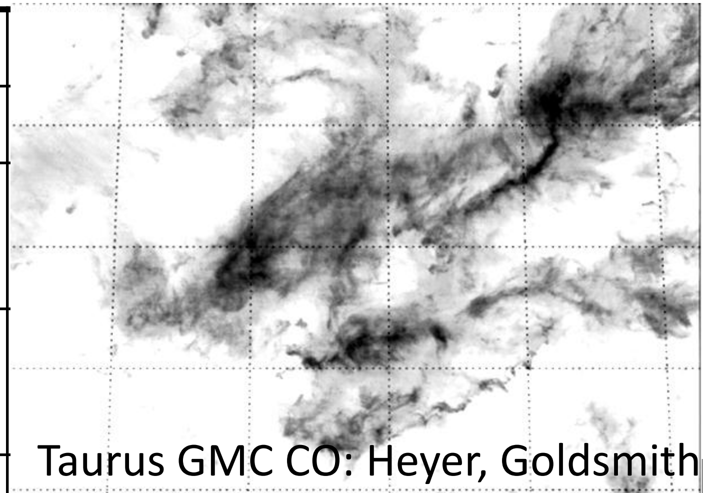
gas & star formation in local disk galaxies

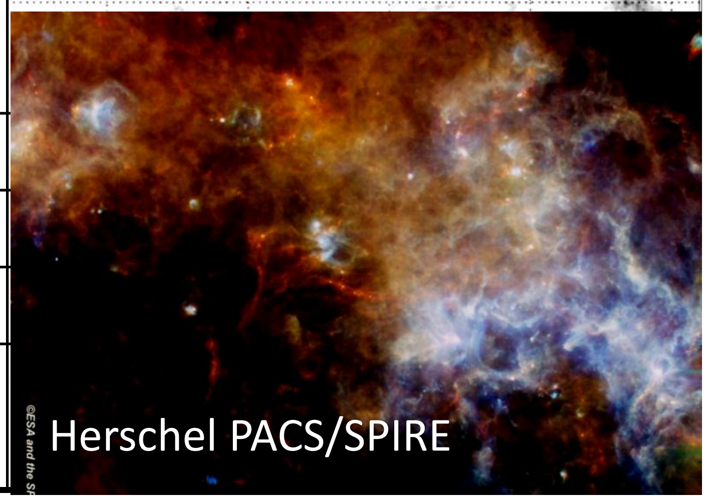
Mark Krumholz lectures 1,2

see McKee & Ostriker 2007 ARAA
Kennicutt & Evans 2012 ARAA

star formation in the MW occurs in dusty Giant Molecular Clouds (GMCs)

	Milky Way
M_{cloud}	$10^3 \ldots 10^{6.5}$
<Σ(gas)> $M_\odot pc^{-2}$	200 (N(H)~10^{22},A_V~5)
P/k~19 Σ^2 (cm^{-3} K)	$10^{5.9}$ (<MW>~10^5)
<ρ(H_2)> (cm^{-3})	$10^{2\ldots4}$ (<MW>~1)
σ (km/s)	5 >> c_S(10-30 K)
$\mathcal{M}$	25
Q	0.5-3
<f_{H2}>(MW)~ [(P/k)/$10^{4.4}$]	0.25





GMCs are highly structured (~log-normal density structure) with highly supersonic local motions

$\sigma \propto l^{1/2}$ (Larson 1981)

virialized on large scales $\alpha = \frac{5\sigma^2 R}{GM} \leq 1$ but α(l<<R)>1 because Larson relation

Krumholz et al. 2005, McKee & Ostriker 2007

star formation is inefficient

$$SFR = \varepsilon_{ff} \frac{M_{mol-gas}}{\tau_{ff}}, \quad \text{where } \tau_{\text{ff}} = \sqrt{\frac{3\pi}{32 G \rho_{H2}}} \sim 4.3x10^6 \left(\frac{n(H)}{10^2\, cm^{-2}} \right)^{-1/2} yr$$

$$M_{mol-gas}(MW) \sim 10^9 M_{\odot}, SFR(MW) \sim 3 M_{\odot} yr^{-1}$$

$\Rightarrow \quad \varepsilon_{ff}(MW) \sim 0.02$ why is star formation so inefficient ?

on the other hand $\tau_{\text{gas-depletion}} = \frac{M_{gas}}{SFR} \sim 1-2x10^9 \ll t_{Hubble},$

are galaxies going to stop forming stars tomorrow?

two competing explanations:

a) MHD pressure (Alfven) prevents collapse on free-fall time scale, which happens on an ambipolar diffusion time scale $\tau_{\text{ambipolar}} \sim 10\text{-}30\ \tau_{\text{ff}}$ (Mouschovias, Shu): stars form slowly

b) GMCs are magnetically super-critical but highly super-sonic; because of the log-normal density distribution resulting from the interplay between compressing and dispersing shocks only a small fraction of the gas can collapse at any given time (E.Ostriker, MacLow, Elmegreen, Klessen, Krumholz, McKee): stars form inefficiently

theoretical work and observations over the last decade+ tend to favor the second explanation. However, this then requires a semi-continuous replenishment of the pervasive turbulent energy throughout clouds (including clouds without much internal SF)

Zuckerman & Evans 1974, Williams & McKee 1997, Heyer & Brunt 2004, Elmegreen & Scalo 2004, McKee & Ostriker 2007

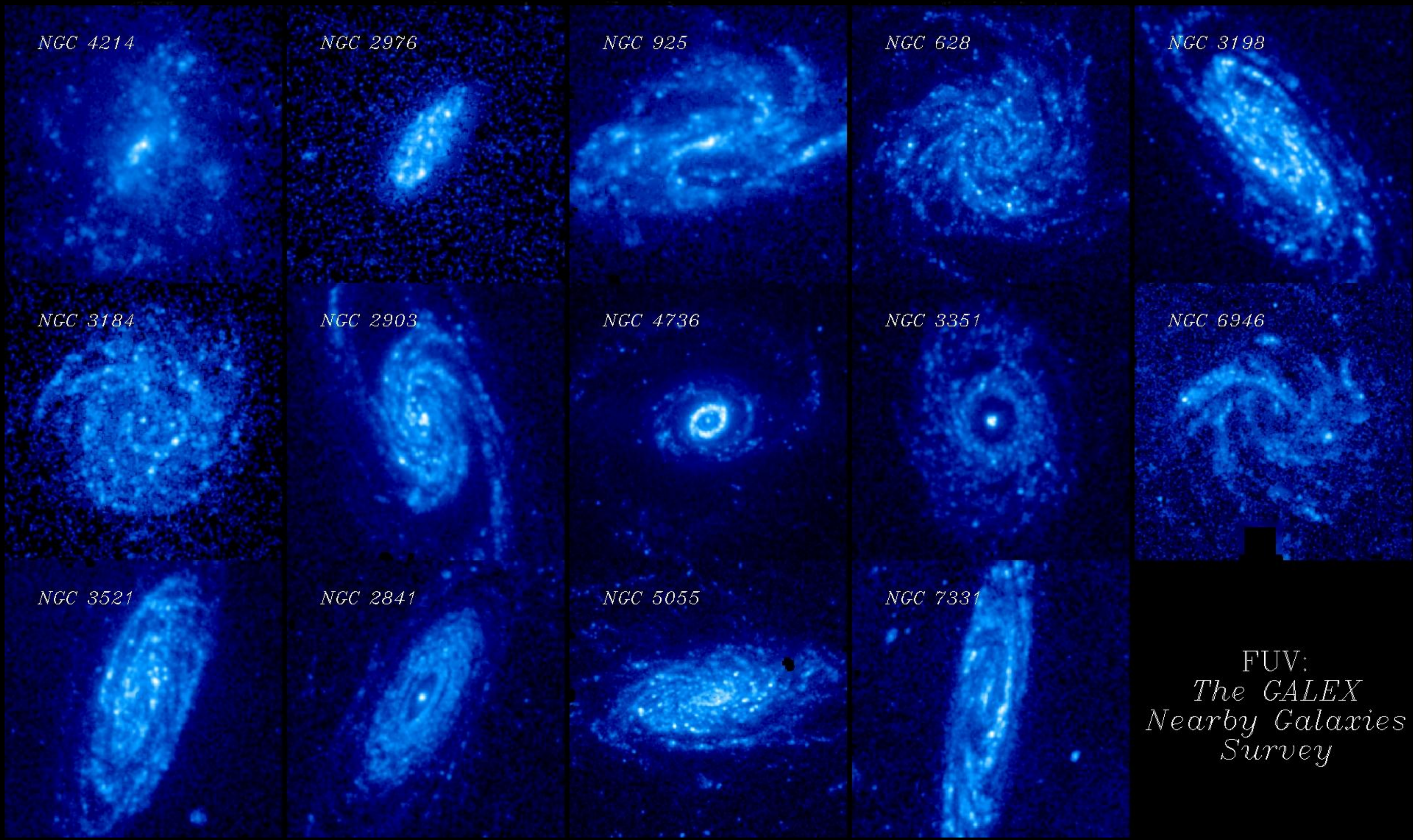
star clusters in galaxies

70-90% of star formation in the MW occurs in clusters (Lada & Lada 1993)

NGC3603: massive star forming region in the Milky Way & local Universe: $10^4\ M_\odot$ clusters with ~100 O stars

"super" stars clusters with 10^4 O-stars

Surveys of SF in nearby galaxies: SINGS (Kennicutt +)/GALEX (Gil de Paz+)/THINGS (Walter+)/HERACLES (Leroy+)



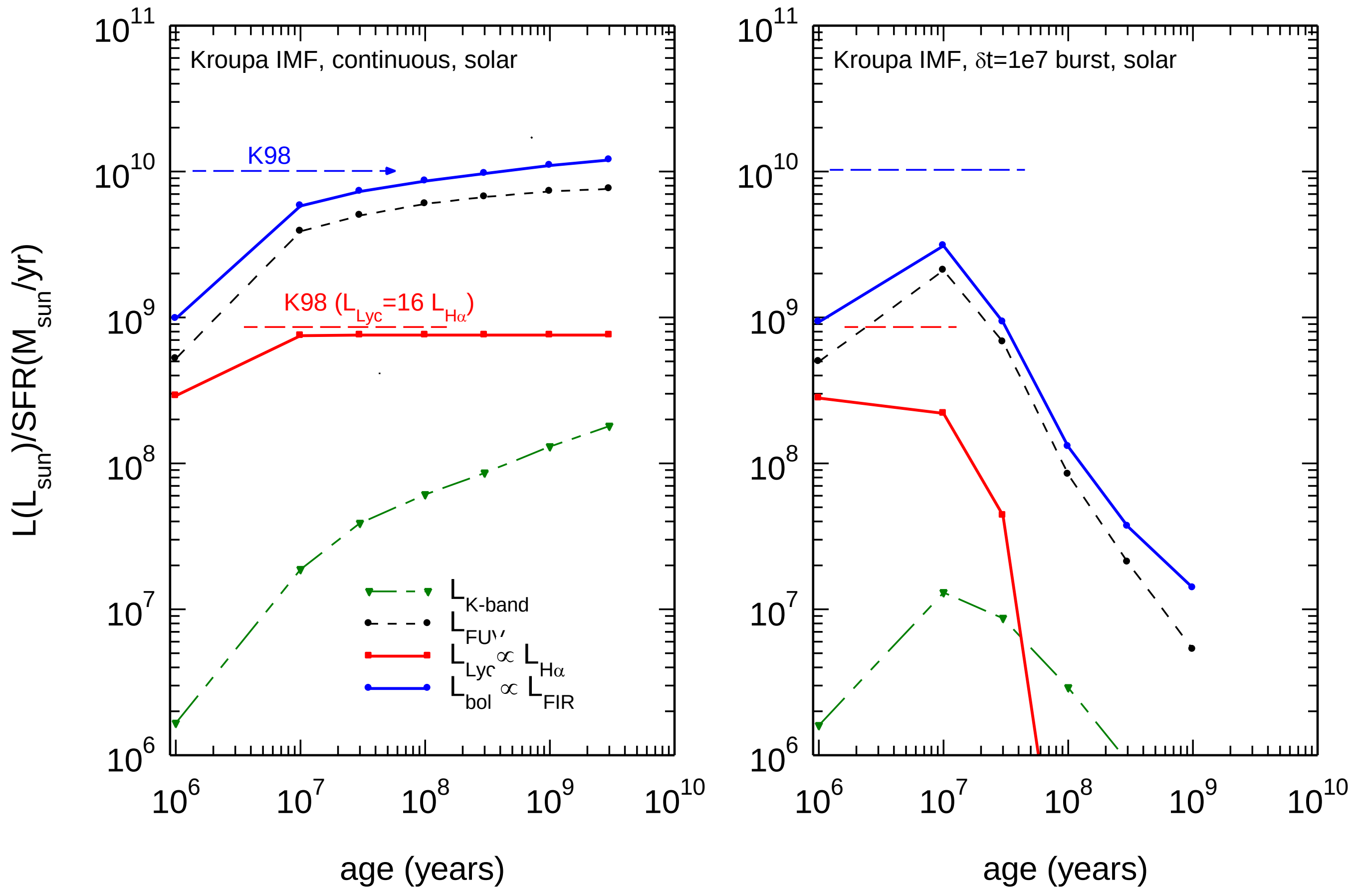
Simon Lilly lecture 1

star formation tracers

Kennicutt 1998, ARAA

	traces	Disadvantage	Technical issues
Hα (or Pα, Brγ)	Lyman continuum luminosity and formation rate of recently formed massive stars	regions with A_V>>1 not sampled, escape of L_{Lyc}, ISM physics, traces only upper IMF	Extinction correction (from Hα/Hβ=2.9 in $T_e=10^4$ K case B)
UV-continuum (or [OII], or 158 [CII])	FUV continuum of moderately massive stars	need SFH for interpretation of SFR Regions with A_V>1 hard to sample	Extinction correction SFH for lines line emission f(n,T)
Mid-IR continuum	all luminosity heating ISM dust	needs extrapolation to FIR and SFH to get SFR PAH-strength? AGN contamination Escape of UV-radiation	Mid-to-Far-IR SEDs SFH
Far-IR continuum	all luminosity heating ISM dust	spatial resolution and sensitivity poor (but Herschel!) Needs SFH to get SFR Escape of UV-radiation	SFH
Radio continuum	synchrotron emission ∝ FIR luminosity (FIR-radio relation)	AGN contamination Unclear physical origin	Changes with z & SFH ?

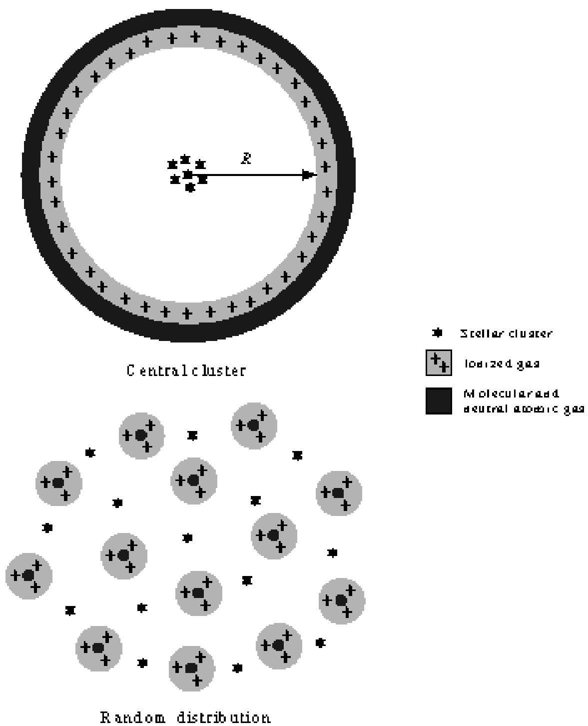
dependence on time & SF history (SFH)

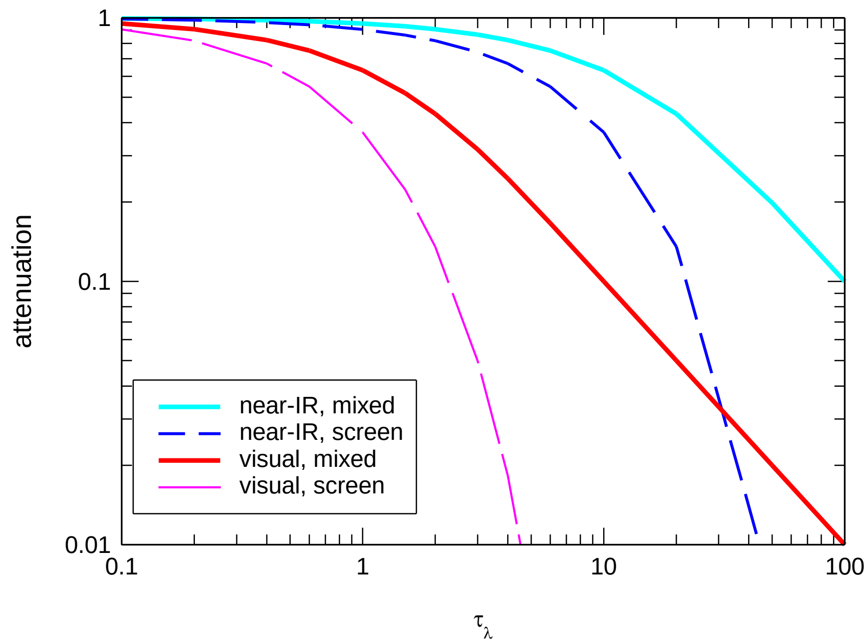


even the best star formation tracers are no better than ±0.3dex, because of uncertainties in in the underlying SFH and the assumed IMF. For extinction dependent UV/optical estimators the situation is worse.

extinction : dependence on geometry

'screen' : attenuation ~ exp $(-\tau_\lambda)$
'mixed' : attenuation ~ $(1-\exp(-\tau_\lambda))/-\tau_\lambda$

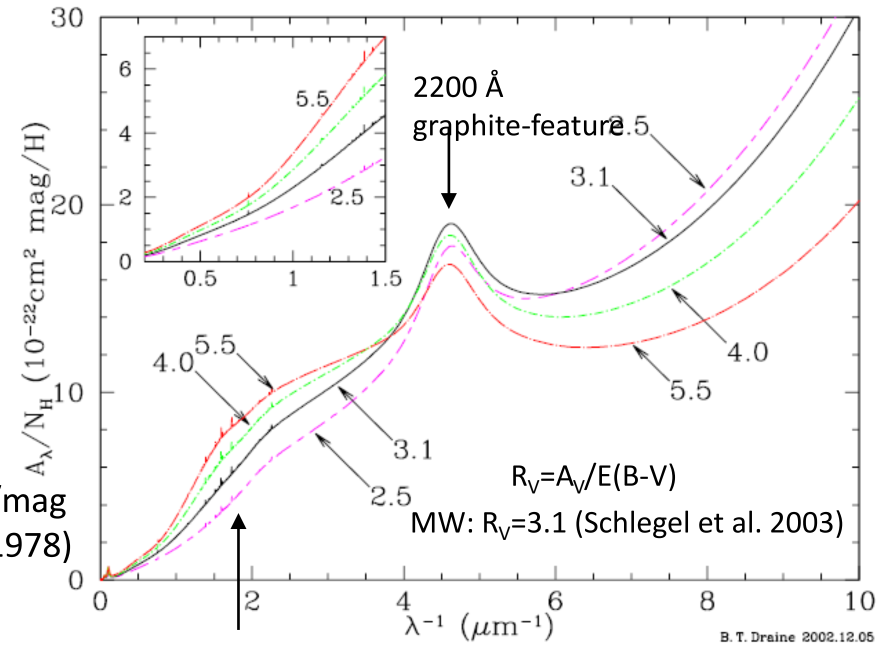




Foerster-Schreiber et al. 2000
Rieke et al. 1993

modified screen extinction estimators (Calzetti 2000) often are a reasonable description of the diffuse galactic extinction but fail in dense, dusty environments, where 'mixed' extinctions are more appropriate

dust extinction

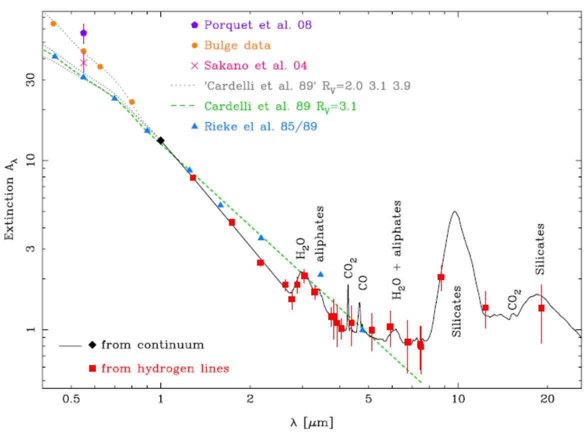


N(H)/A_V= 1.8×10^{21} cm^{-2}/mag (Bohlin et al. 1978)

V=0.556µm

a dust model with a 'Draine & Lee" mixture of graphites and silicates gives a good description of Galactic extinction. The LMC/SMC and starburst galaxies are better described by a greyer 'Calzetti (2000) extinction curve'

Draine 2003, astro-ph0304489



the near- and mid-IR extinction toward the Galactic Center & nearby starbursts is greyer than the Draine & Lee silicate/graphite dust model and requires the presence of ices, increasing the 2-20µm dust absorption (Lutz 1996, 1999, Fritz et al. 2011). The far infrared opacity $\tau(\lambda)\sim\lambda^{\beta}$, $\beta\sim-1.5..-2$ (Eales et al. 2012, Scoville 2012, Magnelli et al. 2012)

Simon Lilly lecture 1

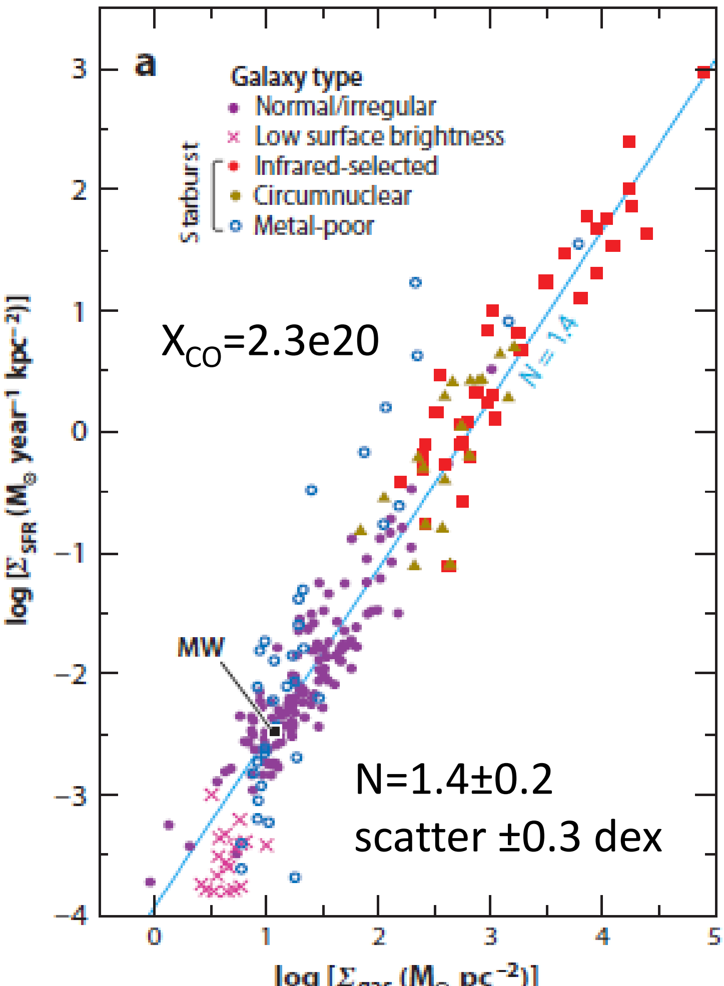
mass tracers

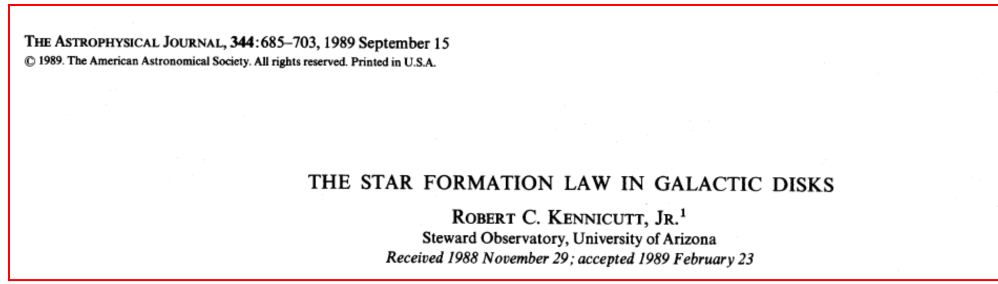
systematic uncertainties are particularly hard to quantify and are often neglected

	traces	issues	uncertainties
UV to IR SED fitting	live stellar mass	requires simultaneous fitting of M*, SFH, A_V and assumption of IMF best if rest-frame NIR covered	overcoming degeneracies, especially if z is unknown, old stellar component uncertainty 1.3-3
rotating curve in Hα or CO	total dynamical mass	requires spatially resolved v(R) , fitting/info on inclination, deviations from rotation? Mass outside bright region sampled by line emission?	requires high SNR and <2kpc resolution with R>3000 uncertainty 1.5-2
velocity dispersion in absorption or CO/Hα emission	total dynamical mass	uncertain relation between $R_{1/2}$ and $R_{h,m}$ requires assumption on mass distribution in R deviation from virial equilibrium	requires very long integrations for absorption lines uncertainty 2
gravitational lensing	total mass	only possible for galaxies in or behind clusters, or for chance alignments	requires knowledge about mass distribution uncertainty 1.5
CO (HI) luminosity	molecular (atomic) gas mass	requires assumption on $CO \Rightarrow H_2$ conversion factor	HI not accessible for high-z until SKA uncertainty 1.3->3
submillimeter dust luminosity	dust mass ⇒ gas mass	requires knowledge of T_{dust} and $\kappa_{dust}(\lambda)$ and M_{gas}/M_{dust}	uncertainty >2

stellar, dynamical and gas mass estimators have uncertainties of ≥0.3 dex, because of uncertainties in the underlying SFH, IMF and extinction for the former, and for uncertainties in spatial distribution, kinematics and conversion factors for the latter.

gas-star formation (Kennicutt-Schmidt) relation in z=0 star forming galaxies




THE ASTROPHYSICAL JOURNAL, 344:685–703, 1989 September 15

THE STAR FORMATION LAW IN GALACTIC DISKS

ROBERT C. KENNICUTT, JR.[1]
Steward Observatory, University of Arizona
Received 1988 November 29; accepted 1989 February 23

simple physical motivation:

$$\Sigma_{SFR} \sim \rho_{\rm SFR} h_z \sim \left(\frac{\rho_{gas}}{\tau_{ff}} \right) h_z \sim \left(\frac{\rho_{gas}}{\left\{ \rho_{gas} \right\}^{-1/2}} \right) h_z \sim \Sigma_{gas}^{1.5} h_z^{-1/2}$$

for cloudy medium a filling factor enters in galactic averages, for marginally stable systems (Q_{toomre}~1) τ_{ff}(local) → τ_{dyn}(galactic)

Kennicutt 1998, Kennicutt & Evans 2012

classical papers star formation in nearby galaxies

THE ASTROPHYSICAL JOURNAL, 179:427–438, 1973 January 15

THE HISTORY OF STAR FORMATION AND THE COLORS OF LATE-TYPE GALAXIES

LEONARD SEARLE, W. L. W. SARGENT, AND W. G. BAGNUOLO
Hale Observatories, Carnegie Institution of Washington, California Institute of Technology
Received 1972 June 13; revised 1972 August 9

late type galaxies formed over a long period of time with a Salpeter IMF, while dwarfs show bursts

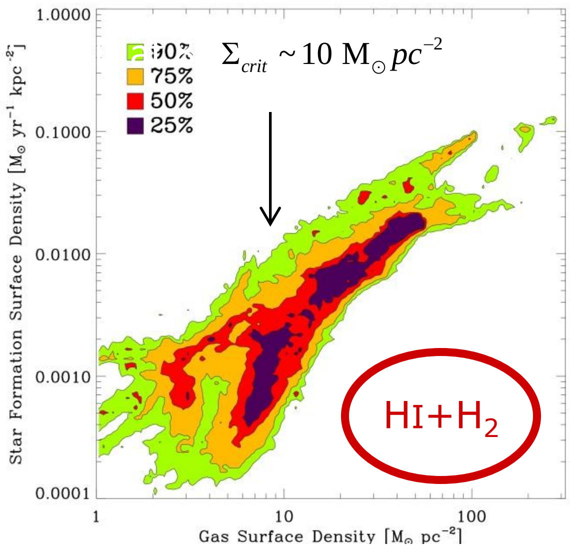
THE ASTROPHYSICAL JOURNAL, 272:54–67, 1983 September 1

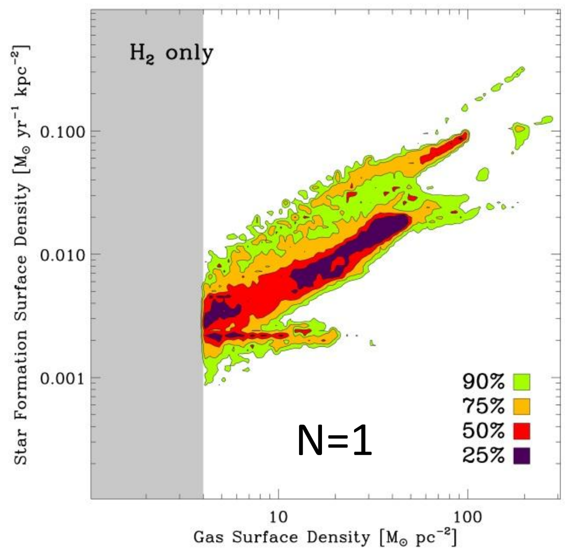
THE RATE OF STAR FORMATION IN NORMAL DISK GALAXIES

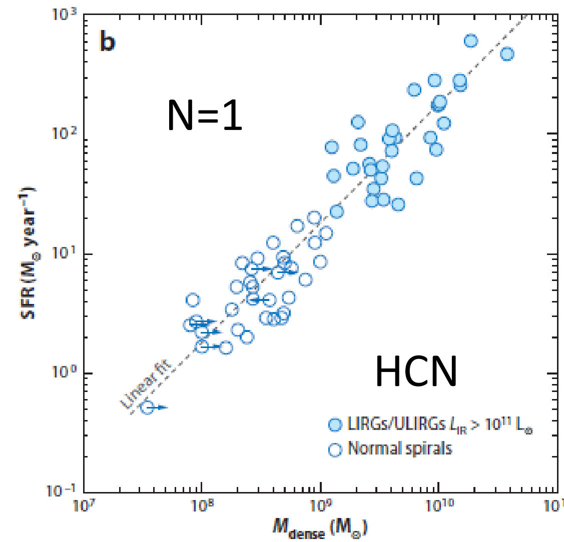
ROBERT C. KENNICUTT, JR.
University of Minnesota, Department of Astronomy
Received 1982 October 11; accepted 1983 February 9

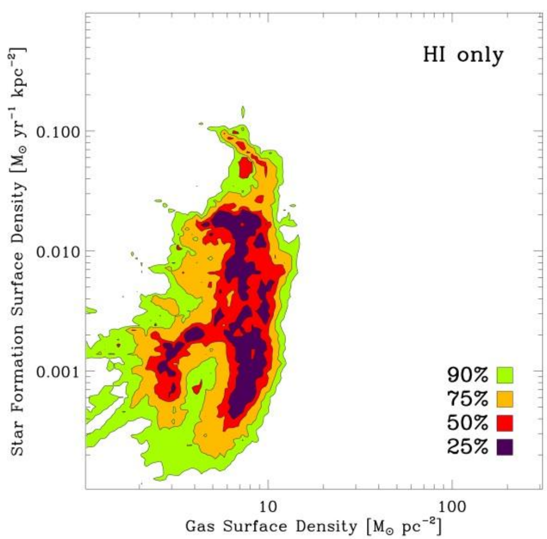
normal disk galaxies (SFGs) use up their gas reservoir on a time scale ~Gyr << t_{Hubble}, requiring gas infall over cosmic time

spatially resolved SF- relation: THINGS/HERACLES









in the regions where CO/HCN plausibly trace the molecular hydrogen content the average star formation is linearly correlated with molecular gas and dust, resulting in an approximately constant molecular depletion time scale ~1-2 Gyrs; it is unclear whether stars can form from atomic gas

- Little correlation between SFR and HI
- Σ_{HI} saturates at 9 M$_\odot$ pc^{-2}

Bigiel, Leroy, Schruba et al. 2008-2011, Gao & Solomon 2004

(specific) star formation rates depend sensitively on galaxy properties

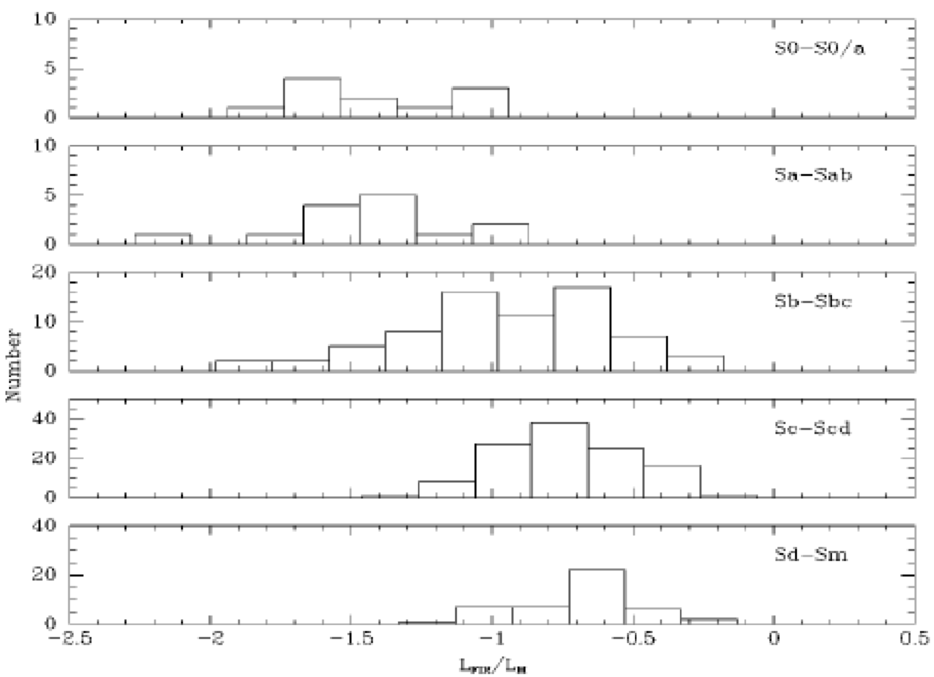
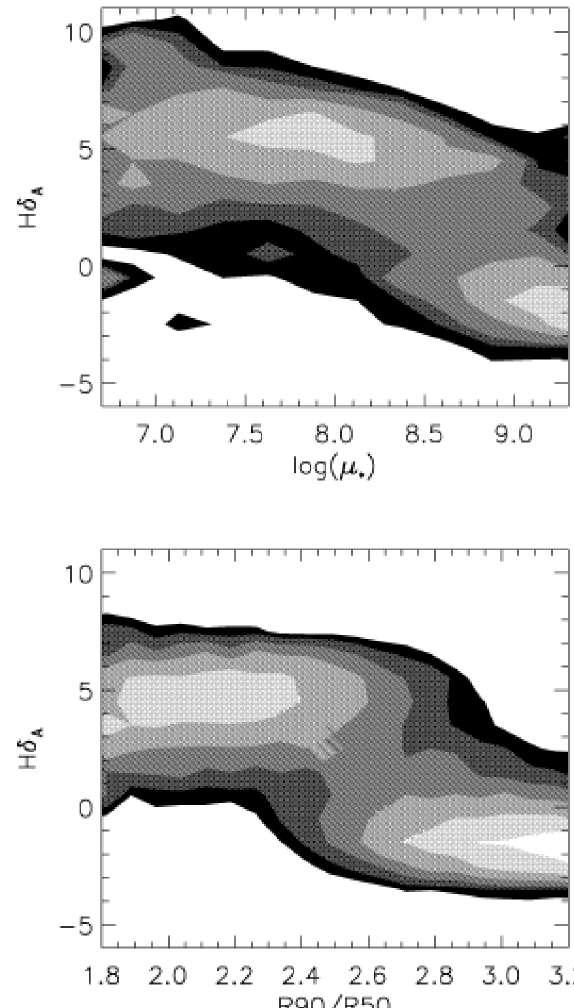


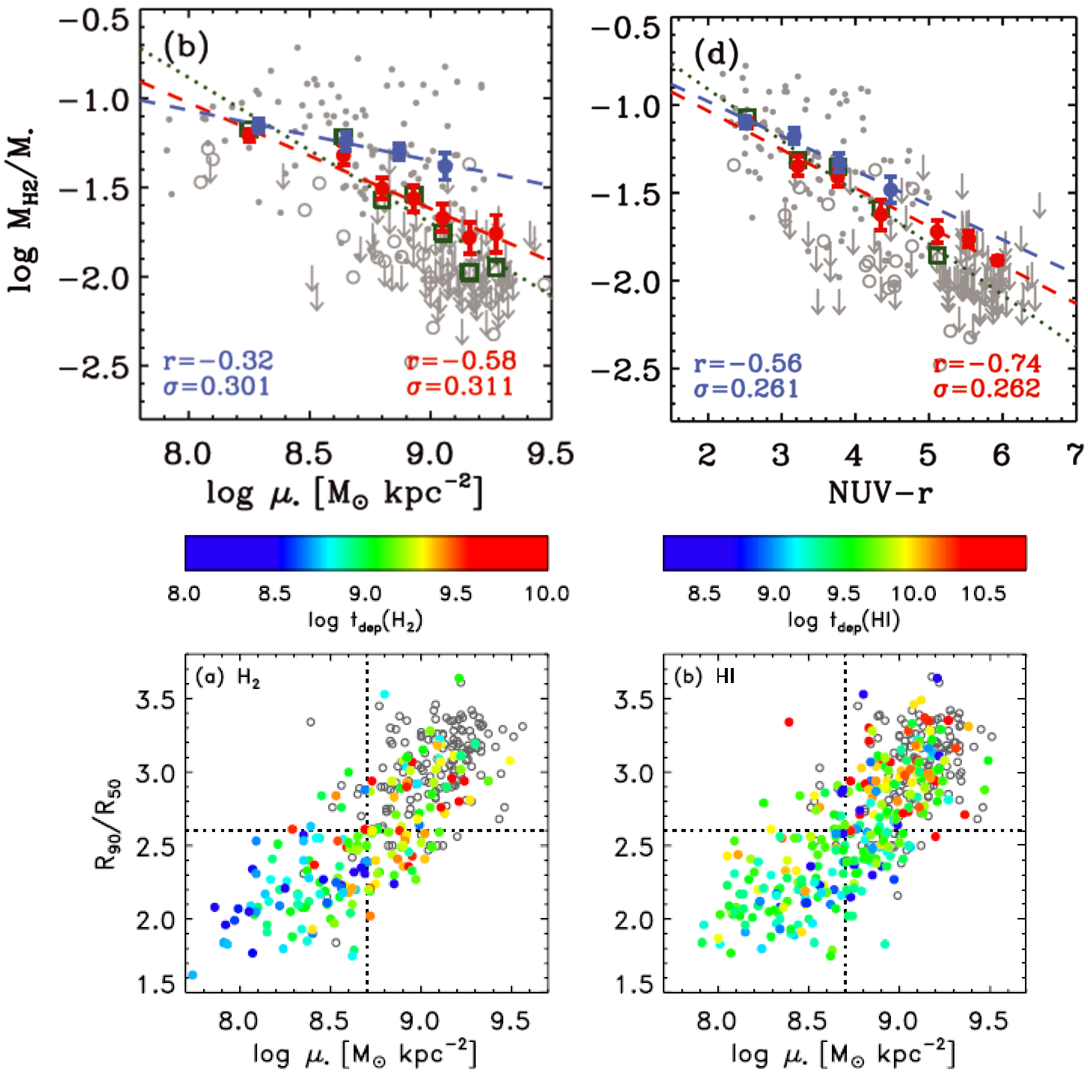
Figure 4 Distributions of 40- to 120-μm infrared (IR) luminosity for nearby galaxies, normalized to near-IR *H*-band luminosity, as a function of Hubble type. Adapted from Devereux & Hameed (1997), with elliptical and irregular galaxies excluded.

Pre-SDSS: dependence on Hubble type
Kennicutt 1998, ARAA



SDSS: dependence on concentration and surface density
Kauffmann et al. 2003b

recent z=0 unbiased surveys of cold gas in normal star forming galaxies (SFGs)

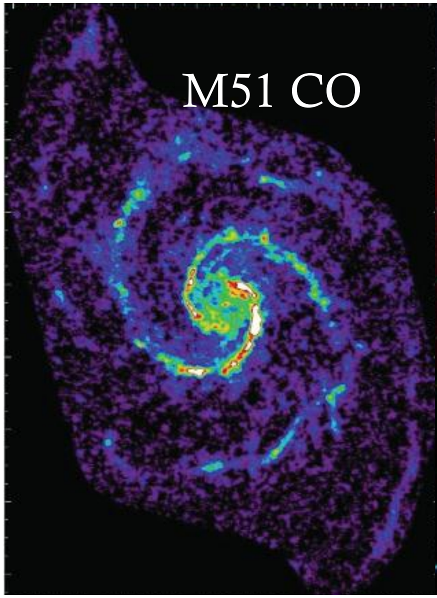


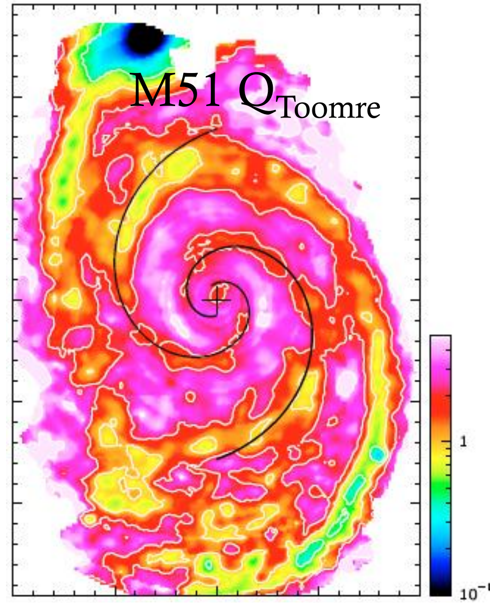
GASS/COLDGASS (PI G.Kaufmann) : stellar mass selection > 10^{10} $M_\odot$,0.025<z<.05 from SDSS/GALEX, ~350 SFGs

There are sharp thresholds in structural parameters (especially stellar surface density), above which the fraction of galaxies with detectable HI or H_2 decreases strongly. H_2/HI and f_{molgas} are only weakly correlated with galaxy mass. High mass density galaxies are forming stars yet less efficiently, or have little gas.

Catinella et al 2010, Schiminovich et al. 2010, Saintonge et al. 2011a,b, 2012, Kauffmann et al. 2012

star formation efficiency on galactic scales



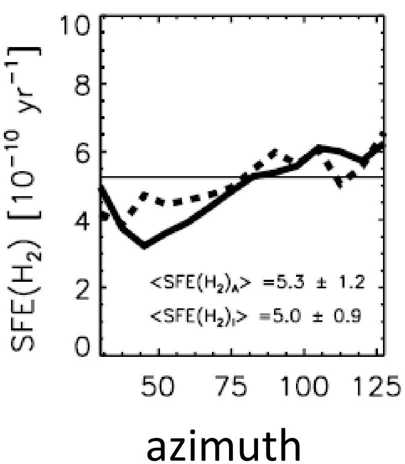


while molecular gas is present everywhere in the disk, the most luminous GMCs/dusty HII regions are located in the spiral arms and are associated with Giant Molecular Associations (~$10^{7.4}$ $M_\odot$); spiral arms are regions with Q≤1 where GMCs are 'formed'

CARMA CO: Koda et al. 2009

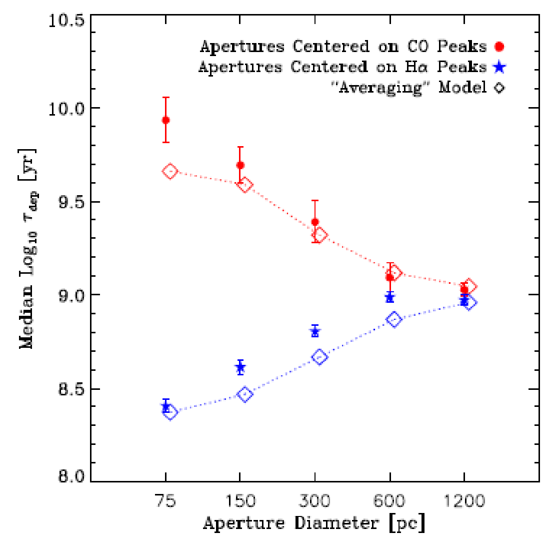
Spitzer near-IR-mid-IR (PAH)

IRAM CO Hitschfeld et al. 2009



star formation efficiency (1/depletion time) is similar in/outside spiral arms
Foyle et al. 2010

the KS relation breaks down on <500 pc scale, because of local evolutionary effects



Schruba et al. 2010, Onodera et al. 2010

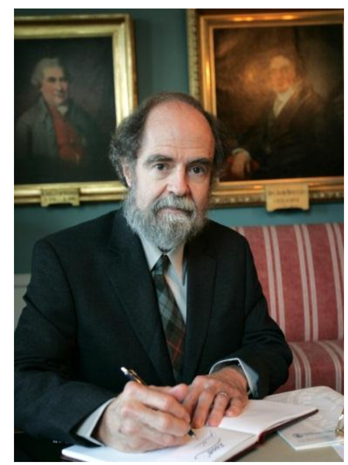
discourse on observational capabilities for galaxy evolution, from UV to radio

Key developments over the past 15 years (in terms of the experimental work)

- combination of efficient low noise, semi-conductor imaging detectors (e.g. CCDs, current record holder ~2×10^9 pixels) & dedicated telescopes or large survey programs on the ground as well as in space

Simon Lilly lecture 1

W. Boyle & G. Smith
Nobel Prize Physics 2009

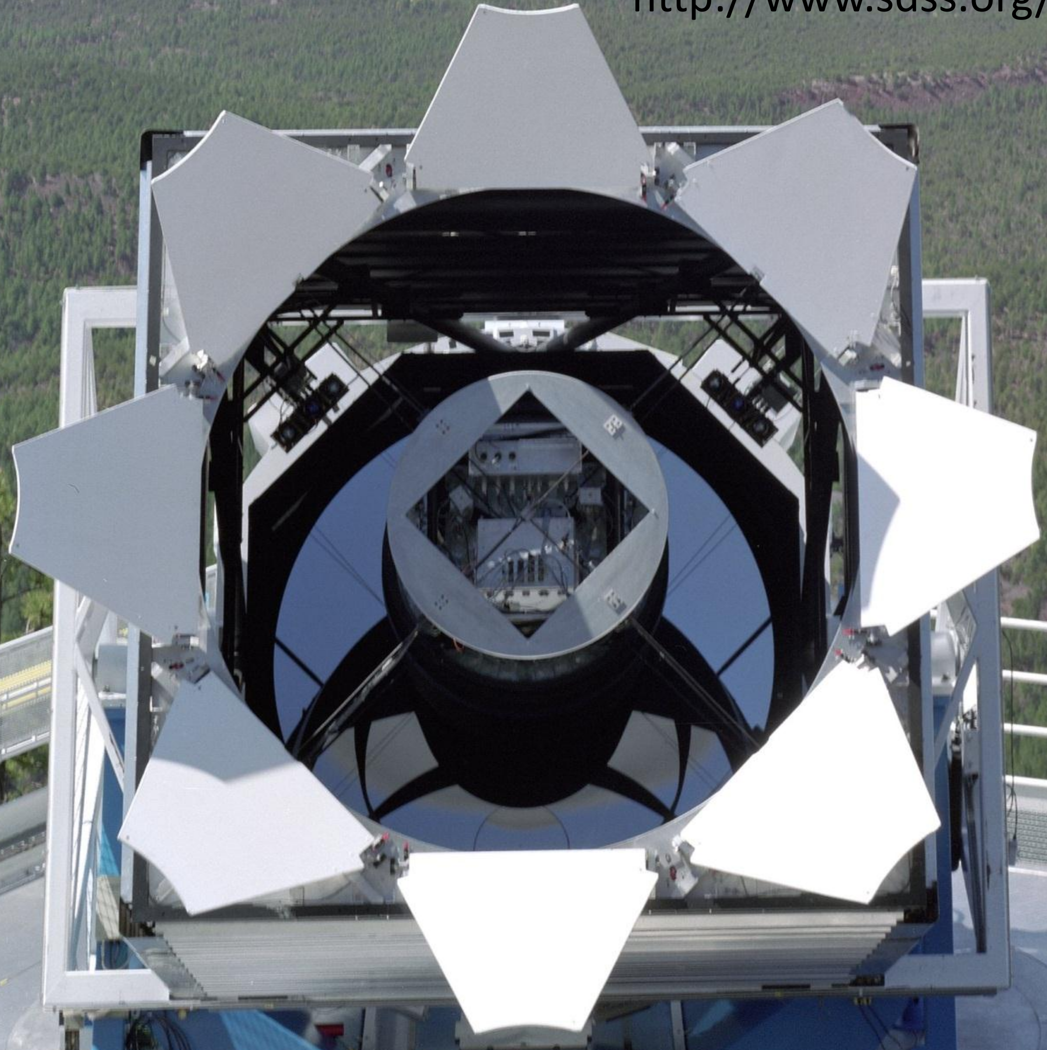


J.Gunn
Crafoord Prize 2005

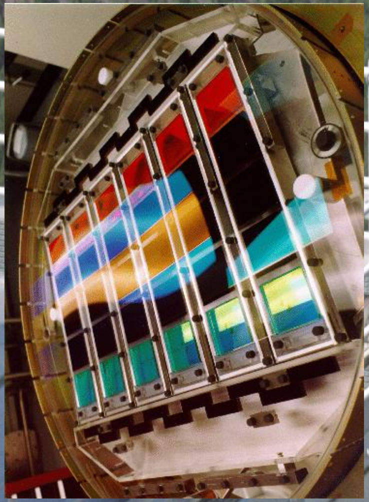
dedicated imaging surveys

http://www.sdss.org/

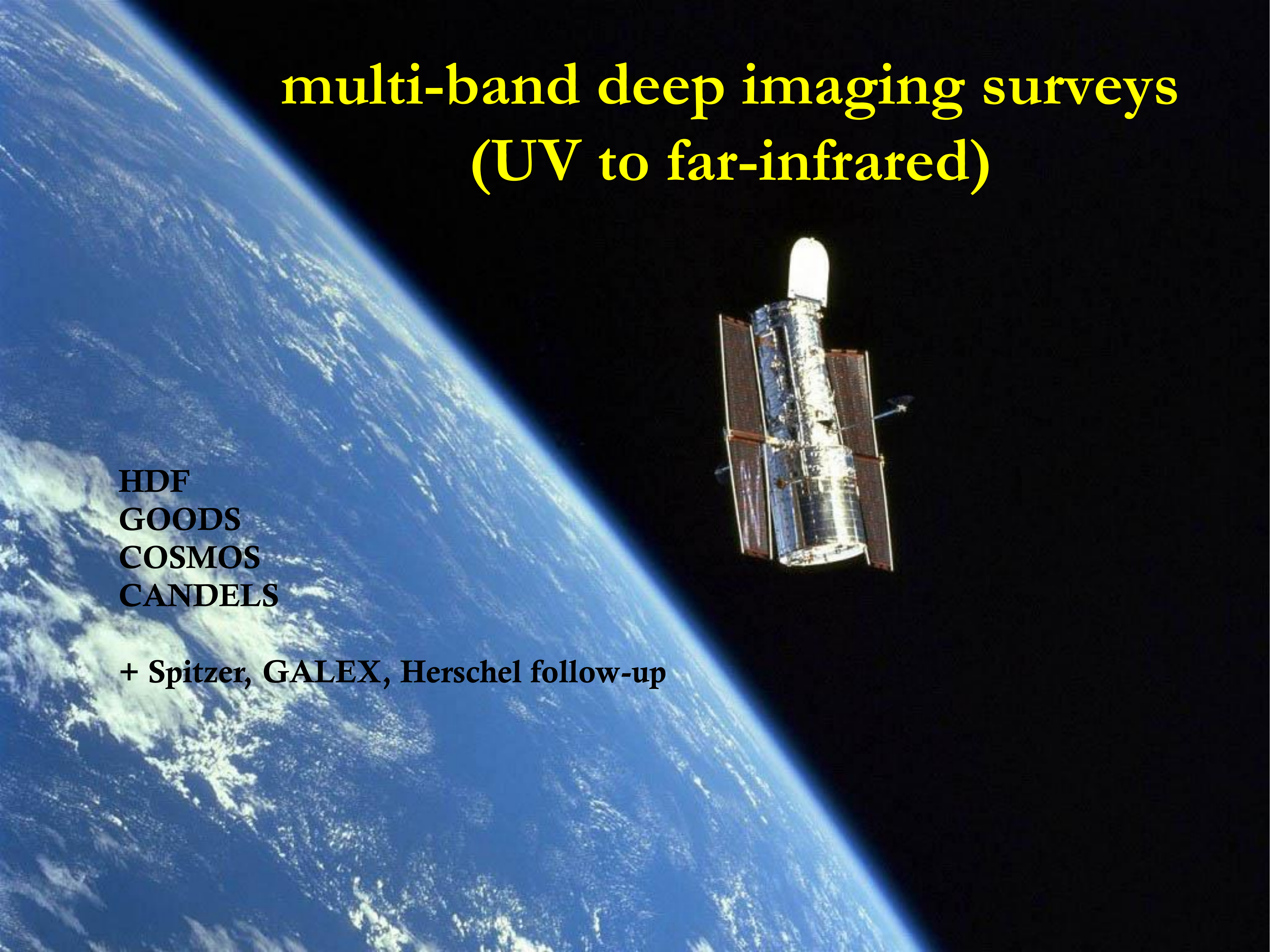
SDSS I-III
PanSTARRS
VISTA-VST
BigBOSS
DES
LSST
EUCLID
WFIRST
………



Gunn et al. 1998



multi-band deep imaging surveys (UV to far-infrared)



HDF
GOODS
COSMOS
CANDELS

+ Spitzer, GALEX, Herschel follow-up

Large optical/infrared telescopes

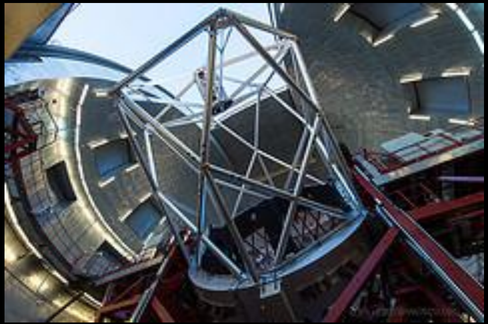

2x10m Keck


2x 6.5m Magellan Telescope

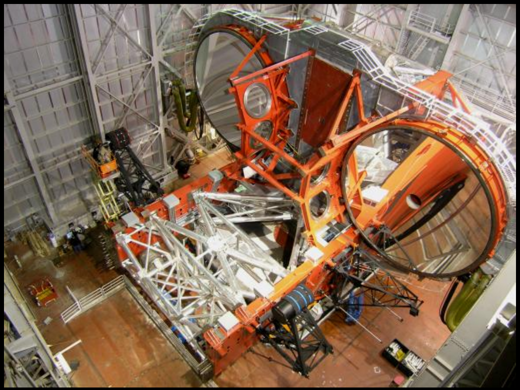

8m Gemini North


4 x 8m VLT

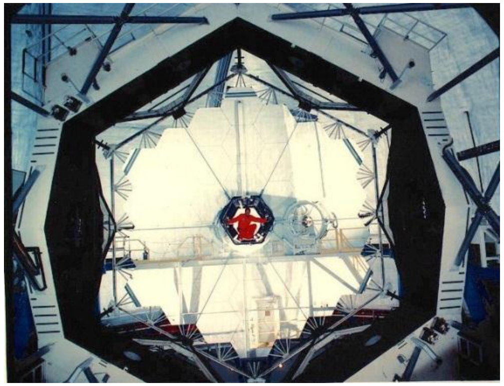

10m Hobby Eberly Telescope


10m Gran Telescopio Canarias


8m Subaru

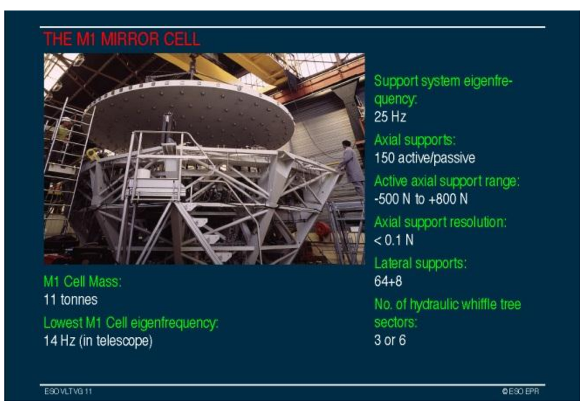

2x 8.2m Large Binocular Telescope

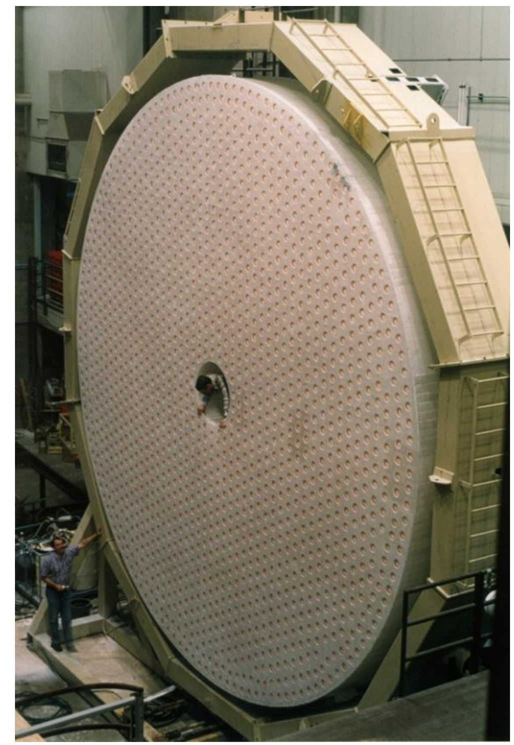
1990-2000 progress in large optical telescopes: light-weighting!



Keck concept (Jerry Nelson): segmented mirror, with stress-lapped hexagonal ~1.8m mirrors which are co-aligned to better than 1/10 wavelength on stars

VLT concept: thin meniscus zerodur mirror (Schott), supported by a large number of active optics pads (Wilson)





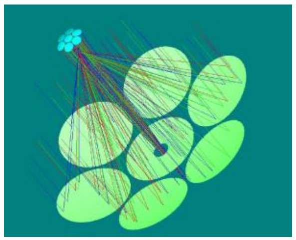
LBT concept (Roger Angel): thin faceplate on stable, lightweighted honeycomb ceramic structure (boro-silicate)

Kavli Prize 2010 to Nelson, Wilson, Angel

http://www.kavliprize.no/seksjon/vis.html?tid=45348

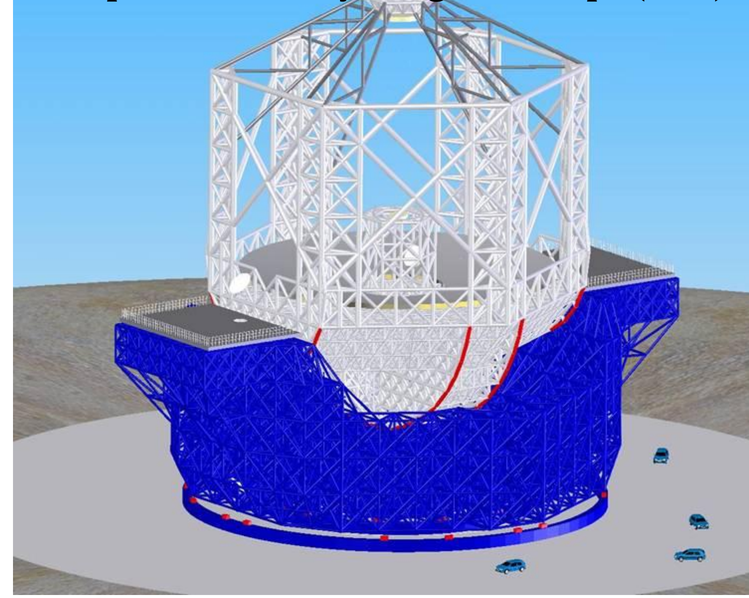
Concepts for >20m telescopes

Giant Magellan Telescope (GMT=7x 8m telescope = Super-LBT ~ 22m)

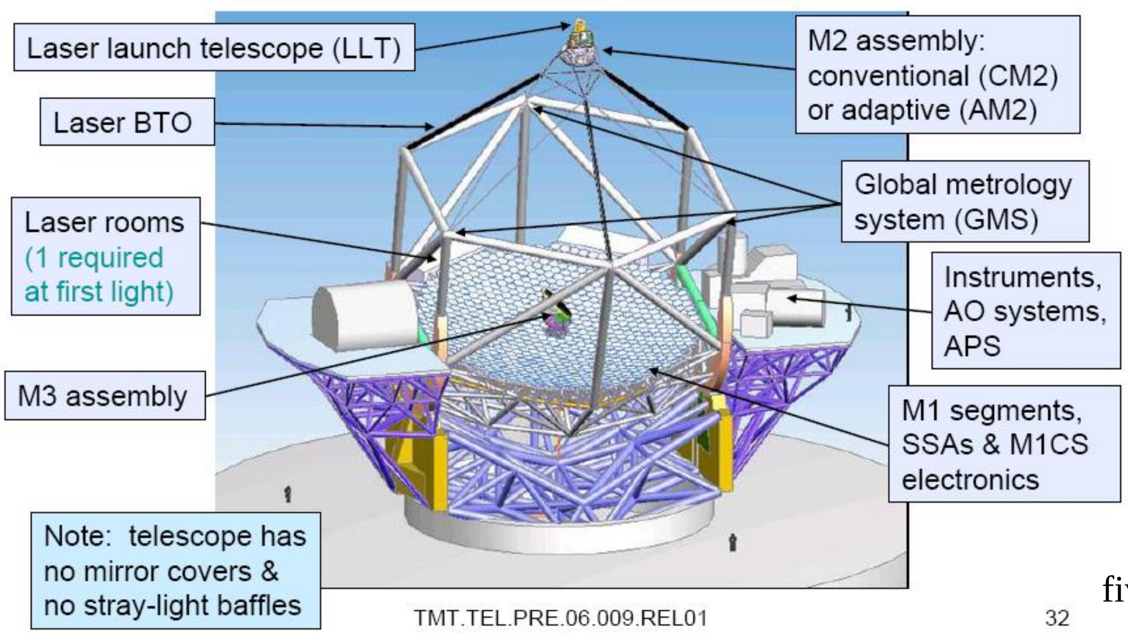


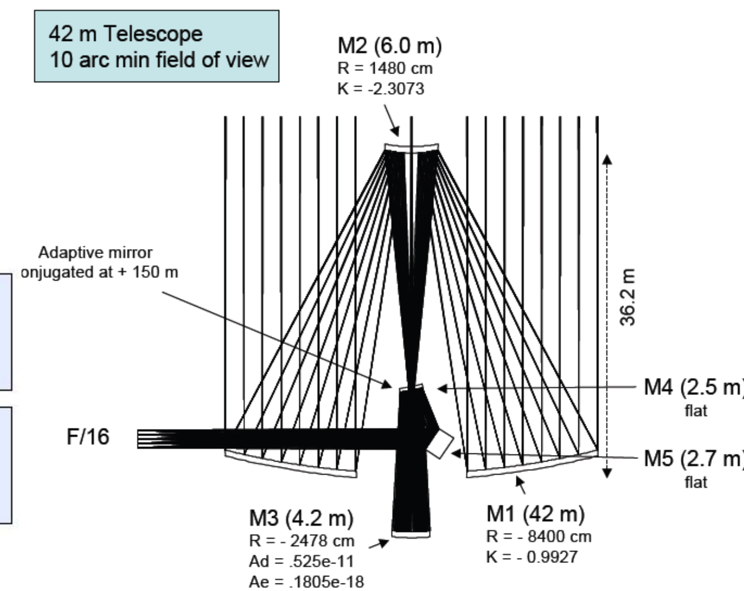
aplanatic Gregorian optics

European Extremely Large Telescope (42m)



Thirty Meter Telescope (TMT= CELT+GSMT)



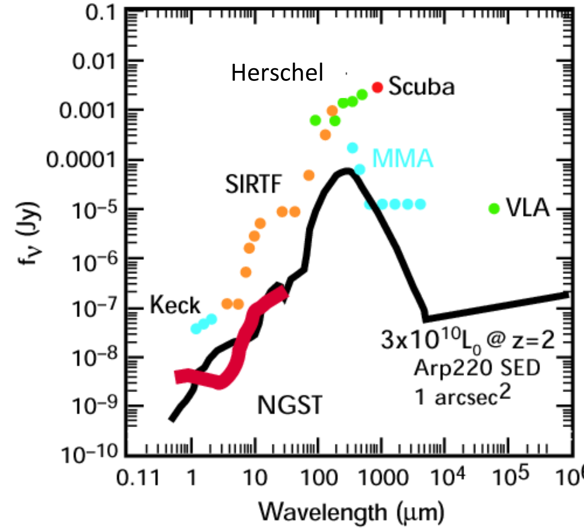


five mirror, full adaptive, field stabilized design

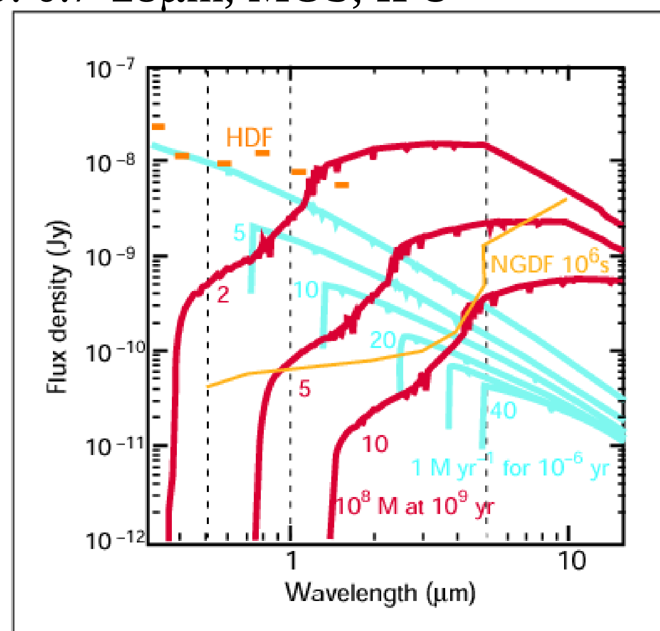
Challenges for > 20m telescopes

- reduction of current size-cost scaling by mass production of segments
- design and construction of large (adaptive) secondary/tertiary etc. optical mirrors
- achieving a reasonable and ‘instrument-friendly’ field-of-view (~5-10’)
- dynamic telescope control and field stabilization under realistic wind-shake conditions
- adaptive optics systems with large enough actuator density (several 10^3 elements) and bandwidth for realizing ‘D^4’near-diffraction limited-science (especially <1.5μm)
- design and construction of (cryogenic) instruments, especially with significant field
- cost, especially also for operation (~30-50 M€/year)

James Webb Space Telescope



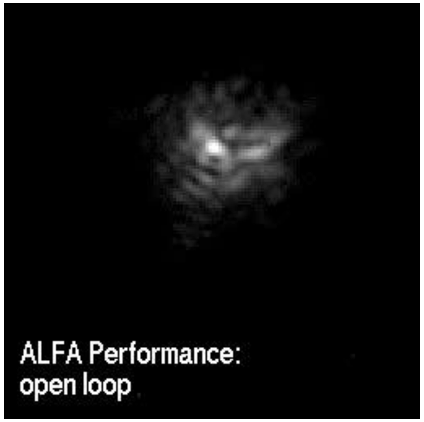
- 6m diameter telescope, self-deployable, assembled from 18 1.3m hexagon segments, passively cooled, L2, launch 2018?
- 4 instruments: NIRCAM, NIRSPEC, MIRI, FGS: 0.7-28μm, MOS, IFU

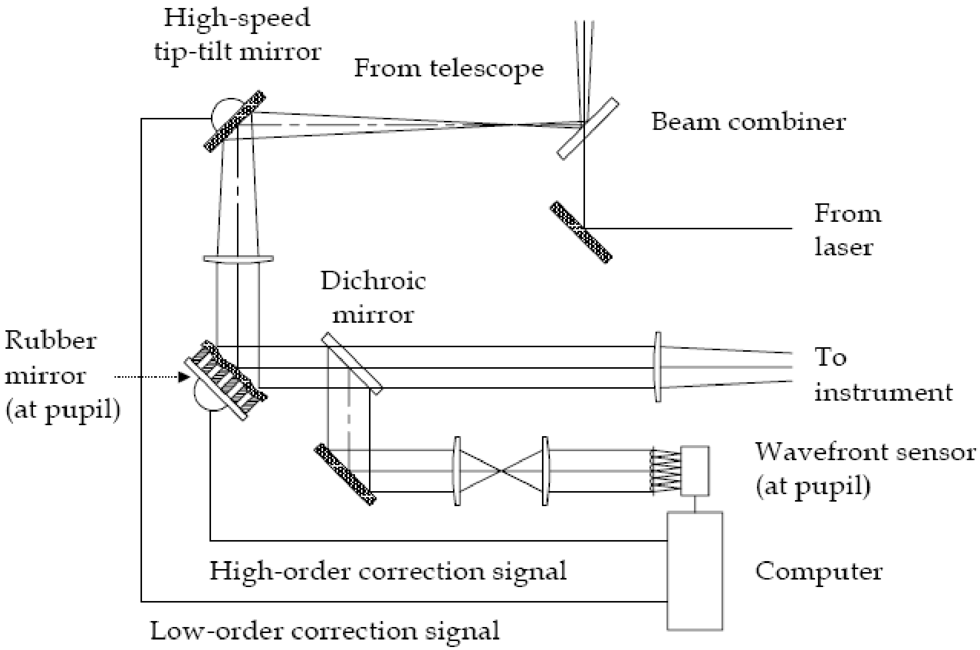


10σ, 1Msec deep field, broad band sensitivity

presentations: http://www.jwst.nasa.gov/publications.html,
Gardner et al. 2007, Space Science Rev. (astro-ph0606175)

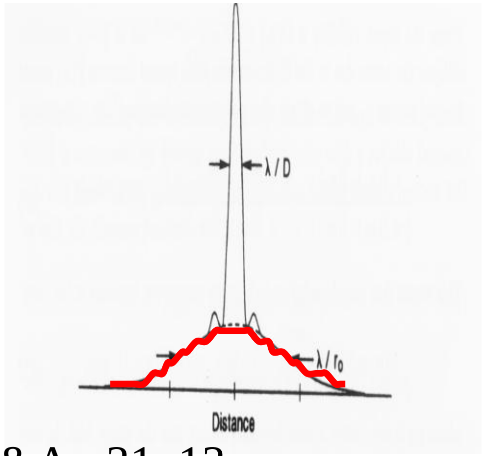
Adaptive optics

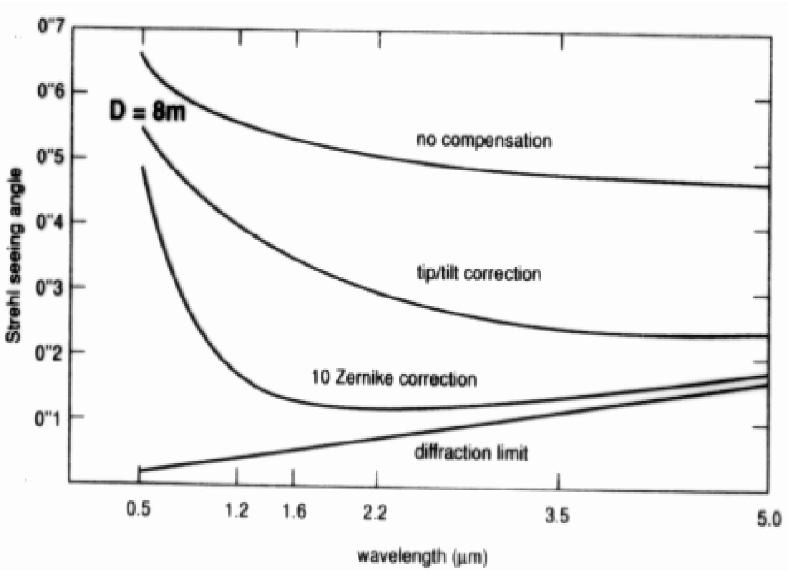




- wavefront sensor
- deformable mirror
- feedback with computer
- guide star(s)
- sensing/observing wavelength

'Strehl ratio' = fraction of energy in central diffraction limited spike: SR=1-Σ_j(Δ_j (rad))





Beckers 1993, Ann.Rev.A&Ap 31, 13

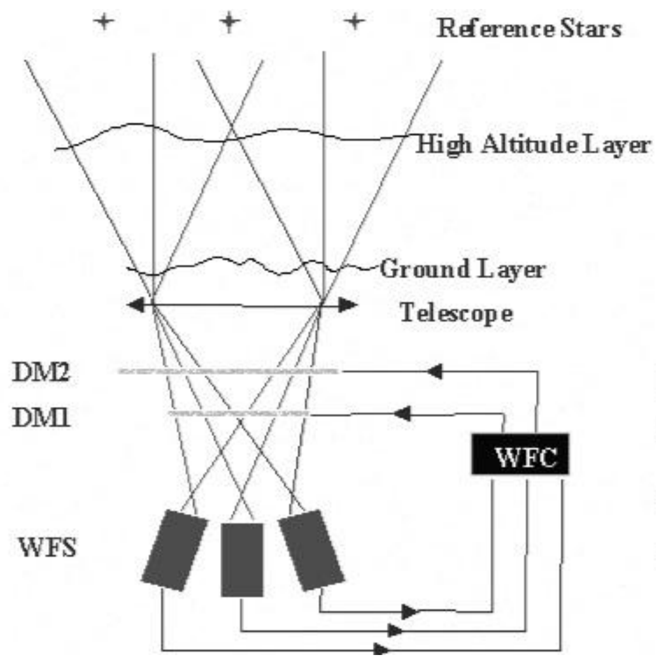
laser guide stars in action at all major large telescopes

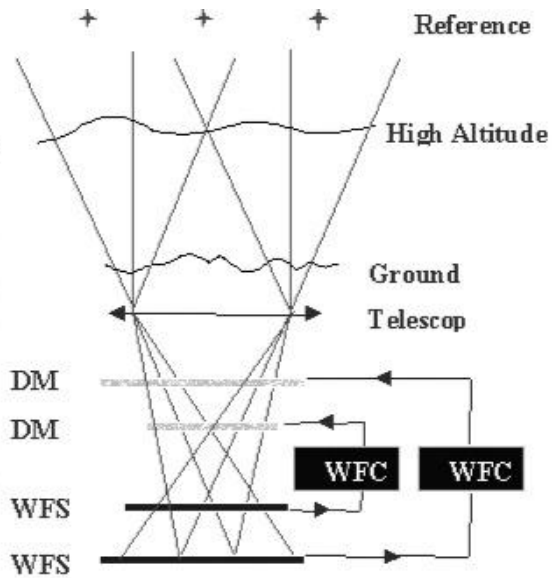
(Keck, Gemini, VLT)

Keck/LLNL team
ESO/MPE/MPIA team
Gemini team

Multi-Conjugate Adaptive Optics for correction of a field

basic concepts





tomography
(first order: GLAO)

layer oriented approach

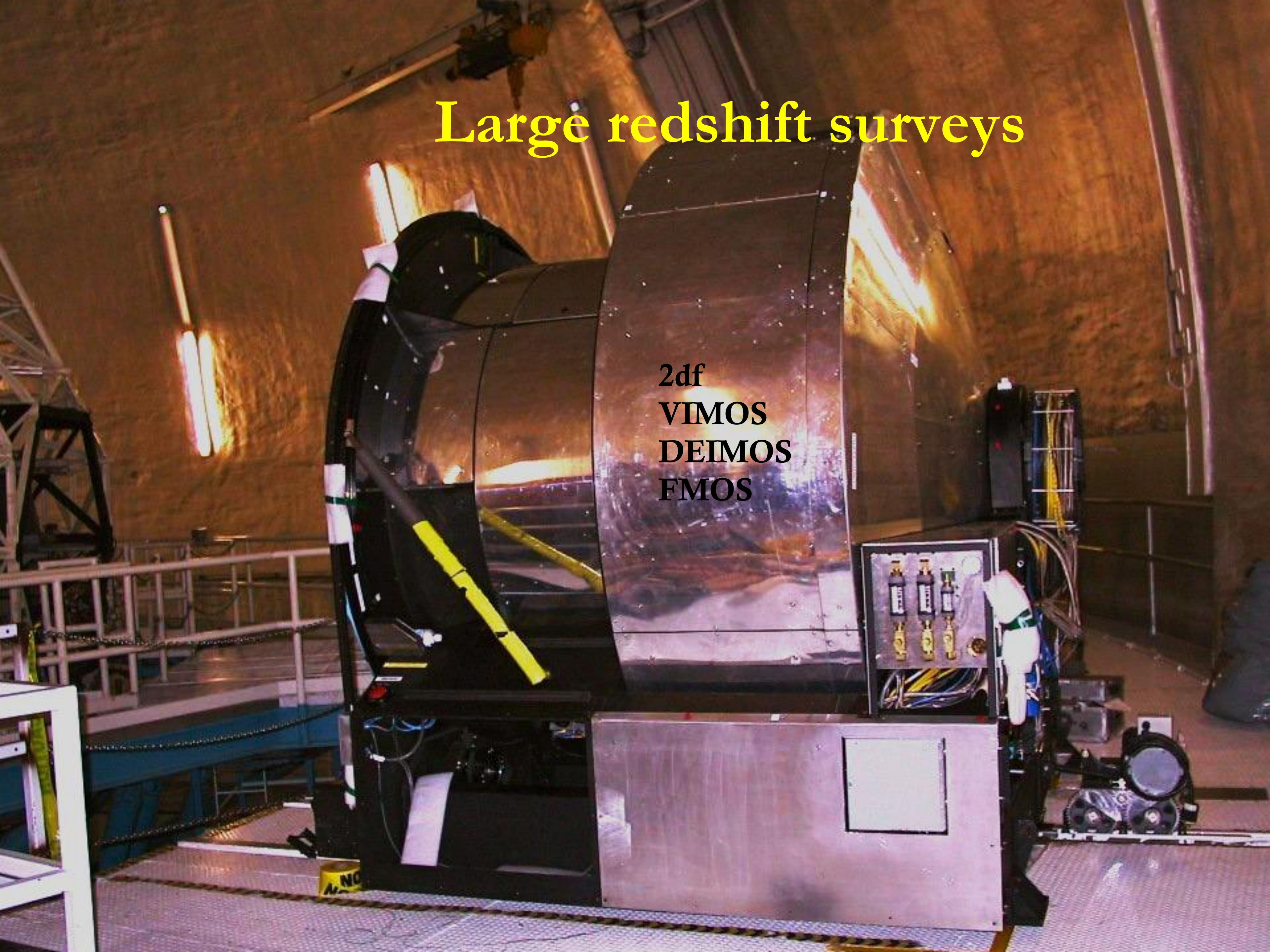
wide field AO (4’) 0.2-0.3” FWHM
3 laser guide stars (x 2 telescopes) GLAO
pulsed green laser system (12 km altitude)

Comissioning @ LBT in 2013/2014

From Ragazzoni 2000

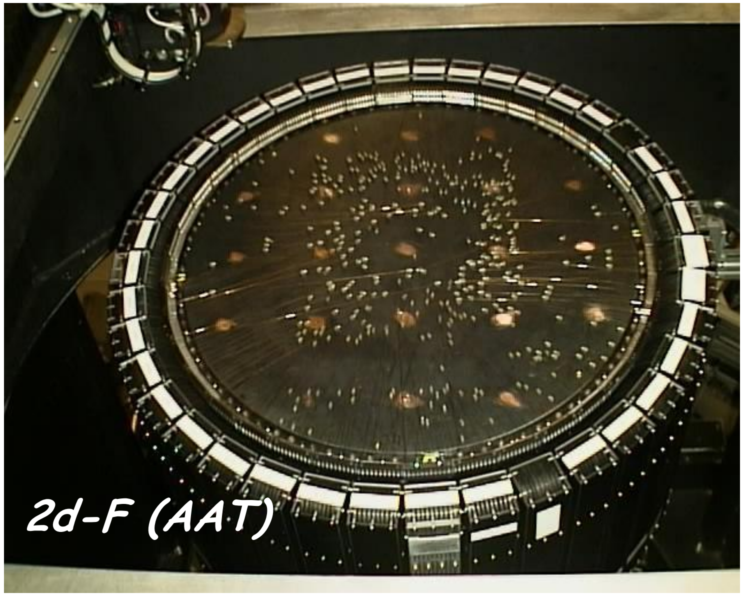
http://www.mpe.mpg.de/ir/projects/LBTLaser/index.php

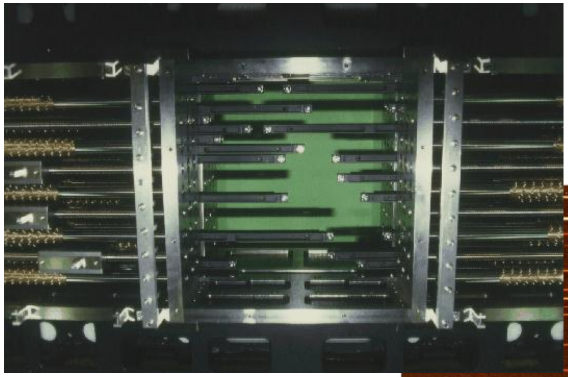
Large redshift surveys

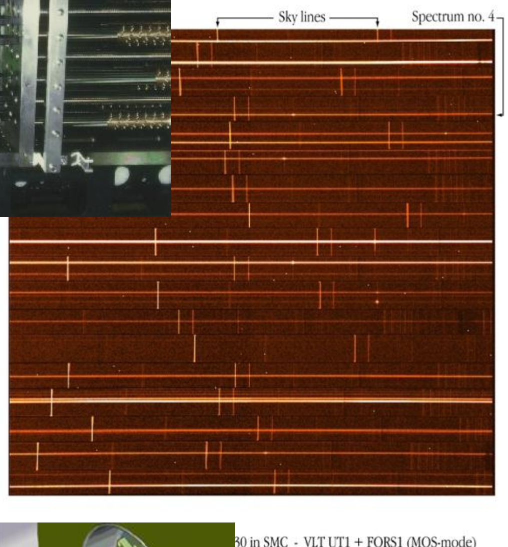


Multi-object spectroscopy
(multiplex 10-200)

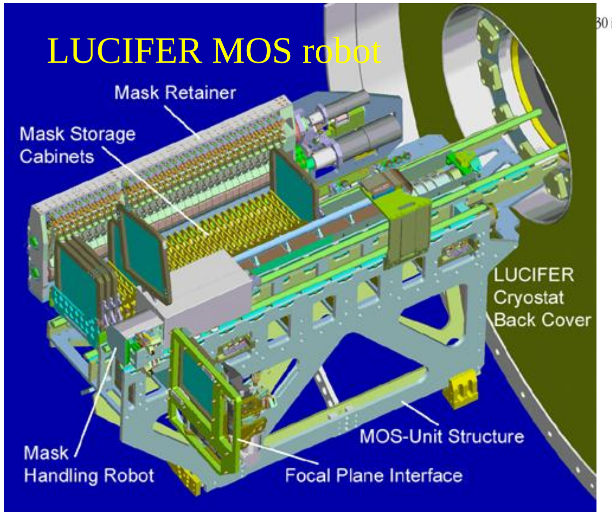
http://www.aao.gov.au/2df
fiber positioner on AAT

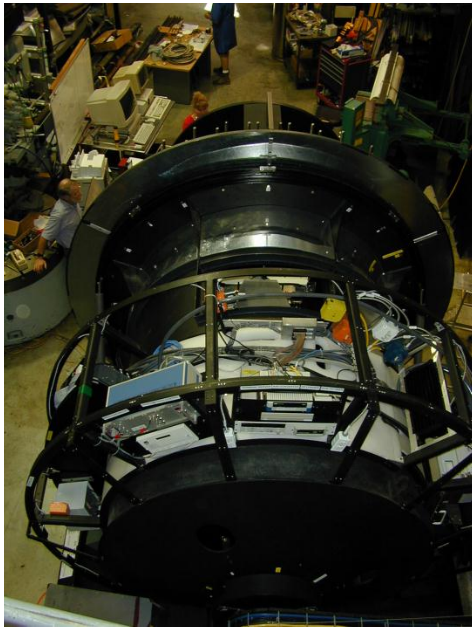






FORS/VLT-multi-slit unit and spectra; upgrade to cryogenic + near-IR MOSFIRE @Keck



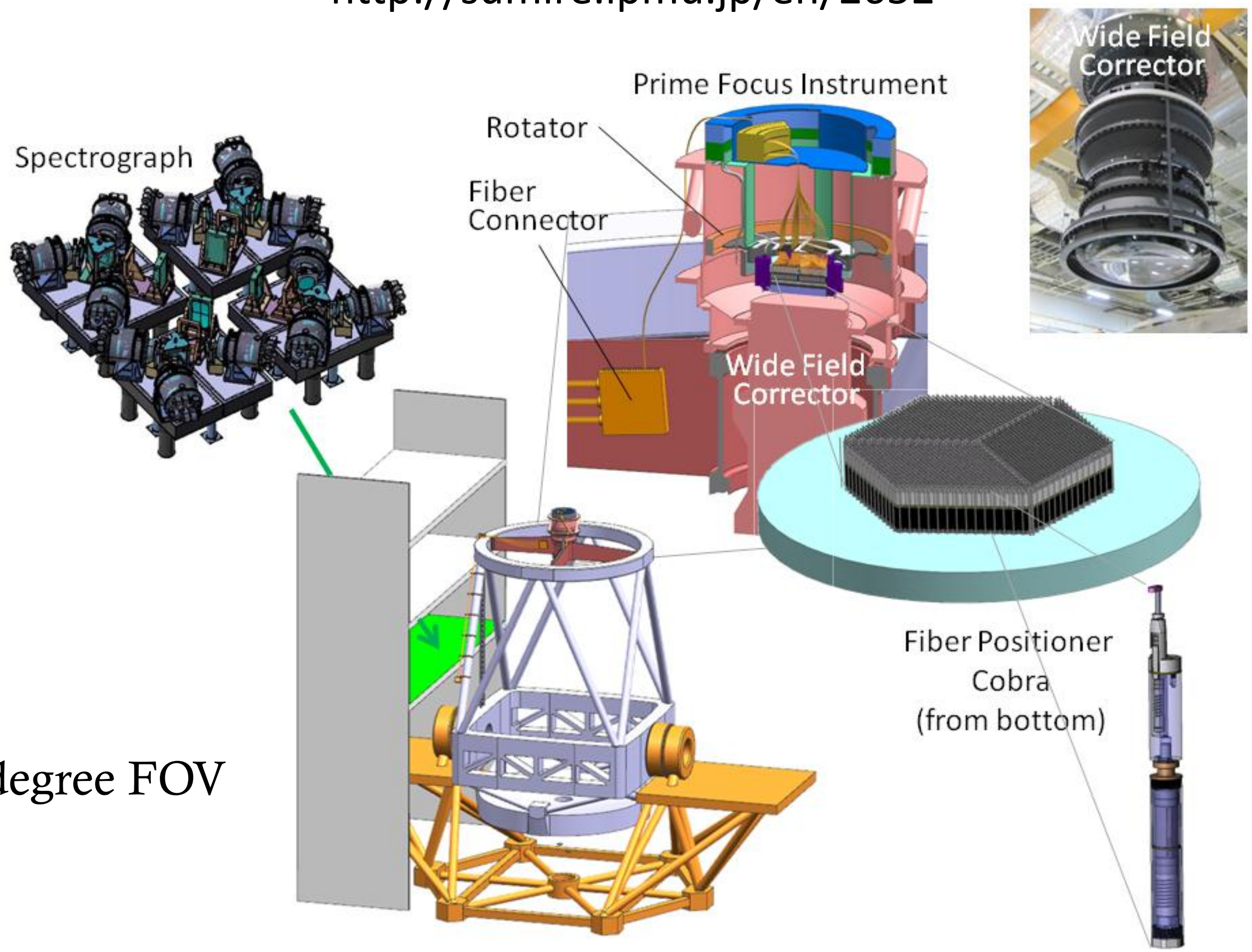


the multi-ton DEIMOS, VIMOS, MOIRCS mask spectrographs at Keck/VLT/SUBARU

http://loen.ucolick.org/Deimos/deimos.html
http://www.eso.org/instruments/vimos/
http://www.subarutelescope.org/Observing/Instruments/MOIRCS/index.html

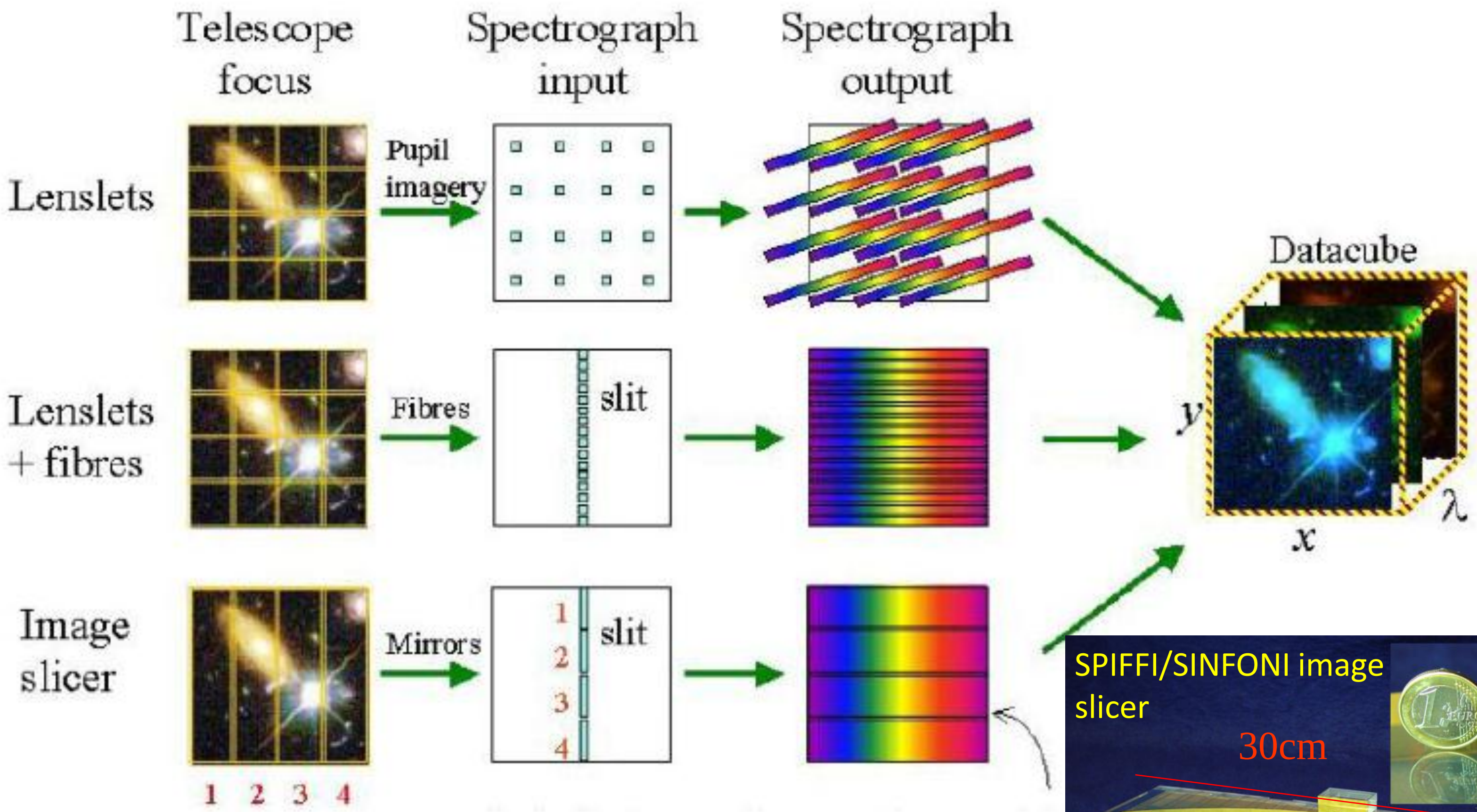
Next generation: Prime Focus Spectrograph Subaru

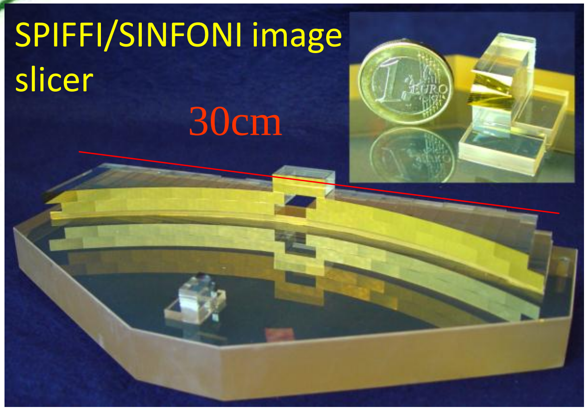
http://sumire.ipmu.jp/en/2652



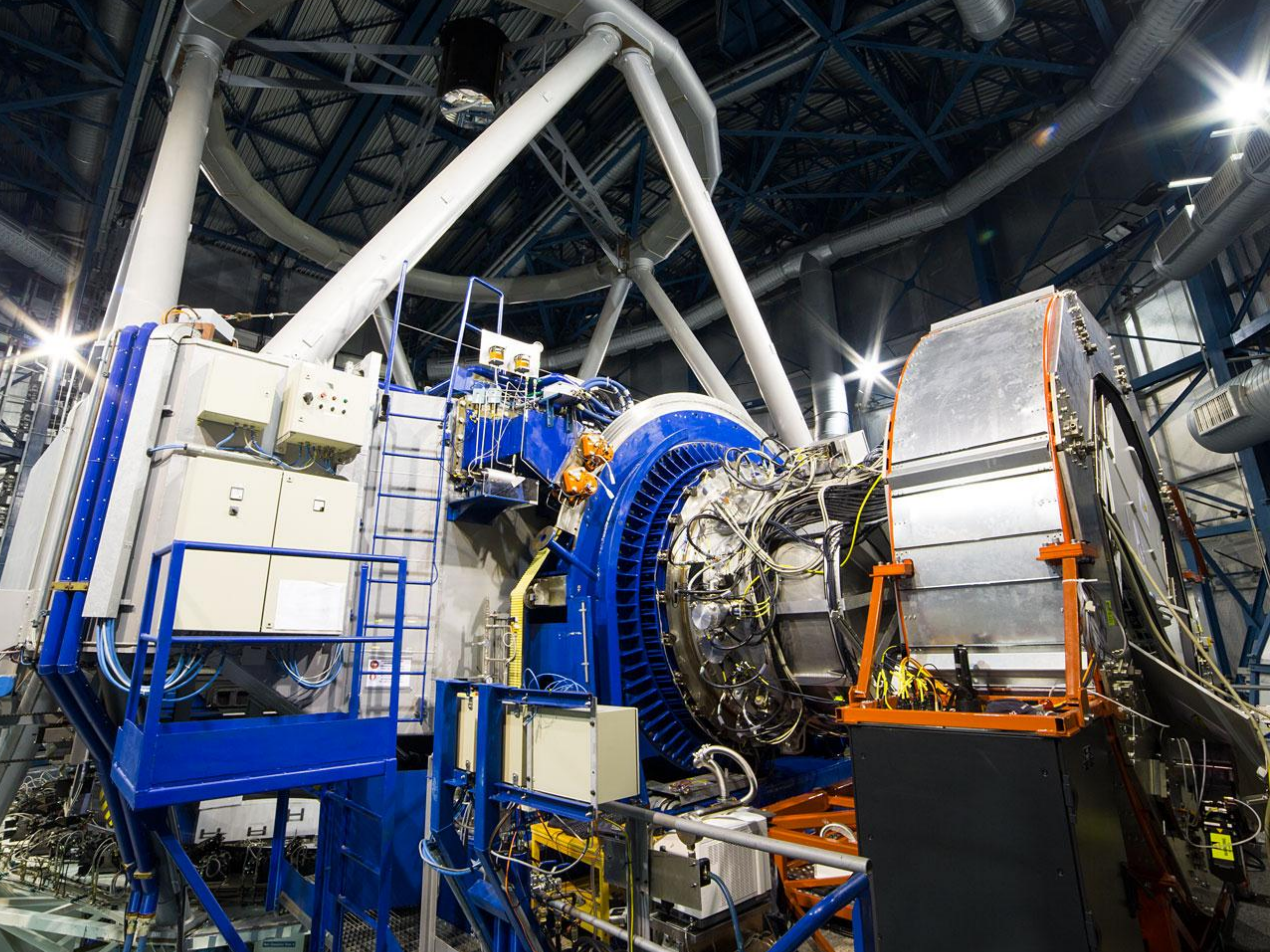
2400 fibers
across 1.3 degree FOV

Multiplexed Near-IR spectroscopy: integral field spectroscopy

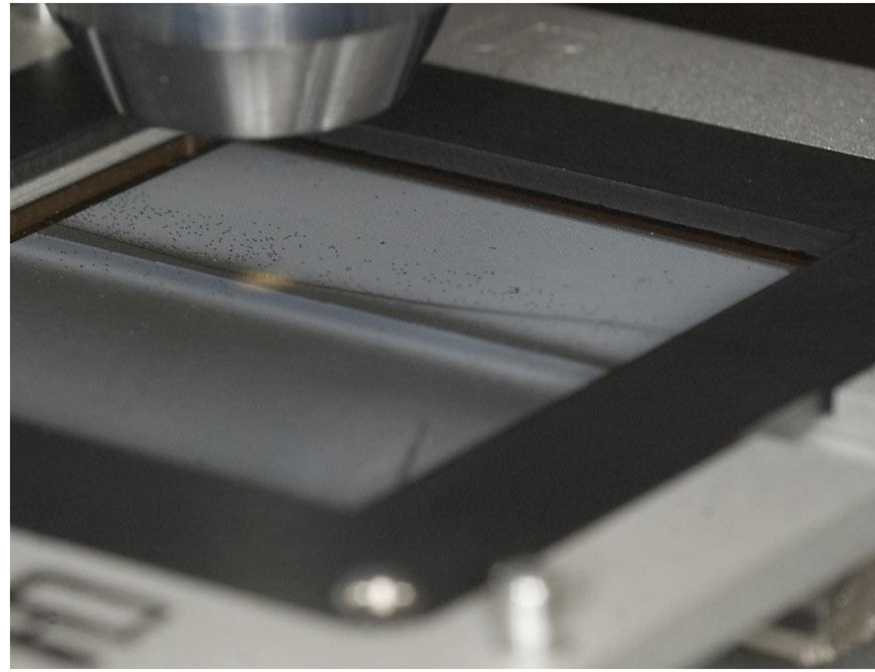


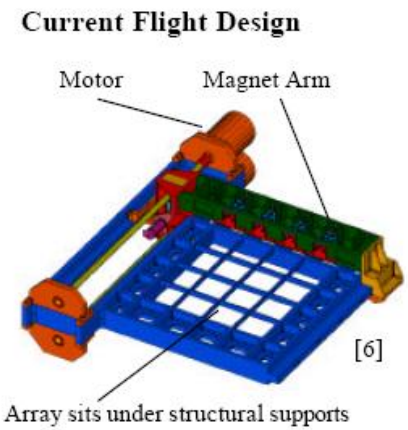


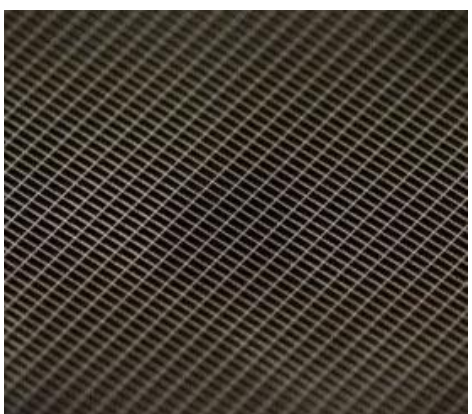
"3D": Weitzel et al. 1994, 1996,
"Tiger": Bacon et al. 1995

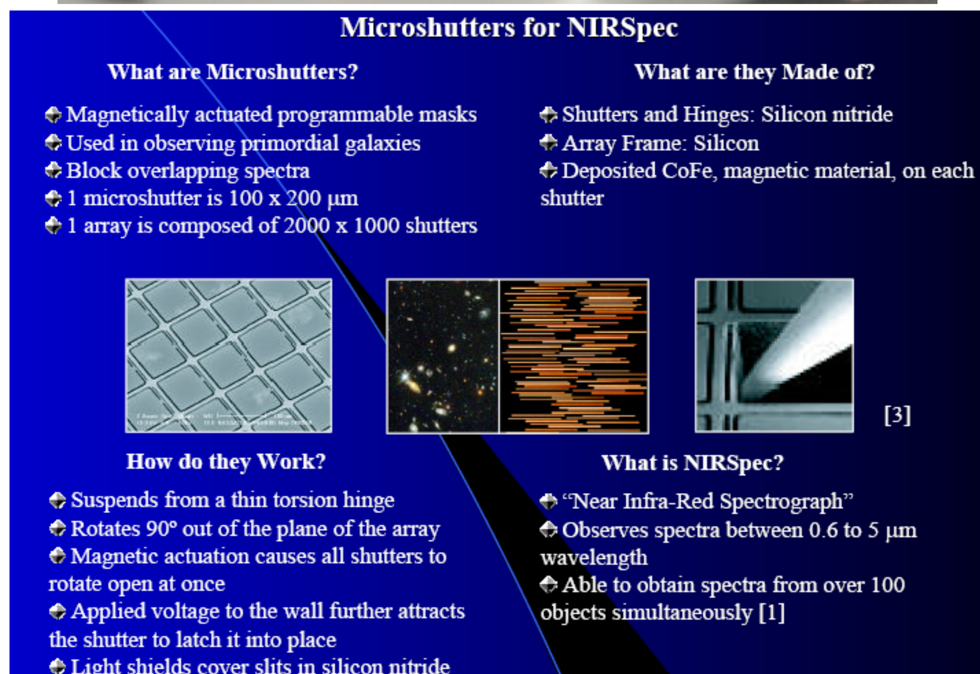


Multi-object spectroscopy: JWST MEMS microshutters





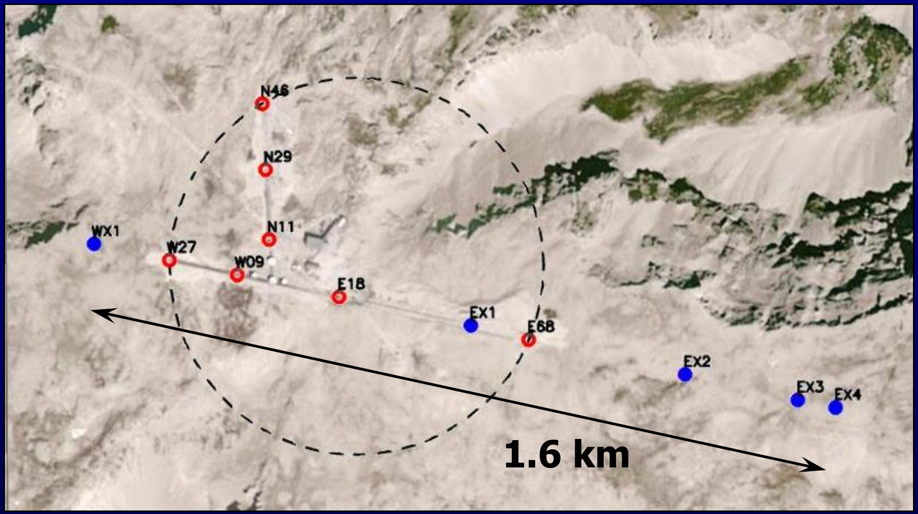




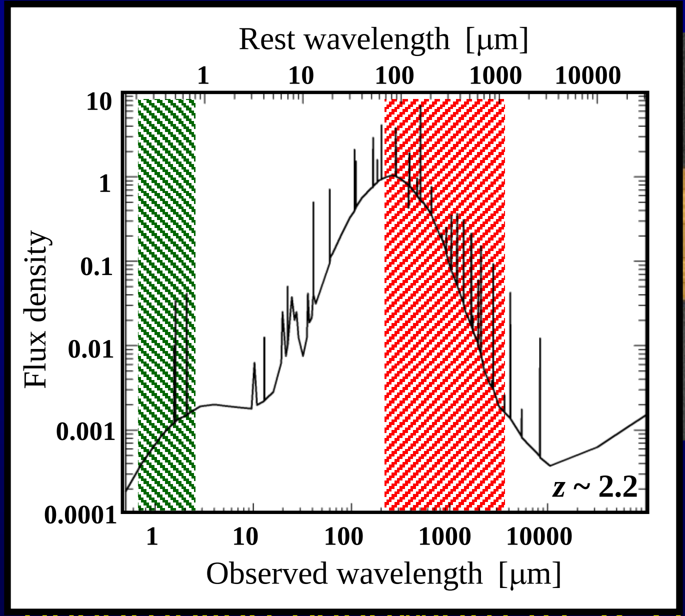
http://www.nasa.gov/centers/goddard/news/topstory/2007/microshutters.html

Millimeter interferometry of cold gas: IRAM Plateau de Bure & NOEMA

doubling the collecting area: 6 ⇒ 12 telescopes



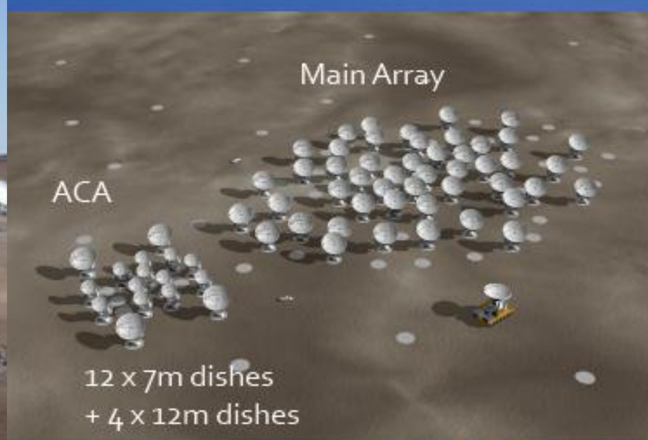
improving resolution by factor ~2 to 0.2″



quadrupling bandwidth to 32 GHz

ALMA

the ultimate mm-interferometer



ALMA (ESO/NAOJ/NRAO)

- Array of 50 dishes with 12 m diameter + ALMA Compact Array (ACA)
- Frequency range 30 – 950 GHz
- (1cm – 0.3 mm)
- High dry site, Chajnantor Plateau (5000m)
- Baselines up to ~14.5 km
- Maximum resolution ~0.005 arcsec
- Continuum & high spectral resolution imaging (R=30,000,000, < 0.05 km/s)
- Wide bandwidth (8 GHz/polarization)
- Full Polarization

currently: 32 12m antennas

factor 10-30 improvement over current capabilities

Sensitivity of mm/submm-interferometry