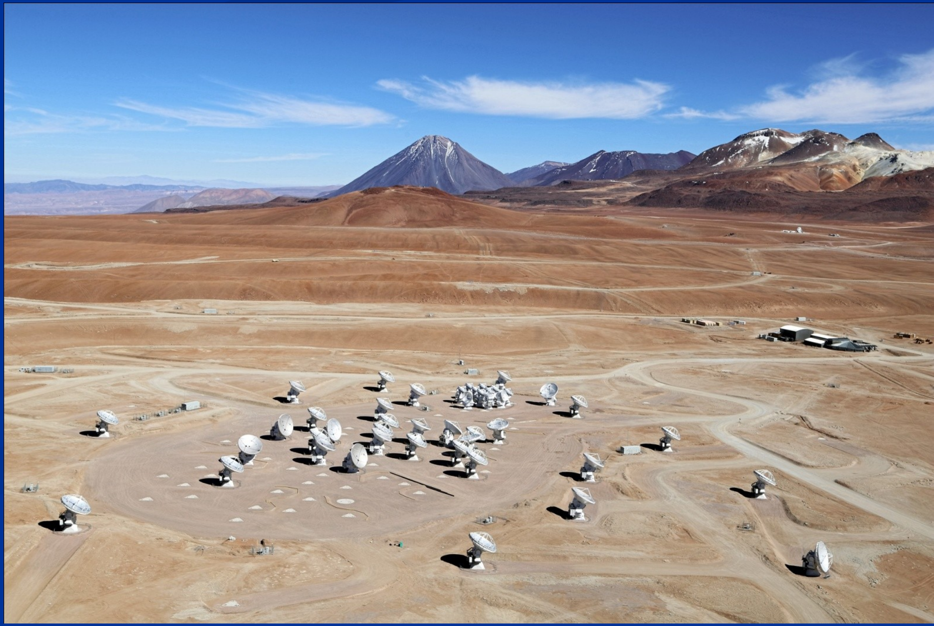
ALMA: Status and 3D Capabilities



Robert Laing
European ALMA Instrument Scientist

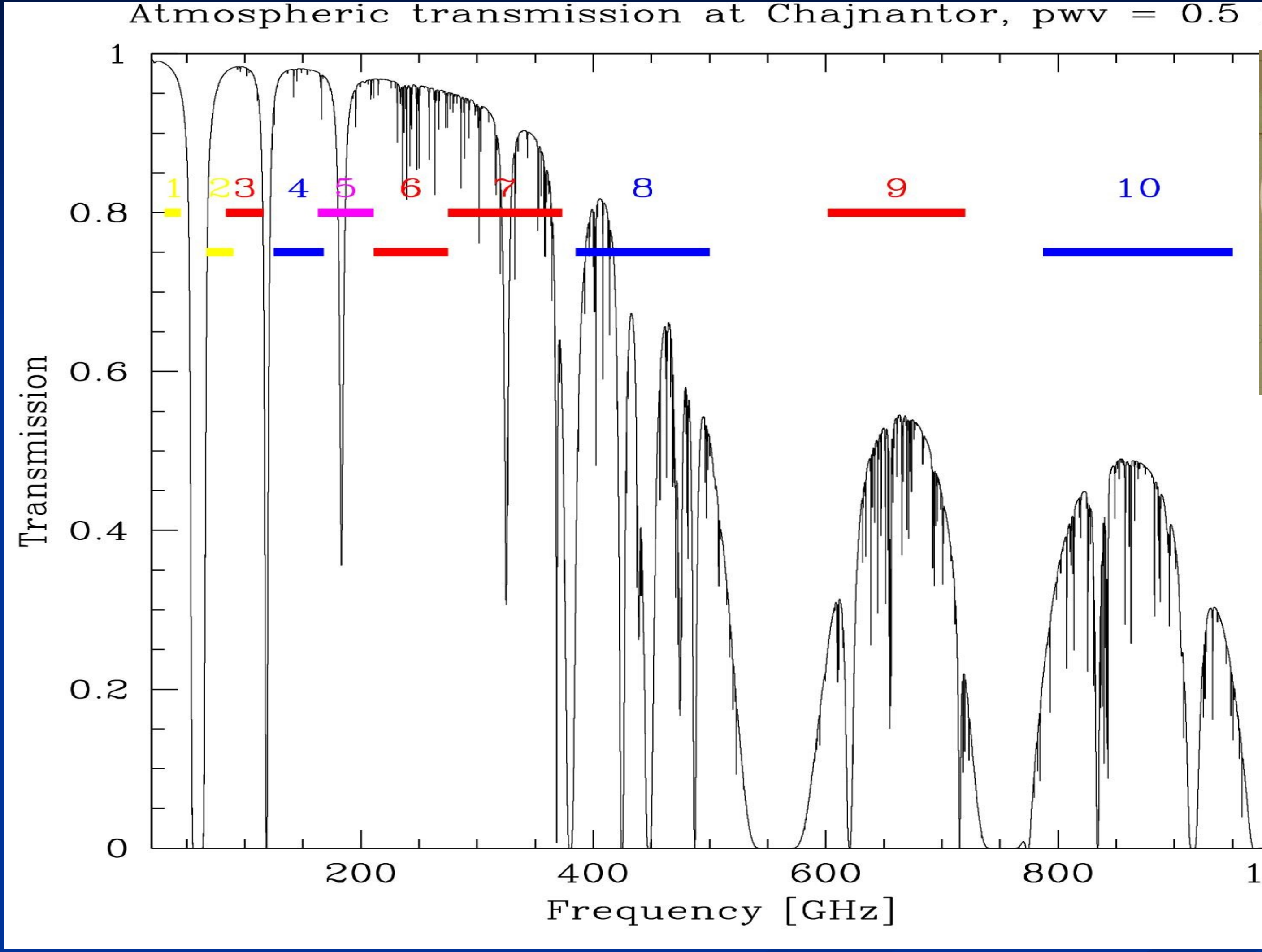
ALMA Basics

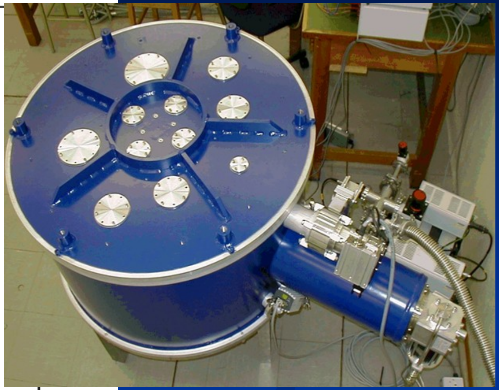
- Aperture synthesis array optimised for wavelengths of 1cm – 0.3mm (35 – 950 GHz)
- **High, dry site**, Chajnantor Plateau, Chile (5000m)
- 54 12m + 12 7m antennas
- Good coverage of the u-v plane (many antennas, Earth rotation) allows high-quality imaging.
- Antenna separations (baselines) from ~15m to 16km
  - Configurations (resolution vs max scale)
- **Sensitive**, wide-band (8 GHz) receivers; full polarization
- **Flexible** digital correlator giving wide range of spectral resolutions.
- (Lots of) **software**

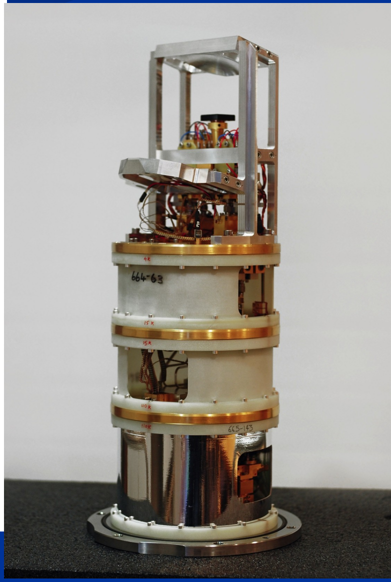
Physical processes

- **Galaxy**, star and planet formation are the key science drivers
- **Temperatures are < at stellar surface – the “Cool Universe”**
- Continuum: thermal emission from dust (scattered emission polarized)
- **Lines: molecular rotational transitions + redshifted atomic**
- Heating via stellar UV, cosmic rays, hard photons from AGN – hence the link to star and galaxy formation
- Non-thermal mechanisms include synchrotron (lower frequencies) and Compton scattering (S-Z).

Receiver Bands







Resolution, maximum scale and field size

More detail in Thomas Stanke's presentation at the ALMA Workshop

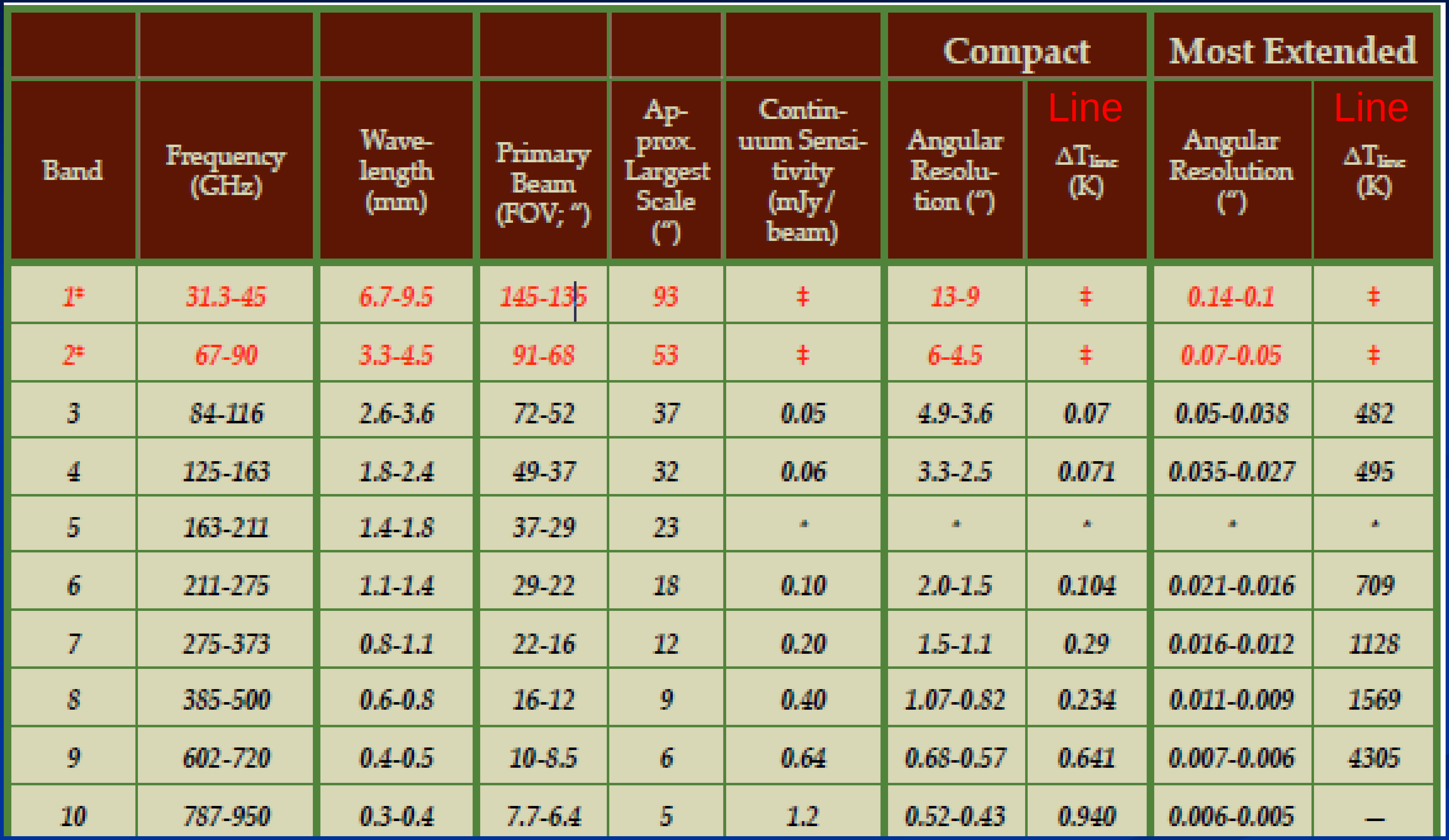
- Some useful parameters:
  - Resolution $\approx \lambda/d_{max}$ rad = 0.2(λ/mm)/(max baseline/km) arcsec
  - Maximum observable scale $\approx \lambda/d_{min}$ rad = 14 (λ/mm) arcsec [15m separation]
  - Field of view $\approx \lambda/D$ rad = 17 (λ/mm) arcsec [12m dish].
  - Sources with all brightness on scales $>\lambda/d_{min}$ are **resolved out** (not detected).
  - Sources with brightness on scales $< \lambda/d_{max}$ are **unresolved**
- To observe big objects and/or wide fields:
  - Mosaic (multiple pointing centres) or on-the-fly
  - Compact Array gives larger field of view (7m antennas) and max scale (smaller d_{min})
  - Total power observations fill in $d_{min} < 12$m.

Noise

- RMS noise level S_{rms}
  - T_{sys} is the system temperature, A_{eff} is the effective area of the antennas, N_A is the number of antennas, $\Delta\nu$ is the bandwidth, t_{int} is the integration time and k is Boltzmann's constant
- For good sensitivity, you need low T_{sys} (receivers, atmosphere), large A_{eff} (big, accurate antennas), large N_A (many antennas). For line work, $\Delta\nu$ is of course set by the desired spectral/velocity resolution.

$$S_{rms} = \frac{2kT_{sys}}{A_{eff}\sqrt{N_A(N_A-1)t_{int}\Delta\nu}}$$

Numbers



						Compact		Most Extended	
Band	Frequency (GHz)	Wave-length (mm)	Primary Beam (FOV; ″)	Approx. Largest Scale (″)	Continuum Sensitivity (mJy / beam)	Angular Resolution (″)	Line ΔT_{line} (K)	Angular Resolution (″)	Line ΔT_{line} (K)
1‡	31.3-45	6.7-9.5	145-135	93	‡	13-9	‡	0.14-0.1	‡
2‡	67-90	3.3-4.5	91-68	53	‡	6-4.5	‡	0.07-0.05	‡
3	84-116	2.6-3.6	72-52	37	0.05	4.9-3.6	0.07	0.05-0.038	482
4	125-163	1.8-2.4	49-37	32	0.06	3.3-2.5	0.071	0.035-0.027	495
5	163-211	1.4-1.8	37-29	23	*	*	*	*	*
6	211-275	1.1-1.4	29-22	18	0.10	2.0-1.5	0.104	0.021-0.016	709
7	275-373	0.8-1.1	22-16	12	0.20	1.5-1.1	0.29	0.016-0.012	1128
8	385-500	0.6-0.8	16-12	9	0.40	1.07-0.82	0.234	0.011-0.009	1569
9	602-720	0.4-0.5	10-8.5	6	0.64	0.68-0.57	0.641	0.007-0.006	4305
10	787-950	0.3-0.4	7.7-6.4	5	1.2	0.52-0.43	0.940	0.006-0.005	–

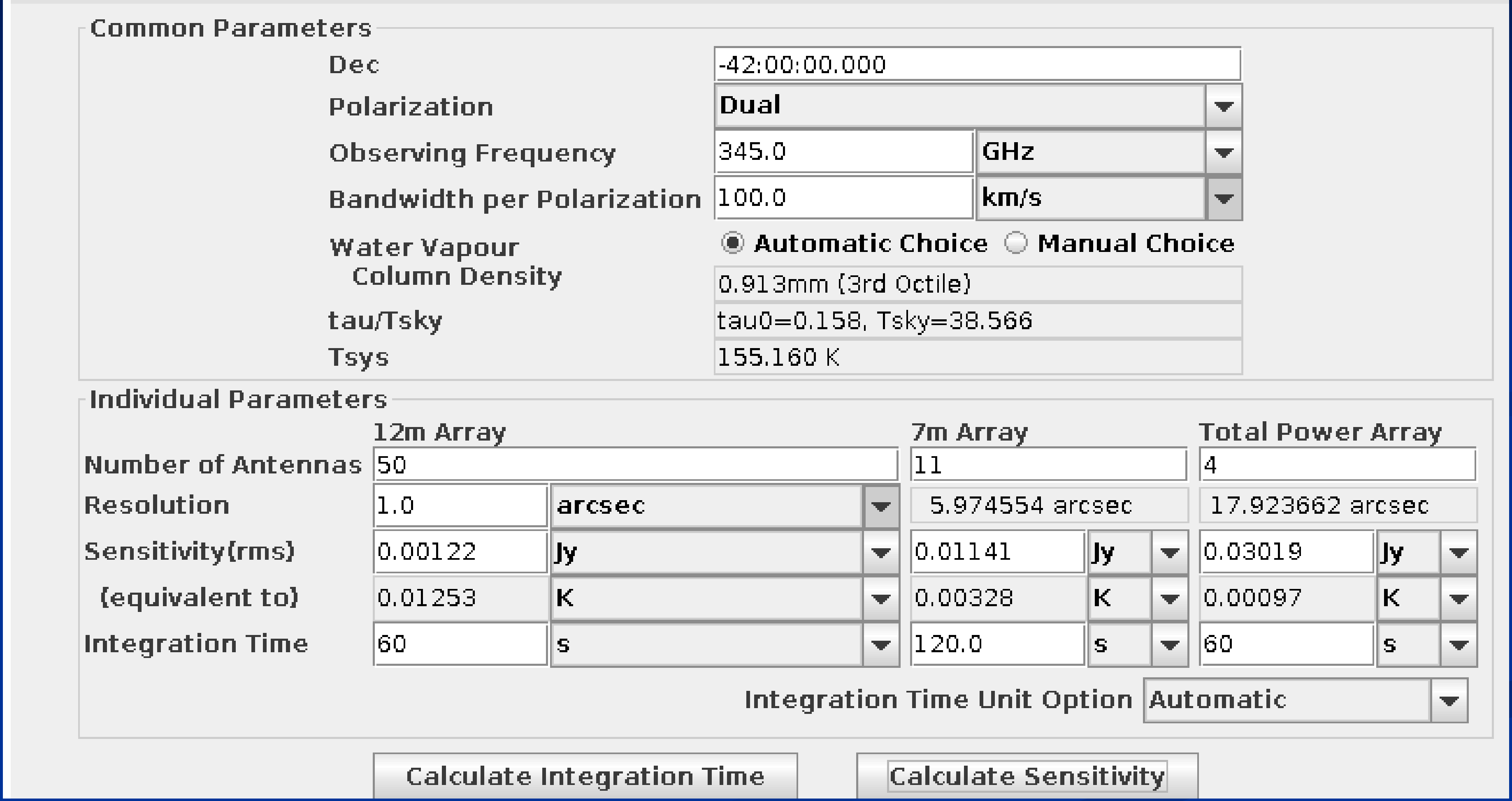
1 minute, 2 polarizations

Continuum 8 GHz; Line 1 km/s

$S/\Omega = 2kT_b/\lambda^2$

Default weather

ALMA Exposure Time Calculator



Common Parameters

Dec: -42:00:00.000

Polarization: Dual

Observing Frequency: 345.0 GHz

Bandwidth per Polarization: 100.0 km/s

Water Vapour Column Density: ● Automatic Choice ○ Manual Choice

0.913mm (3rd Octile)

tau/Tsky: tau0=0.158, Tsky=38.566

Tsys: 155.160 K

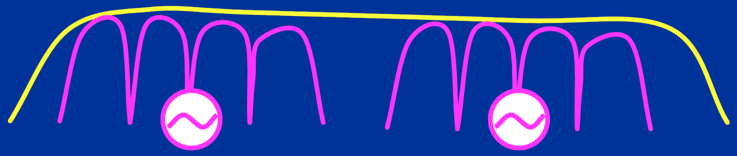
Individual Parameters

	12m Array		7m Array		Total Power Array	
Number of Antennas	50		11		4	
Resolution	1.0	arcsec	5.974554 arcsec		17.923662 arcsec	
Sensitivity(rms)	0.00122	Jy	0.01141	Jy	0.03019	Jy
(equivalent to)	0.01253	K	0.00328	K	0.00097	K
Integration Time	60	s	120.0	s	60	s

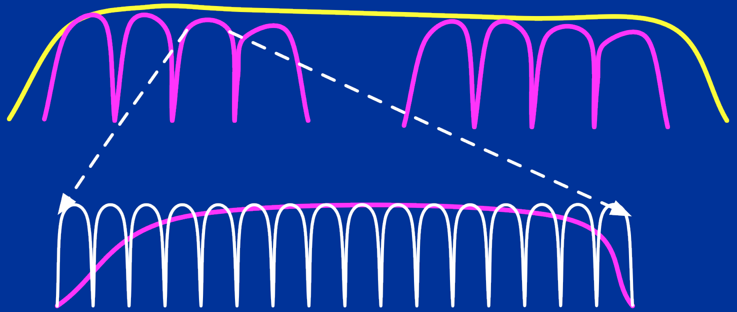
Integration Time Unit Option: Automatic

3D ALMA (1): subdividing the frequency band

Overall receiver response (“passband”)



Subdivide into sidebands and basebands (typically 4 GHz and 4 x 2 GHz for ALMA)



Subdivide basebands into sub-bands using digital filters

3D ALMA (2): making the spectral channels

- We make multiple channels by correlating with delays introduced into the signal from one antenna with respect to another. For each quasi-monochromatic frequency channel, a lag is equivalent to a phase shift $2\pi\tau\nu$, i.e.

$$V(u,v,\tau) = \int V(u,v,\nu)\exp(2\pi i\tau\nu)\,d\nu \quad \text{[V is visibility]}$$

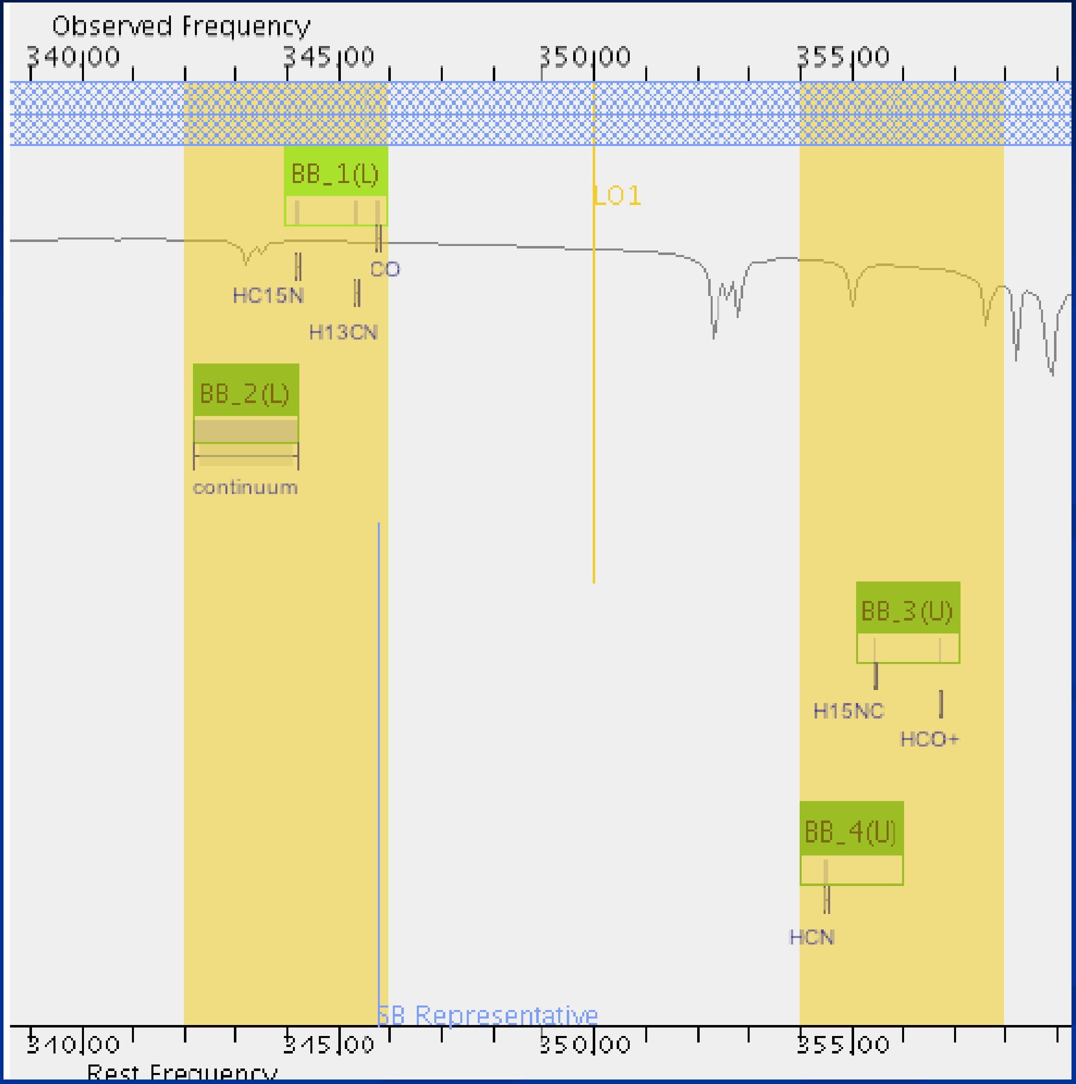
- This is a Fourier transform relation with complementary variables ν and τ, and can be inverted to extract the desired visibility as a function of frequency.
  - Compact Array Correlator works somewhat differently, but gives almost the same spectral response
- In practice, we do this digitally, in finite frequency channels:

$$V(u,v,j\Delta\nu) = \Sigma_k\, V(u,v,\, k\Delta\tau)\, \exp(-2\pi ijk\Delta\nu\Delta\tau)$$

ALMA spectral setups

- 4 x 2 GHz basebands
- Maximum 8192/N_{pol} channels per baseband
- Wideband mode with full bandwidth (TDM)
- For line work, subdivide each baseband into up to 32 independently-tunable sub-bands of 62.5 MHz (some special modes 31.25 MHz) – FDM mode
- Allocate channels flexibly to sub-bands → max spectral resolution 3.86 kHz
- Complications:
  - Sub-band edges not used, so fewer channels available in practice
  - Quantization, sampling, smoothing, ...

A Cycle 2 example



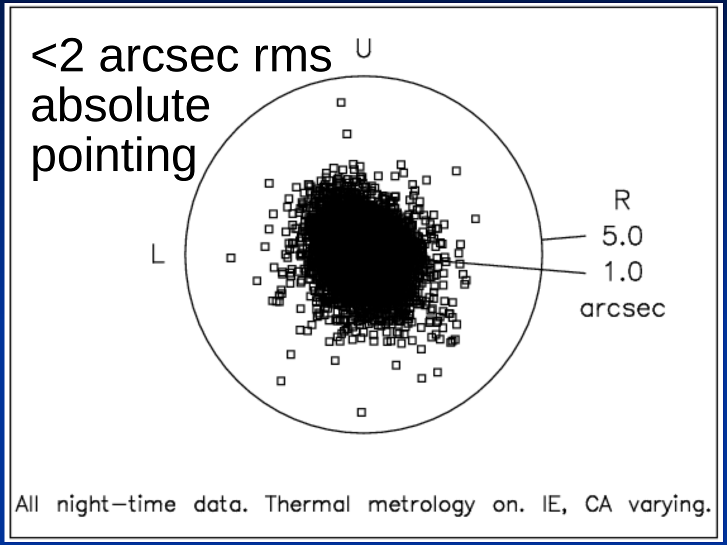
This may all seem rather complicated ....

... but the ALMA staff will always provide help if you need it

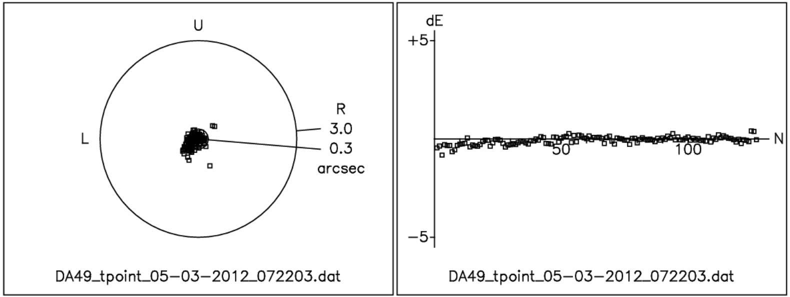
Construction Status

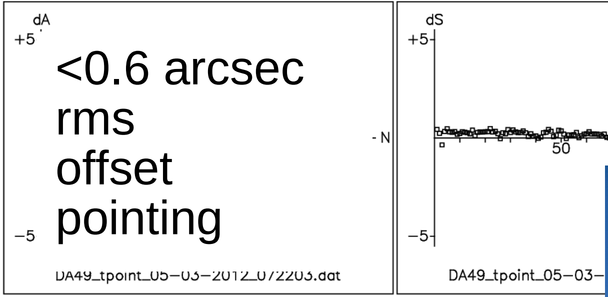
- Antennas: All 66 delivered; 62 at 5000m site
- All have Bands 3, 6, 7, 9. Bands 4, (5), 8, 10 arriving.
  - Band 8 and 10 deliveries complete by end 2014
- Both correlators complete
- Full sets of almost all key components
- Permanent power supply operational
- Inner pads fully ready
  - More distant pads becoming available
- Residencia contract under negotiation

Antenna Performance

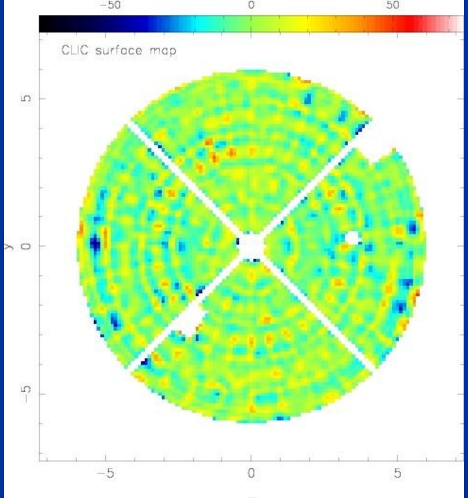


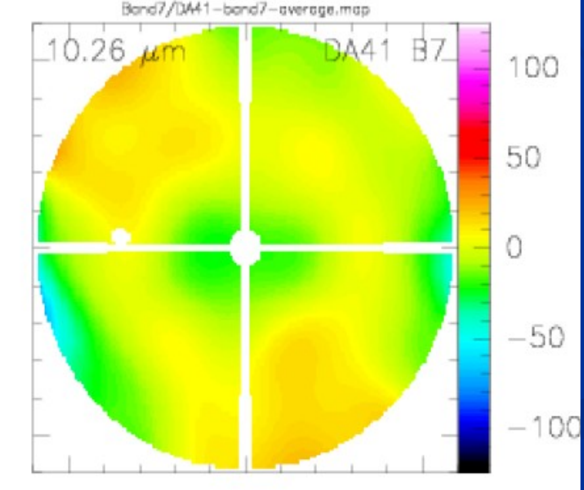
<2 arcsec rms absolute pointing





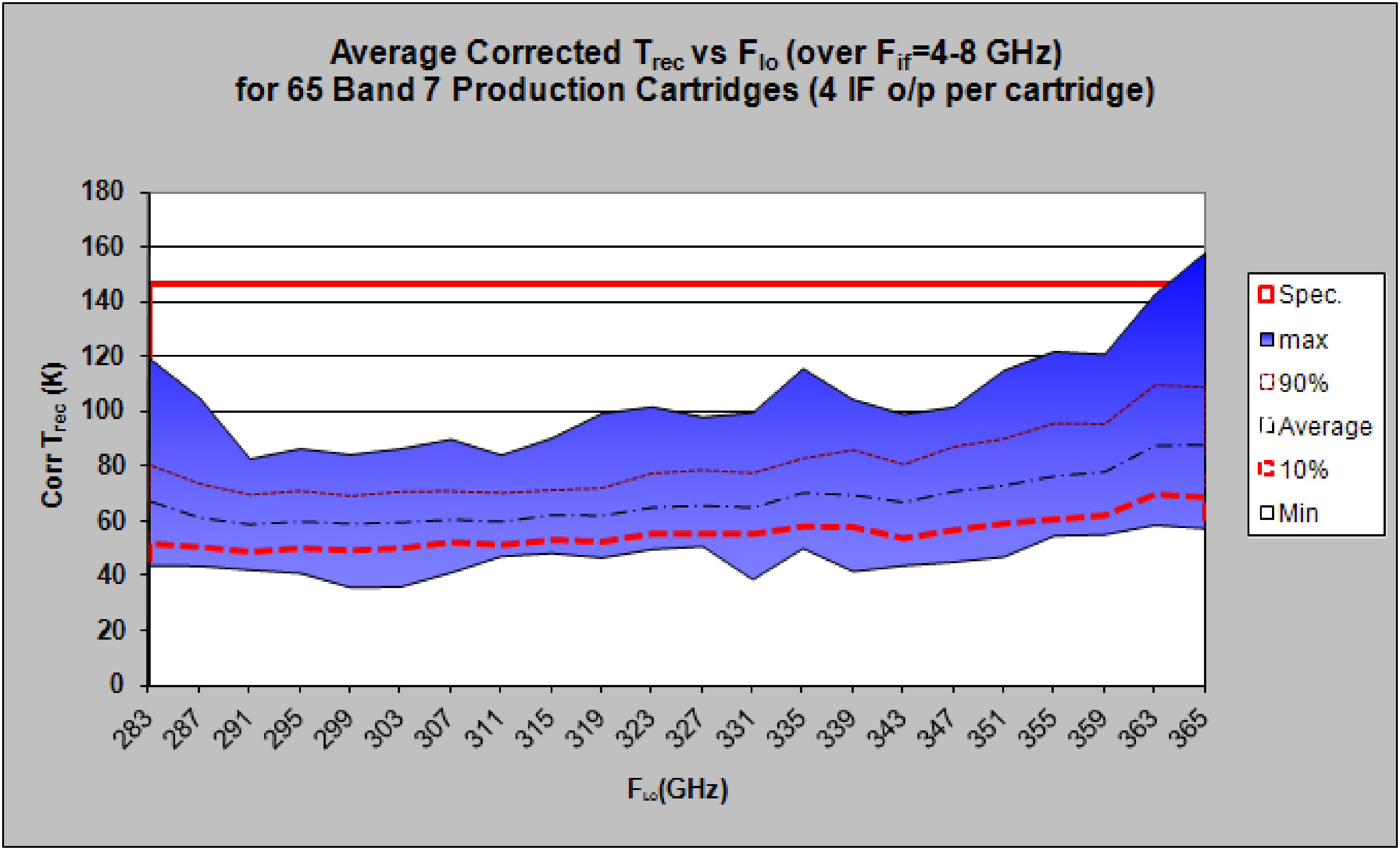
<0.6 arcsec rms offset pointing





<25 µm rms surface accuracy

Band 7 receiver performance (IRAM)



Noise temperatures a factor of 2 better than specification

Operations Status

- Cycle 1: issues caused by infrastructure, weather, speed of restart after down-time, etc., caused serious delays to the effective start of the Cycle
- However, observations are now being taken routinely

Cycle 2

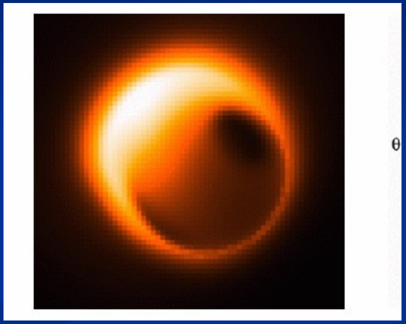
- June 2014 – October 2015
- Capabilities
  - 34 12m antennas in Main Array; 9 7m antennas in Compact Array; 2 12m antennas for total power
  - Receiver bands 3, 4, 6, 7, 8, 9
  - Single-field interferometry + mosaics with up to 150 pointings per science goal
  - Small-field linear polarization (bands 3, 6, 7; continuum)
  - Spectral scans (up to 5 tunings)
  - Mixed (high and low spectral resolution) correlator modes
  - Baselines up to 1.5 km (3, 4, 6, 7) or 1 km (8, 9)
- Proposal review ongoing

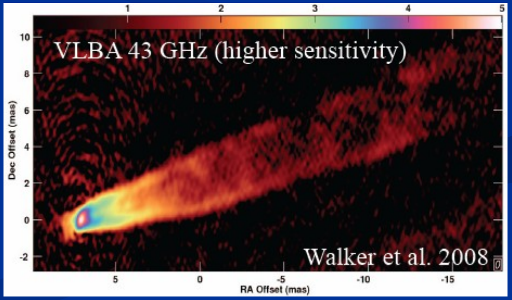
Prospects for Cycle 3 (Preliminary!)

- Possible new capabilities
  - Long baselines: 5 - 10 km; to be tested in Sept – Nov 2014; max baseline offered likely to be a function of frequency
  - Requires band-to-band phase transfer, optimized WVR correction
  - Band 10; 90 deg phase switching for sideband separation in Bands 9 and 10
  - Polarization: spectral resolution; linear and circular (wider fields)
  - Additional single-dish modes
  - First Solar modes
  - 40 12m, 10 7m, 3 total power antennas
- Likely shift to shorter (~1 year) cycles

Current Development Projects

- Band 5 (167-211GHz) full production
  - water in the nearby Universe; [CII] from the EoR
  - NOVA/Chalmers/NRAO (2013-2017)
- Fibre connection OSF – Santiago
- Artificial source (polarization, holography)
- ALMA phasing project/VLBI
  - MIT Haystack/NRAO/MPIfR/OSO/NAOJ/ASIAA/...
  - Image the event horizon around the Sgr A* black hole and resolve the jet-formation zone in M87
- Band 1 (35 – 52 GHz)
  - evolution of dust in protoplanetary disks
  - CO(3-2) in EoR, ...
  - led by ASIAA; approved to prototype; PDR passed





Science

- Heavily oversubscribed
  - ~9:1 in time, Cycles 0, 1, 2
- Many results in published papers
  - telbib.eso.org (telescope = ALMA)
  - High-z, Disks, ISM, Star Formation, Local Universe, Solar System, Stellar Evolution, Supernovae, Cosmology, Fundamental Physics

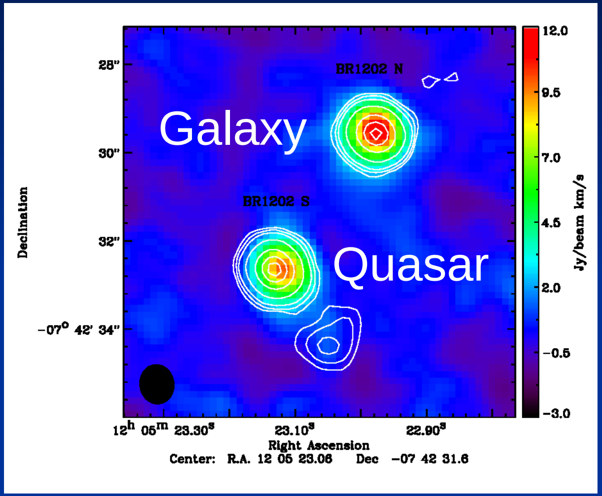
Gas in Galaxies: Disks and Outflows

Gas disk in Cen A

LABOCA 870µm + Chandra X-ray
+ optical (WFI)

ALMA SV CO (2-1) + JKH
(Espada et al. 2012, Espada 2013)

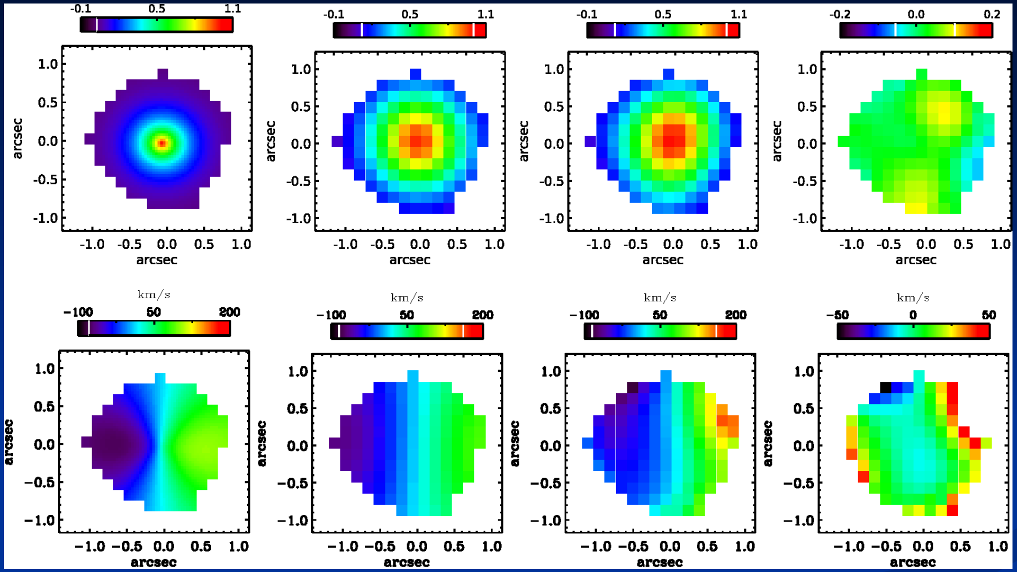
Star-forming rotating disks at z = 4.7



[CII] integrated intensity

BR 1202-0725
[CII]
ALMA SV data

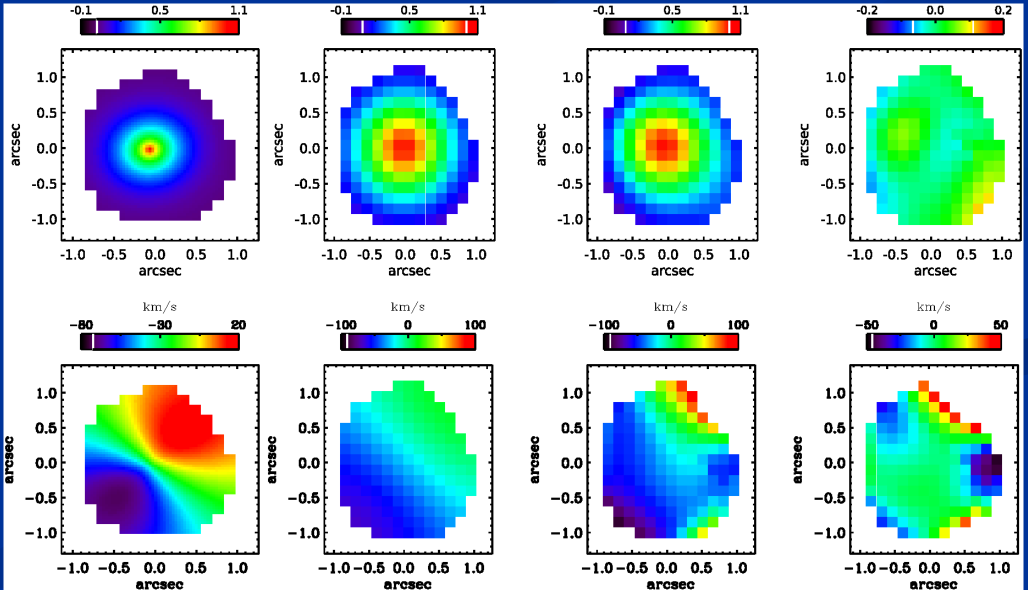
Carniani et al. (2013)



Intensity

Velocity

Model Convolved Obs Residual



Intensity

Velocity

Gas disks in quasar host galaxies at z ~ 6?

Wang et al. (2013)

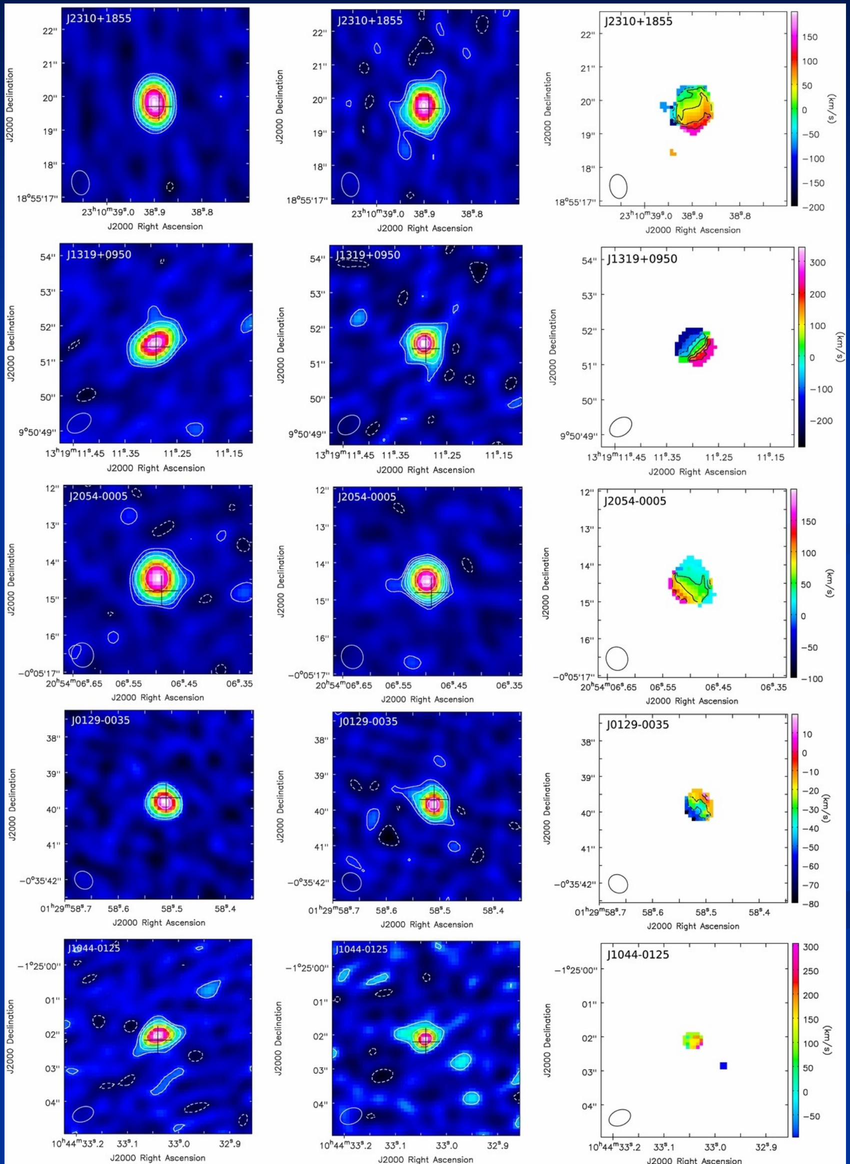
Left: dust continuum

Centre: [CII] 158μm (integrated)

Right [CII] velocity field

If rotation (not unique) then dynamical masses are $10^{10} - 10^{11}$ M_{Sun}

Implied black hole masses 10x above local BH – bulge relation

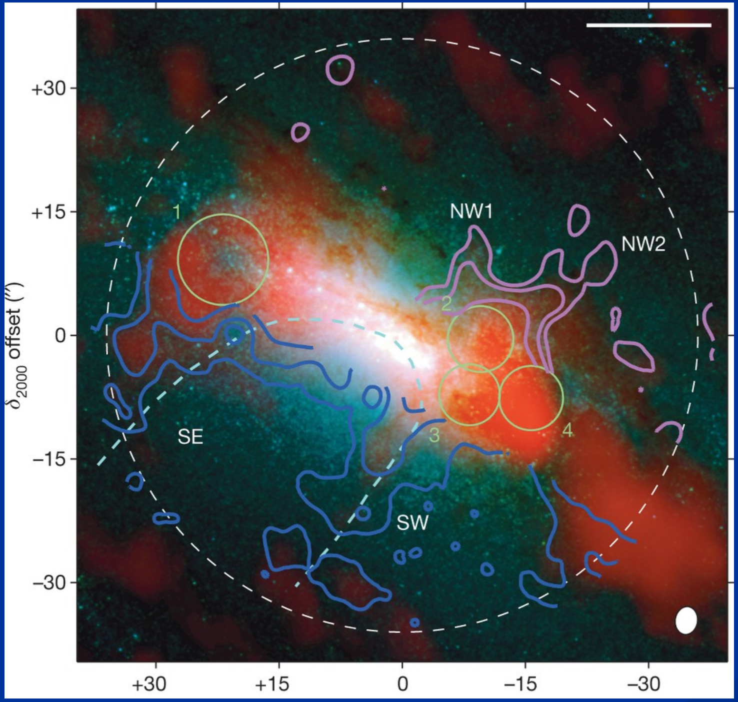


Suppression of star formation by a starburst-driven molecular outflow

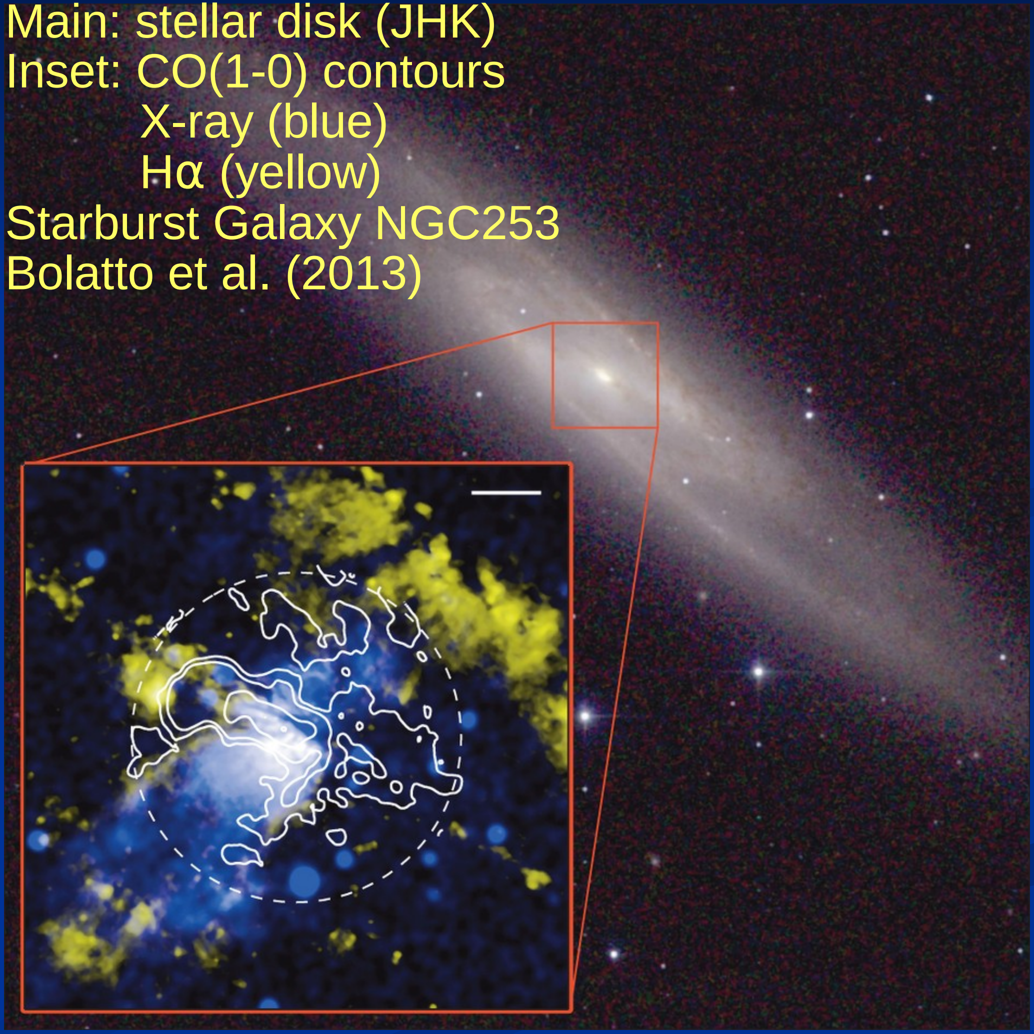
Blue contours: approaching CO
Magenta contours: receding CO

Red: integrated CO; blue: J; green H.

Molecular outflow rate $\sim 9 M_{Sun}$/yr



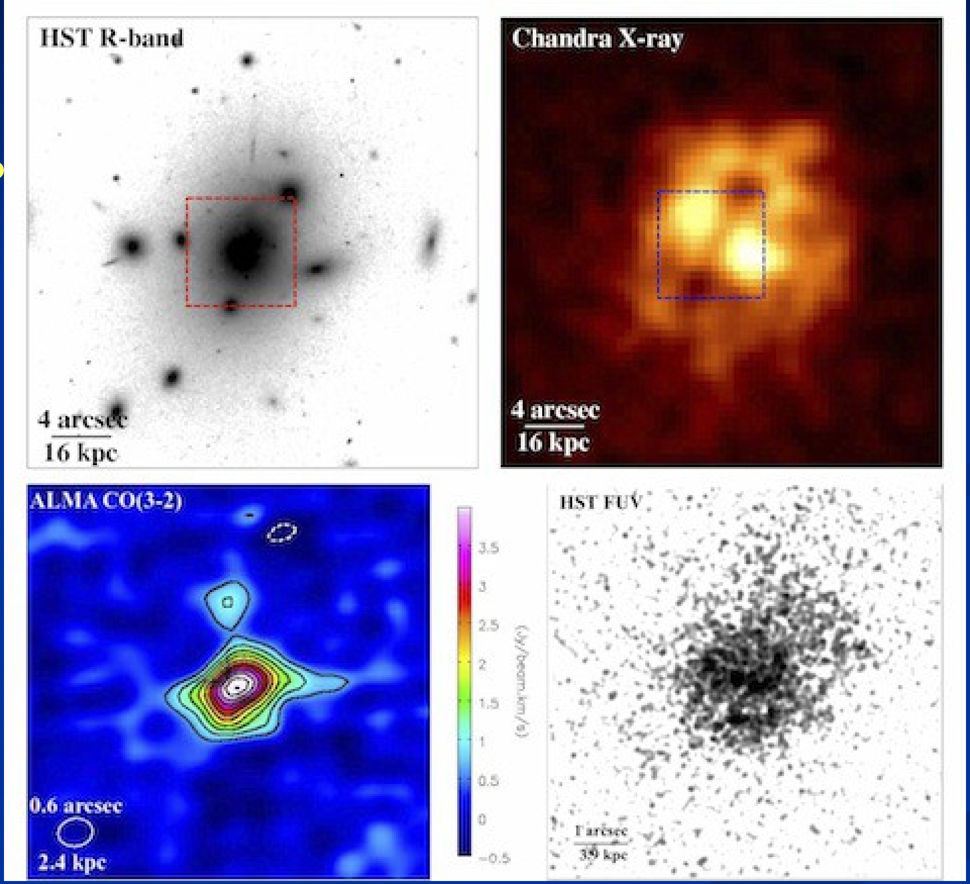
Main: stellar disk (JHK)
Inset: CO(1-0) contours
X-ray (blue)
Hα (yellow)
Starburst Galaxy NGC253
Bolatto et al. (2013)

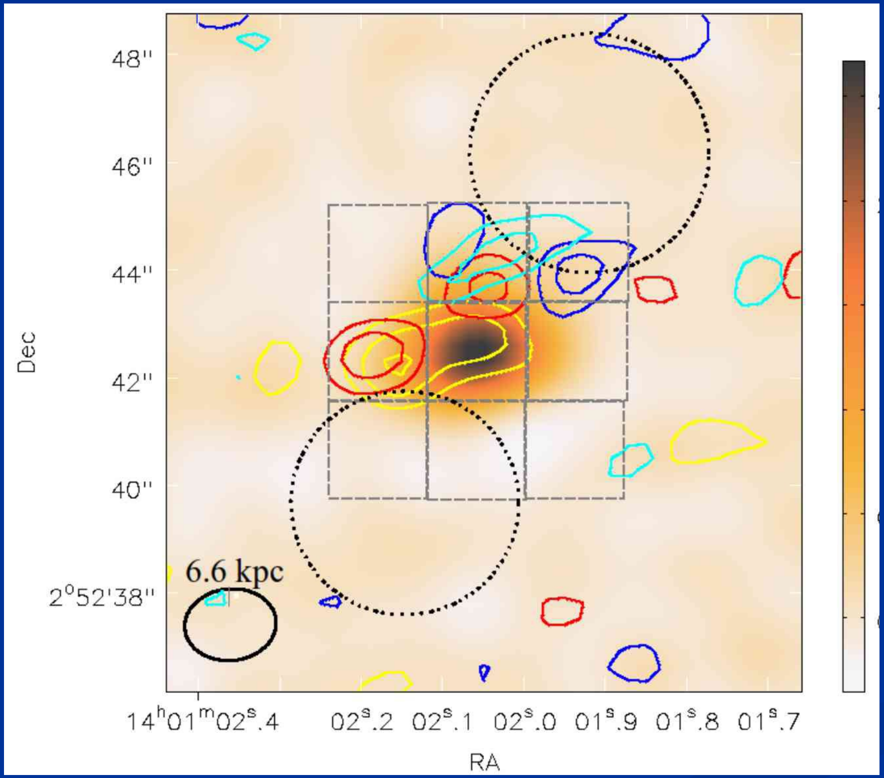


AGN-driven outflow in a BCG

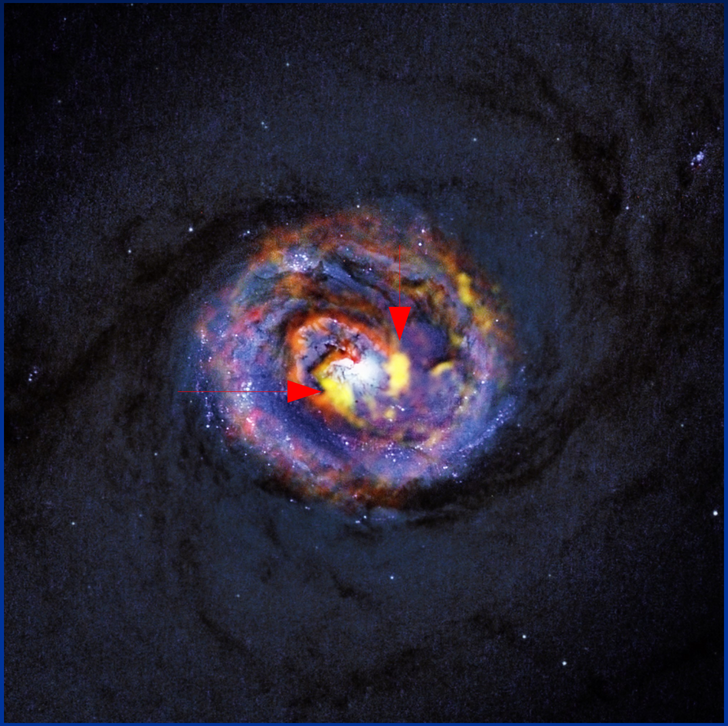
BCG in Abell 1835
McNamara et al. (arXiv 1309:0013)

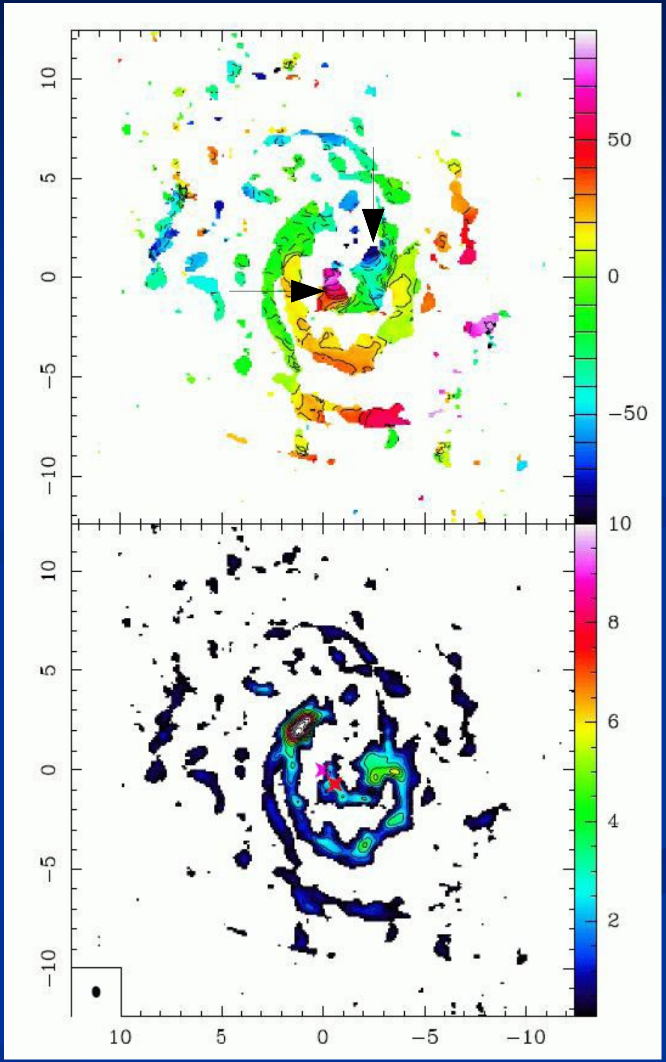
Molecular gas pulled up by rising bubbles?





Disk and feedback in a nearby Seyfert Galaxy





CO(3-2)
velocity

Integrated
intensity

Seyfert 2 Galaxy NGC1433
(Combes et al. 2013)

Intense, high-velocity blue- and redshifted features near the nucleus: outflow ~7 M_{Sun}/yr

Lots still to do, but ALMA works