Increasing the Collecting Area of ALMA in the 2030s

Photo credit: Pablo Carillo (ALMA)

Todd Hunter & Crystal Brogan
(NRAO-CV / NAASC)

Cost for more collecting area is beyond scope of the normal ALMA Development program. Requires major investment from all partners. (Target: ASTRO 2030).

Science motivations for more collecting area

- from Astro2020 white papers and recent ALMA results

How to achieve more collecting area:

- More antennas! (better sensitivity and image fidelity for all)
- Focal plane arrays (more limited use cases)

Impacts

- Correlator design
- Operational concerns (power)
- Operational opportunities (flexibility)

Science Motivations from Astro2020 White papers

Expressing the need for <u>significantly</u> more spectral sensitivity (x3 to x5):

Oberg+: **Astrochemical Origins of Planetary Systems** (disk mid-plane, terrestrial zone, H_2O, organics)

Cleeves+: **Realizing the Unique Potential of ALMA to Probe the Gas Reservoir of Planet Formation**

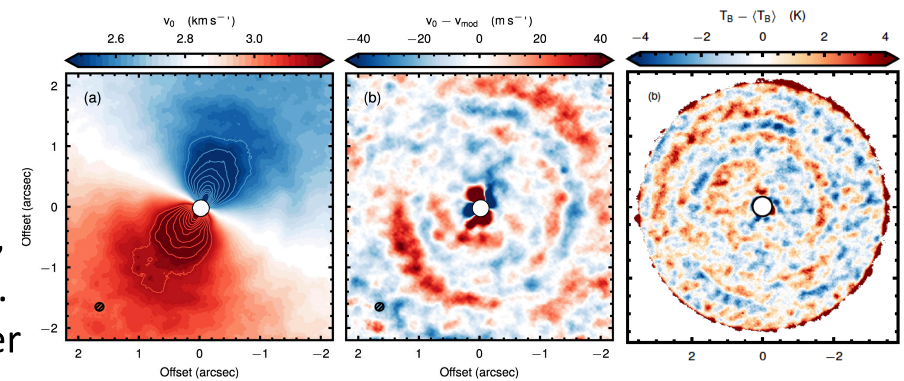
Brogan+: **A Science-Driven Vision for ALMA in the 2030s** (cites dozens of other WPs)

Such large gains of 3-5x in sensitivity are not feasible from receiver improvements and digital processing improvements alone. <u>More collecting area is essential!</u>

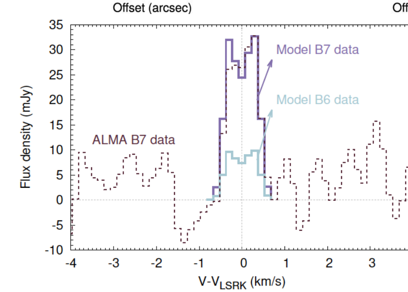
Why a factor of 5?

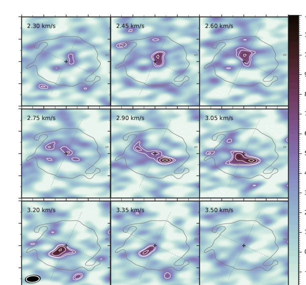
Currently, ALMA can barely detect:

- Kinematic evidence for protoplanets inducing spirals in CO emission in nearest disk (TW Hya, Teague+ 2019) at 54 pc with <u>6.6 hrs</u> on source. Need to reach Taurus at 140pc, i.e., 6.7x fainter



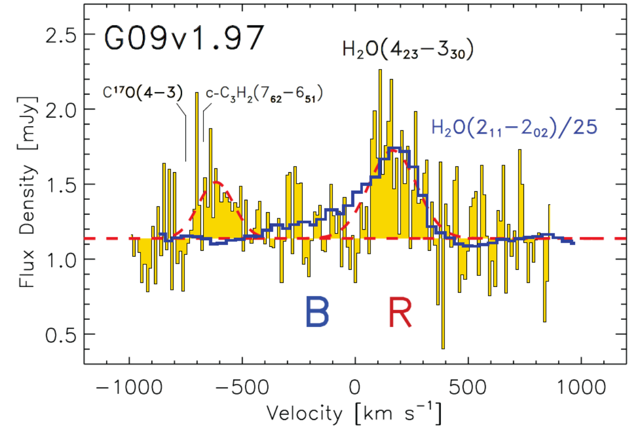
- Methanol: pre-cursor molecule of complex organics in nearest disk (Walsh+ 2016) was detected at only <u>5 sigma</u> by stacking 3 lines of in Band 7 (<u>2 hours equivalent</u>) in 350m config

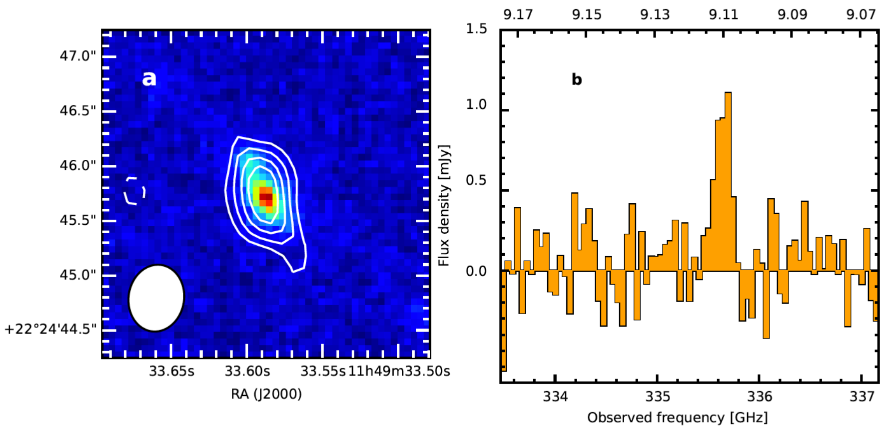




Science Motivations from high redshift universe

First high-redshift (z=3.63) detection of 448 GHz H_2O line (pumped by strong FIR emission, E_{Lower}=410K)
5 sigma after 2 hours on source in Band 3, 200m config. Coming from lensed 100-pc nucleus of a starburst galaxy (Yang+ 2020)





Earliest star formation: 88 um OIII (z=9.1) detection of MACS1149-JD1 at 5 sigma with 2 hrs (4.5 hrs counting all tunings) in Band 7, in 500m config (Hashimoto+ 2018, Nature)

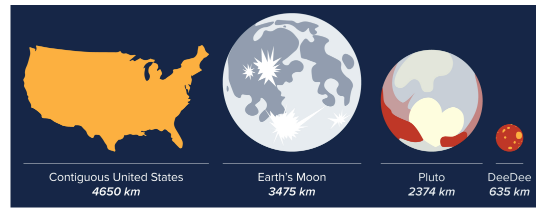
Motivations from our Solar System

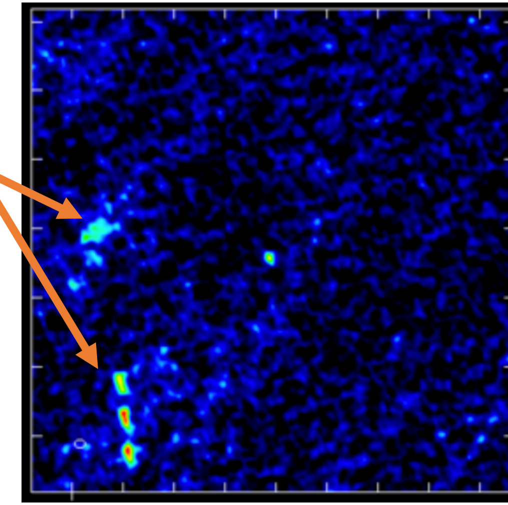
Trans-Neptunian Object “DeeDee” at 92 au (2nd most distant) detected in continuum at 7 sigma with 3 hours on source

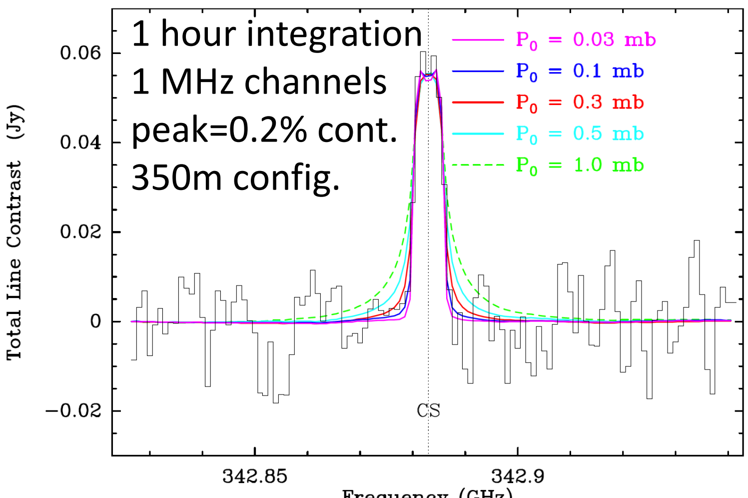
Band 6, 1.4km configuration

Yields size=635km (Gerdes+ 2017)

A submm galaxy is flying past over the course of 2 nights!







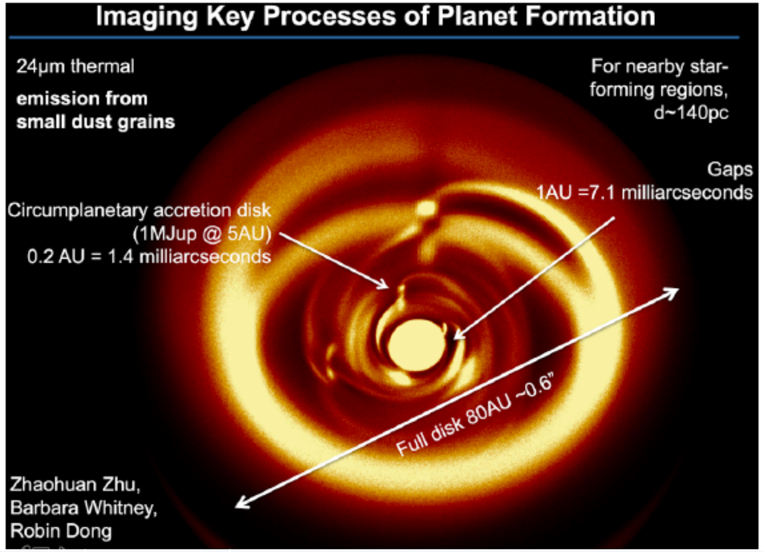
Moreno+ 2017: Neptune: First unambiguous detection of a sulfur-bearing species in a giant planet beyond Jupiter (CS 7-6, τ<<1)

At this SNR (7), can only constrain vertical profile to heights where P_0 < 0.5 mbar, much higher than CO’s lowest extent. Challenges the common-origin theory of a comet-impact ~1000 yr ago

Science Motivations from ALMA 2030 Roadmap

Additional antennas are mentioned in context of Longer Baselines:

"The Working Group assumed that at least six additional antennas, permanently stationed on new pads, would be needed to provide minimal u,v coverage on the longest baselines."



- Upgrading ALMA's resolution to <1 AU is also highlighted in Astro2020 WP by John Monnier et al.: **Imaging the Key Stages of Planet Formation**
- However, 6 antennas is not much increase in collecting area; and it would only benefit a fraction of ALMA science.
- For greater impact, we need more collecting area and have it available on more angular scales.

Feature	Scale	Methods
Overall Disk	80 au	mm-wave (**ALMA**); Coronography on 8m+ telescopes; JWST
Large gaps and Structures	5-20 au	mm-wave (**ALMA**); Radio (ngVLA); Coronography on 8m+ telescopes; JWST
Terrestrial Planet Zone	< 4 au	30m telescope; IR interferometry (CHARA, VLTI, MROI)
Gaps and accretion streams from individual planets	< 1 au	mm-wave (**ALMA**); 30m telescope; IR interferometry (CHARA, VLTI, MROI)

The ALMA2030 Vision: Design Considerations f

How much more area can we imagine building?

Recognizing that antennas and their contents are costly to build <u>and</u> power….

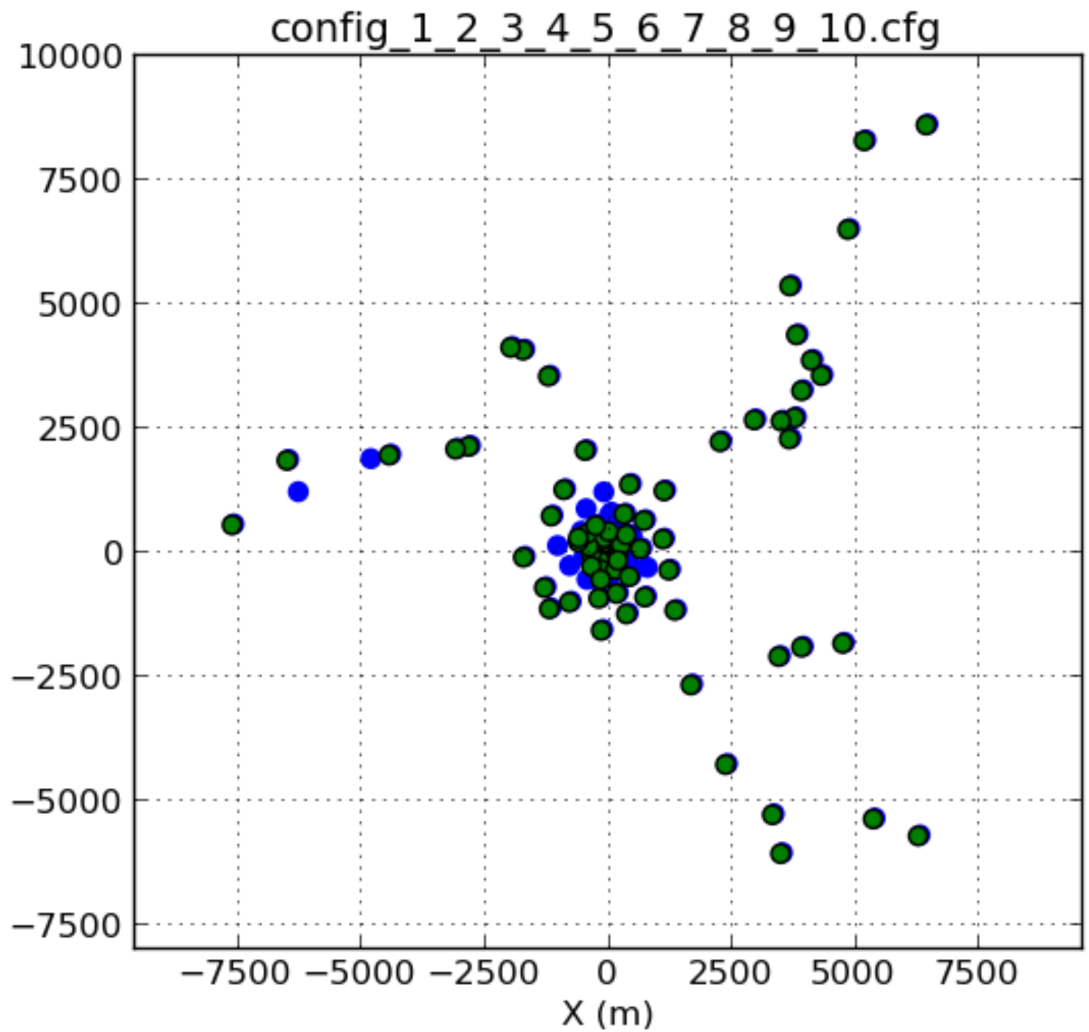
Desired increase in collecting area	Reduction in integration time for equivalent SNR	Extra antennas needed	
		if D=12 m, 25 um rms, all bands	if D=18 m, 40 um rms, bands 1-7 only
x 2	4	50*	27*
x 1.41	2	20*	11*

*If you cannot (or will not) move these antennas, then you need a <u>factor of 2 more</u> to realize equal improvement on <u>all spatial scales</u>.

There are plenty of pads: 192

- **145 of 170 non-ACA pads are routinely used**
- **the notional 12m configs use only 124**

Normal linear display
spiral pattern is apparent but inner pads are not distinguishable

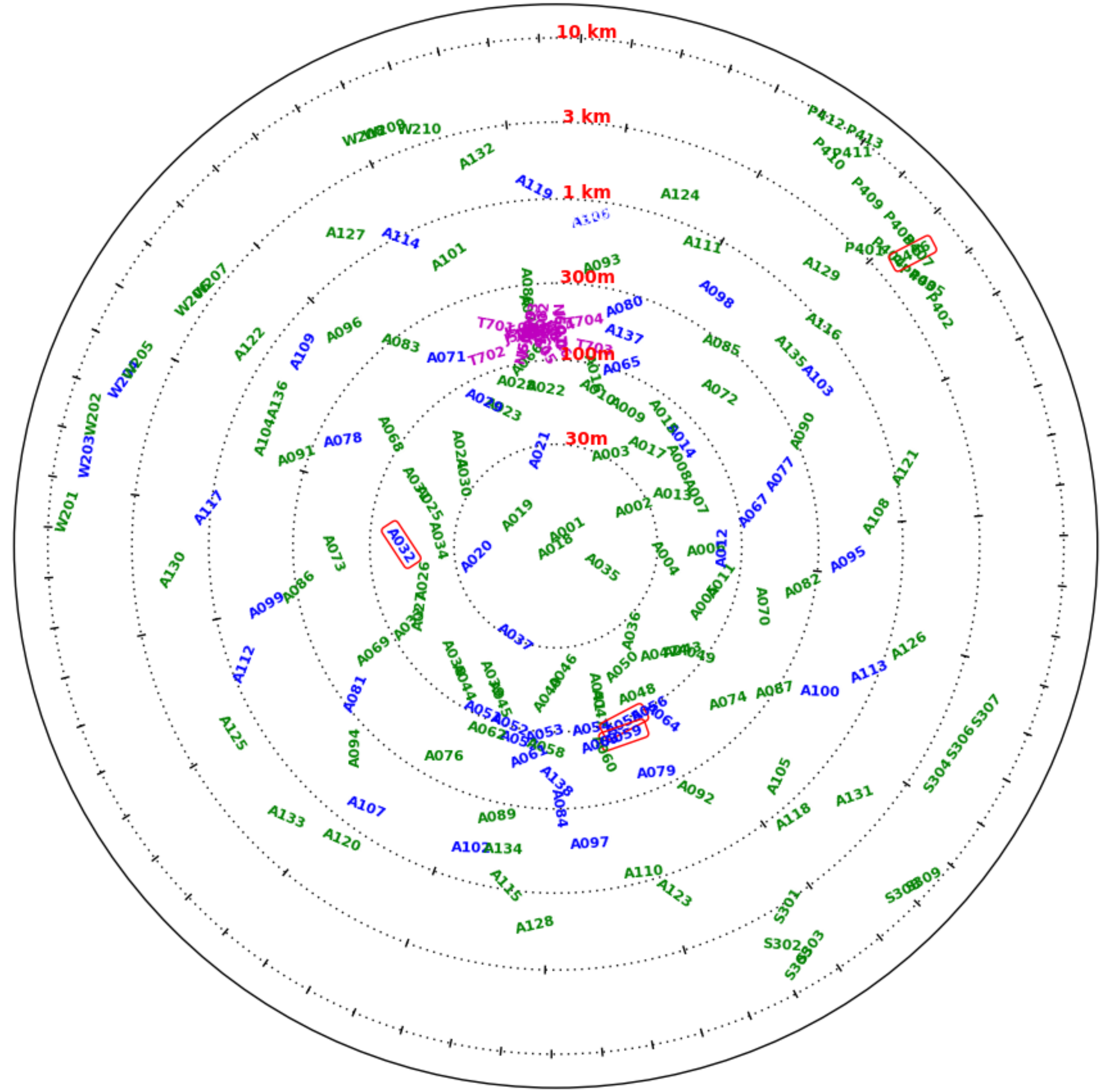


There are plenty of pads: 192

- **145 of 170 non-ACA pads are routinely used**
- **the notional 12m configs use only 124**

Radially-logarithmic display with orientation of name labels pointing to nearest neighbor (to show the spiral pattern better)

Only 4 pads have never been occupied:
A032, A055, A059, P406

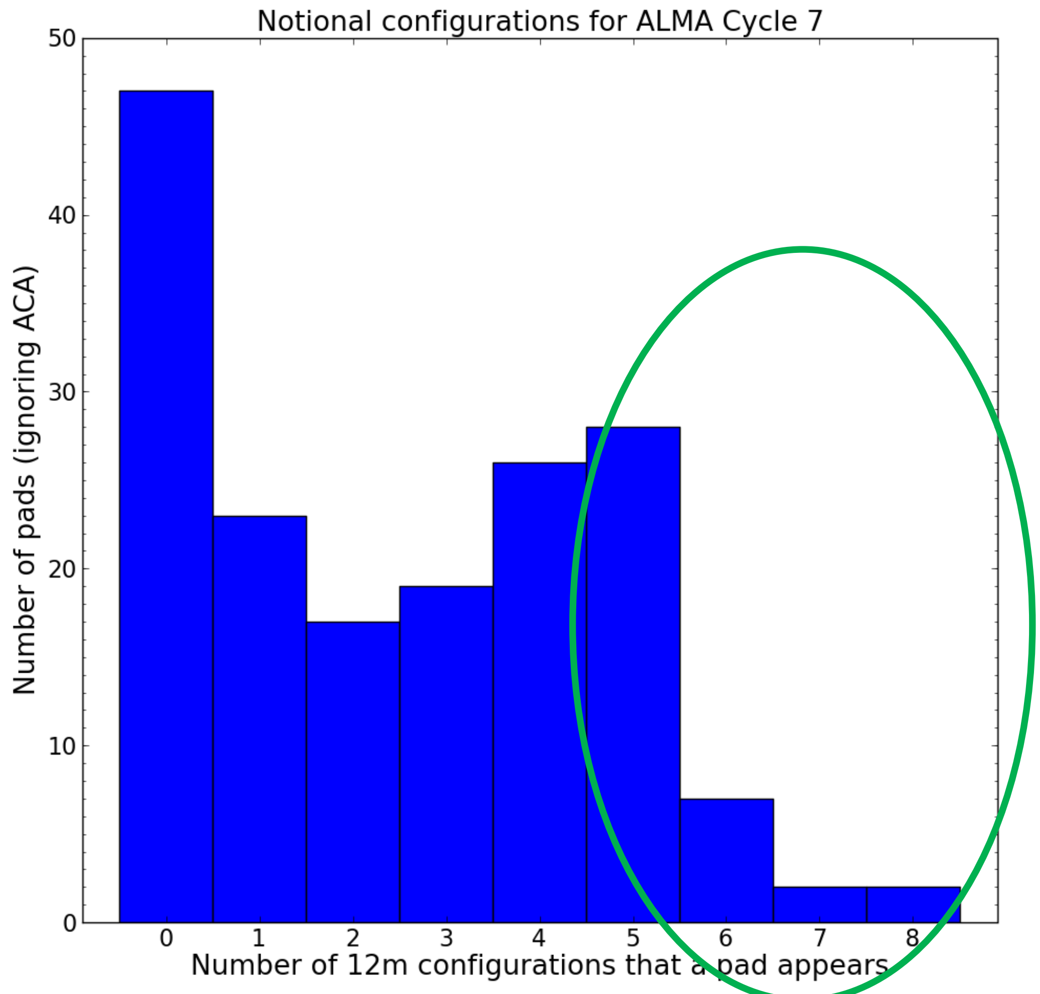


With 20 more fixed antennas, where to put them?

An interesting fact about the current (Cycle 7) notional antenna configurations:

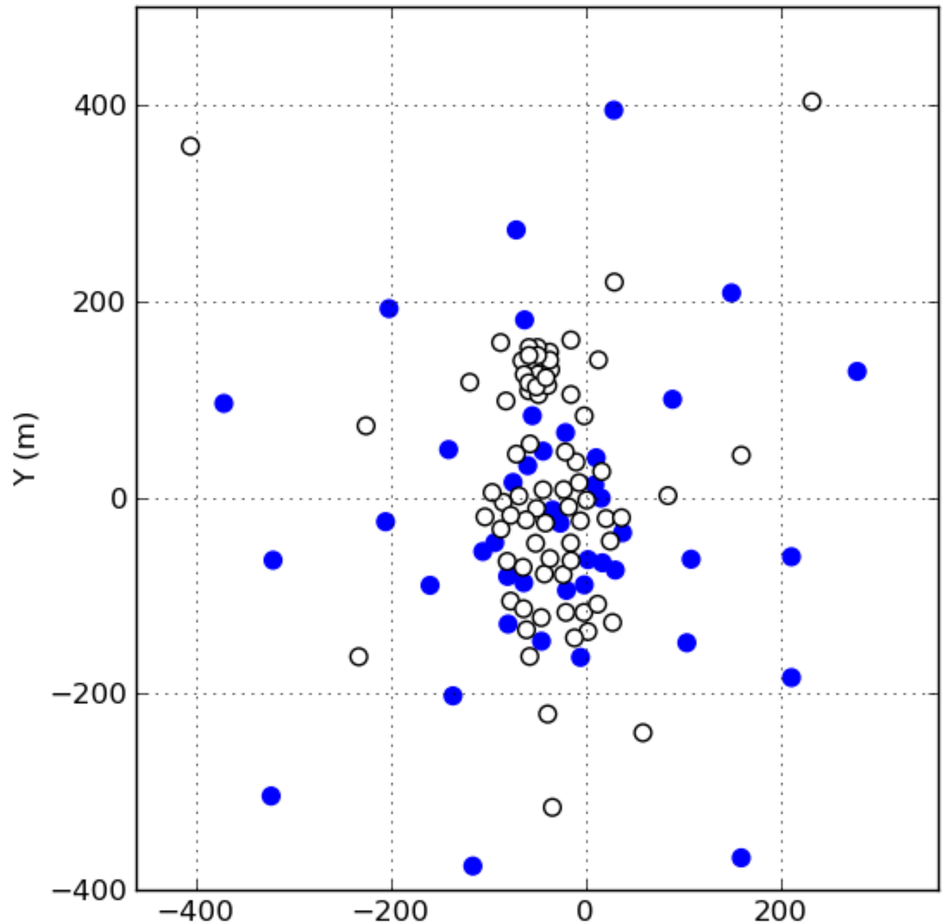
Many pads (39) appear in half (or more) of the ten configurations

This suggests that 20 new antennas could be kept stationary and still benefit a large fraction of science 😀



Example: find pads in common to configurations 4, 3, 2, 1

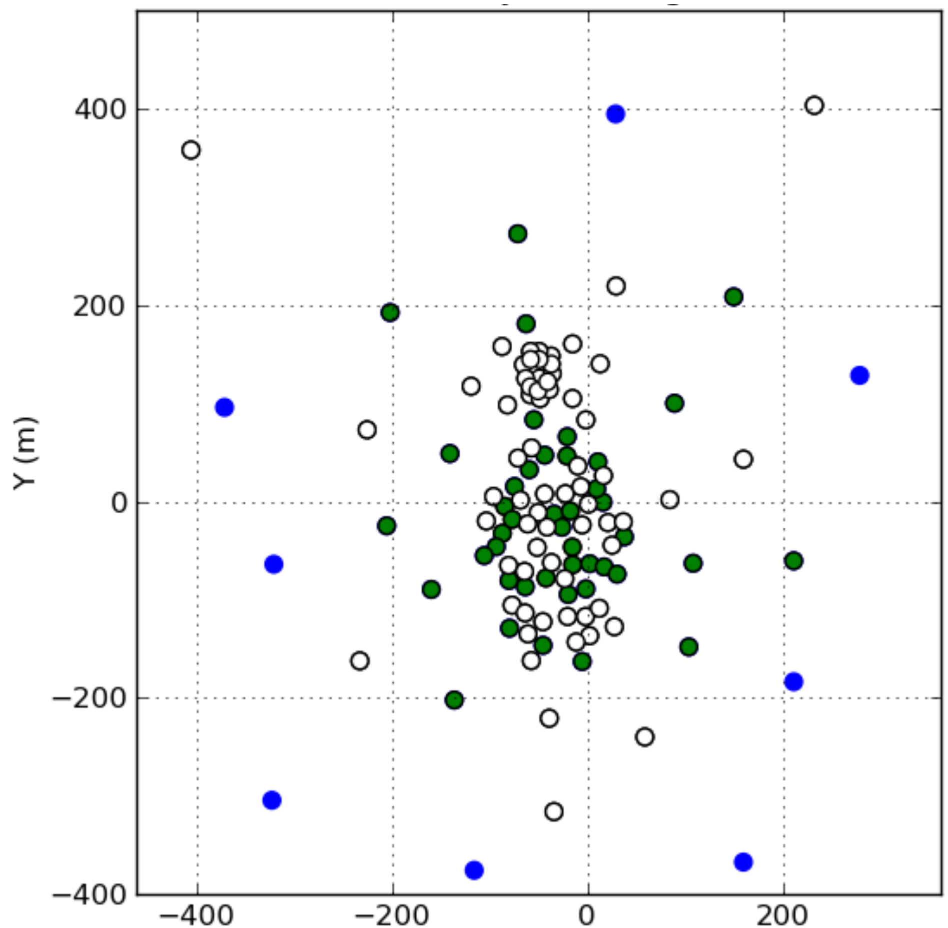
Config 4



Example: find pads in common to configurations 4, 3, 2, 1

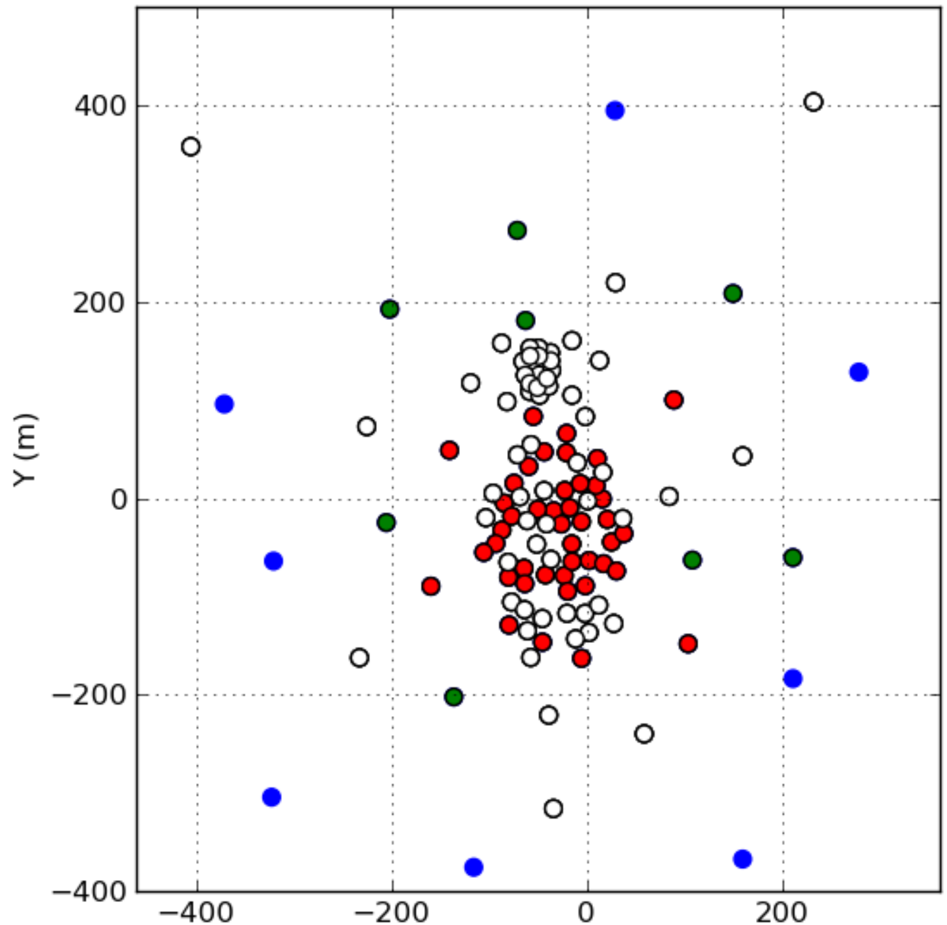
Config 4

Config 3



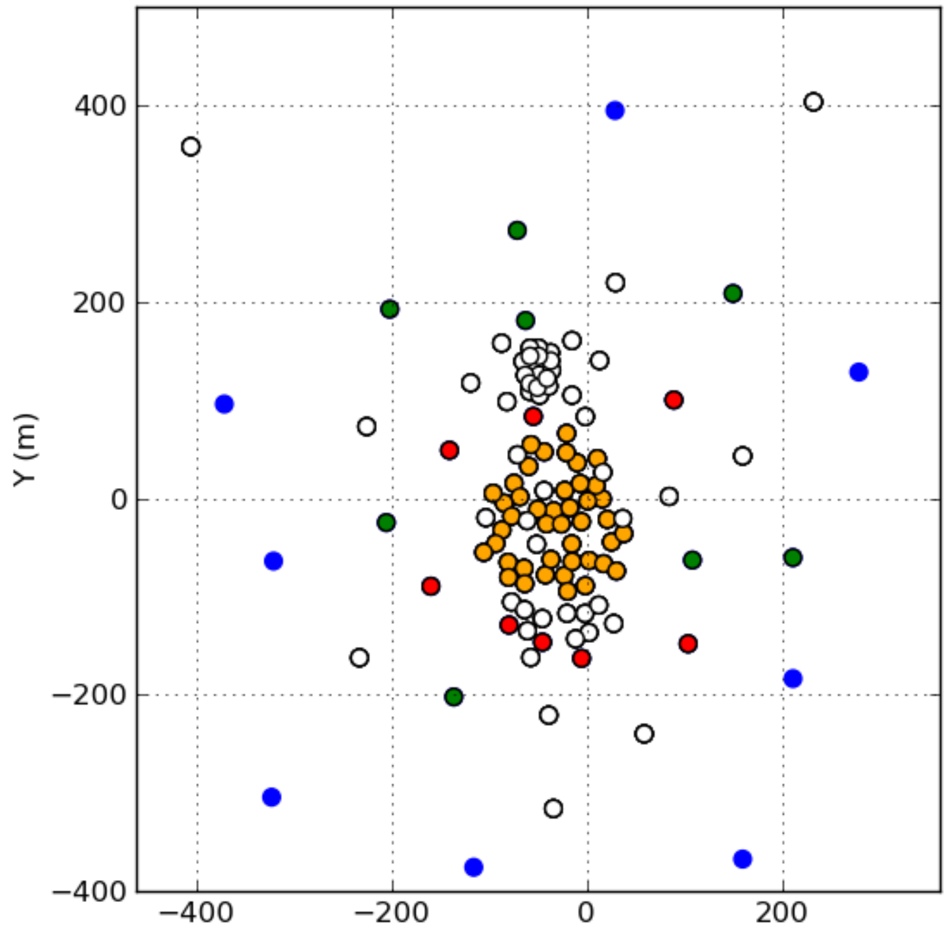
Example: find pads in common to configurations 4, 3, 2, 1

Config 4
Config 3
Config 2



Example: find pads in common to configurations 4, 3, 2, 1

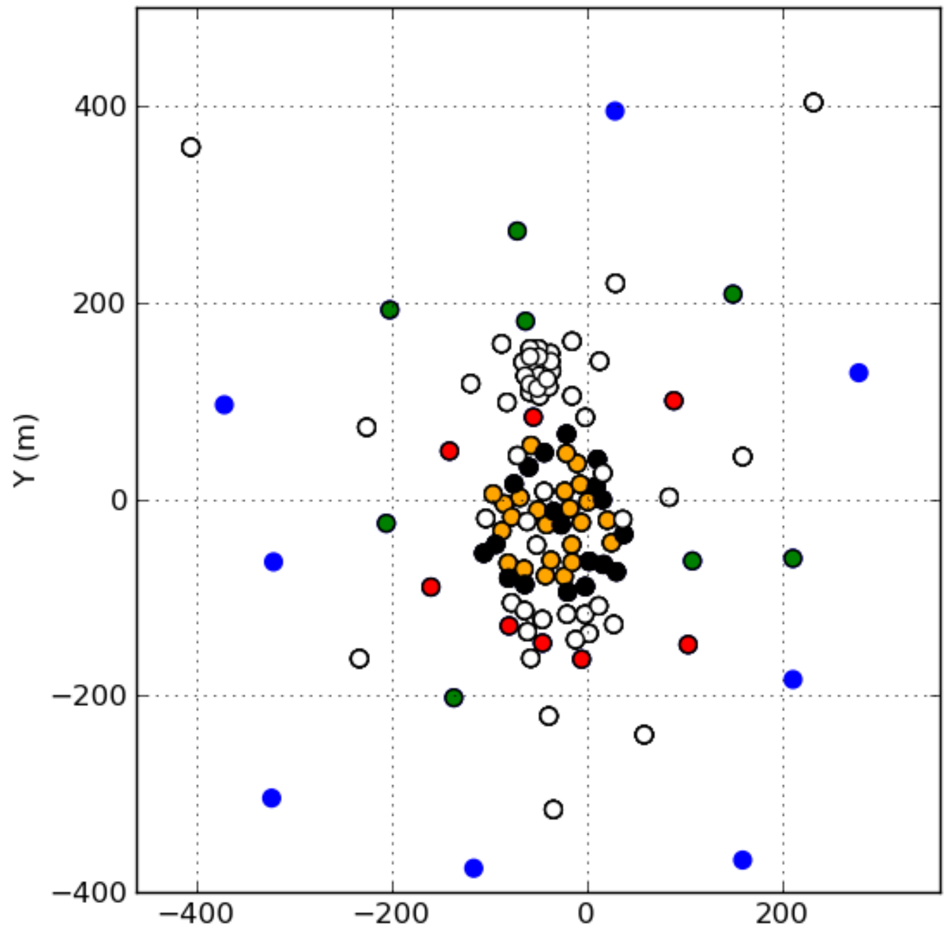
Config 4
Config 3
Config 2
Config 1



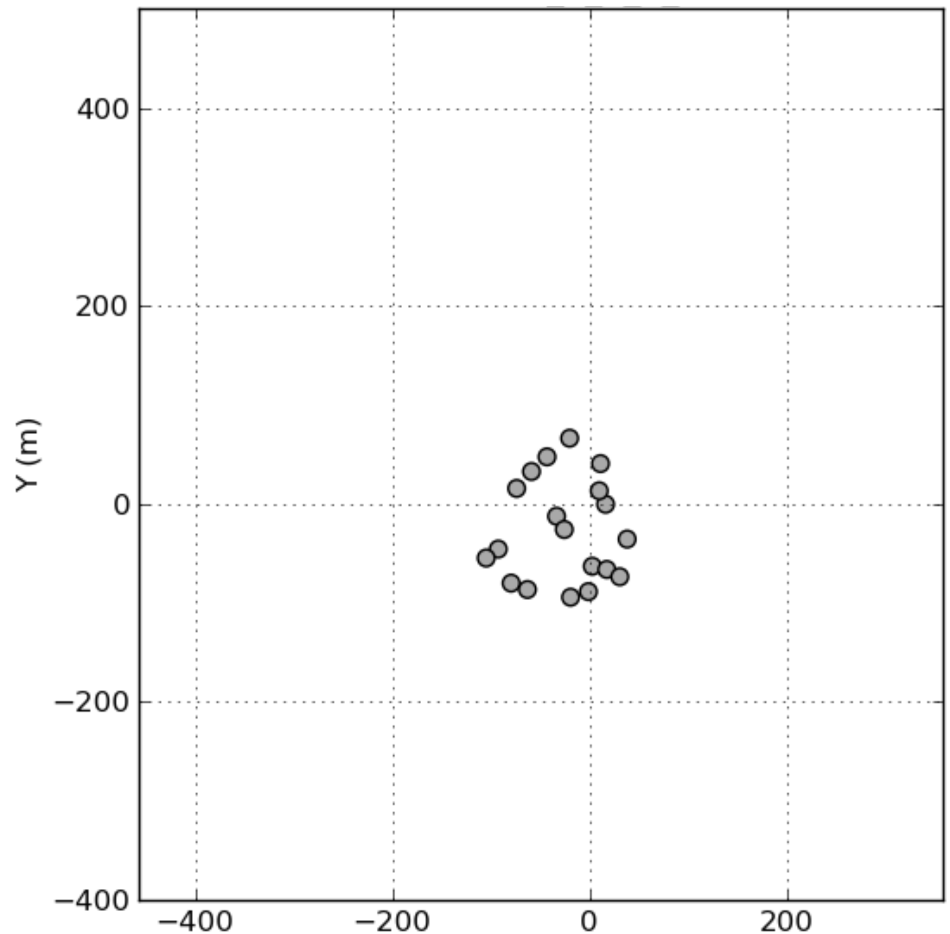
Example: find pads in common to configurations 4, 3, 2, 1

Config 4
Config 3
Config 2
Config 1

19 pads in common!



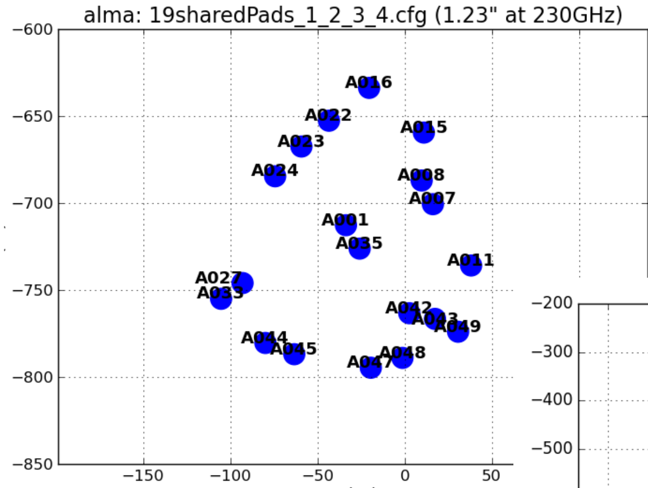
Example: pads in common to configurations 4, 3, 2, 1



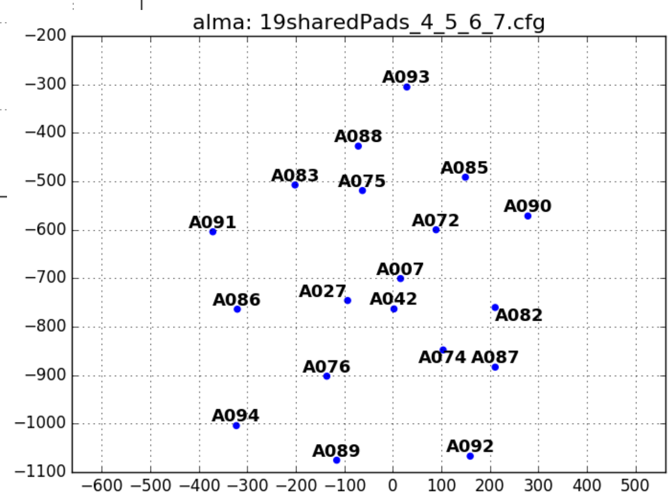
Looks like a useful standalone array!
similar resolution and LAS as smallest

Same thing can be done for larger groupings of 19 pads

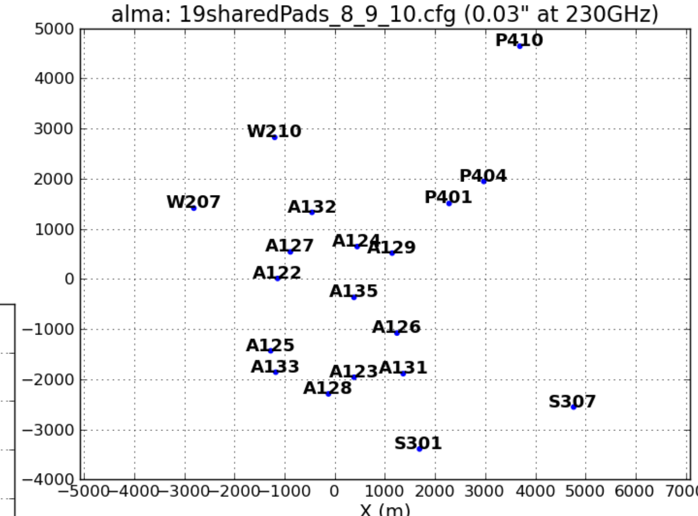
Configs 1-4



Configs 4-7

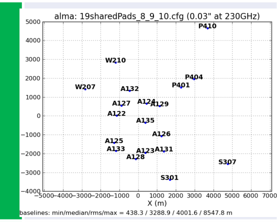
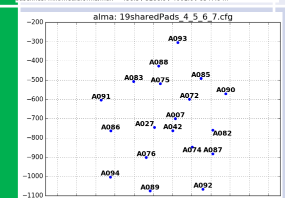
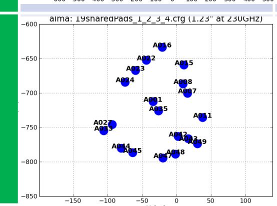


Configs 8-10



Also, the union within each of these 3 groups has only 67 unique pads

Three options for placing 20 more fixed antennas

<table>
<tr><th rowspan="2">Desired Science Focus</th><th rowspan="2">Subset of current (Cycle 7) configurations</th><th rowspan="2">Current pads in common</th><th colspan="3">Standalone configuration:
a potential “second ALMA” available for proposals & DDTs (when not in use!)</th></tr>
<tr><th>size, beam at 37 & 230GHz</th><th>antenna layout</th><th>use cases</th></tr>
<tr><td>(1) High-resolution</td><td>8-9-10</td><td>19</td><td>8.5 km,
0.2” & 0.03”</td><td>
</td><td>dust in disks; sub-arcsec DDTs</td></tr>
<tr><td>(2) Mid-resolution</td><td>4-5-6-7</td><td>19</td><td>800 m,
2” & 0.3”</td><td>
</td><td>lines in disks and galaxies</td></tr>
<tr><td>(3) Low-resolution</td><td>1-2-3-4</td><td>19</td><td>150 m,
9” & 1.3”</td><td>
</td><td>lines in clouds</td></tr>
</table>

Impact of 20 more antennas

A) On the correlator design and cost: probably minor

- 70 antennas produce 2x more baselines than 50 (only 20% more than BLC max)
- "Kitchen Sink Array", would require 70+12+4 = 86 inputs (22 more than now)

B) On operations and maintenance cost: major

- 20 more antennas to maintain and power
- 20*N more receivers and electronics to maintain (N = # bands populated)

  Mitigation: only populate popular bands (3, 6, 7) to begin,
  add more with $$$ from later development years

C) But would also offer new opportunities and economies

- Likely fewer configurations are needed, meaning fewer moves (savings)
- A "second ALMA" available ~half the year
- Provides more flexibility in the era of transient science (LIGO, LSST, etc.)

Power concerns: Electrical draw of current antennas

~ 50-60 % of observatory total (Laborelec report, Nov. 2015)

Total observatory

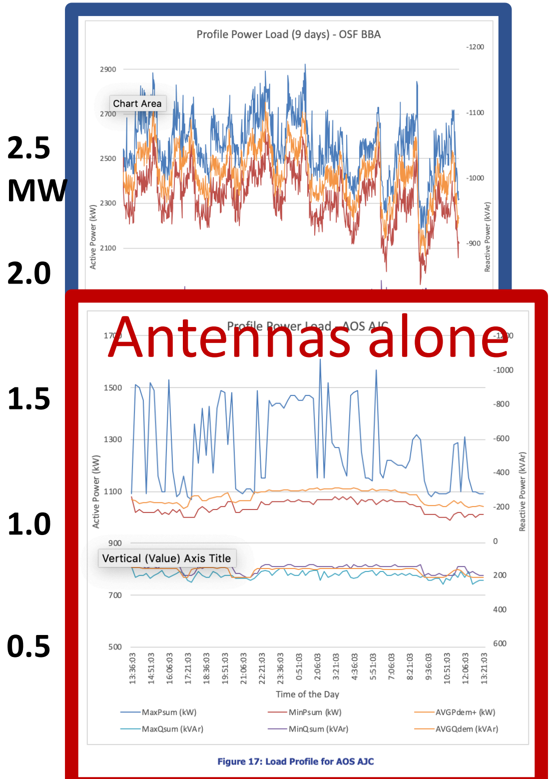


Fig 4 and 17 from report on ticket PT-1142

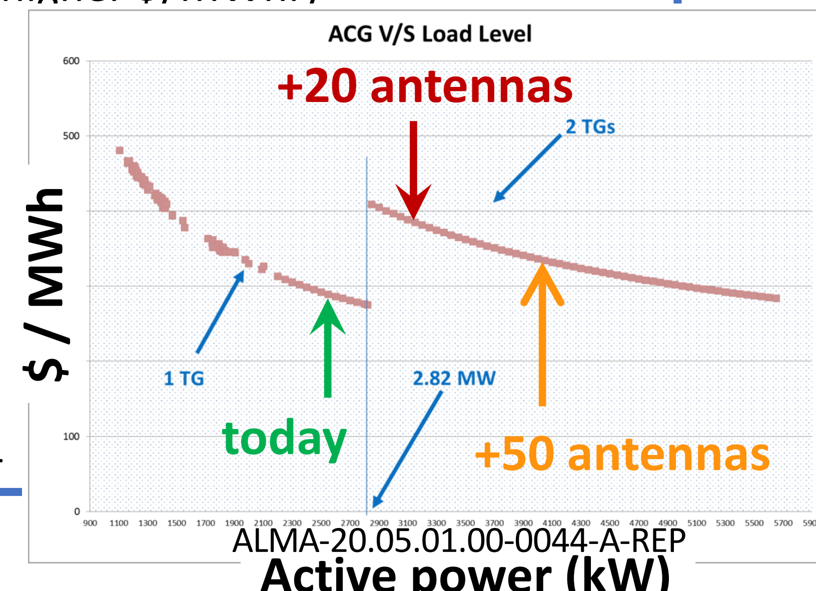
20 more antennas:

- ➢ Total draw would be only 18% higher, but available headroom for 1 turbine is only ~8%.
- ➢ Need 2 turbines at all times. Inefficient if not both loaded well (35% higher $/MWhr)

50 more antennas:

45% higher total but similar effective cost to only 20 more!

1.18*1.35 = 1.45*1.1



Focal plane arrays are mentioned in the ALMA2030 Roadmap…

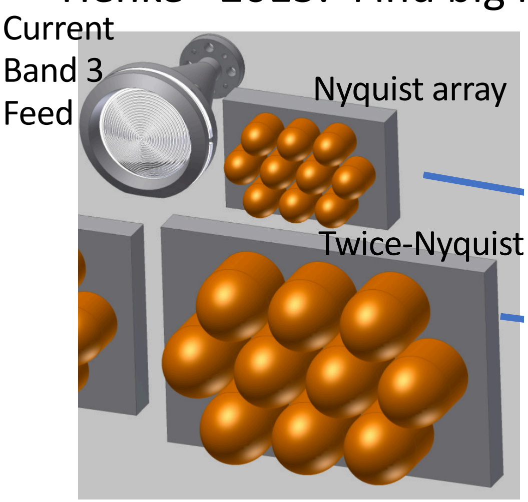
"FPAs could significantly increase ALMA's wide-field mapping speed to survey large regions of molecular clouds, image nearby galaxies, and conduct deep-field cosmological surveys."

FPAs have appeared in ALMA Development Studies:

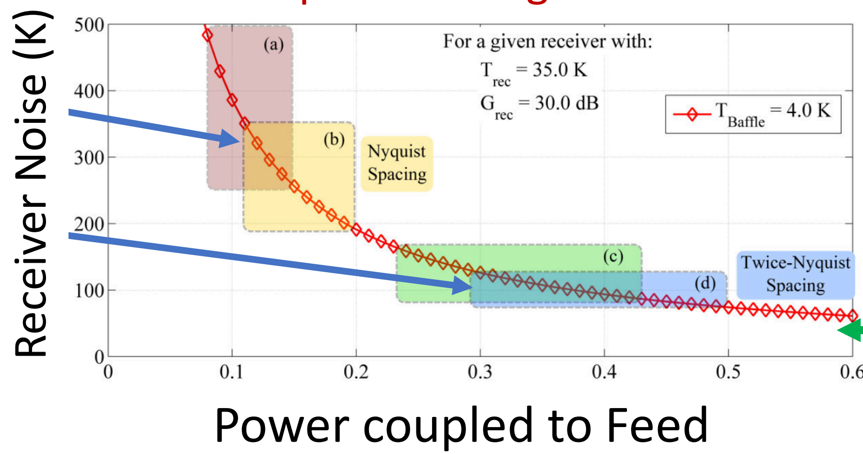
For TotalPower: "Concept Study of a Millimeter Camera for ALMA" (Band 3; 2SB, 2pol, hexagonal, Henke+ 2015)

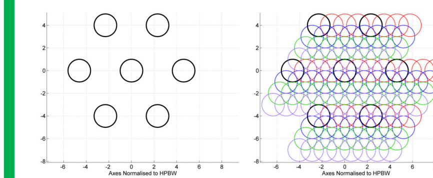
Research is also underway at Univ. of Chile: "Development of Suitable Technologies for Heterodyne W-Band Focal-Plane Arrays" (Mena+ 2018)

Henke+ 2015: Find big noise penalty for densely-packed arrays



This would penalize single-field science!



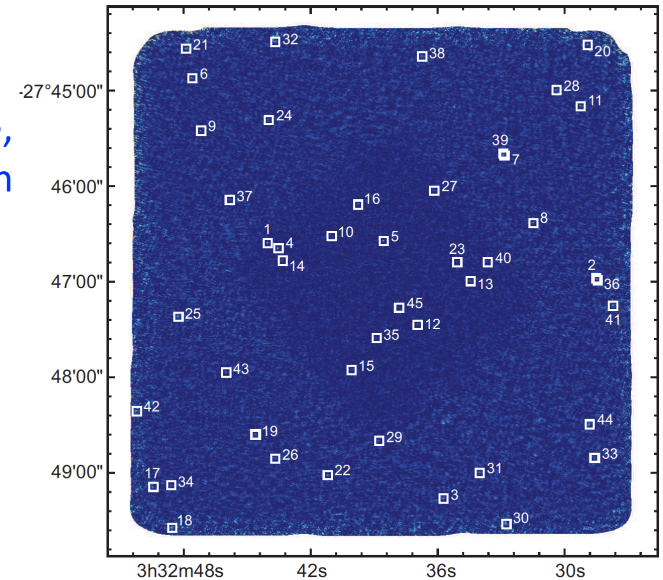


sparse array (spacing = 2x FWHM) needs 16 pointings but can provide a Trx closer to what we require (35K), but harder to fit in allotted space

What science cases could make use of FPA Interferometry?

1) Deep-field galaxies (needs 12m sensitivity):

Hatsukade+ 2018: GOODS-S, Band 6, 29 hours on-source, 9 tiles x 90 pointings x 2 tunings each



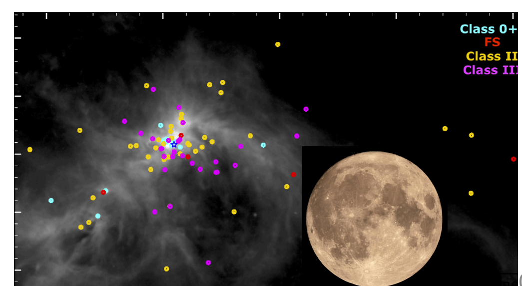
5 arcmin, ~12x12 primary beams

2) Wide-area surveys for CO in molecular clouds (7m)

ACA 7m Band 6 by Katie Jameson (CSIRO) 1 x 0.5 deg

Note: Both of my examples are <u>Band 6</u>.

Not Protoplanetary disks: ☹ are too far apart to benefit from FPAs: see ALMA 1.3mm survey of 43 YSOs in CrA (Cazzoletti+ 2019)



Possible path forward for Focal Plane Arrays

1) Pick a Band to concentrate on (optics constraints and community input)
2) Build and deploy on one Total Power antenna
3) Consider expanding to the 12 x 7m array antennas

   If 2 other bands can be combined, more space in optics might be found

   But less attractive if large southern single-dish (>30m) gets built (AtLAST)

Impacts:

- on correlator design:

  An N-feed element array operating on the ACA would require either:

  - N subarrays of 7m antennas, or
  - N times the nominal "bandwidth" on current 7m subarray

- on rest of system

  - Challenges for IF Transport and LO Distribution

Summary

- Community has identified key science cases for improving ALMA's sensitivity by 3 to 5 times, and improving its resolution
- Both improvements require more collecting area.
- Increasing the number of antennas in the main array will deliver the broadest science impact, but power draw is a big issue
- An expanded array offers new operational possibilities and economies that may help to offset the higher electricity requirement