Science with EoR Arrays

A Case Study

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Purpose of Talk

HERA has multiple attributes:

- Small, autonomous experiment(s) now
- Larger merged project later
- Driven by killer application, single science goal
- Flexible technology capable of broad science

Useful case study for how we design, market, evaluate and fund projects of different types and scales

What is HERA?

- Hydrogen Epoch of Reionization Arrays program
  - Characterize redshifted 21cm emission/absorption, z=5 to ~15
  - Power spectrum and (later) direct imaging
- HERA-I (now)
  - Measure power spectrum, <~10^4 m^2
  - MWA (512 tiles), PAPER 128, 256, ...?
- HERA-II (2nd half of decade)
  - Precise power spectrum dissection, perhaps imaging?
  - Merged project, design, ~10^5 m^2
- HERA-III (>2020)
  - Direct imaging
  - ~10^6 m^2, SKA-low scale

Design Drivers for HERA

- Wide FoV (= small antennas)
  - Even for EoR imager, power spectrum still vital
- Larger arrays, (modestly) longer baselines
  - More sensitivity allows deeper probe into k-space
  - Surface brightness sensitivity is key FoM
- Early digitization
  - Minimize need for analog components
- Large-N correlation and analysis
  - Maximize information content as far into data flow as possible

Design Drivers (secondary)

- Long baselines
  - Possibly - depends on error budget for EoR
  - Higher precision ionospheric corrections
  - Better discrete source foreground model
- Frequency resolution
  - Higher is better (for calibration purposes)
  - For EoR, depends on nature of signal
- Calibration approach
  - Different emphases based on behavior of foregrounds

Murchison Widefield Array

Frequency range	80-300 MHz (optimized for ~100-200 MHz)
Number of receptors	8192 dual polarization dipoles
Number of tiles	512
Collecting area	~8000 m^2 (at 200 MHz)
Field of View	~15°-50° (1000 deg^2 at 200 MHz)
Configuration	Core array ~1.5 km diameter (95%, 3.4′) + extended array ~3 km diameter (5%, 1.7′)
Bandwidth	220 MHz (Sampled); 31 MHz (Processed)
# Spectral channels	768 (3072)
Temporal resolution	8 sec (0.5 sec)
Polarization	Full Stokes
Point source sensitivity	20mJy in 1 sec (32 MHz, 200 MHz) 0.34mJy in 1 hr
Multi-beam capability	32, single polarization
Number of baselines	130816 (VLA: 351, GMRT: 435)

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Complementarity

- MWA
  - Large-N architecture, aggressive calibration strategy
- PAPER
  - Optimized antenna properties, staged development
- LOFAR
  - Industrial scale, facility model, long baseline imaging

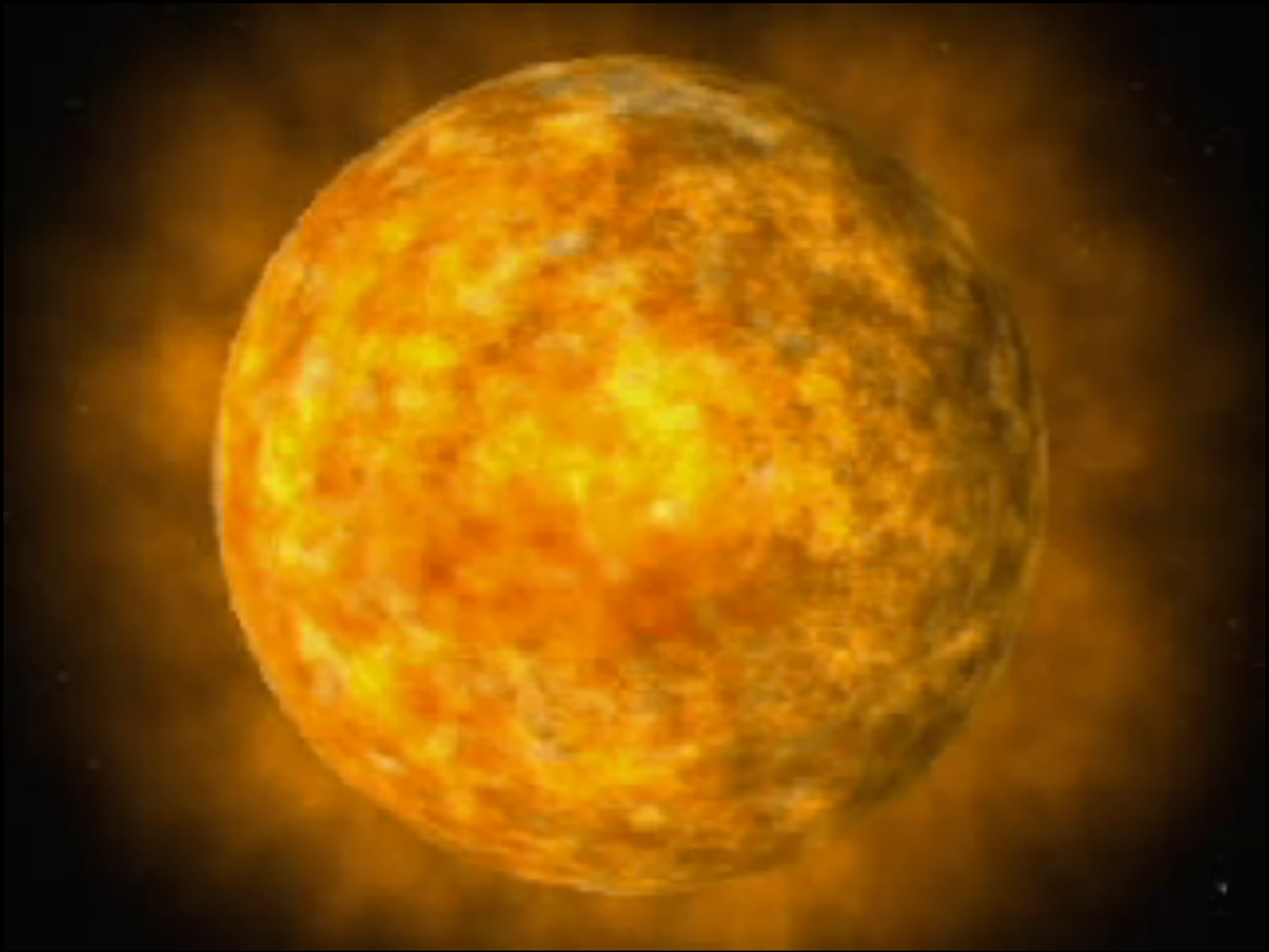
Complementarity

Next generation low frequency instruments:

- High performance, low cost dipoles *(all sky)*
- Per-dipole digitization *(minimize analog, preserve FoV)*
- Massive DSP capacity, full band, full correlation *(cheap silicon)*
- Flexible, hemispheric calibration *(optimal use of information)*

Details require comparisons using data
But basics look secure

Solar and Heliospheric Science



Heliospheric Propagation

- Interplanetary scintillation
  - High sensitivity + wide field of view
  - Many IPS sources simultaneously = huge improvement
  - Detailed mapping of IPM density/turbulence
- Faraday rotation
  - High sensitivity + wide field of view
  - Many background polarized sources measured at once
  - Detailed mapping of density x B-field - new capability
- Improved space weather prediction capability

Ionospheric Research

- Rich phenomenology
  - Before we even look with HERA instruments ...
- Exquisite sensitivity
  - Precision: milli-TEC units
  - Extraordinary spatial resolution
  - Phase gradients
  - Faraday rotation
  - Scintillation and resolution on the ground
- 3D tomography possible
  - Currently in progress @LOFAR
- Byproduct of normal operation

Phenomenon	Time scale	Spatial scale	Amplitude	Height	Frequency of occurrence	Expected RM/FR (rad/m^2, ° at 150 MHz)	Remarks
Medium Scale TIDs	Vel=100-300 m/s, 1000s	100-300 km, 20°-60°	~1-5 % of the background TEC	~300 km	Daily	5×10^{-2}, ~11°	1 Based on GPS measurements
	Vel=100m/s, 2000s		0.1 - 1 TECU		Daily	0.01-0.1, 2.3° - 23°	2 Based on radio interferometry
Large Scale TIDs	Vel=300-1000 m/s, ~3000s	1000-3000 km, > 180°	~5-10 % of the background TEC	~300 km	few times a month	8×10^{-2}, ~18°	3
Spread F		50-100 km	depletions of ~0.1 ambient	~300 km	Common except during June solstice		4
Sporadic-E	few to many hours	Patchy, 200-300 km	~0.05 TECU	~100 km	Seasonal,~1/wk during the season	6×10^{-3}, ~1.4°	5
SEDs	Many minutes to hours	200-300 km	Gradients of few TECU/min	From ~250 km to plasma sphere	Infrequent (occur when Kp > 2)		6
Solar cycle	Years	Global			Always present		7
Day to day variability		Global	~20% (day), ~33 % (night) of base TECU	Mostly F layer (200-500 km)	Daily	0.2-0.3, 45°-70°	8

Transient Radio Source Examples

- RRATs
  - Pulsar-like behaviour, period 3-4 sec
  - Activity intermittent on timescales of minutes to hours
- Ultracool dwarf stars
  - Pulsar-like periodic pulses
  - Periods of hours (assumed rotation)
- Stellar bursts
  - Like solar bursts, much stronger
- Galactic center transient
  - Observed a few times, 77 min period
- Scintillations, ISM
- Giant pulses
- GRB prompt emission
- Etc ...

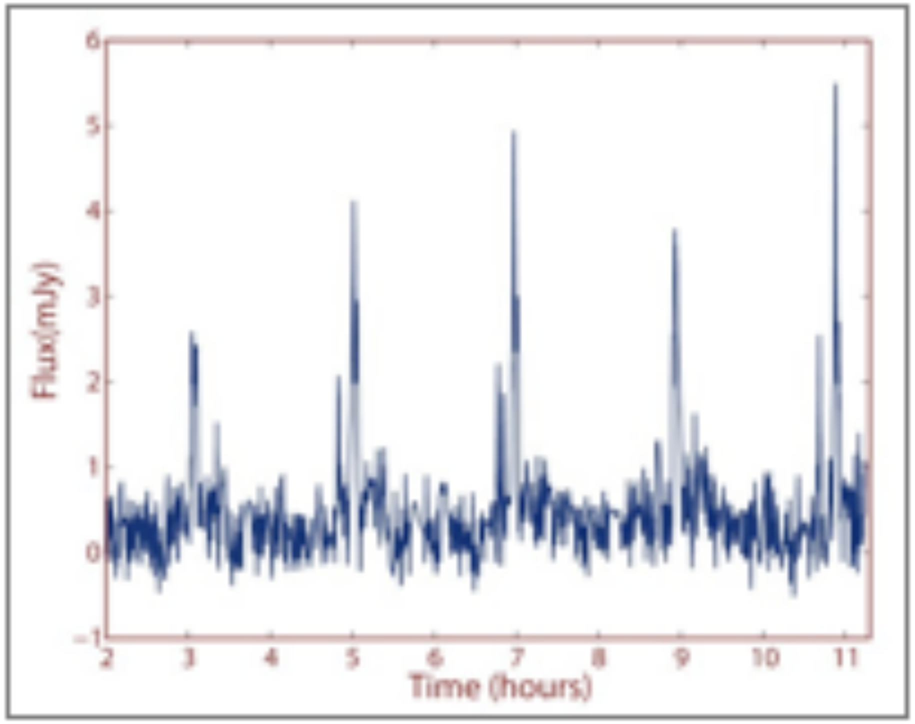


Figure 3: Time series of the radio emission detected with the VLA from the M9 dwarf TVLM 513-46546. Every 1.958 hours a periodic pulse is detected when extremely bright, beams of radiation originating at the poles sweep Earth when the dwarf rotates.

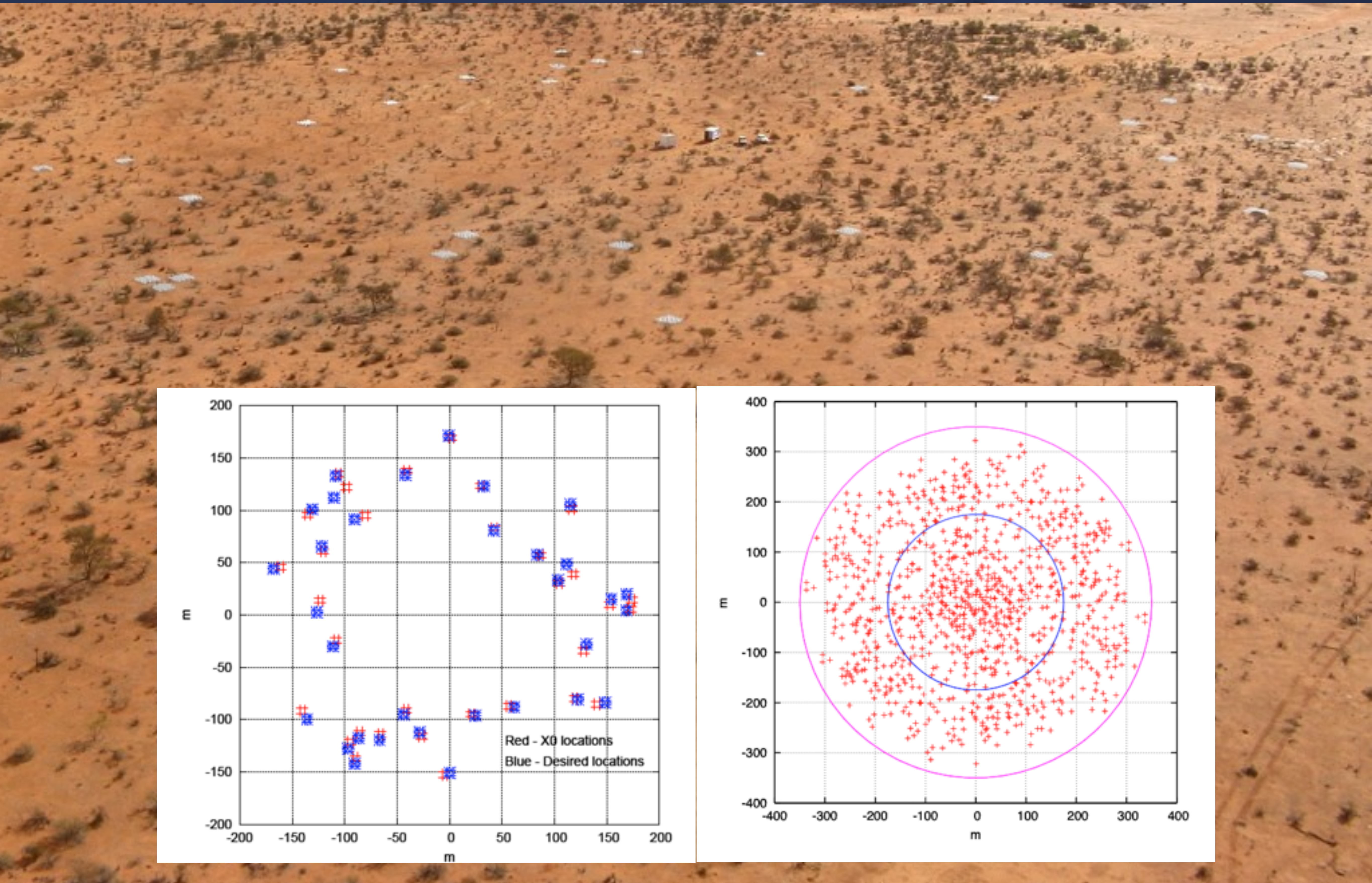
MWA transient science packages

- All Sky Monitor (ASM)
  - Search phase space: direction, timing, freq., dispersion measure
  - Look for single pulse off-on-off
  - Blind search in primary field of view
  - Power of two image binning 8s $\rightarrow$ 16s $\rightarrow \ldots \rightarrow$ days
- Transient Lightcurve Analyzer (TLA)
  - "Watch list" of single pixel positions
  - Light curve saved at these positions at full time resolution
  - $\sim 10^2$ pixels in the FoV
  - Allows more complex offline analysis of light curves
- Short & Long Term Synoptic Surveys
  - Dedicated, periodic observations of the whole sky
- Beamformer Light Curve (BLC)

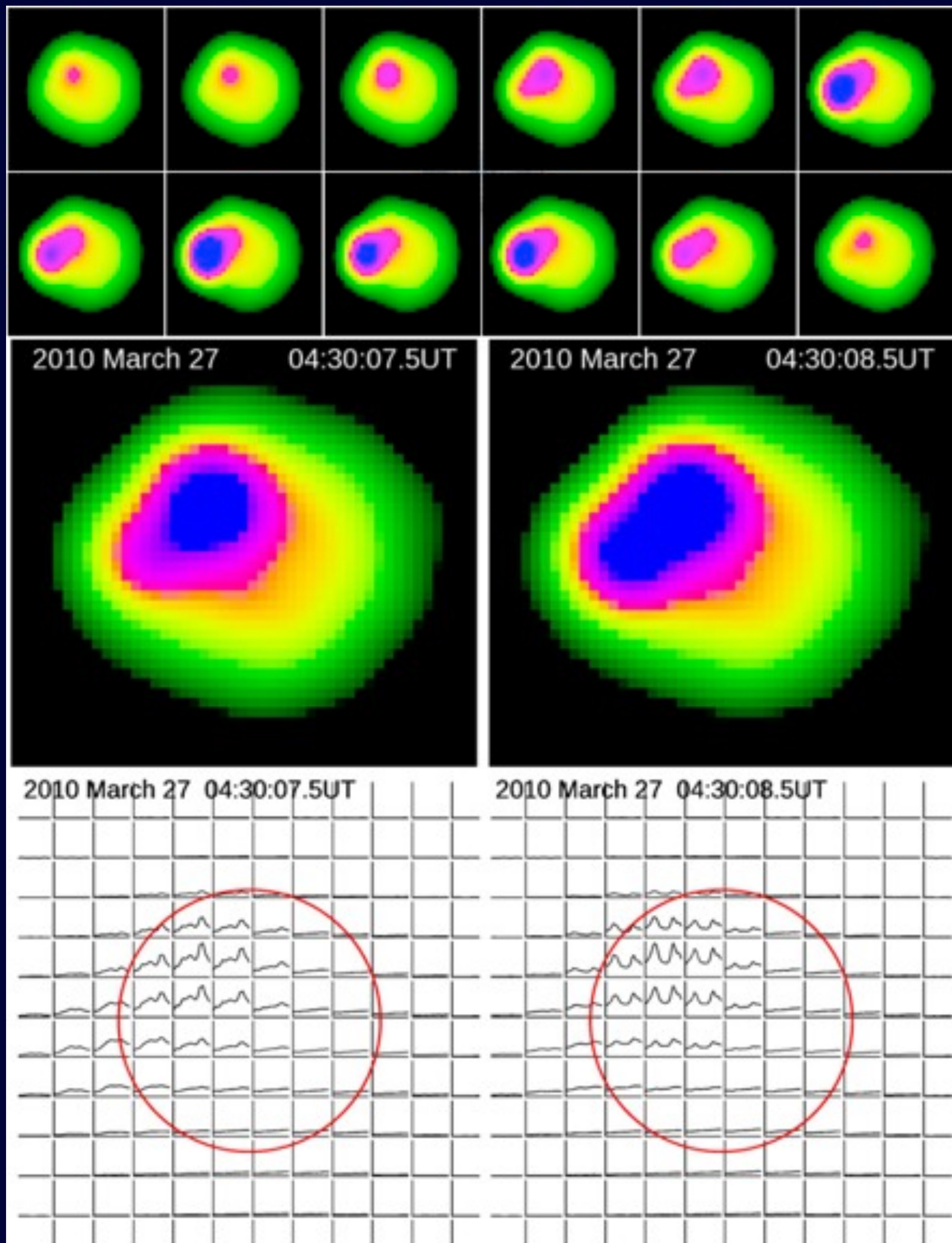
Ref: Cappallo et al., Kerastari Meeting, 2007

Aerial view of 32T

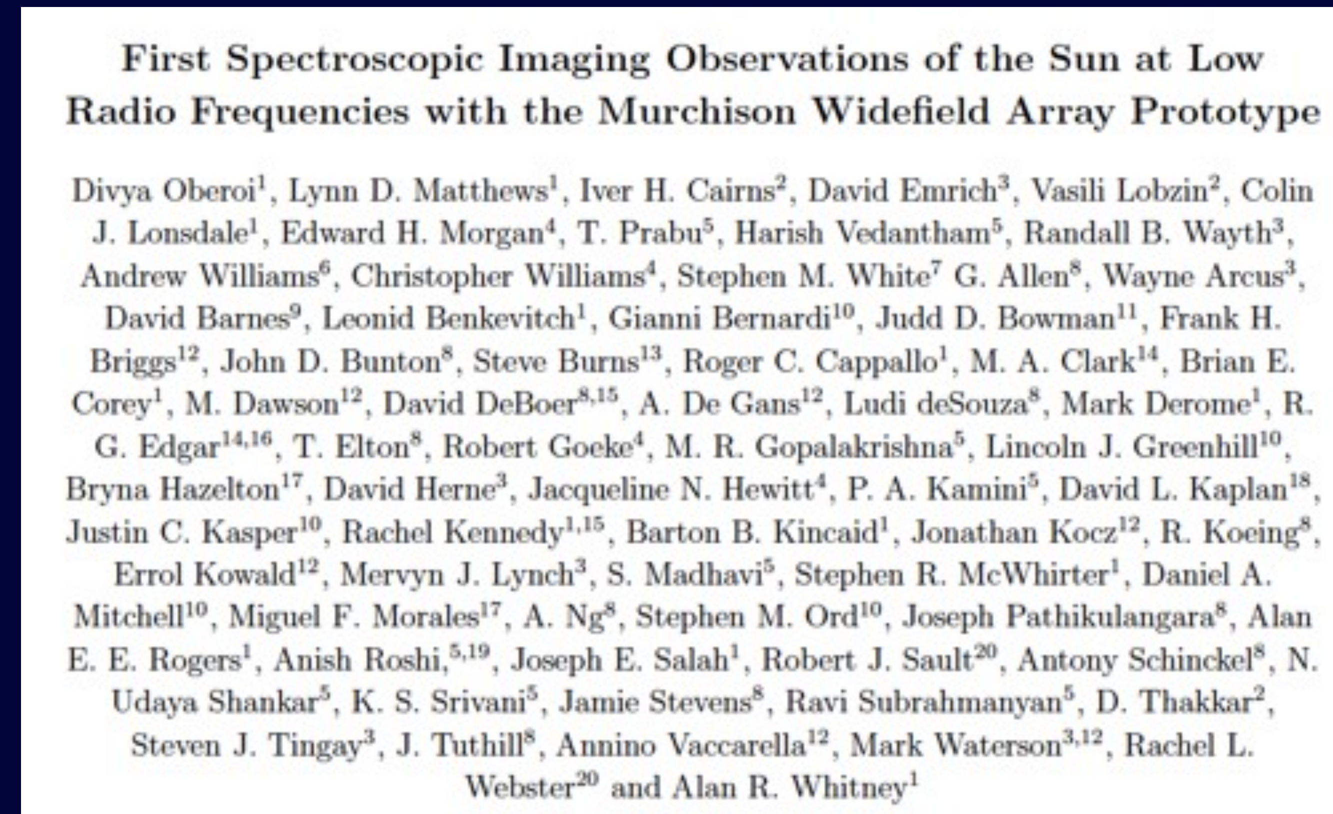
Aerial view of 32T



Solar Imaging



Lynn Matthews & Divya Oberoi (Haystack)

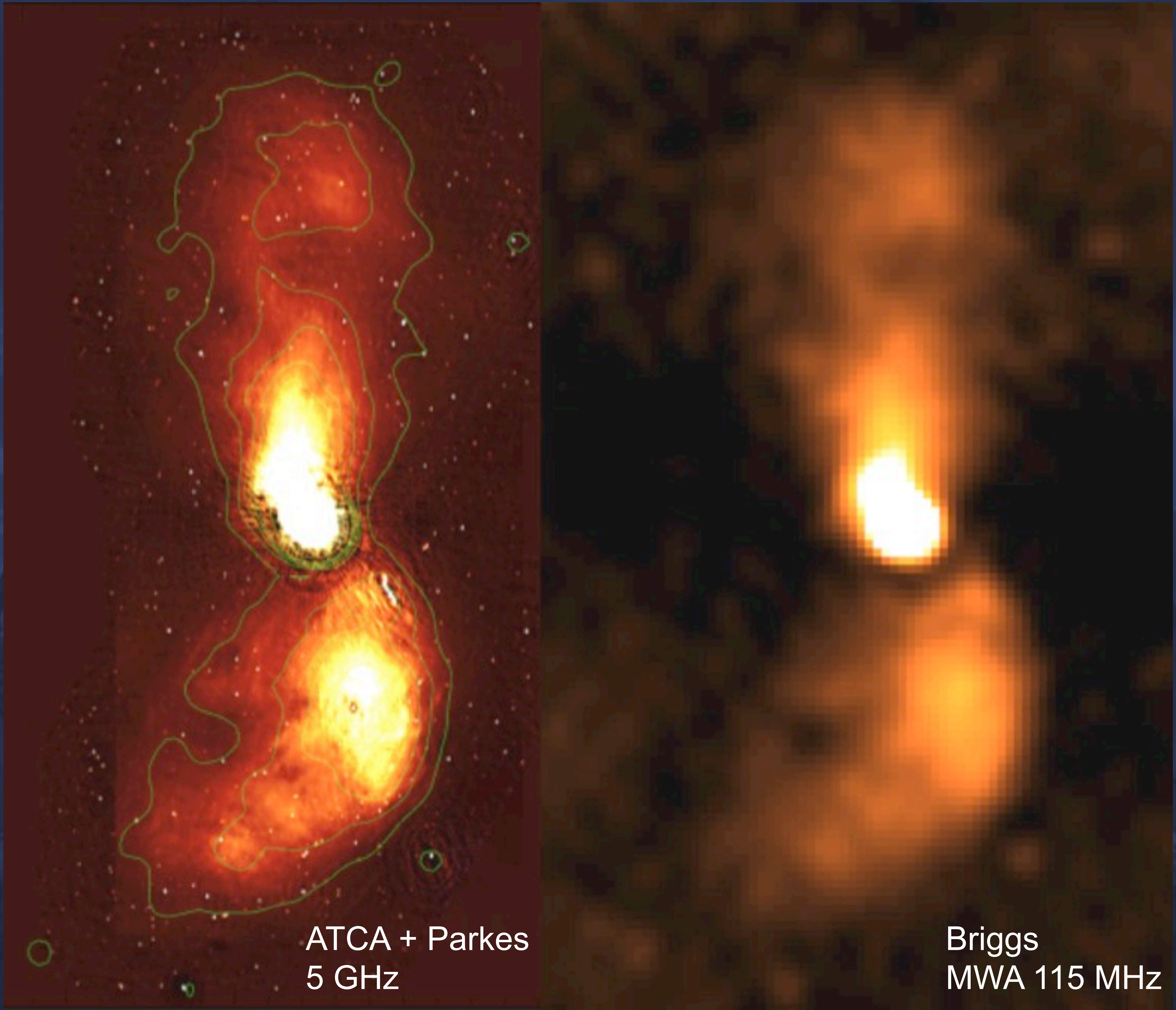


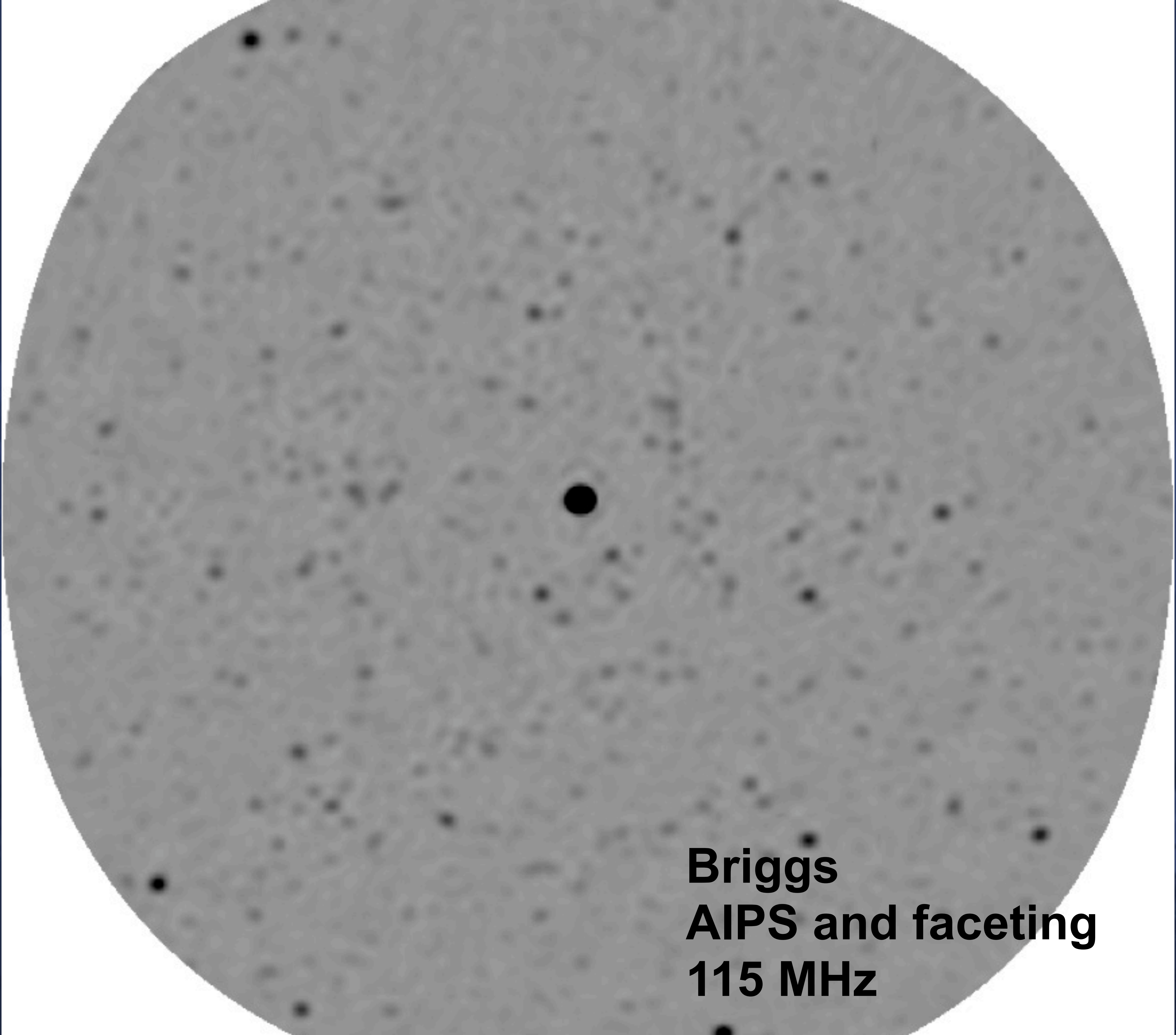
First Spectroscopic Imaging Observations of the Sun at Low Radio Frequencies with the Murchison Widefield Array Prototype

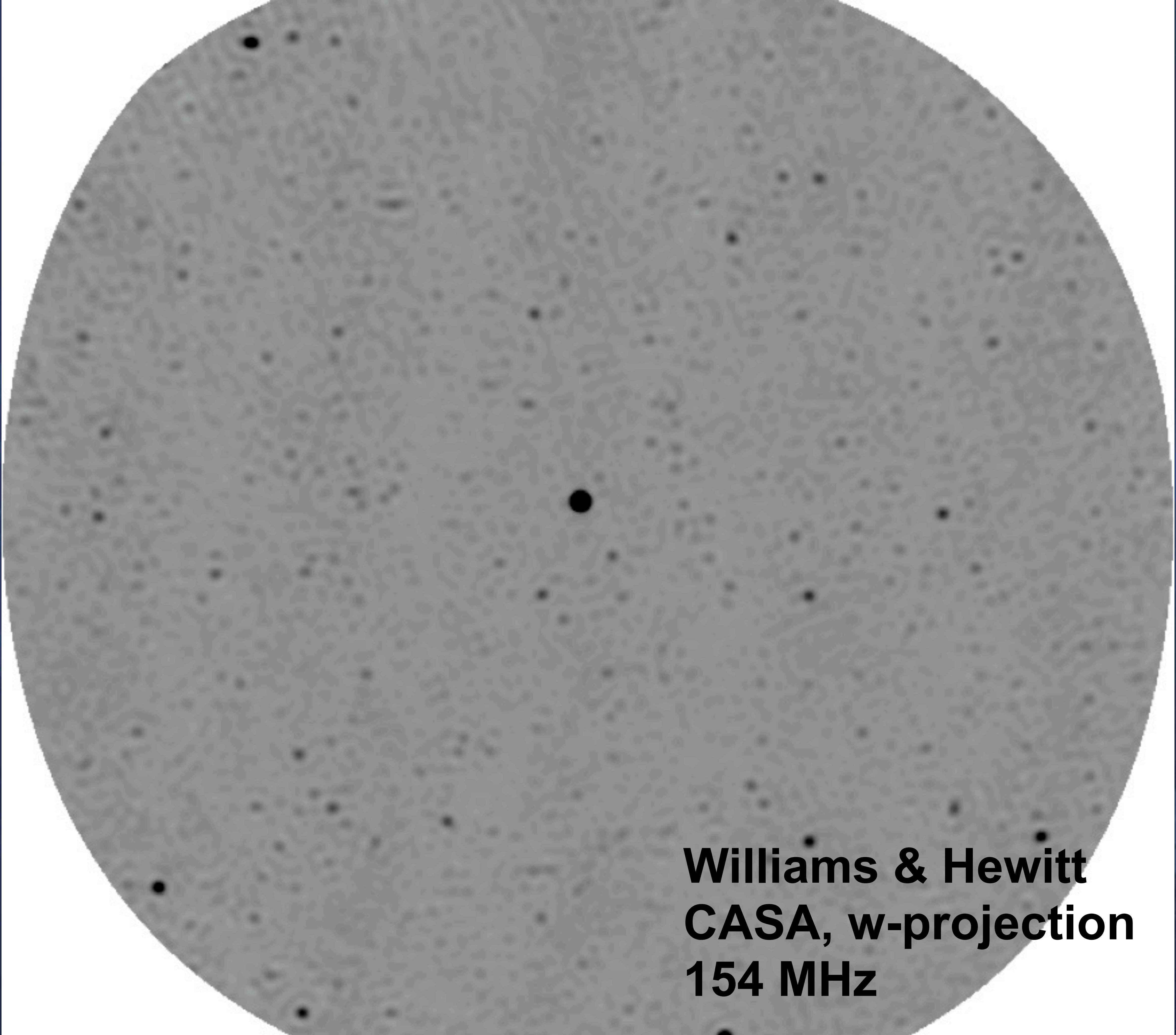
Divya Oberoi[1], Lynn D. Matthews[1], Iver H. Cairns[2], David Emrich[3], Vasili Lobzin[2], Colin J. Lonsdale[1], Edward H. Morgan[4], T. Prabu[5], Harish Vedantham[5], Randall B. Wayth[3], Andrew Williams[6], Christopher Williams[4], Stephen M. White[7] G. Allen[8], Wayne Arcus[3], David Barnes[9], Leonid Benkevitch[1], Gianni Bernardi[10], Judd D. Bowman[11], Frank H. Briggs[12], John D. Bunton[8], Steve Burns[13], Roger C. Cappallo[1], M. A. Clark[14], Brian E. Corey[1], M. Dawson[12], David DeBoer[8,15], A. De Gans[12], Ludi deSouza[8], Mark Derome[1], R. G. Edgar[14,16], T. Elton[8], Robert Goeke[4], M. R. Gopalakrishna[5], Lincoln J. Greenhill[10], Bryna Hazelton[17], David Herne[3], Jacqueline N. Hewitt[4], P. A. Kamini[5], David L. Kaplan[18], Justin C. Kasper[10], Rachel Kennedy[1,15], Barton B. Kincaid[1], Jonathan Kocz[12], R. Koeing[8], Errol Kowald[12], Mervyn J. Lynch[3], S. Madhavi[5], Stephen R. McWhirter[1], Daniel A. Mitchell[10], Miguel F. Morales[17], A. Ng[8], Stephen M. Ord[10], Joseph Pathikulangara[8], Alan E. E. Rogers[1], Anish Roshi,[5,19], Joseph E. Salah[1], Robert J. Sault[20], Antony Schinckel[8], N. Udaya Shankar[5], K. S. Srivani[5], Jamie Stevens[8], Ravi Subrahmanyan[5], D. Thakkar[2], Steven J. Tingay[3], J. Tuthill[8], Annino Vaccarella[12], Mark Waterson[3,12], Rachel L. Webster[20] and Alan R. Whitney[1]

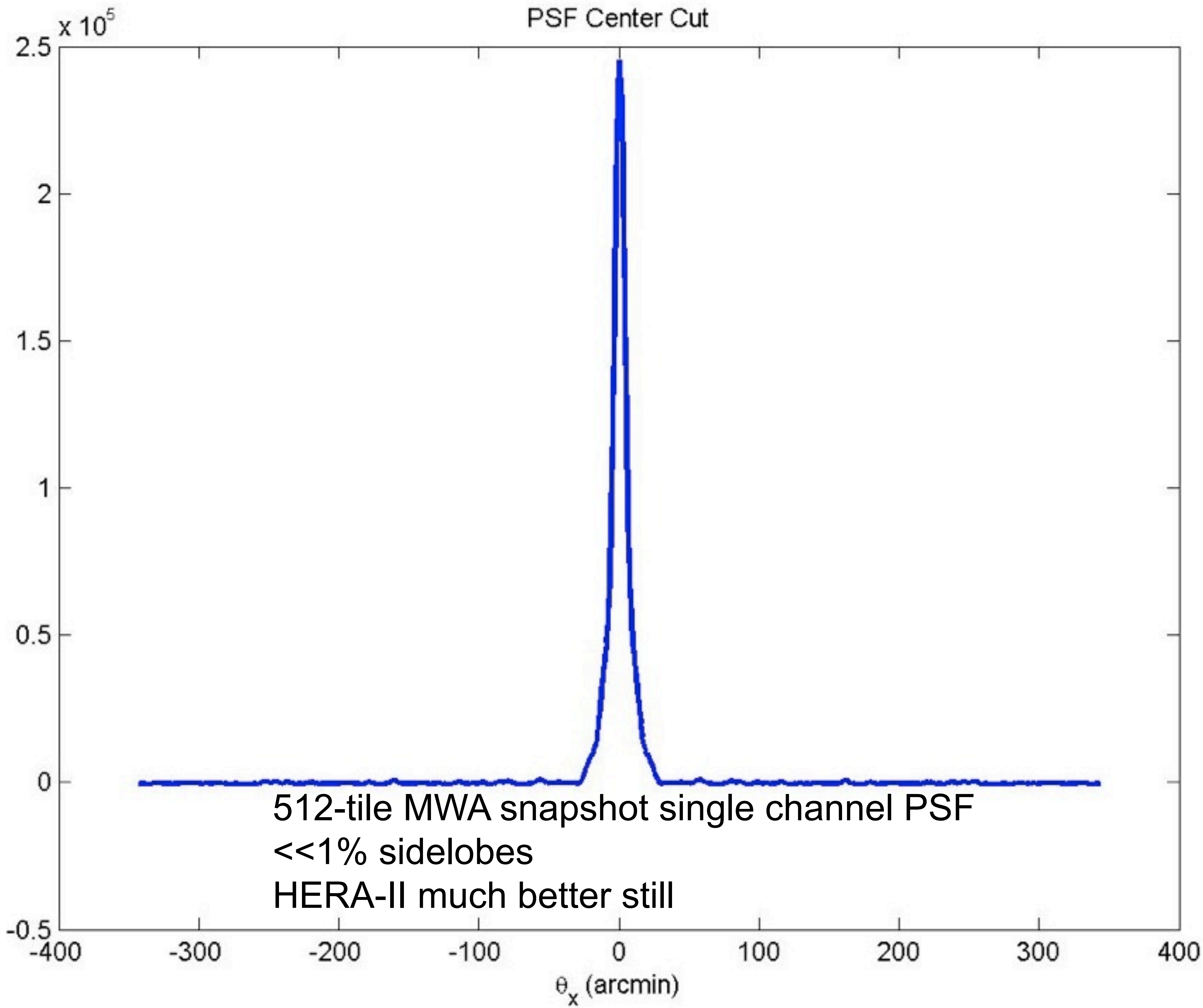
Oberoi et al., Ap.J.Letters

Cen A, Image Fidelity

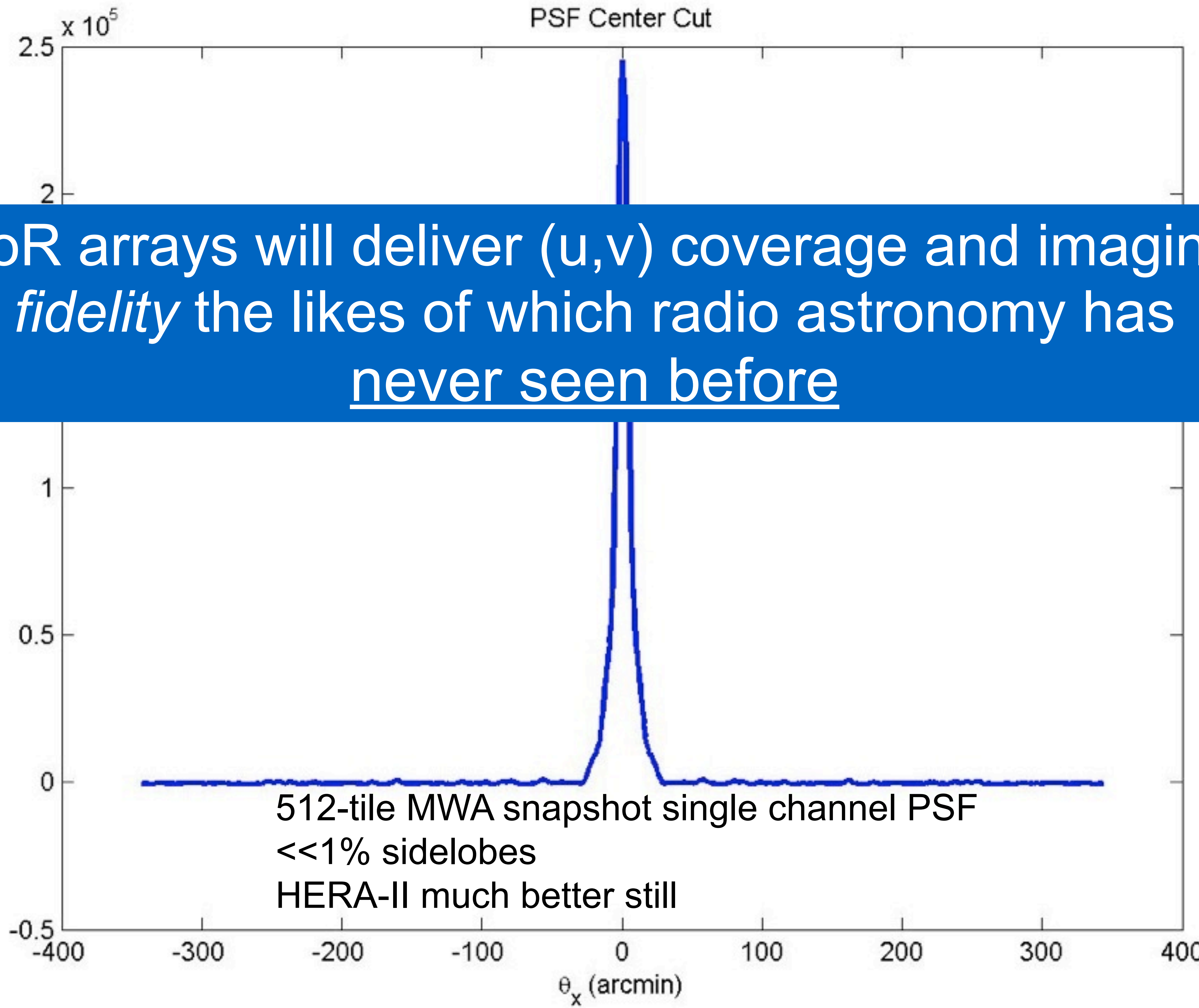



Briggs
AIPS and faceting
115 MHz

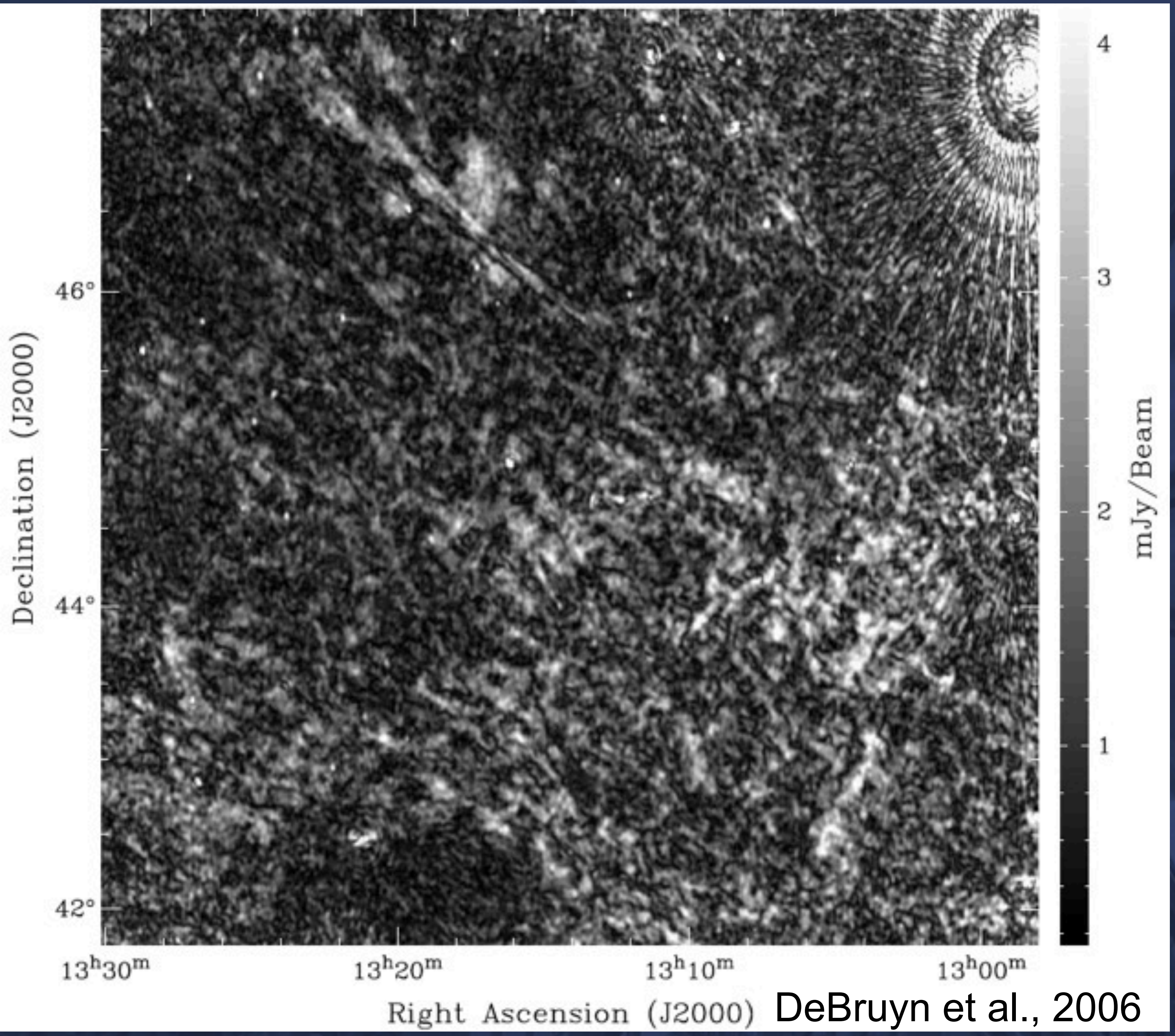

Williams & Hewitt
CASA, w-projection
154 MHz


PSF Center Cut
x 10^5
2.5
2
1.5
1
0.5
0
-0.5
-400
-300
-200
-100
0
100
200
300
400
θx (arcmin)
512-tile MWA snapshot single channel PSF
<<1% sidelobes
HERA-II much better still

EoR arrays will deliver (u,v) coverage and imaging *fidelity* the likes of which radio astronomy has never seen before



Polarized Galactic Emission



DeBruyn et al., 2006

- WSRT 350 MHz
- 6x6 degrees
- Gal. latitude +71
- T_b ~ a few K
  - 1000 x EoR
  - 150 MHz value unknown

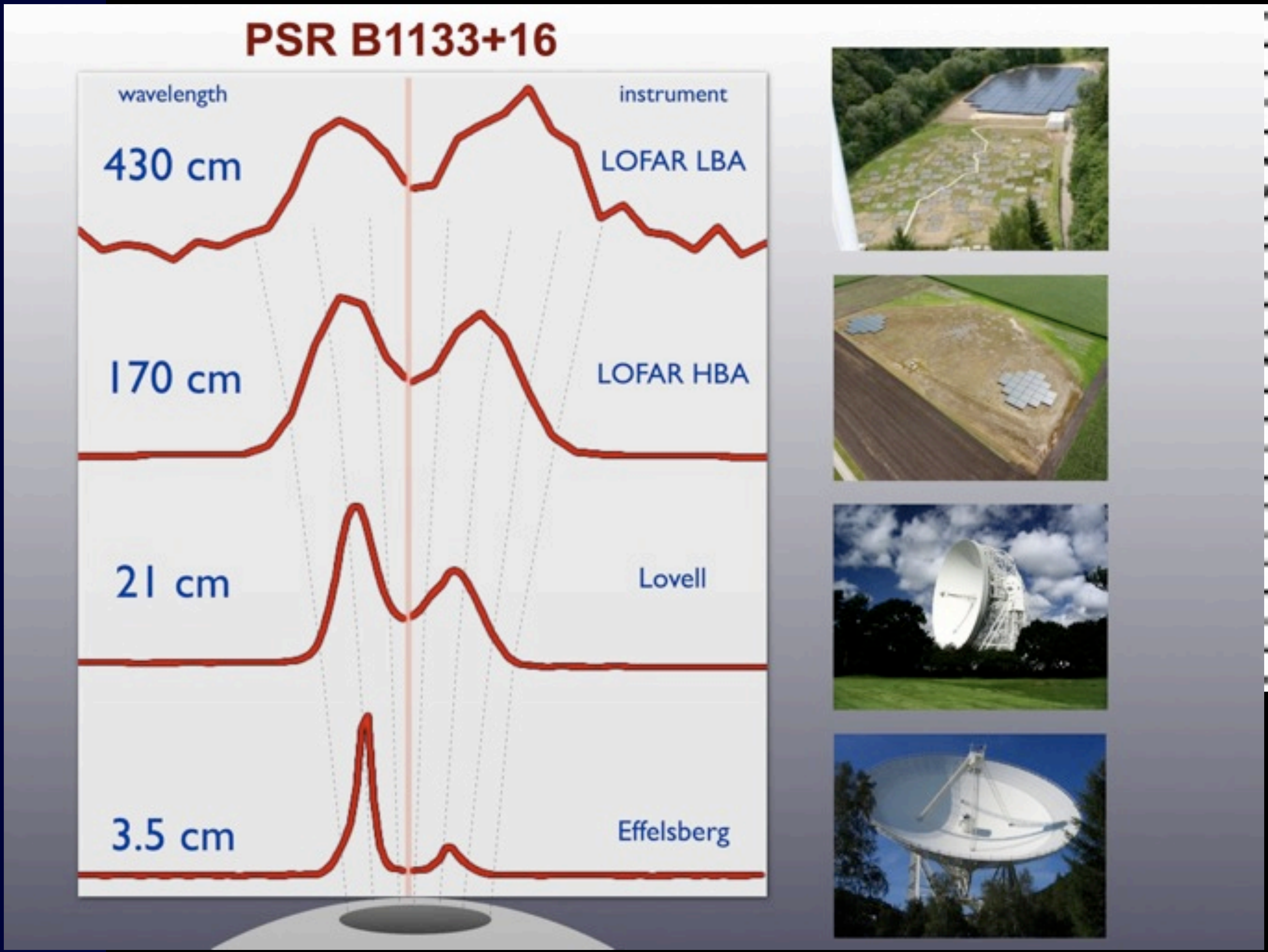
Challenging ... BUT:

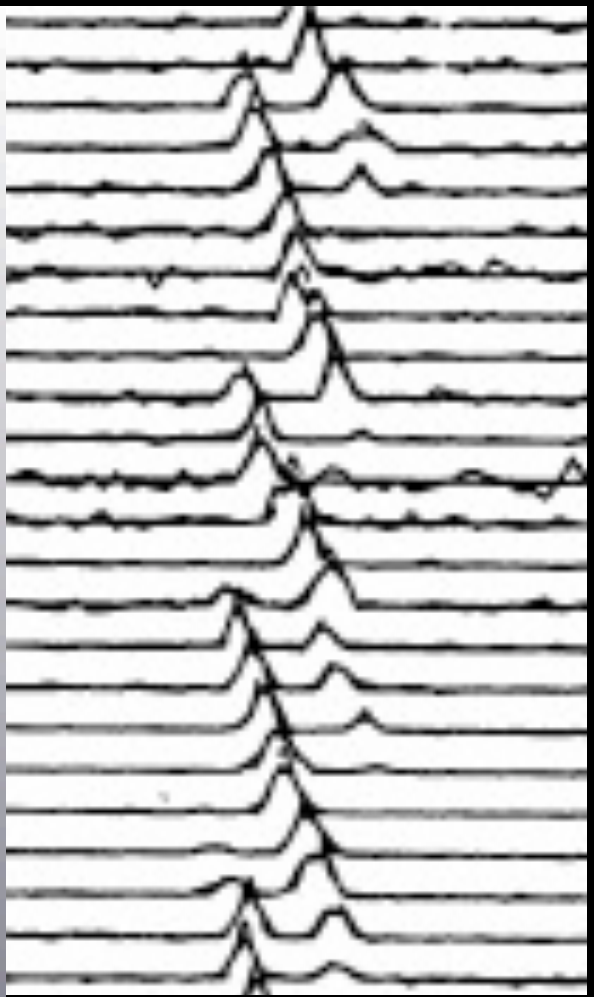
- Powerful new probe of ISM
- Wide frequency range probes different regions, size scales
- RM synthesis methods

Pulsar Astrophysics

- Current emphasis on timing, exotic objects
  - Stable millisecond pulsars, timing network
  - Strong field tests of GR (BH-NS binary, ...)
- Many mysteries remain in pulsar astrophysics
  - Complex emitting regions
  - Dynamic behaviors
- EoR arrays can address the astrophysics
  - Sensitivity, time resolution, ν range, polarimetry
  - Precision multidimensional single-pulse studies

Pulsar Astrophysics





- Drifting subpulses
- Mode changes
- Nulling
- Etc.

Galactic and Extragalactic (GEG)

- Radio galaxies & clusters
- Faraday tomography & Galactic magnetic field
- Radio recombination lines, H II regions, diffuse ISM
- Surveys
- Magellanic Clouds & nearby galaxies
- Supernova remnants, pulsar wind nebulae & cosmic rays
- Other topics
  - Planets
  - Stars
  - planetary nebulae
  - Galactic Centre
  - pulsars
  - XRBs ...

Arrays built for EoR **must:**

- be very sensitive
- cover a wide frequency range
- have a very wide field of view
- achieve high calibration precision

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They have extraordinary potential for **non-EoR** science on a broad front

Incremental Capabilities/Costs

- Frequency resolution
- Time resolution

} Moore's Law

- Beamforming
  - Modest hardware, significant engineering effort
- Longer baselines
  - Somewhat costly in infrastructure
  - Increased calibration complexity, effort
- Wider frequency range
  - Costly, system impacts, compromises for EoR

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- Time resolution

} Moore's Law

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How should (can) we assess incremental science per $?

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Project Personalities

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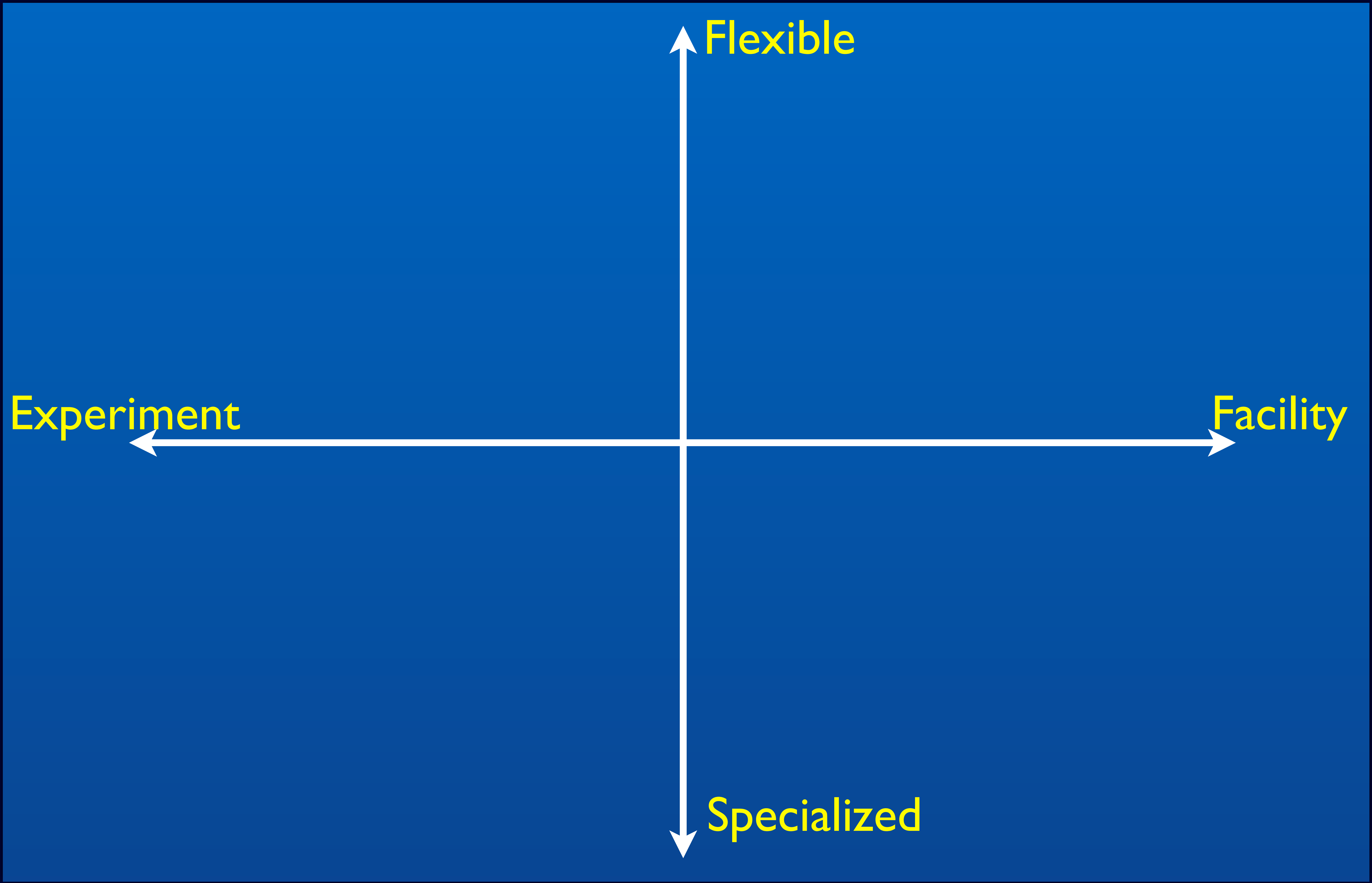

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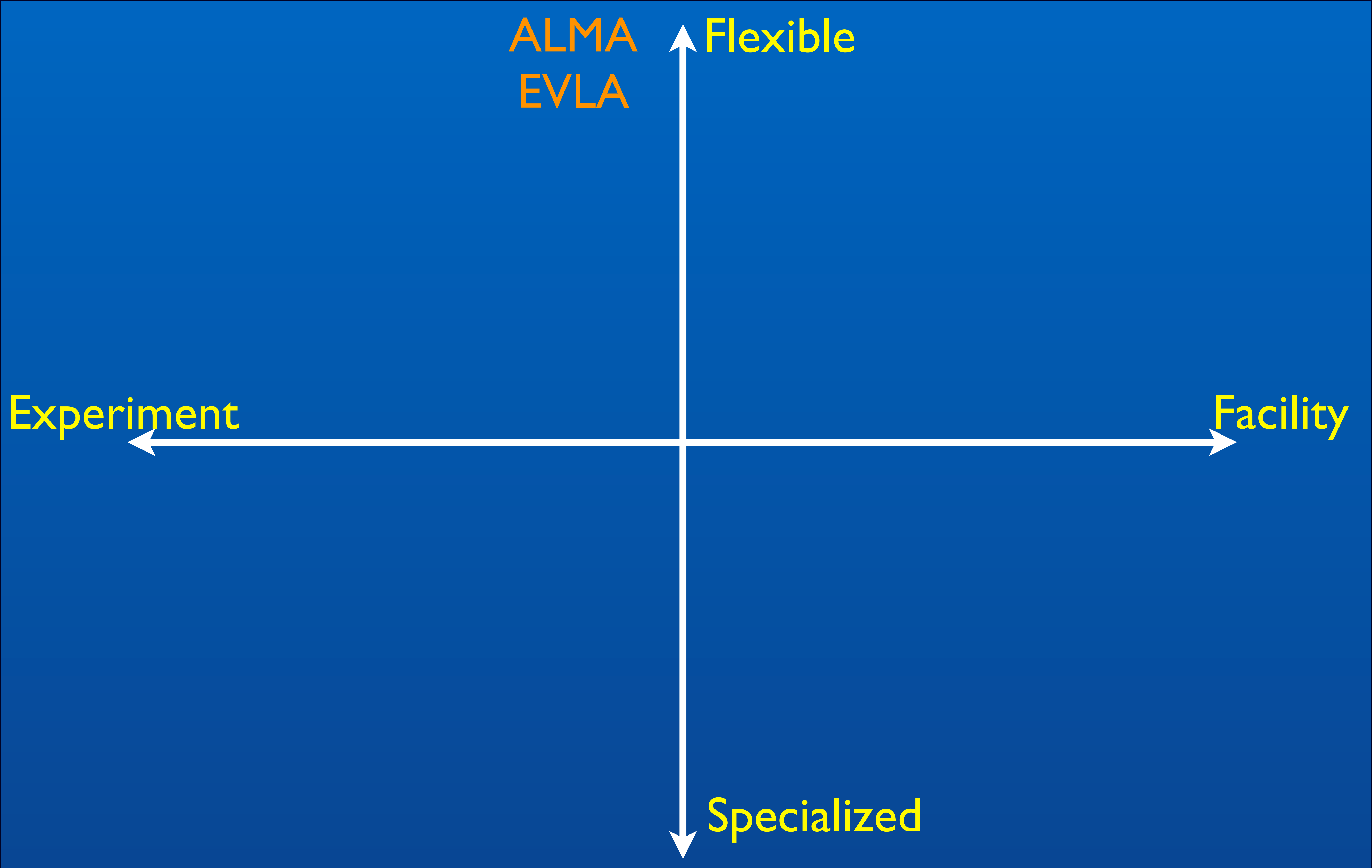

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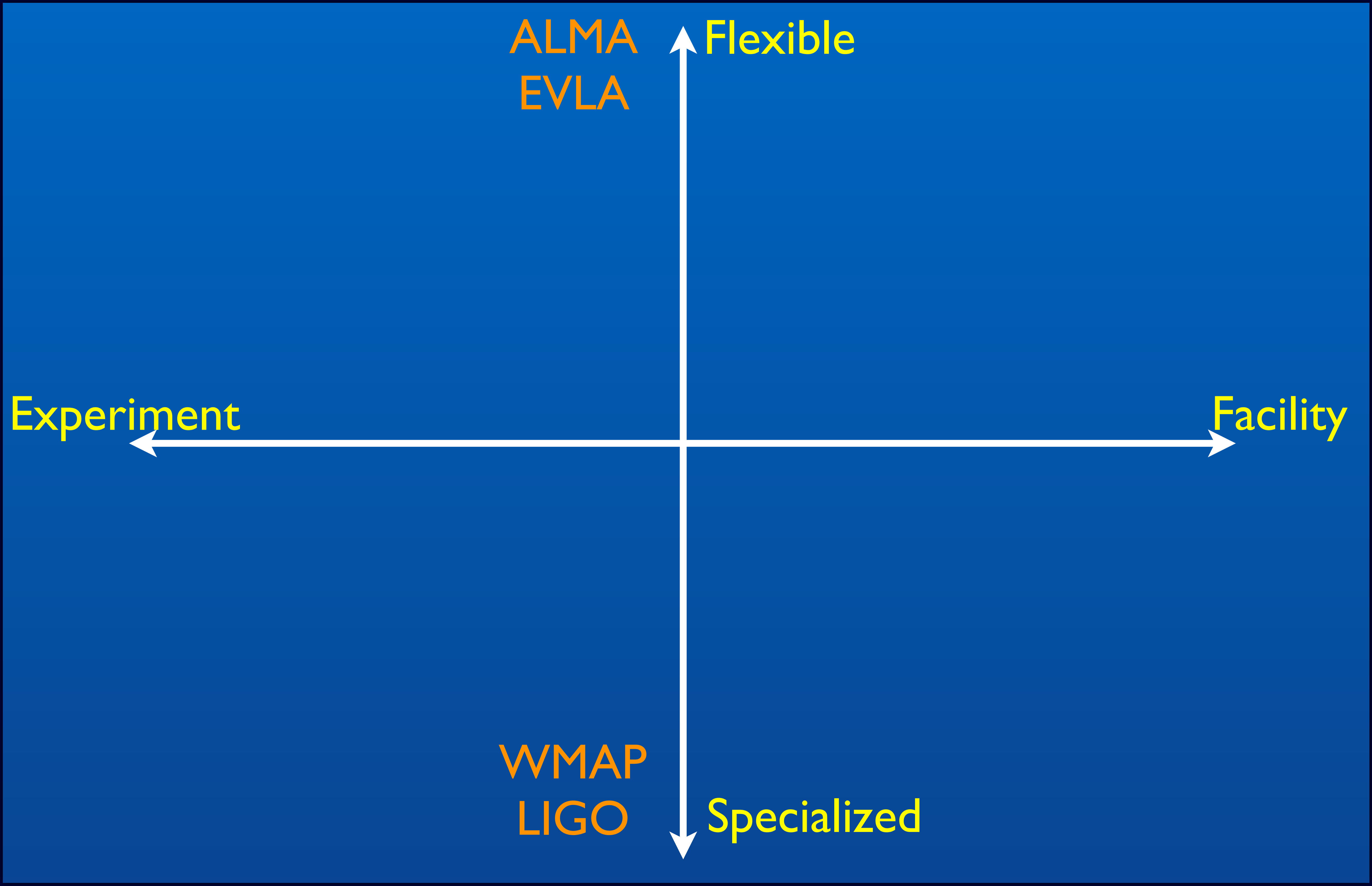

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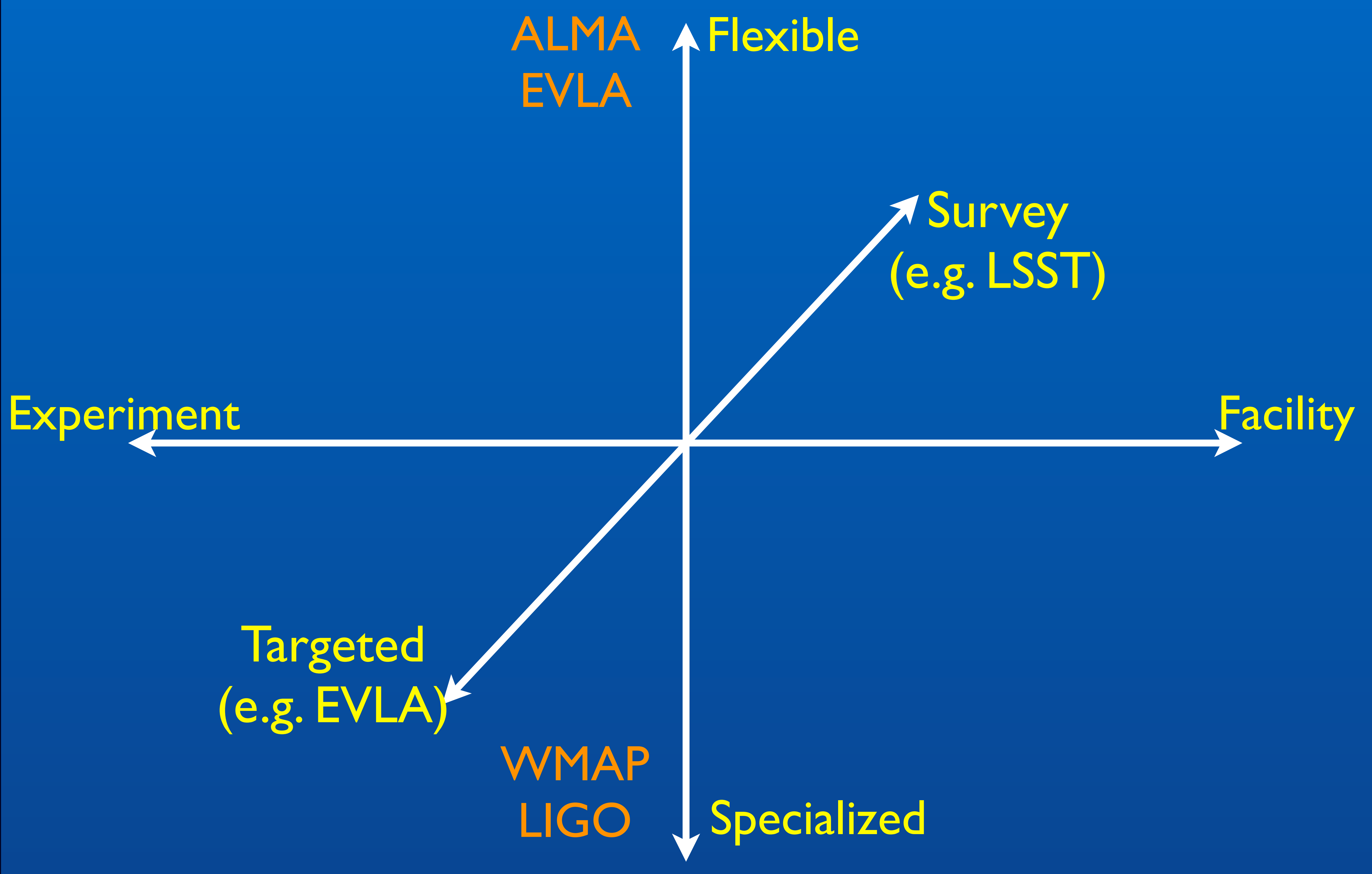

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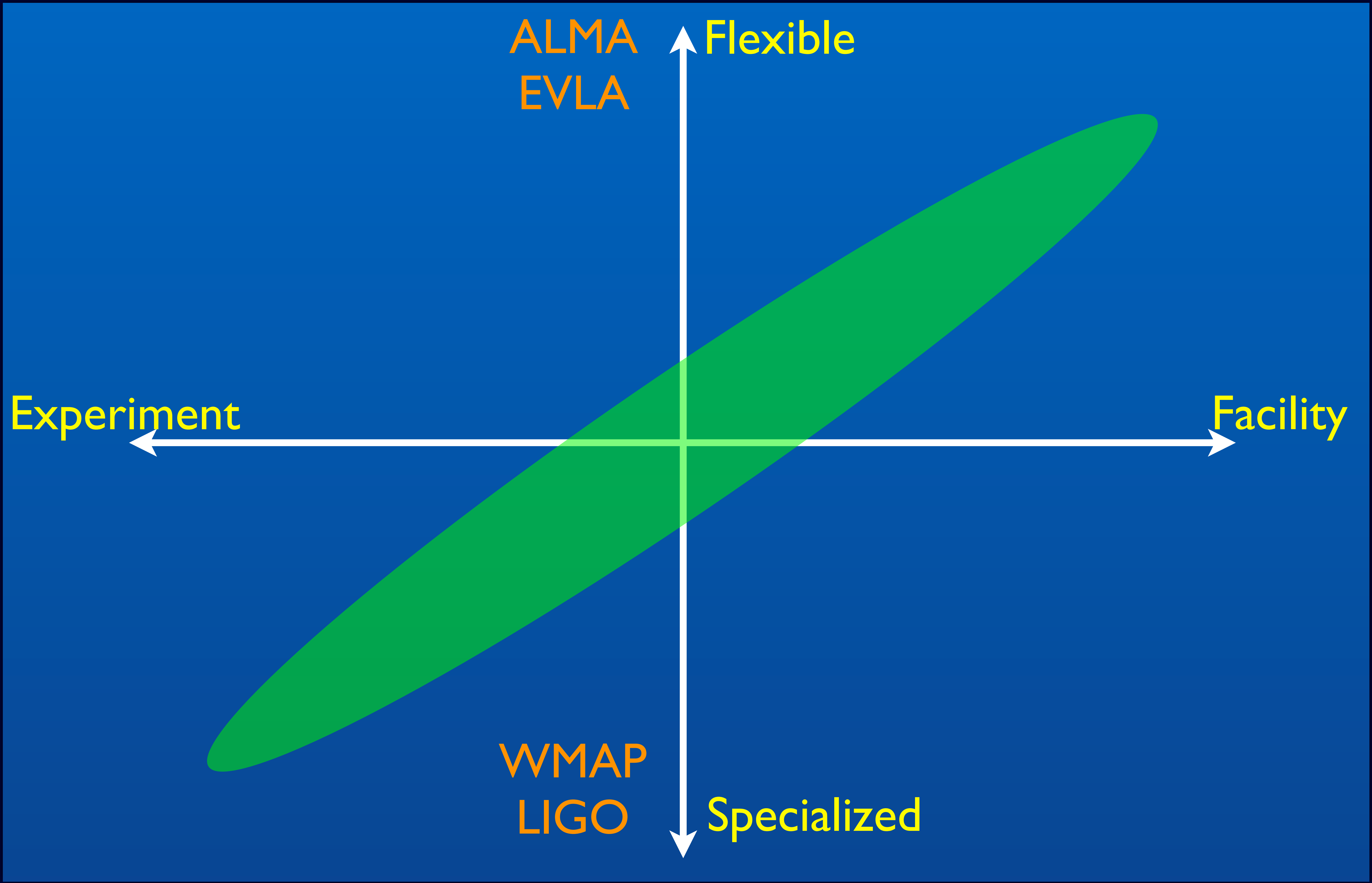

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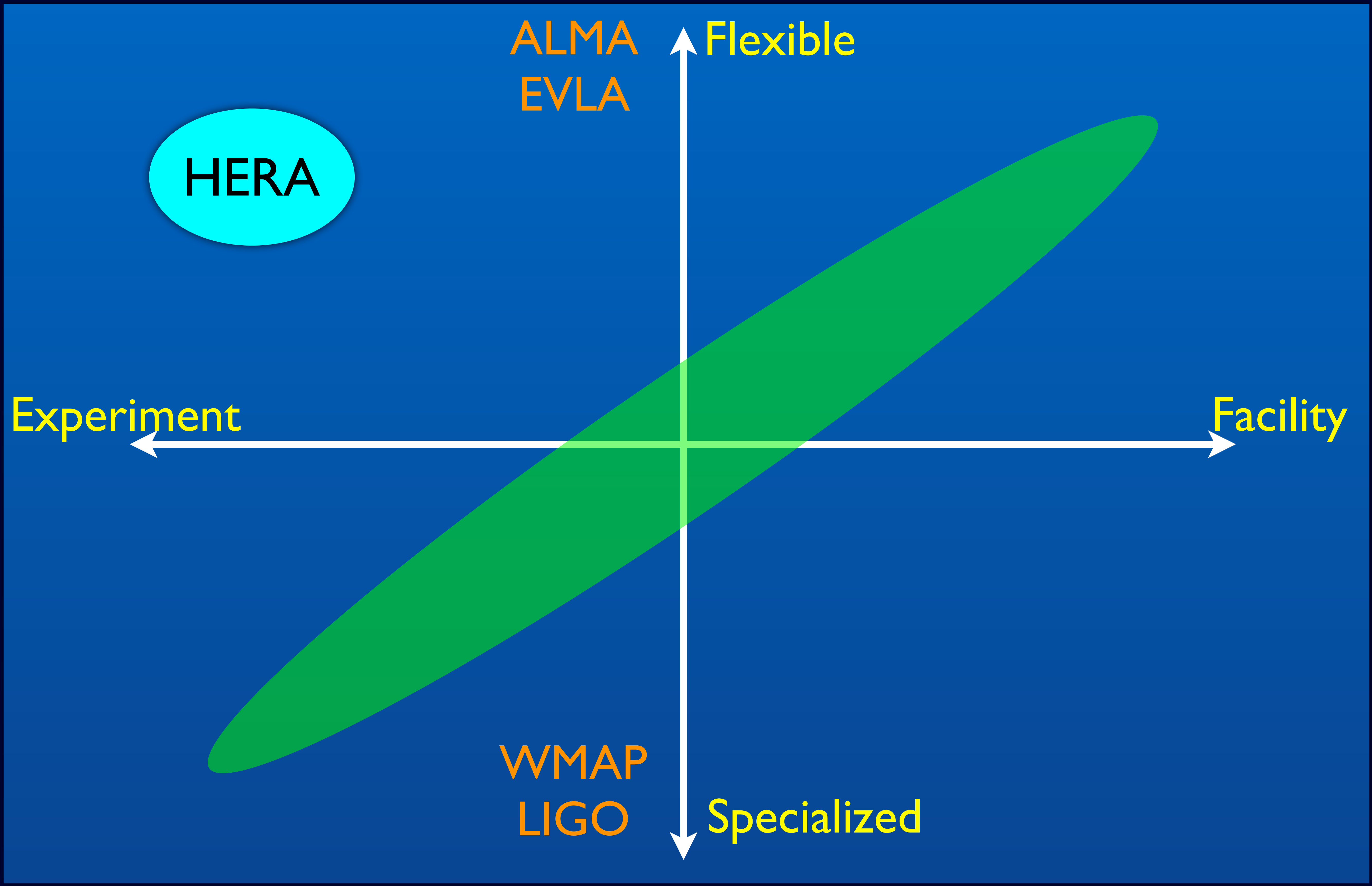

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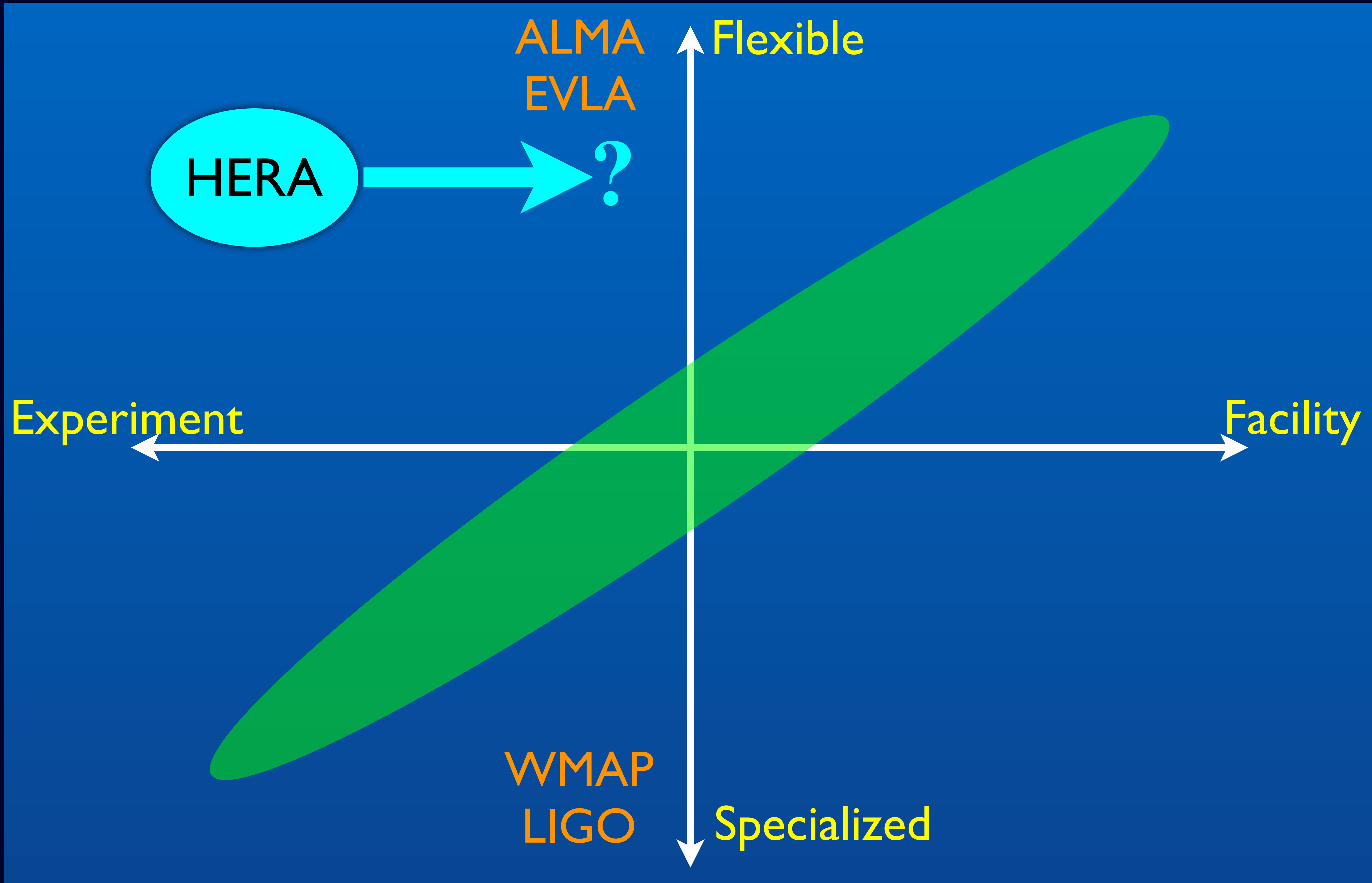

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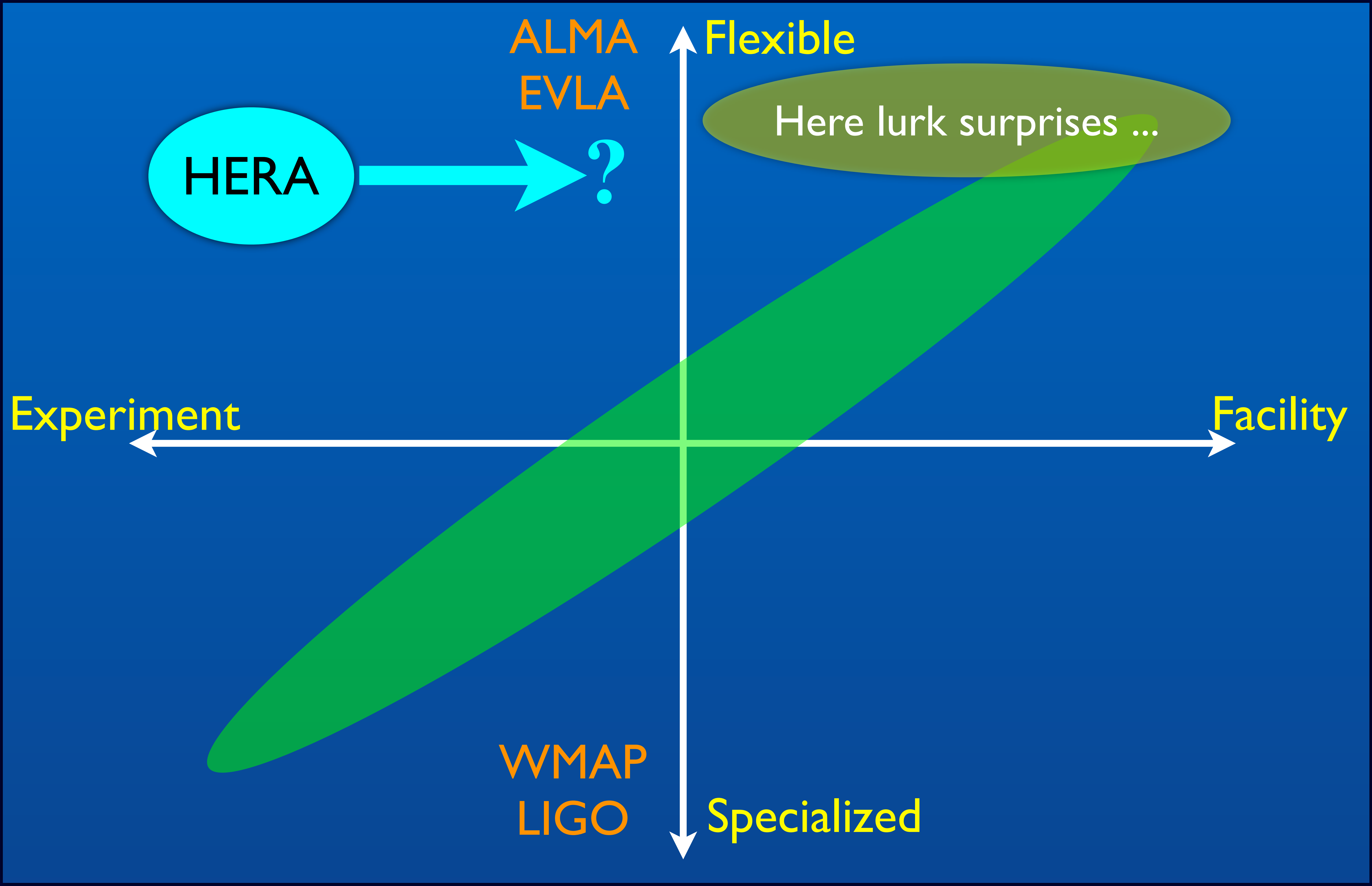

Hypothesis:

The system often

- Overemphasizes “killer apps”
- Underemphasizes science breadth
- Underemphasizes “discovery space”
- Fails to achieve optimum science per dollar