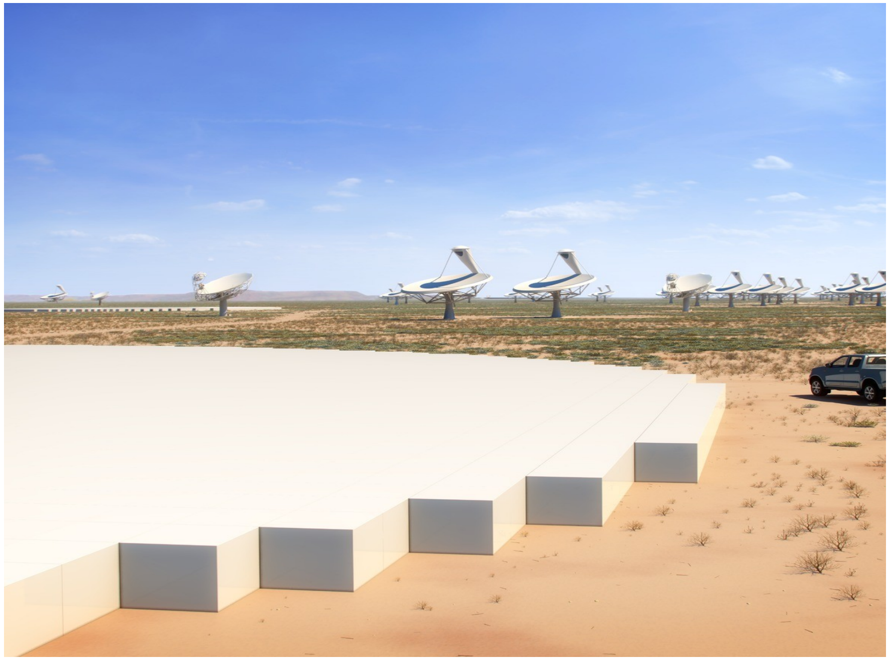
SKA2: some brief thoughts on survey science

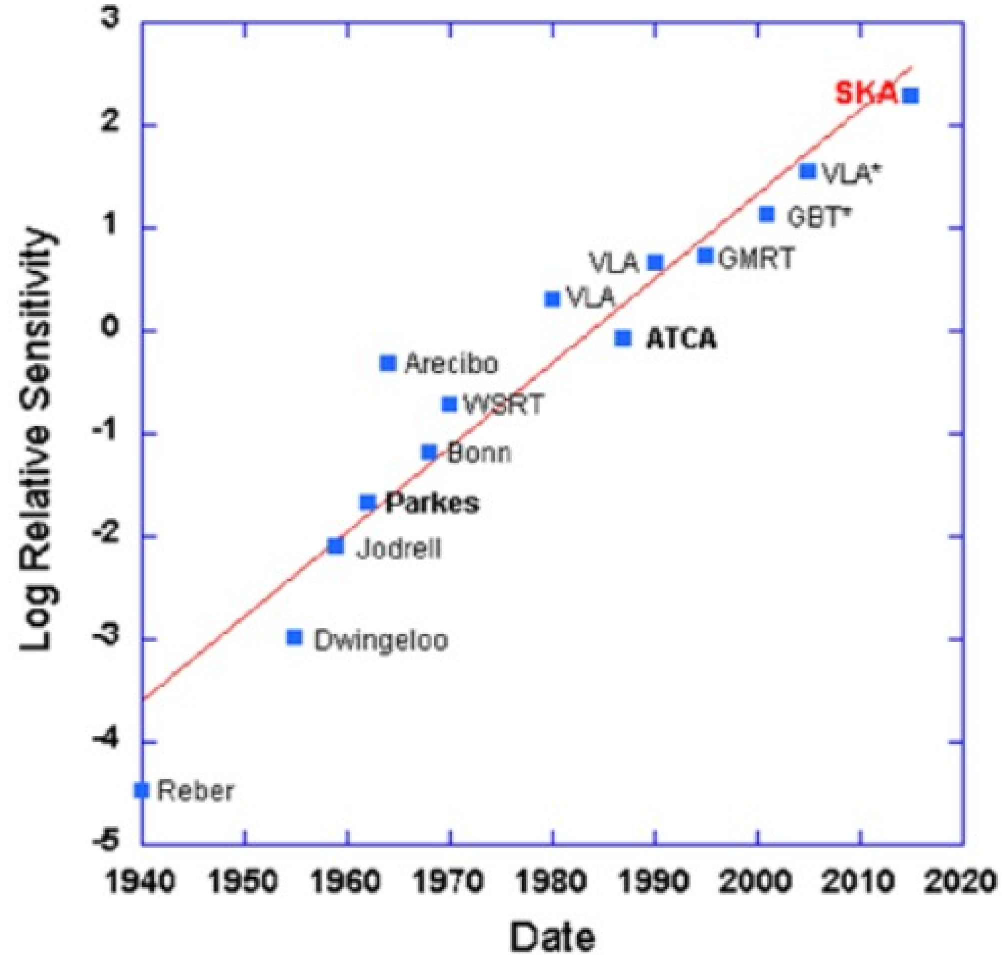
Jess Broderick (ASTRON)



SKA2 is about exponential growth

Braun et al. 2015, AASKA14, 174

- Target (e.g. SKA Design Reference Mission):
  - Sensitivity (A/T) > 10 000 m^2 K^{-1} (~10x SKA1)
  - **Survey speed $(A/T)^2$ x FoV > 10^{10} deg^2 m^4 K^{-2} (~10^4x SKA1)**



Ekers 2010; arXiv:1004.4279

- Technological capability leads to discoveries in astronomy.
- A single technology saturates in capability.
- **Innovation is needed to continue exponential growth!**
- **AIP technologies will result in exciting, cutting-edge science!**

	SKA1	SKA2
The Cradle of Life & Astrobiology Hoare, M. et al. 2015 PoS(AASKA14)115	Proto-planetary disks; imaging snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars.
Strong-field Tests of Gravity with Pulsars and Black Holes Kramer, M. & Stappers, B. 2015 PoS(AASKA14)036	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
The Origin and Evolution of Cosmic Magnetism Johnston-Hollitt, M. et al. 2015 PoS(AASKA14)092	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg^2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg^2.
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ $z \approx 0.04$.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ $z \approx 0.13$.
Galaxy Evolution probed by Neutral Hydrogen Staveley-Smith, L. & Oosterloo, T. 2015, PoS(AASKA14)167	Gas properties of 10^7 galaxies, $\langle z \rangle \approx 0.3$, evolution to $z \approx 1$, BAO complement to Euclid.	Gas properties of 10^9 galaxies, $\langle z \rangle \approx 1$, evolution to $z \approx 5$, world-class precision cosmology.
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.
The Transient Radio Sky Fender, R. et al. 2015 PoS(AASKA14)051	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.
	Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.	Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.
Galaxy Evolution probed in the Radio Continuum Prandoni, I. & Seymour, N. 2015 PoS(AASKA14)067	Star formation rates (10 $M_\odot$/yr to $z \sim 4$).	Star formation rates (10 $M_\odot$/yr to $z \sim 10$).
	Resolved star formation astrophysics (sub-kpc active regions at $z \sim 1$).	Resolved star formation astrophysics (sub-kpc active regions at $z \sim 6$).
Cosmology & Dark Energy Maartens, R. et al. 2015 PoS(AASKA14)016	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.
	Primordial non-Gaussianity and the matter dipole: 2× Euclid.	Primordial non-Gaussianity and the matter dipole: 10× Euclid.
Cosmic Dawn and the Epoch of Reionization Koopmans, L. et al. 2015 PoS(AASKA14)001	Direct imaging of EoR structures (z = 6 - 12).	Direct imaging of Cosmic Dawn structures (z = 12 - 30).
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages ($z > 30$).

$$\boxed{\Omega \left(\frac{A_{\rm eff}}{T_{\rm sys}}\right)^2} \quad [\times B]$$

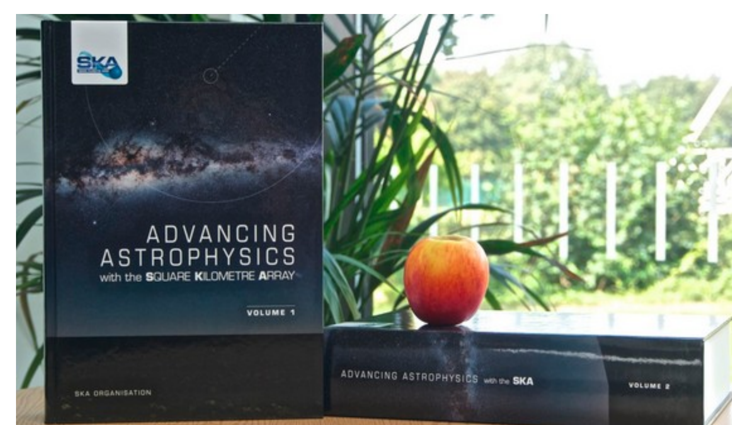
* Billion galaxy surveys (continuum and HI)

* Tens of millions of rotation measures (cosmic magnetism)

* Detailed studies of ~hundreds of nearby galaxies (+ cosmic web, Milky Way, etc.)

How are we going to meet the (very) challenging requirements to do these projects in a timely manner?

For example, SKA2-MFAA requirements: Torchinsky, Broderick et al. 2016, arXiv:1610.00683



HI surveys (21-cm spectral line)

- All-sky billion galaxy survey out to *z*~2 (~470 MHz).
- Cosmology (e.g. BAO – constraining dark energy).
- HI absorption spectroscopy.
- Galactic HI, ISM in nearby galaxies, cosmic web.

- **Example key parameters:**

  * Sensitivity of a few microJy/beam over a bandwidth of ~10 kHz. Column densities < $10^{17\text{-}18}$ cm^{-2}.

  * Moderate angular resolution (~ few - 10 arcsec).

  * Spectral dynamic range ~60 dB.

  * Bandpass stability ~ 1 in 10^6 for up to 1000 hr integration.

- **Thoughts on AIP technologies:**

  * Survey speed of WBSPF dish generally won't meet current requirements (but see next slide).

  * MFAA and PAF – what is the minimum acceptable FoV to do a large survey in a timely manner? Really need an MFAA solution...but what about studies of nearby galaxies?

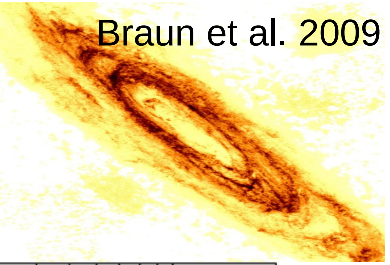
  * Differences in survey speed as a function of frequency – at what redshifts will the key science be?

  * Get all the bandwidth in one go (no band 1 / band 2 split as in SKA1) → map HI over 10 Gyr of cosmic time.

  * Will there be a role for intensity mapping in SKA2?

$$N_{\rm HI} = \frac{2.34 \times 10^{20}}{\theta_1 \theta_2}(1+z)^4 \int s(\nu)d\nu \ ({\rm cm}^{-2}),$$

e.g. Fernández et al. 2013



Braun et al. 2009

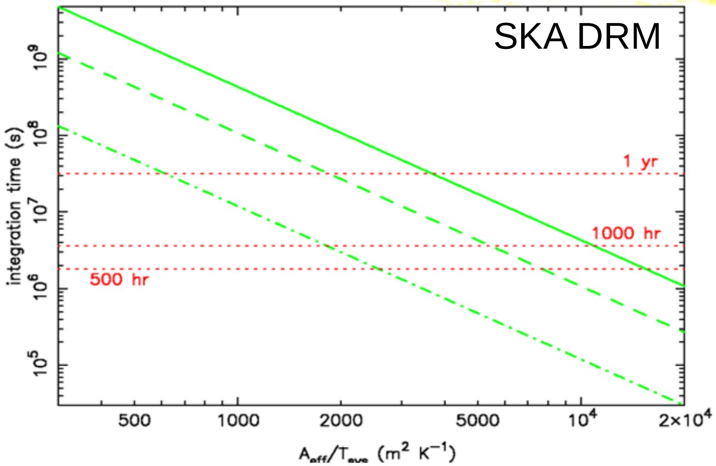
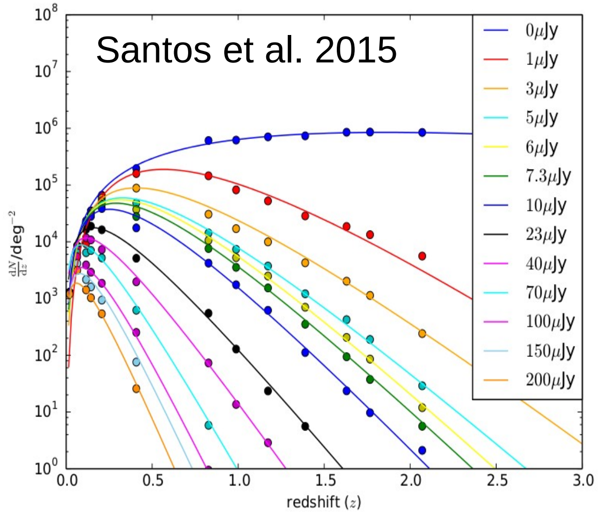


Figure 7.1. Integration time required to detect H I galaxies at redshift $z = 2$ as a function of telescope sensitivity. Three H I masses are shown, 5×10^9 M$_\odot$ (solid), 10^{10} M$_\odot$ (dashed), and 3×10^{10} M$_\odot$ (dot-dash). Horizontal dotted lines indicate various fiducial integration times.



Continuum surveys – total intensity

- Three billion galaxy survey.
- Star formation rates / astrophysics out to high redshift; interplay between star formation and AGN activity.
- Weak/strong lensing.
- Galaxy cluster science.

- **Example key parameters:**

  * Sensitivity of a few nJy/beam over a bandwidth of ~few hundred MHz. Excellent surface brightness sensitivity and image fidelity.

  * Angular resolution < 0.5 arcsec.

  * Image dynamic range ~70 dB.

  * Frequencies ~600 MHz – 10 GHz.

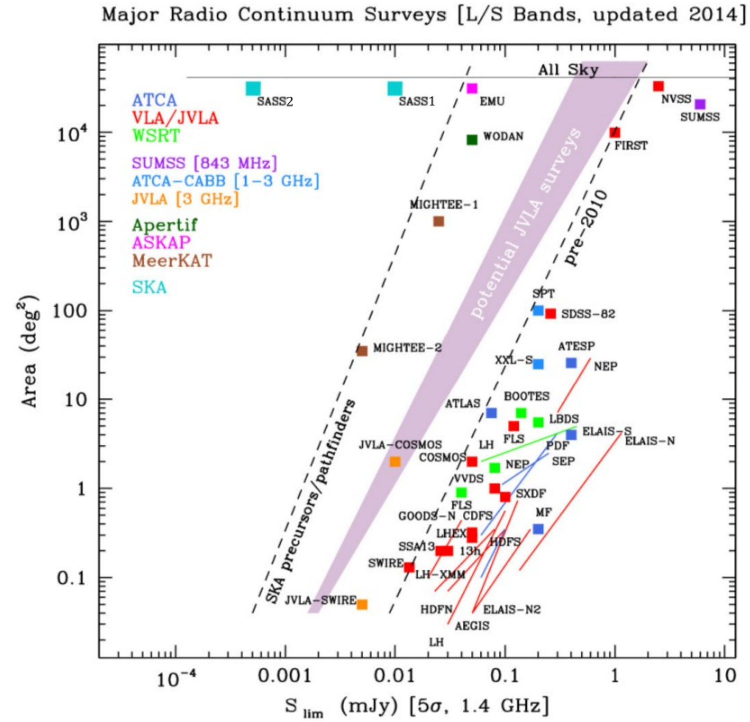
- **Thoughts on AIP technologies:**

  * Probably more of a focus on resolution, rather than FoV. What is a sufficient FoV? Or do we get the survey speed from the wide bandwidth?

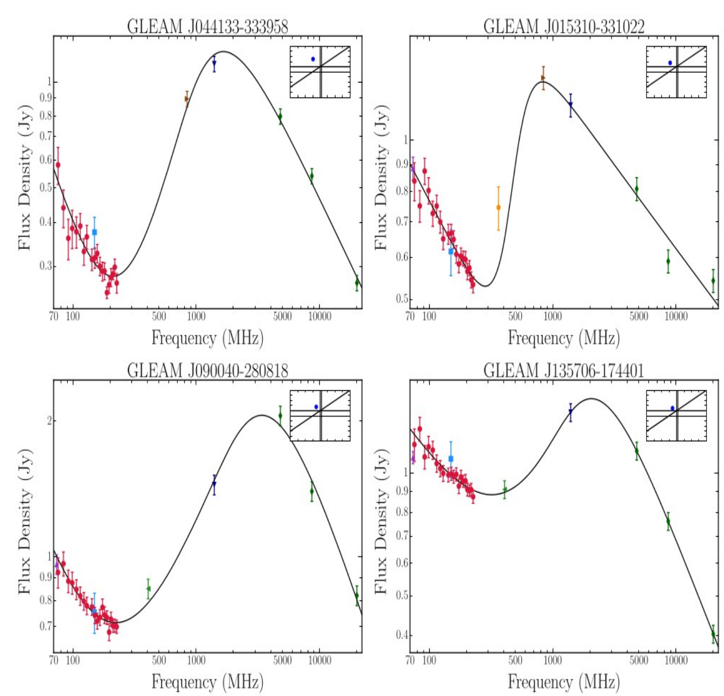
  * There is a push to focus on smaller regions with high-quality ancillary data, and really go to high resolution (e.g. 30 mas; Jarvis et al. 2015)

  * Wide-band radio SEDs – multi-epoch activity, non-thermal/thermal components, energy losses, etc.

  * Wide bandwidths: commensality with HI – e.g. breaks degeneracies in mass models used in strong lensing studies.



Norris et al. 2015



Callingham et al. 2016

Continuum surveys - polarization

- Dense rotation measure grids; magnetic field structure of Milky Way, magnetoionic media of intervening galaxies along line of sight to distant radio sources.
- Magnetic field tomography of nearby galaxies.
- Deep polarization source counts; broadband spectropolarimetry.

- **Example key parameters:**

  * Stokes Q, U sensitivities of a few tens of nJy/beam over a bandwidth of > 500 MHz.

  * Angular resolution ~ few arcsec.

  * Polarization purity ~ -25 dB.

  * Frequencies ~ 400 MHz – 2 GHz and above.

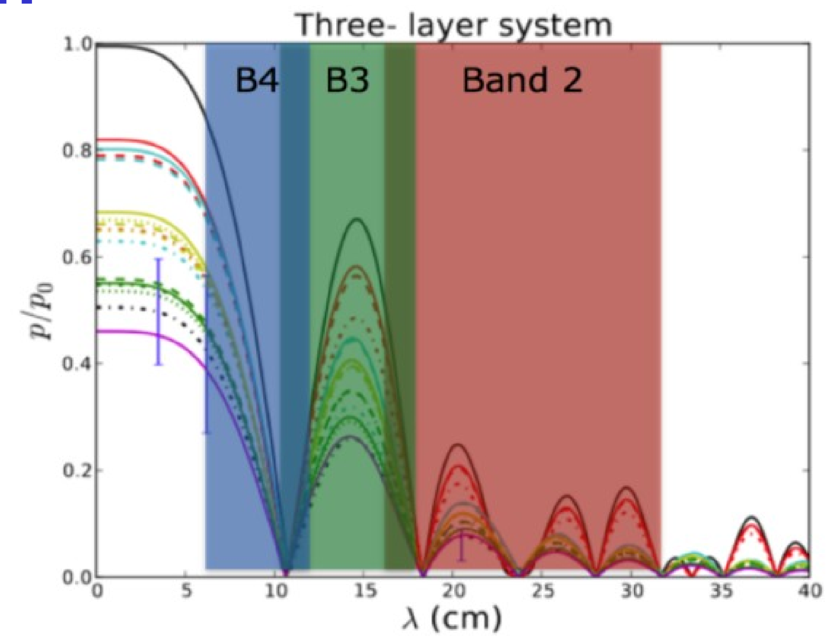
- **Thoughts on AIP technologies:**

  * Clear commensality with the continuum surveys. Large FoV and/or wide bandwidths for survey speed.

  * Wider bandwidths definitely help with RM resolution, although diminishing returns going to higher frequencies.

  * But potentially very interesting wide-bandwidth science to be done in terms of models for depolarization (e.g. Burn 1966; Tribble 1991; Sokoloff et al. 1998). Higher frequencies to recover polarized source population?

  * Challenges with polarization calibration, especially off-axis response? E.g. discussion in Braun et al. 2013. Removing polarized foregrounds important for e.g. BAO studies!



Heald et al. 2015

$$\mathrm{RM} = 0.812 \int_{\text{source}}^{\text{observer}} n_e(l) B_{\parallel}(l)\, dl \ \ \mathrm{rad\ m^{-2}}$$

$$\delta\phi \approx \frac{2\sqrt{3}}{\Delta\lambda^2}$$

$$\text{max-scale} \approx \frac{\pi}{\lambda^2_{\min}}$$

Brentjens & de Bruyn 2005

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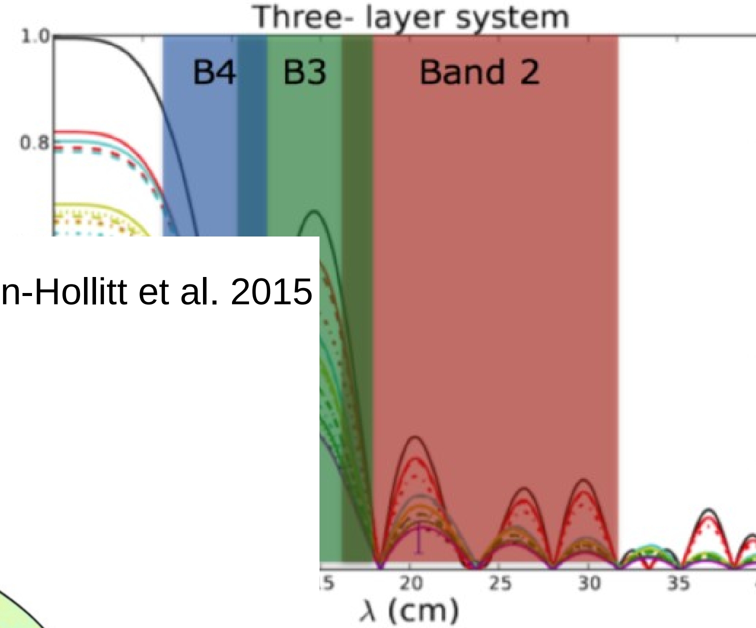
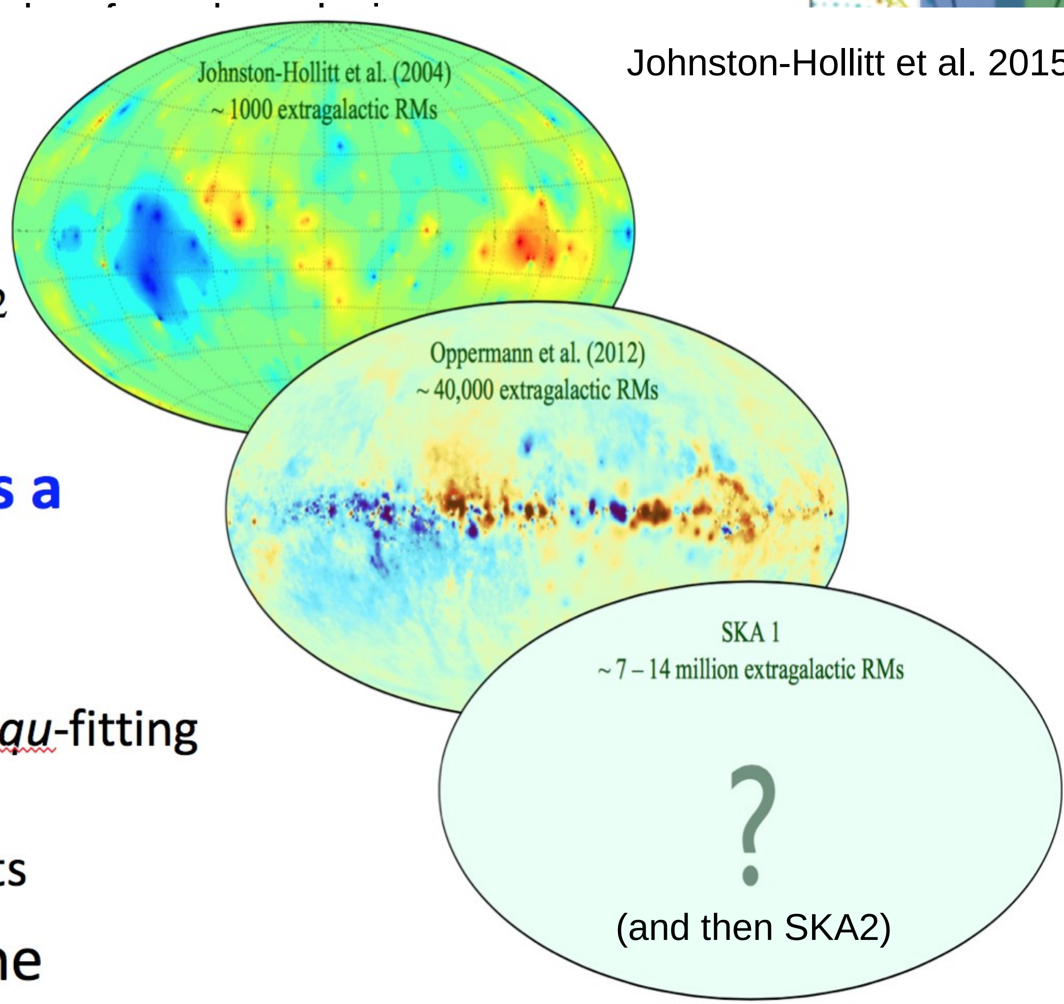


et al. 2015



Johnston-Hollitt et al. 2015

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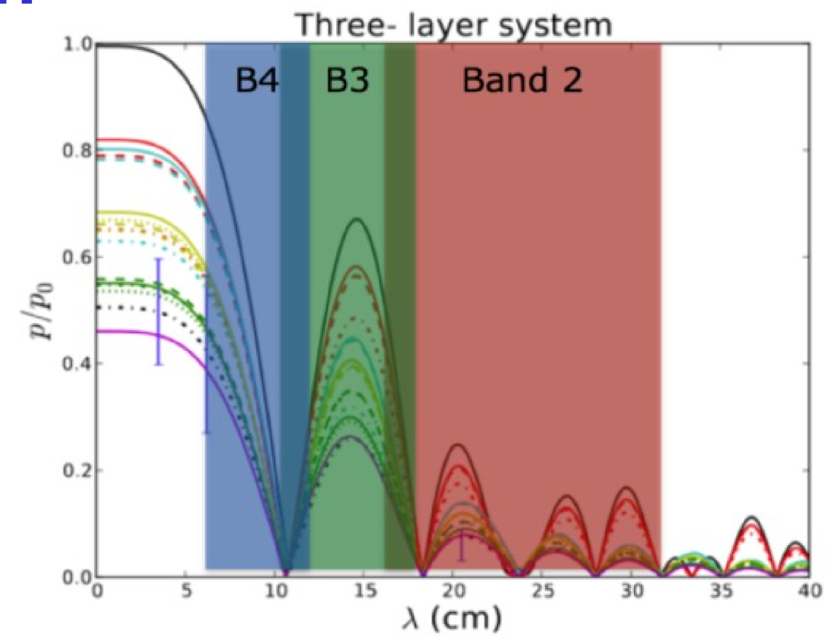

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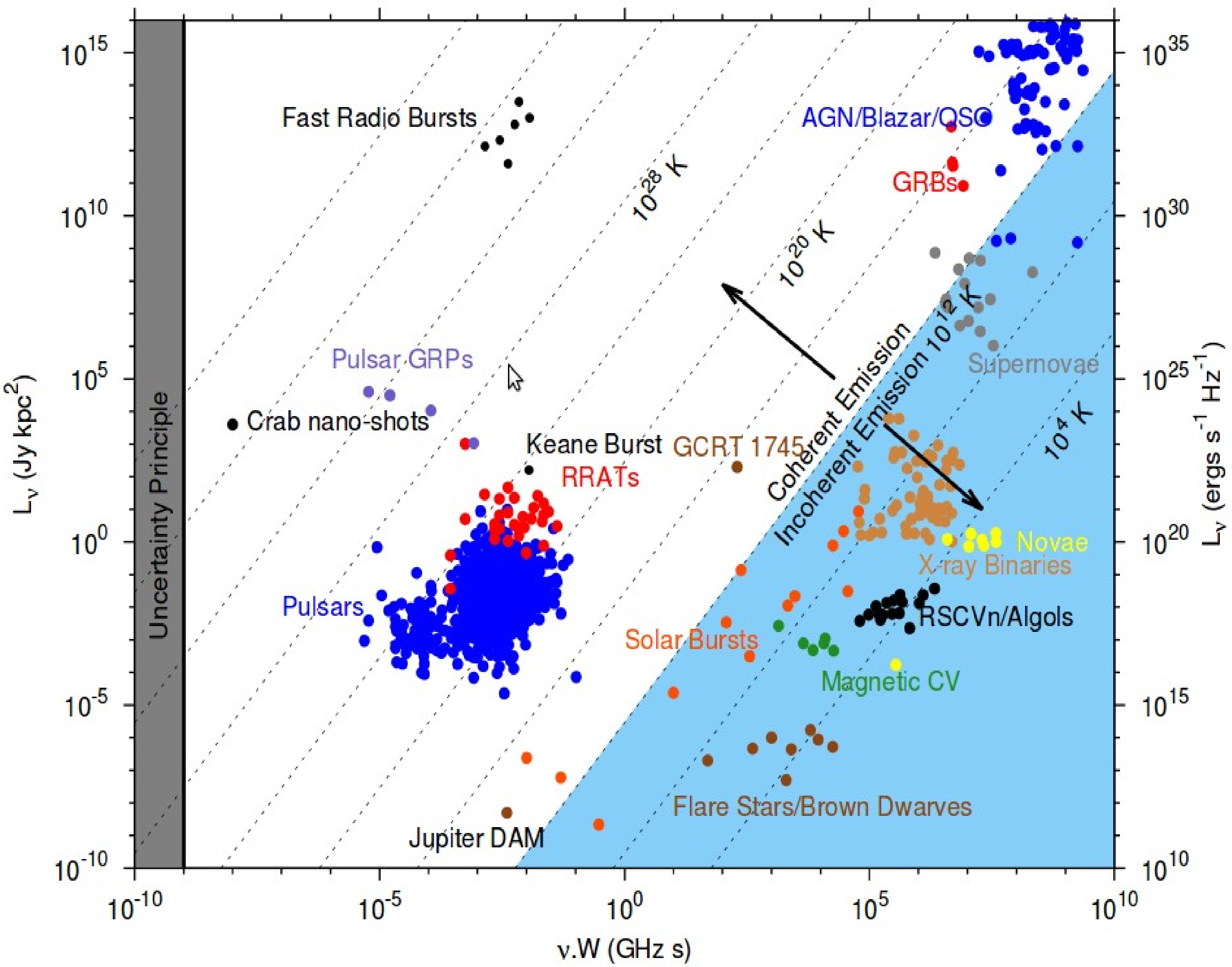
Quick remark on transients

Pietka, Fender & Keane 2015



$$\Omega S_0^{-3/2+\delta}$$

- No substitute for FoV!
- Cosmology with FRBs; exploration of the unknown.
- Wide bandwidth to constrain physics of ejections.
- Commensality with general surveys; polarization as a diagnostic.

Other remarks

- **AIP technologies are absolutely necessary to ensure that the SKA2 survey science goals can be met!**
- But there isn't an obvious single solution just yet. This will depend on how the various science cases evolve with the SKA pathfinders, and SKA1. The relative importance of all-sky, deep HI may tip the balance towards a very wide FoV solution, though.
- Other important science too (e.g. simultaneous observations of spectral lines).

- Hybrid combinations?

  * e.g. MFAA core + PAF dishes on the longest baselines.

  * PAF + WBSPF dishes?

  * Other combinations?

- If we make sacrifices to e.g. sensitivity of one component, what is deemed 'graceful' degradation?

- How much flexibility do we incorporate into the design to ensure unexpected discoveries (e.g. Wilkinson et al. 2015).

- Is there a successor to the current generation of AIP technologies?

- Are there new and smarter ways to process the data?

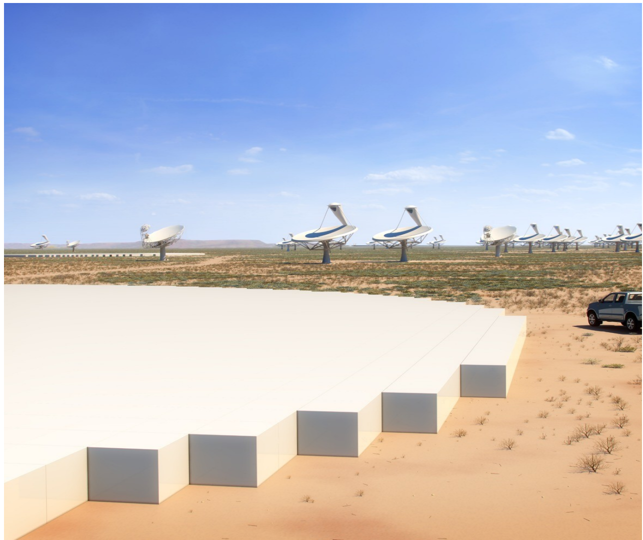


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Table 1: Selection of molecular line tracers between 1-10 GHz and within the bands of SKA-1. Lines of the OH radical and various other species are also of key importance but for brevity not included below.

Line	Rest freq (MHz)	SKA-1 MID band	SKA-1-SUR band
HCN $v_2 = 1, \Delta J = 0, J = 2$	1346.765	2	2
HCN $v_2 = 1, \Delta J = 0, J = 4$	4488.4718	4	-
H_2CO	4829	4/5	-
N_2H+	5009.8278	4/5	-
H_2CNH $1_{10} - 1_{11}, \Delta F = 0, \pm 1$	5289.813	5	-
HCO+	6350.908	5	-
HNC	6484.497	5	-
CH_3OH $5_1 - 6_0 A^+$	6668.5192	5	-
HCN $v_2 = 1, \Delta J = 0, J = 5$	6731.9098	5	-
HCO+	8890.452	5	-
HCN $v_2 = 1, \Delta J = 0, J = 6$	9423.3338	5	-
HNC	9724.644	5	-

Beswick et al. 2015

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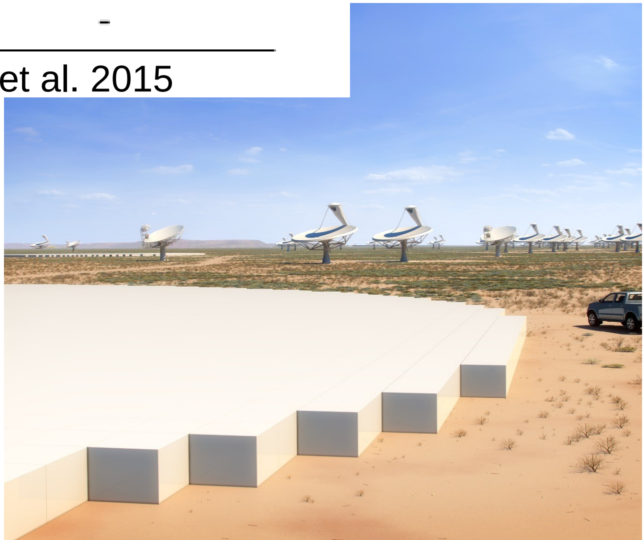

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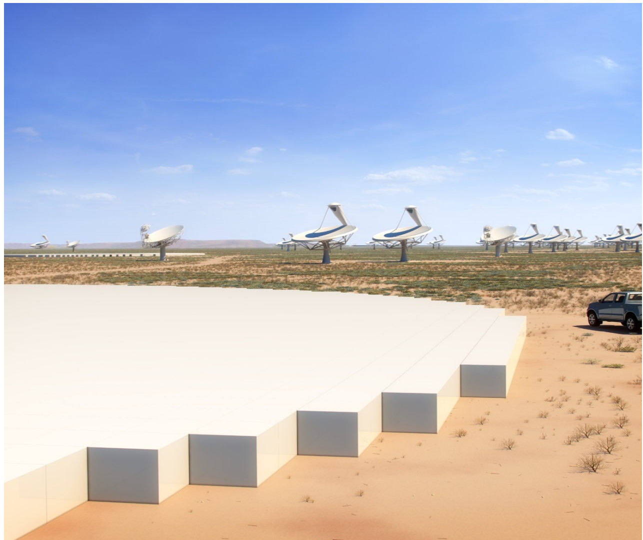

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