SKA Science Case for the ASTERICS Policy Forum

1. Correlated survey constraints on cosmology and dark energy

Studies of the Universe's large-scale structure (LSS) constitute the future of Cosmology. After extracting almost all the information we could from the Cosmic Microwave Background, which tells us about the primordial Universe, we now need to understand its latest times. We recently entered the Dark Energy (DE) dominated era, therefore it is with late-time probes that we have our best chance to understand what this mysterious component really is, for example by constraining its equation of state.

The Square Kilometre Array (SKA), thanks to its redshift depth and survey speed, will provide LSS surveys with game-changing potentialities to deepen our understanding of the Universe. Fully realising such potential, however, strongly relies on the use of Multi-Wavelength/Multi-Messenger (MW/MM) information:

1. By measuring redshifts, therefore enabling a fully 3D continuum survey;
2. By allowing cross-correlations of different tracers, which ~~reduces~~ systematics and improves the constraints;
3. By identifying different radio galaxy populations, therefore allowing the application of the powerful multi-tracer technique.

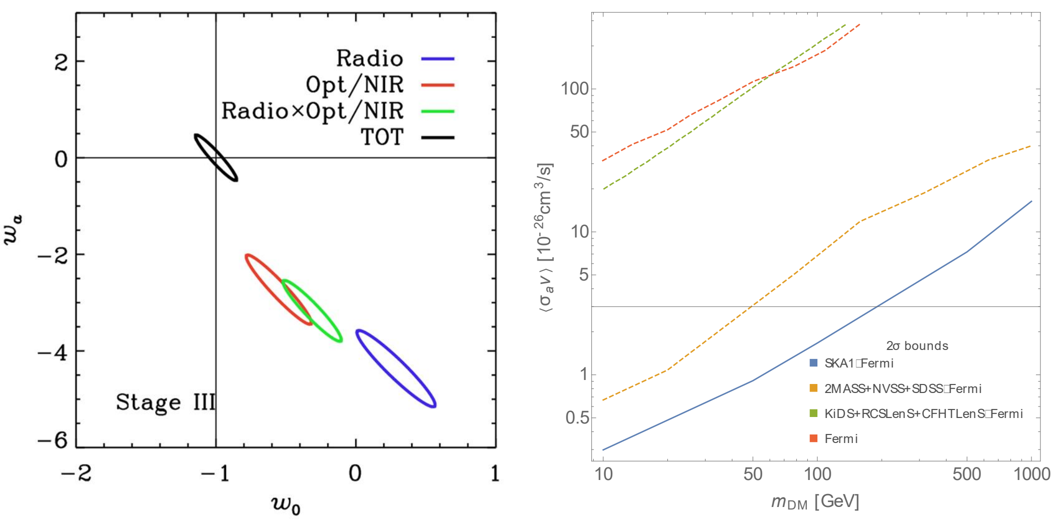

Figure 1 Left: constraints on the DE equation of state from Stage III (SKA1, DES) WL surveys. Individual surveys are strongly biased in the presence of calibration errors, while the cross-correlated signal is unbiased. From Camera et al. (2017). Right: The area above each curve represents the DM particle models probed (at 2σ) by existing datasets. Gamma-ray data alone (Fermi) have limited power, while the forecast of SKA1 with Fermi has by far the best constraining power.

1.1. Measuring redshifts for SKA continuum surveys

Surveys in radio continuum are strictly 2-dimensional (2D), because the featureless frequency spectrum of radio sources does not contain any redshift information. Measuring redshifts enables us to construct a 3D survey of the LSS, which is a much more powerful cosmological probe. Optical/IR data for the same survey area (e.g. Euclid, LSST/WFIRST) would provide spectroscopic redshift counterparts for the radio catalogue. Additionally, follow-ups with an instrument like E-ELT would provide high-accuracy spectroscopic redshifts for a subset of the sources, therefore enabling an optimal calibration and correction of systematics for the sample of photometric redshifts.

1.2. The power of cross-correlation

Cross-correlation of different probes is immune to certain systematics that affect each of them individually. Fig. 1, left illustrates the power of cross-correlation to remove systematics for a Weak Lensing (WL) survey performed in the radio with SKA1 and in optical/IR. Moreover, cross-correlations can be sensitive to a specific component of the total signal. This is the case of radio and gamma rays, which can isolate the signal due to Dark Matter (DM) annihilation from the astrophysical one due to blazars. Fig 1, right illustrates the resulting improved constraint on DM particle models, which strongly motivates the synergy between SKA, Fermi and CTA. In the context of DM searches, neutrino emission (KM3NET) would also be extremely valuable, to probe DM annihilation/decay, and to test neutrino DM scenarios.

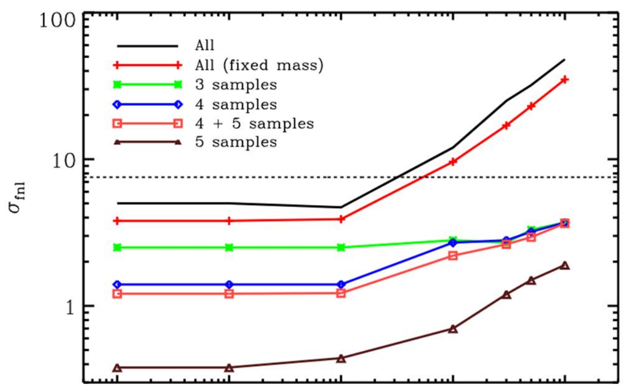

Figure 2 Error on the primordial non-Gaussianity from LSS radio surveys as a function of detection limit and number of source populations. For an SKA1 survey (1 μJy limit) at least 3 populations are needed to improve over the current constraint (dotted line). From Ferramacho et al. (2014).

1.3. The multi-tracer technique

Different populations of radio sources - Active Galactic nuclei (AGNs), star-forming galaxies, and their sub-populations - are typically associated with a DM halo of different mass. Therefore, being able to separate radio galaxies into different populations effectively adds an extra layer of information. This is illustrated in Fig. 2, for the constraining power of LSS surveys on primordial non-Gaussianity. Classification of radio sources relies on MW data. In particular, high-energy radiation (X, gamma rays) is a strong indicator of AGN activity, while star formation would have an optical/IR counterpart but weaker high-frequency emission.

1.4. Common observing strategies

The science cases described involve SKA, CTA, E-ELT and KM3NET together with other optical (LSST, Euclid), IR (WFIRST) and gamma-ray (Fermi) instruments. The specific needs are:

- For survey instruments, observing the same area of the sky as the SKA cosmological radio surveys, ideally with comparable depth;
- For single-object instruments, a follow-up program of a subsample of the objects detected by those surveys.

Time synchronization is not required, because the SKA deep radio surveys require long integration time. The use of archival data is therefore in principle a valid option. Given the critical importance of the MW/MM information to enable the science described, however, a data-sharing policy is advised during the period observations are taken, and before the various datasets are publicly released. This would allow a timely inclusion of the MW/MM information in the scientific analysis of the SKA data, and would prevent the risk of the joint analysis being performed by external teams. A complication is given by the fact that time for all SKA observations will be allocated through normal submission and review procedures, therefore the exact details of the surveys, as well as time for completion, cannot be planned much in advance.

2. Coordinated FRB localization and characterization

Fast radio bursts (FRBs) are millisecond-duration pulses of radio waves that appear to originate from vast cosmological distances. The progenitors of these signals are as yet unknown and identifying what causes FRBs is one of the biggest mysteries in current-day astrophysics. While the question of what they are is open, it is already clear that they can be used for a number of key applications in astrophysics and cosmology. For example, they can be used to weigh the so-called "missing baryons", study intergalactic magnetic fields and measure the dark energy equation of state parameter. This is because the cosmological characteristics of the Universe are imparted onto the radio signals as they propagate through the cosmos, and these characteristics can, if the FRB is detected, readily be gleaned from radio telescope data. However, FRBs are very difficult to catch. Although they happen quite often, many thousands per sky per day, they are observed only very rarely; the FRB Catalogue (a query-able MySQL-based online database at the following URL: http://frbcat.org/) lists just 29 known, at the time writing.

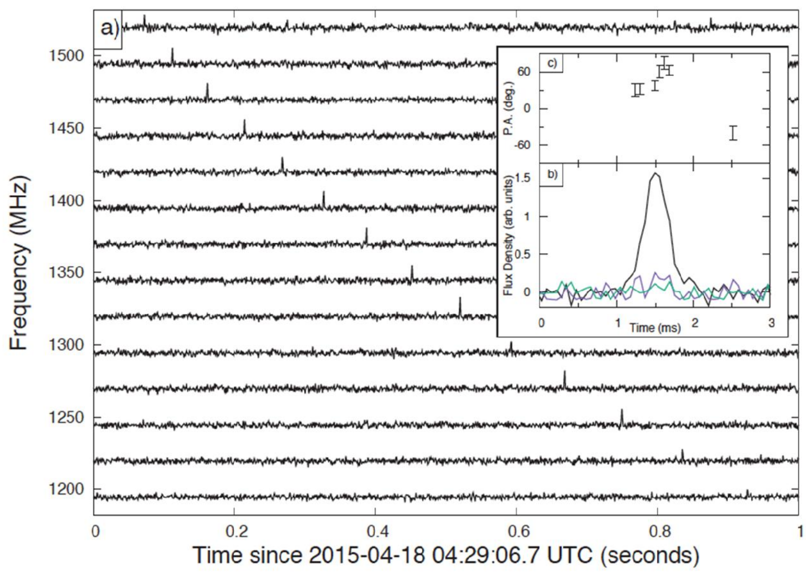

Figure 3: An example of a fast radio burst detected with the Parkes radio telescope in Australia from Keane et al. 2016, Nature, 530, 453. The dispersion of the signal can be seen as the pulse arrives first at the higher frequencies with the lower frequencies coming in later, according to a strict frequency-dependent law. The amount of dispersion maps to the amount of material the signal has passed through en route to Earth and, if an ensemble of localized FRBs could be detected, can be used to weigh the baryons in the Universe.

To address both key lines of investigation with FRBs (What are they? What can be done with them?) one must find *many* more, thousands of FRBs are needed. To fully exploit the science applications all of these must be localized. Here we meet a problem – to detect FRBs requires large sensitivity and this has so-far involved large single dish telescopes. This means that the localization is very poor, so that the underlying host galaxy is difficult/impossible to identify meaning most science applications cannot be addressed. To localise requires a large array of smaller elements, with a large-scale beam-former. The Square Kilometre Array (SKA) fits the bill perfectly for this, and this is why FRB studies are of its 13 High Priority Science Objectives. Using the SKA for FRB studies gives the simultaneous benefits of a wide field of view arising from the small elements (increasing the detection rate), the sensitivity of a large collecting area (further increasing the detection rate, and more impactful than the field of view), and the spatial resolution of the array size. The latter allows localisation of each FRB to a unique host galaxy. With this done one can obtain the redshift of the galaxy (via optical observations) and combine this with the radio information to exploit the science.

The SKA cannot do FRB science in isolation. Multi-wavelength synergy is needed. With the SKA one can measure the dispersion measure (DM, not to be confused with dark matter) of an FRB, and identify the galaxy wherein it came. However, the DM must be compared with the redshift of the galaxy, and this requires optical/infra-red observations. How the DM and redshift relate (and the variation in this relation as a function of redshift) is a key scientific diagnostic. FRBs can already be detected with DMs corresponding to roughly redshift 2, with the 64-m Parkes telescope. As the comparative gain of SKA1-Mid is an order of magnitude more even higher redshift FRBs are expected, requiring very powerful optical follow-up and suggesting a natural need for synergy with the ELT. Another need that the SKA has to maximise FRB science output is to have synchronised observing programmes – if there are multi-wavelength associations (currently unknown) of FRBs then we would ideally like to have 'before' as well as 'after' (and of course 'during') images of the fields.

Furthermore, we want simultaneous coverage across the radio band. For example, SKA1-Mid could detect an FRB and then alert SKA1-Low as to where to point so as to measure the DM more precisely at the lower frequencies; this is possible as the delay from Mid to Low frequencies can be several minutes. Similarly, the wider world must be triggered, and be able to trigger the SKA (if a putative high-energy FRB-associated signal is seen before the radio signal). To this end an FRB VOEvent standard has recently been developed and a white paper prepared and issued. Currently the world-wide community of FRB search teams is beginning to adopt this model and in 2018 we should see rapid public alerts of FRB discoveries from the established telescopes (Parkes, UTMOST, ASKAP) and up and coming facilities (CHIME, MeerKAT). The progress in terms of specific VO tools to assess these VOEvents (some will be false positives) has not yet been made as these are the early days of this work, but scientific benefit is certainly foreseen with progress in this area.

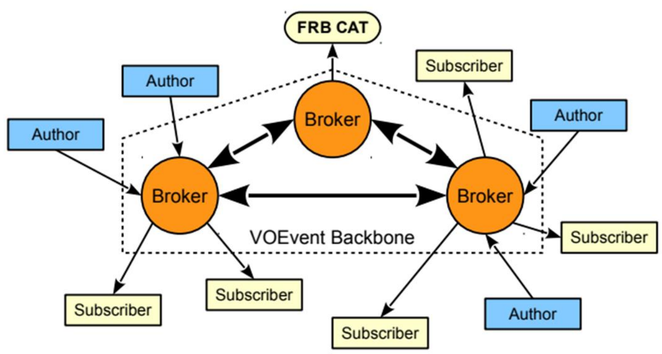

Figure 4: A schematic of how the FRB VOEvent framework interacts with the FRB Catalogue, and the outside world from Petroff et al. 2017, astro-ph/1710.08155

FRB science puts unique constraints on facilities operationally. For example, with SKA, it is a driver behind the need to perform commensal searches. The more you observe the more FRBs you find. With the addition of computing capabilities one can push this to 24/7 observing to maximise this parameter to the search, and this is what is planned for SKA. With FRBs being detected many times per day there is a need for redundancy in the other facilities working with SKA; it is no use having nice optical telescopes working in tandem if it is day-time there when you find an FRB!

3. Operational considerations

The sections above describe two SKA science cases and how they would benefit from multi-messenger/multi-wavelength data. In this section, we discuss the operational support of a MM/MW strategy by considering what mechanisms are currently in place, some options for new processes and issues that would need to be addressed.

3.1. Current operational support models

Most observatories will instruct their time allocation committees (TACs) to consider proposals that require complementary data sets from other observatories to realise the proposal's science goals. Such proposals are regarded on their individual scientific merit and may be recommended for an allocation of observing time on the provision that time is also awarded on the other facilities. In some cases, time may be awarded on the basis of the scientific value of the data from that particular observatory alone, irrespective of the existence or prospect of ancillary data. So although avenues for MM/MW projects exist, in general there is no formal process which approaches the issue in a coordinated way.

3.1.1. Existing support for MW/MM proposals in the SKA operational concept

In the operational model for the SKA, there exists the concept of a coordinated proposal, which is defined as a proposal requiring observing to be coordinated with observations at another facility (either ground-or space-based).

The SKA is designed with commensal observing and 24/7 operations, maximising the flexibility and opportunity to support MM/MW observing. Additionally, there are stringent requirements in place on the response time to triggers to specific transient astronomical events.

3.2. Time allocation of MM/MW proposals

3.2.1. Options for allocation of MM/MW proposals

In order to facilitate MM/MW proposals in a coordinated way there are various options that could be explored. The following is a short and non-exhaustive list:

1. allow projects to go through the normal time allocation process but only allocate time if positive recommendation for time also received at the other facilities
    - this is the same as most processes currently in place and will require communication between the respective TACs before time is formally allocated to those projects
    - clearly, the science case would need to pass the acceptable threshold for each respective TAC (by how much this threshold is passed is a matter for debate)
    - for those successful proposals consideration could be given to boost to their priority to improve the chances of success
    - of course, each facility could still award time independently of others if they see value in the stand-alone proposal (which is the *status quo* situation described in §3.1 above)
2. make decisions at the Director-General (D-G) level
    - this could be a favoured mechanism for high-profile projects (e.g. GW follow up) whose high impact and importance is self-evident, and require a rapid response
    - these proposals are approved at each participating observatory's D-G's discretion (or their nominees)
    - each D-G would still have the freedom to ask for scientific and technical review to ensure that the proposal is feasible and significantly exceeds scientific thresholds for their observatory
    - however, the amount of time available via such a channel would likely be more limited
3. identify blocks of time on observing schedules at participating facilities for MM/MW projects
    - the amount of time reserved for MM/MW proposals at each facility will be dependent on the amount of time agreed to be allocated to proposals
    - dependent on the urgency and scientific justification for contemporaneous data, this time may be scheduled in common observing windows across all facilities

We note that time exchange agreements do exist between observatories with similar interests but serving different communities[1]. However, this time is usually made generally available to the respective communities

[1] We do not consider time that is made available to a community in exchange for some other service (e.g. in lieu of payment for services or equipment).

with no requirement for projects to be coordinated between those facilities.

3.2.2. Issues to address

As with any system that may be adopted, there will be issues and problems that will need addressing (or accepting):

1. how is the allocated time charged and how is it compensated between different communities?
    - could consider reciprocal access rights across all facilities?
    - all data for MM/MW proposals could be made immediately public to those communities involved, although this prove an obstacle for some high-profile projects (e.g. GW follow up) and would require to them to approach the D-Gs directly for access
2. specific to the SKA, for MM/MW proposals coming from communities outside the SKA membership, there will be a cost incurred in the SRCs for processing the data
    - how is this to be compensated when the funding of SRCs sits outside of the SKA observatory? This places a premium on SKA data obtained on MM/MW proposals