SKA SWG Pulsars

Stappers & Kramer
for the Pulsar SWG

Headlines

- Baseline design captures many requirements but we would request:
  - Tied-Array beamforming capabilities for SKA_1-LOW plus associated processing capabilities for Timing and Searching.
  - To maintain (or increase) the collecting area in the core of SKA_1-MID.
  - We strongly support a VLBI capability for SKA_1.
  - We strongly support the ability to sub-array all telescopes.
- Pulsar science requires that the baseline specifications for LOW (+search/timing) and MID be kept. If not, science goals cannot be met.

Headline Science

- Fundamental Forces:
  - Pulsars, gravity and gravitational waves.
  - While Phase II will provide full science capacity, already Phase I will give unprecedented results for gravitational physics. We expect:
  - The best tests of theories of gravity in strong-field regime
  - Direct detection of gravitational waves - long-wavelength regime probed by Phase I fully complementary to AdvLIGO
  - Understanding the equation of state of super dense material through the discovery and study of the most - massive and/or rapidly rotating neutron stars - tests QCD.

Gravity Theory Needs Testing.

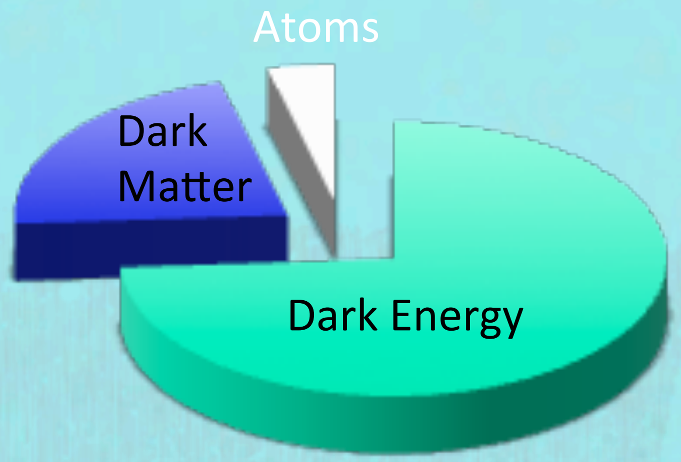
General relativity conceptually different than description of other forces but GR has been tested precisely, e.g. in solar system

Classical tests:
- Mercury perihelion advance
- Light-deflection at Sun
- Gravitational redshift

Modern tests in solar system (see PPN formalism by Will & Nordvedt), e.g.
- Lunar Laser Ranging (LLR)
- Radar reflection at planets, Cassini spacecraft signal
- LAGEOS & Gravity Probe B

But, is there a problem..?

Yes, precision cosmology: Inflation?
Dark Matter?
Dark Energy?

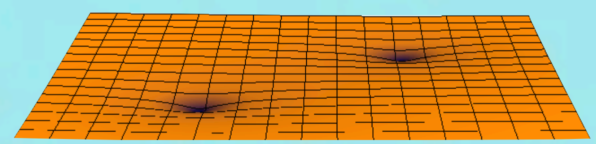


Important: Will Einstein have the last word on (macroscopic) gravity or does GR fail far below the Planck energy?

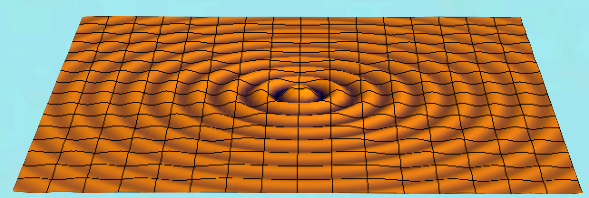
Strong Field Tests Important.

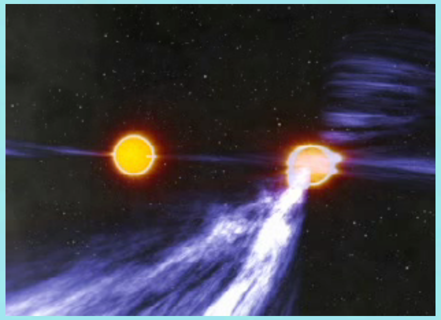
- We need clean tests where gravity is strong and non-linear.
- We must test the radiative properties of gravity.

Quasi-stationary
weak-field regime

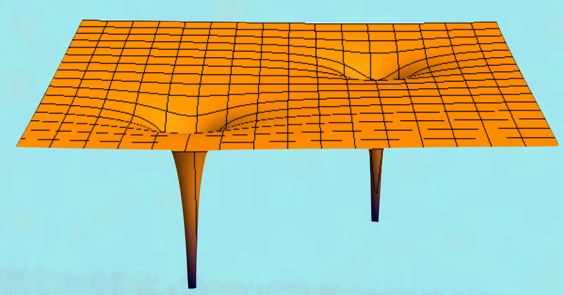


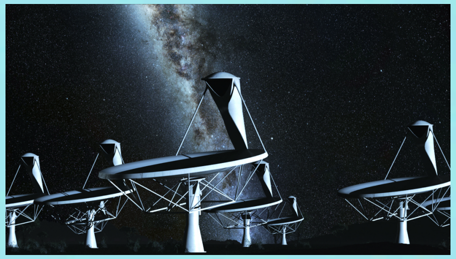
Quasi-stationary
strong-field regime



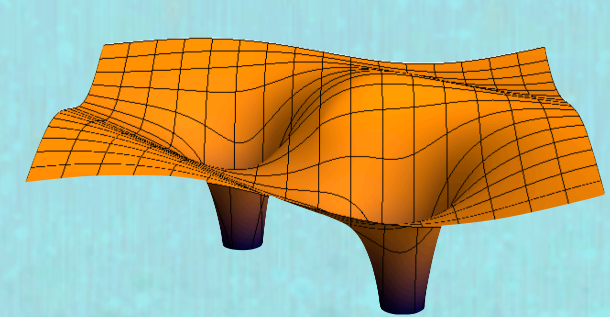


Radiative
regime





Highly relativistic
regime



PSR-BH binary

- Unlike GR, most alternative theories of gravity – including tensor-scalar theories –predict other radiation multipoles that <u>dominate</u> the energy loss of the orbital dynamics (1.5 pN)

- Easy to distinguish from GR in systems with different types bodies as measurable as large orbital decay expected from dipolar radiation:

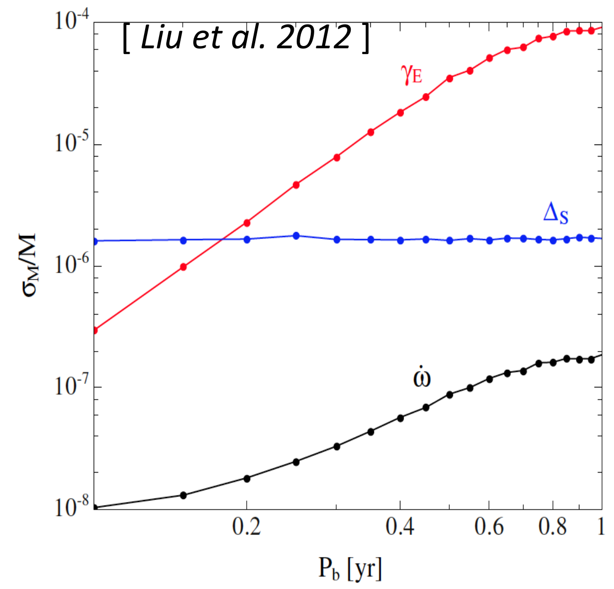
$$\dot{P}_{\rm b}^{\rm dipole} = -\frac{4\pi^2}{P_{\rm b}} \frac{G m_{\rm A} m_{\rm B}}{c^3 (m_{\rm A} + m_{\rm B})} \frac{1 + e^2/2}{(1 - e^2)^{5/2}} (\alpha_{\rm A} - \alpha_{\rm B})^2$$

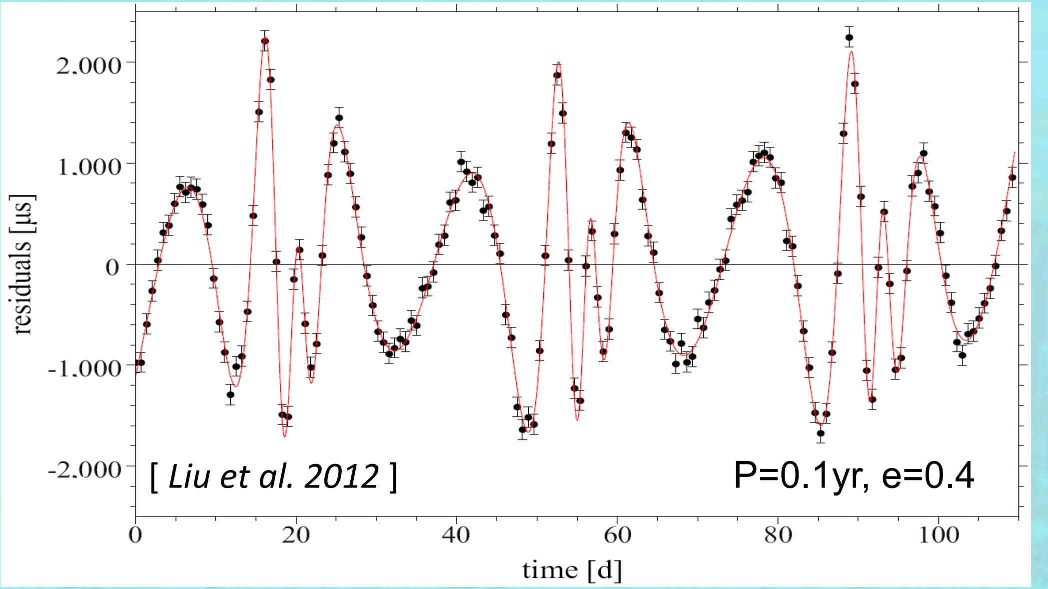
- PSR-BH system would be best as BH would have zero scalar charge

- We can also directly measure the spin of the black hole, allowing us to test the "Cosmic Censorship Conjecture" (= all black holes have an event horizon that prevent us seeing the naked singularity)

- If we can measure also the quadrupole moment, we can test the "No-Hair theorem" (= BHs are simple, they can be all described by simply their spin and mass, i.e. quadrupole moment is determined - testable!)

- For stellar BHs, quadrupole measurement is difficult - but for pulsar around SGR A* easy (cf. Eatough et al. 2013)



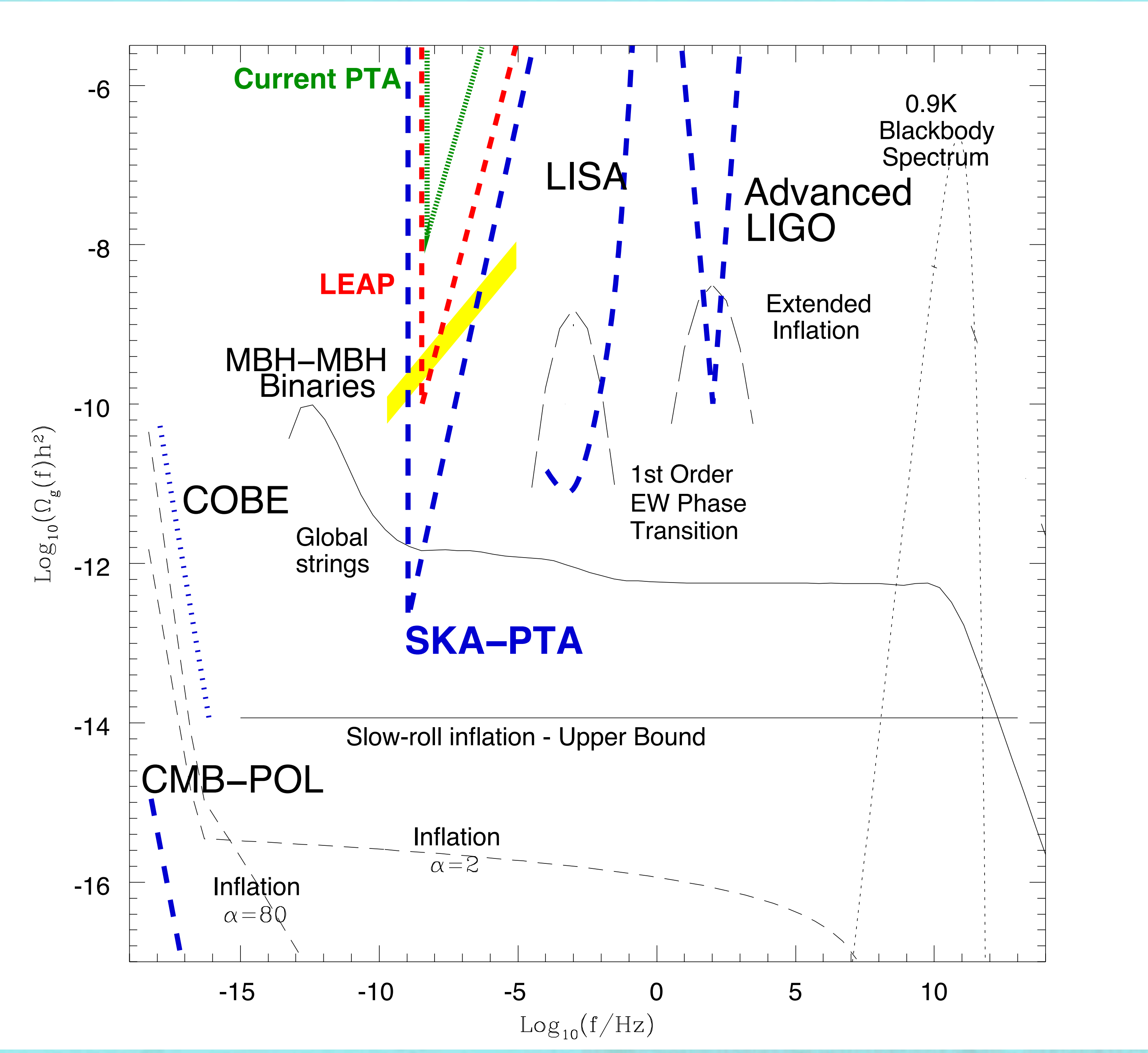


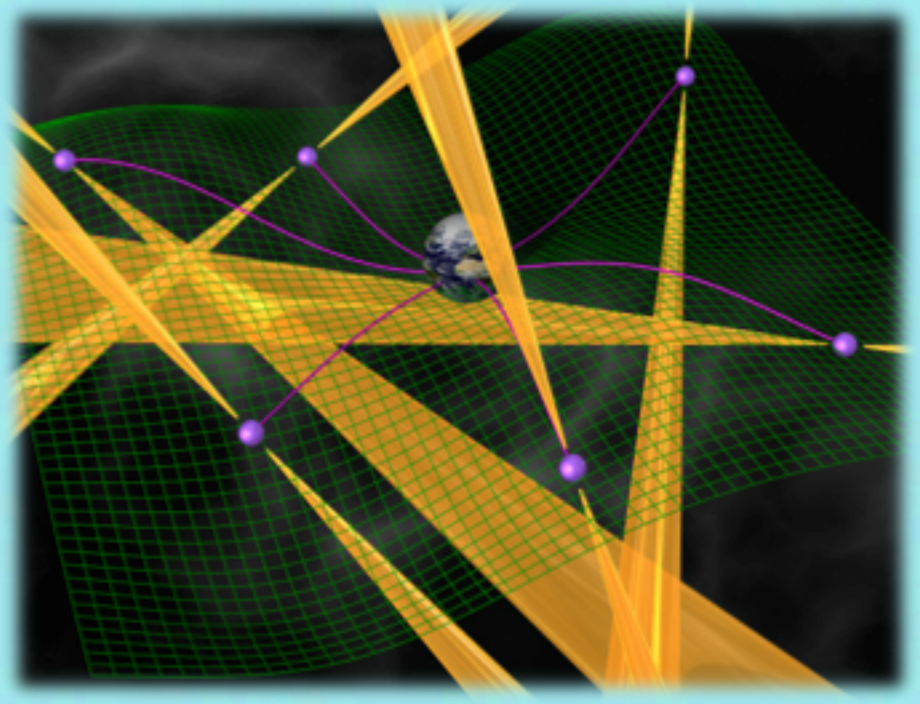
BH mass with precision < 0.001%
= precision of 1 solar mass!
BH spin with precision ~ 0.1%, hence
Cosmic Censorship: $S < GM^2/c$ to 0.1%
BH quadrupole moment with precision ~ 1%
No-hair theorem to ~1%

Pulsars as Gravitational Wave Detectors

Pulse arrival times will be affected by low-frequency gravitational waves – correlated across sky!

In a "Pulsar Timing Array" (PTA) pulsars act as the arms of a cosmic gravitational wave detector:





- -PTA is sensitive to nHz gravitational waves
- - Complementary to LISA,LIGO and CMB-pol band

Expected sources:

- - binary super-massive black holes in early galaxy evolution
- - Cosmic strings
- - Cosmological sources

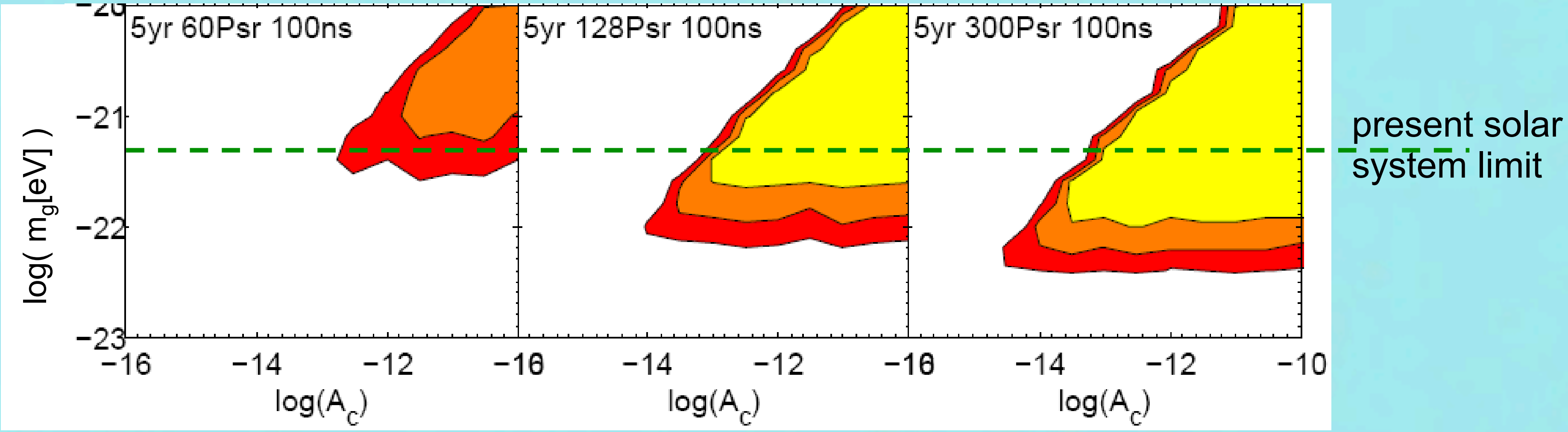
Types of signals:

- - stochastic (multiple)
- - periodic (single)
- - burst (single)

Gravitational Wave Astronomy

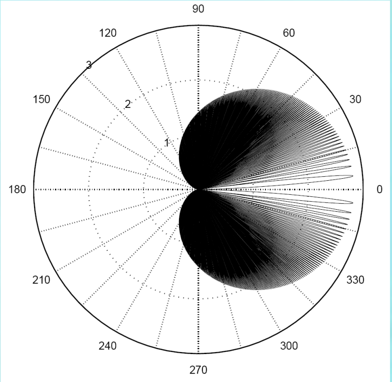
We can do more than "only" detect gravitational waves:

- With SKA sensitivity we can study GW properties: polarisation & graviton mass (Lee et al. 2009, 2010)



- Single binary super-massive black hole produces periodic signal:

  - Perhaps rare but complementary in mass range to LISA (Sesana et al. 2009, Sesana & Vecchio 2010)
  - If SNR is high (or source and orbital period known!) we can search for signature
  - Expect periodic signal but also dc-term due to memory effect (van Haasteren & Levin 2010)
  - Signal contains information from two distinct epochs: t and t-d/c - looking back in time!
  - We can pinpoint a single GW source to possibly arcmin precision
    when combined with precision pulsar distance from parallax
    measurement thanks to "PTA Beam Pattern" (Lee et al. 2011):



==> unique EM - follow-up!

Requires High Precision Timing &...

- We need lots of collecting area to achieve the required sensitivity.
- At least 10 beams for timing (as currently specified in the baseline design) are needed to achieve the necessary cadence/efficiency
- Good polarisation purity, linearity and stability (i.e. easy to calibrate)
- We need access to wide range of frequencies to correct for propagation effects, i.e. bands in SKA_1-MID but also SKA_1-LOW
- We need an accurate, stable and transferable time standard.

...need to find them, search the sky.

- to find the pulsars that we need to achieve the key science goals we need to search the sky with the maximum possible sensitivity.
- the gravity tests require new NS-WD, NS-NS and NS-BH binaries to extend the current limits to where GR might break.
- The PTA / GW work can begin with the known sources, BUT new sources will be needed to perform gravitational wave astronomy.
- As we don't know where these sources are we need to survey the entire sky seen from the site.
- ... will also enable lots and lots of other science.

The case for SKA$_1$-LOW - Surveys

- SKA$_1$-LOW has many excellent attributes that make it good for pulsar searching: Very Sensitive & Large FoV
- It could be use to search for pulsars very efficiently off the Galactic plane
- Recent successful examples of low frequency, GBT, GMRT, LOFAR
- Observing time available when not in EOR "sweetspots"

Requires:

- Modest (few hundred) beamformer
- Associated pulsar search capability
- No decrease in transition freq. below 110 MHz.

We would like:

- More effective area at 350-600 MHz, i.e. increase in transition freq.

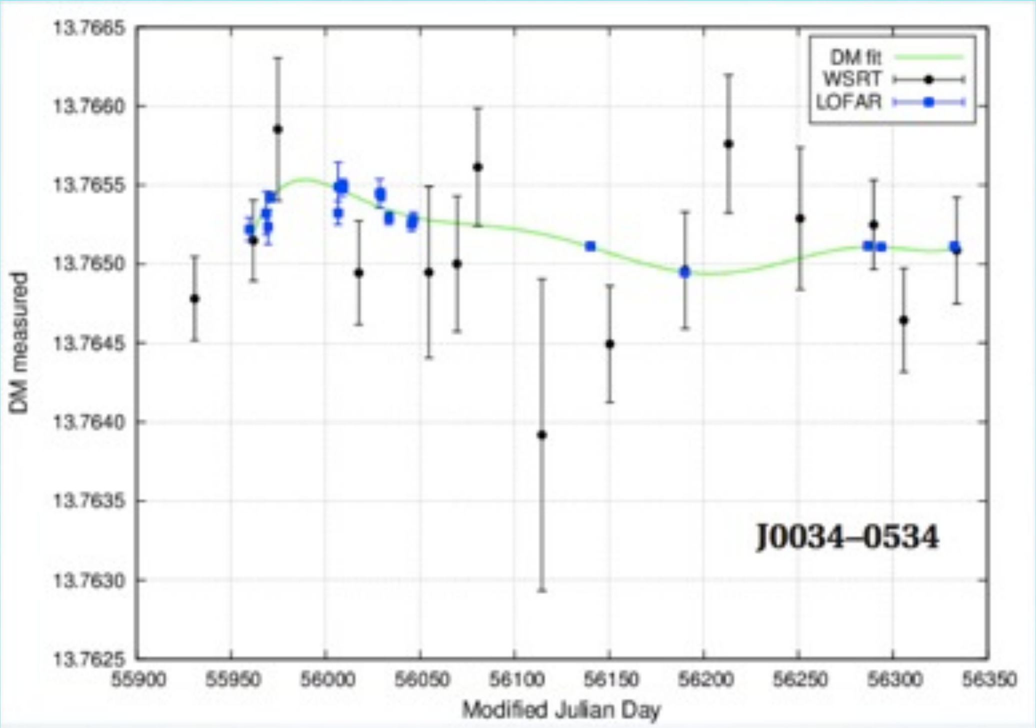
Freq (MHz)	100	200	300	400
All Sky	6800	7700	8000	6300
b < 5	2800	3300	3500	2800
b < 10	4700	5500	6000	4500
b < 15	5500	6600	6900	5400

The case for SKA$_1$-LOW Timing

- One of the key elements of achieving the required timing precision and long term stability required is to correct for the influence of the ISM.
- Observations at low frequencies are being shown to be increasingly useful, alongside those made at multiple frequencies like those in SKA$_1$-MID
- LOFAR is showing that the majority of MSPs can be seen at low freqs.
- The combination of high sensitivity, wide bandwidths and low frequencies enable this.

Requires:

- ~10 "timing beams" like for SKA1-MID
- Ability to do coherent dedispersion etc.



Less collecting area in the core of SKA_1-MID for surveys would…

- Depending on exact nature, for surveys, would require either or both of:
  - increased number of beams due to smaller FoV for tied-array beams
  - increased observing time to recover loss of sensitivity,
- In both cases would increase the processing load significantly due to processing of more beams,
- and longer data sets,
- more expensive acceleration processing (scales ~(Obs time)^3).
- Survey speed is of course also affected: time as in current baseline designed to get it done in 2 years, would be longer!
- Further optimisation of survey strategy is of course still possible.

Less collecting area in the core of SKA_1-MID for timing would…

- Impact depends on the exact nature, but if parts of collecting area moved beyond distance that they can be phased-up, then for pulsar timing:
  - Reduced sensitivity, thus longer integrations required: problematic for most interesting (probably weakest) sources, such that we cannot resolve the binary orbit with high precision
  - If single TOAs cover too much orbital phase, Shapiro delay and other structure (BH's quadrupole moment!) cannot be detected
  - In contrast, for many sources (i.e. strongest - aka known already but needed for GW detection), integration time will be dominated by pulse-jitter time scales
  - For bulk of sources longer integration time will mean simply mean less "throughput" and hence reduced cadence which is likely to affect GW detection - in particular if multiple receivers are needed for ISM correction

Optimising Pulsar Searches - SKA_1

- We are working on optimal search scenarios within the SKA_1 baseline design.
- As shown above SKA_1-LOW can be used to survey off the Galactic plane
- On the plane, and at zenith angles greater than 60 degrees we need the full capacity of SKA_1-MID to beat dispersion and scattering!
- This combined approach means that it might be possible to trade some of the required beam-forming / search capacity at SKA_1-MID in order to achieve that required for SKA_1-LOW
- Moreover this would enable more observing time in MID to go deeper!
- A first & preliminary simulation of such a survey results in 2000 pulsars found off the plane (LOW) and 10000 (MID) in the plane.

Sub-arraying

- Large number of SKA pulsar discoveries (~10,000) that need to be timed to determine properties, ~15 obs/source needed - requires lots of telescope time - sub-arraying will improve efficiency.
- Sub-arraying with different sets of receivers within SKA_1-MID would be highly desirable to enable efficient ability to get data for ISM corrections.
- Combinations (coherent or incoherent) of longer baseline dishes/stations can be used in parallel with survey observations, for example, to do timing etc… further improving observing efficiency.
- Simultaneous observing of multiple sources outside of primary/station beams may be required for calibration purposes.
- Can also enable the efficient testing of new observing modes.

Pulsar VLBI/Astrometry

✳ Precision differential astrometry of pulsars allows astrometric parameters to be accurately measured/fixed in pulsar timing = better strong field tests and GW probes (amongst other things).

✳ SKA_1 will not have the required baselines, however providing the capability for it to participate in VLBI projects globally will enable parallax distances for very many pulsars (e.g., 10% error at 15 kpc for 40 uJy pulsar)!

Requires:

- A phased up SKA_1 (SURVEY & MID) core with *at least* 10 tied-array beams (similar to timing beams) for pointing at calibrators and source.
- Capacity to record, or preferably transfer directly to a VLBI correlator, data in the appropriate VLBI format (just (4 Gbps/beam))
- Coordination for proposing / scheduling of VLBI observations with other VLBI antennas

Other Survey Issues

- We will want to revisit the number of channels that are specified in the baseline design as being necessary for the survey, it is likely that it is more than is needed and a smaller number (4000) also better fits the processing architectures.
- We strongly support simultaneous imaging and beamforming. When doing survey observations the former will allow for more precise position determination and speed up pulsar timing for new pulsars
- If available it may be desirable to have a wider bandwidth than 300 MHz, but not if it comes as a trade off with the number of beams.
- The requirements for candidate identification need to be built in to required processing capability (being worked on....)

Acceleration Processing

- Essential for finding the best gravity-labs, e.g. Double NSs, PSR-BH binaries.
- Baseline Design has the number of operations (~10 PetaOps) about right.
- Range of accelerations to be probed is "OK" - better if the step size and range be increased by up to an order of magnitude to catch the "extreme" systems.
- Still too early to make a choice between time-domain and frequency-domain methods, and perhaps a hybrid is needed
- Having some Acceleration searching is better than none!
- The exact architecture that should be used to perform the acceleration processing, i.e. GPUs, FPGAs others still needs to be determined.
- Getting the right balance between when technology choices are frozen is very important due to the acceleration processing being a significant cost driver.

Data Requirements.

- Something that still needs to be addressed for all science goals.
- For Searches the main requirements are:
  - To allow human/AI to determine if candidate is a likely pulsar.
  - To provide a first TOA for any pulsar discovery.
- Both goals could be achieved with a single data product an archive file, with each being about 1.2 MBytes. Corresponding to about 1.2 Gbytes for each survey observation. Investigating storing more information.
- Definition of other data products will be completed before end of month.
- Metadata of just a few kbytes is also needed.
- For timing observations freq/time/poln cube of about 10's GBytes/hr

Conclusions

- Baseline design captures majority of pulsar search and timing requirements.
- Our major requested change is the inclusion of tied-array beamforming capabilities for timing and searching with SKA_1-LOW
- We support a VLBI capability and we support the sub-arraying abilities for all the telescopes.
- Optimisation of survey strategies with LOW & MID are ongoing but a transfer of some resources between them could address cost issues.
- To support searching with MID we would like to maintain, as much as possible, the current collecting area in the core.
- To achieve the SKA_1 Pulsar Key Science goals we need the specifications of MID & LOW outlined in the BD with the extensions proposed here.