SKA Science Town Hall

18-19 May 2017
Cottons Hotel
UTC timezone

Required accuracy for precision pulsar timing

(SAT 2: progress report)

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SAT session – 18 May 2017

Members of the Assessment team

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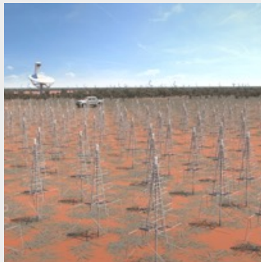
Top goals for PSR KSP

Understanding gravity and fundamental interactions using pulsars and black holes

1. Tripling the currently known pulsar population
2. Finding highly relativistic systems and improving tests of gravity in the strong field regime by at least one order of magnitude
3. Finding at least one pulsar - black hole binary and informing quantum gravity
4. Detecting gravitational waves at nano-Hertz frequencies
5. Improving the mass-radius relation (NS equation of state) by more than an order of magnitude

There will be superb synergies in the context of pulsars' studies with GAIA, ELTs, LSST, CTA, AdvLIGO, AdvVIRGO, eLISA etc



Top goals for PSR KSP:

this report is mostly focus on...

Understanding gravity and fundamental interactions using pulsars and black holes

1. Tripling the currently known pulsar population
2. Finding highly relativistic systems and improving tests of gravity in the strong field regime by at least one order of magnitude
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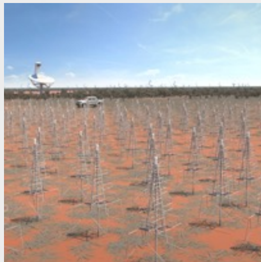
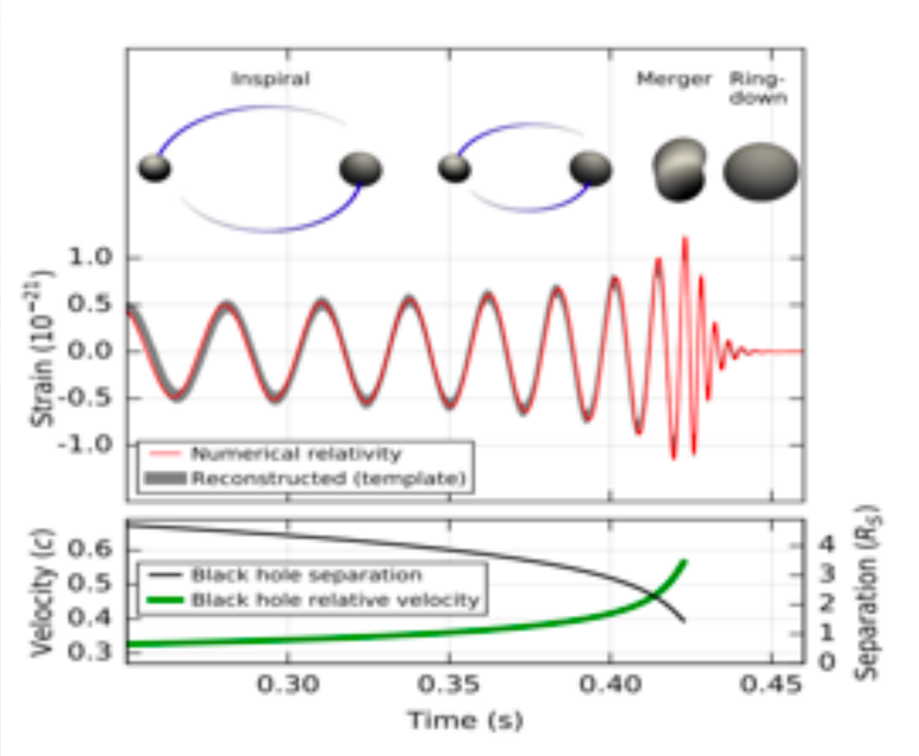
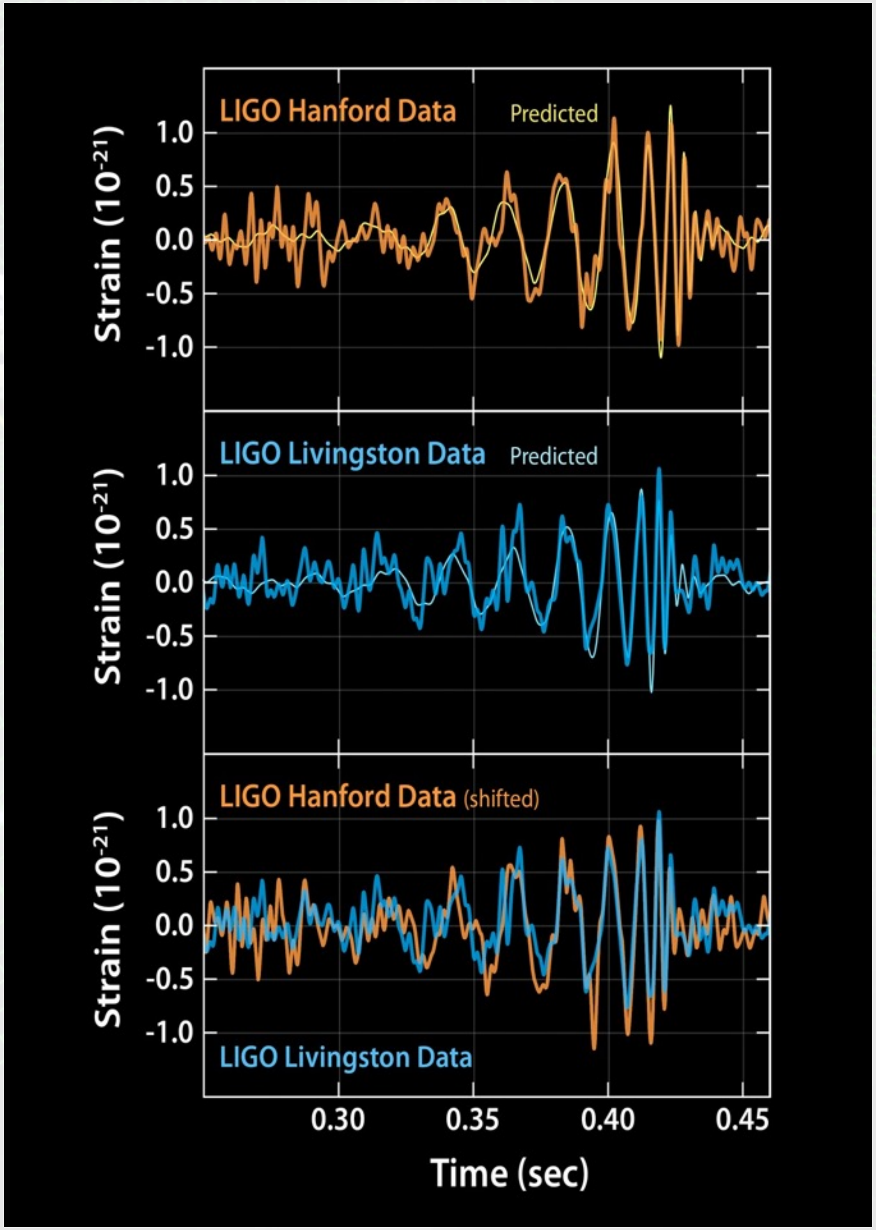


Big news since SKA Science Book

Detection of GWs from merging of a Double Black-Hole Binary





PTAs: Current limits on GWB amplitude

- EPTA, PPTA, NANOGrav + IPTA have all published improved limits on GWB

NANOGrav — **Arzoumanian et al., 2016: A < 1.5 x 10^{-15}**

EPTA — **Lentati et al., 2015: A < 3 x 10^{-15}**

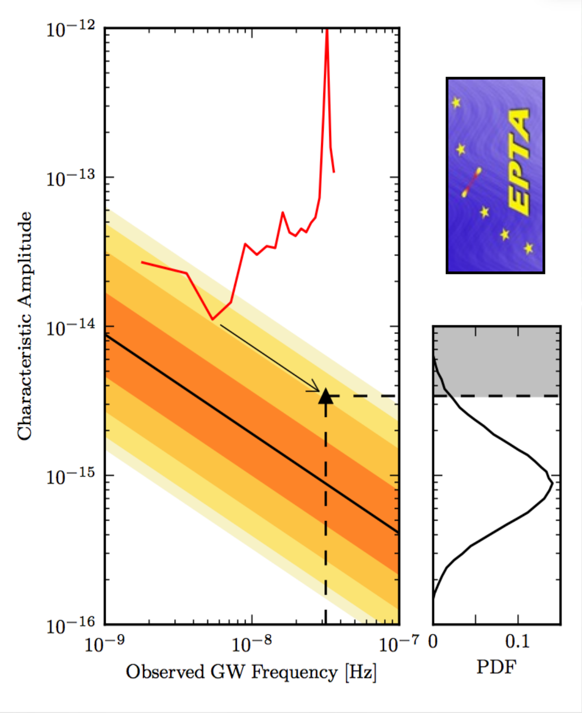
(robust limit including additional effects)

PPTA — **Shannon et al., 2015:**

A < 1.0 x 10^{-15} [Ω_{GW} < 2.3 x 10^{-10}]

IPTA — **Verbiest et al., 2016: A < 1.7 x 10^{-15}**

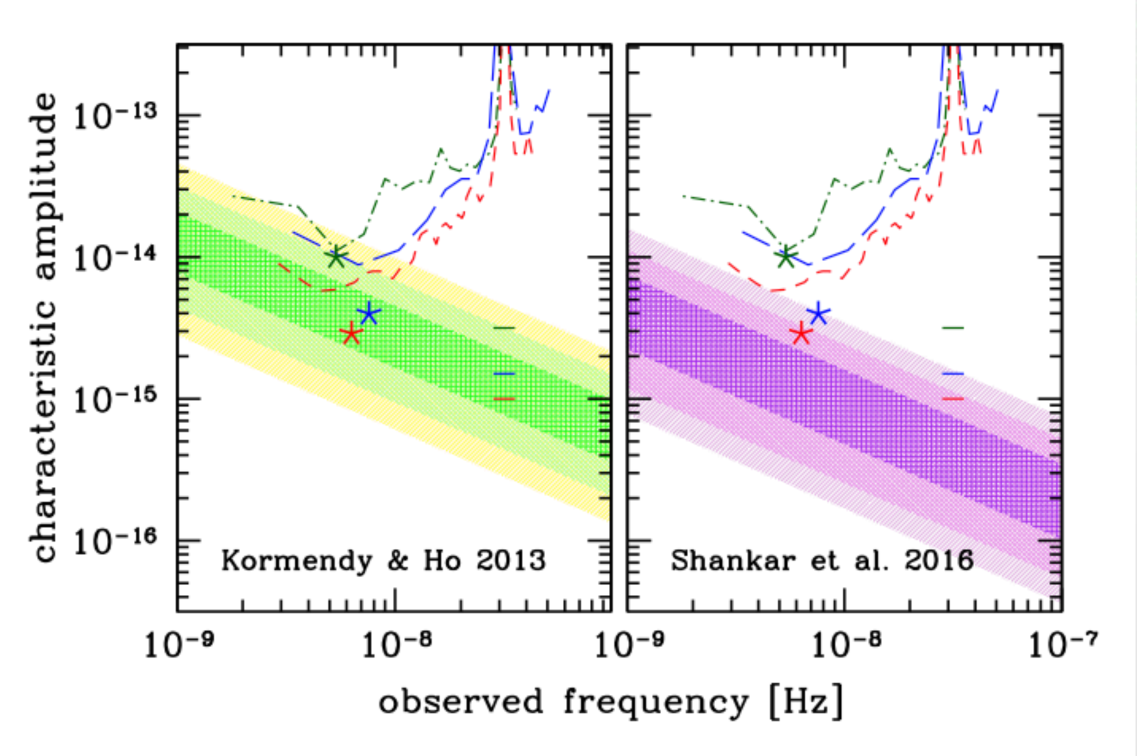
(based on relatively old data only)



[Lentati et al. 15]

GWB amplitude predictions

- Already ruling out most generous theoretical models for stochastic GWB
- Newer model predictions (including more physics, accounting for biases)
  - Expected GWB slightly lower
  - Still large range allowed



Nowaday expected a signal with $\approx 5 \times 10^{-16}$ amplitude at 1 yr period

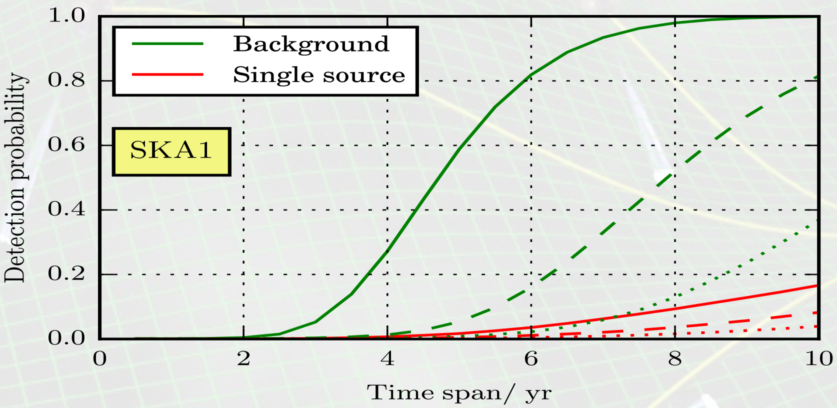
[Sesana et al. 16
Kelly et al. 17]

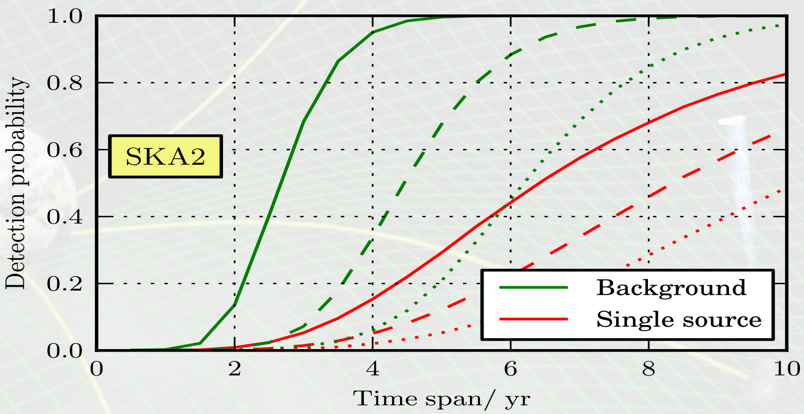
Time to detection of the GWB and of a GW-emitting SMBHB

Based on simulations to predict the SMBHB population

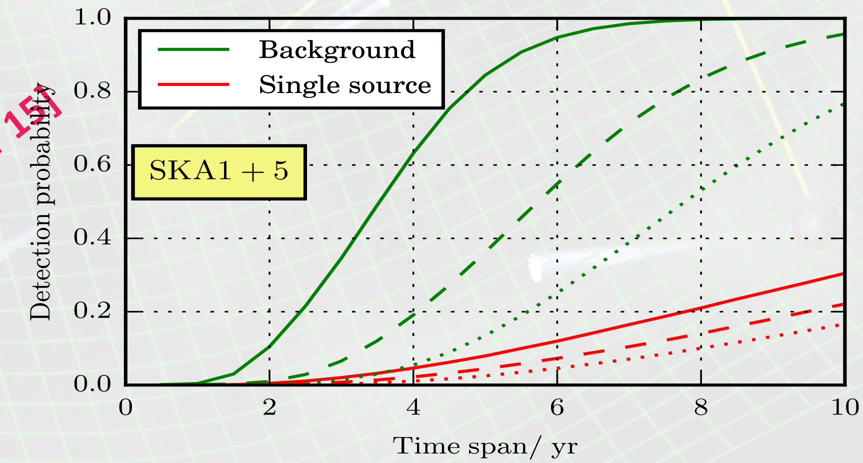
Updated to be consistent with recent upper limits (e.g. Shannon et al. 2015)

More physics included in binary models





[Now updated from Rosado, Sesana & Gair 15]



SKA1 = 50 PSRs, 100ns

SKA2 = 200 PSRs, 50ns

SKA1+5 = 50 PSRs, 100ns + 5 PSR, 10ns

5 PSRs with 10ns uncertainty (plausibly available if SKA1 will keep the baseline sensitivity and preserve optimal timing capabilities, including the clock system) will lead to counterbalance the smaller (than previously thought) GWB amplitude, approaching the original expected timescale for detection with SKA2

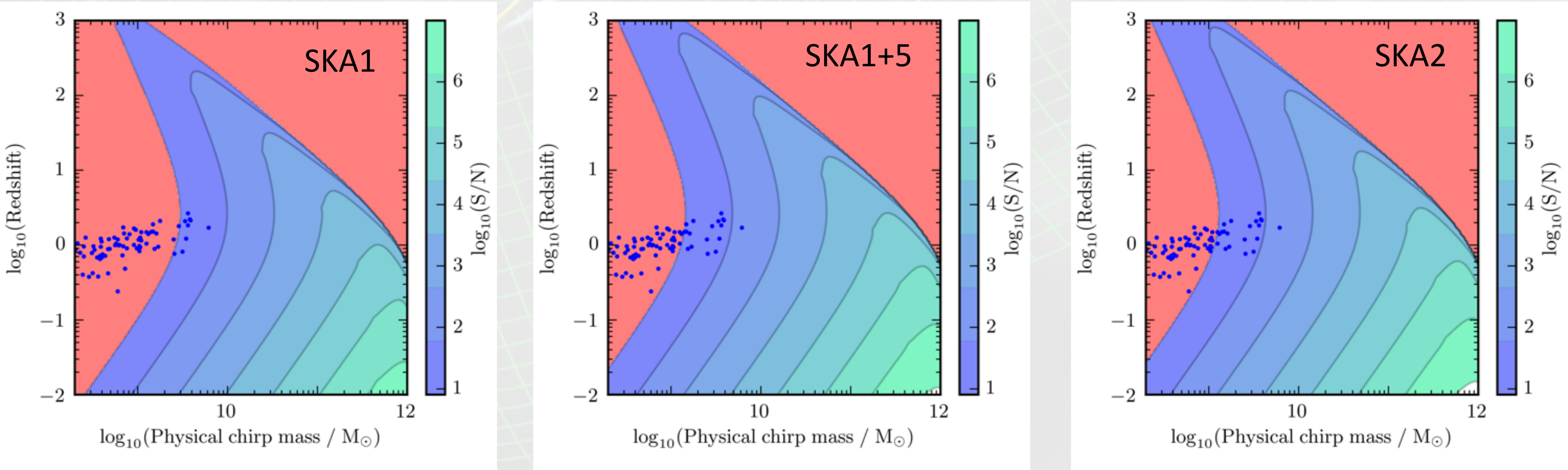
Sensitivity to SMBHBs

Currently, PTAs sensitive to $>10^{10}\,M_{sun}$ SMBHBs.
SKA sensitive to smaller-mass binaries – more common !

Availability of **a handful of ultra good timers** (pulsars with rms noise ≈ 10 ns), on top of few tens of pulsars with rms of order 100 ns, which are crucial to properly map the quadrupolar nature of the GW signal **[Taylor et al 16]** , can significantly change the detection probabilities of SMBHSs

SKA1 = 50 PSRs, 100ns
SKA1+ = 50 PSRs, 100ns + 5 PSRs, 10ns
SKA2 = 200 PSRs, 50ns

[Now updated from Rosado et al. 16]

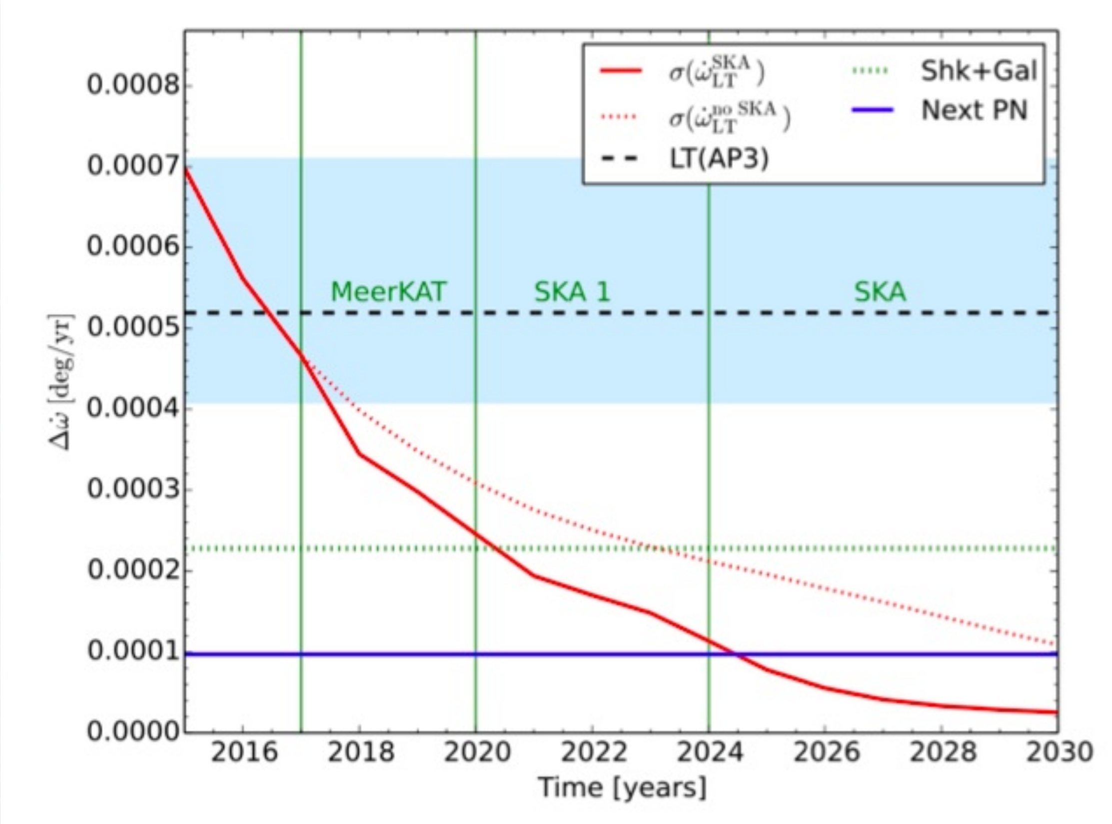


the capabilities of SKA1 close to those previously predicted for SKA2

Relativistic binaries and gravity theories tests

- Relativistic binaries will keep doing better at constraining the radiative terms at the leading 2.5 PN order and also at the 3.0 PN order
- the Lense-Thirring effect in the Double pulsar system will be measurable with SKA1. Subsequent monitoring of the binary could also finally lead to constraints on the moment of inertia for the pulsar down to 10% accuracy

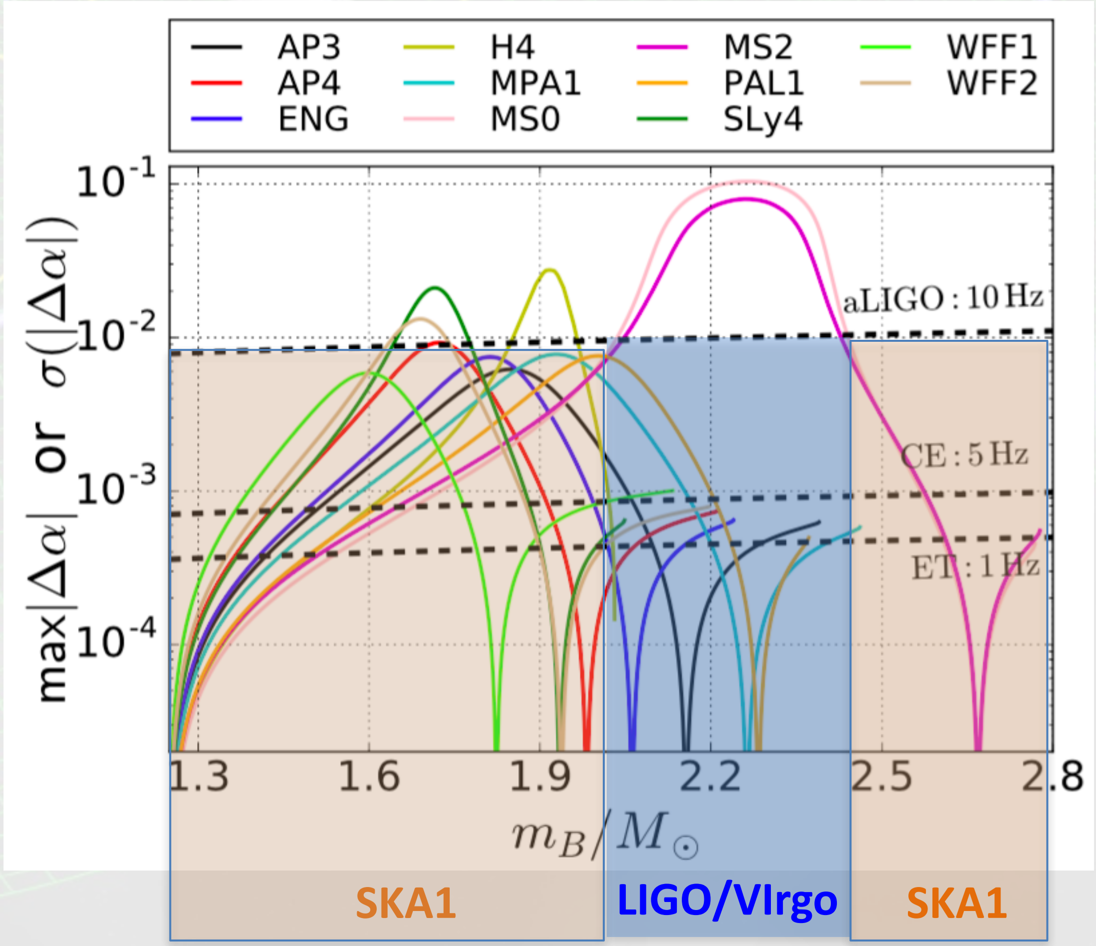
[Kehl et al. 16]



Complementarity with aLIGO/advVirgo

GW detectors and the pulsar timing will really be complementary in testing the radiative predictions of GR, doing their best for different ranges for the masses of the involved neutron star

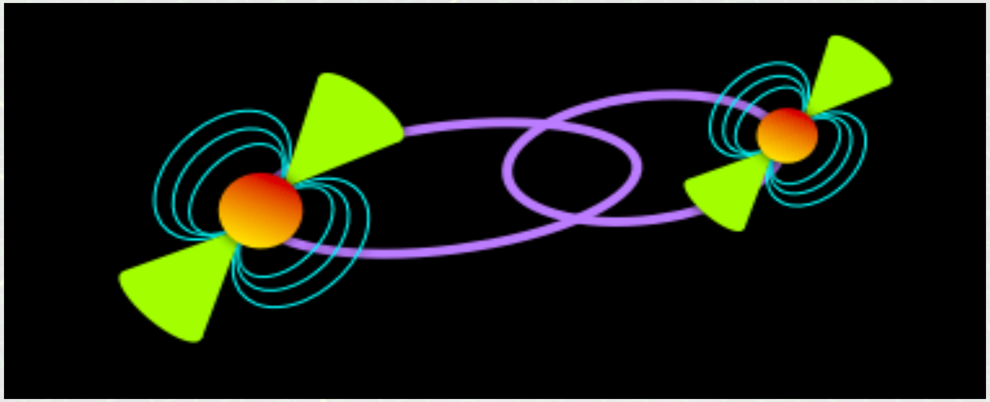
[Shao et al., in prep]



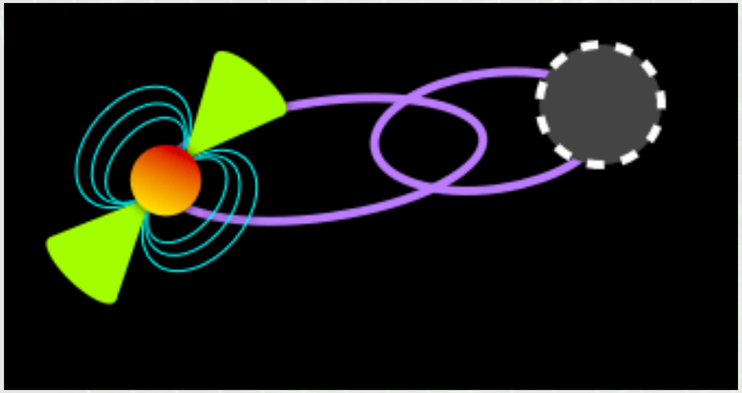
New unprecedented tests with ...

Provided the timing capabilities of SKA will be kept at the nominal capabilities of the instrument, a wealth of new unique test will stem from ....

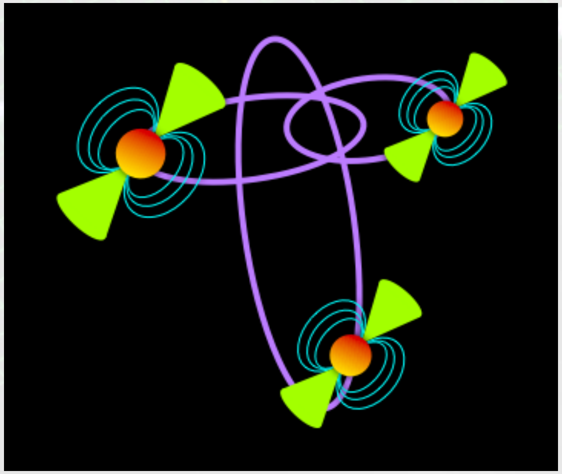
Potentially testing dark matter
[e.g. Kavic et al 2017]



MSP+MSP binary



MSP+BH binary or MSP+IMBH/SMBH



Triple MSP system

Providing tests of contributions from spin(s)

[Images: edited from Hessels 2014]

New telescopes

MEERKAT

64 dishes of 13.5 m
0.6 – 1.0 GHz
0.9 – 1.7 GHz

FAST

500 m wide
19 beams at 1230-1530 MHz

CHIME

5 cylinders of 100 m x 20 m
0.4 – 0.8 GHz

Lesson learnt from LEAP

LEAP experience of finding clock irregularities at specific telescopes

Loss of a clock such that precision timing will not be possible for significant periods **counts double**

because:

1. observing time is lost
2. one needs to *recover* missing ToA

Science-wise summary of the impact of suggested cuts on timing results

As to the case of the **Reference clock**

- **That can be limiting factor in noise budget for very stable pulsars**
- **Best quality clock essential to reach science goals**
- **Redundancy in clock setup is important to find errors**
- **No room for concessions**

Also we note:

- We do not want to upgrade the clock system for SKA2, but keep on going with the same clock. In term of pulsar science the advent of SKA2 will simply imply a large jump in sensitivity, not be able to counterbalance the uncertainties due to an inadequate clock system.

- High precision pulsar timing requires years to tens of years and skimping now on the timing precision could potentially drastically decrease its potential

Science-wise additional considerations about the impact of suggested cuts on timing results

Reduction in **number of search beams**

- Finding “good” pulsars will take longer
- Missing “good” pulsars, will imply that also timing monitoring will take more time

Removing dishes: overall sensitivity reduced -> lower TOA precision

- Reaching GW sensitivity levels takes longer
- Instantaneous sensitivity for relativistic binaries essential

SKA **Band 3** for timing

- Strongly suggested for prioritization of future funding and so in detail...

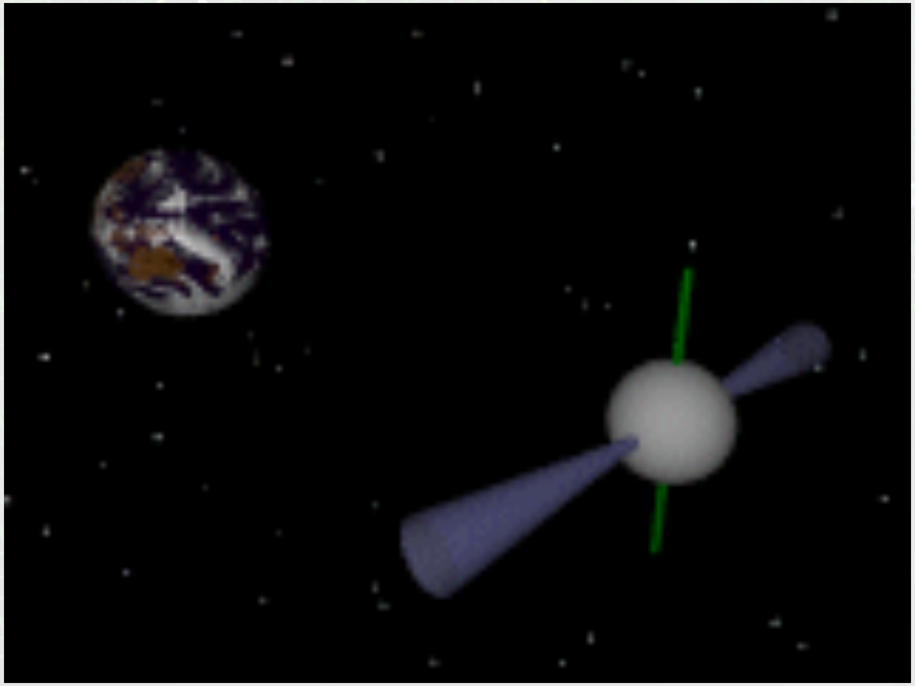
how does that translate in the required accuracy for precision pulsar timing ?

Basics of the timing procedure

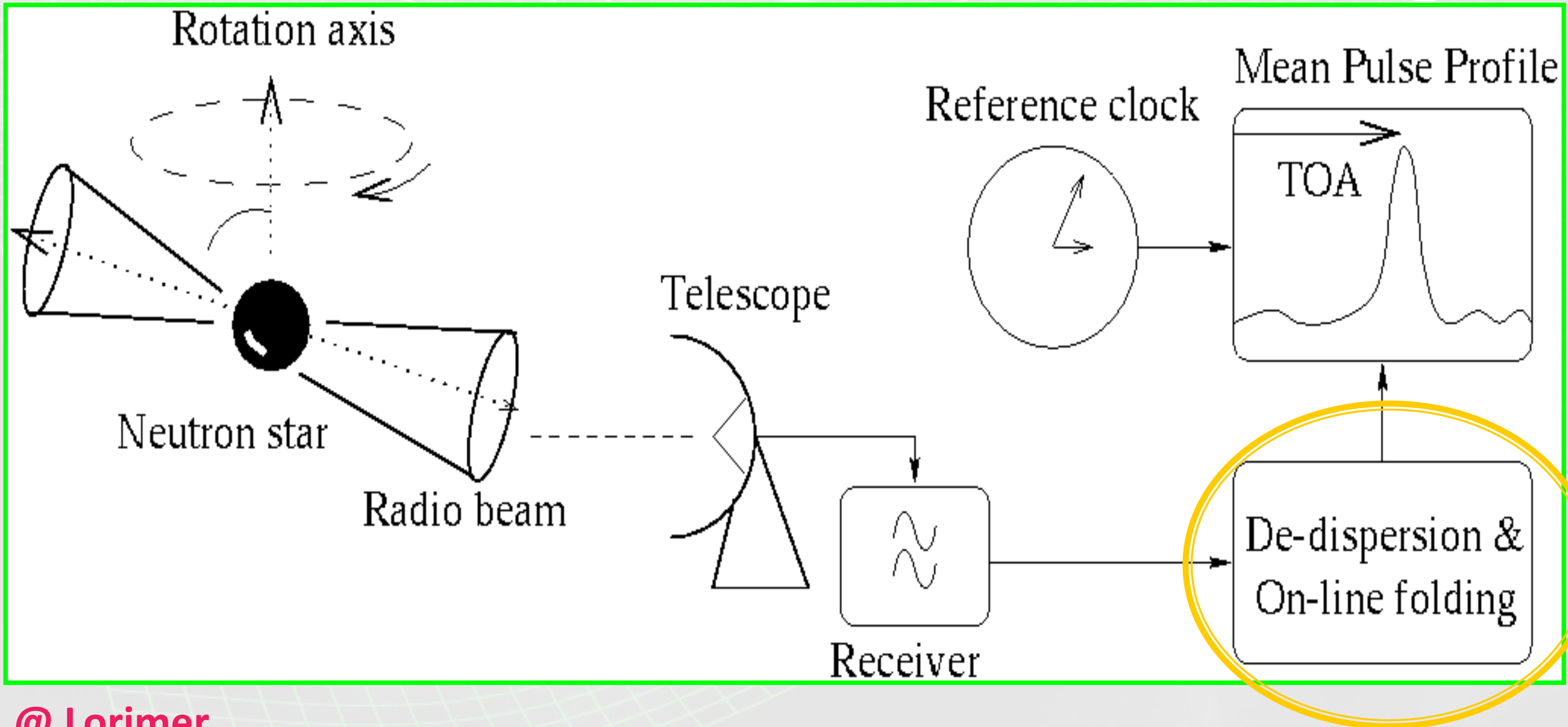
Performing repeated observations of the Times of Arrival (ToA) at the telescope of the pulsations from a given pulsar

and

searching the ToA for systematic trends on many different timescales, from minutes to decades

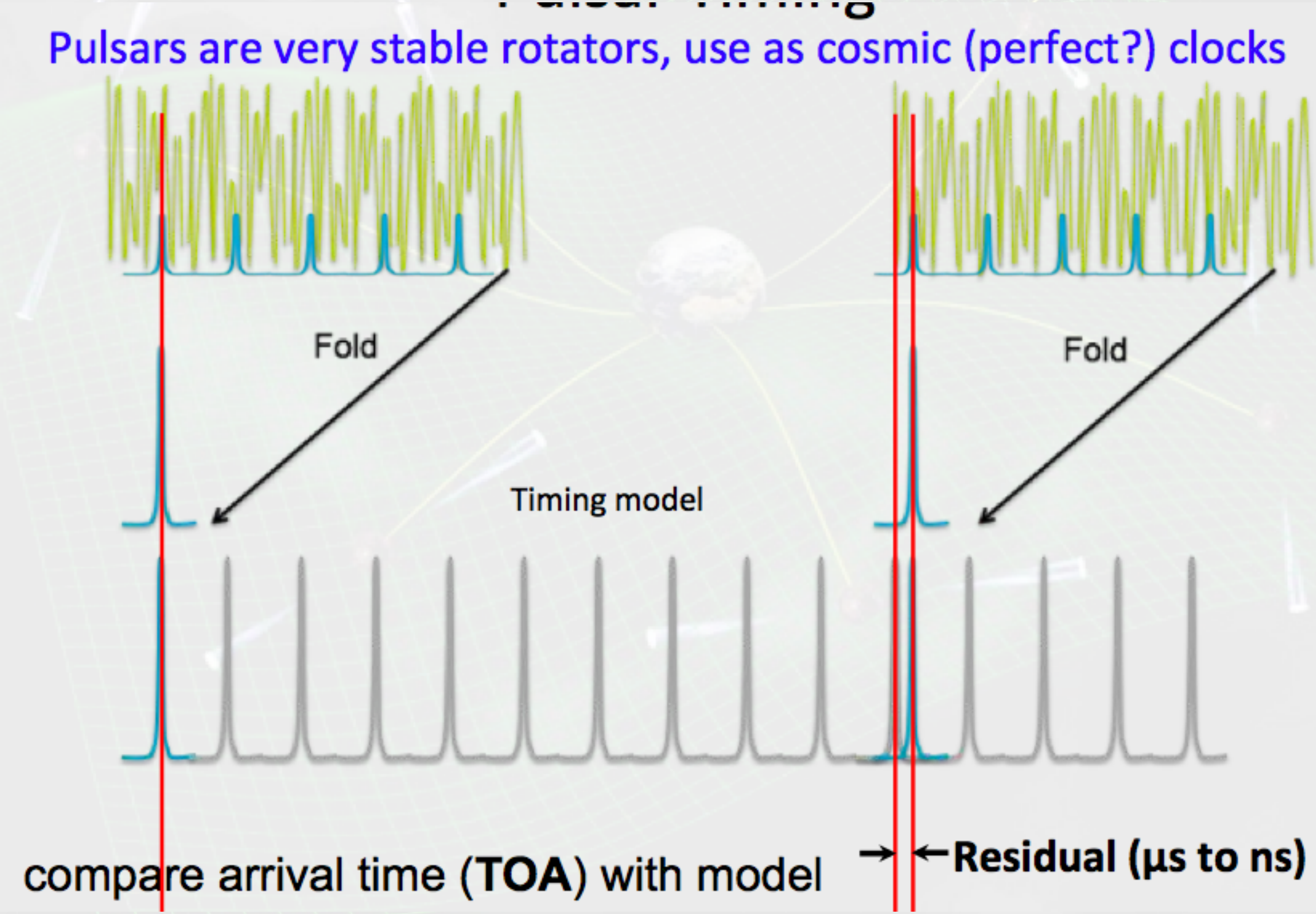


Basics of the timing procedure: observations



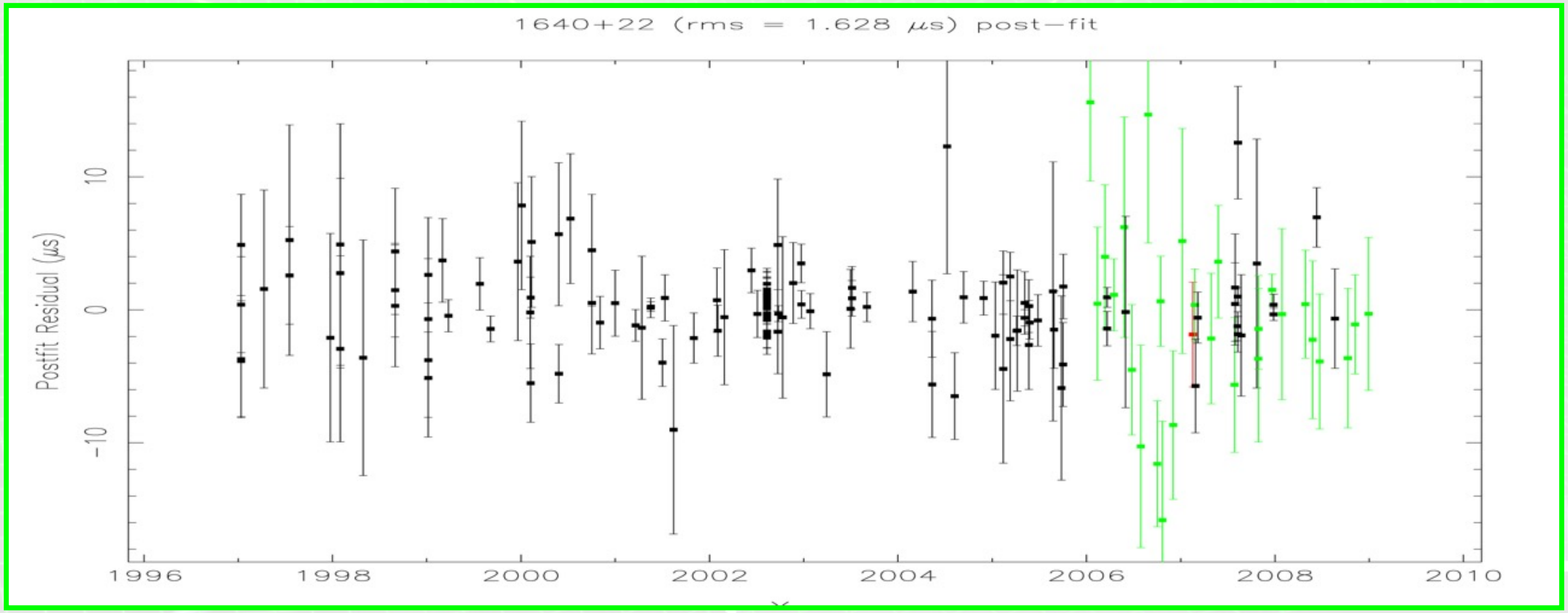
@ Lorimer

Basics of the timing procedure: modelling



Basics of the timing procedure: figure-of-merit

Good timing solution → no evident trend and $r_i << 1$ for all observed pulses



The quality of the timing solution is usually given in term of the root mean square rms of the residuals:

the smaller rms is, the smaller physical effects can be measured

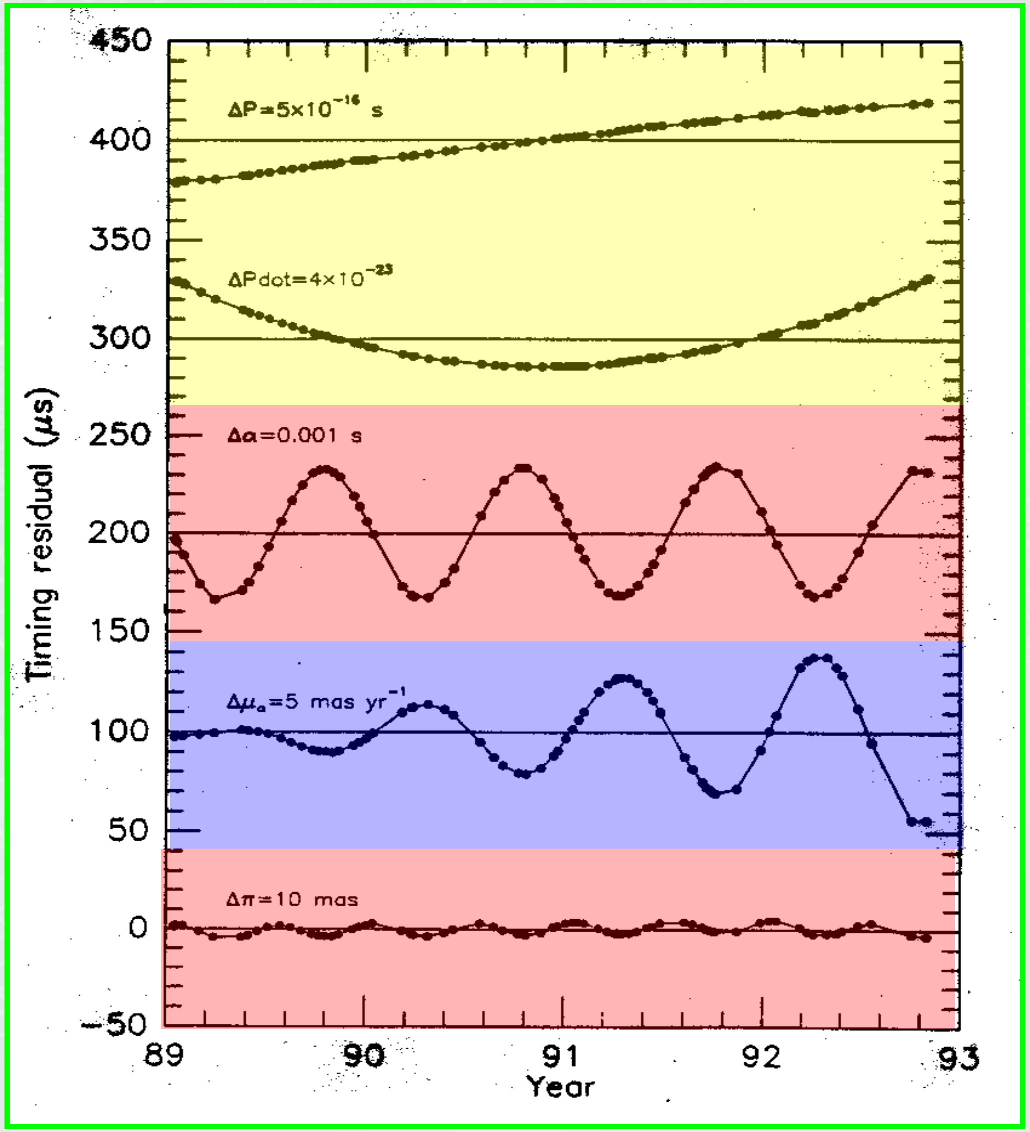
Basics of the timing procedure

Timing model contains:

_ rotational parameters
_ astrometric parameters
_ classical binary parameters
_ gravity theory dependent parameters

plus unmodelled effects:

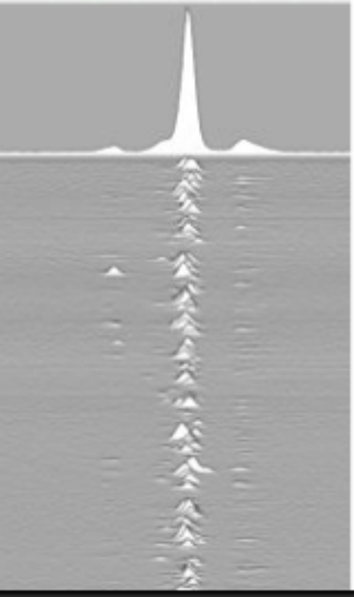
_ measurement errors
_ **clock uncertainties**
_ spin irregularities
_ interstellar weather effects
_ planetary ephemeris uncertainties
_ **gravitational waves**

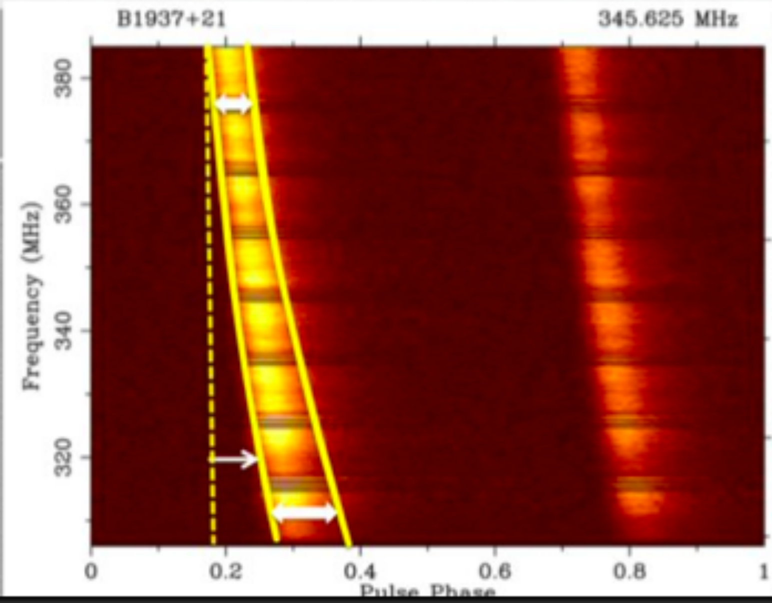


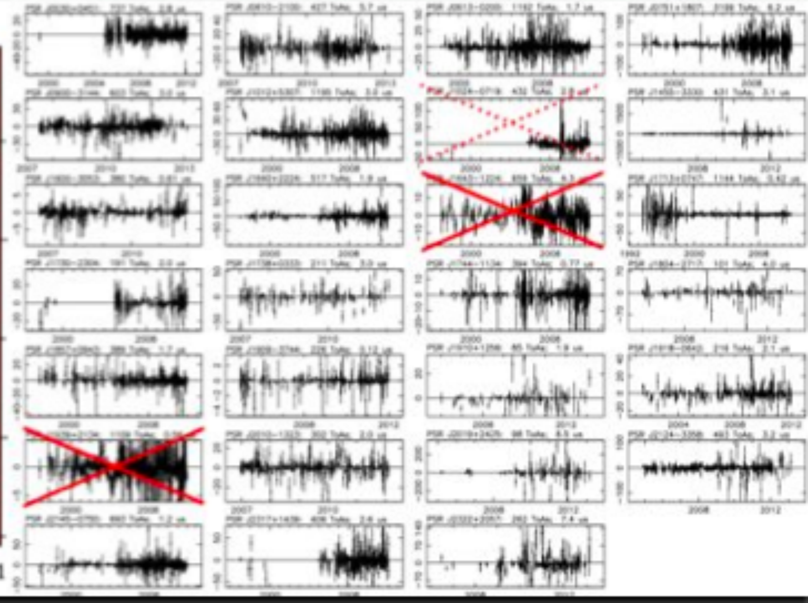
Basics of the timing procedure: noise contributions

- Even when timing model is good, still effects that disturb quality of residuals

- Pulse jitter (30 ns): need minimum integration time to get stable profile; can't go to larger telescopes
- ISM effects (100 ns – 10 μs): DM and scattering
- Timing noise (10 μs – 1 ms): Random rotational/magnetospheric/glitches
- Planetary ephemeris uncertainties (10 ns – 20 ns on long term)
- **Need to understand and disentangle these effects from potential GW signal (10ns), or to do GR tests that require precision measurements**

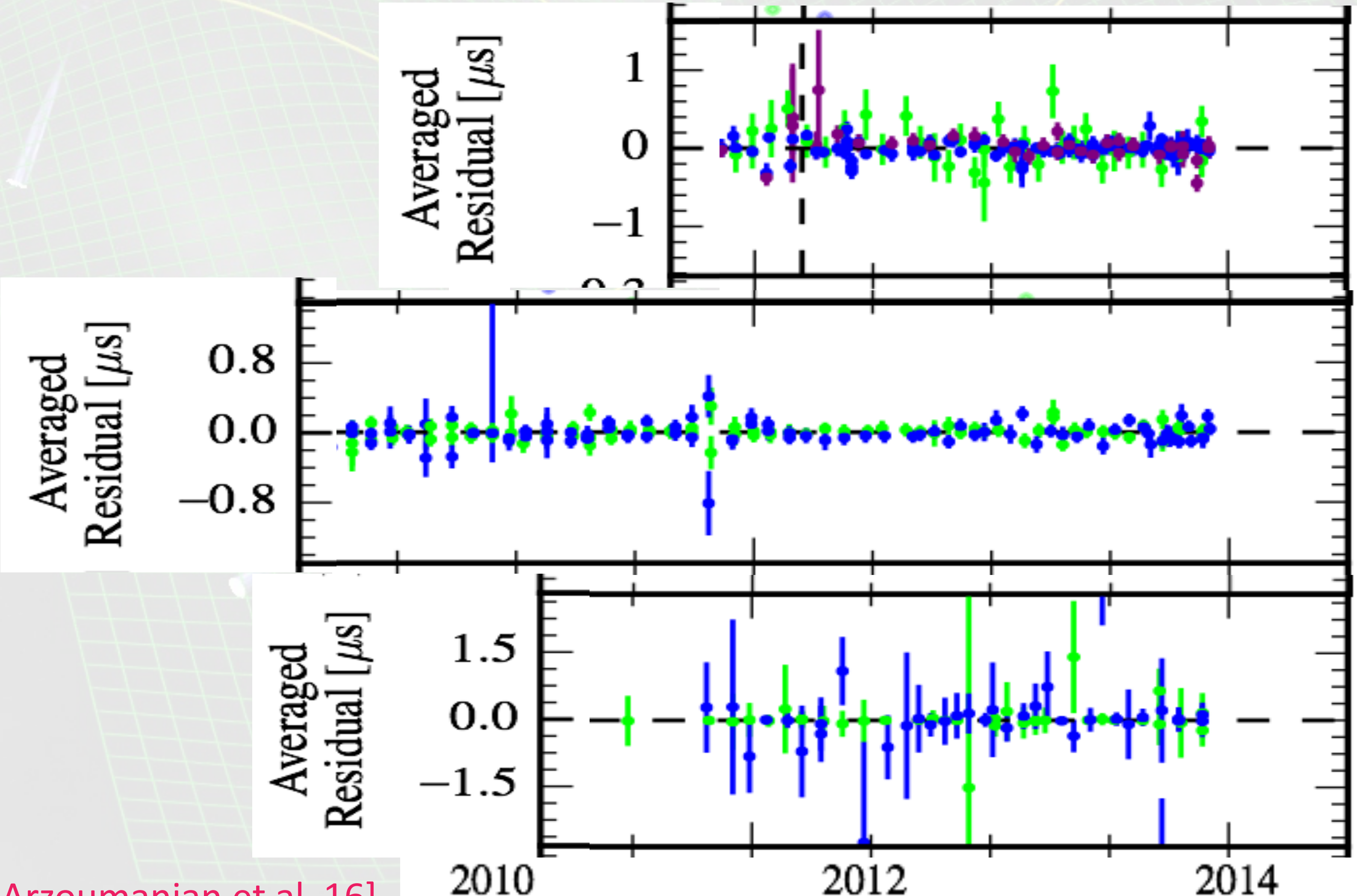






Some good timers, using available telescopes

1400 MHz
800 MHz



J1713+0747
rms = 116 ns
over 9 yrs

J1909-3744
rms = 79 ns
over 9 yrs

J0645+5158
rms = 52 ns
over 2.5 yrs

[Arzoumanian et al 16]

Where might we go with SKA1 sensitivity ?

Applying the Radiometer equation:

$$S_{\rm mean} = \frac{({\rm S/N})T_{\rm sys}}{G\sqrt{n_{\rm p}\, t_{\rm int}\, \Delta f}} \sqrt{\frac{W}{P-W}}.$$

and the 1st approx scaling of the ToA uncertainties with the S/N of the observation:

$$\sigma_{\rm ToA} \approx \quad 1/({\rm S/N})$$

The rms in the timing solutions for some very good pulsar-timers could go down to ≈ 10 ns !

And thus, which uncertainty in the clock system?

SYS-REQ 2274: The SKA1_Mid and SKA1_Low timescales shall be traceable to UTC with an uncertainty of no more than 9 ns (1 σ).

For the aimed very good timers - potentially showing residuals at the level or rms ≈ 10 ns - a mere **9 ns** uncertainty due the clock system will be significantly detrimental to the level of achievable noise in the timing solution
that will contribute about 40% to the error budget

Whence, the SYS_REQ 2274 has to be modified imposing that
the uncertainty must be no more than 5 ns at 1 σ
for which the **contribution to the uncertainty budget** will be limited to **about 10%**

We also note that **5 ns at 1 σ is technically achievable by modern clock systems,**
(see e.g. TOW 2015)

And thus, which uncertainty in the clock system?

SYS-REQ 3293 Each SKA1_Mid subarray shall have a common delay centre at or near its centre with a time accurate to the SKA timescale and a precision of better than 2 ns (1 σ) over periods of one observation and at least 10 years.

Given the uncertainties should add in quadrature, **the claimed 2 ns (1 σ) appears acceptable**, provided the global uncertainty of no more than 5 ns (1 σ) is preserved

SYS-REQ 2275 In order to avoid large offsets, the SKA1_Mid Central Reference Frequency shall be steered to UTC to within at least 1 microsecond, with a frequency drift of less than 10 ns/day.

During the "steering" to UTC is important **not to introduce uncontrolled uncertainties** larger than the aforementioned 5 ns (1 σ)

Ongoing simulations will finally confirm whether the 10 ns/day should be a 1 σ value or a more stringent requirement should be imposed

And thus, which uncertainty in the clock system?

SYS-REQ 3292: Each SKA1_Mid VLBI data sample shall be directly traceable to the time at the common delay centre of the SKA1_Mid telescope, with an accuracy of better than 2 nanoseconds

SYS-REQ 3095: The SKA1_Mid timescales shall have a frequency stability, expressed as Allan Deviation, of at least:

AVERAGING TIME [S]	STABILITY
1	$2.0.10^{-13}$
10	$5.0.10^{-14}$
100	$1.3.10^{-14}$
1000	$3.2.10^{-15}$
floor up to 10^5	$3.0.10^{-15}$

These questions are **mostly related to** the requirements for properly performing **state-of-the-art VLB**I observations, which there is a specific focus group looking into

All the VLBI requirements, which we are aware of, are compliant with the pulsar requirements

Requirements of SKA1_LOW vs SKA1_MID

SYS-REQ 2274: The SKA1_Mid and SKA1_Low timescales shall be traceable to UTC with an uncertainty of no more than 9 ns (1 σ).

SYS-REQ 3294: Each SKA1_Low subarray shall have a common delay centre at or near its centre with a time accurate to the SKA timescale and a precision of better than 2ns (1 σ) over periods of one observation and at least 10 years.

SYS-REQ 3280: In order to avoid large offsets, the SKA1_Low Central Reference Frequency shall be steered to UTC to within at least 1 microsecond, with a frequency drift of less than 10 ns/day.

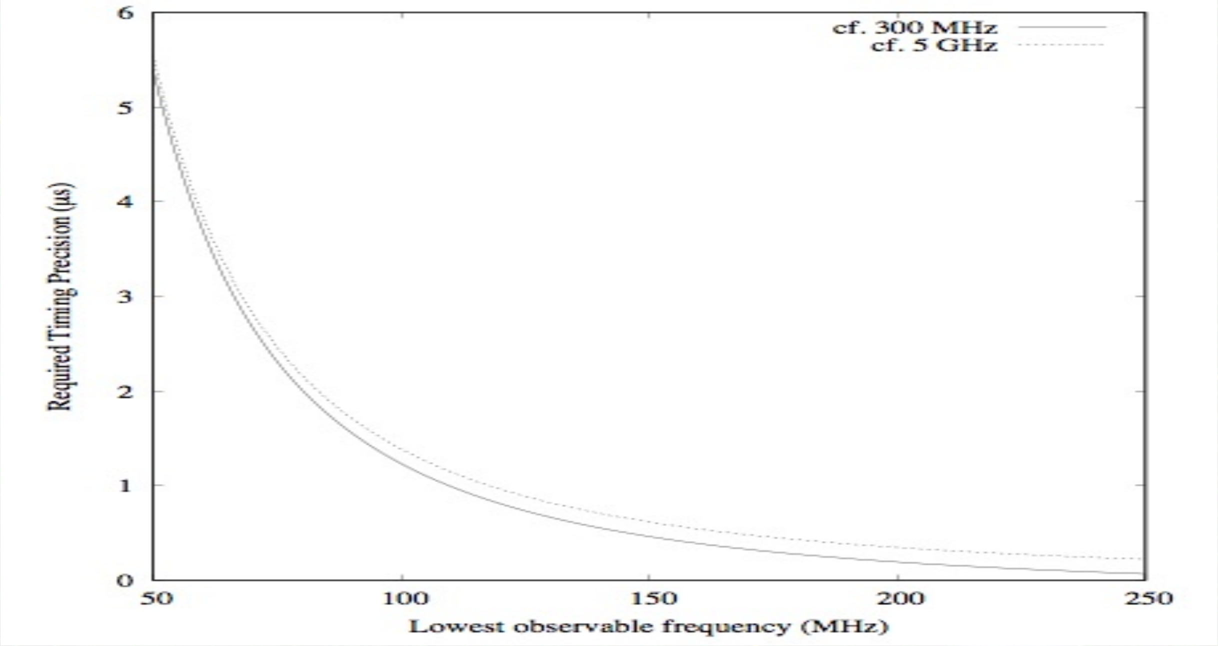
Pulsar timing precision at low frequencies is unlikely (yet not impossible) to be as good as at high frequencies

The main uses of the pulsar timing with SKA1_LOW will then be:
(i) to monitor variations in pulsar dispersion to correct dispersive delays in observations made at higher frequencies;
(ii) to study the IISM and to monitor the interstellar/interplanetary weather;
(iii) to investigate pulsar electrodynamics and radio emission processes.

Requirements of SKA1_LOW vs SKA1_MID

Allowed timing precision for SKA1_LOW in order to correct the DM for a pulsar with 10 ns rms at 1.4 GHz

[van Straten 17]



The **timing precision at the frequencies of SKA1_LOW does not have to be as precise as at** the operational frequencies of **SKA1_MID**.

The absolute **upper limit** for the level of relaxation of the constraints **is about an order of magnitude larger than for SKA1_MID, i.e. 100 ns (3 σ)** for SYS-REQ 2274 and correspondingly scaled values for SYS-REQ 3294, and SYS-REQ 3280. However, **the need of stronger constraints cannot be excluded yet and is still under investigation** (i.e. for millisecond pulsars which display ONLY at SKA1_LOW band)

Misnomer for "Dynamic Spectrum"

SYS-REQ 2956: Each SKA1_Low pulsar timing and dynamic spectrum measurement shall be directly traceable to the time at the common delay centre of the SKA1_Low telescope, with an accuracy of better than 2 nanoseconds (TBC).

We strongly advise that **the name "dynamic spectrum" be modified** here and in all other instances where it appears. A more suitable name would be e.g. **pulsar search filter-bank format data stream.**

Summary

✧ **The SYS_REQ 2274 has to be modified imposing a 5 ns uncertainty at 1 σ for SKA1_MID. The mentioned 9 ns (1 σ) is certainly fine for SKA1_LOW (see also below).**

✧ **The SYS-REQ 3293 can remain as it is.**

✧ **The SYS_REQ 2275 has to be completed with the indication that the frequency drift of 10ns/day is meant as a 1 σ limit.**

✧ **The SYS_REQ 3292, dealing with VLBI requirements, is compliant with the pulsar science requirements.**

✧ **The timing precision at the frequencies of SKA1_LOW does not have to be as precise as at the operational frequencies of SKA1_MID. The constraints could be nominally relaxed up to about an order of magnitude larger than for SKA1_MID, but the need for stronger constraints cannot be excluded yet and is still under investigation.**

✧ **Redundancy in the adopted clock systems is very necessary to ensure that the many year investment that is required for the high precision timing projects is not diminished by longer periods without access to clock corrections and/or significant un-modelled steps in the time transfer.**