AEÑEAS – European SKA Regional Centre Design Meeting

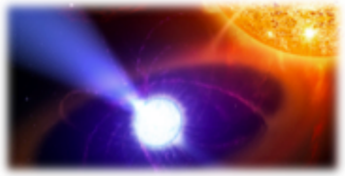
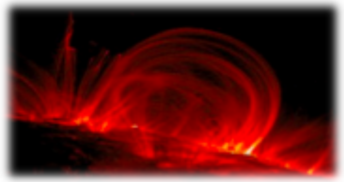
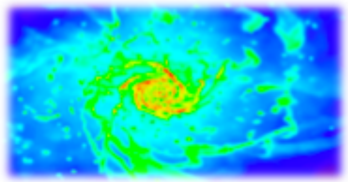
Pulsar science at SKA Regional Centres

Andrea Possenti

Lyon - 27 June 2019

Flagship science

	SKA1	SKA2
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the 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	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	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ z ≈ 0.04.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z ≈ 0.13.
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid.	Gas properties of 10^9 galaxies, <z> ≈ 1, evolution to z ≈ 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.

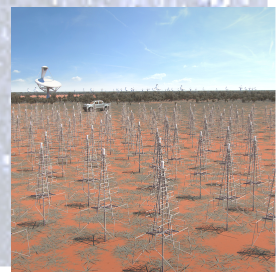
Summary

The SKA Pulsar Science one-sentence-summary and the top-priorities set in August 2015, at Stockholm

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



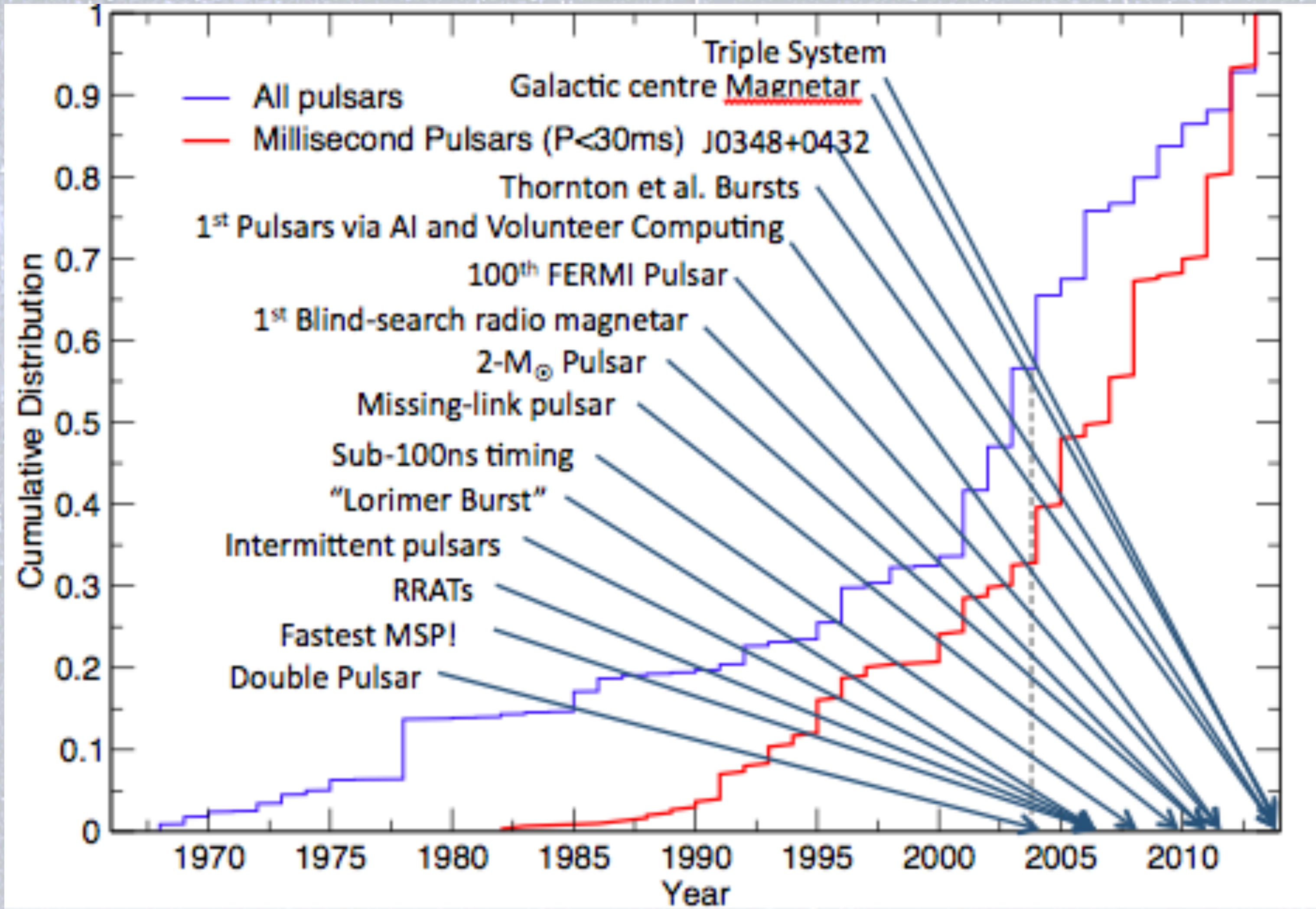
Reference literature

from SKA Science book (Sicily 2014)

- Cosmic census (Keane et al. 1501.00056)
- Testing Gravity (Shao et al. 1501.00058)
- GW astronomy (Janssen et al. 1501.00127)
- Understanding PSR Magnetospheres (Karastergiou et al 1501.00126)
- Understanding NS population (Tauris et al. 1501.00005)
- Galactic & Intergalactic medium (Han et al. 1412.8749)
- NS Equation of State (Watts et al. 1501.00042)
- Pulsars in the Galactic centre (Eatough et al. 1501.00281)
- Pulsars in Globular clusters (Hessels et al. 1501.00086)
- Pulsar wind nebulae (Gelfand et al. 1501.00364)

Overview (Kramer & Stappers 1507.04423)

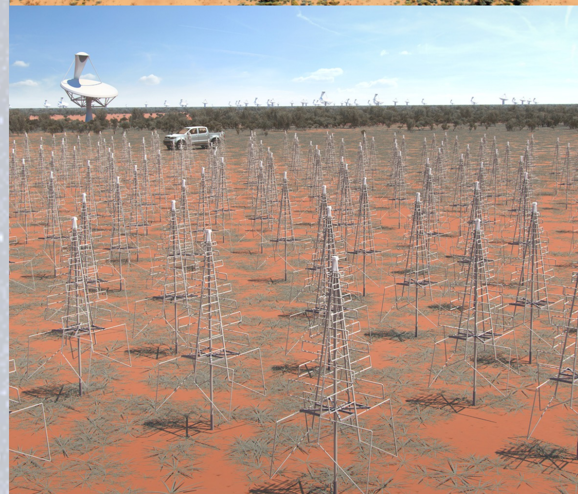
1st flavor of pulsar studies: searches



The impact of SKA1 on pulsar searches

Search speed ≈ $(A_{eff}/T_{sys})^2\ \Omega$

The current pulsar population ≈ 2700 (with ≈ 350 MSPs)



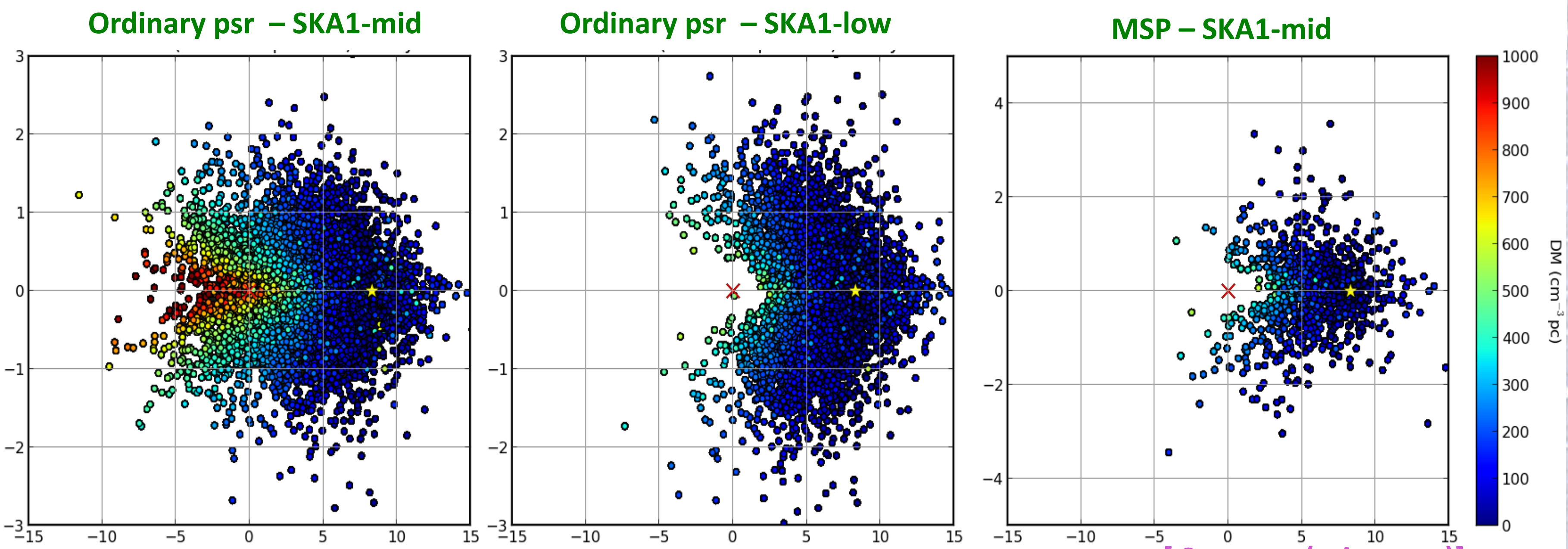
The post-SKA1 pulsar population ≈ 9000 and in particular a population of Millisecond pulsars ≈ **1500**

[Keane et al 2015]

The impact of SKA1 on pulsar searches

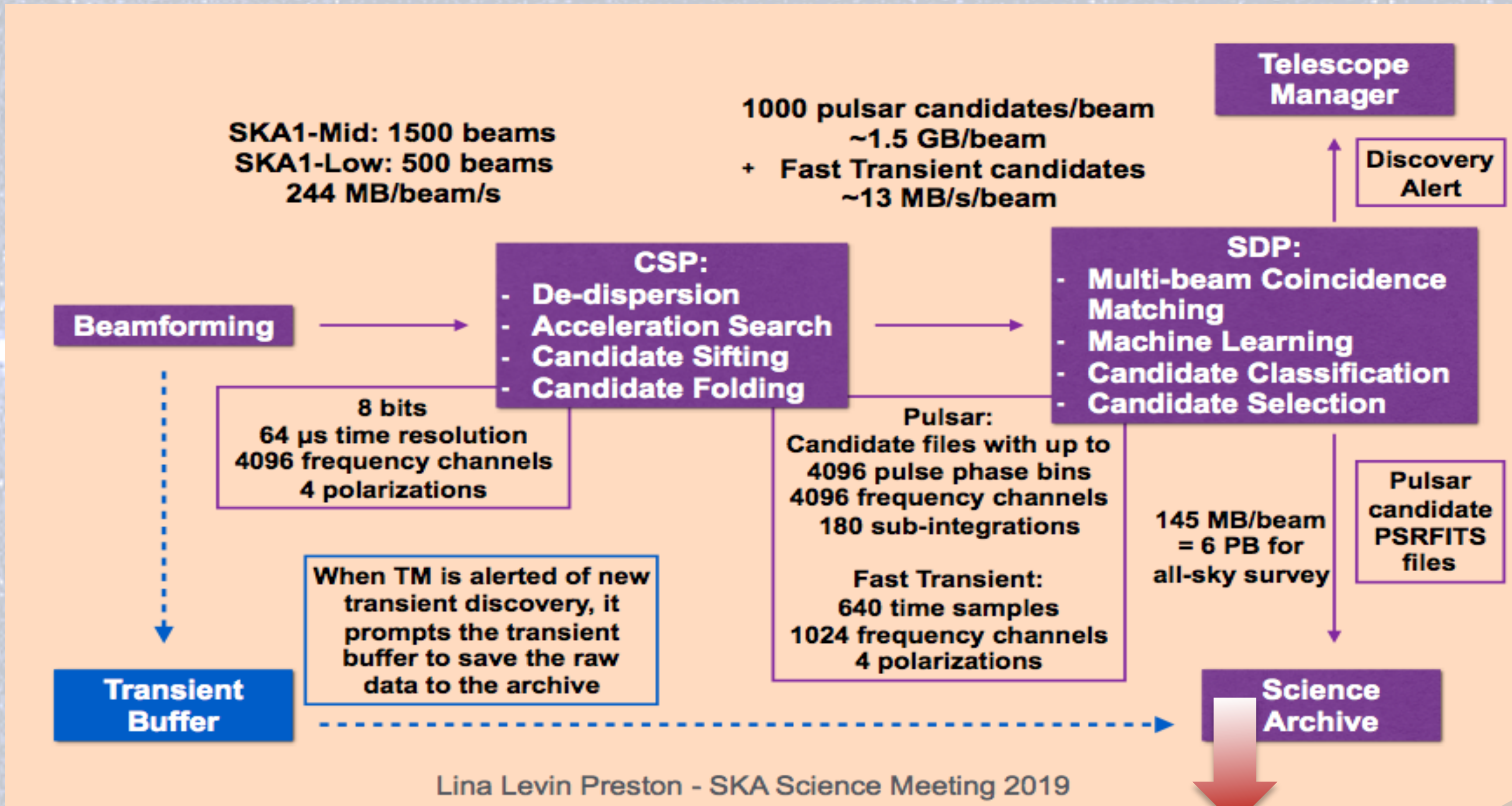
Almost half of all pulsars will be discovered with Phase I already

by using in combination SKA-low and SKA-mid



[Stappers (priv. com.)]

Pulsar search flowchart in CSP+SPD



Single Beam Search candidate data Size = Assuming parameters: 100 candidates = 0.107 GBy + 1.2 Gby for single pulse candidates (at rate = 1/sec)

Expected Total number of Beams over 5 years =

3200 hours at SKA1-MID1x 6 scans/hour x 1500 beams = 28.8x10^6

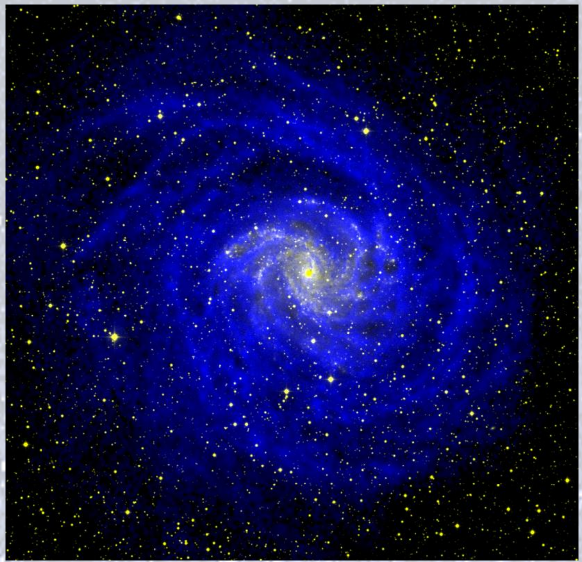
12750 hours at SKA1-LOW x 6 scans/hour x 500 beams = 38.25x10^6

PRELIMINARY

Total amount of data sent to SRCs over 5 years → 6-7 PBy + single pulse

Data streams not searched in real-time

Targeted searches for
Globular Clusters, Srg A* region, Pulsar Wind Nebulae, Gamma-ray sources, external galaxies**, etc**



<u>Single beam dynamic spectrum data size</u> = 30 minutes data streams with 4096 channels, 50 μs sampling, 4 Stokes and 4 bits quantization = 2.2 TB

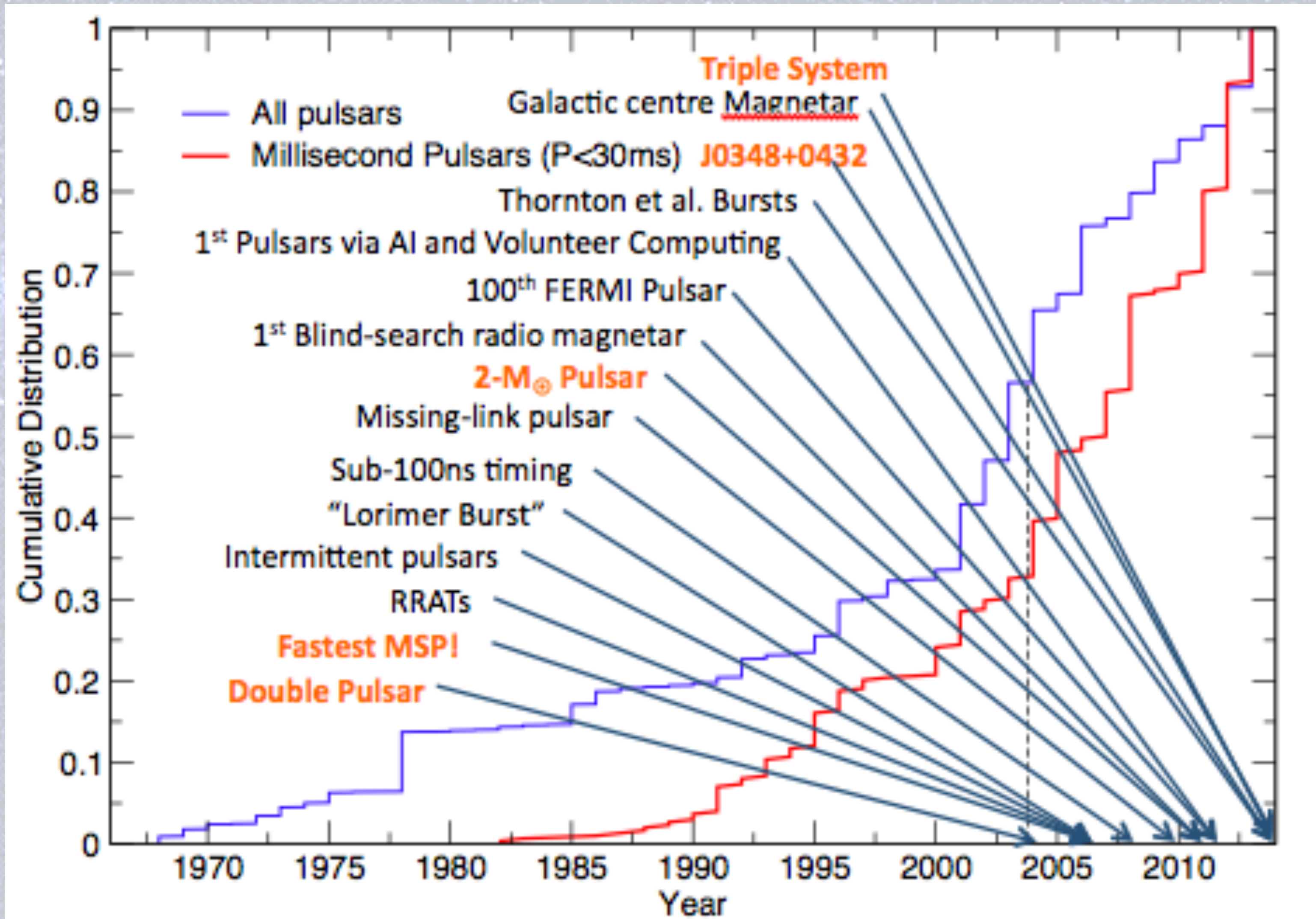
<u>Dynamic spectrum data size per pointing</u> = 16 simultaneous beams = 35.1 TB

<u>Expected Total number of Pointings over 5 years</u> = (guessed) 300

PRELIMINARY

Total amount of data sent to SRCs over 5 years → ≈ 10 PBy

2nd flavor of pulsar studies: timing



In orange the pulsars the timing of which has so far contributed the most to constrain the laws of fundamental physics

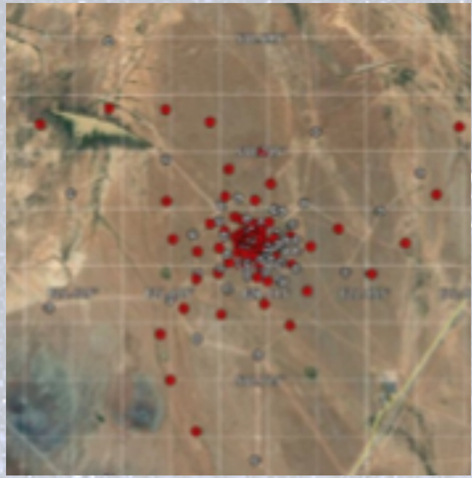
The impact of SKA1 on fundamental physics

Timing quality $\sigma_{ToA} \approx T_{sys} / A_{eff}$

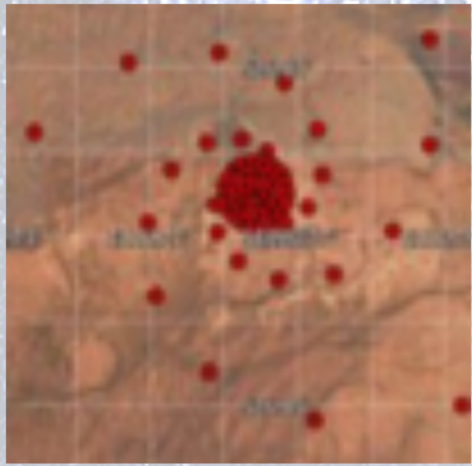
The current relativistic pulsars population ≈ 20-30

The SKA1 relativistic pulsar population ≈ 100-200 and a timing precision better by a factor ≈ 5-10

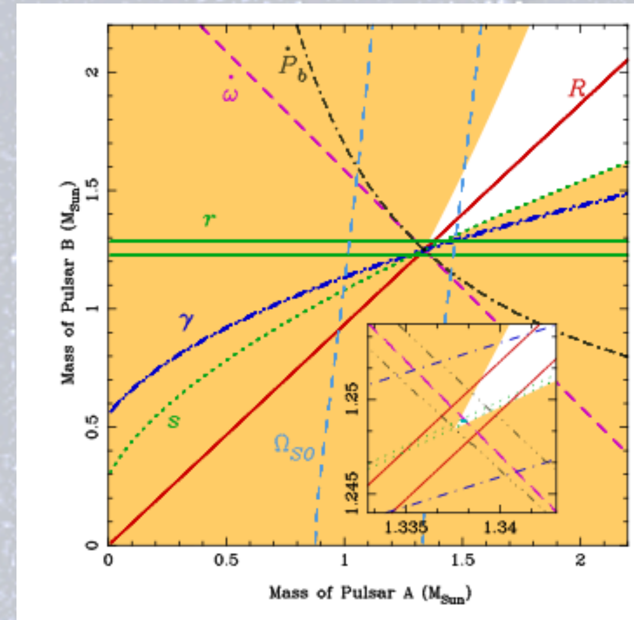
[Keane et al 2015; Shao et al 2015]



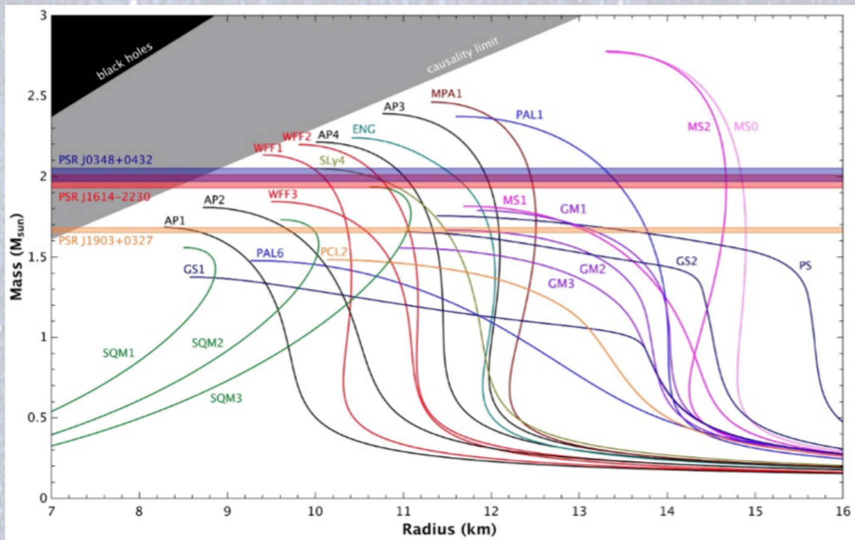
Larger areas than searches
Sub-arraying
Multiple frequencies



Constraining GR and alternate theories



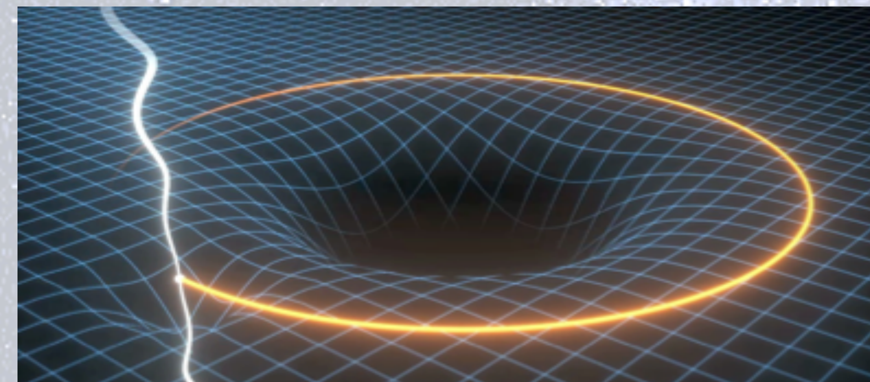
[Kramer et al 2019 (in prep.)]



[Watts et al. 2015]

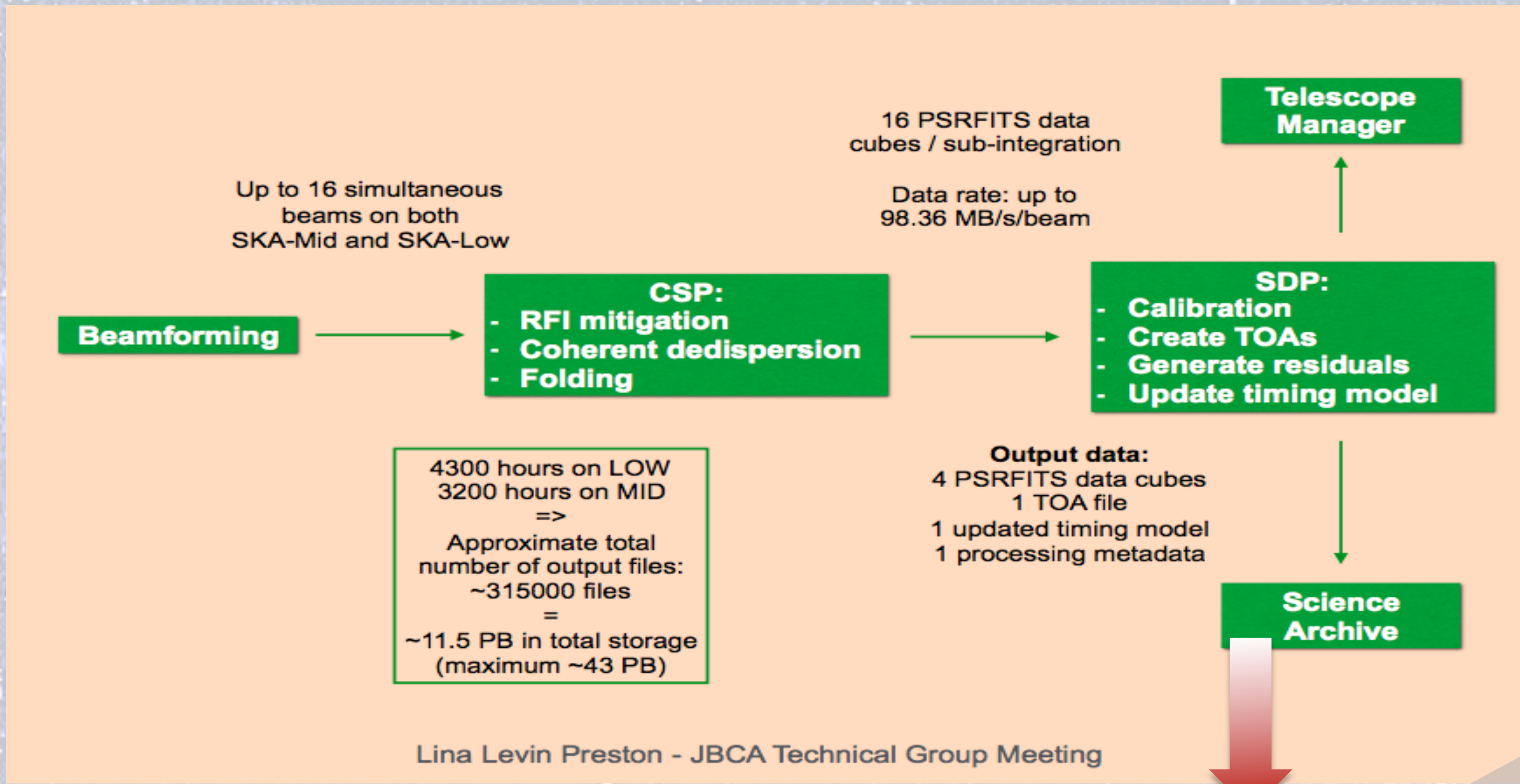
Constraining Principles and Eq of State of nuclear matter

The exciting perspectives of a PSR+BH system



[Liu et al. 2013]

Pulsar Timing flowchart in CSP + SDP



Single Beam Timing data Size = Assuming parameters: 4096 channels, 2048 phase bins, 180 sub-ints, 4 pols, 64 bit = 48.3 GBy

Expected Total number of Beams over 5 years =

3200 hours at SKA1-MID x 6 scans/hour x 16 beams = 307,200 data cubes

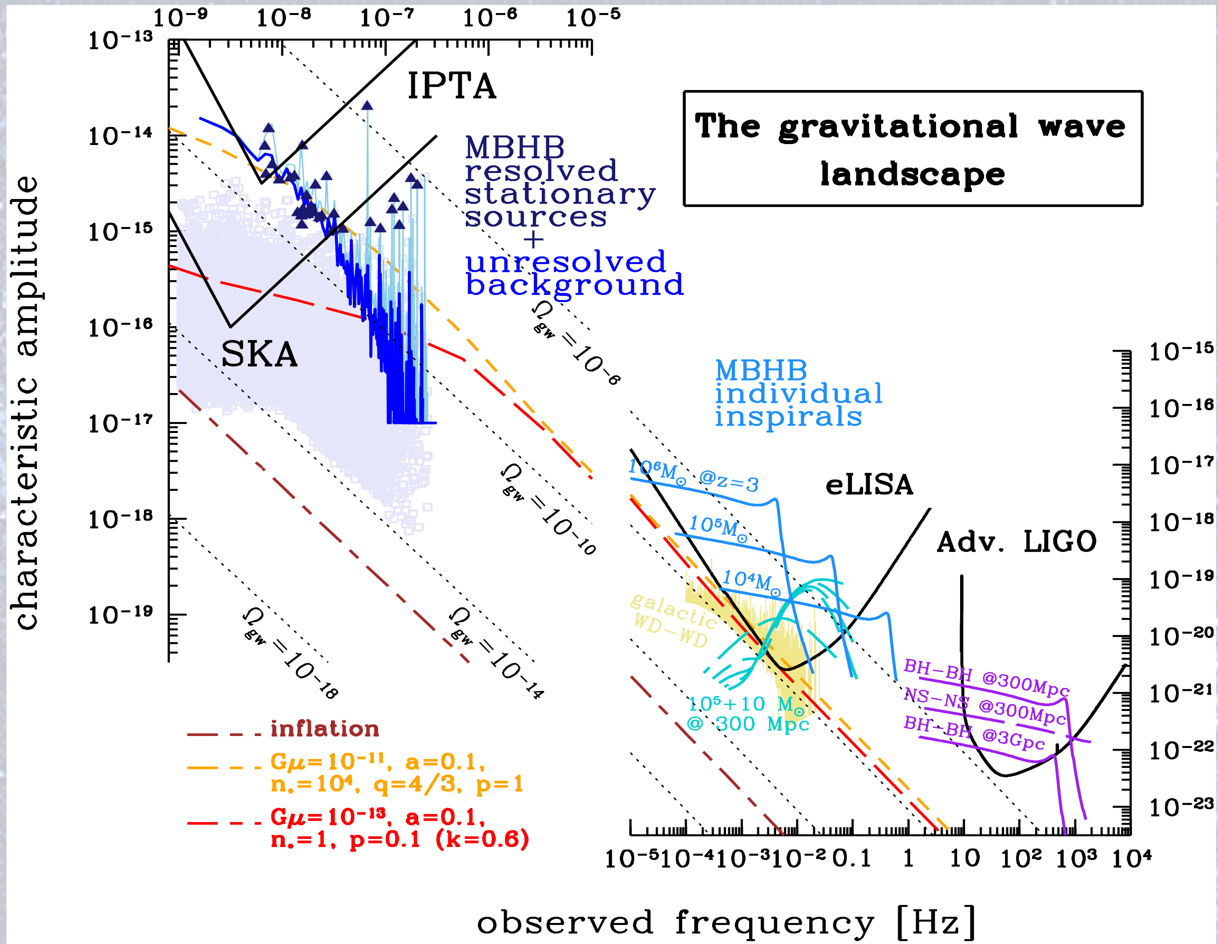
4300 hours ay SKA1-LOW x 6 scans/hour x 16 beams = 412,800 data cubes

Total amount of data sent to SRCs over 5 years → 35 PBy

PRELIMINARY

3rd flavor of pulsar studies: direct GW detection via use of Pulsar Timing Array

- **Expected sources:**
  - super-massive BH binaries in early Galaxy evolution
  - cosmic strings
  - cosmological sources
- **Types of signals:**
  - stochastic (multiple)
  - periodic (single)
  - burst (single)

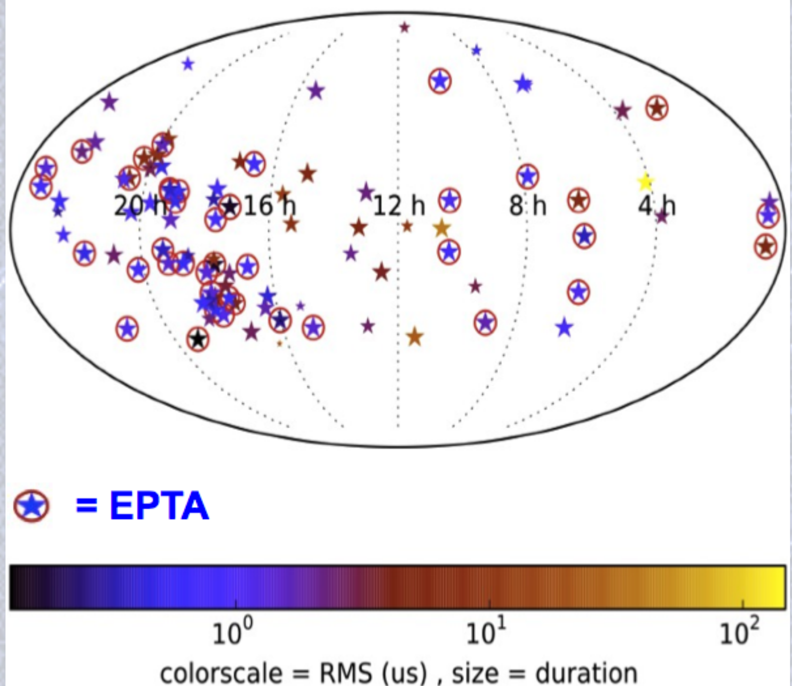


[Janssen et al 15]

Note the complementarity in explored frequencies with respect to the current and the future GW observatories, like advLIGO, advVIRGO and eLISA

for a detection one needs a ...

Pulsar timing array (PTA)



The current sample of MSP of IPTA ≈ 40, of which only a handful with precision < 100 ns

IPTA (International Pulsar Timing Array)

[Shao et al 2015]

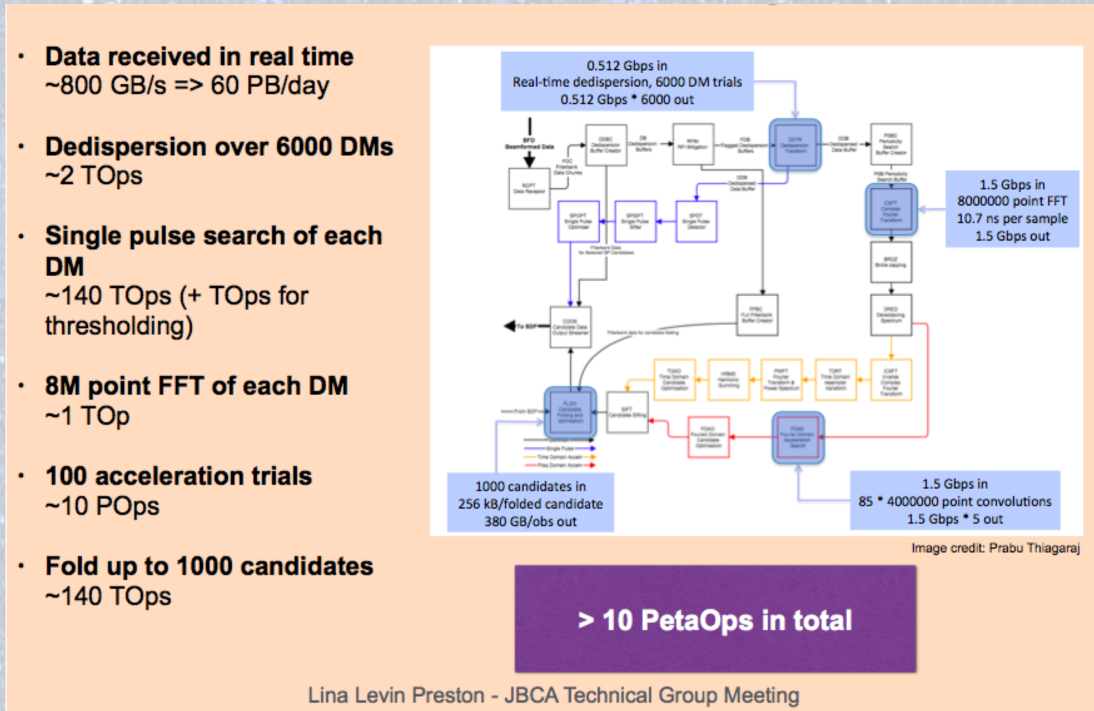
SKA1 will provide ≈ 100 MSPs with timing precision < 100 ns

What is left to do at the SRCs machines

A PRELIMINARY LIST OF TASKS TO BE PERFORMED AT SRCs FOR PULSAR SCIENCE

- Targeted pulsar not real time searches (aka dynamic spectrum analysis data)
- Additional Deep Learning approaches to better extract candidates: billions of them are expected
- Develop new algorithms to be potentially rolled out on the SKA CSP+SDP
- Post processing of pulsar timing data for studies like pulse profile evolution, DM changes, Rotation Measure changes etc
- Improved pulsar timing including higher order relativistic effects
- Single pulse and giant pulse studies
- Search for nanoHz Gravitational Waves signatures and parameters in very large SKA datasets, also by combining MID and LOW observations
- Especially for LOW baseband data, perform "cyclic spectroscopy" and "phase-coherent de-scattering" of pulsar timing observation
- For the brightest millisecond pulsars belonging to the SKA-Pulsar Timing Array, perform single-pulse analysis of correlated sub-pulse structure and correction of arrival time jitter

Computational requests for the not real time search at the SRCs



The acceleration search gives, by far, the largest contribution, and – for the other parameters fixed – that scales as at least the cube of the integration time.

Going from 10 to 30 min integrations, means approaching ≈ 1-10 PetaOps for the analysis of guessed number of pointing

A DETAILED QUANTIFICATION OF NEEDED FLOPS IS IN PROGRESS

Of course there is not the need of real time processing

Current hardware solutions for the pulsar search machines at CSP

- Current best solution is a combination of GPUs and FPGAs
  - GPUs mainly focussed on dedispersion and acceleration searching
  - FPGAs mainly focussed on long FFTs and convolution
- Power consumption is a big challenge: need ~260 W/beam = 35 Gflops/W
- Improvements to algorithms are being developed continuously
- Building 3% prototype: ProtoNIP

Two statement summary of the major pulsar activities at the SRCs machines

1) SRCs must be able to tackle all the analyses that are currently done for pulsar science, but all of them run over much larger datasets or much larger data files (typical factor 10x): hence cleverer and <u>always in development</u> hardware and software solutions

2) Location of data is not critical, provided data for a given project are in the same SRC and that SRC has the required minimal level of Flops and Storage

A DETAILED QUANTIFICATION OF FLOPS AND STORAGE NEEDED FOR THE REGULAR OPERATIONS, AS WELL AS FOR COMMISSIONING IS IN PROGRESS

Thank you