# Radio Aspects of the Transient Universe

- Time domain science: the transient sky = frontier for all $\lambda\lambda$
  - Less so at high energies
    - BATSE, RXTE/ASM, Beppo/Sax, SWIFT, etc.
  - More so for optical, radio
- LSST = Large Synoptic Survey Telescope
  - Rename to OLSST
- Consider RLSST (Radio LSST)
- The dynamic radio sky (DRS) = SKA science area
- SKA specifications $\Rightarrow$unprecedented blind surveys of the DRS
- The science is important for the known knowns
- There are bound to be many unknown knowns and unknown unknowns
- Fast and slow transients:
  - What capabilities are needed

# The Dynamic Radio Sky

- Poorly known compared to the high-energy sky (X, $\gamma$-ray)
- Known transients span a wide range of time scale, frequency and luminosity (brightness temperature)
- Characterizing the DRS requires
    - Wide FoV "staring" for fast transients
    - Efficient raster scanning for slow transients
    - Discrimination from RFI
    - Dealing with plasma dispersion and scattering for fast transients

# What is important about the transient sky?

Fast transients (< few sec): compact objects

- Relativistic
  - Extreme states of matter (WD, NS, BH)
  - Unknown manifestations of fast spin, magnetic field
  - New kinds of compact objects? (quark stars)
  - New emission processes
- Planetary
  - Planet-star interactions (~ Jupiter-Io)
- ETI

# What is important about the transient sky?

- Slow transients: new populations of brown dwarfs, flare stars, SNAe …
- Large populations of objects otherwise missed
  - Probes of intervening media (ISM, IGM)
  - Objects for probing gravity
- The ultimate fishing expedition: the unknown

# The 6th Key Science Area: Exploration of the Unknown

**Entirely new classes of objects and phenomena will be discovered if the SKA has appropriate flexibility in its operations (digital signal processing capabilities, array configuration, field of view, etc.)**

c.f. Science with the SKA (Rawlings & Carilli, eds.), New Astronomy, 2004

*Exploration of the Unknown*, Wilkinson et al.

*The Dynamic Radio Sky*, Cordes et al.

**Radio transient sky:** very poorly known compared to the high-energy (X-ray, gamma-ray) sky

The key to making discoveries: Sensitivity + Field of View

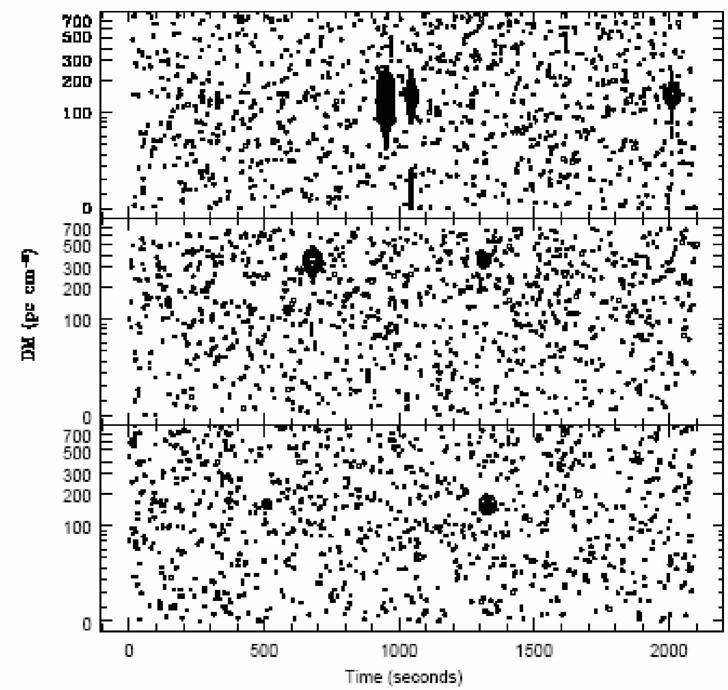
# Transient radio bursts from rotating neutron stars

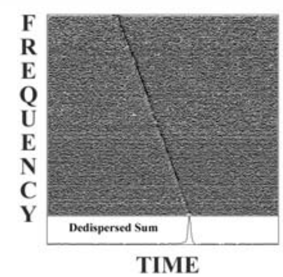
M. A. McLaughlin [*], A. G. Lyne[*], D. R. Lorimer[*], M. Kramer[*], A. J. Faulkner[*], R. N. Manchester [†], J. M. Cordes [‡], F. Camilo [§], A. Possenti [¶], I. H. Stairs [||], G. Hobbs[†], N. D'Amico [**¶], M. Burgay[¶] & J. T. O'Brien[*]

"RRATs"

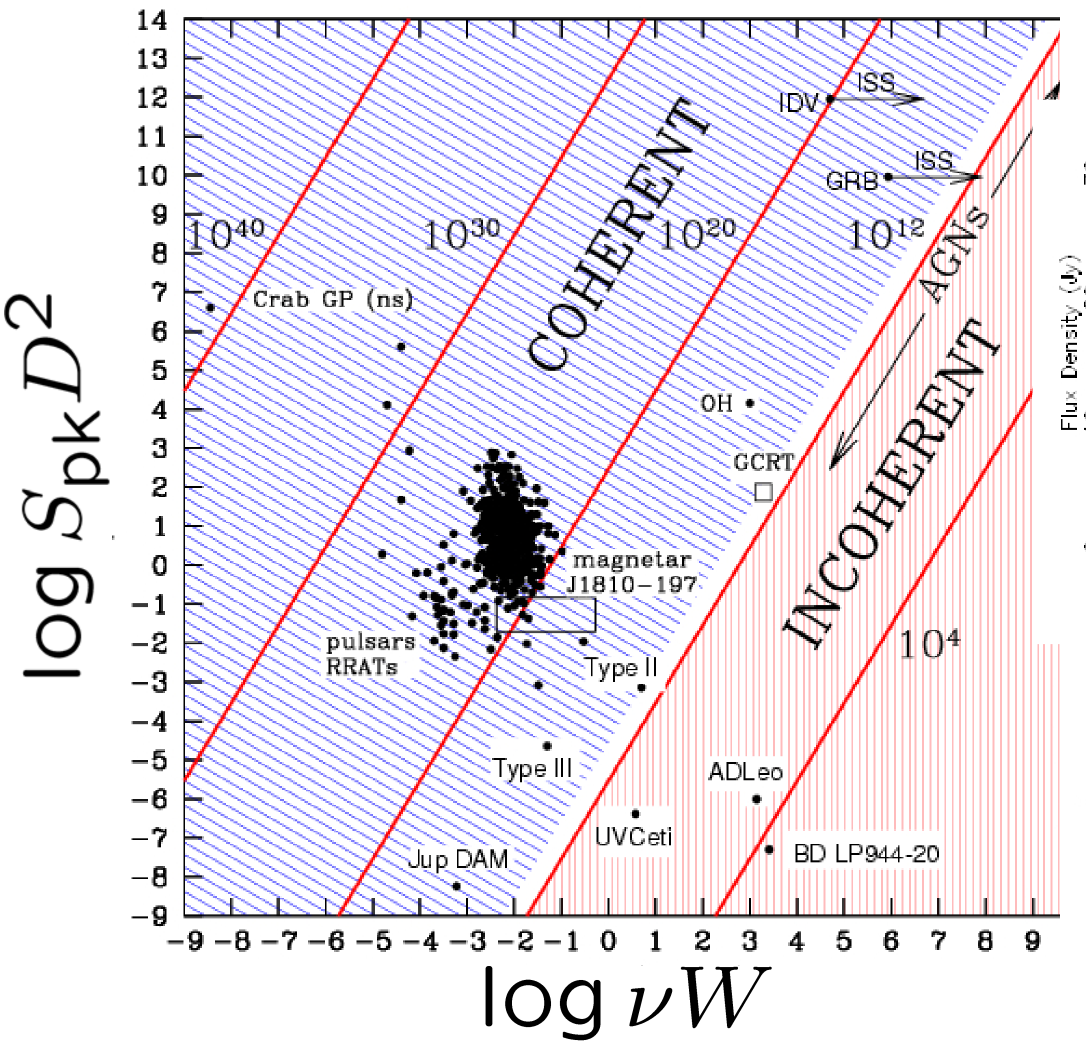
**Nature (2006)**

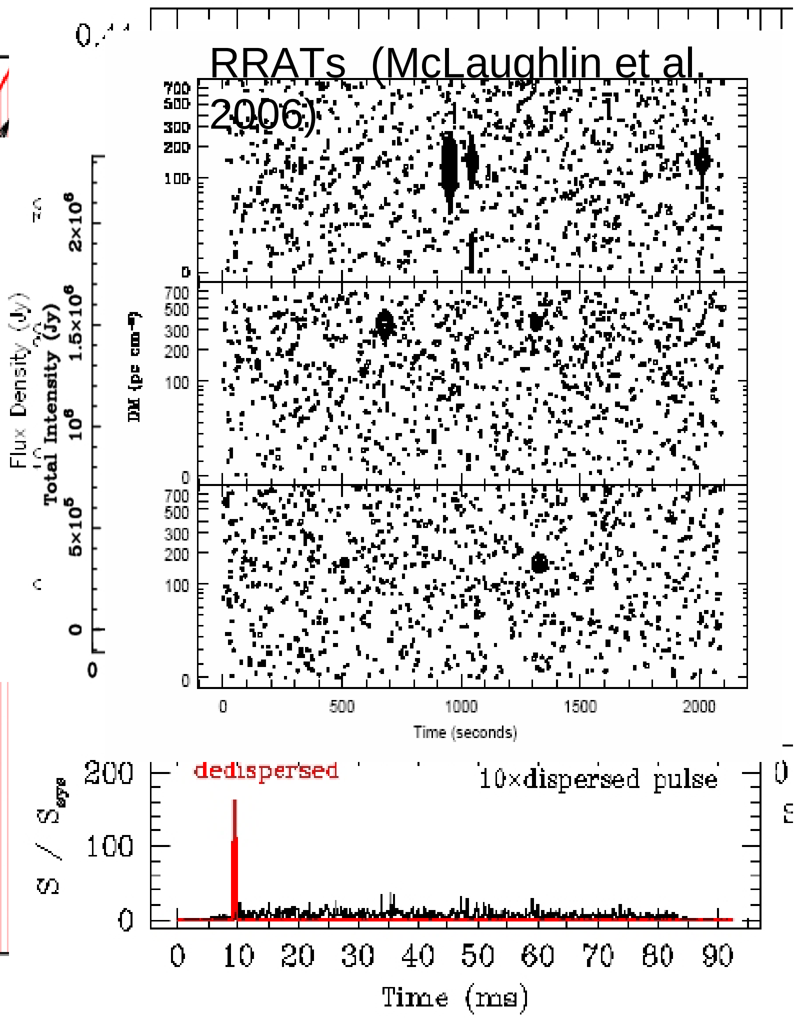
- 11 sources found in reanalysis of Parkes MB survey
    - missed in periodicity search
- Pulse rates ~ 0.3 to 20 pulses hr$^{-1}$
- Extreme cases of pulse nulling?
- Implied Galactic population > "normal" pulsar population (i.e. ~ $2\times10^5$ objects)



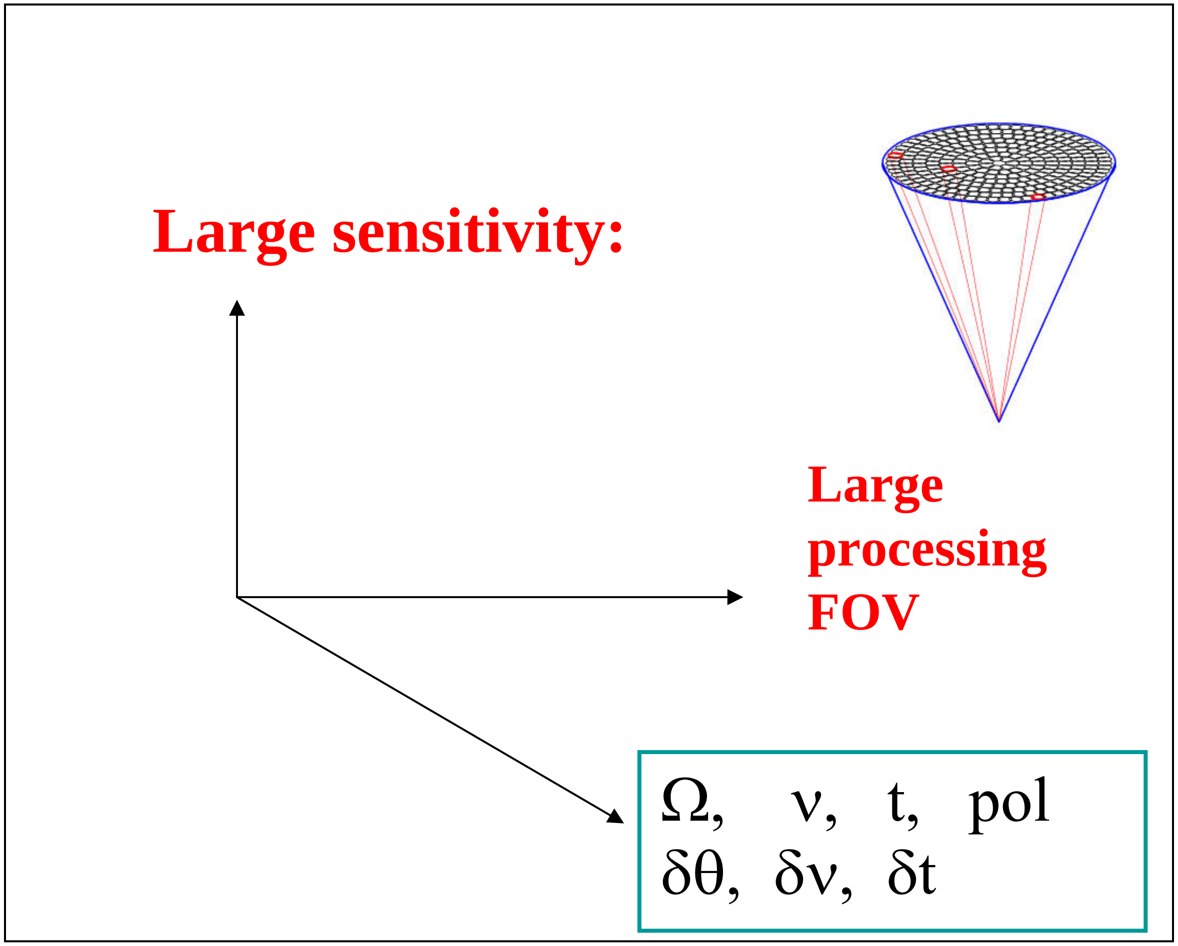



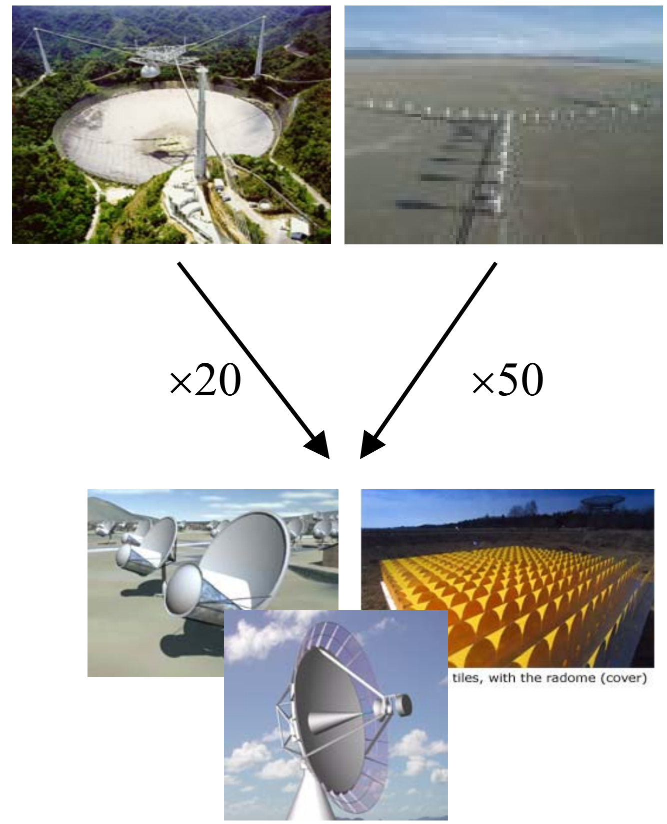
# Phase Space for Transients: $S_{pk}D^2$ vs. $\nu W$



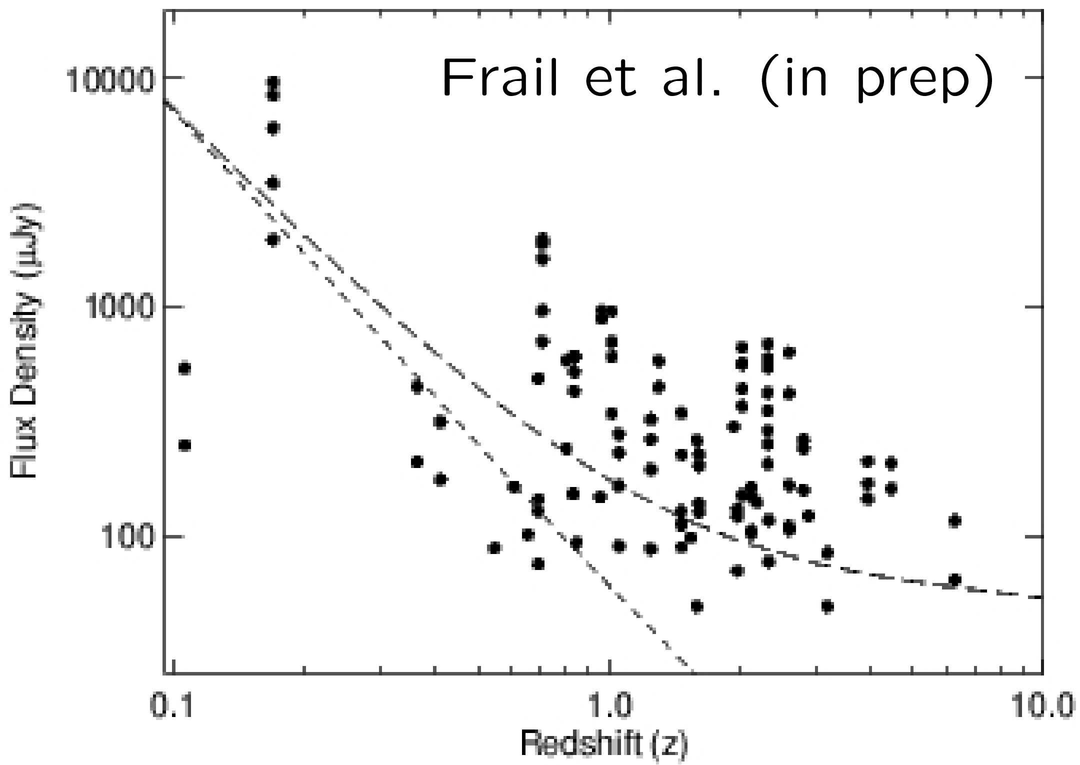
# The Essence of the SKA for Time-domain Science



# GRB radio afterglows vs. z

Flux density ~ independent of z at higher z



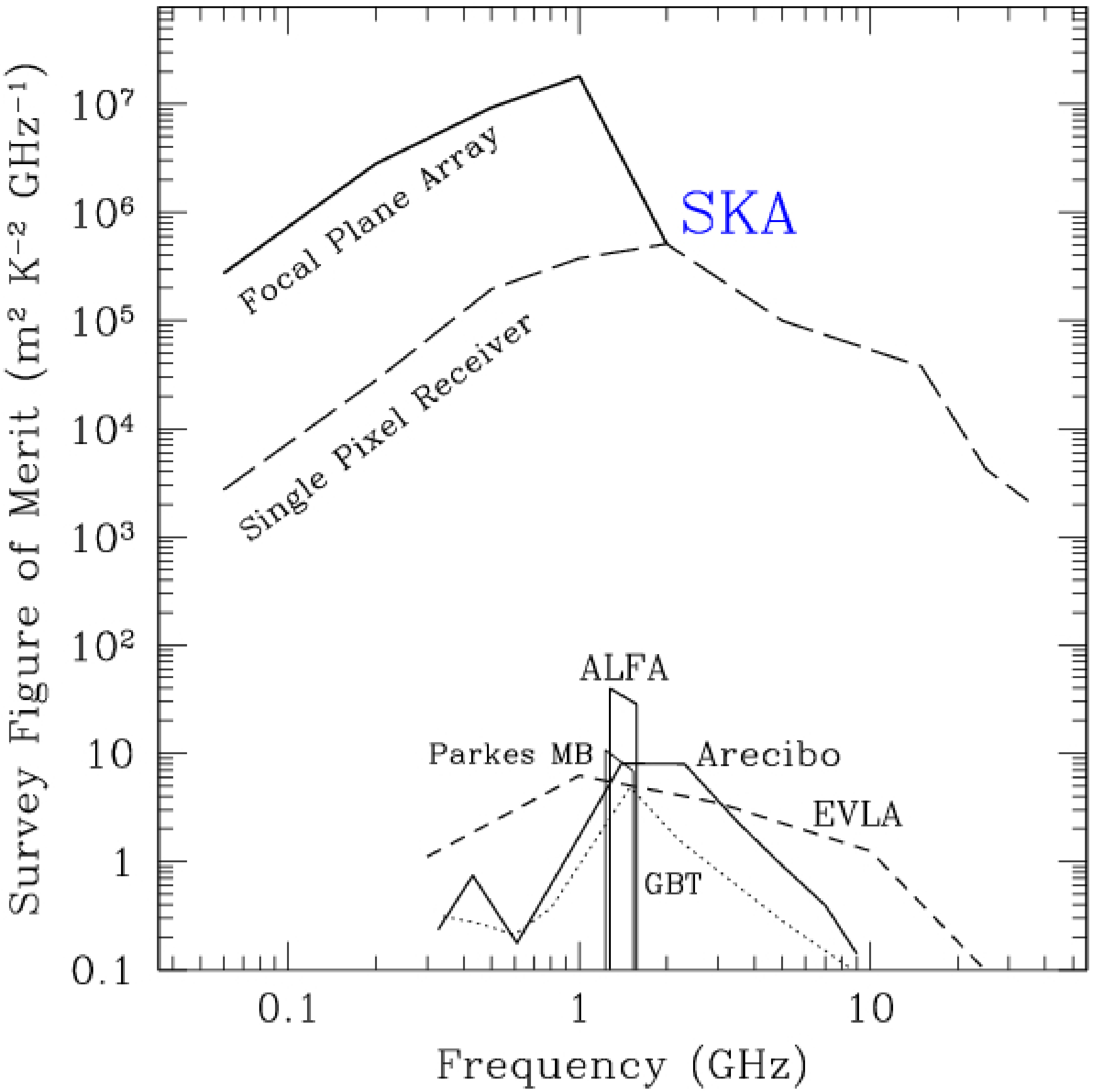

EVLA → SKA

×100 greater sensitivity

⇒ blind surveys for GRB afterglows

## Figure of Merit for Radio Survey Capabilities

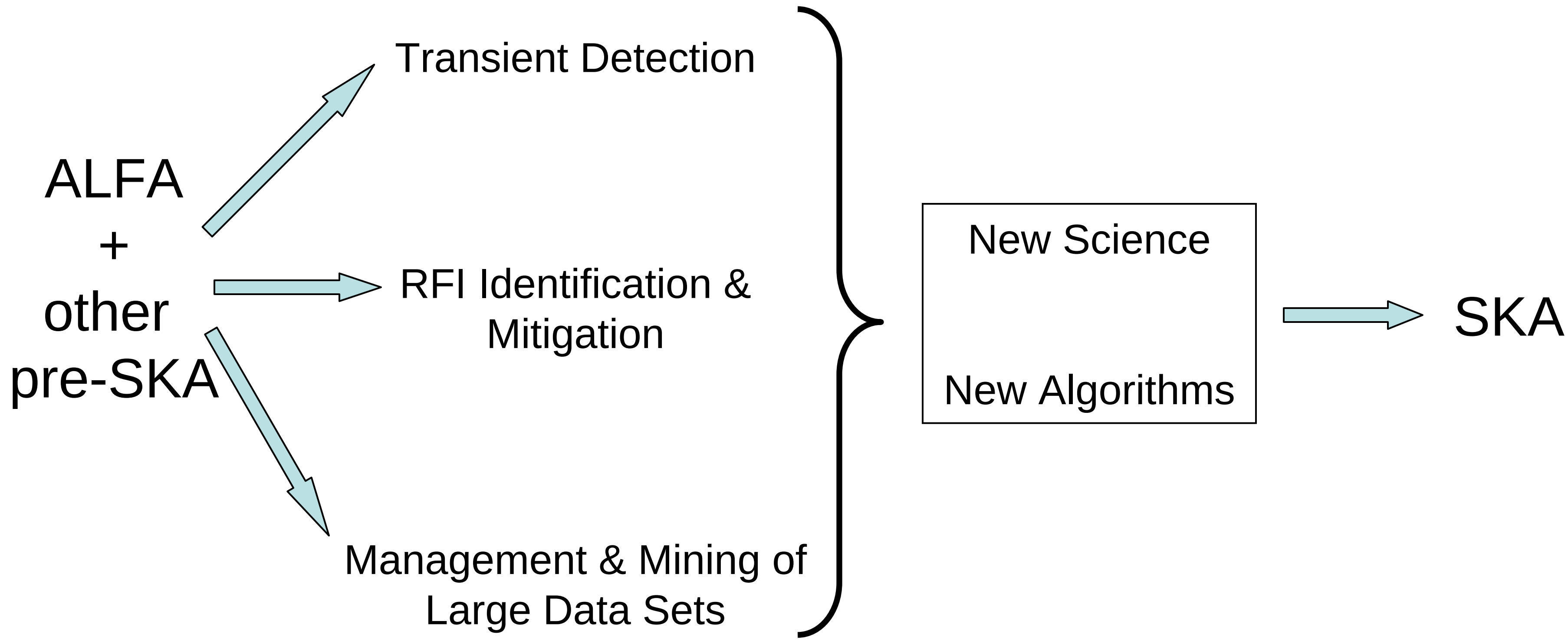
$$\mathrm{FoM} = N_{FoV} f_c A_e N_A B (\nu T_{sys})^{-z}$$

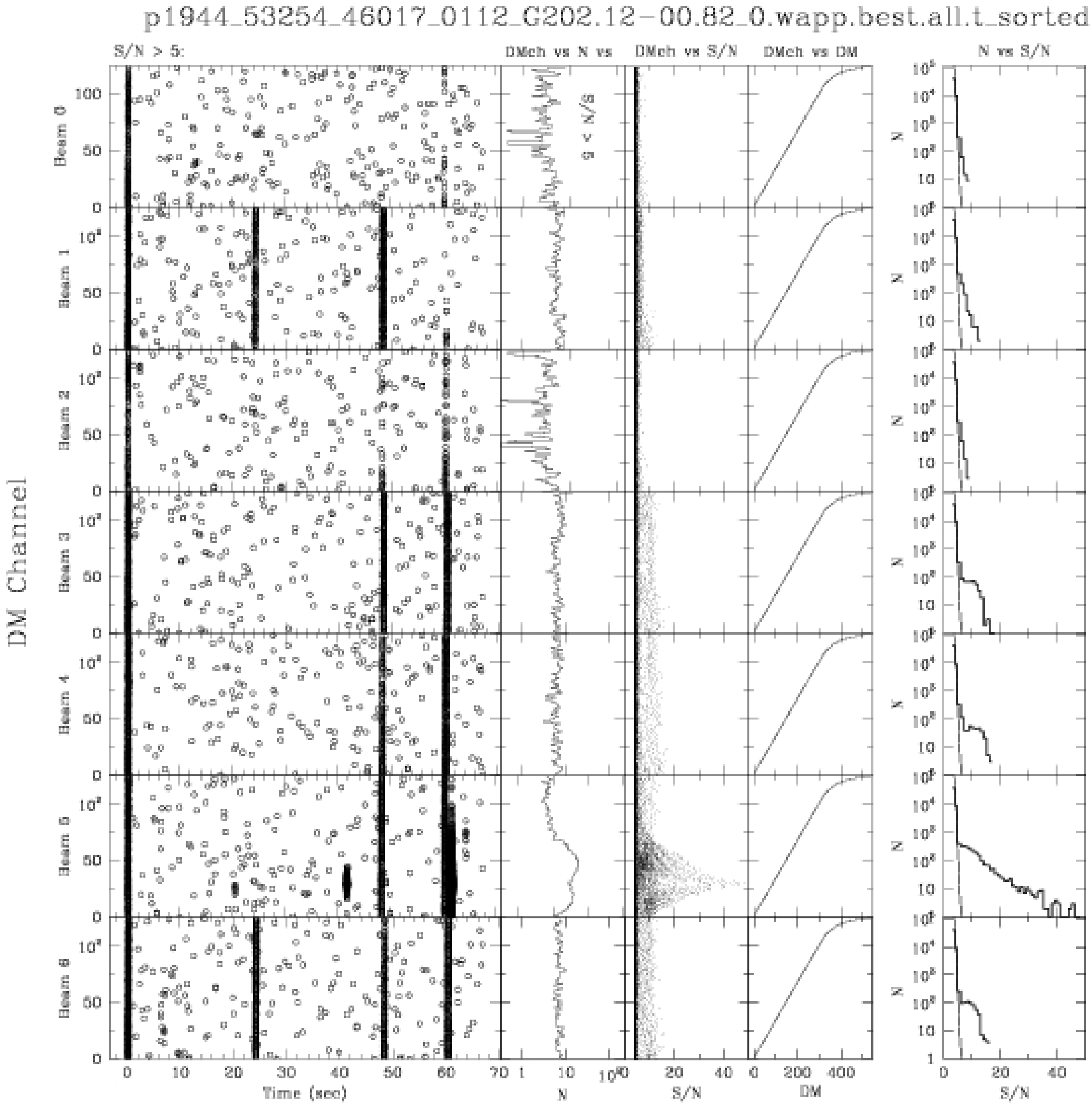



$$\mathrm{FoM} \propto \frac{\text{Surveyed Volume}}{\text{Integration Time}}$$

# Radio Transients

## Developing a new paradigm for radio science






A pulsar found through its single-pulse emission, not its periodicity (c.f. Crab giant pulses).

Algorithm: matched filtering in the DM-t plane.

ALFA's 7 beams provide powerful discrimination between celestial and RFI transients

# Transient Surveys

- Fast
  - Too fast to be sampled by raster scanning (<< 1 day)
  - Produced by compact sources (size < $c\Delta t$)
  - Coherent radiation
  - Influenced by diffractive interstellar scintillations

    $\Rightarrow$ imposed $\nu$-t structure on intrinsic signal
  - Sampled by “staring” for long dwell times
  - Large solid angle coverage needed for blind surveys
- Slow
  - Durations longer than time to raster scan relevant solid angle
  - Incoherent radiation

# Example Raster Scan Survey

- 1 $deg^2$ FoV
- Full sky survey (80% of 40,000 $deg^2$)
- $T_{scan}$ = 5 days
- T ~ 10 sec = time per sky position
- $S_{min}$ ~ 15 μJy at 10σ with full sensitivity and on axis
- Subarrays reduce the sensitivity but speed up the survey
- Multiple FoVs increase the sensitivity and speed of the survey

# Frequency Ranges

- Low: < 0.3 GHz
  - Coherent sources with low-pass spectra: planets, pulsars, other (prompt GRB radio?)
  - Fast transients difficult because of temporal smearing from dispersion/scattering
- Mid: 0.3 to 2 GHz
  - Pulsars, RRATs, magnetars, OH masers, brown dwarfs, planets, other
  - Propagation effects significant, mostly manageable
- High: 2 to 25 GHz
  - GRB afterglows, GC transients, pulsars, RRATs, $H_2O$ masers, magnetars
  - Propagation effects small/manageable

# Some Implications for Large-N/Small D Concepts for the SKA

- Significant collecting area in a core array is needed to keep processing requirements manageable
- Number of operations for beam forming

$$N_b = 10^{16}\, s^{-1} \left(\frac{f_c}{0.5}\right)\left(\frac{N_a}{4400}\right)\left(\frac{N_{\rm pol}}{2}\right)\left(\frac{b_c/1\,{\rm km}}{D/\,12\,{\rm m}}\right)^2\left(\frac{B}{400\,{\rm MHz}}\right)$$

- Need subarray and multiple FoV capability
- Big Gulp (antennas smaller than 12 m): T. Cornwell
    - e.g. $10^4$ 5m antennas
    - may have trouble handling wide-FoV searches

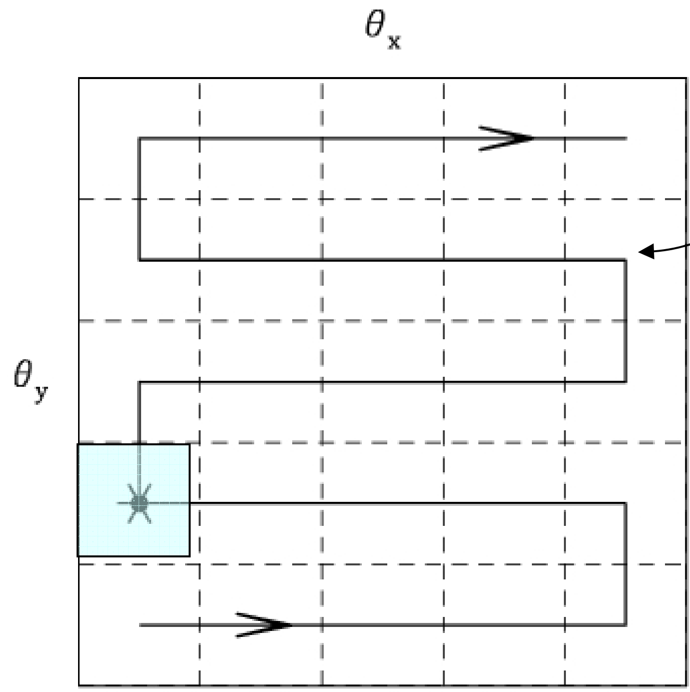
  $\Rightarrow$ Big Choke?

# Summary/Conclusions

- New radio capabilities needed for complete surveys of the transient sky:
  - Wide field of view
  - High-rate signal processing (dedispersion, matched filtering with families of templates)
  - High sensitivity
  - Data management
- $\Rightarrow$ an SKA-type instrument
- SKA $\approx$ Radio LSST (in part)
- Optical LSST + Radio LSST highly synergistic
- Radio LSST also highly synergistic with high-energy instruments and gravitational wave telescopes

# Extra Slides

# Raster Scanning for Slow Transients



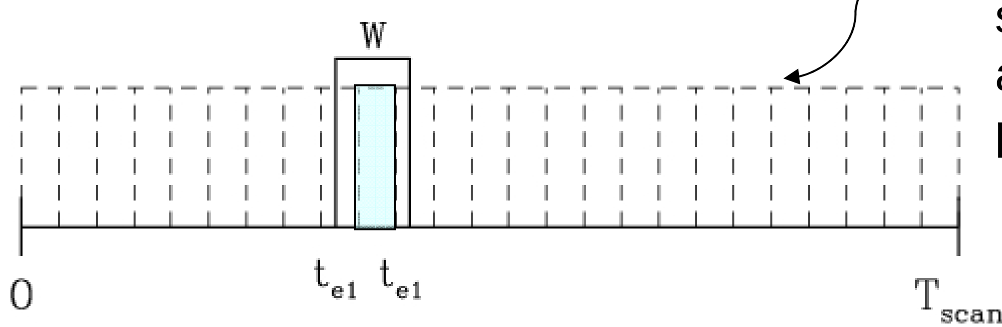

pixel

**W** = event duration

$\mathbf{T_{scan}}$ = time to scan all pixels

**Slow transients**: W > $T_{scan}$

tra




Duration of sampling of a given pixel

# Some Implications for Large-N/Small D Concepts for the SKA

- Processing demands are severe
    - Beam forming through correlation or otherwise
    - Pulsar/transient processing per pixel
- Require X years of Moore’s law

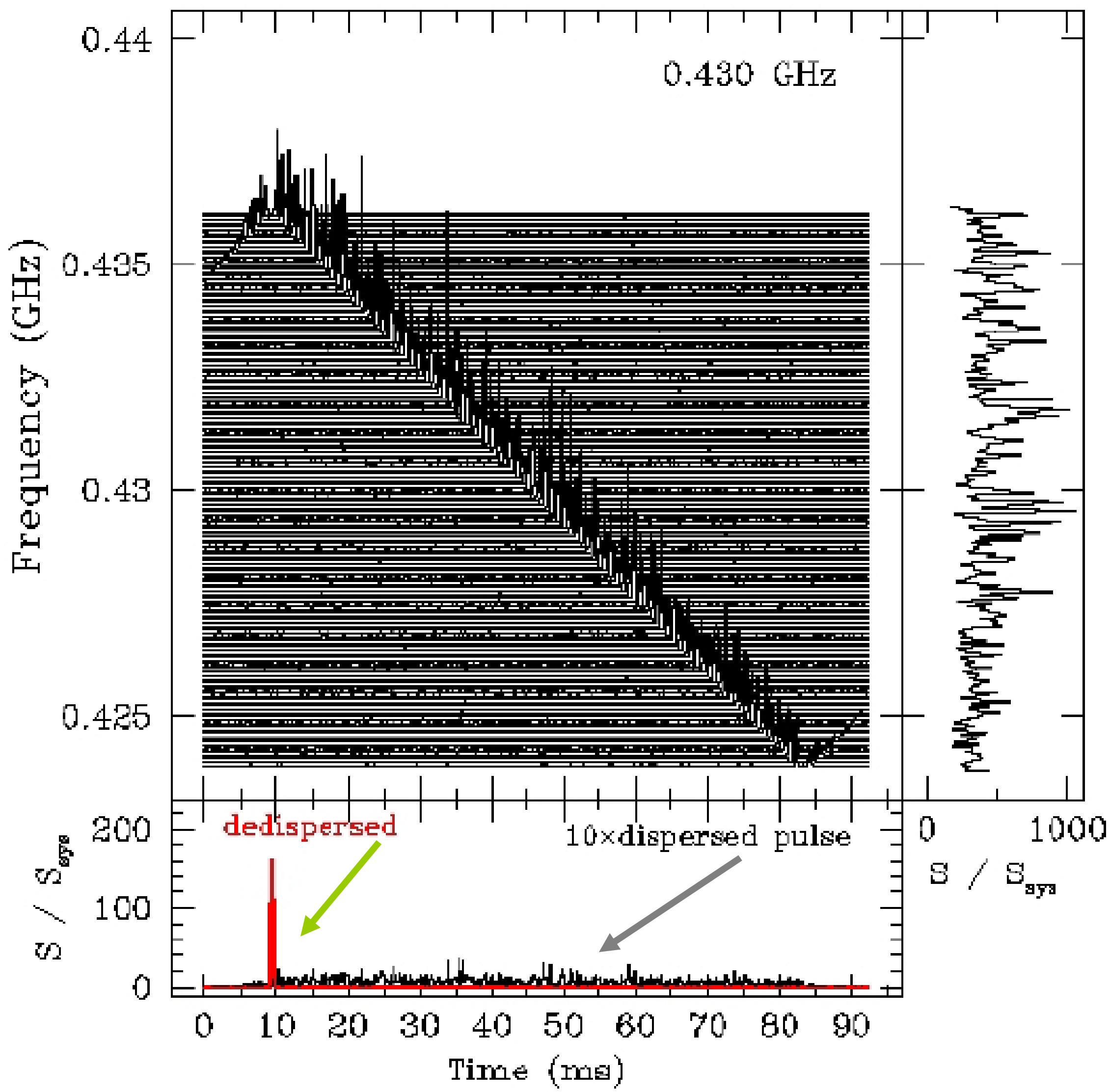
  + innovative real-time processing
- Optical processing?

# How does the SKA need to function?

The SKA needs to be an instrument that has

- High sensitivity
- Wide field of view (FoV)
- Configuration that allows a wide range of spatial scales to be sampled
- Flexibility in using collecting area for wide FoV surveys for objects that emit signals with various time-domain structures

# The brightest pulses in the Universe




Giant pulse from the Crab pulsar

S ~ 160 x Crab Nebula

~ 200 kJy

Detectable to

~ 1.5 Mpc with Arecibo

~ 5 Mpc with the SKA

Brighter pulses detectable to the Virgo cluster?

Cordes et al 2004

# Searching Observational Space

$$I(\nu, t, \vec{\theta}, \vec{x})$$

**RF**

**Time domain**

**Direction on sky**

**Location of collecting area**

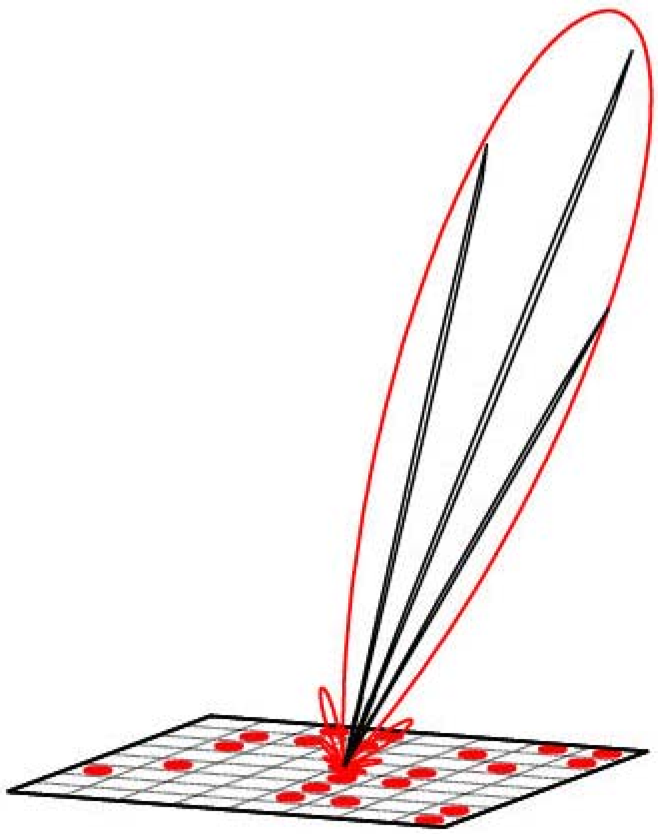
**Celestial transients vs. RFI:**

- May have similar $\nu$-t signature (e.g. swept-frequency radar and pulsars)
- Will have very different occupancy of $\theta$-X space:
    - celestial signals will appear in a narrow range of $\theta$ but at all x (modulo scintillation effects that cause spatial decorrelation**)**

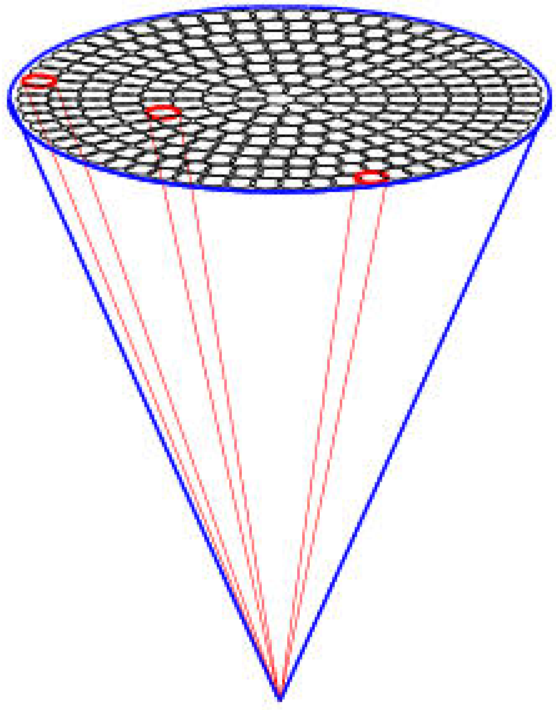
# Issues for Wide FoV Non-Imaging Surveys

- Pixelization of the field of view
  - Correlation approach favored over beam forming
  - Number of pixels $N_{\mathrm{pix}} \sim 0.85 \left(\frac{b_c}{D}\right)^2 \sim 10^{3.8} \left(\frac{b_c/1\,\mathrm{km}}{D/12\,\mathrm{m}}\right)^2$
- Sky coverage
  - Raster scanning (slow transients)
  - Staring in wide (fast transients)
- Analysis
  - Full search analysis on each pixel
  - Extensive for pulsars and fast transients
    - E.g. 1024 frequency channels $\times$ 64 $\mu$s samples from each pixel
  - Frequency-time plane analysis for all cases to discriminate RFI from celestial signals

**Primary beam & synthesized beams**



**Blind surveys require full FOV sampling**



# Blind Surveys with SKA

- Number of pixels needed to cover FOV:
  - $N_{pix} \sim (b_{max}/D)^2 \sim 10^4$
- Number of operations to form beams
  - $N_{ops} \sim$ petaop/s
- Post processing per beam:
  - Single-pulse and periodicity analysis
  - Dedisperse (~1024 trial DM values)
  - FFT + harmonic sum
  - Orbital searches (acceleration ++)
  - RFI excision
- Correlation is more efficient than direct beam formation
- Requires signal transport of individual antennas to correlator
- Post processing ~ 10% of beam forming

$\geq 10^4$ beams needed for full-FOV sampling