ICRAR

International Centre for Radio Astronomy Research

Transients Science with AA-mid/AERA^3

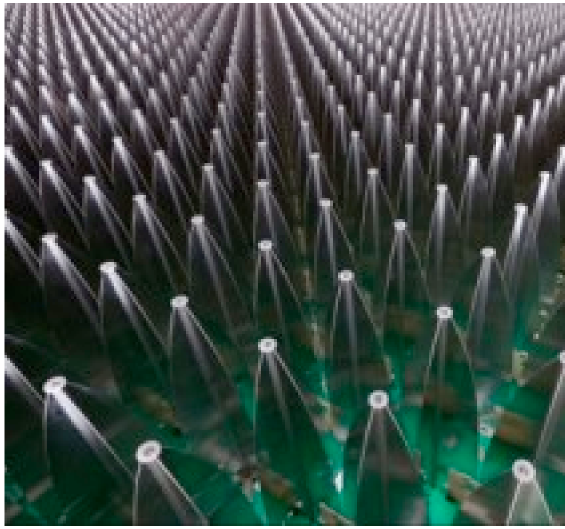
Jean-Pierre Macquart

Curtin University

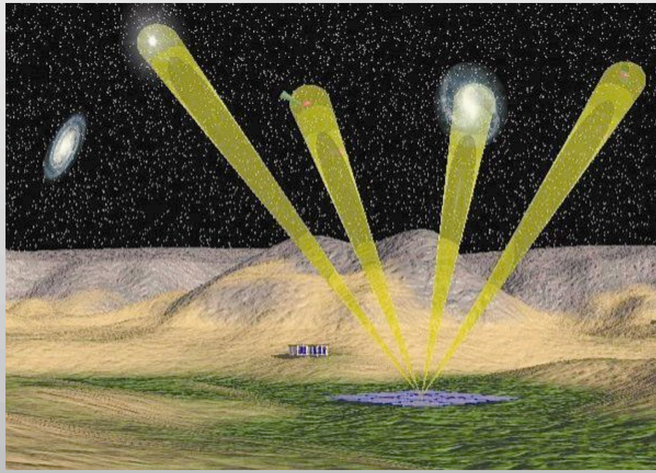
The Government of Western Australia

The University of Western Australia
Achieve International Excellence

Overview: Why AA-mid for Transients?

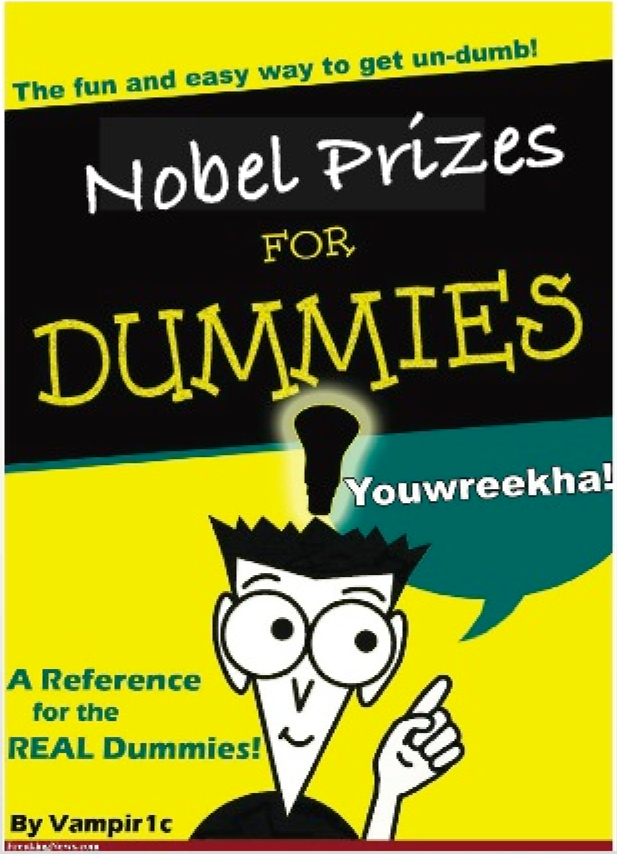


- Large Field of View
  - Transients science linearly proportional to FoV
  - Twice the beams = twice the science
- A detection machine for FAST transients
  - At a sweet spot in the frequency range for impulsive transients
  - lower frequency events more susceptible to temporal smearing by ISM/IGM turbulence
- Fast telescope pointing/response possible



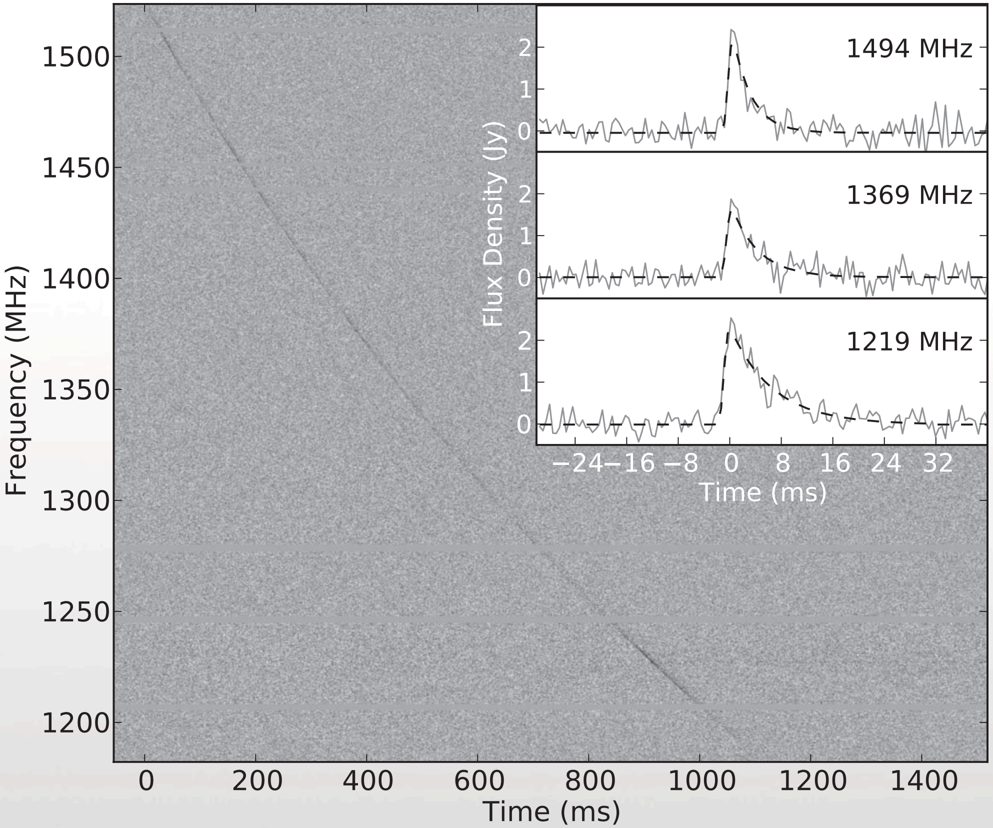
Mid-frequency transients science

- Fast timescale (<5s) transients probe
  - high brightness temperature emission
  - extreme states of matter
  - physics of strong gravitational fields
- Targets include
  - pulsar giant pulses, RRATs & magnetars
  - Impulsive extragalactic events (FRBs)
  - SETI emitters
  - the UNKNOWN
- Extragalactic fast transients
  - probe the ionized IGM
  - are cosmic rulers



Mid-frequency science

- Less scattering for fast transients
  - better for searching high DM events in the Galaxy
  - Probably **not optimal for slow** (synchrotron) **transients** since outburst peaks are larger and faster at higher frequencies
    - better done with SKA-mid at 5-8 GHz



There is no substitute for Field of View

- For most survey science the appropriate metric of telescope performance is the survey speed

$$\text{Survey Speed} \propto \Omega \times \left(\frac{A_{\text{eff}}}{T_{\text{sys}}}\right)^2$$

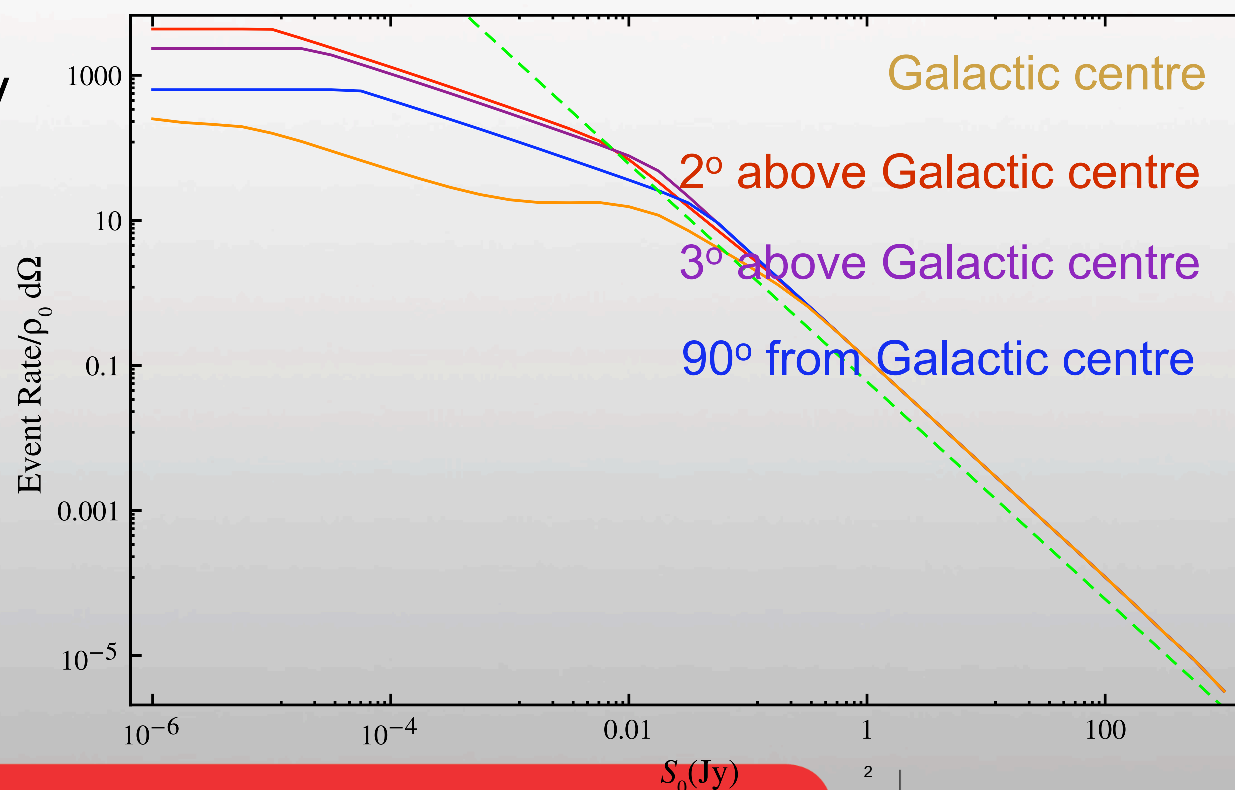
- But for transients a better metric is the event detection rate

$$\mathcal{R} \propto \Omega S_0^{-3/2+\delta}$$

where $\delta=0$ for a homogeneously distributed population with no evolution

$\delta>0$ if interstellar or intergalactic scattering alter the pulse shape (fast transients only)

$-0.3 < \delta < 0.5$ for evolution in a cosmological population



Survey Effectiveness for Transients

- Rate-based metric underscores the importance of FoV vs sensitivity

Survey metric	$R \propto \Omega S_0^{-2}$	$R \propto \Omega S_0^{-3/2}$	$R \propto \Omega S_0^{-1}$
R_{survey}/R_{mid} (coherent/fast imaging)	2.1	4.3	8.8
$R_{survey}/R_{1\text{-}low}$ (coherent/fast imaging)	0.10	0.16	0.26
R_{survey}/R_{mid} (incoherent)	6.2	9.7	15
$R_{survey}/R_{1\text{-}low}$ (incoherent)	1.1	0.9	0.8

This table uses the numbers in Table 1 of the Baseline Design document, and ignores the additional sky contribution to T_{sys} for SKA1-low, and it assumes SKA1-low forms only a single station beam on the sky.

Once temporal smearing is important (at low frequency) the S/N of an impulsive event degrades as ν^{-2}. There is a factor **34** degradation between 1160 and 200 MHz if scattering evident at 1.2 GHz.

AERA^3 Survey Effectiveness for Transients

- Rate-based metric underscores the importance of FoV vs sensitivity

Survey metric	$R \propto \Omega S_0^{-2}$	$R \propto \Omega S_0^{-3/2}$	$R \propto \Omega S_0^{-1}$
$R_{AERA\text{-}3}/R_{survey}$ (coherent/fast imaging)	0.1	0.3	1.0
$R_{AERA\text{-}3}/R_{survey}$ (incoherent)	0.7	1.3	2.6

- For incoherent assume 15 AERA^3 stations and 96 SKA-survey dishes

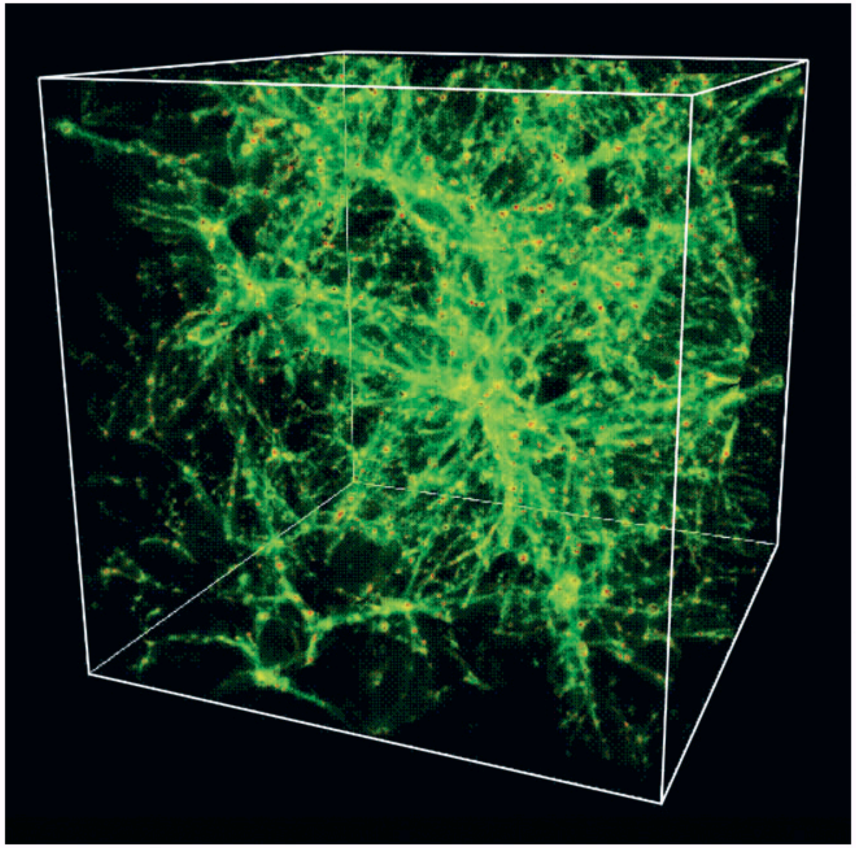
- Assuming 175 sq deg FoV at 1GHz
  - Rate better by $(\nu/1\text{GHz})^{-2}$ at lower frequency
- Coherent estimates assumes we can process full (primary) station FoV

Killer Science with Extragalactic Bursts

- FRBs are
  - common (10^4 sky^{-1} day^{-1})
  - bright (detectable to z>1 even with Parkes!)
  - millisecond duration, so DM determination easy
- Killer Science:
  - Solve the missing baryon problem (McQuinn 2013; Deng & Zhang 2014)
  - Use them as cosmic rulers to measure dark energy equation of state parameter w at z>2 (Zhou et al. 2014)

Detecting the “Missing” IGM Baryons in the low redshift Universe

Most of the mass of the Warm-Hot Intergalactic Medium (WHIM) lies within the filaments that connect the higher density regions.



The density distribution of baryons at low redshift from the simulation of Cen & Ostriker (2006)

Most baryons in the z~0 Universe undetected

- 5% of the baryons within galaxies
- 5% in X-ray coronae in massive groups & clusters
- 30% in a warm phase observed in Lyα abs’n

Remaining 60% believed to reside at temperatures and densities difficult to detect via spectral line absorption and emission diagnostics

Cen & Ostriker 1999, 2007
Shull et al. 2012

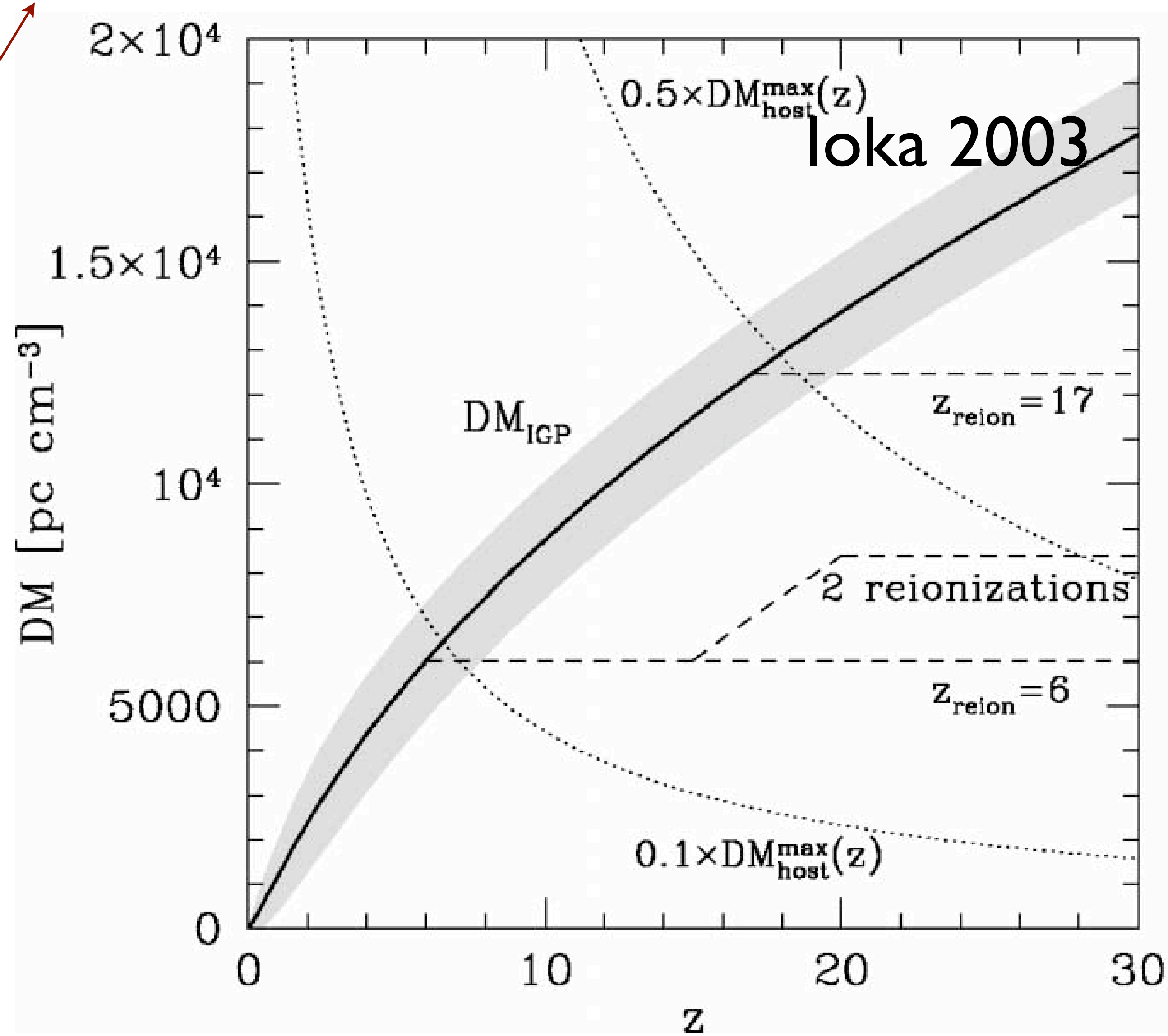
Extragalactic Dispersion

unknown & probably small ∝1/(1+z)

$$\mathrm{DM_{tot}} = \mathrm{DM_{MW}} + \mathrm{DM_{IGM}} + \mathrm{DM_{host}} + \mathrm{DM_{FRB}}$$

small & “known”

key measurable
& dominant component

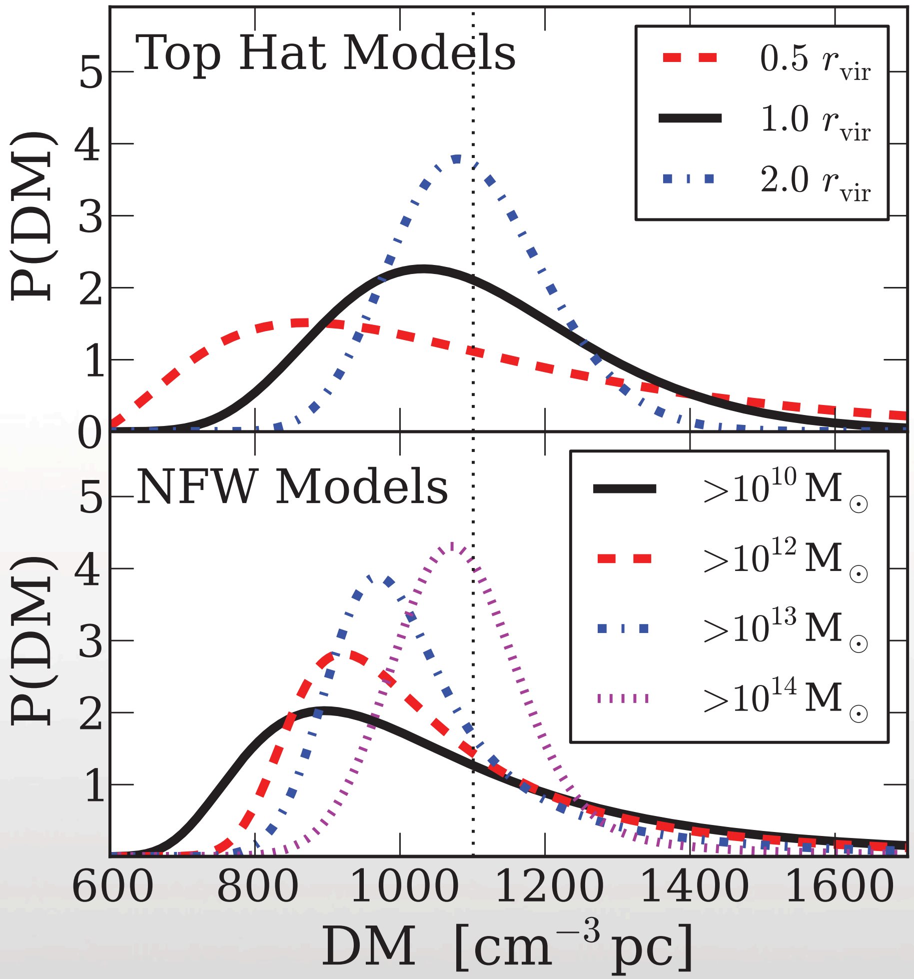


Missing Baryons

FRB DMs can resolve the origin of the missing baryons

McQuinn 2013

- Missing baryons location an important element of galaxy halo accretion & feedback
- Most dark matter found in galaxy halos, but most baryonic matter outside this scale (>100s kpc)
- For a set of FRBs at the same redshift, the DM distribution function depends on the extent of the distribution of the baryons around the halos



PDFs DMs for bursts located at z=1.
Distribution function more centrally peaked if the gas around the halo is more diffuse or if halos capable of retaining their gas are rarer

Killer Science with Extragalactic Bursts
Cosmic Rulers

Zhou et al. 2014

- Type Ia SNe out to z ~ 1.5 have determined the dark energy content of the Universe
- FRBs offer access to the dark energy equation of state parameter *w*(z)=p/ρ
- Even Parkes easily sees bright FRBs to z>1
- For z>2 the DM contribution is dominated by the IGM
- Measure the *average* DM as a function of z:

H and He ionization fractions

$$\mathrm{DM} = \int n_e dl \Rightarrow \int n_e(z) \left| \frac{cdt}{dz} \right| dz$$

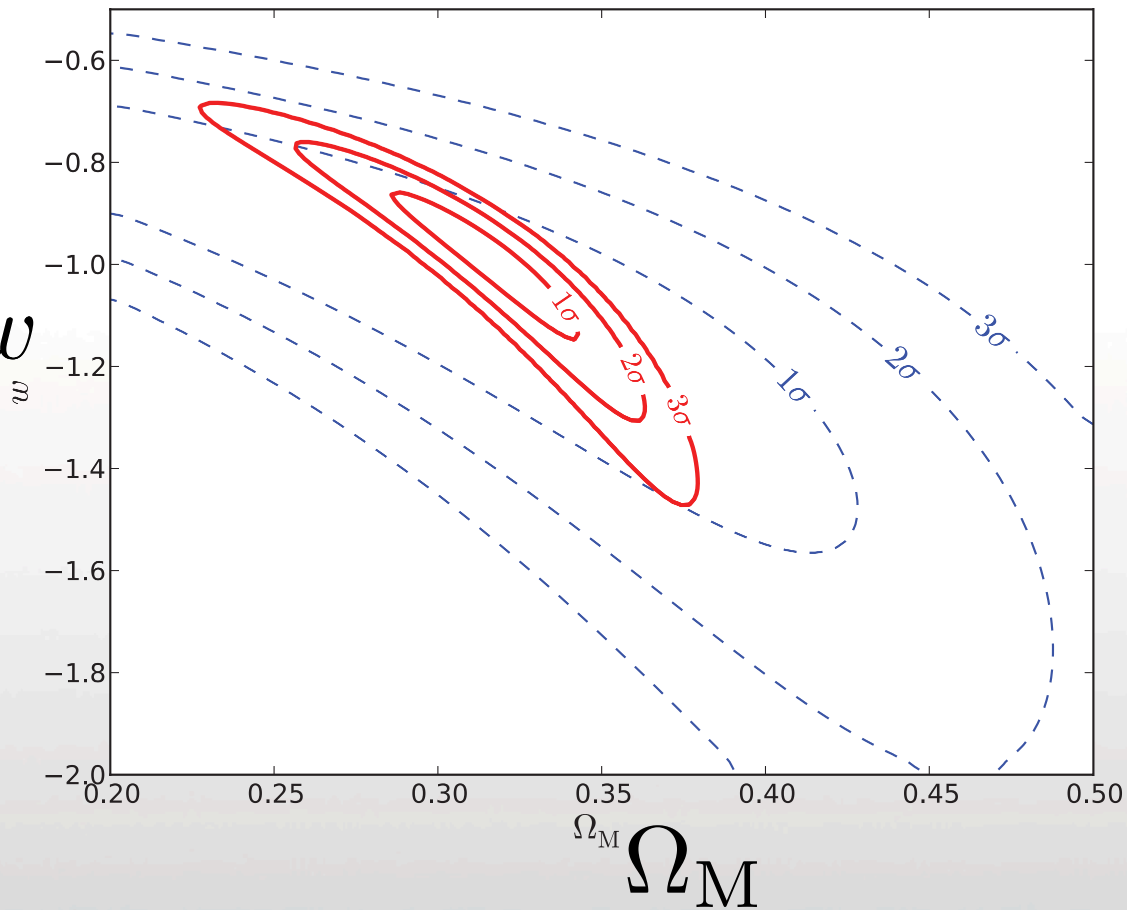
$$\langle \mathrm{DM}_{\mathrm{IGM}}(z) \rangle = \Omega_b \frac{3H_0 c}{8\pi G m_p} \int_0^z \frac{(1+z')f_{\mathrm{IGM}}\left[\frac{3}{4}X_{e,H}(z') + X_{e,He}(z')\right]}{\left[\Omega_{\mathrm{M}}(1+z')^3 + \Omega_{\mathrm{DE}}(1+z')^{3[1+w(z')]}\right]^{1/2}} dz'$$

baryonic density *matter density* *dark energy density*

w(z): equation of state parameter

Killer Science with Extragalactic Bursts
Cosmic Rulers

- Determination of *w*: measure the average DM with z
- Contaminants are DM_{host} & DM_{FRB}
  - Contributions diminish relative to local contribution as $(1+z)^{-1}$ and relative to an IGM whose mean density increases $(1+z)^3$
  - Technique viable for z>2
- Zhou et al. 2014 estimate ~10^3 FRBs detected in order to place significant constraints on *w*



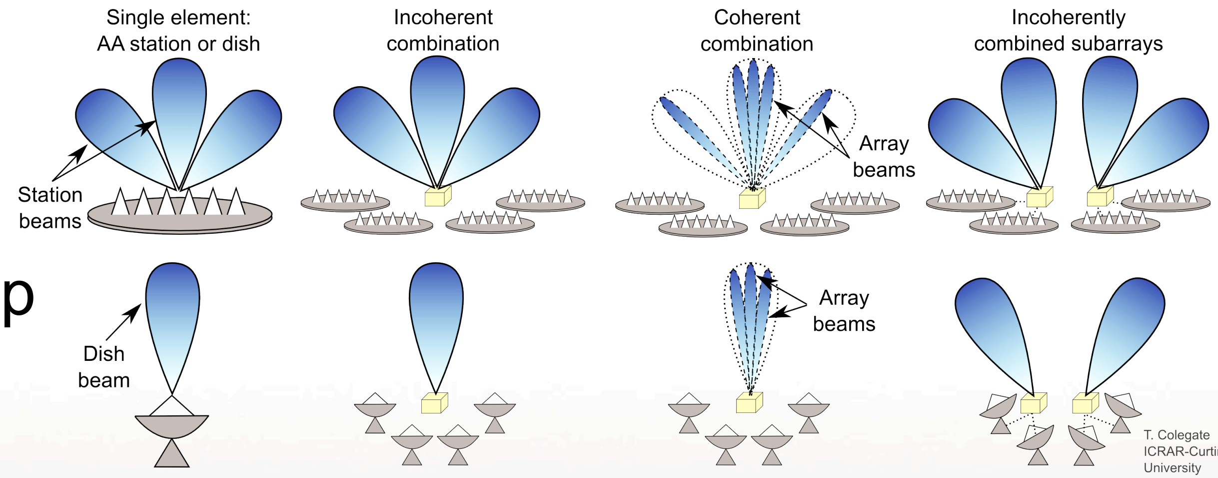
Constraints on *w* vs Ω_M for 580 FRBs jointly with 580 Type Ia SNe (red), or 580 Ia SNe alone (dotted)

What does this science require?

- Top Level Requirement:
  - Cosmic web: 10^3 FRBs per redshift bin, so need to accumulate at least 10^4 FRBs in total
  - Cosmic rulers: at least 10^3, but precision increased with more events and only a fraction will be at $z>2$
- Only an SKA transients factory will be capable of performing this science

Technical Requirements - Detection

- Three main steps:
  - Detection
  - Verification
  - Localisation & Followup



- ***Detection***
  - wide field of view
  - Commensality essential - affords time on sky to net the needed number of events and discover rare types of events
    - a 20 sq. deg. FoV at 10^4 events/sky/day nets 5 events per day
      - cosmic missing baryons a multi-year commensal project
  - want both incoherent and coherent signal combination paths available
    - This flexibility naturally provided by a data spigot-based system (cf. V-FASTR)

Technical Requirements - Verification

How will we believe it otherwise?

Transient Buffers an essential element of verification

– Detection at multiple separated stations the best “proof”
  - if signal was detected using incoherent (total power techniques with wide FoV) then buffered baseband data will
    - – verify the event and characterise it at high S/N
    - – determine the DM to much higher precision
  - Less than ~1s latency needed in detection signal path
    - – in order to signal to dump station buffers
  - Capitalizes on the advantage of aperture arrays, which see the whole sky (or a large fraction of it)
    - – can respond retroactively to transient alerts from other instruments (LSST, Fermi, Swift)
    - –*Only Aperture Arrays do this!!!*

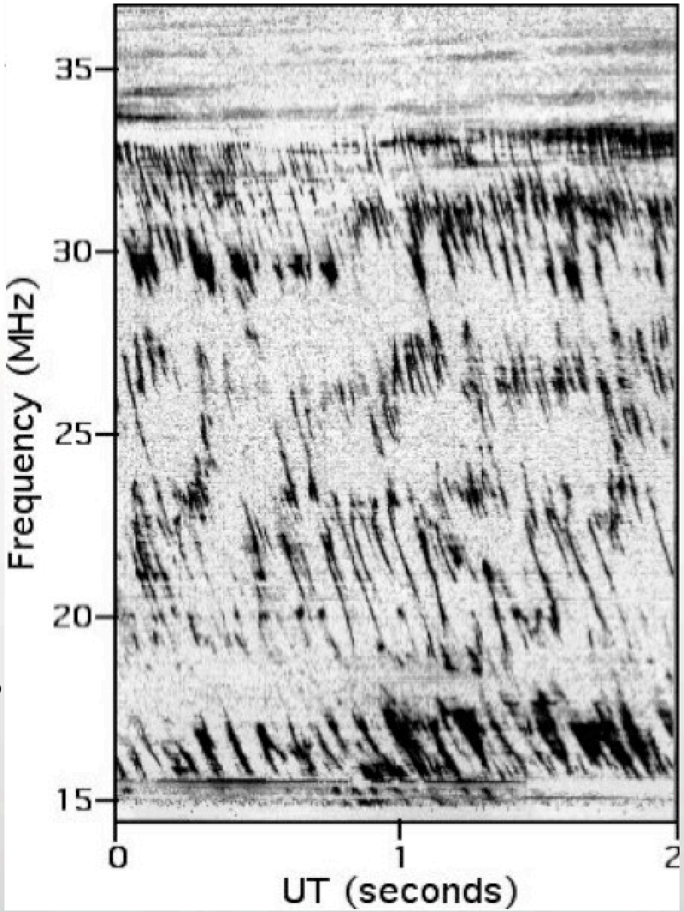
Gravitational Wave Events & Extrasolar Planets

- Gravitational wave events may trigger bursty coherent emission as the energy couples with plasma
  - Bursty emission easier to detect than faint slow synchrotron fireball in crowded fields

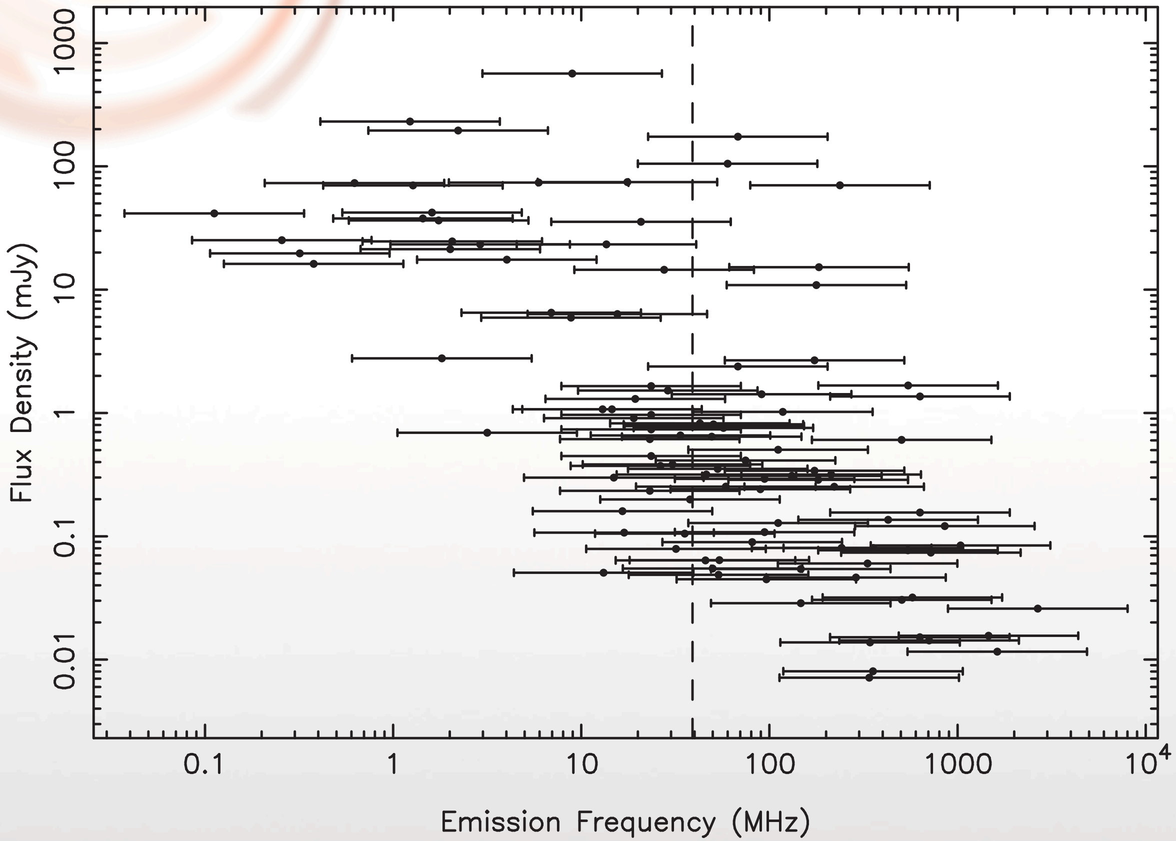
- Interaction between solar wind and planetary magnetic fields causes bright bursty low frequency radio emission (e.g. Jupiter cyclotron emission)

- An entirely new way of detecting extrasolar planets yields
  - planetary rotation period (test spin-orbit synchronization)
  - orbital inclination
  - magnetic field implications for exobiology (shield against cosmic ray bombardment)

Bursty emission from Jupiter



Extrasolar Planets



Predicted burst flux densities for 106 known exoplanets vs their predicted characteristic emission frequency (Lazio, Farrell et al. 2004)

Radiometric Bode's law - relation between incident solar wind power and emitted planet radio power) implies many planets detectable

(more if solar wind is variable in speed by a factor of 2, increasing luminosity by a factor ~100)

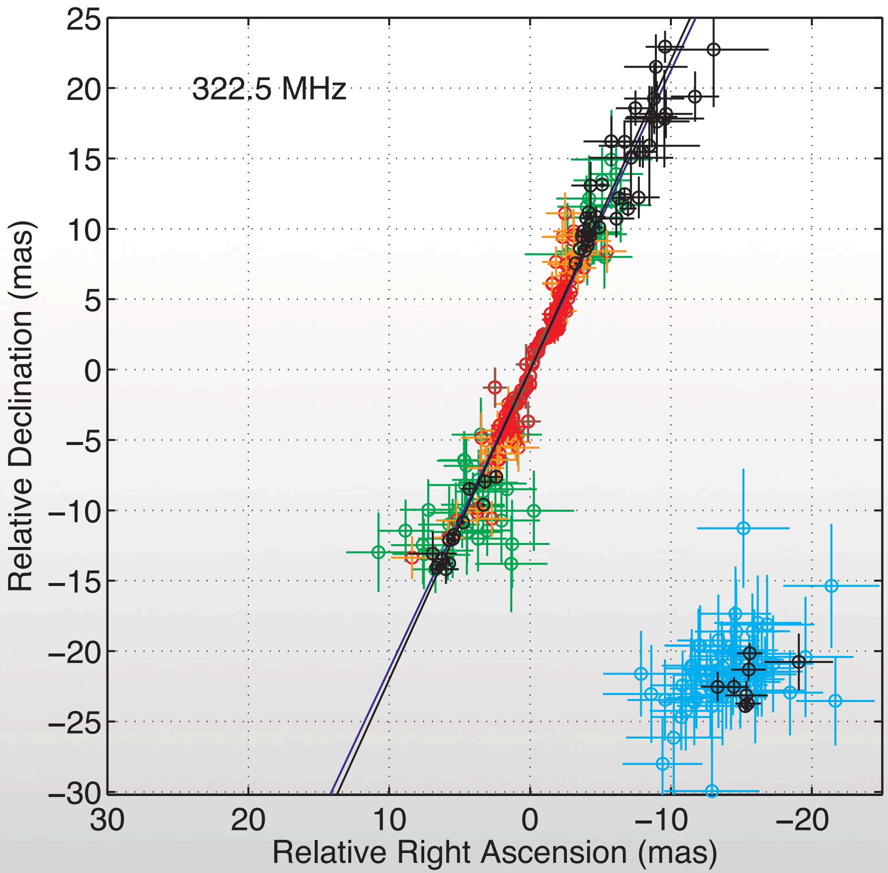
$$\nu_c \sim 23.5 \left(\frac{\omega}{\omega_J}\right) \left(\frac{M}{M_J}\right)^{5/3} R_J^3 \,\mathrm{MHz}$$

Other high time resolution science

- Pulsars (not strictly transients but...)
  - Overcome pulsar scattering that hampers LOFAR/SKA-low surveys
    - RRATs
    - Giant pulses
    - The Galactic Centre at 1.5 GHz???

- Pulsar Speckle Astrometry
  - sub-second timeresolution
  - ~10 Hz spectral resolution
  - record in tied-array mode

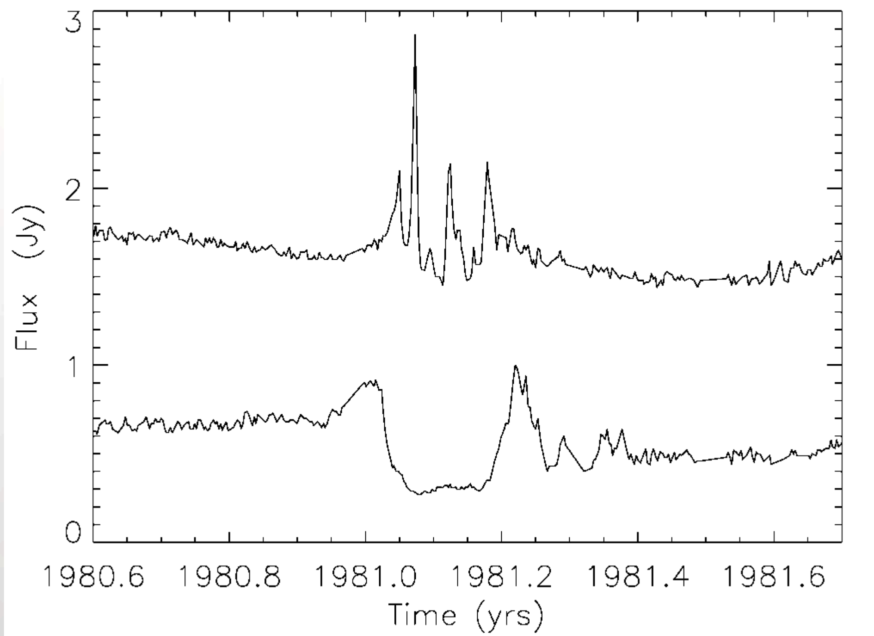
- ***Rare*** unknown unknowns



327 MHz speckle image of the scattering to PSR B0834+06

Imaging Science
benefiting from wide fields of view

- Quasar Intra-Day Variability
  - High brightness temperature quasar emission
  - Intermittency of Interstellar Turbulence
  - >50% of all flat/inverted spectrum sources exhibit IDV during the course of a year
  - >1% of all radio source
- Extreme Scattering Events
  - 1 event/source/(70 years)
  - inferred to be caused by clouds in ISM
  - (i.e. $>10^4$ clouds per pc^3)
  - optics require high plasma density
  - objects $>10^3$ overpressured wrt ionized ISM
  - origin unclear
  - rapid detection and VLBI followup required



An ESE detected at 2 and 8 GHz

In summary: AA-mid as a fast transients instrument

- 500-1500 MHz the sweet spot for bright coherent emission from distant (high DM) objects if we wish to avoid the deleterious effects of scattering
- Large field of view with an excellent sensitivity
- No “analogue” beamforming (i.e. optics) to limit telescope capability at the front end
  - Capacity to bring back signals from *all* antennas to the central processing hut provides the capacity to tailor searches (e.g. trade beams for bandwidth)
  - Transient buffers to retroactively respond to alerts at other wavebands
- Better localisation than AA-low
  - for a given baseline
- Lower T_{sys} than AA-low
  - since T_{sky} not dominant except towards parts of the Galactic plane and the Galactic centre
- Ionosphere/calibration not so problematic as at lower frequencies

Summary

- Even AERA^3 is competitive against SKA-survey ***if*** we can exploit its entire FoV at full sensitivity
  - but is this possible?
    - fast imaging?
    - cost probably prohibits tiling full FoV with beams and searching
  - like going into Moon orbit and turning back to Earth because I forgot lunch
- Commensality is a requirement

- How feasible is it to implement buffers within the system architecture?

- what is the preferred frequency range for your science?

End of SKA-low to as high as possible

- what is the minimal bandwidth you need continuous access to? Does it need to be contiguous?

More always better (but not at expense of FoV or beams). Contiguous unnecessary

- is the sensitivity sufficient for your science?

Maybe

- what time and/or frequency resolution do you need?

Sub-ms. ~10-100 kHz to dedisperse DM>2000 pc cm^{-3} events

- what do you need in terms of spatial resolution?

Sub 1". 0.1" preferable for unambiguous localization of z~1-2 events

- do you prefer a centrally condensed array, or a more widely spaced configuration?

Mainly centrally condensed for searching, but some long baselines for localisation

- how large a field-of-view should be accessible in a single observation?

As large as possible. Event detection rate linearly proportional to FoV.
- how many independent fields-of-view do you require?