ICRAR

International Centre for Radio Astronomy Research

# Fast transient radio astronomy with the Square Kilometre Array: fast radio bursts and cosmic rays

CRAFT


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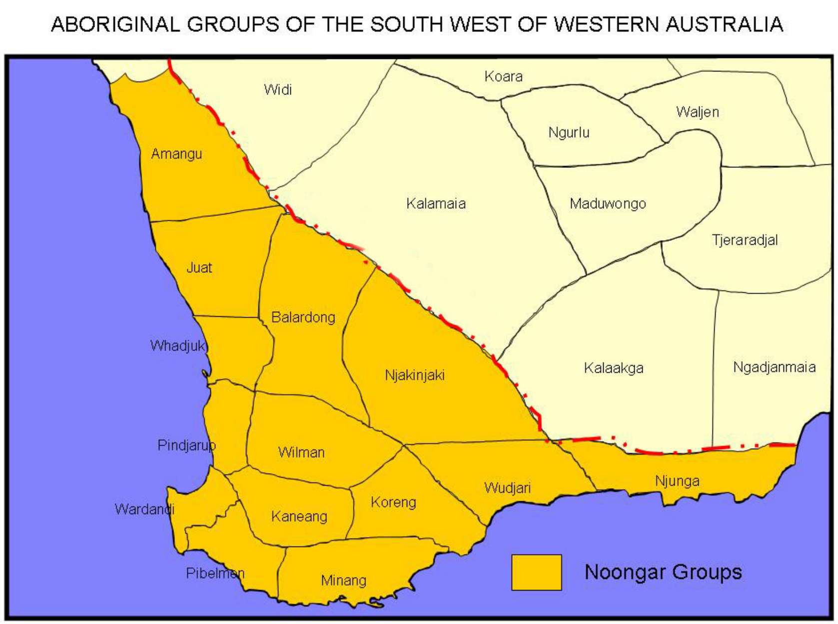
THE UNIVERSITY OF WESTERN AUSTRALIA

Government of Western Australia
Department of the Premier and Cabinet
Office of Science

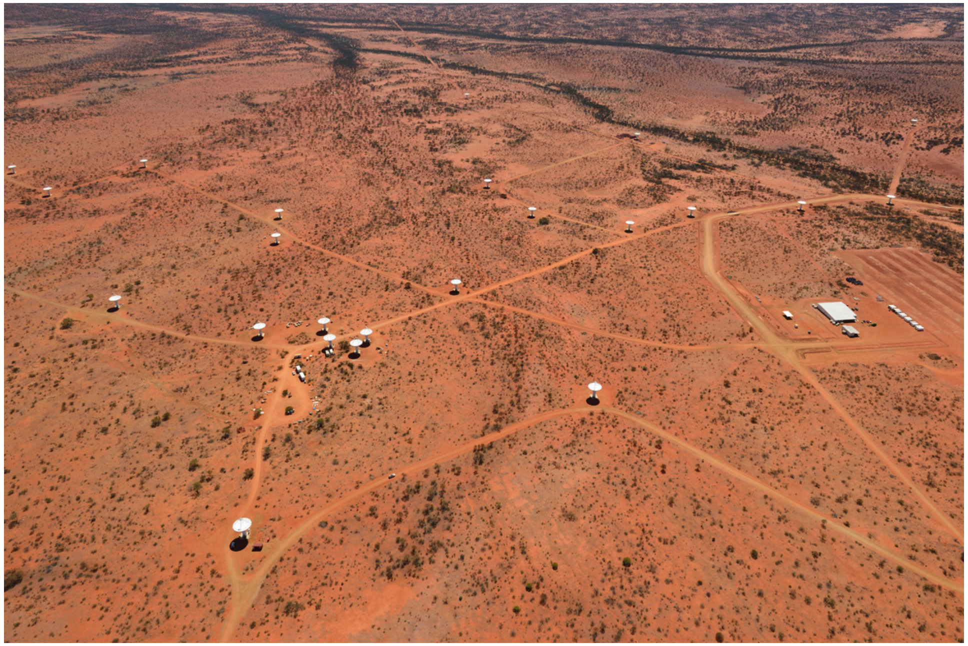
# Acknowledgement of country

**I would like to pay my respects to:**

- the Wadjuk people of the Nyungar Nation, the traditional owners of the land on which the Curtin Bentley Campus is located;
- the Wajarri Yamatji as the traditional owners of the Murchison Radio-astronomy Observatory site (MWA, ASKAP, SKA-low)




Credit: John D. Croft



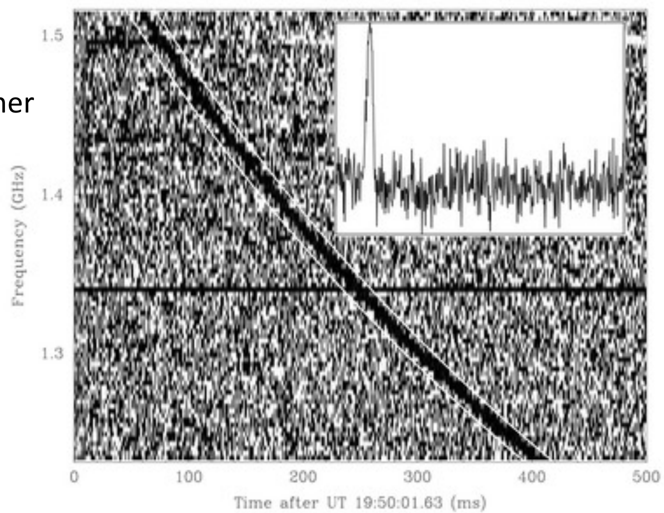
Credit: CSIRO

# Fast transient radio astronomy

## #1: Fast radio bursts

- Millisecond duration transients
- Extragalactic (by definition)
- Frequency sweep (dispersion)

Courtesy Lorimer et al. 2007 & Swinburne U.



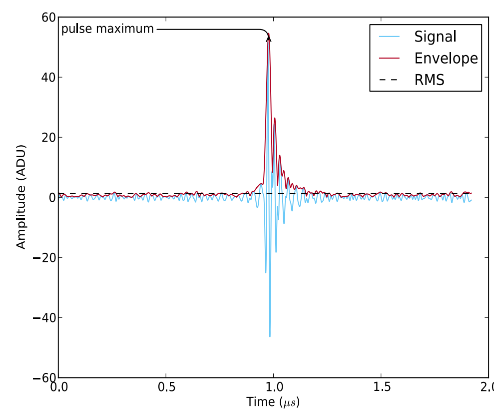

$$\mathrm{DM} = \int \frac{n(e)}{1+z} d\ell \ \mathrm{pc\ cm^{-3}}$$

- Progenitor(s) unknown
- **Focus: SKA-mid**

## #2: Cosmic rays

- Relativistic particles from space
- Galactic and extragalactic


- Nanosecond radio emission




P. Schellert et al, A&A 560, A98 (2013)

- Origin unknown
- **Focus: SKA-low**

# Key Players in FRB land

## Parkes (Oz)

- Had 13 beam multibeam
  Single dish – no localisation


Image courtesy CSIRO Astronomy Space Sciences

## CHIME (Canada)

- Huge field of view: >1 FRB/day!)
- Poor localisation
- (outriggers: => arcsecond accuracy)

Image courtesy Caltech

## DSA 10 (USA)

- Small dishes (FOV)
- Good localisation (array)
- Upgrade: 1000 antennas

## Westerbork (NL)

- Phased array feed (FOV)
- 1D baseline (OK loc.)

Image courtesy ASTRON

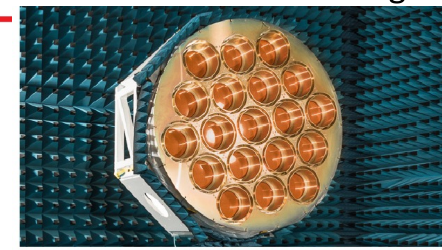
# Key Players in FRB land

## VLA
- High sensitivity
- Low FOV
- Excellent for localisation

Credit: NRAO

## FAST
- Huge sensitivity
- Multibeam
- Poor localisation

Credit: A. Dunning et al.



Credit: NAOC

Credit: skatelescope.org

## Meerkat
- High sensitivity
- Discoveries – paper in prep
- Fully commensal

**Apologies to these collaborations**

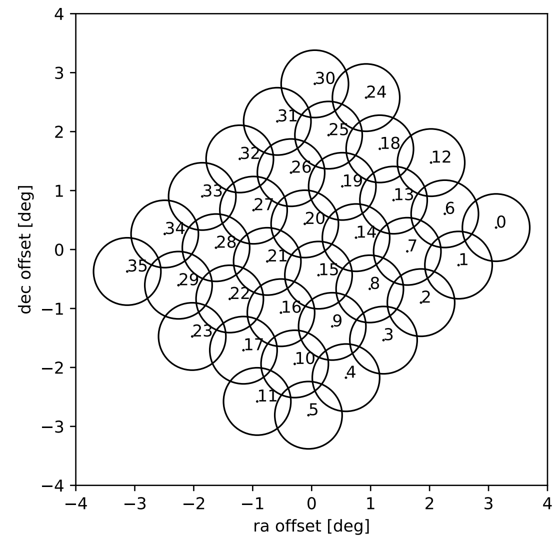
**Sardinia too!**

Credit: Mike Peel

# CRAFT project

## CRAFT: Commensal Real-time ASKAP Fast Transients survey

- 36 x 12m antennas, 30 deg$^2$ FOV
- 336 MHz bandwidth
- Mostly ~1.028-1.464 GHz



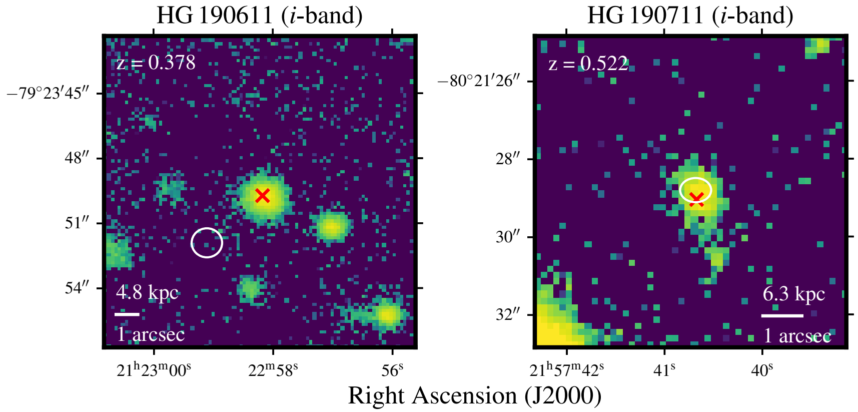

## Stages

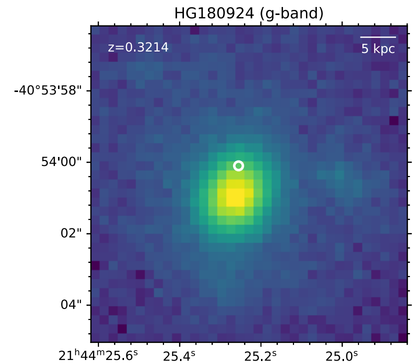
- 2016-2018: Fly's Eye mode (26 FRBs)
- 2018-2021: Incoherent sum (19 new FRBs)
- 2022- coherent upgrade (CRACO)
- Same telescope, improved detection modes
- ***Claim to fame: FRB localisation to host galaxies***

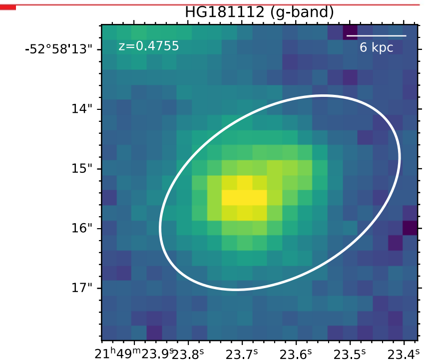
Image courtesy CSIRO Astronomy Space Sciences

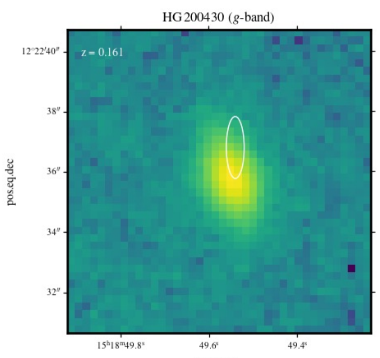
FRB images: Bannister et al., Prochaska et al, Macquart et al., Bhandari et al., Lachlan Marnoch, Xavier Prochaska, Stuart Ryder, ….

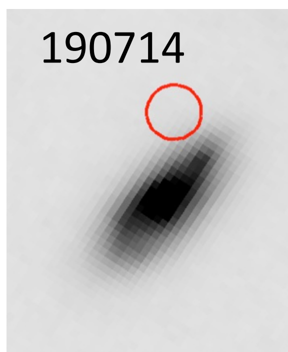
# Host galaxies: optical facilities critical!

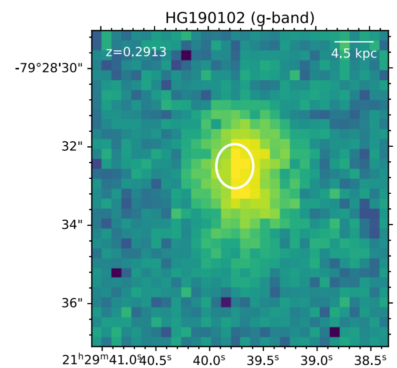


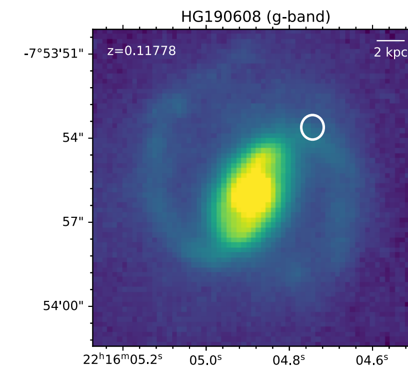

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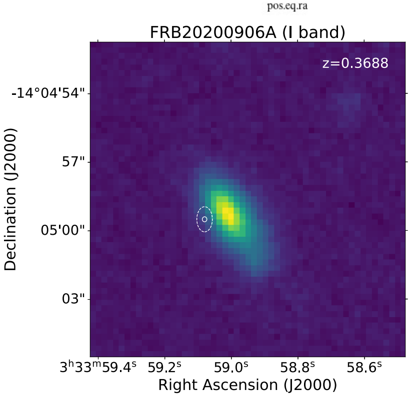
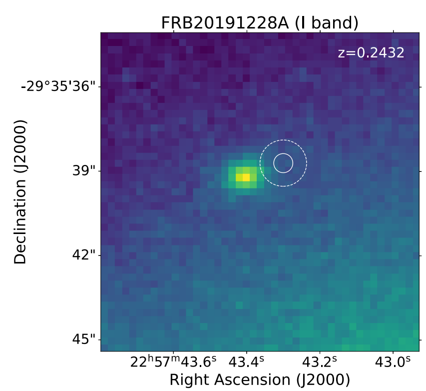
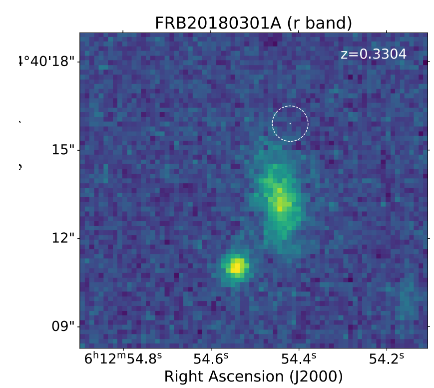



Credit: ESO/G. Hüdepohl



# Host galaxies – initial trend

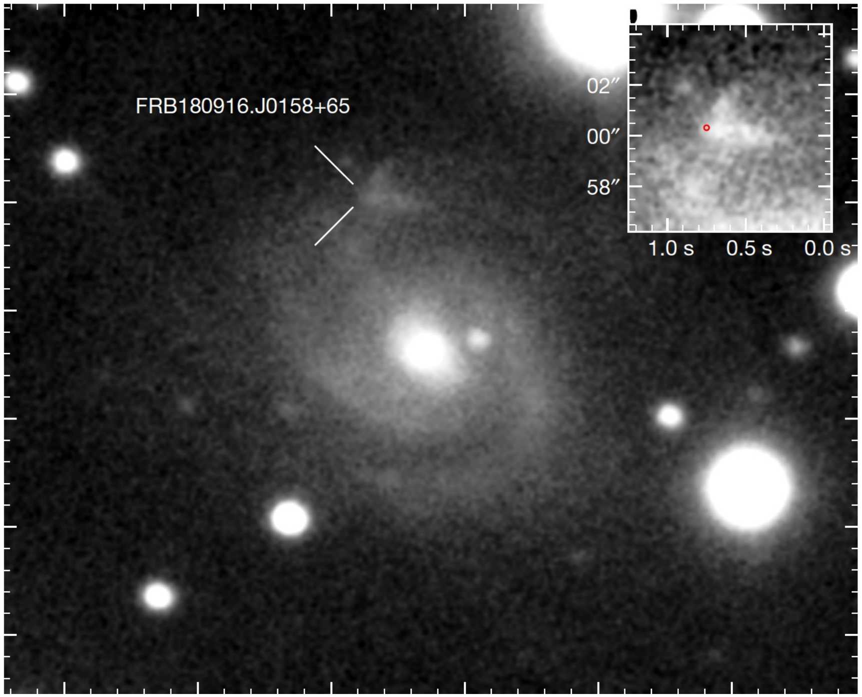
**ASKAP mostly once-off FRBs**

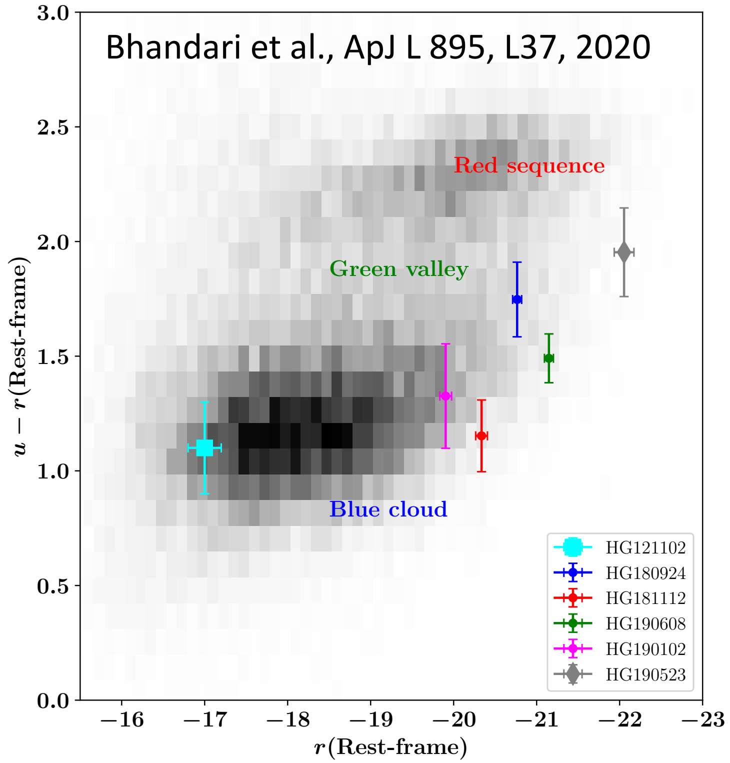
- "green valley" galaxies

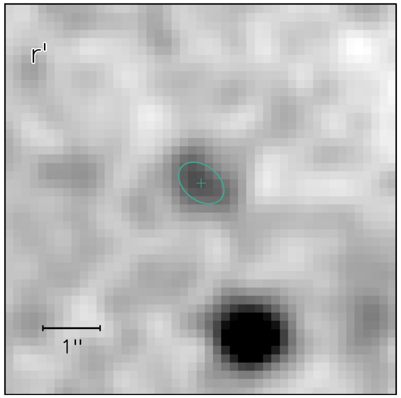
**Strong repeating FRBs**

- Strong star-forming regions

Marcote et al., Nature 577, 190 (2020)



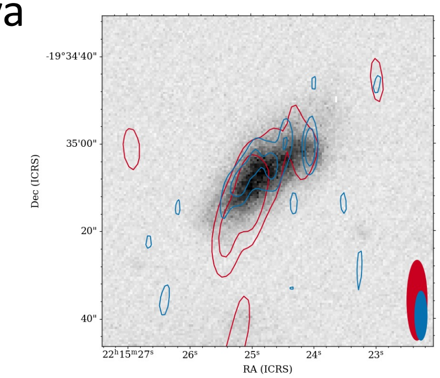

FRB 121102 host
Tendulkar et al., ApJ L 834,L7, 2017

# Host galaxies - mystery

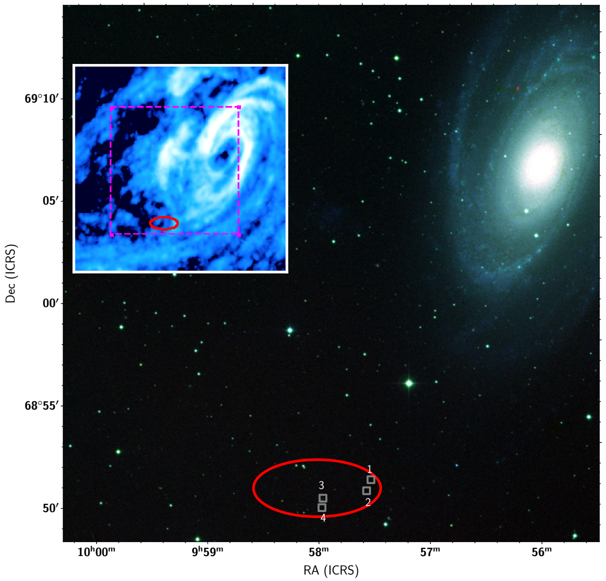
**Two nearby FRBs**

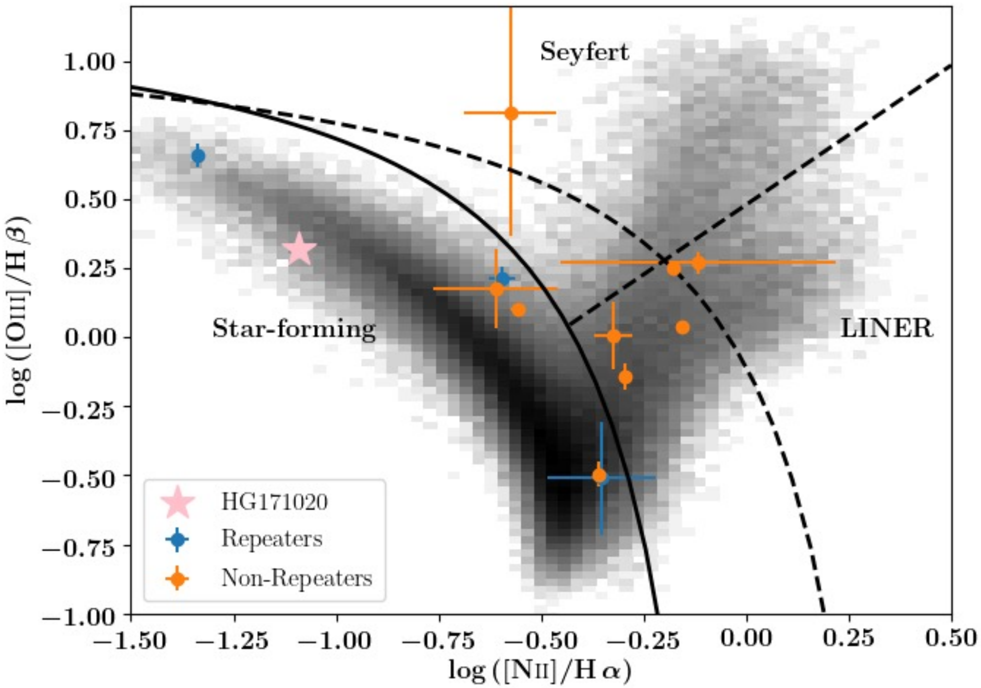
- FRB 171020: does NOT repeat, high SFR
- FRB 20200120E repeats – in a globular cluster (low SFR)

Paper in prep: Freya North-Hickey




**CHIME:** A Nearby Repeating Fast Radio Burst in the Direction of M81




Bhardwaj et al,ApJ L 910 (2021) L18
Kirsten et al., arXiv:2105.11445

**SKA:** **huge increase in localised FRBs**

# FRB 210407

**Highest ASKAP DM: 1785.3 pc/cm3**

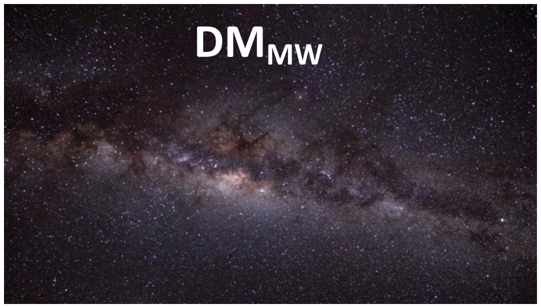
- Optical data: no host galaxy found (must be distant – z>1?)
- Need powerful telescopes to find z>1 hosts! (JWST? 30m class?)

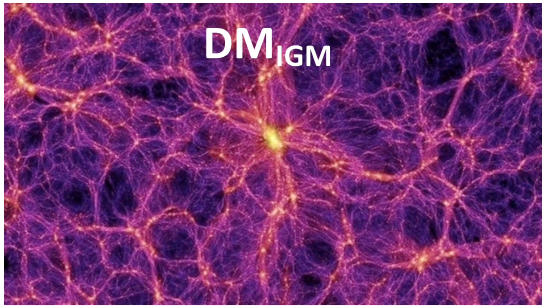
Credit: Alexa Gordon

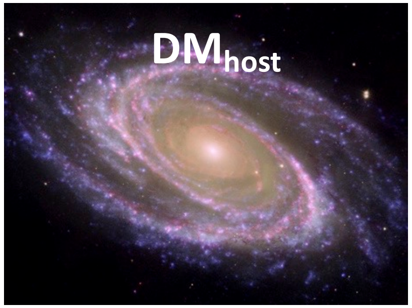
# FRB cosmology

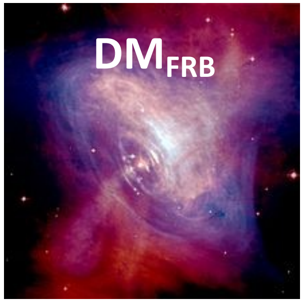
$$\mathrm{DM} = \int \frac{n(e)}{1+z}\, d\ell \ \mathrm{pc\ cm^{-3}}$$

## Dispersion measure (DM) – ionised gas is everywhere



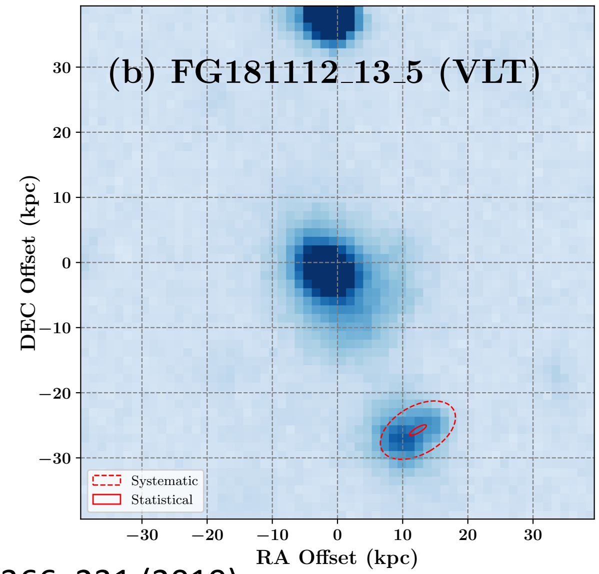

## Science goals

- MW halo gas
- Cosmic baryon density, intervening halos, H0
- Host halo density
- FRB progenitor = ???

## Other observables

- Scattering
- Faraday rotation
- Optical host galaxies

Host: z=0.4755
Foreground: z=0.3674
29 kpc offset

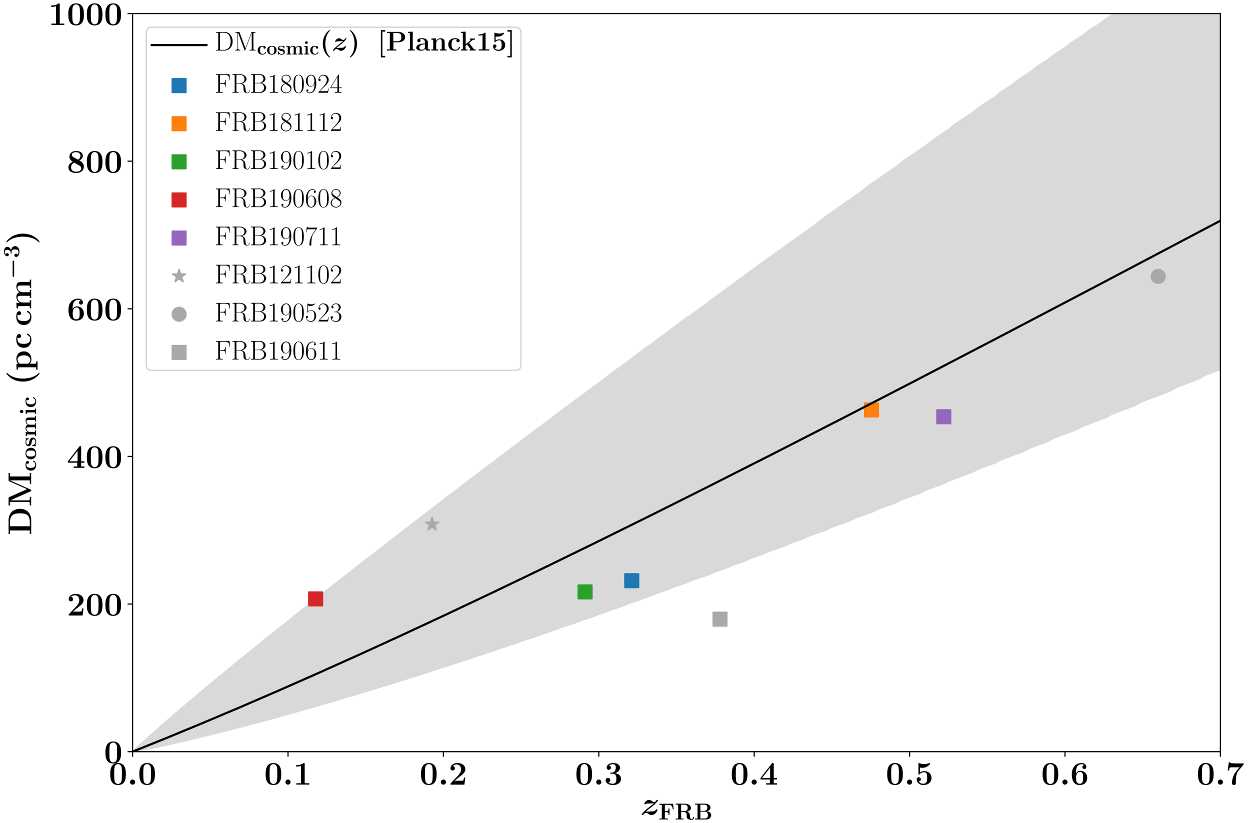



J. X. Prochaska et al, Science 366, 231 (2019).

# The Macquart relation!

- DM(z) consistent with total matter density of

$$\mathrm{DM}_{\mathrm{LSS}}(z) = \frac{3\Omega_{\mathrm{b}} H_0}{8\pi G m_{\mathrm{p}}} \chi_{\mathrm{e}}\, f_{\mathrm{IGM}} \int_0^z \frac{1+z'}{E(z')} \mathrm{d}z' \,,$$



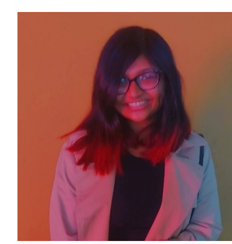

Macquart et al., Nature 581 (2020) 7809

**If H0 correct**

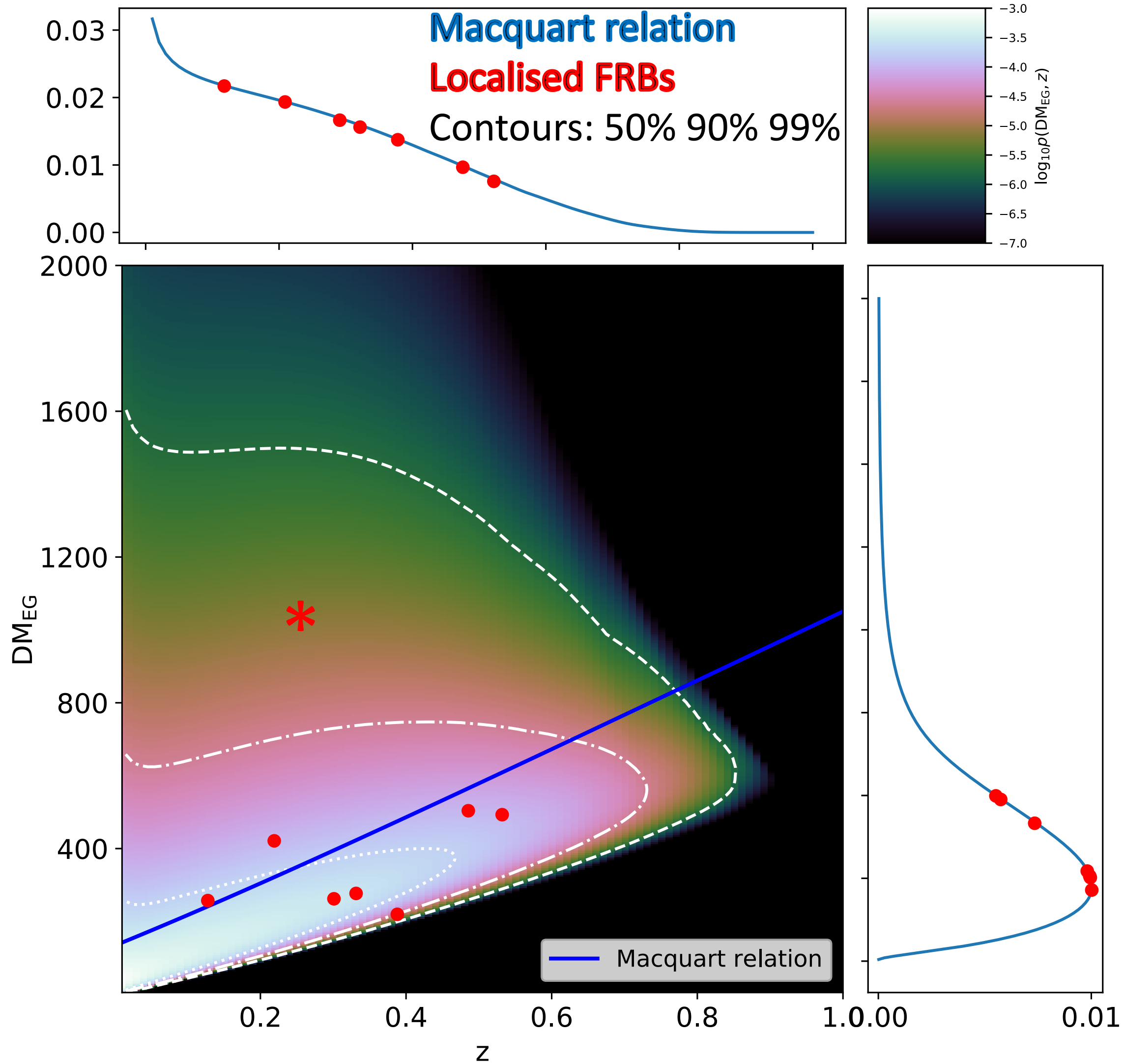
- Baryonic matter density as expected

**What about H0?**

- CMB, BBNS measures $\Omega_b h^2$
- Fix this, vary H0
- Account for observational biases!
- Ongoing work by Esan Mouli Ghosh



# Sensitivity – ASKAP localisations




C.W. James et al, arXiv:2101.08005 (2021)

**What about the SKA?**

- We need to build it to find out
- Don't rely on expectations!

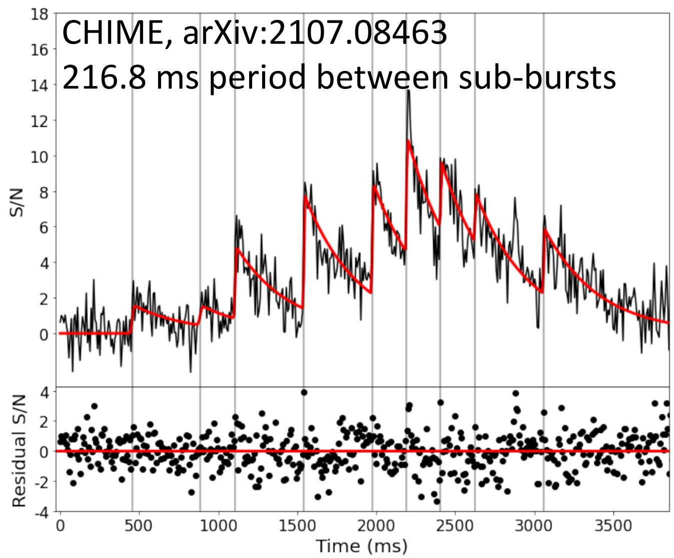
**FAST**

- Sensitivity: ~SKA mid
- FRB 190520
- DM 1210.3 pc/cm$^3$
- z: 0.241!

# Science: burst sub-structure

## Time-frequency structure

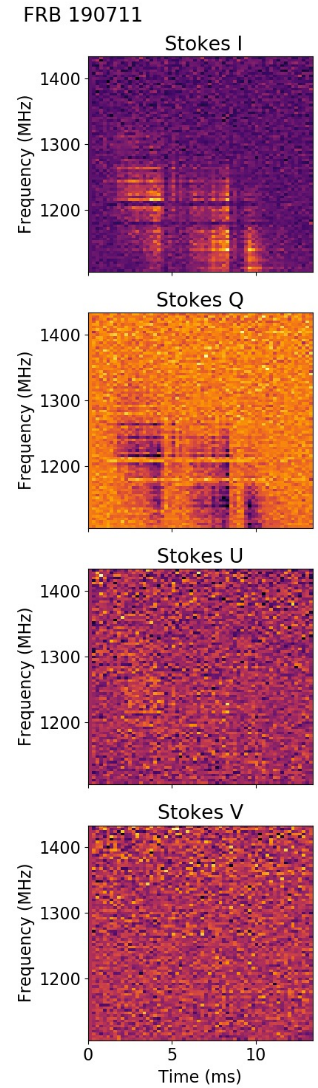
- Key to understanding emission mechanism
- Huge variation in observations!

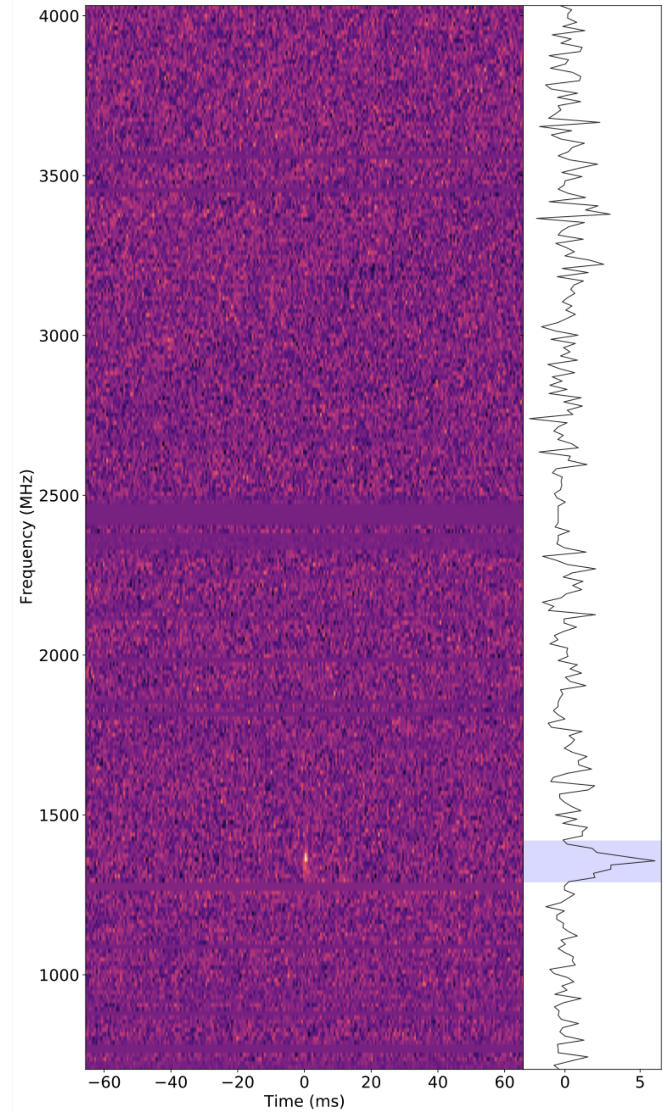



## Key SKA message

- Broad-bandwidth observations, high time resolution
- Need many FRBs to characterize population

Day et al 2020 ASKAP



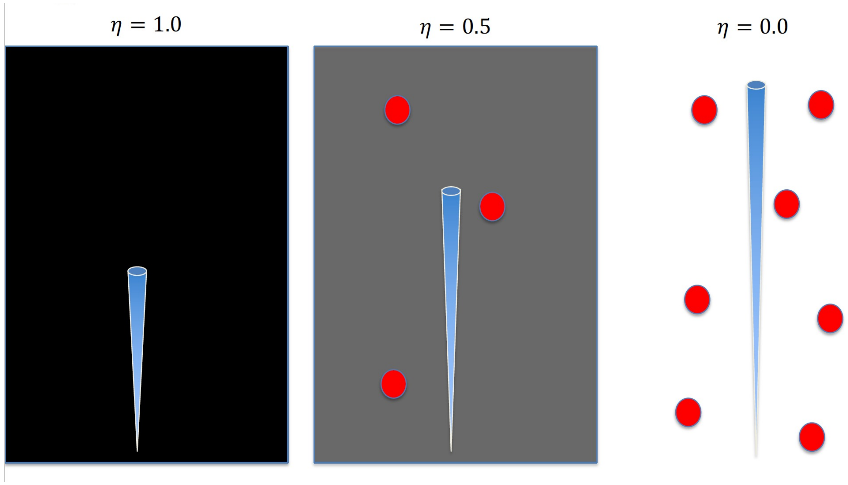

Parkes: Kumar et al, MNRAS 500 (2020) 2525

# Dark matter: lensing?

Mawson Sammons

## Testing dark matter clumpiness

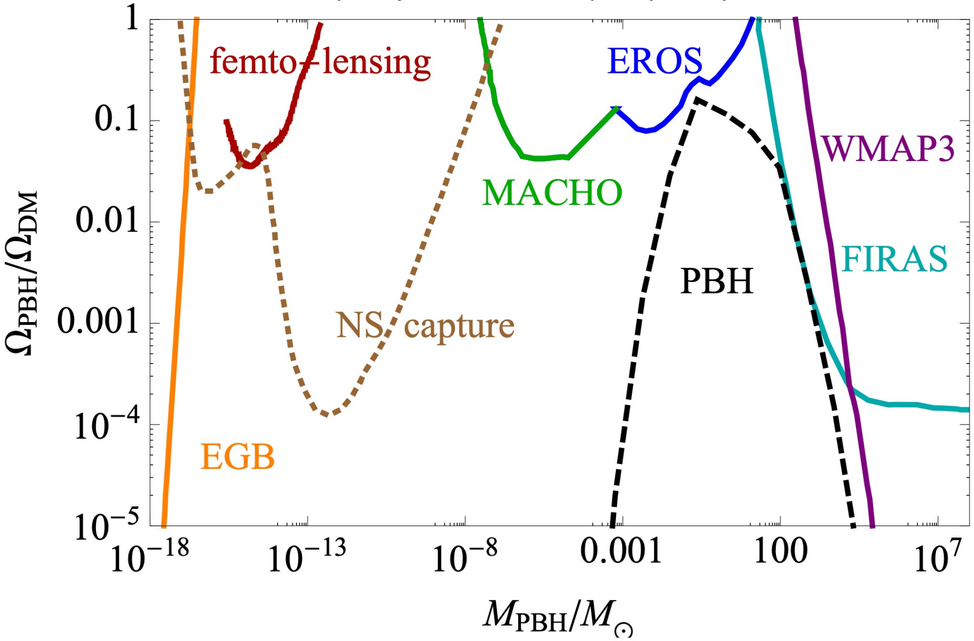
- Limits on dark matter clumpiness: variety of sources
- FRBs – probe a tiny fraction of line of sight. Might not pass through DM at all!
- Or… might we see lensed copes of an FRB signal?
- Volume probed by FRBs: $10^{20}$ smaller than SN
- First constraints: Sammons et al, ApJ 900, 122 (2020). Expect < 1% lensed.




DM: smooth

DM: clumpy

Clesse et al., Physical Review D, 92 (2015) 023524.



# Cosmic rays

## Cosmic ray mystery

- Energies: up to 10 Joules per particle!
- $<10^{15}$ eV: Galactic in origin
- $>10^{19}$ eV: extragalactic
- Where do they come from?
- Study physics at energies >LHC!

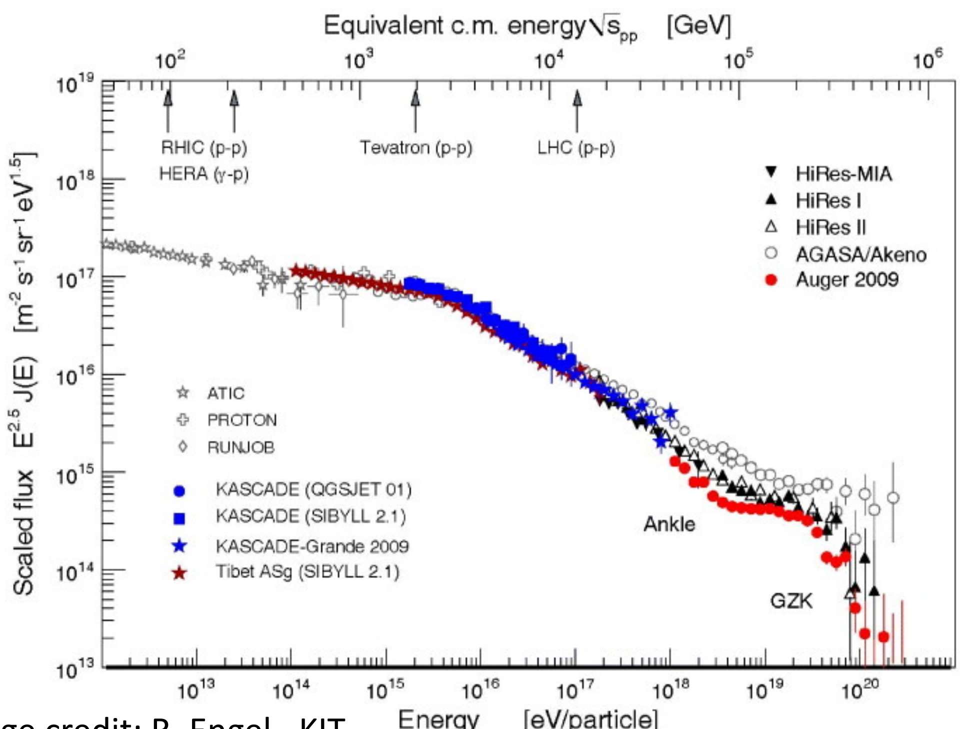



Image credit: R. Engel., KIT

## Sources?

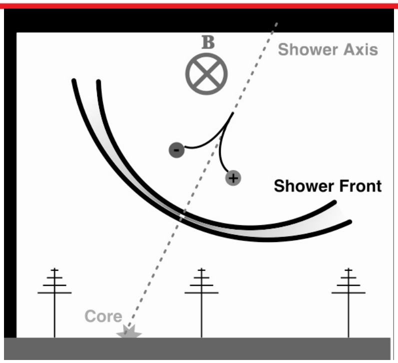
## Composition

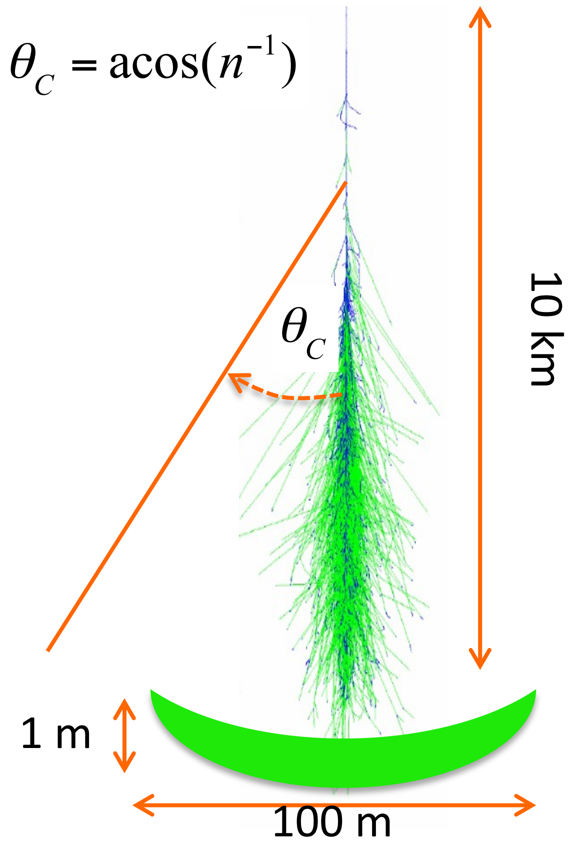
- Relates to ability of cosmic ray sources to accelerate particles
- Expect hints of Galactic to extragalactic transition

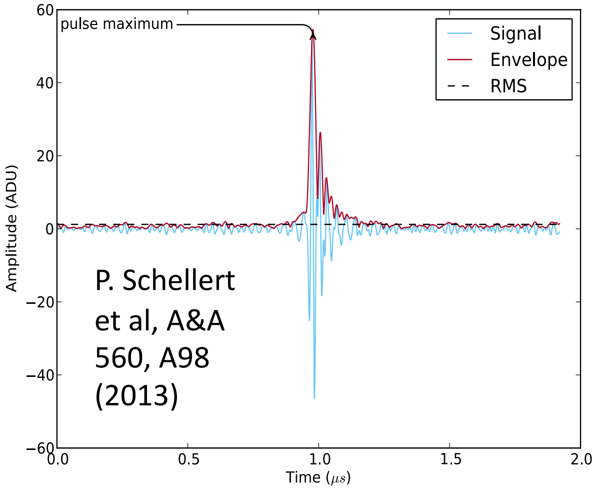
# Cosmic ray extensive air showers

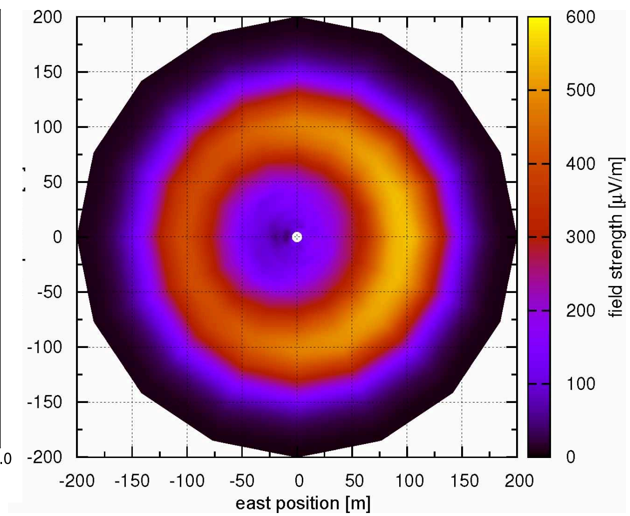
## Radio emission

- Charged particles in cascade: $e^+$, $e^-$
- Accelerated charged particles radiate
- Emit short burst of radio waves (tens of ns)
- Localised ground pattern contains information on primary particle
- Emission peaks near 50 MHz



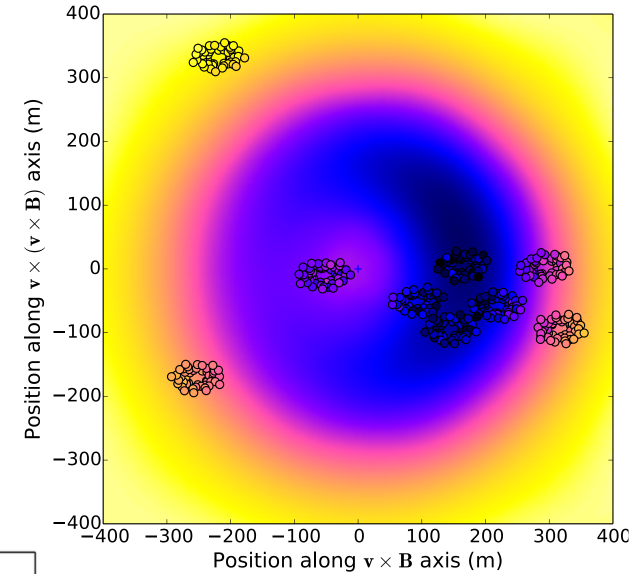




T. Huege, Phys Rep 620 (2016) 1

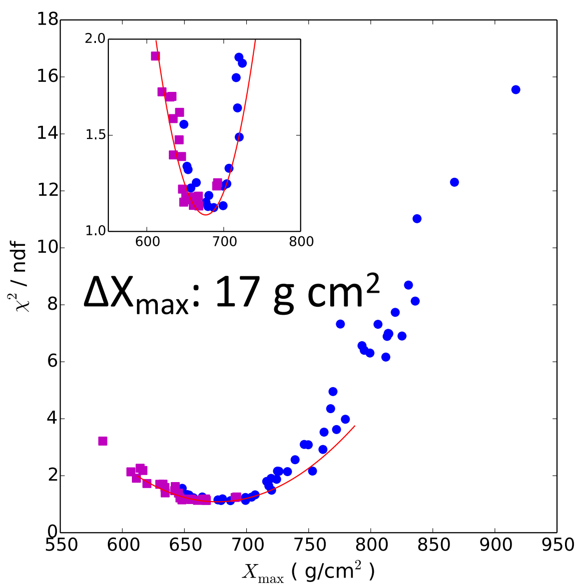
# What information?

## Main observable: “$X_{max}$”

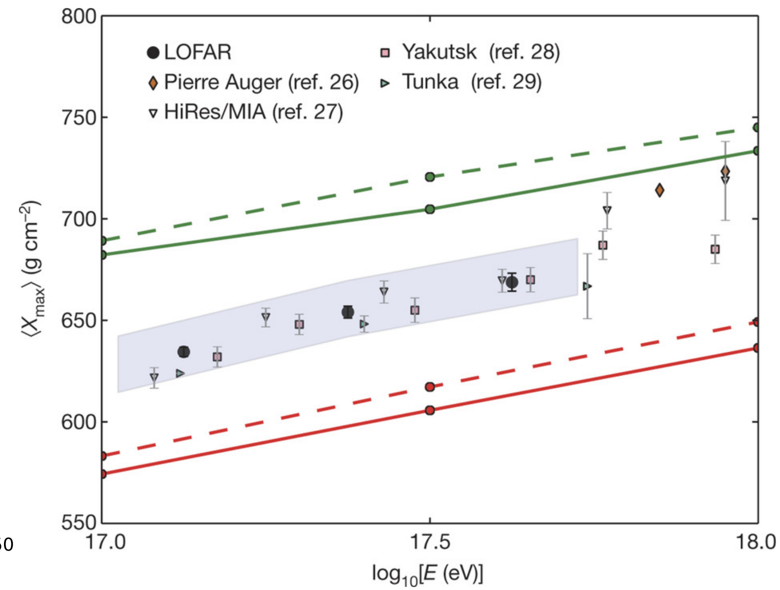
- $X_{max}$: depth in atmosphere (g/cm2) of shower peak
- Depends on:
- Primary particle energy/type (proton, iron, gamma)
- High-energy particle cross-section
- Random fluctuations
- Compare measurements (LOFAR) with simulations
- Study composition and HE physics




S. Thoudam et al, NIMPA 767, 339 (2014)




S. Buitink et al, PRD 90 (2014) 082003




S. Buitink et al, Nature Letters, 531 (2016) 70

## Composition

Relates to ability of cosmic ray sources to accelerate particles

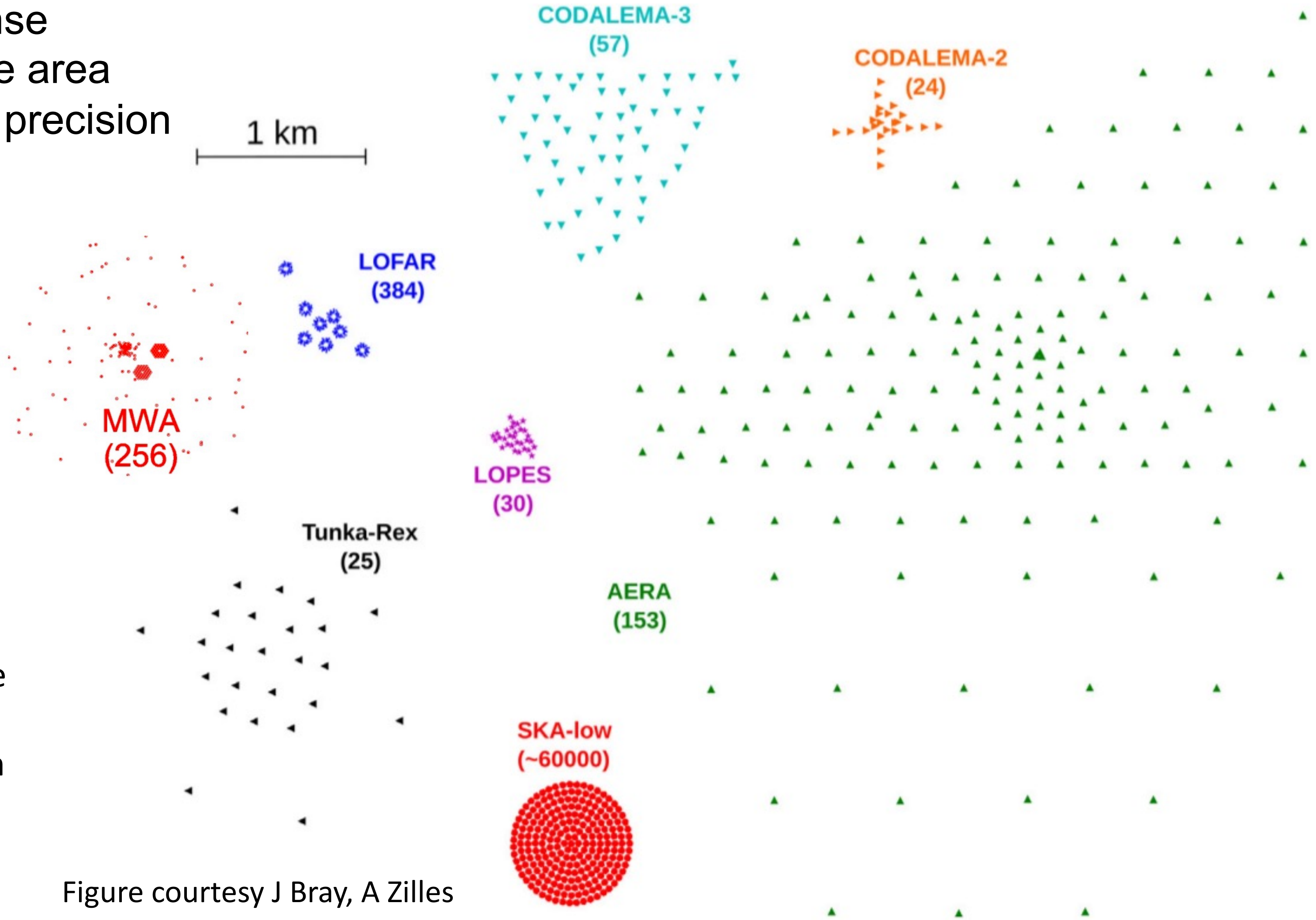
Expect hints of Galactic to extragalactic transition

# Comparisons

**"Ultimate precision"**

**SKA1-low:**

- Very dense
- Moderate area
- Ultimate precision




Missing possible IceTop upgrade 162 detectors in ~$1km^2$

Figure courtesy J Bray, A Zilles

# Plans for the SKA-low

## Step 1: buffer antenna data

- Before broken into frequency channels
- Before added into station beams
- 1 in 4 antennas buffered (tile processing mo
- 12 bits buffered for ~1 second

P. Bentham et al, IAU 2017

## Step 2: trigger on particle detectors

- 180 detectors planned
- Distribute over SKA-low core (~1 $km^2$)
- Piggyback off SKA power/fibre distribution
- Scintillators detect particles, trigger radio data

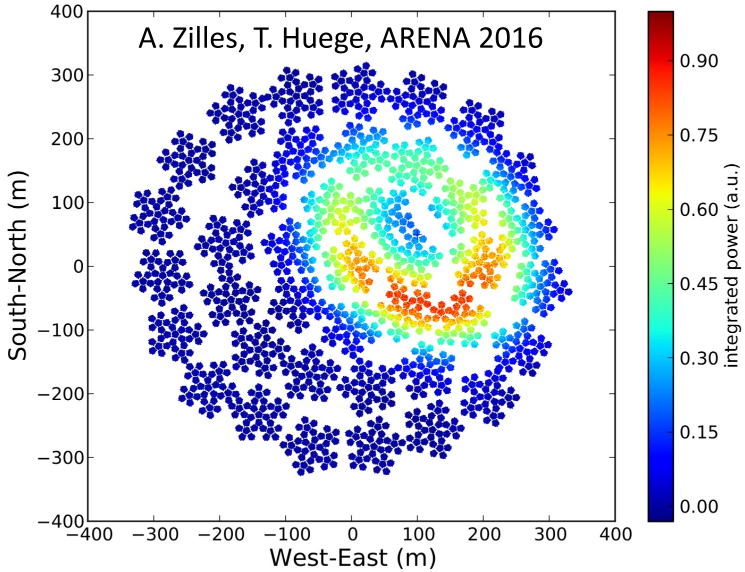

## Step 3: return data

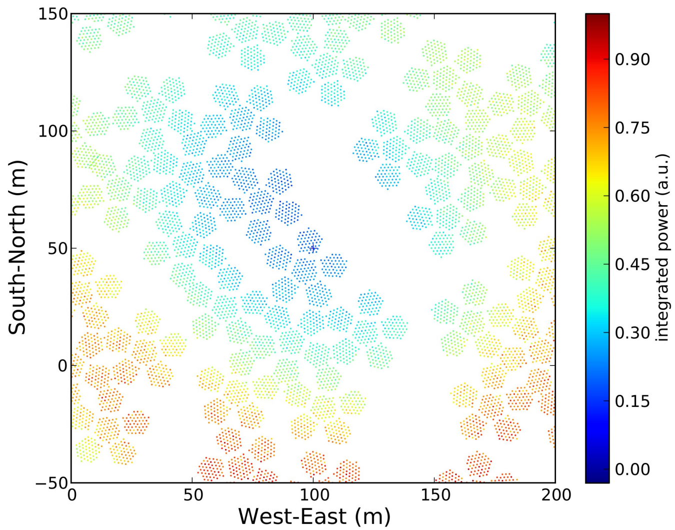
- Only 10 us per event! (x65000 tiles…): few GB
- Trigger rate: O~1/minute (<0.00001 % of data)
- Perform analysis offline in dedicated pipeline

# Estimated sensitivity

## Reconstruction accuracy

- Based on LOFAR pipeline
- Simple models of SKA (outdated layout)
- Use only ¼ antennas (saves time)
- $X_{max}$ resolution: 6.3 g $cm^{-2}$ for $10^{17}$ eV p
- c.f. LOFAR 17 g $cm^{-2}$, Auger 20 g $cm^{-2}$
- "Ultimate precision"!

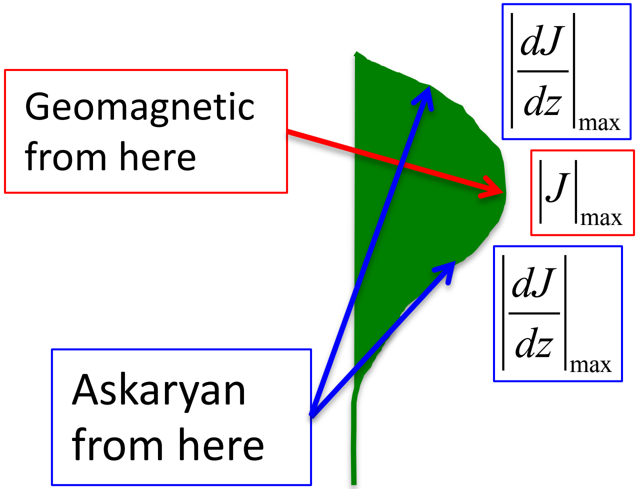


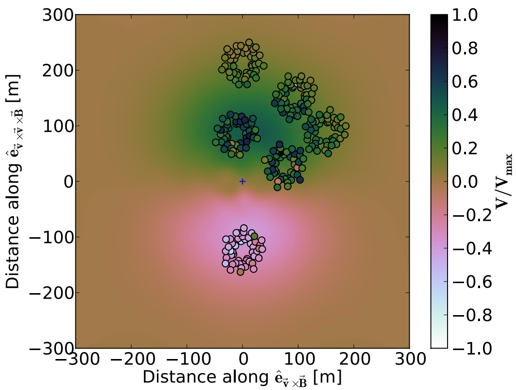



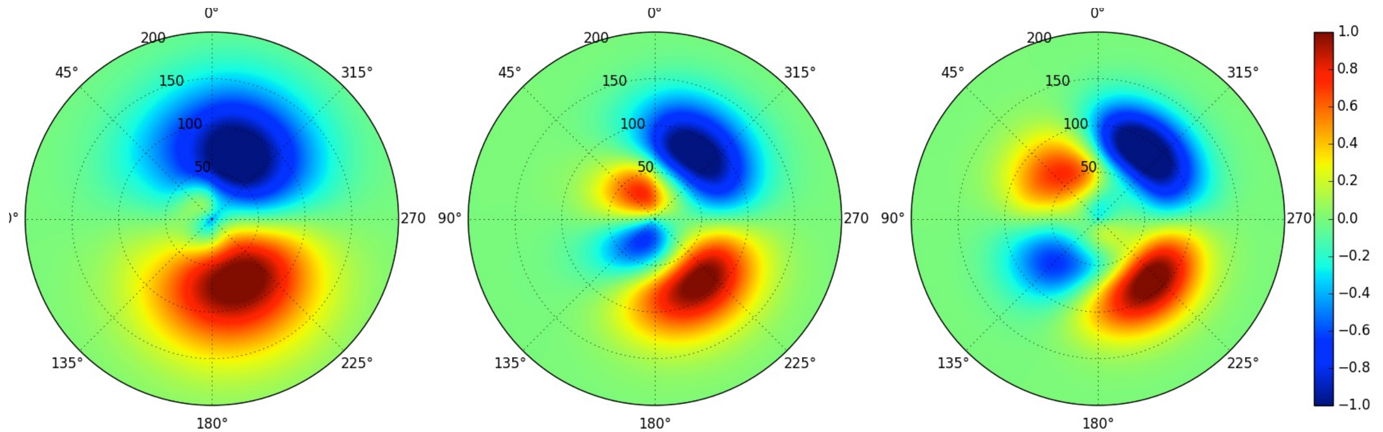
# How can we improve?

## Polarisation above 100 MHz

- Stokes V (circular) shows evolving ground pattern above 100 MHz
- Due to interference of different cosmic ray emission mechanisms
- Should probe shower structure, not just $X_{max}$!




- LOFAR: ~30-80 MHz 80-110 MHz 170-200 MHz 270-300 MHz

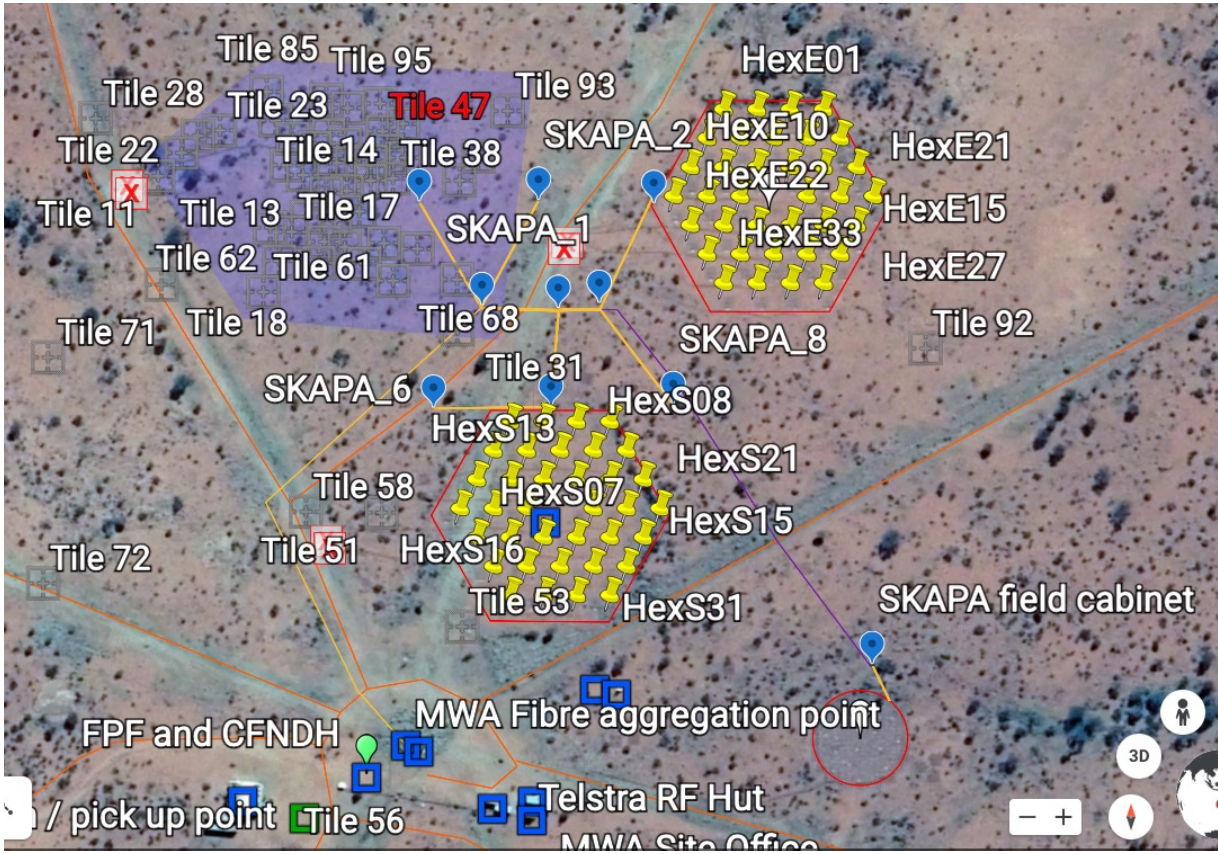
Credit: Scholten et al.

Credit: sims by H. Chen

# Testing – Murchison Widefield Array

## Status

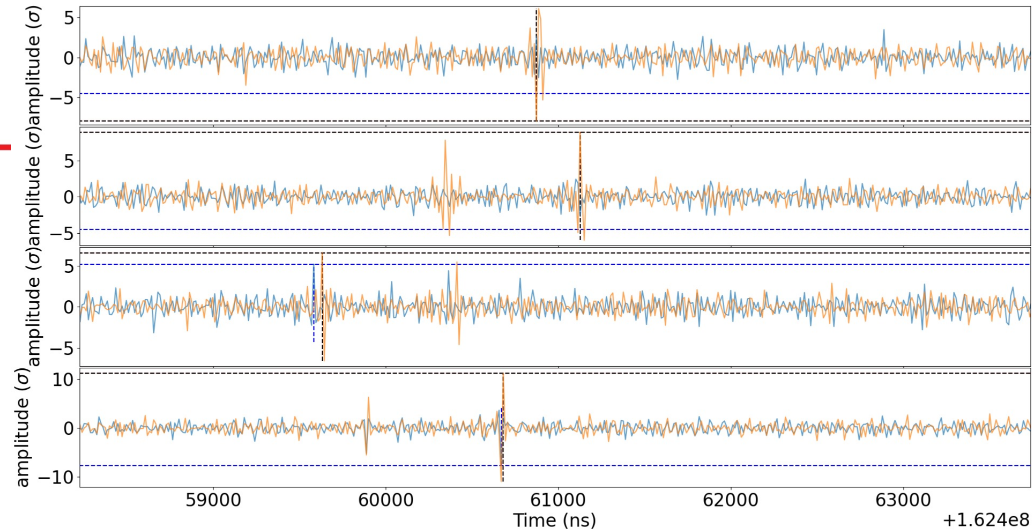
- 8 detectors funded
- Prototypes tested:
    - In-field
    - KIT 'muon tower'
- Performance matches!




## First look

- No triggers
- Record all data!
- Search for pulses

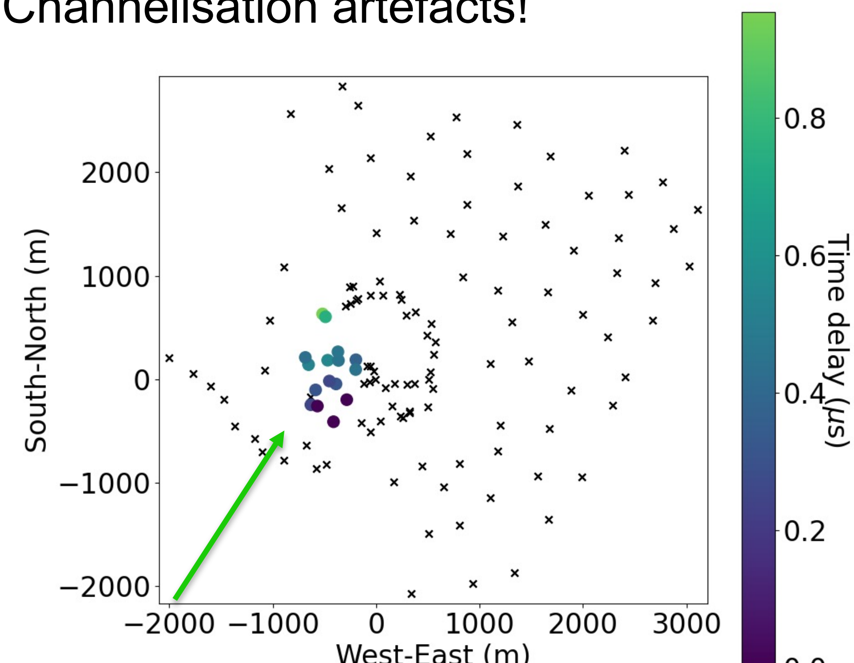
# Cosmic ray

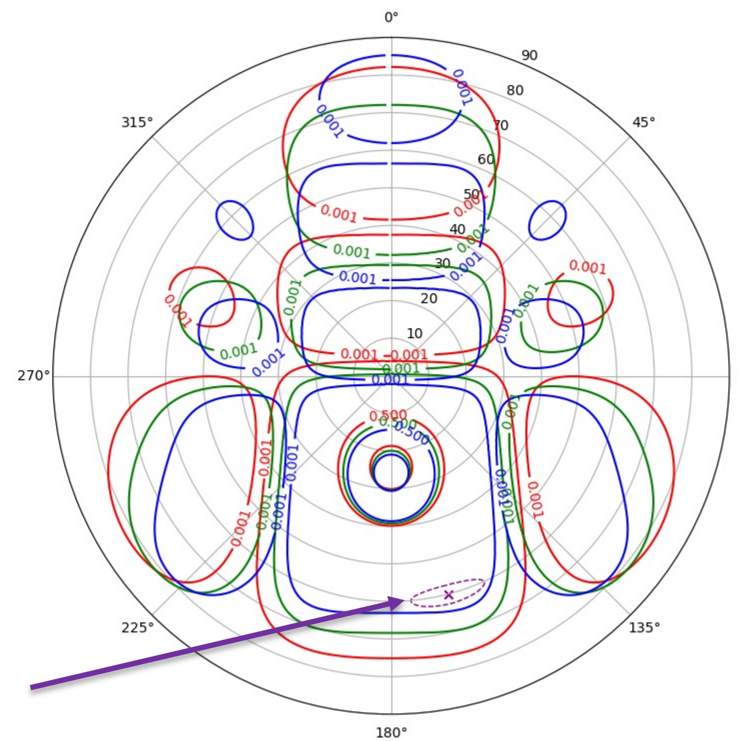



## Best event in 23 hr

- 16 tiles
- E-W > N-S polarisation
- Arrives from main beam
- Perpendicular to local B-field (max Lorentz force)

Channelisation artefacts!



# Multimessenger astronomy

$$\left.\begin{array}{l} p_{CR} + p_{ISM} \\ p_{CR} + \gamma_{\text{light}} \end{array}\right. \rightarrow n / p'_{CR} \left(+p'_{ISM}\right) + \pi^{0,\pm}$$

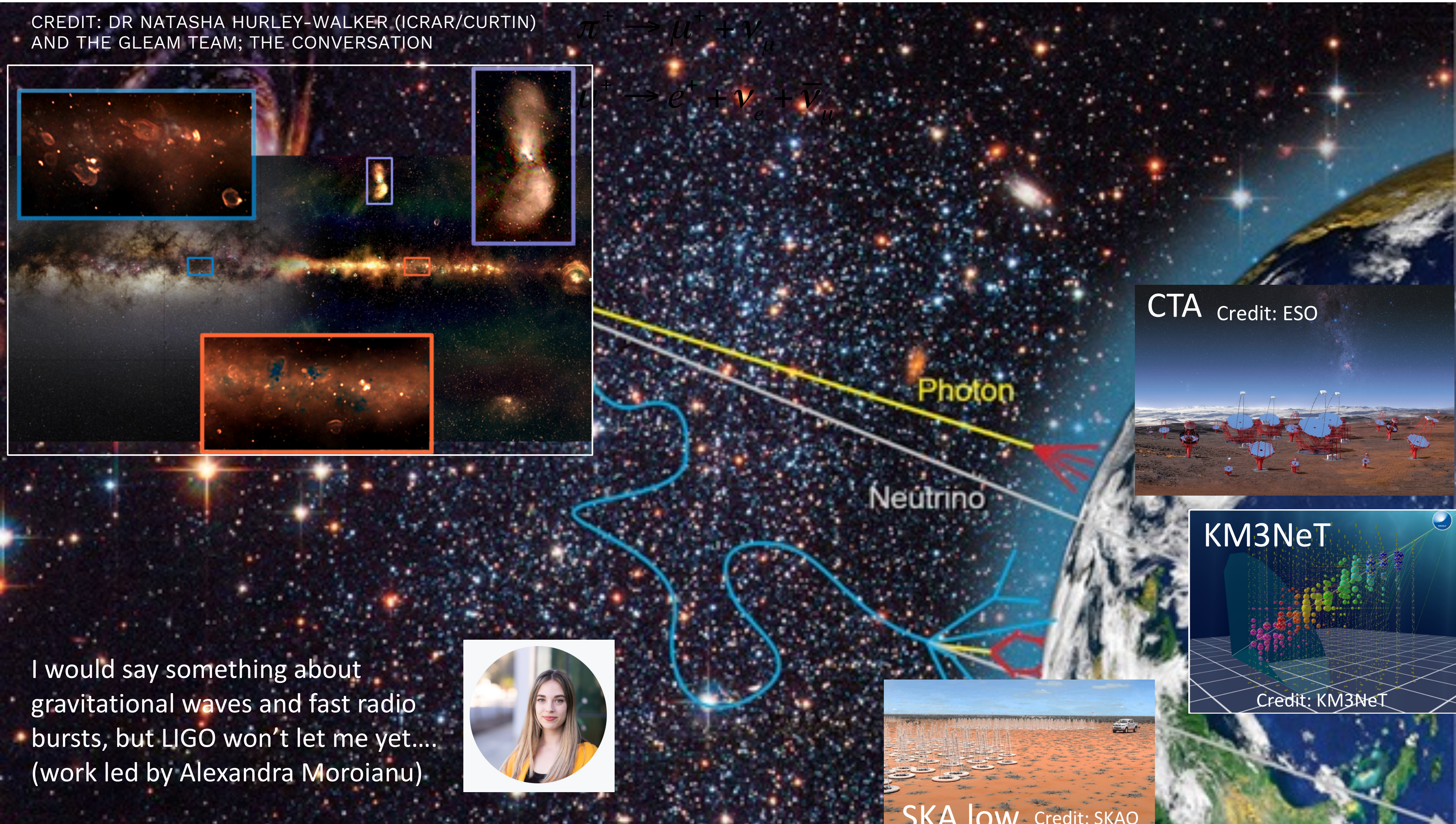
$$n \rightarrow p'_{CR} + e^- + \bar{\nu}_e$$

$$\pi^0 \rightarrow 2\gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Credit: DESY




I would say something about gravitational waves and fast radio bursts, but LIGO won't let me yet.... (work led by Alexandra Moroianu)

# Conclusion

## FRB Science

- High-energy astrophysics (pulsars, GW, ...)
- Cosmology (H0, feedback,…)
- Require large sample of precision-localised FRBs
- Needs world-class optical facilities
- Modelling of detection biases critical (know your instrument!)

## Cosmic ray science

- Strong synergies with CTA, KM3NeT
- Particle physics – how to model high-energy interactions?
- Cosmic ray origins: Galactic => extragalactic transition?

## Transient radio astronomy

- All of this made possible via non-standard processing
- Buffer-search-trigger-dump paradigm
  - FRBs: station-level data
  - Cosmic rays: antenna-level data
- Close cooperation between scientists and engineers required


Thank you Italy!