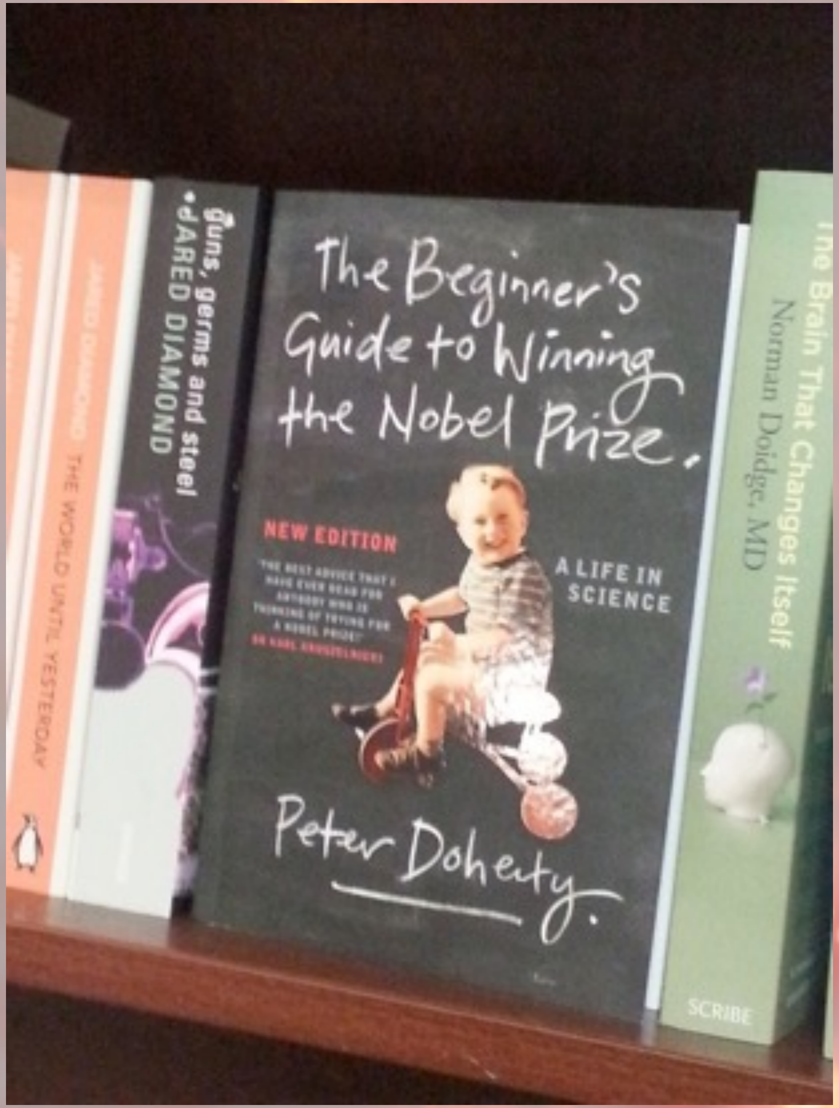
ICRAR

International Centre for Radio Astronomy Research

Transients & Variables with SKA2 & AA-MID

Jean-Pierre Macquart



Curtin University

The Government of Western Australia

The University of Western Australia

The case for high sensitivity & large FoV

Exciting new results

FRBs

- Thoughts on their significance

Gravitational Waves

Other known knowns

Bread and butter science

How does AA-MID fit in the picture?

Transients as a physics lab

Why do we care?

- Cosmology
- Extreme gravity and states of matter
- Accretion physics
- Everybody loves explosions

Known Unknowns

- Fast Radio Bursts
- Extreme Scattering Events
- Gravitational Wave Events
- Flare stars & dwarf novae

Known Knowns & Known Unknowns

Time-domain - bursty and generally coherent

- Pulsars including Magnetar bursts, Transitional XRBs, Giant Pulses, RRATs
- Fast Radio Bursts
- Bursty emission from exoplanet-star systems, brown dwarfs
- Cosmic rays, lunar neutrinos (so far only SKA1_LOW)

Image domain - incoherent synchrotron or thermal

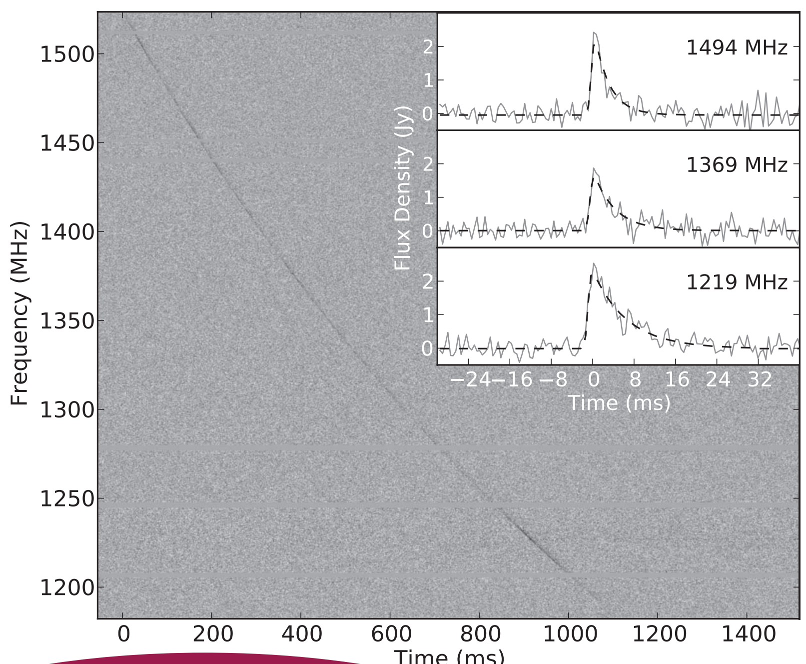
- X-ray binaries
- Tidal Disruption Events
- Novae & Flare stars
- Intra-day variable quasars/Extreme Scattering Events
- System mergers/gravitational wave events

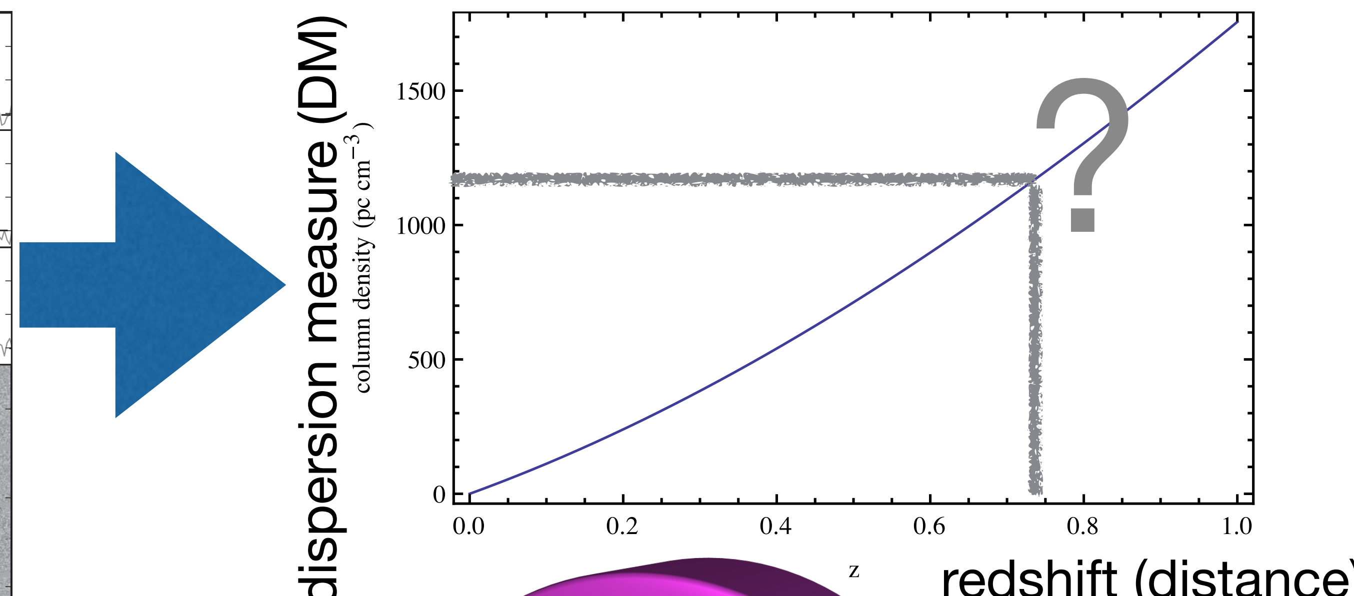
Fast transients as cosmological probes

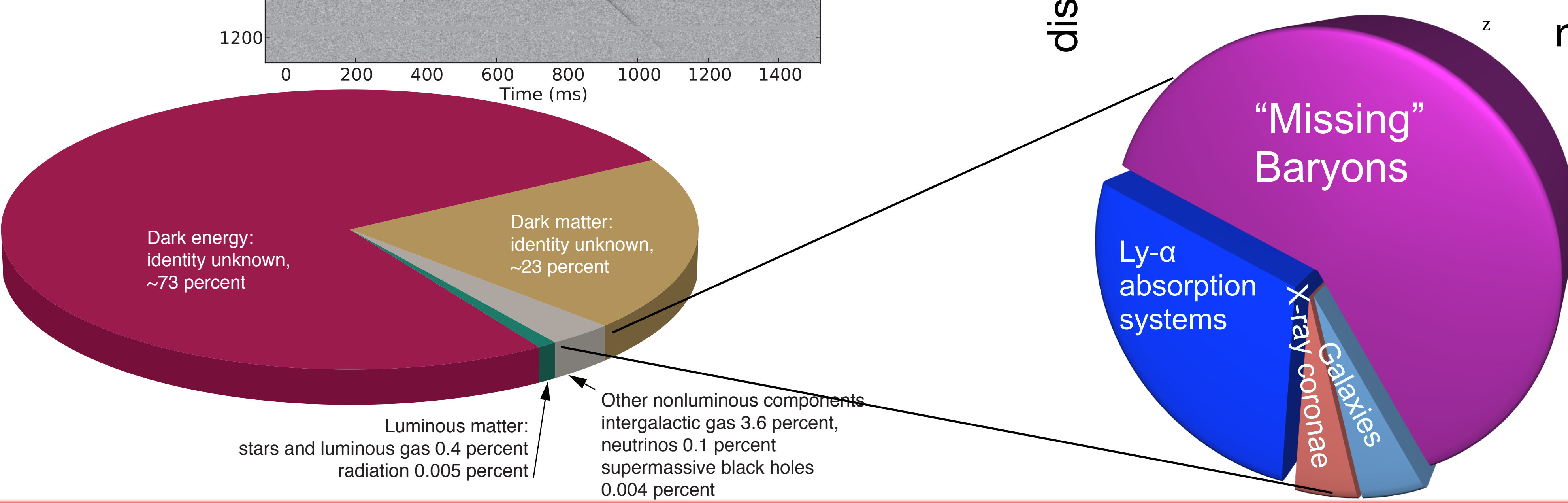
see both *Macquart et al., Fender et al. in the SKA Science book*

We can

- *directly* detect every single baryon along the line of sight!
- use the DM-redshift relation as a cosmic ruler
- measure turbulence on sub 10^8m scales at distances of ~1Gpc
- probe IGM physics: primordial magnetic field & energy deposition







Extraordinary FRB properties

Bright Fluences up to ~10 Jy ms

- 19 events from Parkes (Lorimer et al. 2007;Thornton et al. 2013;Champion et al. 2016)
- 1 at Arecibo (Spitler et al. 2014)
- 1 at Green Bank (forthcoming)

Distant Extremely high dispersion measures for objects above the Galactic plane (375-1500 pc/cm^3)

- Not obviously associated with nearby galaxies

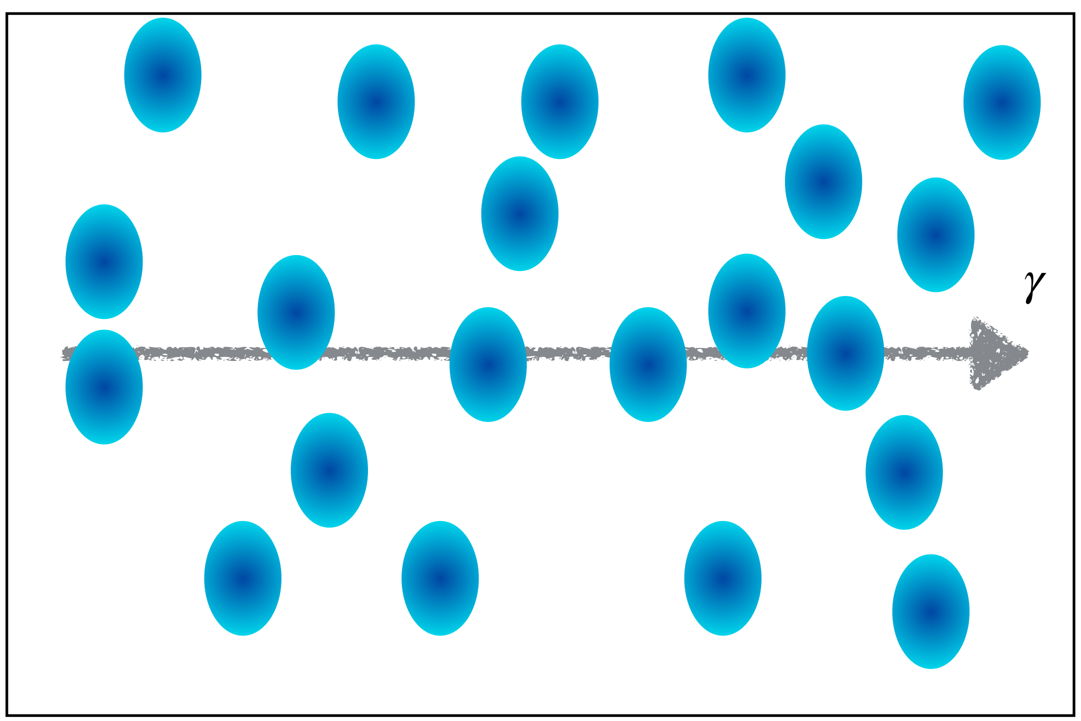
Common Inferred event rate ~ 2-5 x10^3 sky^{-1} day^{-1}

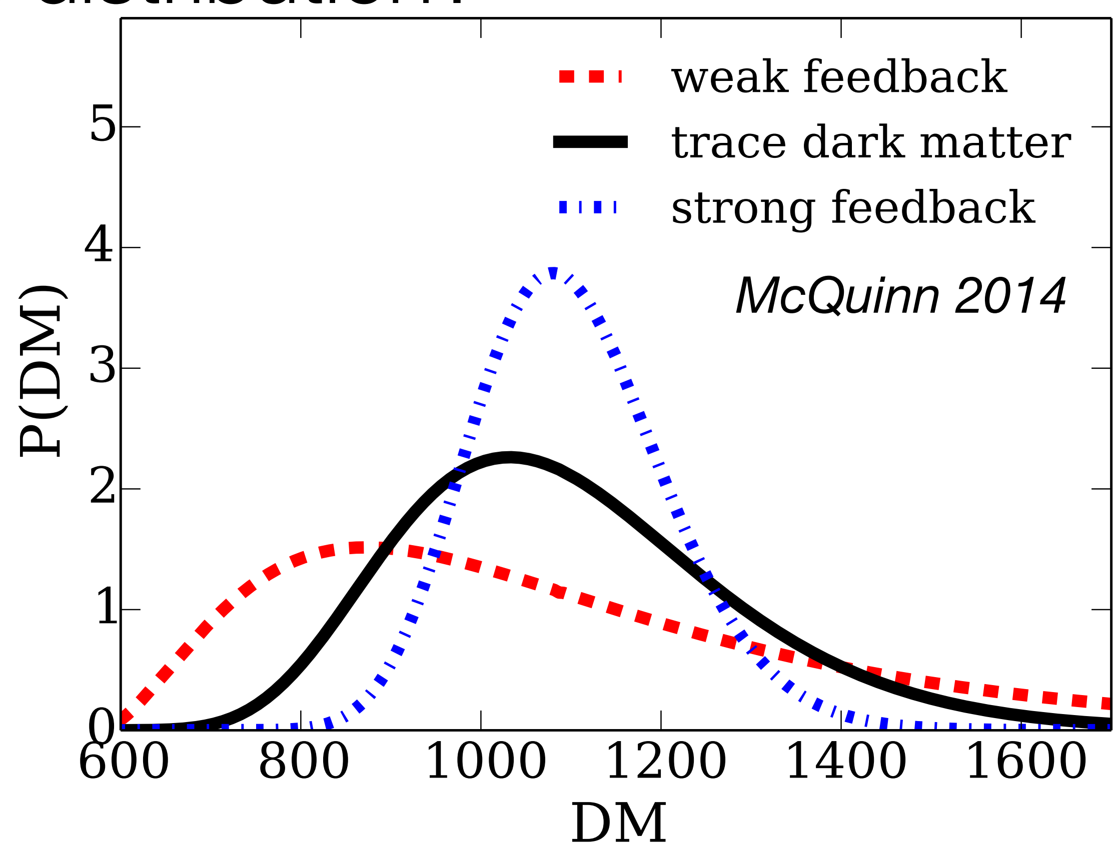
Scattered At least 4 exhibit temporal smearing of order several milliseconds (much larger than expected due to scattering in the Milky Way)

Where are the missing baryons?

FRB dispersion can directly answer this question

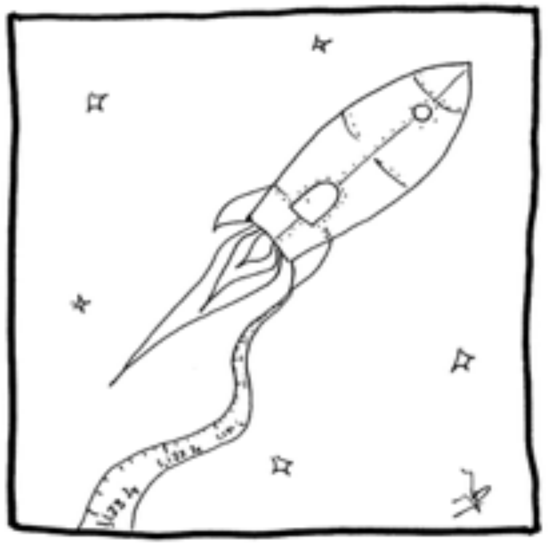
- Missing baryons location an important element of galaxy halo accretion and feedback
- Most dark matter found in galaxy halos, but most baryonic matter outside this scale (>100kpc)
- How do we determine its distribution?





Dark Energy - FRBs as cosmic rulers

Zhou et al. 2014



FRBs measure the dark energy equation of state:

$$w = \frac{p}{\rho}$$

How does *w* evolve with time?

$$\mathrm{DM} = \int n_e dl \rightarrow \int n_e \left| \frac{c\,dt}{dz} \right| dz$$

- The term c dt/dz is a ruler that measures the curvature of the Universe
  - Measure the DM as a function of redshift

□ : Universe curvature terms

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

H and He ionization fractions

baryonic density

curvature due to matter

curvature due to dark energy

w(z): equation of state

Are FRBs really cosmological?

Masui et al. (2015) argue for magnetars based on RM

- Significant amount of DM due to circumburst medium so DM is not related to distance

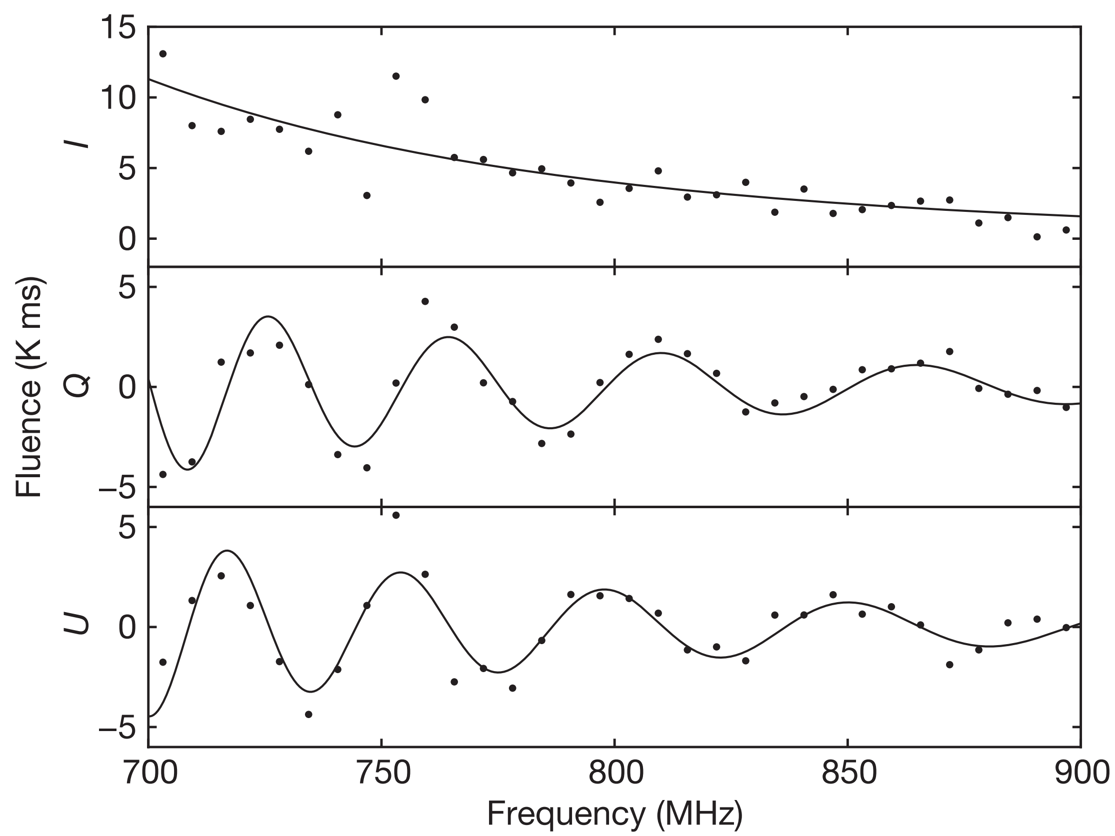


Figure 2 | FRB 110523 spectra in total intensity and polarization. Plotted is the pulse fluence (time-integrated flux) for total intensity (Stokes *I*), and linear polarization (Stokes *Q* and *U*). Solid curves are model fits. In addition to noise, scatter in the measurement around the models is due to the scintillation visible in Fig. 1. The decline of intensity with frequency is primarily due to motion of the telescope beam across the sky and is not intrinsic to the source.

Are FRBs Cosmological?

Keane et al. (2016) present evidence that FRB bursts are clean and that DM maps directly to the DM_{IGM}

- Host galaxy at z=0.492.
- Argument hinges upon correct identification of host galaxy
  - ATCA followup of Parkes detection shows a fading transient
    - Williams, Berger et al. dispute this (in a Telegram and arXiv only)
    - Coincidence only that host distance implies Ω_{IGM}=4.9±1.3%?

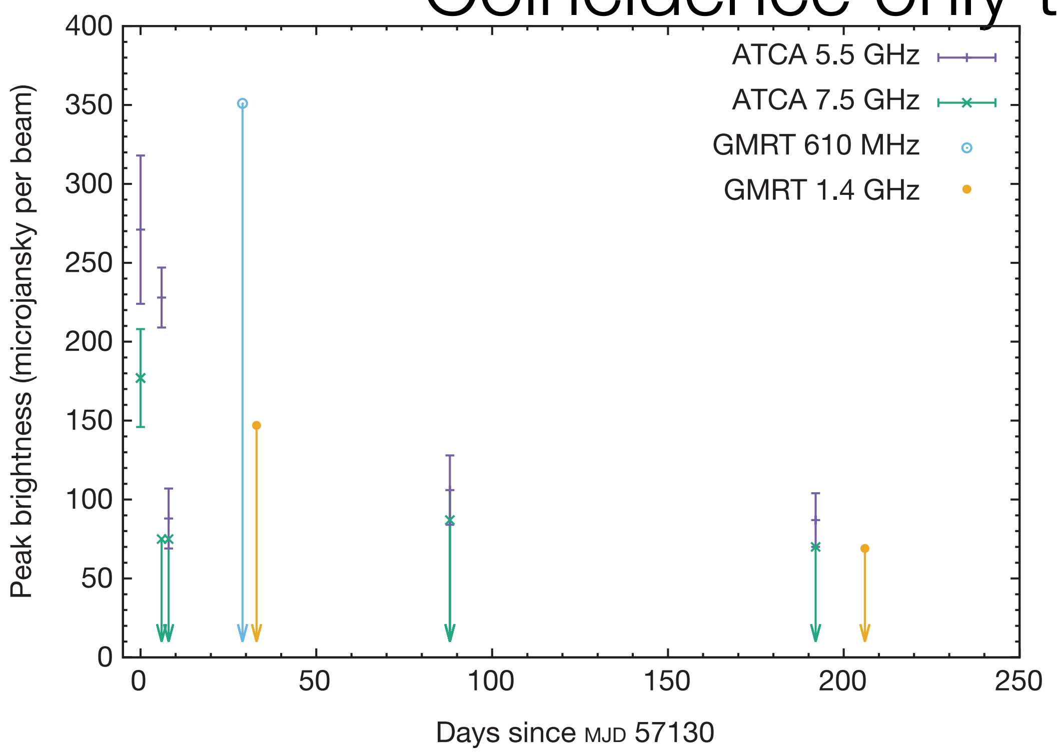
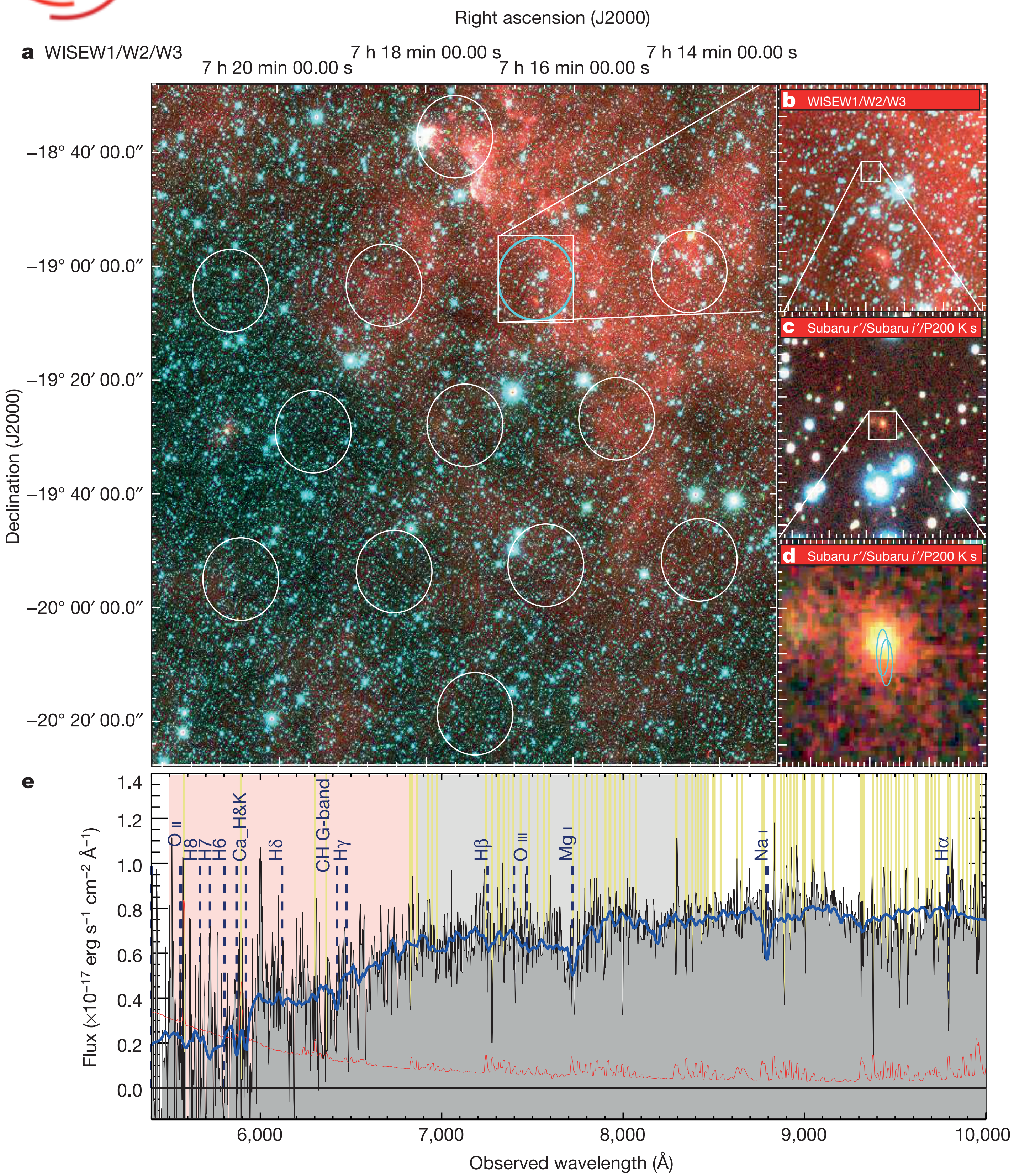


Figure 2 | The FRB host galaxy radio light curve . Detections have 1σ error bars, and 3σ upper limits are indicated with arrows. The afterglow event appears to last ~6 days, after which time the brightness settles at the quiescent level for the galaxy. Here MJD denotes modified Julian day.

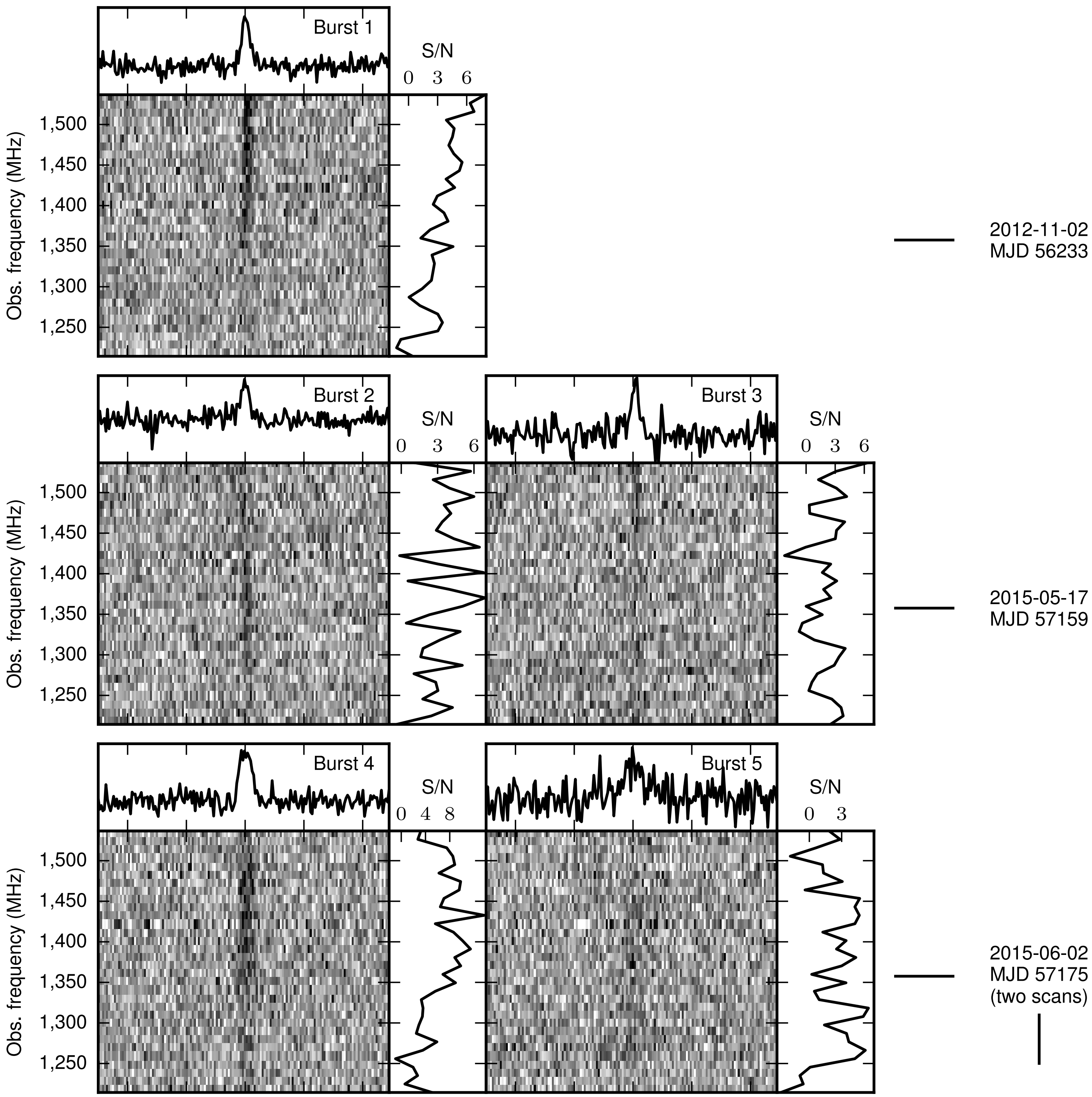
A fading transient or a variable source?

Correct host ID?



No evidence for an AGN (but may be obscured by dust)

Are FRBs Cosmological?



Spitler et al. (2016) report a repeating FRB

- Spectrum is all over the place
- Argue that it favours magnetar origin - but magnetars are not bright enough to be visible at cosmological distances
- Are there two populations of FRB?

Evidence of FRB Cosmological Origin

Observations show there is a 4.7:1 difference in the detection rate between high (>30 deg) and low latitude (*Petroff et al. 2014*)

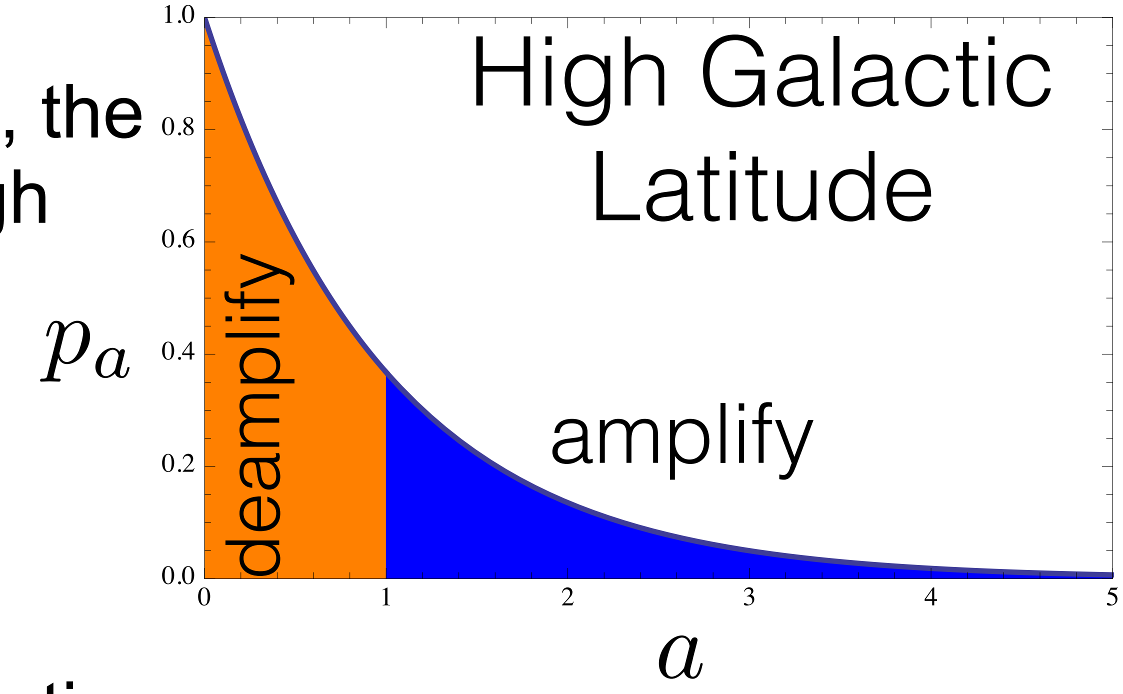
latitude	Hours on sky	Events	Rate (h/event)
|b|<15	1927.7	2	960
30<|b|<45	2128.85	7	300
|b|>45	1030.0	6	170

Interstellar scintillation explains this dependence: also implies source counts are non-Euclidean ($dN/dS_\nu \sim S_\nu^{-3.5}$) (***Macquart & Johnston 2015***)

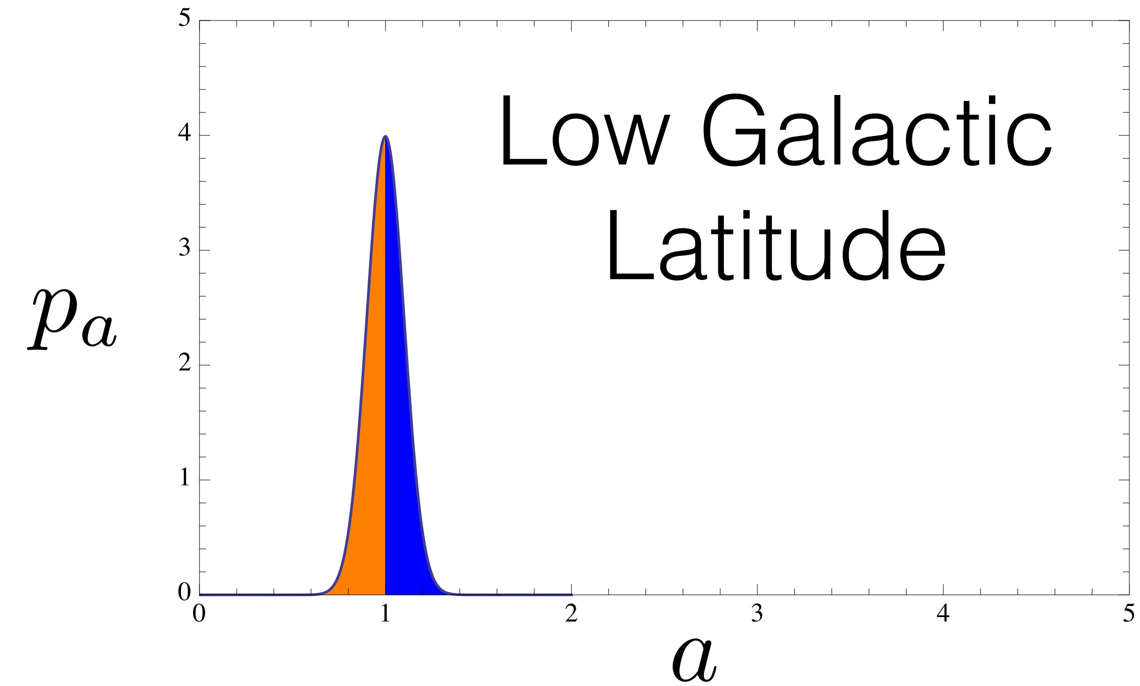
Scintillation enhancement

In the regime of strong diffractive scintillation, the probability distribution of amplifications at high latitude is

$$p_a(a) = e^{-a}$$



vs



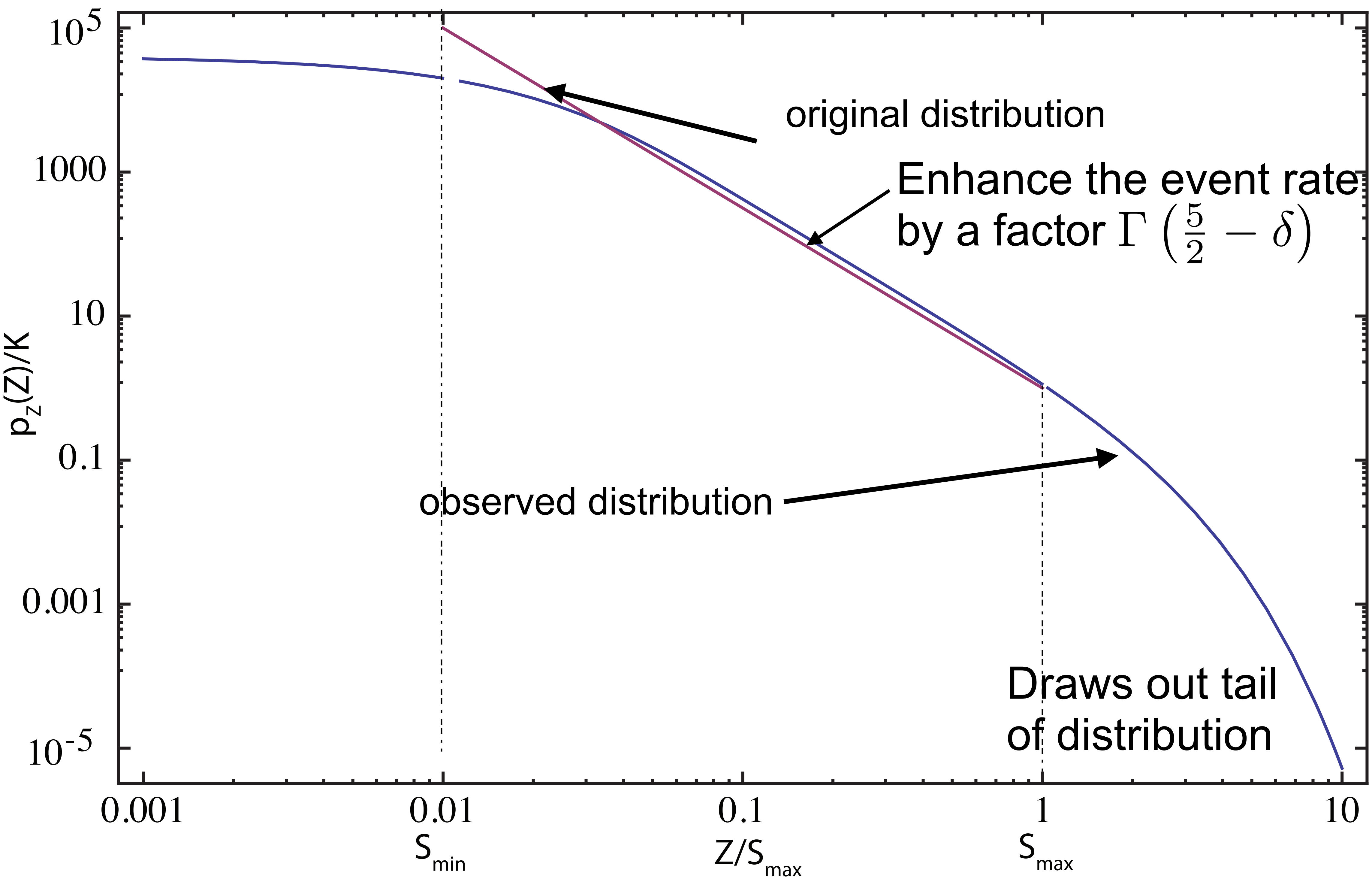
The differential source counts follow a distribution

$$p(S_\nu) \propto S_\nu^{-5/2+\delta}$$

where δ=0 for a Euclidean universe that is homogeneously populated with transients

FRB enhancement

Observed flux density: $Z=S_\nu \times a$: $$p_Z(Z) = \int p_S(S) p_a\left(\frac{Z}{S}\right)\frac{dS}{S}$$



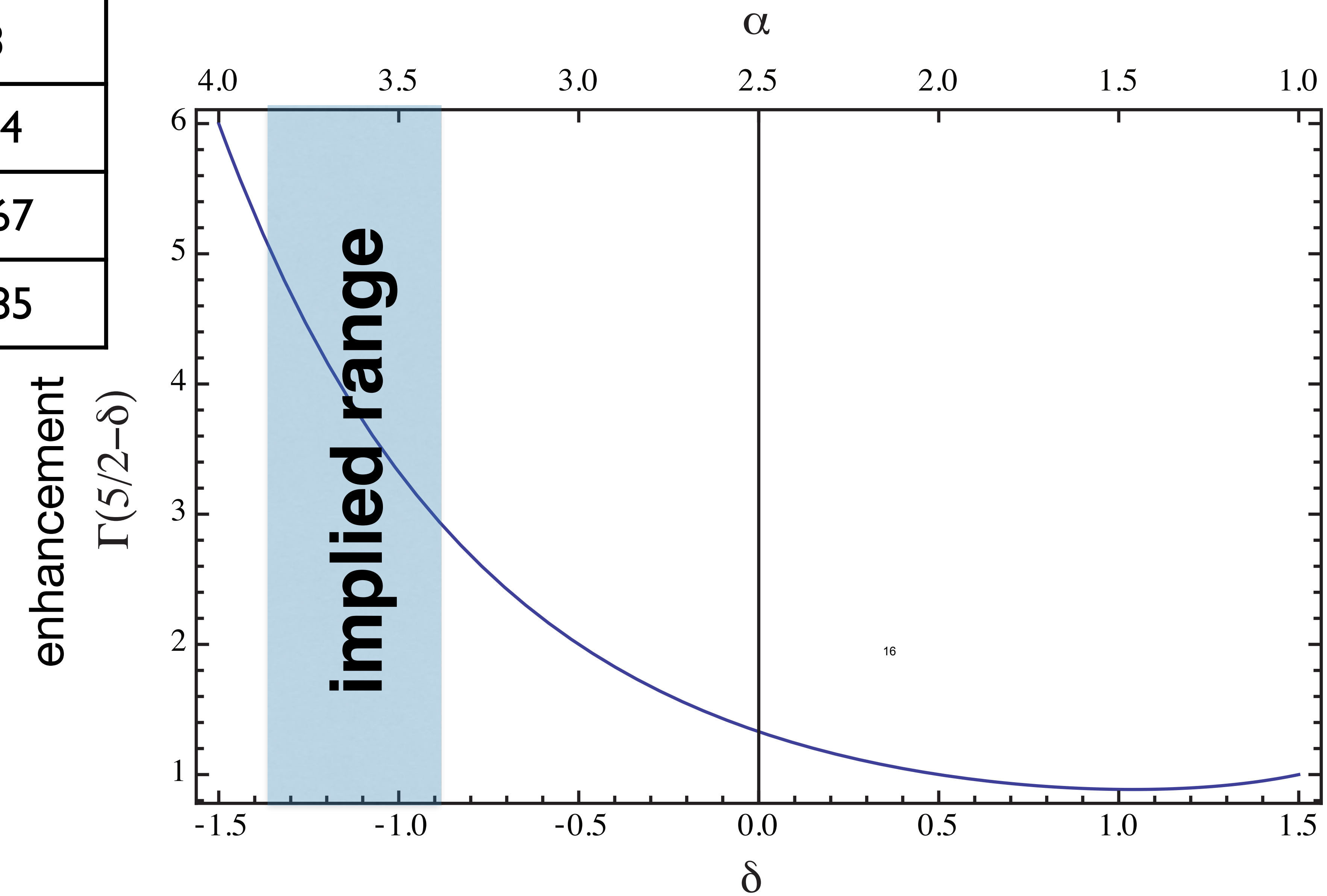
Consequences

An indirect measurement of the source count distribution!

likely range {

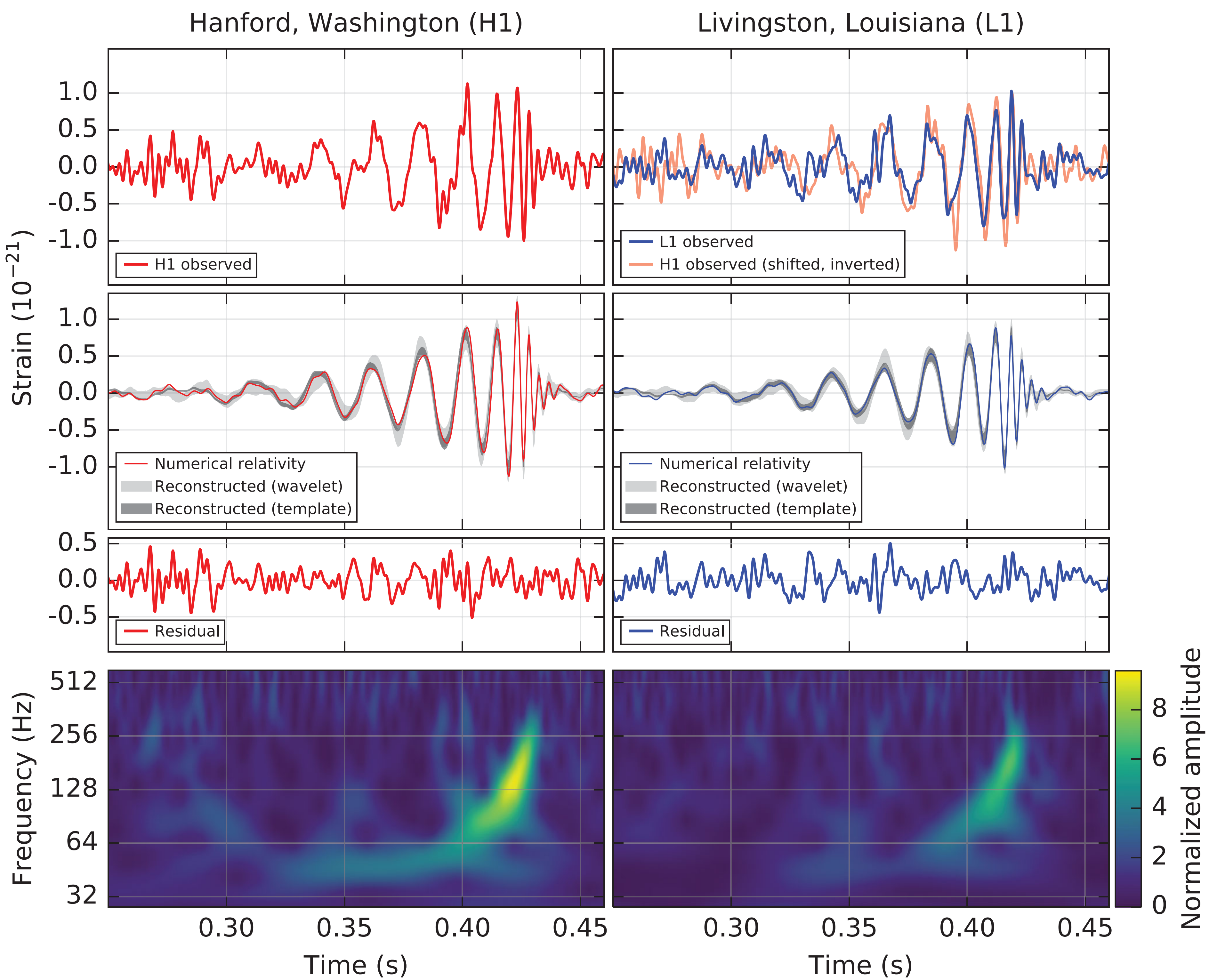
disparity	α
2:1	3
3:1	3.4
4:1	3.67
5:1	3.85

steepness of the source count distribution $N(S_\nu) \propto S_\nu^{-\alpha}$



Macquart & Johnston 2015

Gravitational Wave Events



Where did it come from?

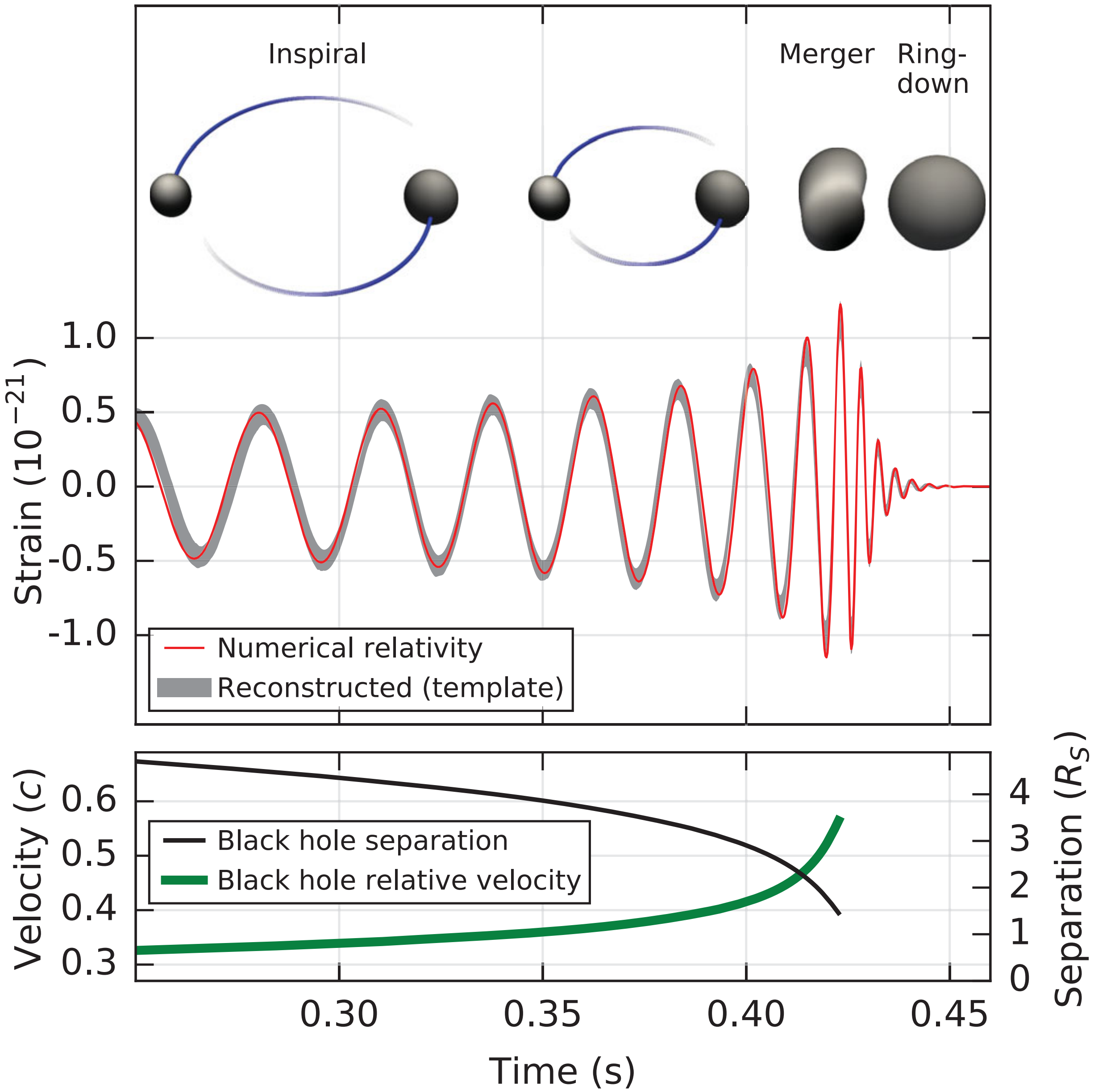


FIG. 2. *Top:* Estimated gravitational-wave strain amplitude from GW150914 projected onto H1. This shows the full bandwidth of the waveforms, without the filtering used for Fig. 1.

Produced by the coalescence of two black holes.

Over 0.2s the signal increases in about 8 cycles from 35 to 150 Hz.

3 $M_\odot c^2$ energy is liberated in gravitational waves during the merger

$z \approx 0.09$ ($D_L \approx 410$ Mpc)

CVs are radio emitters

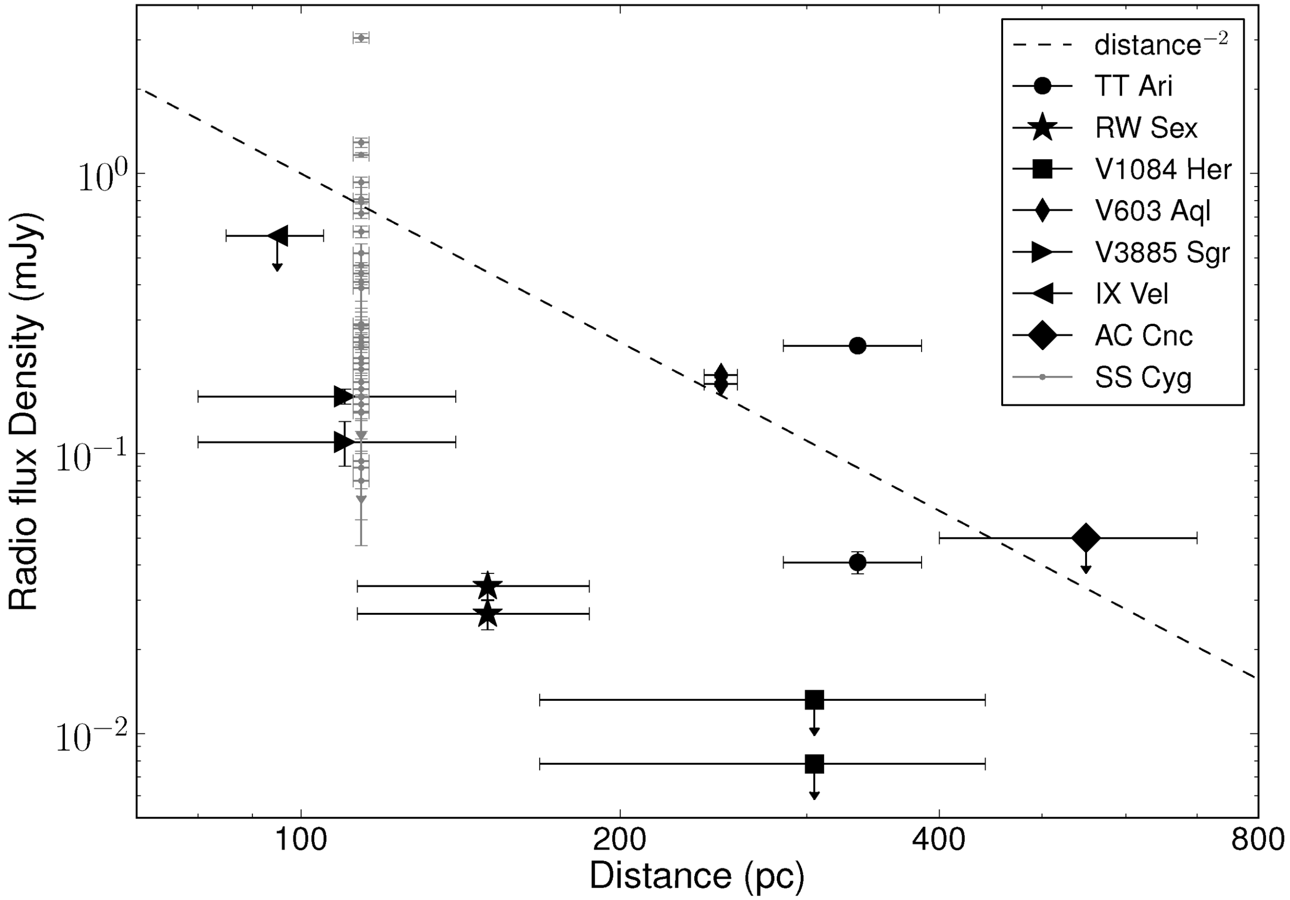
Survey of dwarf novae *in outburst* detected all 5 systems with the VLA, S_ν=15-50 μJy/beam (distances of 100-330 pc)

Undetectable in quiescence if like SS Cyg, so only detectable as transients.

Dwarf novae are numerous, nearby & non-relativistic accretion laboratories —

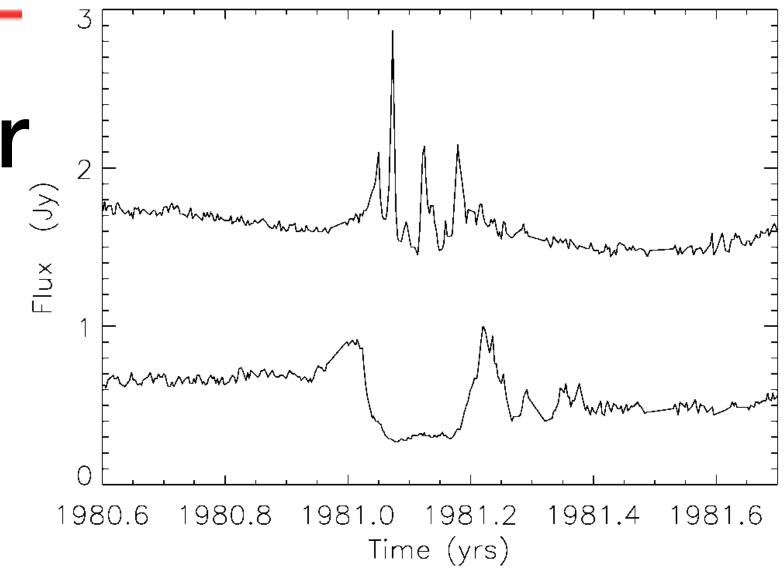
A new probe of the accretion/ejection connection

Comparison with neutron star and black hole systems probes how jet launching is affected by the depth of the gravitational potential well.



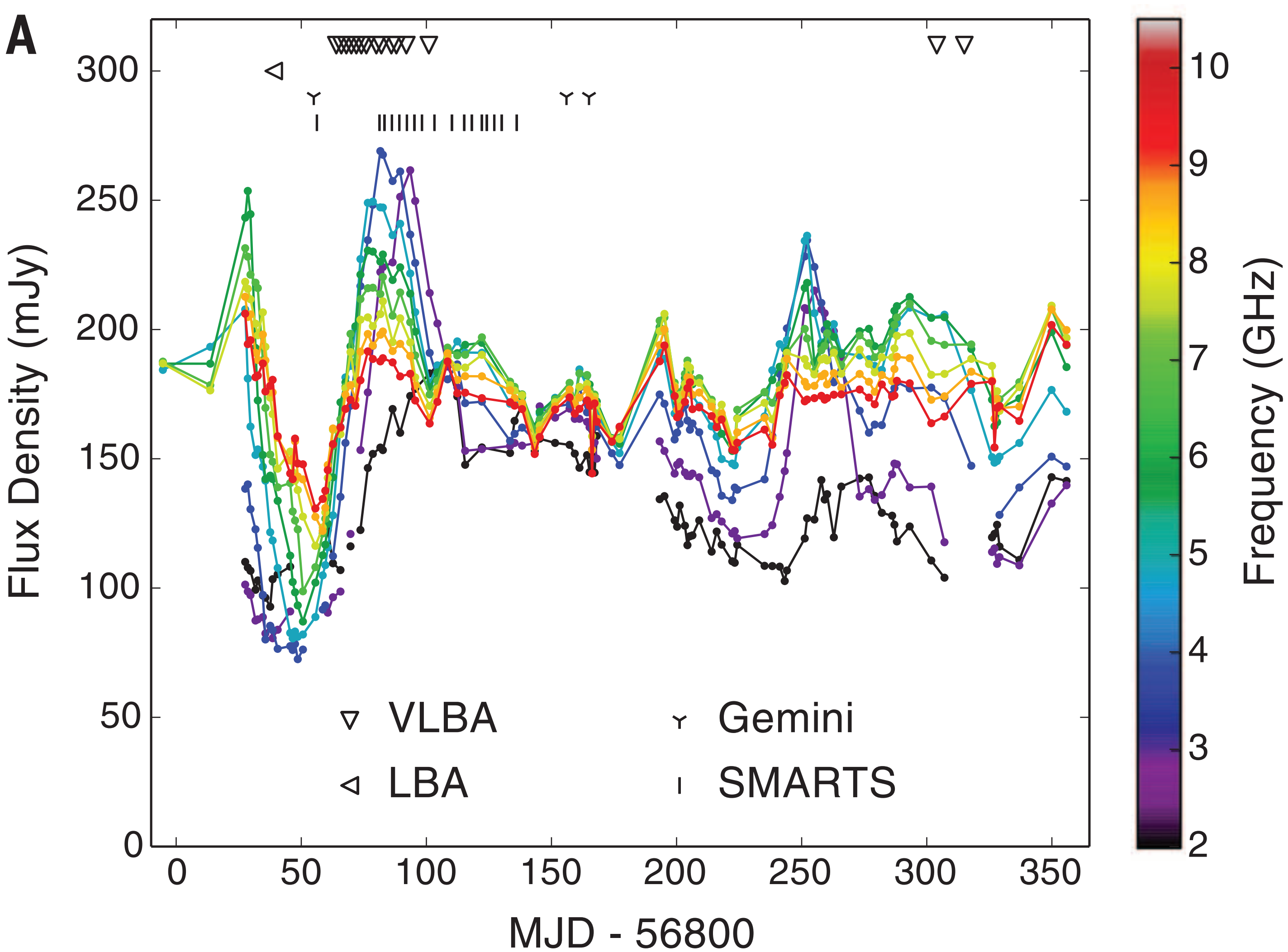
Radio flux density of all high-sensitivity observations of non-magnetic CVs as a function of distance. (Coppejans et al. MNRAS 2015)

Extreme Scattering Events



Occurs in 1 in 70 compact sources per year

(Fiedler et al. 1987)



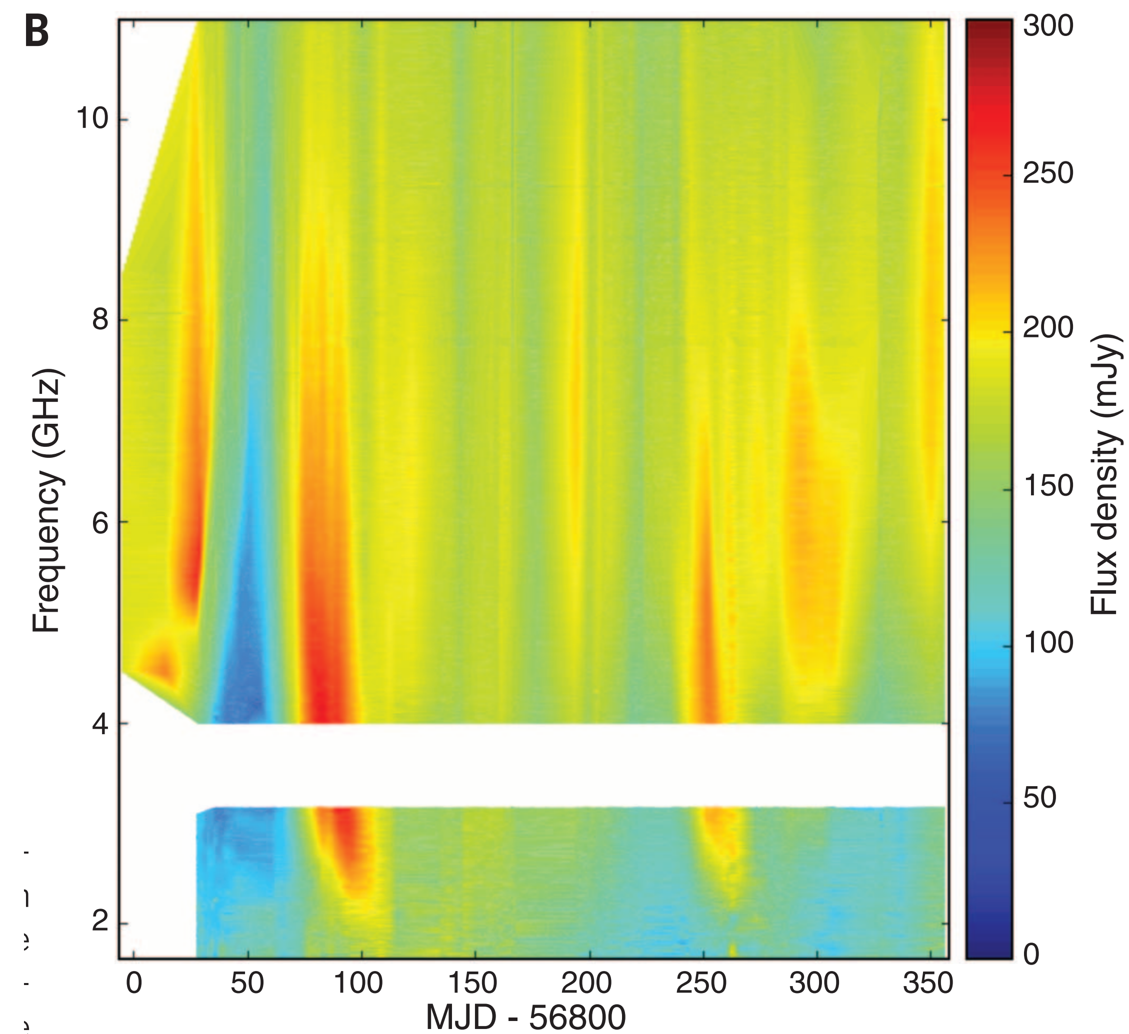
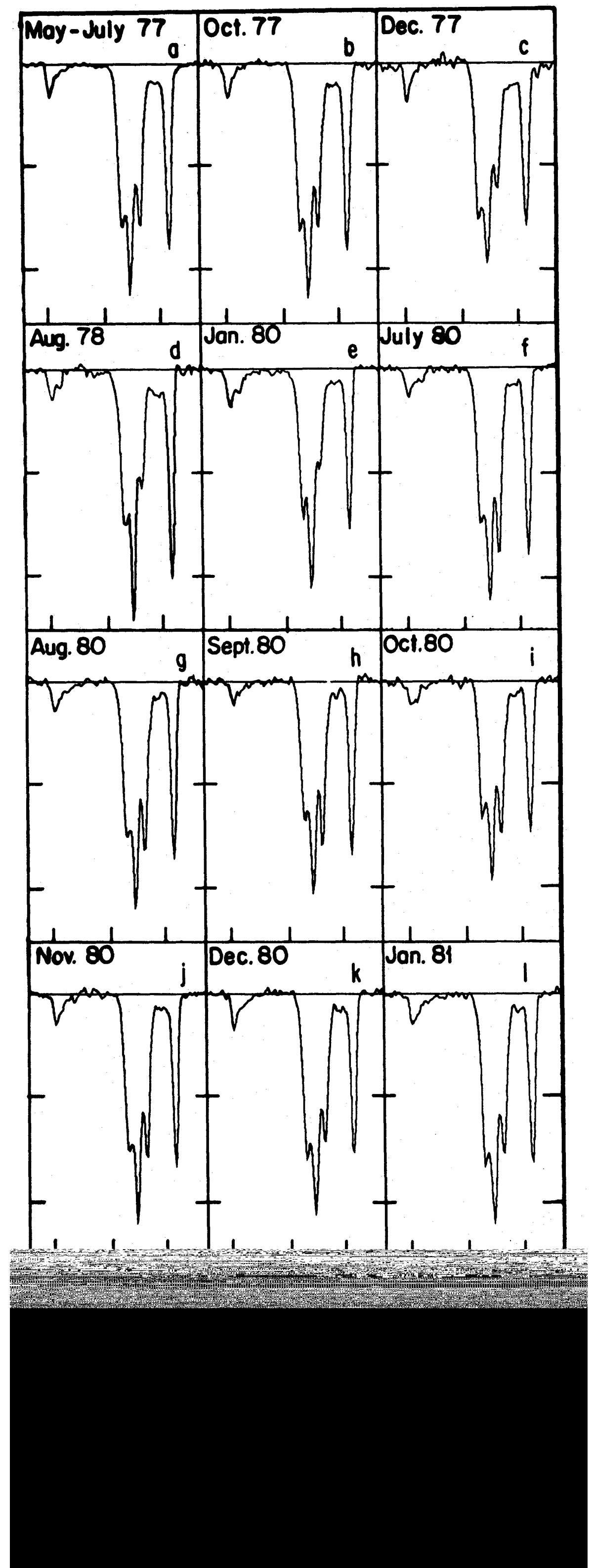


Fig. 2. One hundred four epochs of ATCA radio data of PKS 1939–315. (A)

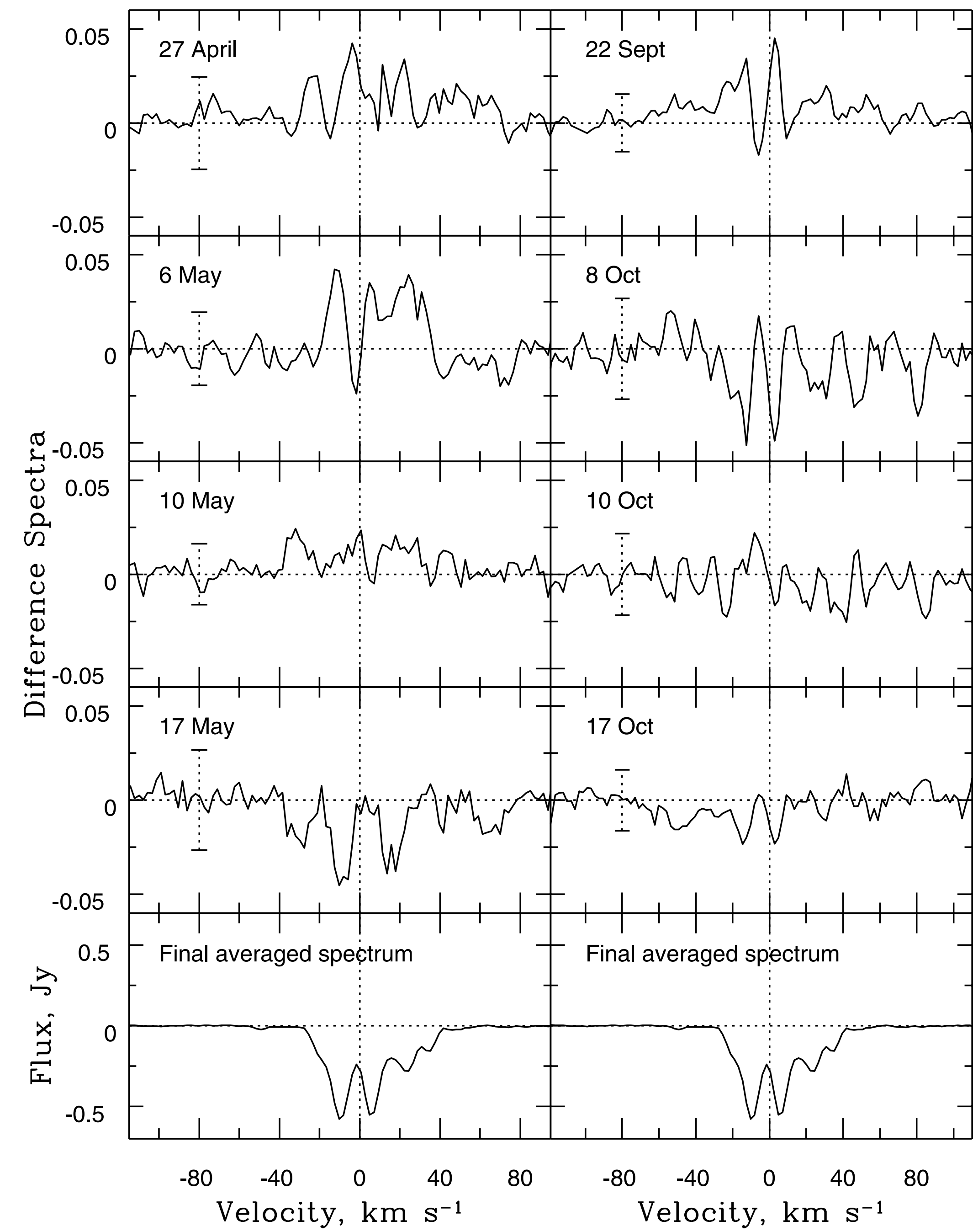
Bannister et al. 2016

Spectral Line Variability

High instantaneous sensitivity is crucial

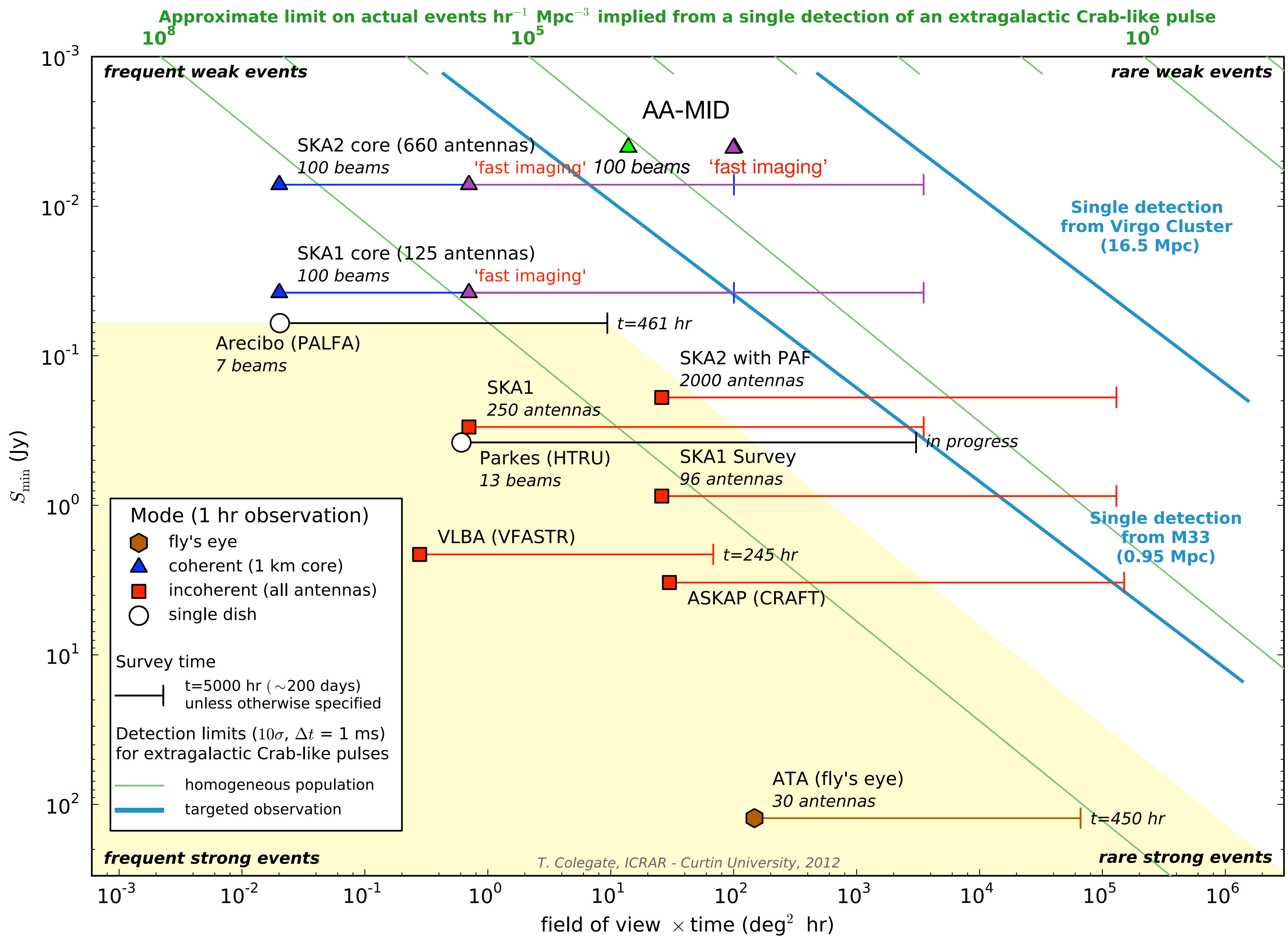


HI Variations in AO 0235+164
Wolfe, Davis & Briggs 1982



HI Variations in PKS 1127-145
Kanekar & Chengalur 2001

AA-MID is a potent transients machine



AA-MID applications

Hard to predict future in SKA2 era but obvious possibilities:

Sensitivity & FoV —High redshift FRBs:

Probe He (z>2) and H reionization (z>6)

Probe *w* (dark energy equation of state) evolution

- 10s buffer is **NOT ENOUGH**
- A DM=5000 pc cm^{-3} event is dispersed 21s between 1.0 and 0.7 GHz

Widefield phenomena

AA-MID can cover entire error region of Gravitational Wave candidates

High instantaneous-sensitivity spectral line (e.g. HI) observations

Chance favours the prepared mind

Reconfigurability is a key advantage of an Aperture Array

- When you don't know what population you will be searching for, see what maximises the detection rate:

$$\mathcal{R} \propto \Omega S_0^{-\alpha},$$

- $\alpha = 3/2$ for homogeneously distributed events in a Euclidean Universe
- Core of the array can be configured for either maximum FoV or sensitivity
  - Crude example: suppose we trade bandwidth for N beams:

$$\mathcal{R} \propto (N\Omega)\left(\sqrt{N}\,S_0\right)^{-\alpha} = N^{(2-\alpha)/2}\Omega S_0^{-\alpha},$$

  - More beams better when $\alpha < 2$

…DIGITAL BEAMFORMING

Conclusions

On paper AA-MID has all the requirements for the most potent transients machine yet

Very high sensitivity - 130x A_{eff}/T_{sys} advantage over Parkes

Potentially large FoV — how many beams?

The populations SKA2 will search for we likely know very little about at present

- Aperture array tradeoff between FoV and sensitivity offers a key future-proof advantage