ICRAR

International Centre for Radio Astronomy Research

Charting the Transients Universe using Continuum Surveys

Jean-Pierre Macquart

Map of Australia, Hessel Gerritsz (1618), cartographer of the Dutch East India Company

Curtin University

The University of Western Australia

Transients as a physics lab

Why do we care?

- Cosmology
- Extreme gravity and states of matter
- Accretion physics

Why you should care

- Fast Radio Bursts
- IDVs & Extreme Scattering Events
- Flare stars & dwarf novae
- *Symbiosis*

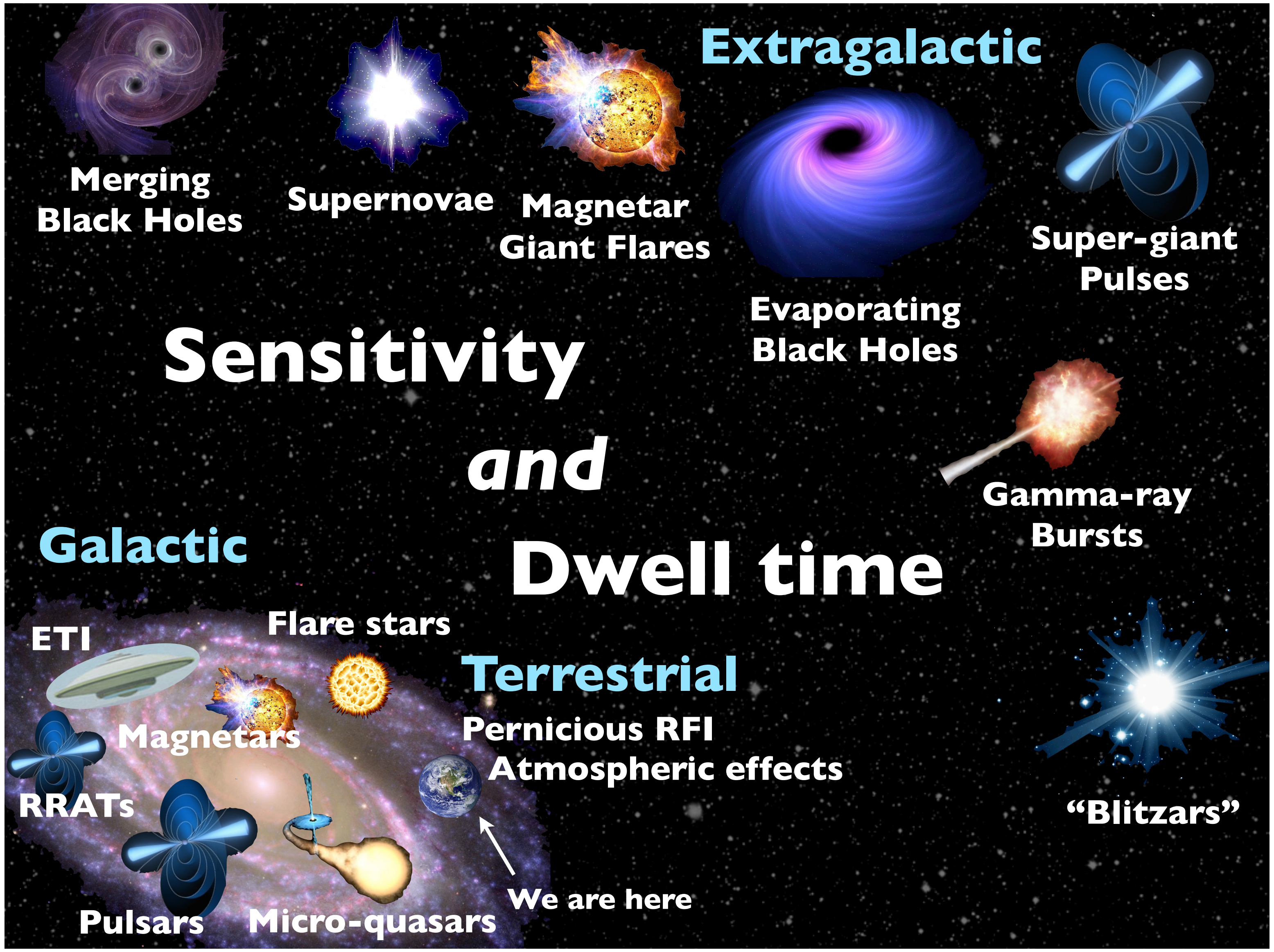
How do we fit in?

- Precursor results
- Meshing with other surveys
- The Four Elements of Transients Survey Science

Scientific Motivation

- Transients probe
  - high brightness temperature emission
  - extreme states of matter
  - physics of strong gravitational fields
  - physics of accretion
  - extreme energy densities
- Impulsive transients are subject to propagation effects that probe
  - the IGM
  - the spacetime metric

Courtesy Jason Hessels



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

Image domain - incoherent synchrotron or thermal

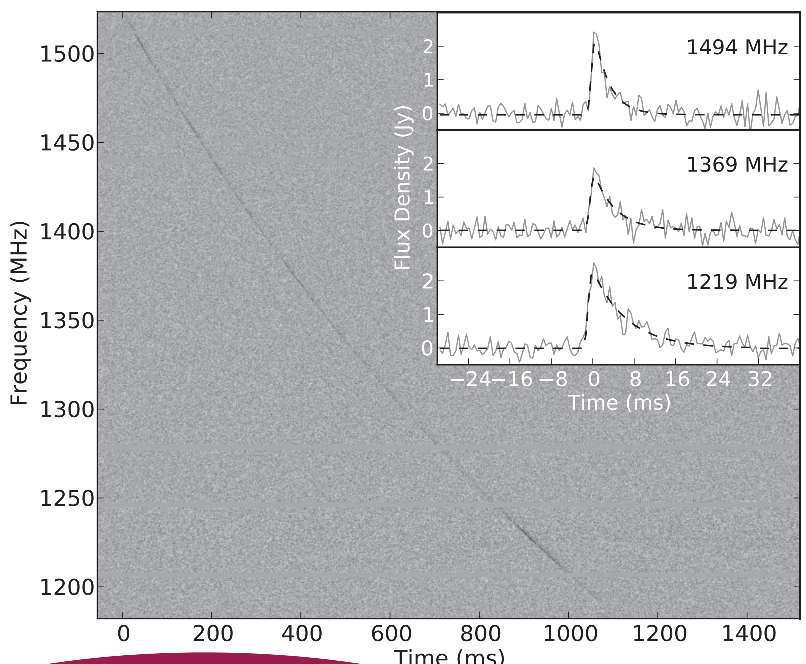
- X-ray binaries
- Tidal Disruption Events
- Novae & Flare stars
- Intra-day variable quasars/Extreme Scattering Events
- System mergers/gravitational wave events

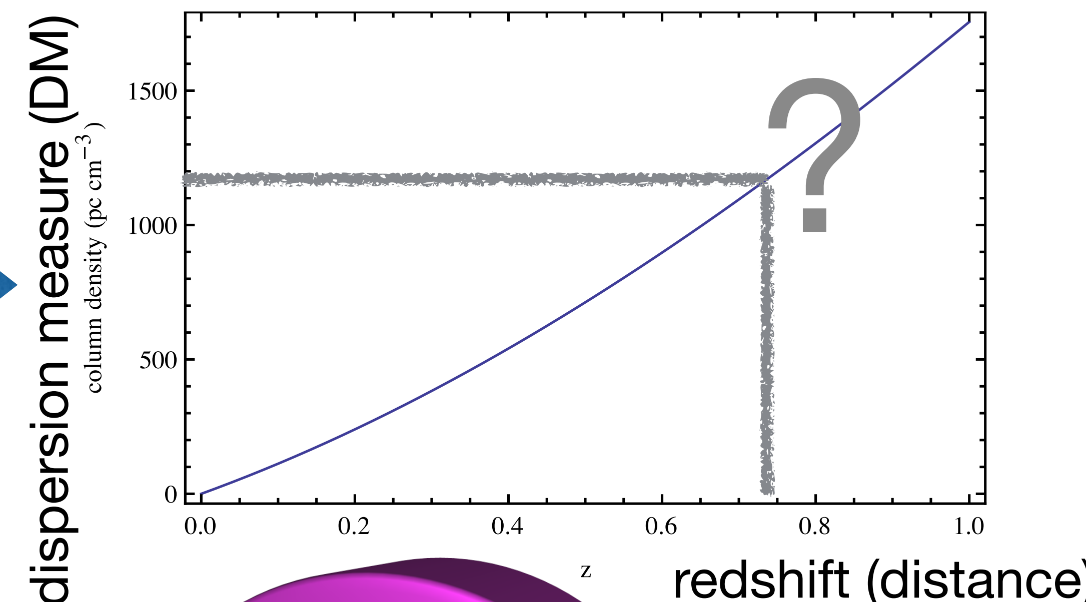
Transients as cosmological probes

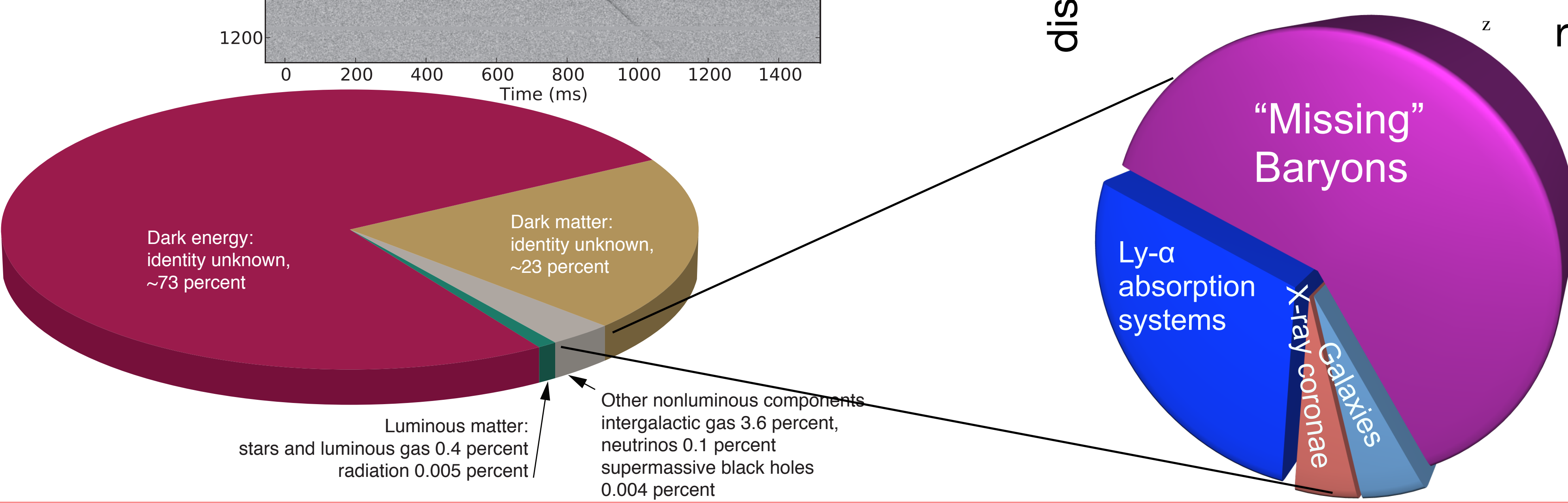
see both *Macquart et al., Fender et al. in the SKA Science book*

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

- ~15 events from Parkes (Lorimer et al. 2007; Thornton et al. 2013)
- 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

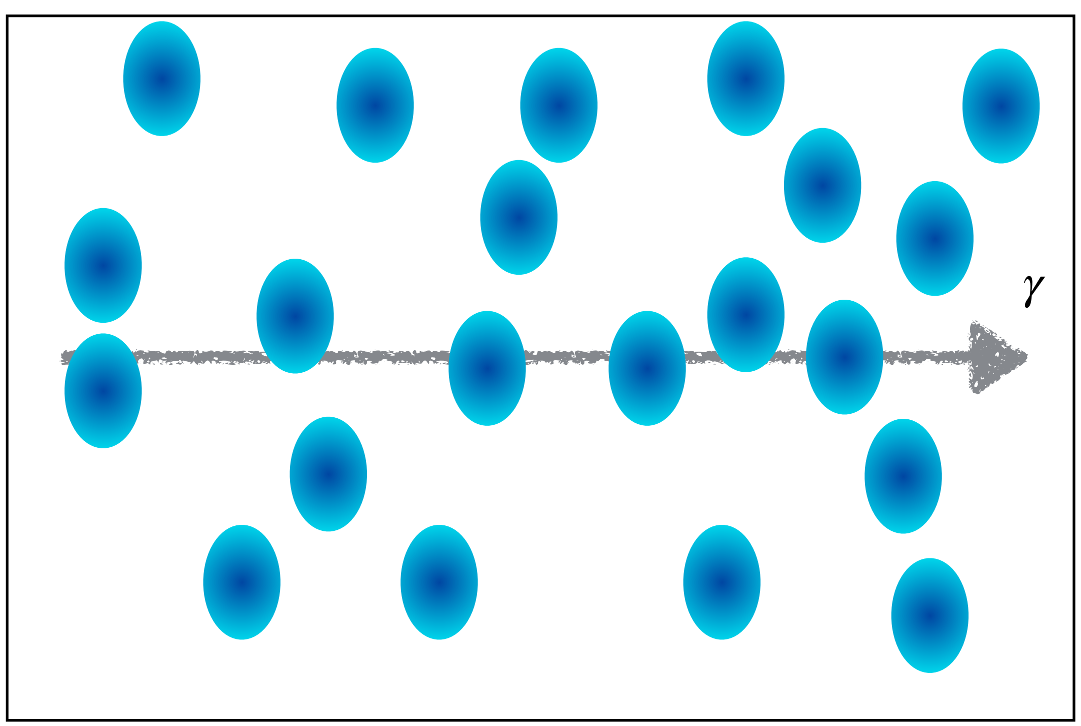
Common Inferred event rate ~ 2-5 x10^3 sky^{-1} day^{-1}

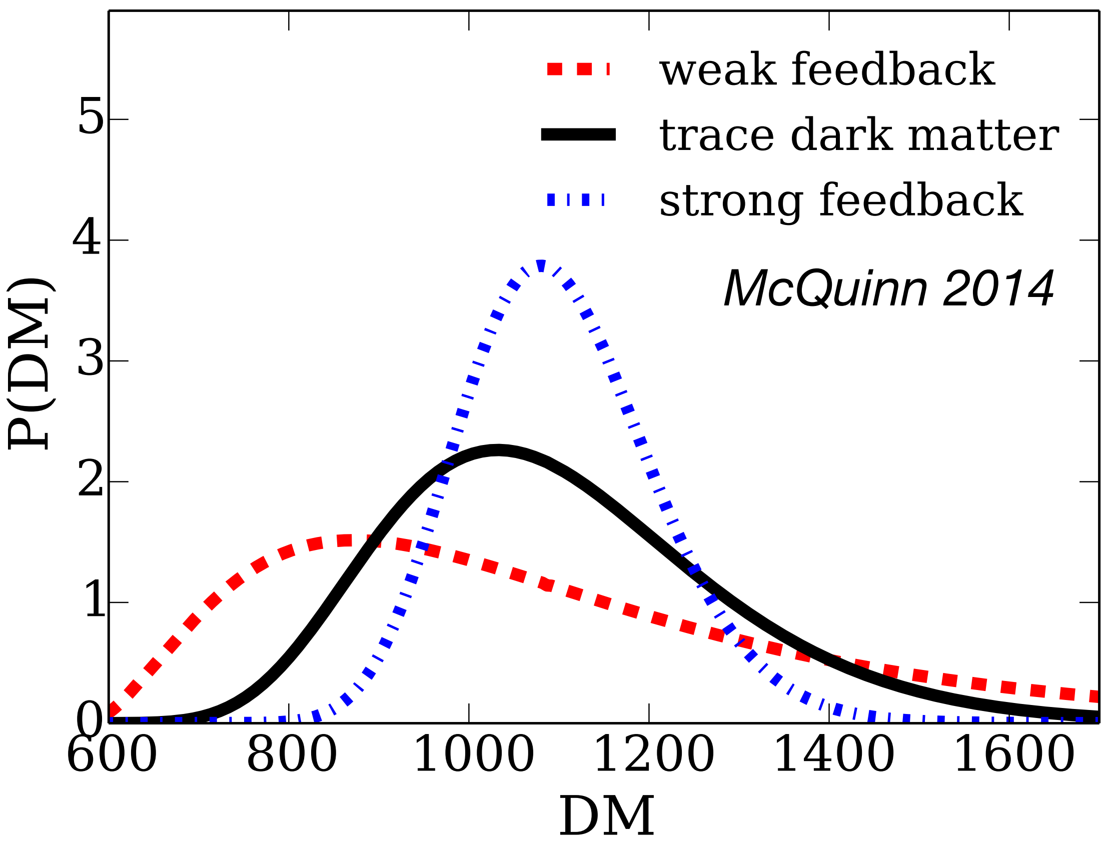
Scattered At least 4 exhibit temporal smearing of order several milliseconds (much larger than expected due to scattering in the Milky Way)

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?





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

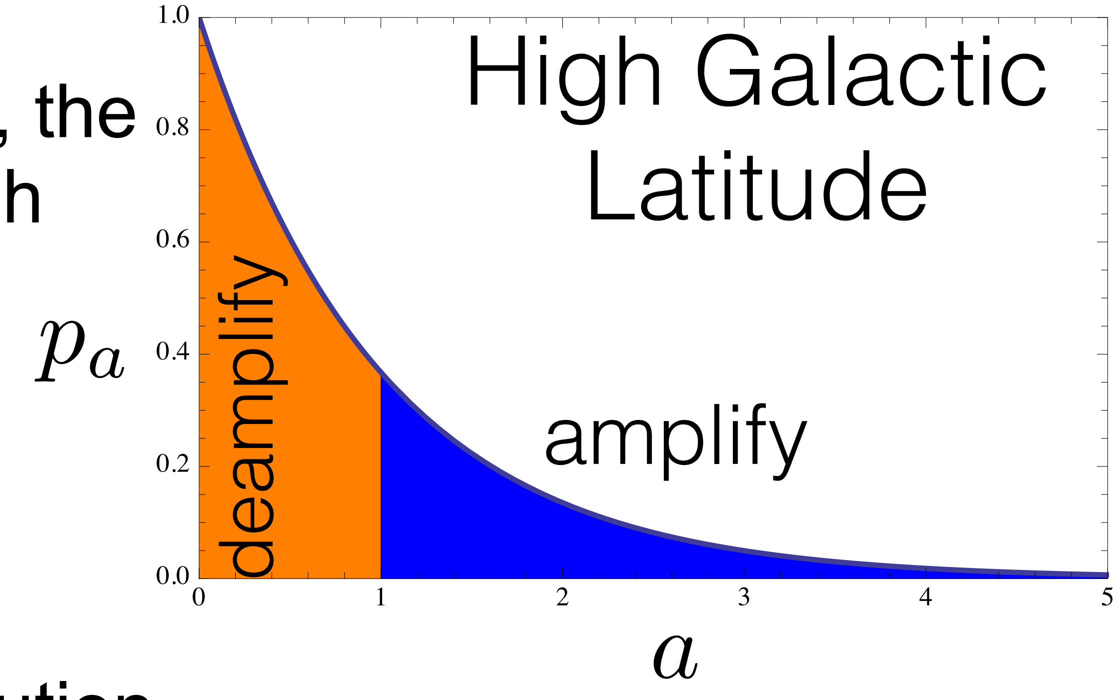
In the regime of strong diffractive scintillation, the probability distribution of amplifications at high latitude is

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

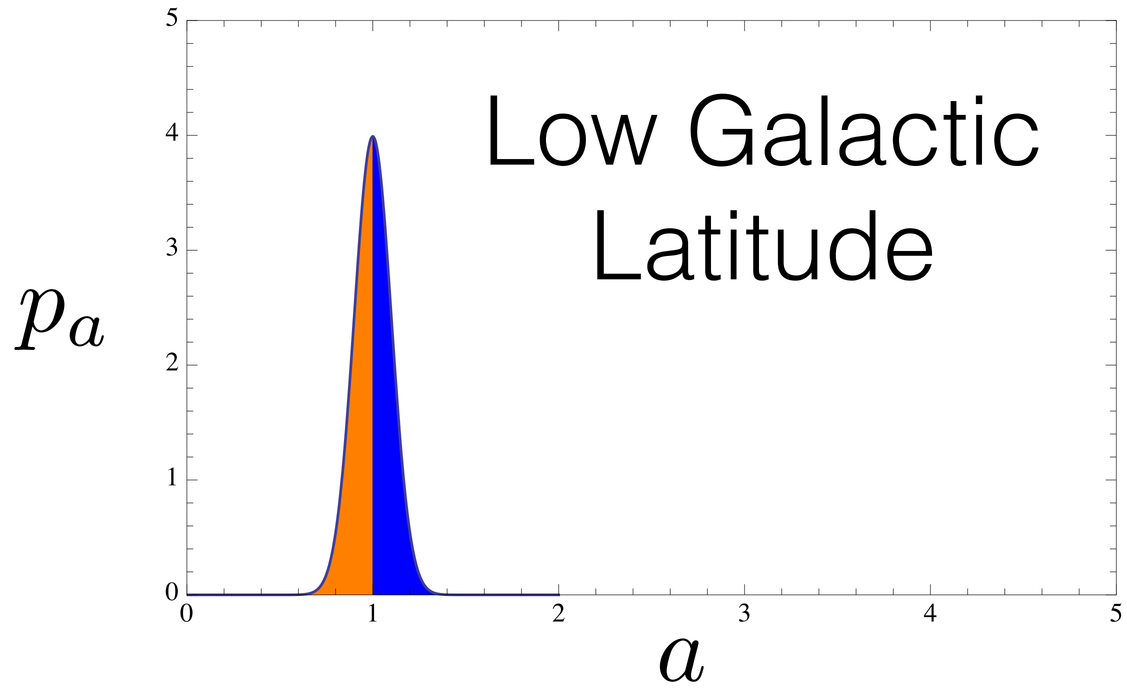
The differential source counts follow a distribution

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

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

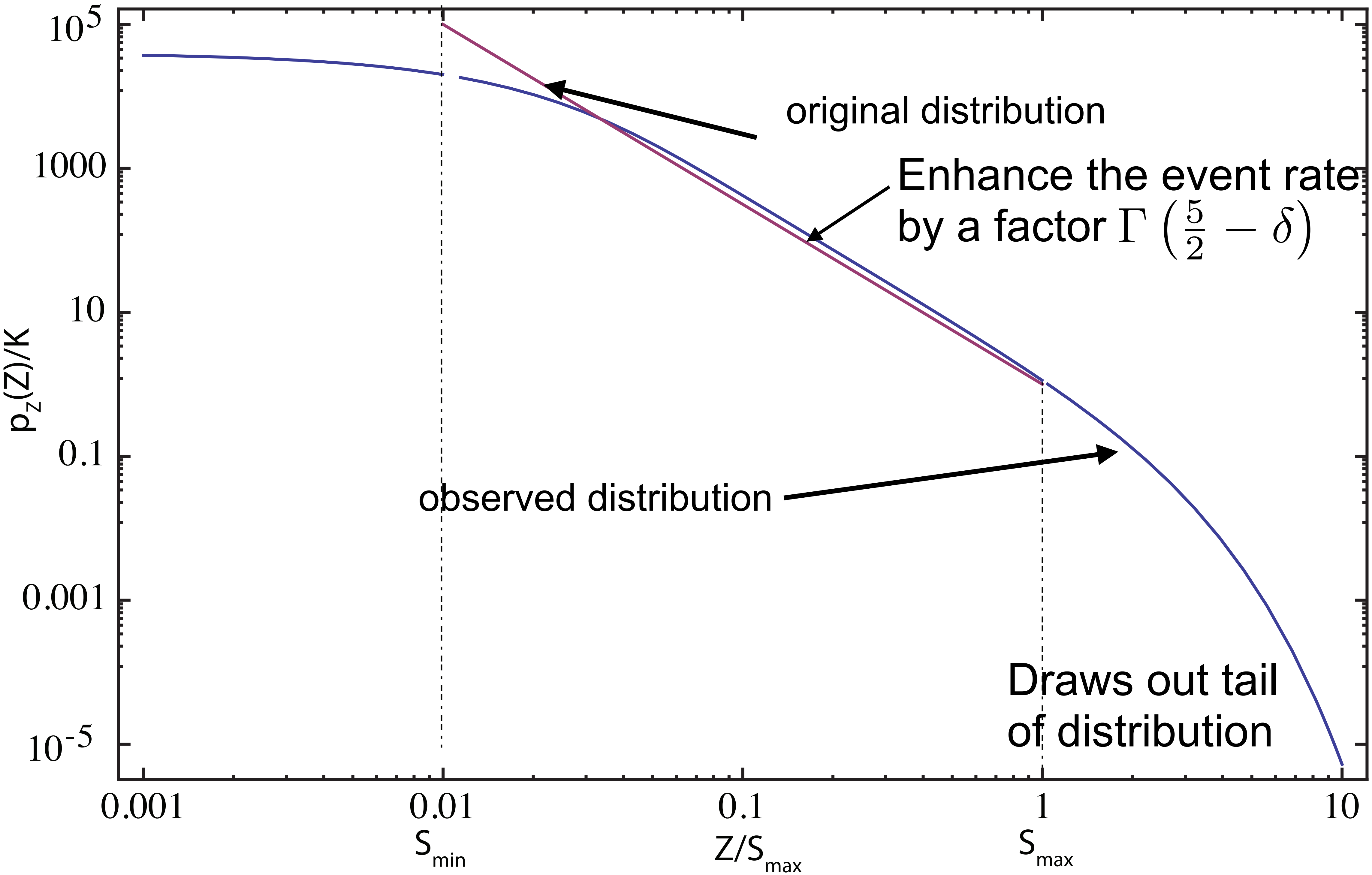


vs



FRB enhancement

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



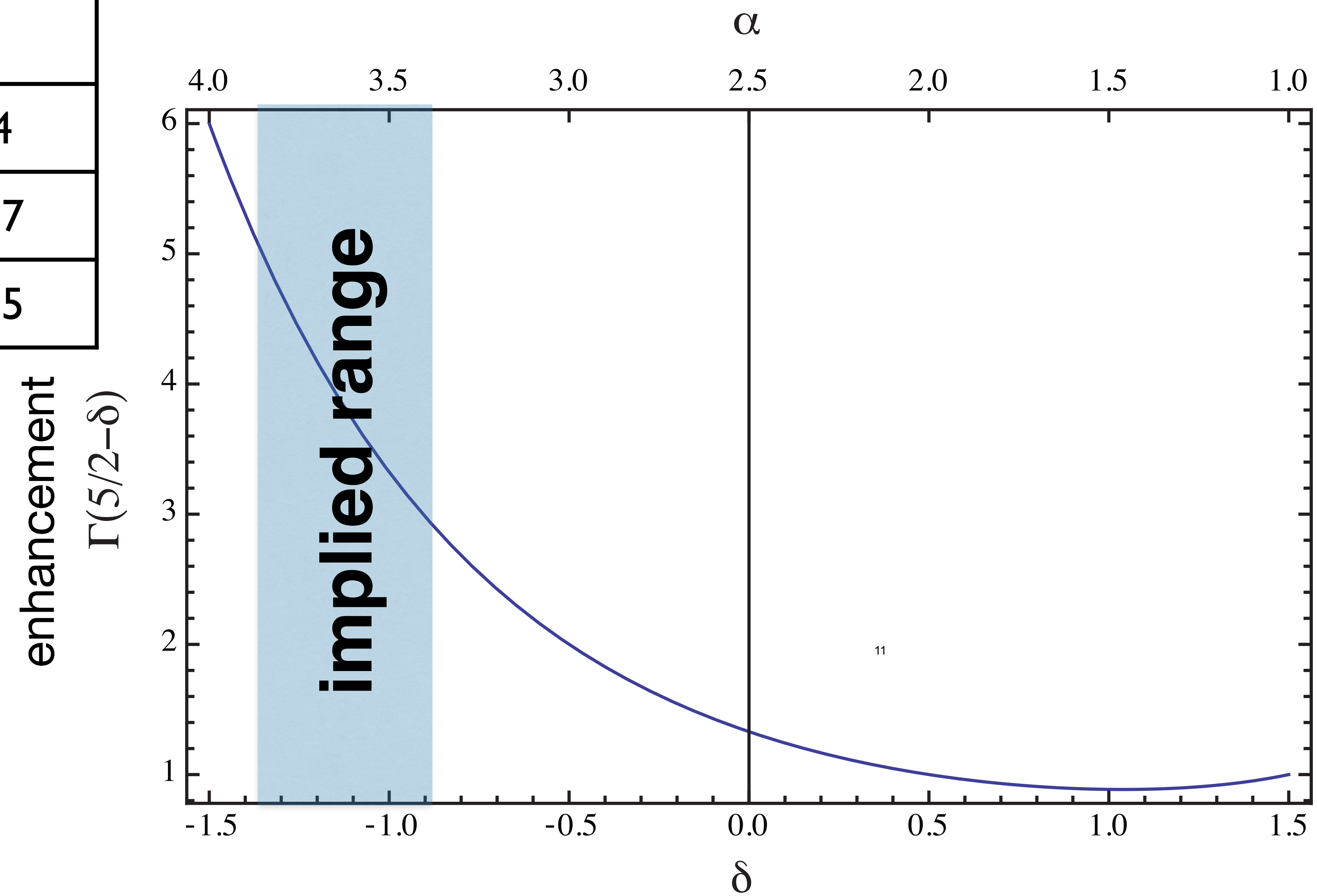
Consequences

An indirect measurement of the source count distribution!

disparity	α
2:1	3
3:1	3,4
4:1	3,67
5:1	3,85

likely range (3:1 – 5:1)

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



Macquart & Johnston 2015

CVs are radio emitters

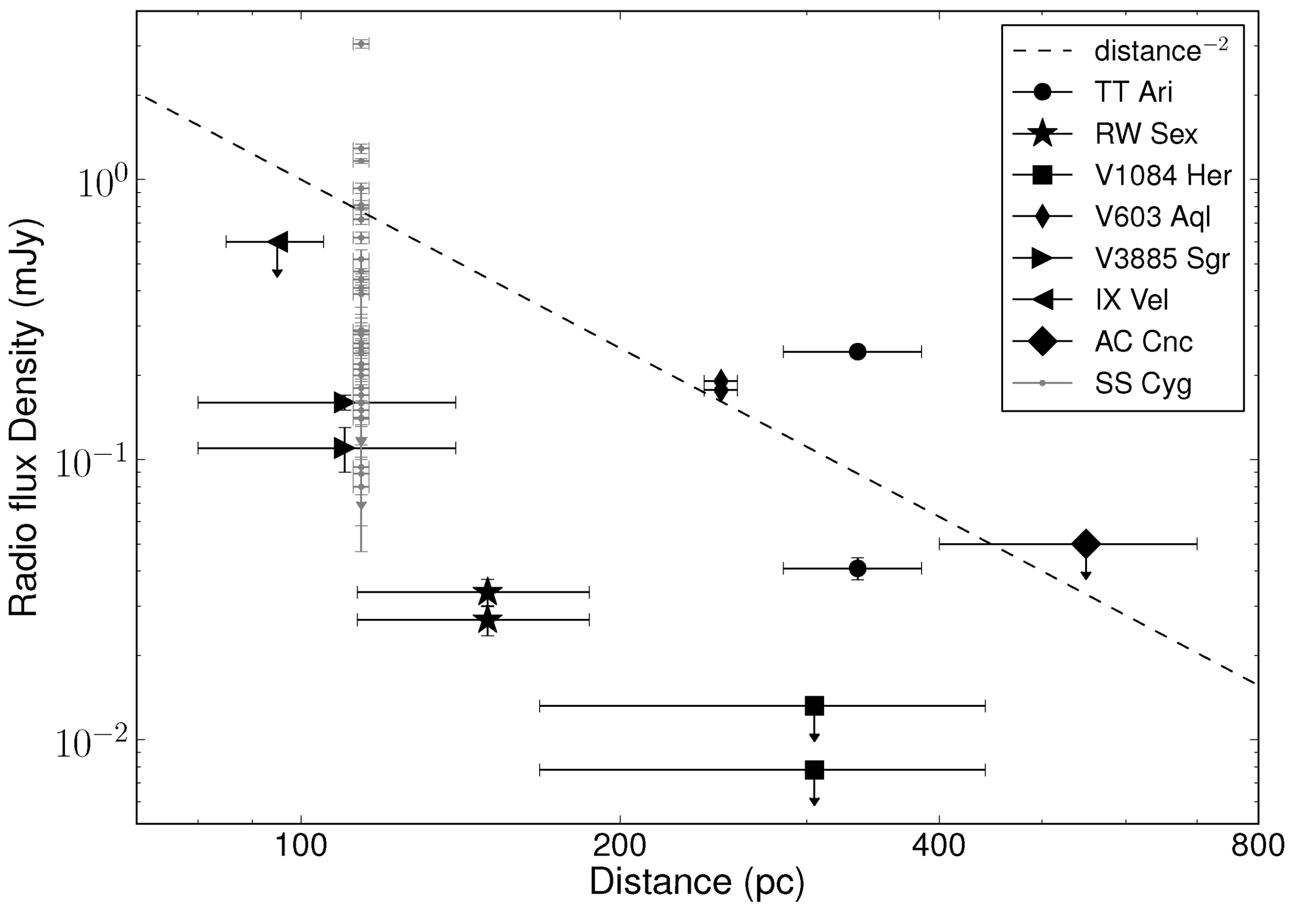
Survey of dwarf novae *in outburst* detected all 5 systems with the VLA, S_ν=15-50 μJy/beam (distances of 100-330 pc)

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

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

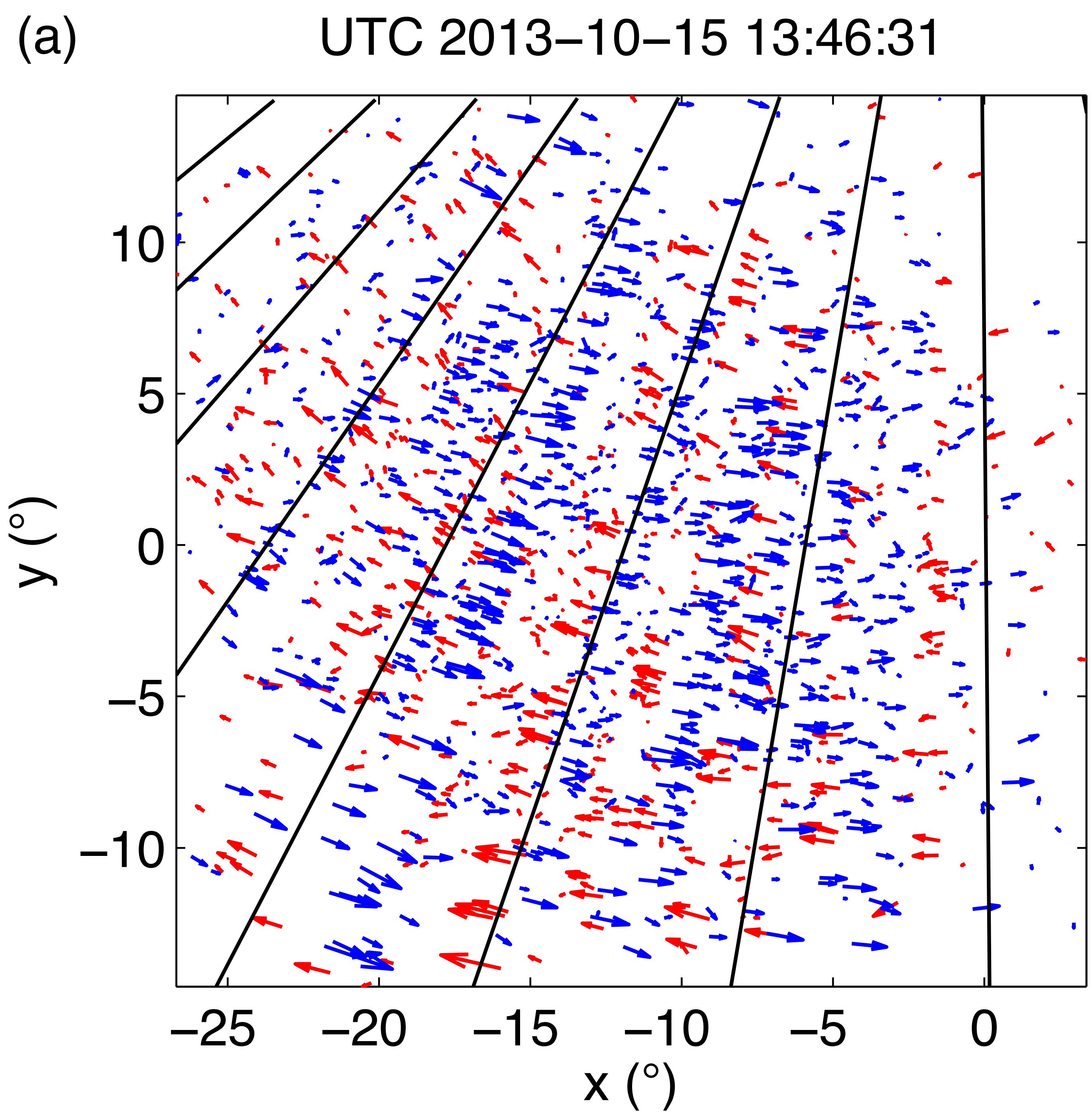
A new probe of the accretion/ejection connection

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



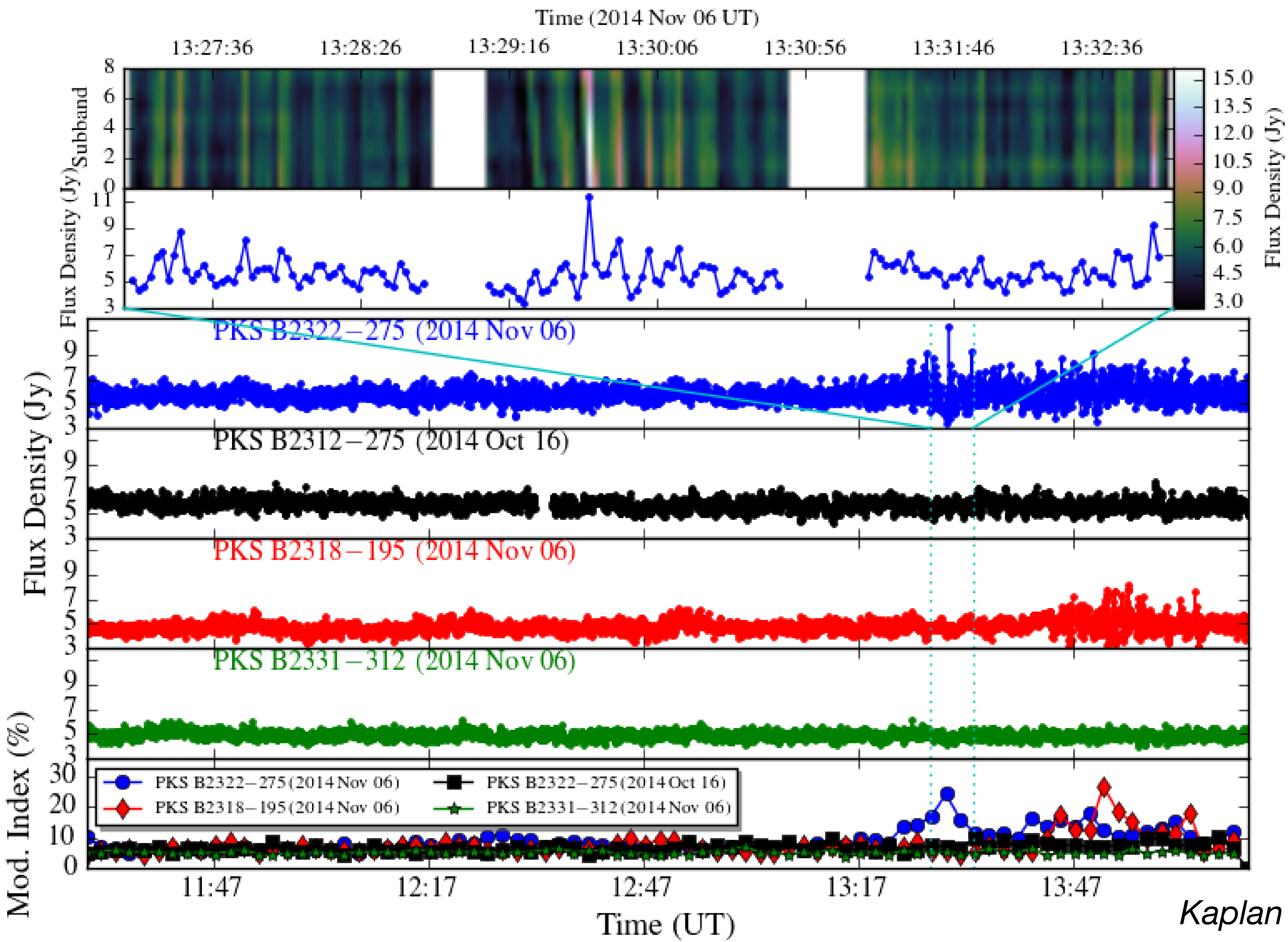
Radio flux density of all high-sensitivity observations of non-magnetic CVs as a function of distance. (Coppejans et al. MNRAS 2015)

Ionospheric Ducts —MWA



The vector field of celestial source offsets, overplotted with the geomagnetic field lines (black solid lines) at an altitude of 600km. (Loi et al., Geo.Res.Lett., 2015)

Night-time IPS @ 155MHz

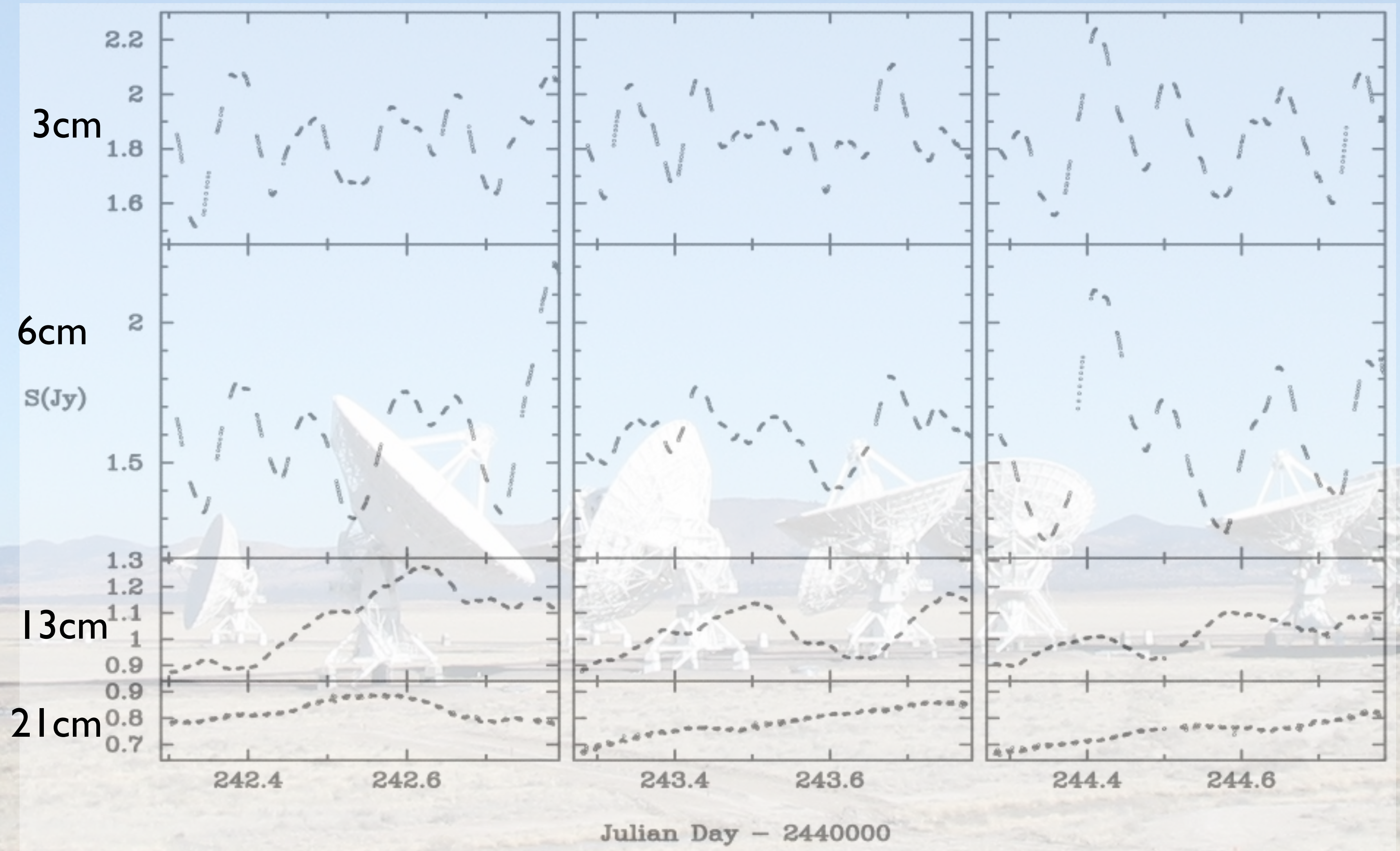


Kaplan et al. 2015

Intra-Day Variability

Over 56% of all flat-spectrum cm-wavelength radio sources exhibit IDV (Lovell et al. 2008)

PKS 0405-385 (Kedziora-Chudczer et al. 1997)

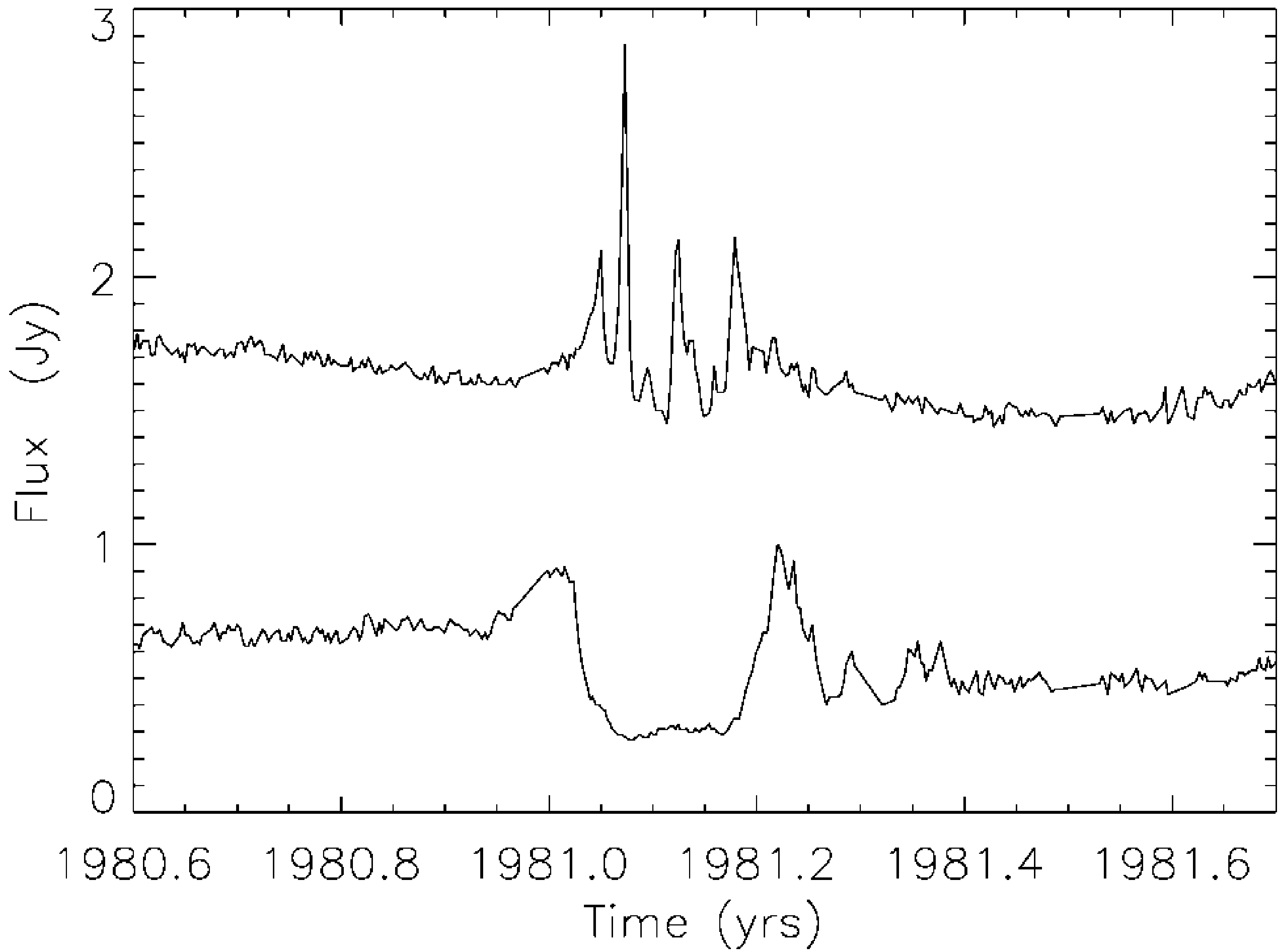


Free VLBI - we will ID a large fraction of AGN automatically!

Extreme Scattering Events

Occurs in 1 in 70 compact sources per year

(Fiedler et al. 1987)



More results from precursors

MWA

- Limits on image plane event rate: 10^{-7} sq.deg.$^{-1}$ @ 28s cadence at 180MHz (Rowlinson et al.)
- Discovery of intermittent IPS very far from Sun (Kaplan et al. 2015)
- Ionospheric scintillation due to large organised structures (Loi et al.)
- Searches for FRBs in both image and time domains

LOFAR

- LOTAAS LOFAR Tied-array All-sky survey - 219 beams (9 sq. deg).

MeerKAT

- commensal interrogation of MeerKAT data for transients was embraced by *all* PIs of the MeerKAT Large Survey Projects

ASKAP-12

VAST

CRAFT - will have ability to read out baseband buffers to search for FRBs

VLA/VLBA

Ongoing high-time resolution searches (FRBs)

V-FASTR

STRIPE-82 (Kunal Mooley et al.)

4 Elements of Transients Surveys

#1 Time on Sky

- output linearly proportional to time on sky

#2 Near real-time detection & localisation

- multi-λ followup requires positions good enough to provide unambiguous matches (~1” or better for extragalactic)

#3 Characterisation

- Amongst all candidates, which merit scrutiny?
- Necessary discriminators:
  - Spectrum, polarisation, outburst timescale and shape, previous behaviour at this position

#4 Followup - milking the science out of it

- Palm off to dedicated monitoring programme?
- Reschedule survey to include this position with the required cadence?

On #1

Planned vs. Opportunistic surveys

- Reasonable to expect at most 10% of the telescope to be dedicated to transients surveys
- The future lies with the opportunistic
  - 100% of the telescope time means we net:
    - 10x more transients & 10x rarer events

- **Altruistic:** SKA transients model is to share *all events* with the community
  - Everybody gets our results for free
  - This model is broadly embraced (e.g. SWIFT and LSST)

On #2 & #4

Build transients searches into the survey strategy *at the beginning*

- Ensure search requirements aren't watered down in the inevitable rush to get the survey underway

Archive facility

- User interface is crucial
  - c.f. the LOFAR experience

Triggers: Formulate a policy to respond to and issue Triggers

  - We can either disrupt/override telescope operations *or*
  - ensure that the underlying survey has the flexibility to make use out of followup time (i.e. build up sensitivity in the region of an event)

On #3 (characterisation)

Respond to (and issue) triggers

- To what extent should we "respond"?

For real-time commensal time-domain & image plane search

- Timely followup required to catch events in the act

Buffer - images & voltages

- A time machine to respond to triggers with some latency (e.g. from our own detection systems)

VLBI: an essential followup component

Which events are the real gems?

SKA will see huge numbers of transients, but need enough information to sort the wheat from the chaff.

Crossover with other science

Everybody will participate in Transients Science

Pulsars

- High time resolution

EOR

- A contaminant that needs to be removed from data

Continuum

- IDV present in >50% of all flat-spectrum AGN

Our Galaxy

- Novae, flare stars, X-ray binaries

Cosmic Rays

- All-sky at sub-ms Δt/Shares several technical requirements

VLBI

- An essential component of followup for some science

HI/Spectral line

- Variable HI absorption by intervening galaxies

Transients community brings friends

***Relevance* is key to us:**

We must have the capacity to link our objects to the rest of the electromagnetic spectrum

Optical in the era of…

- LSST
- OWLs
- *Desert Transients Factory*

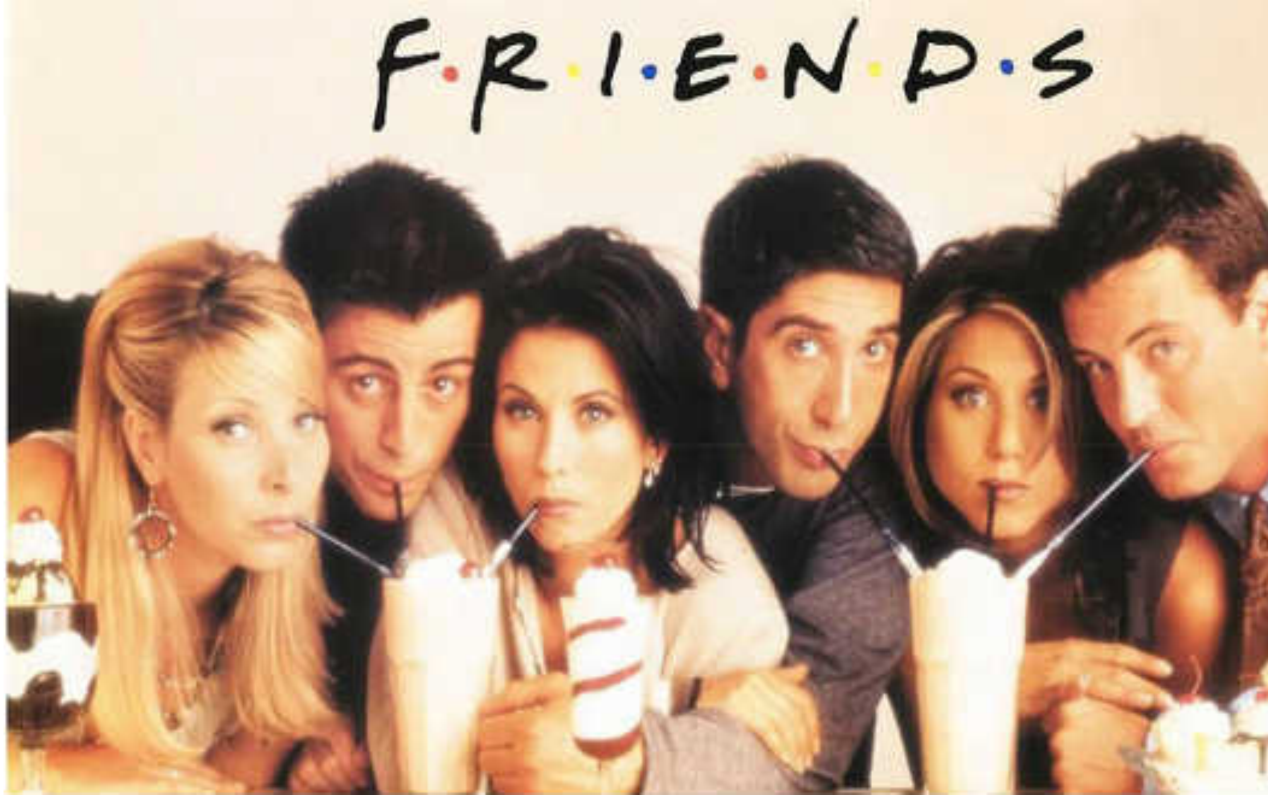
We plug into a network of followup facilities *(MeerLicht)*

JWST

ALMA

X-ray/gamma-ray

Advanced LIGO



The TAKEAWAY message

Symbiosis

Makes telescopes productive out of the blocks

- Significant discoveries while large-scale surveys are still ramping up
- Spot defects in the data that you might not otherwise know exist
- Variability can aid your science too! — IDVs for continuum science

Most Transients science is commensal

- Exceptions: particular targets, e.g. Galactic Centre

Need enough information from the telescope to make transients science useful

- Necessitated by need to separate the wheat from the chaff

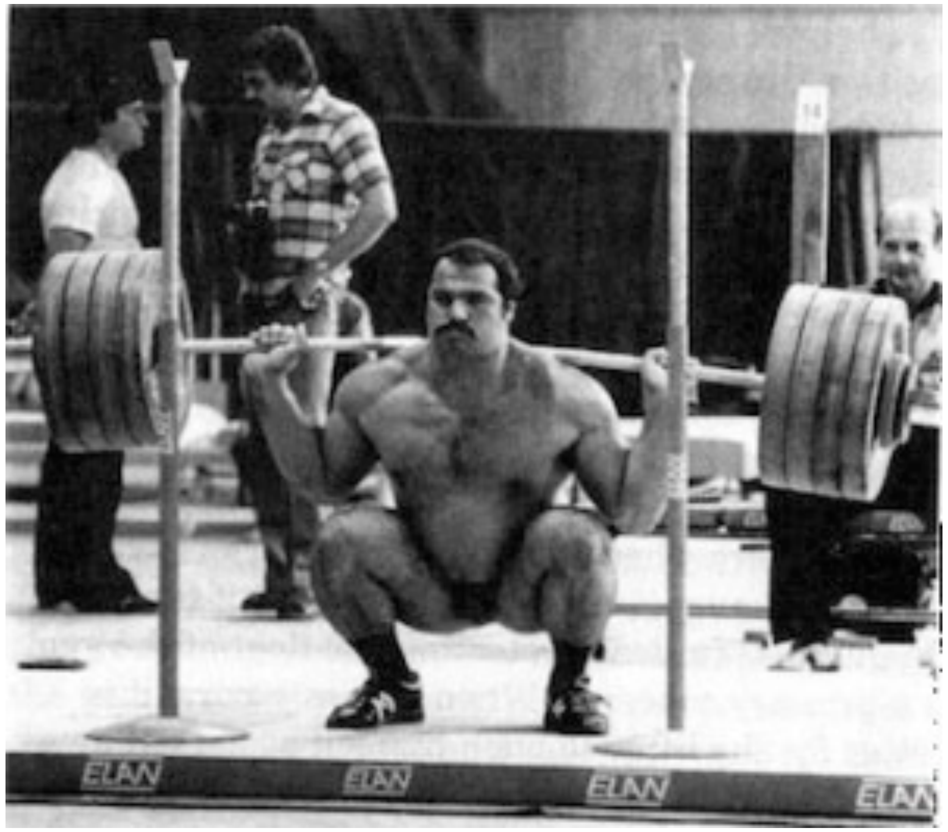
Wide FoV & sensitivity combination is already yielding great surprises

Scintillation can explain this!

Giving FRBs a lift

Macquart & Johnston, MNRAS 2015

- Suggestion: random amplification due to turbulence in our Galaxy "magnifies" events ordinarily too weak to be detected
- How does this work?
  - There is a characteristic bandwidth associated with interstellar scintillation
  - The stronger the scattering (i.e. the more material the radiation propagates through), the *smaller* the decorrelation bandwidth.
  - Closer to the plane the scattering is stronger and the decorrelation bandwidth at smaller.
  - Enhancement can only work *well above* the Galactic plane



Steep source counts — how?

For homogeneously-distributed events in Euclidean space, differential source counts scale as $S_\nu^{-5/2}$:

- With a sensitivity to events down to flux density S_ν we detect events of luminosity L out to distance

$$D_{\max} = \sqrt{\frac{L}{4\pi S_\nu}}$$

The number of events we detect per S_ν bin is

Number of events per unit time per volume

$$\frac{d\mathcal{R}}{dS_\nu} = \frac{4\pi}{3}\rho\frac{d}{dS_\nu}[D^3_{\max}] \propto S_\nu^{-5/2}$$

If the source counts deviate from $S_\nu^{-5/2}$ either

1. non-Euclidean geometry matters (i.e. at high z) *or*
2. they must be distributed inhomogeneously with distance (i.e. at high z)

Chance favours the prepared mind

Most discoveries in this domain are driven by innovations in technology

- High time resolution science limited by I/O capabilities
  - FRBs discovery brought about by advances in compute capacity

- Wide field of view
  - Necessary to find rare events
  - Dictates formidable processing power

  - Radio telescopes are still behind the domain of high energy searches
    - *Fermi*, *SWIFT*, …