CHIME/FRB Detection of the original reacting fast radio burst source FRB121102

+ very briefly…

Fast radio burst as synchrotron maser emission from decelerating relativistic blast waves - *Metzger et al. 2019 [1902.01866]*

The dispersion and rotation measure of supernova remnants and magnetised stellar winds: application to fast radio burst - *Piro & Gaensler 2018 [1804.01104]*

On the time-frequency downward drifting of repeating fast radio bursts - *Wang et al. 2019 [1903.03982]*

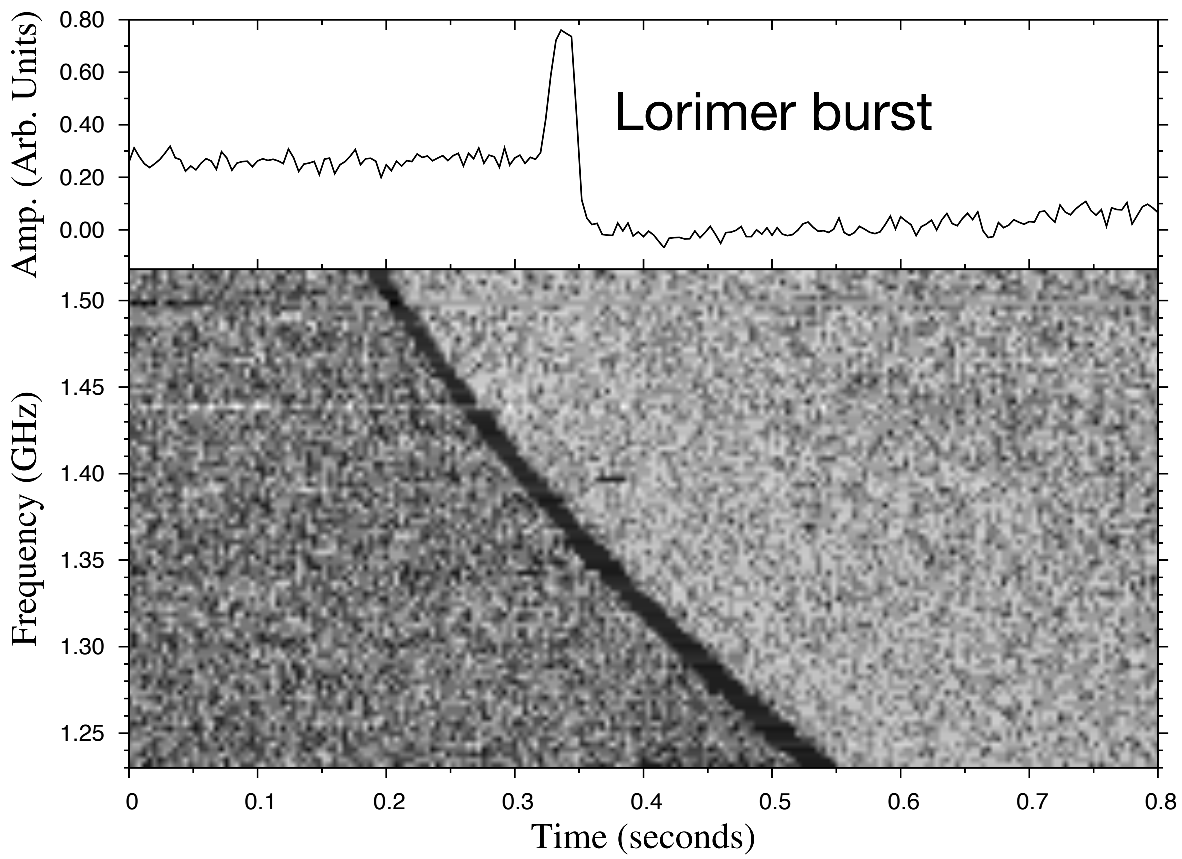
Multi-Messenger Astronomy Journal Club
APC/IPA

Valentin Decoene

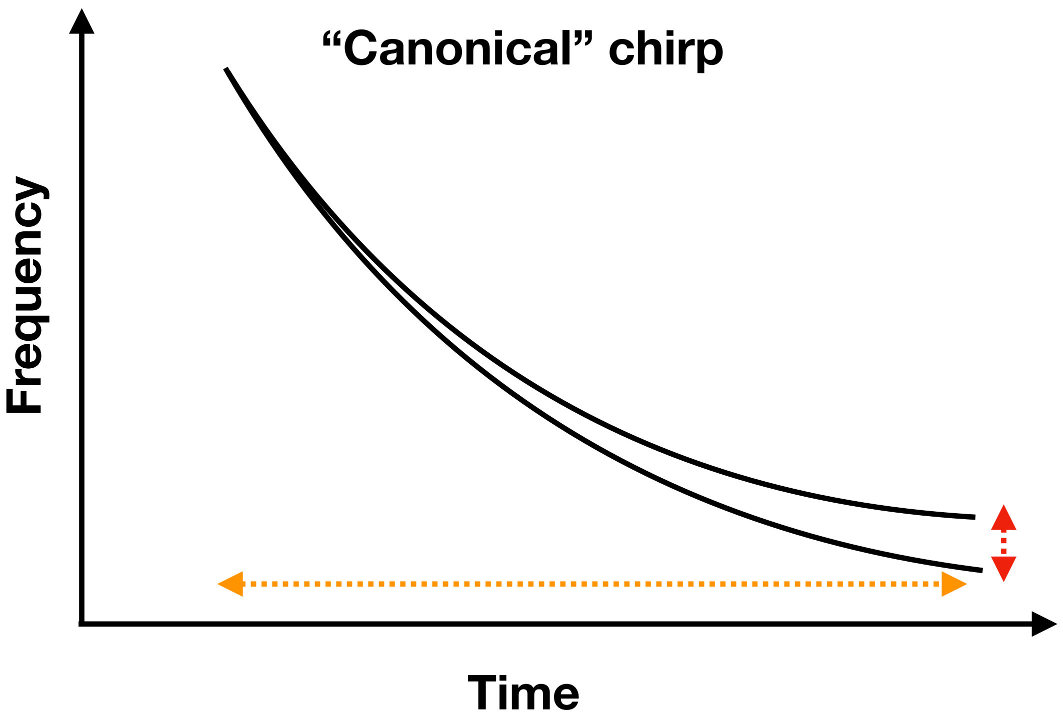
What is a FRB ? What we know…

New astrophysical radio transient events :

- Short radio pulses (≈ms)
- Broad frequency band emissions
- Highly dispersed in arrival times



FRB 010724 - Evan Keane from Duncan R. Lorimer 2018



- **Dispersion effects (propagation)** $\boxed{\Delta t \sim 4.15 \times 10^3 [\mathrm{DM}] \nu^{-2}}$

$$\longrightarrow \Delta t(200 - 100\mathrm{MHz}) \sim 0.3 \times [\mathrm{DM}]\,\mathrm{s}$$

$\boxed{\mathrm{DM} = \int_0^d n_\mathrm{e}\, dl}$ can be related to distances

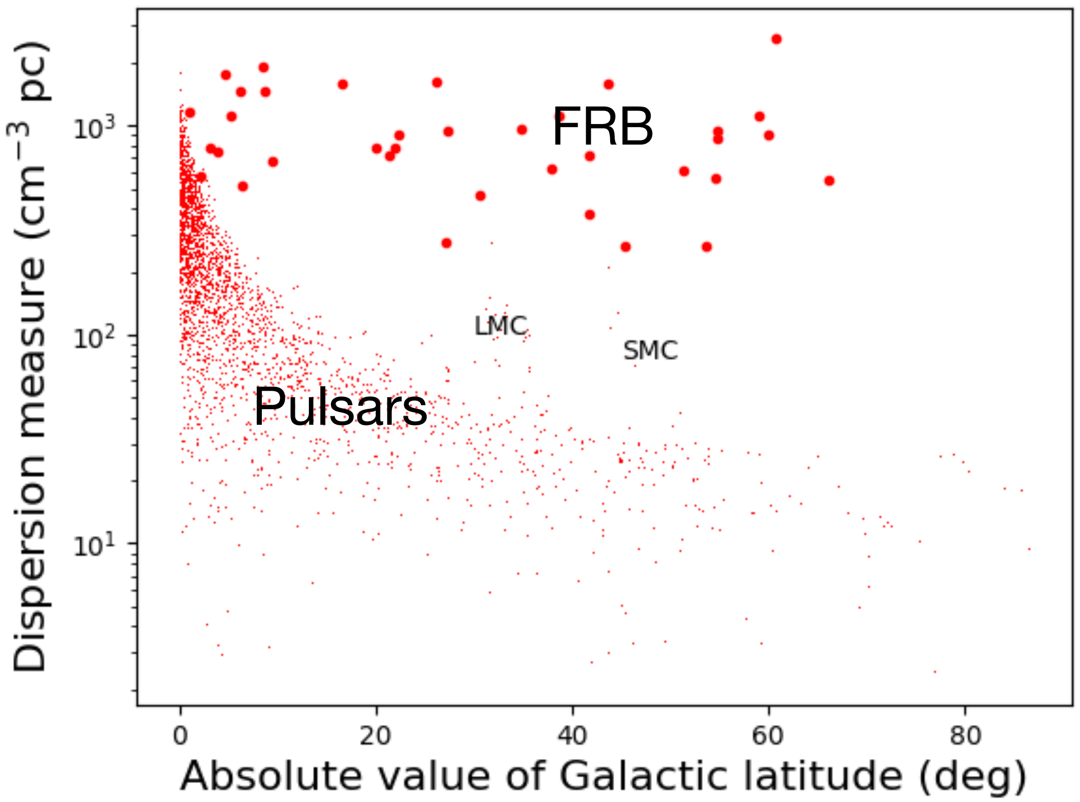
- **Scattering effects (turbulences)** $\boxed{\delta t \propto \nu^{-4}}$

What is a FRB ? What we know…

Extragalactic origin (most likely):

- Large DM
- High galactic latitude *Champion et al., 2016*
- Isotropic distribution over the sky

→ Distinct from giant radio pulses (pulsars)



- More than 100 events published now (http://www.frbcat.org) and ≈ 700 unpublished yet by CHIME
- 18 Repeaters events (121102-Arecibo repeater, 180814 -CHIME, etc..)
- FRB fluencies up to 420 Jy.ms and steep spectra (ASKAP)
- Observations from 8 GHz down to 400MHz

What is a FRB ? What we don't (really) know

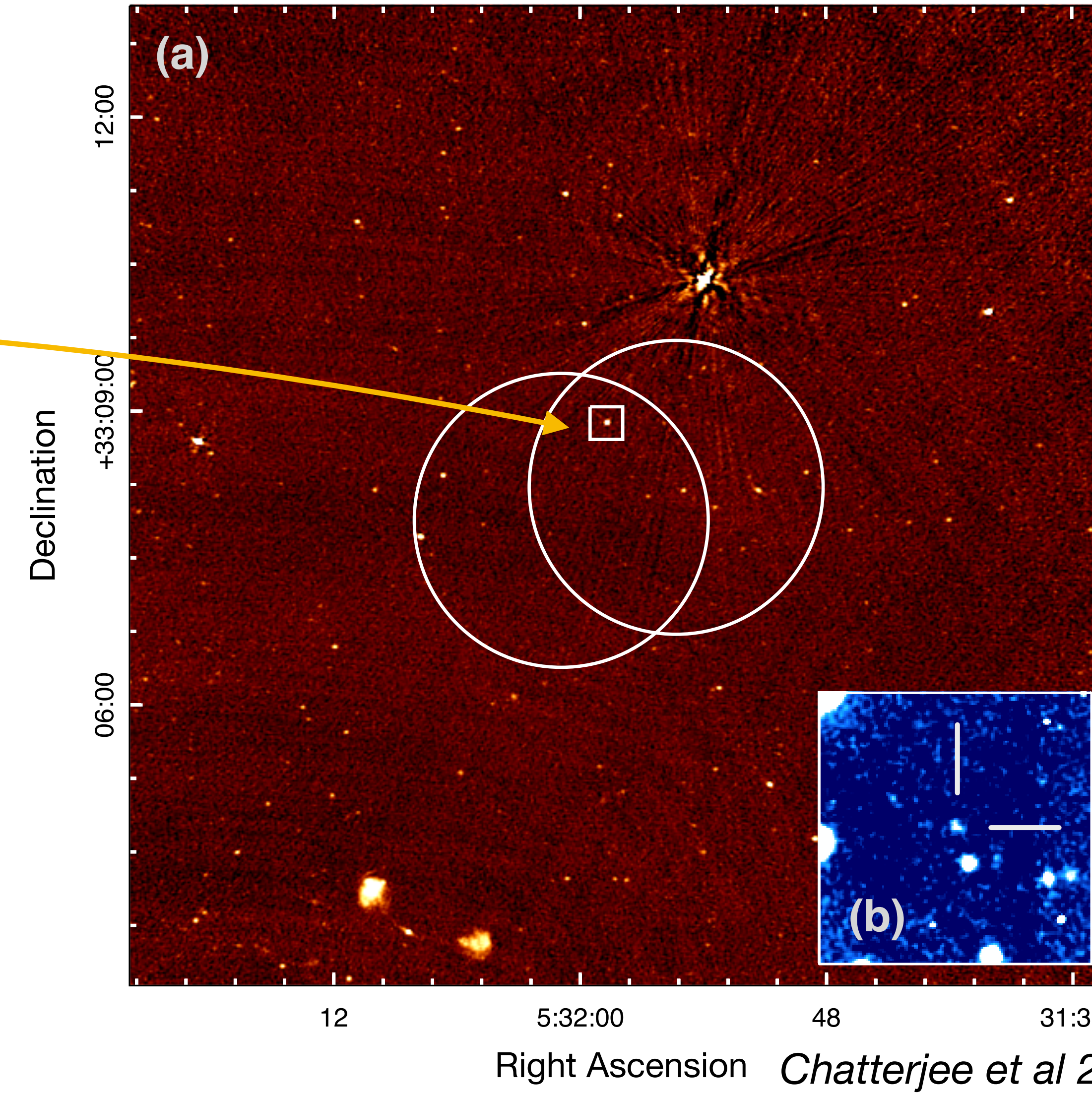
Majors unknowns:

- Existence at low frequencies (below 400MHz)
- Behaviour at low frequencies (turnover ? cutoff ?)
- Polarisation measurements (few stats) consistent with circular/linear and even unpolarised so far…
- High and low rotation measures (RM) found (few stats)…
- Pulse profiles may present in some cases: double/triple peaks + complex substructures and drift features, no real rules…
- DM and scattering fluctuations (event to event)
- Population rate and spectra
- Repeater/non repeater (periodicity?)
- Counterparts

What is FRB121102 ?

First FRB repeater discovered

- Hosted in a dwarf galaxy at z=0.2
- Co-located with a persistent radio source
- Very high Faraday rotation ~10^5 rad/m^2 → extreme magneto-ionic environment
- Upper limit on scattering timescale ~1.5ms @1.5GHz
- Present complex burst morphologies:
  - highly variable spectra
  - sub-burst with frequency drift in time



Chatterjee et al 2017

Observed so far only between 8GHz and 1GHz

until

CHIME/FRB Detection of the Original Repeating Fast Radio Burst Source FRB 121102

A. Josephy,[1,2] P. Chawla,[1,2] E. Fonseca,[1,2] C. Ng,[3] C. Patel,[1,2] Z. Pleunis,[1,2] P. Scholz,[4] B. C. Andersen,[1,2] K. Bandura,[5,6] M. Bhardwaj,[1,2] M. M. Boyce,[7] P. J. Boyle,[1,2] C. Brar,[1,2] D. Cubranic,[8] M. Dobbs,[1,2] B. M. Gaensler,[3,9] A. Gill,[3,9] U. Giri,[10,11] D. C. Good,[8] M. Halpern,[12] G. Hinshaw,[12] V. M. Kaspi,[1,2] T. L. Landecker,[4] D. A. Lang,[10] H.-H. Lin,[13] K. W. Masui,[14,15] R. Mckinven,[3,9] J. Mena-Parra,[14] M. Merryfield,[1,2] D. Michilli,[1,2] N. Milutinovic,[4,12] A. Naidu,[1,2] U. Pen,[13] M. Rafiei-Ravandi,[10] M. Rahman,[3] S. M. Ransom,[16] A. Renard,[3] S. R. Siegel,[1,2] K. M. Smith,[10] I. H. Stairs,[8] S. P. Tendulkar,[1,2] K. Vanderlinde,[3,9] P. Yadav,[8] and A. V. Zwaniga[1,2]

Josephy A. et al, ApJL 882, 2, 2019 https://arxiv.org/pdf/1906.11305.pdf

What is the Canadian Hydrogen Intensity Mapping Experiment (CHIME) ?

Dominion Radio Astrophysical Observatory (near Penticton, British Columbia)

- 4 N-S cylinder reflectors (20mx200m)

Each cylinder:

- 256 equi-spaced antennas feeds
- digitisers accords 400-800MHz

- On-site correlator for the 2048 dual polarisation

- 1024 independent beams

Each beam:

- 16384 frequency channels
- sampling at 1 ms

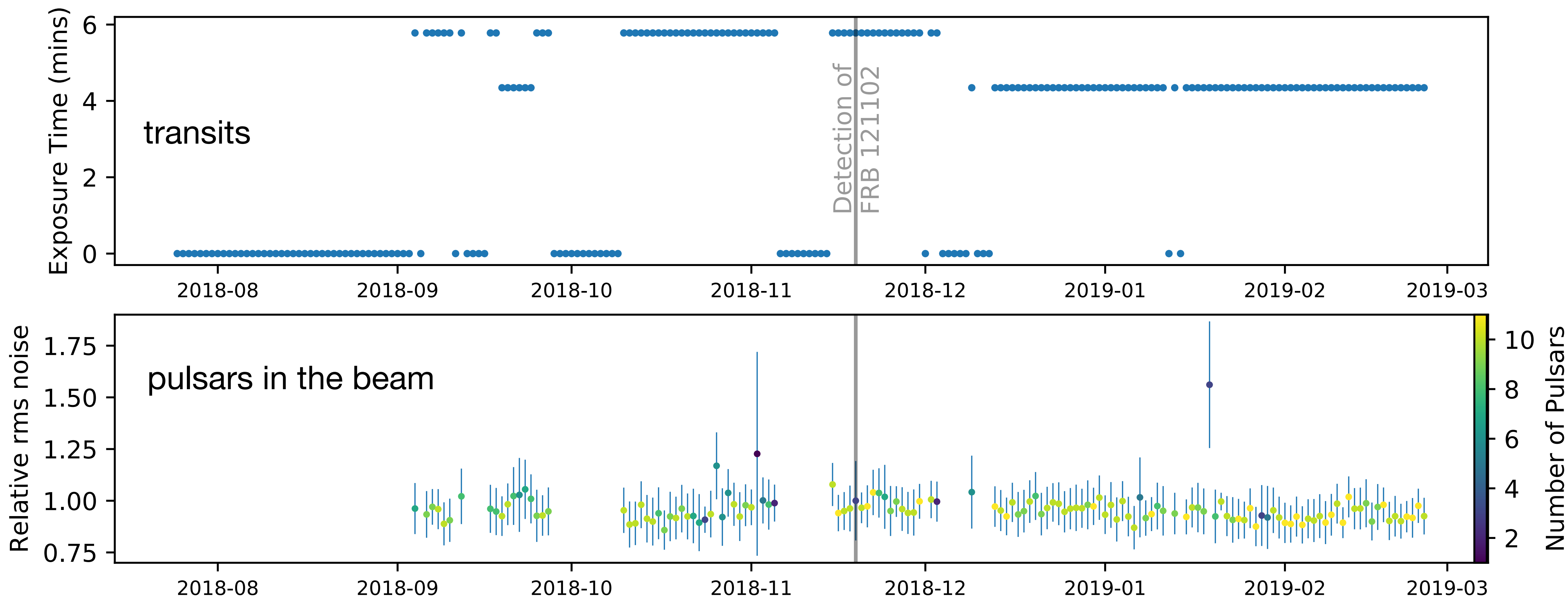
16000 frequency channels over 400MHz bandwidth
→ 25kHz frequency resolution for a ~1ms time resolution

The CHIME/FRB Collaboration. Observations of fast radio bursts at frequencies down to 400 megahertz. Nature

CHIME detection of FRB121102

Observation mode of CHIME: transit of source over one of the beams

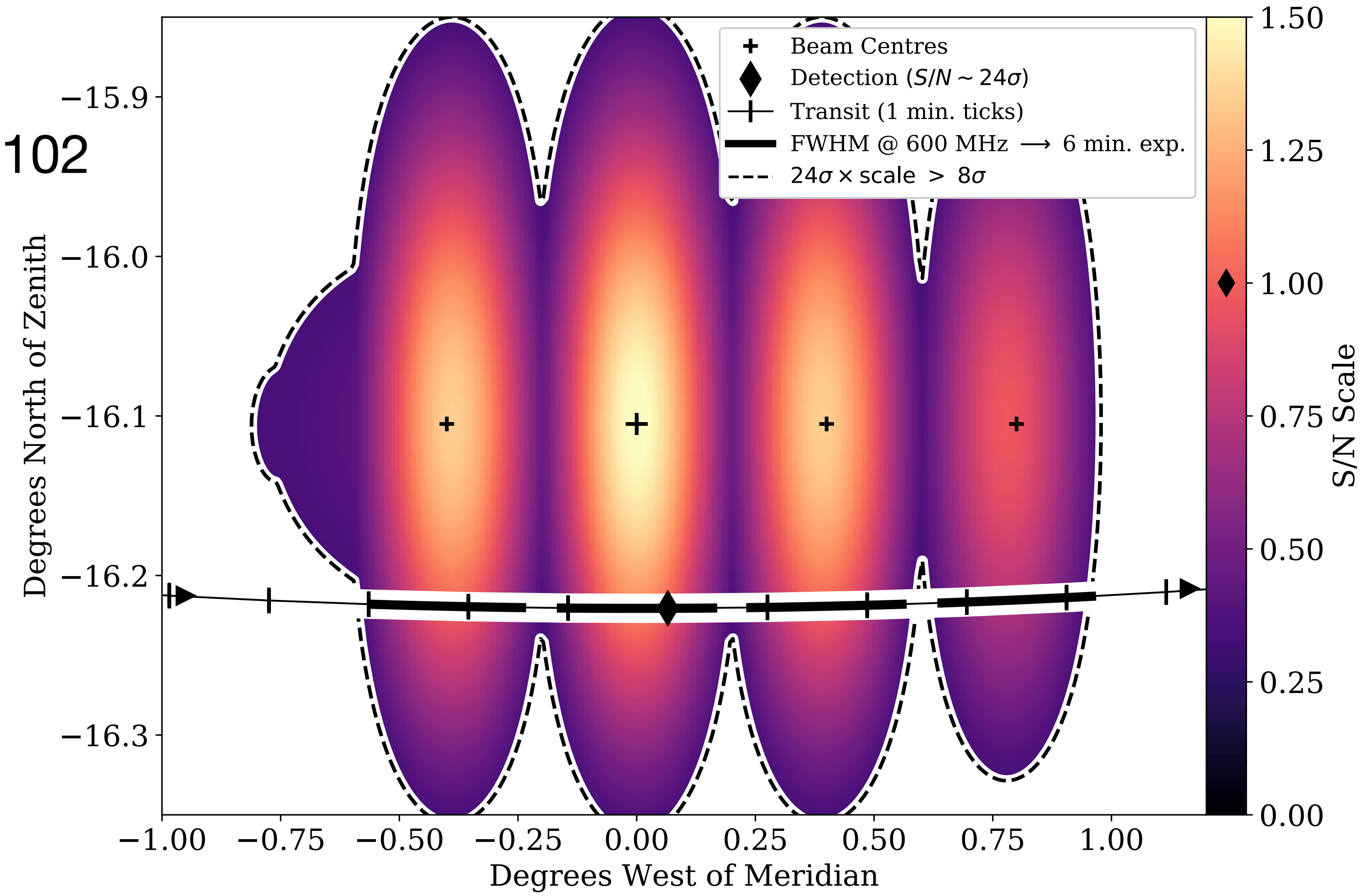
Day to day variations monitored with galactic pulsars



A total of 11.3 hours of observation for FRB121102

Burst width ~34ms (~5ms for ARECIBO @1.5GHz)

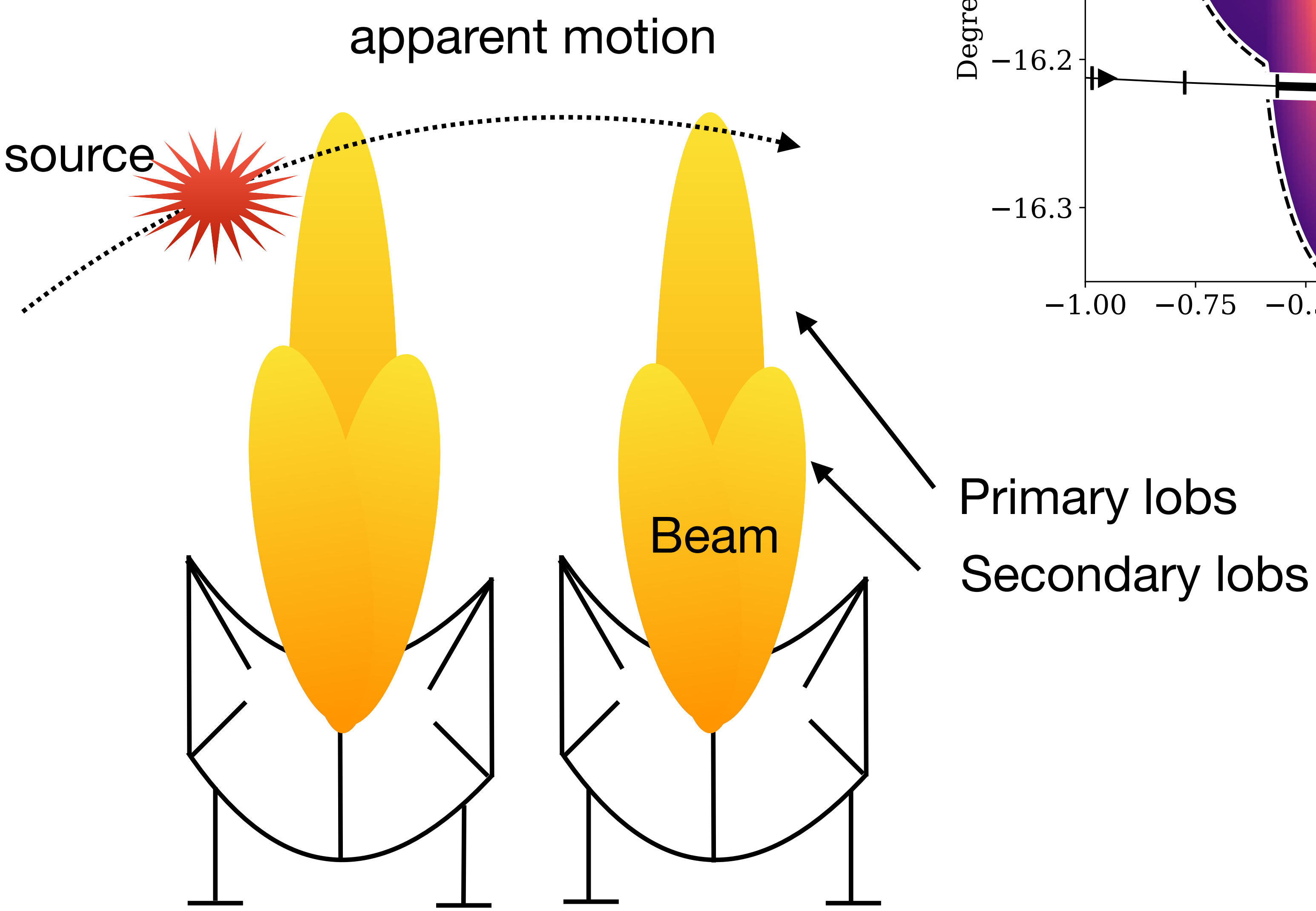
Burst fluence ~ 12 Jy (<1Jy for ARECIBO)



Beam “pointing” to known position of FRB121102

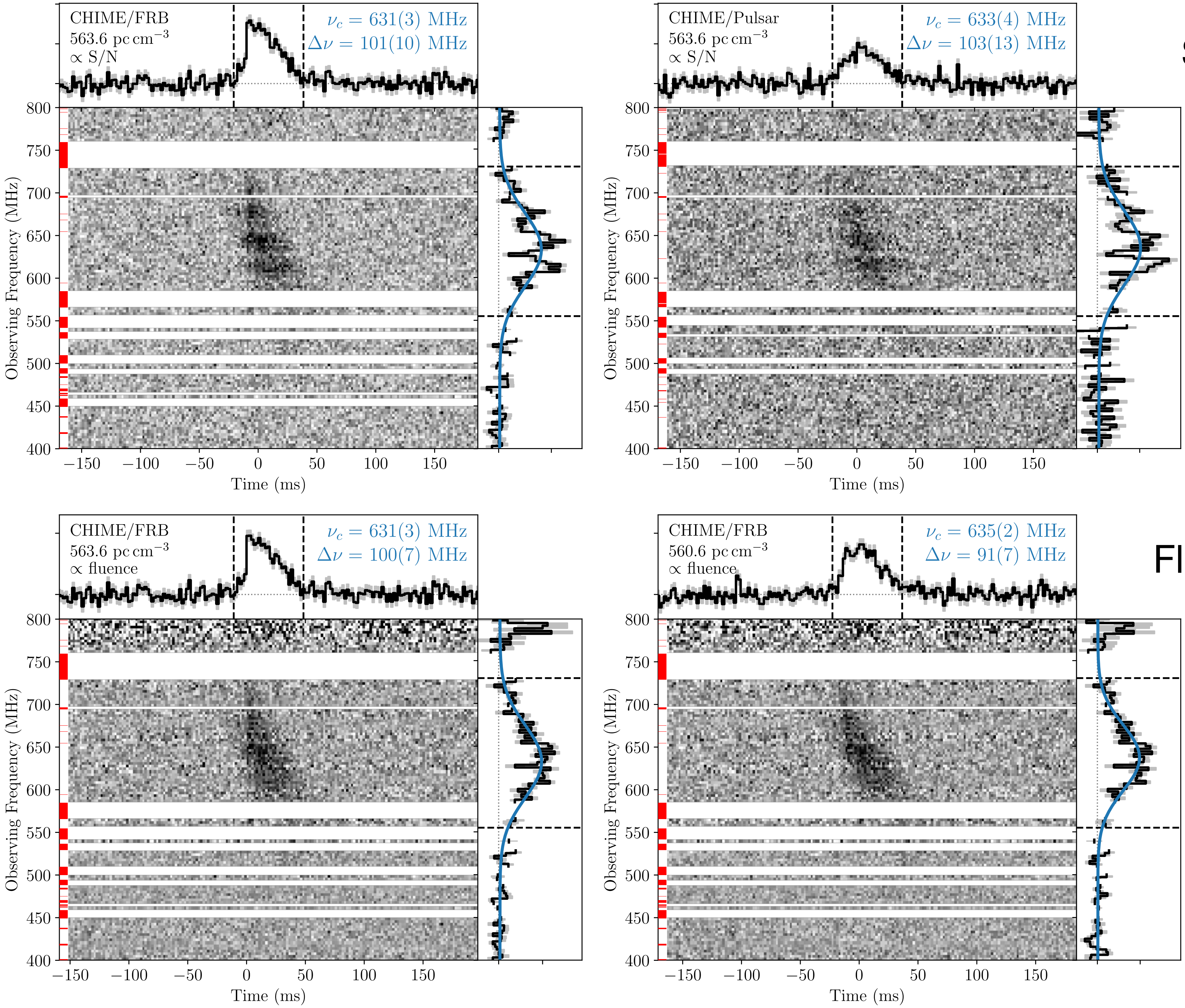
Transit of FRB121102 seen in only one beam

SNR = 23.7



CHIME (obviously)

Waterfall plots of CHIME/FRB121102 burst



SNR

Fluence

DM search → 563.6 pc.cm^{-3} standard DM → 560.6 pc.cm^{-3}

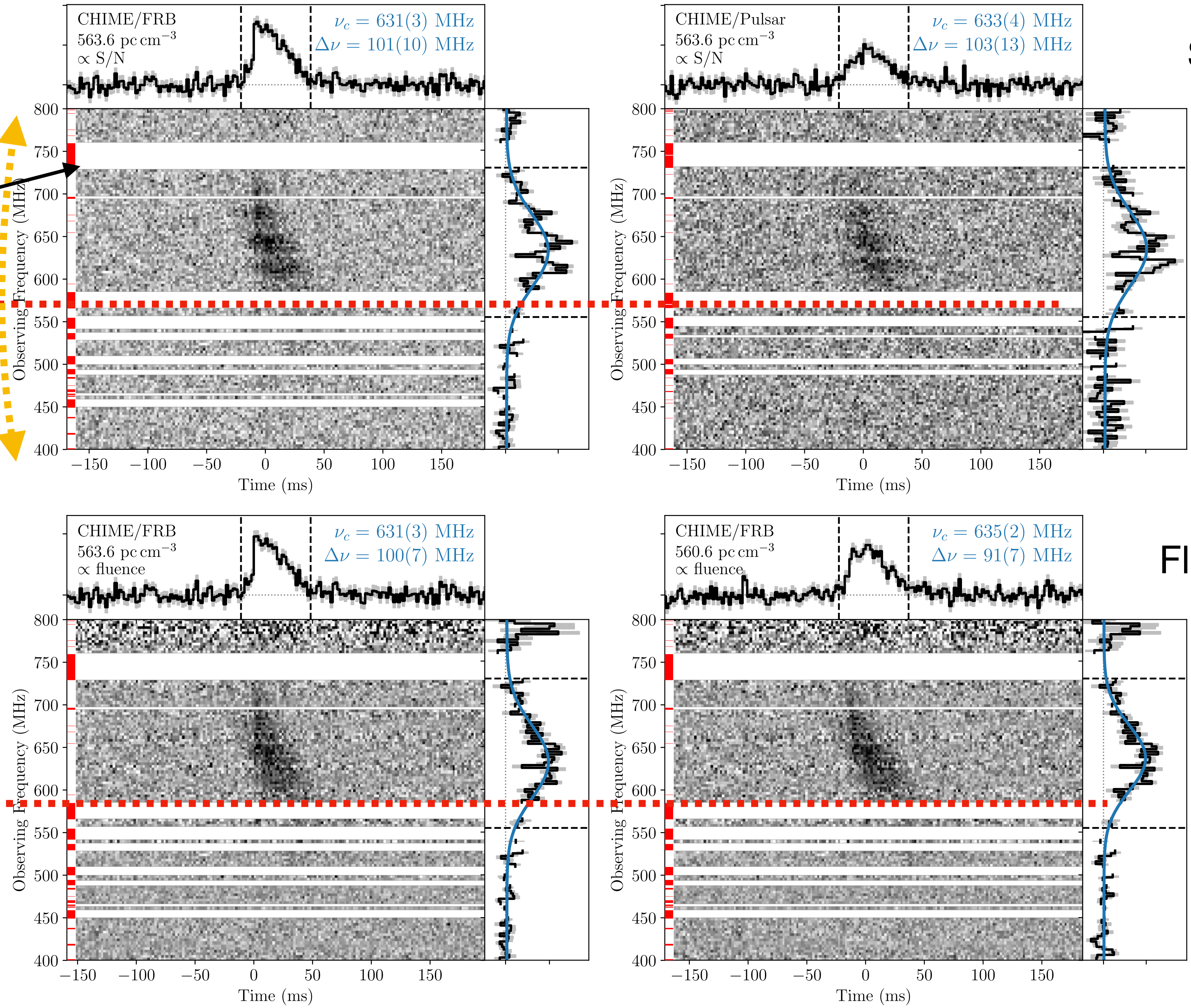
Waterfall plots of CHIME/FRB121102 burst

RFI mitigation

broad frequency emission

cut-off below ~600MHz

narrow impulsion



SNR

Fluence

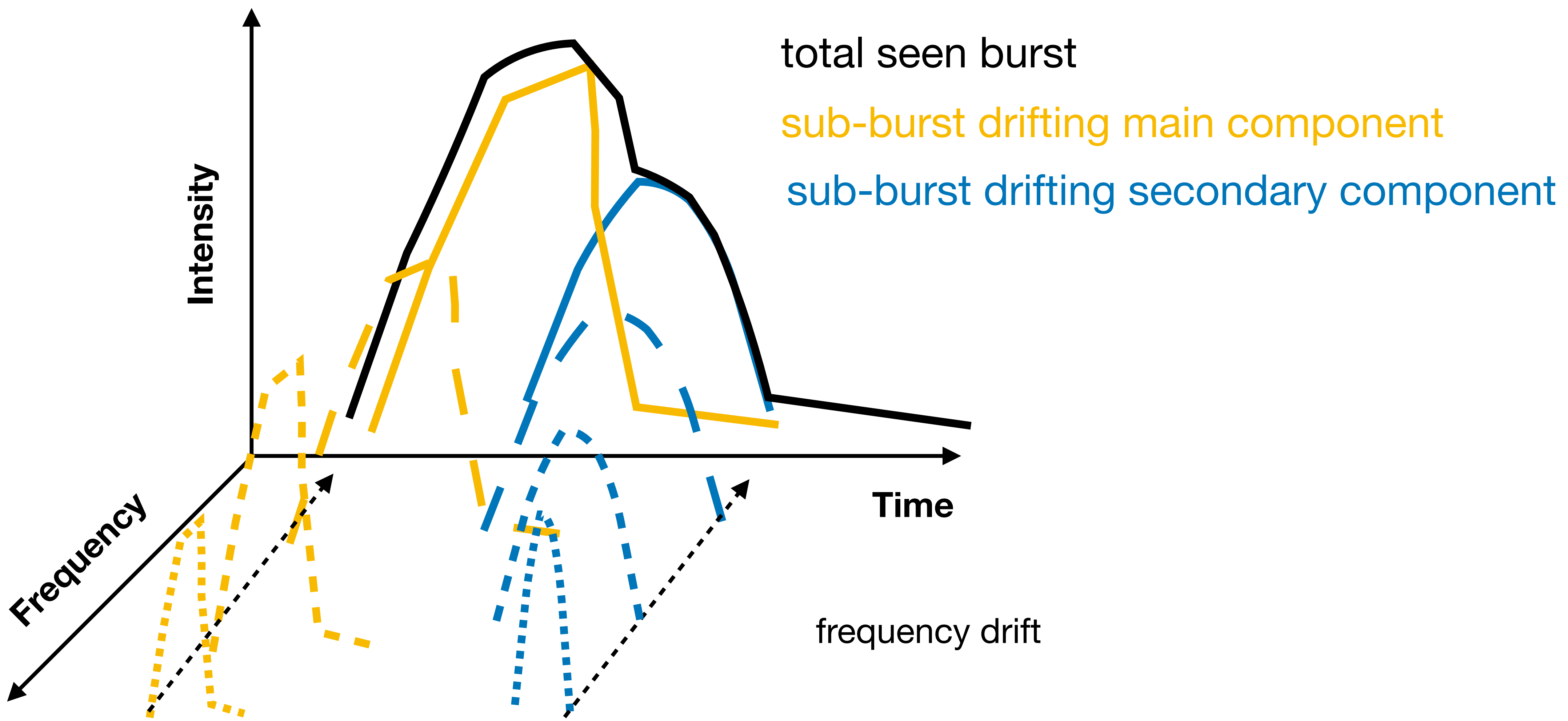
DM search → 563.6 pc.cm^{-3}

standard DM → 560.6 pc.cm^{-3}

Burst morphology analysis

The broad pulse structure might be caused by a combination of sub-burst drifting and scattering

<u>Idea</u>: assume all morphology is caused by sub-burst drifting → burst model includes sub-burst and scattering



<u>Method</u>:

- DM search to optimise the drift of sub-structures
- Pulse shape fit

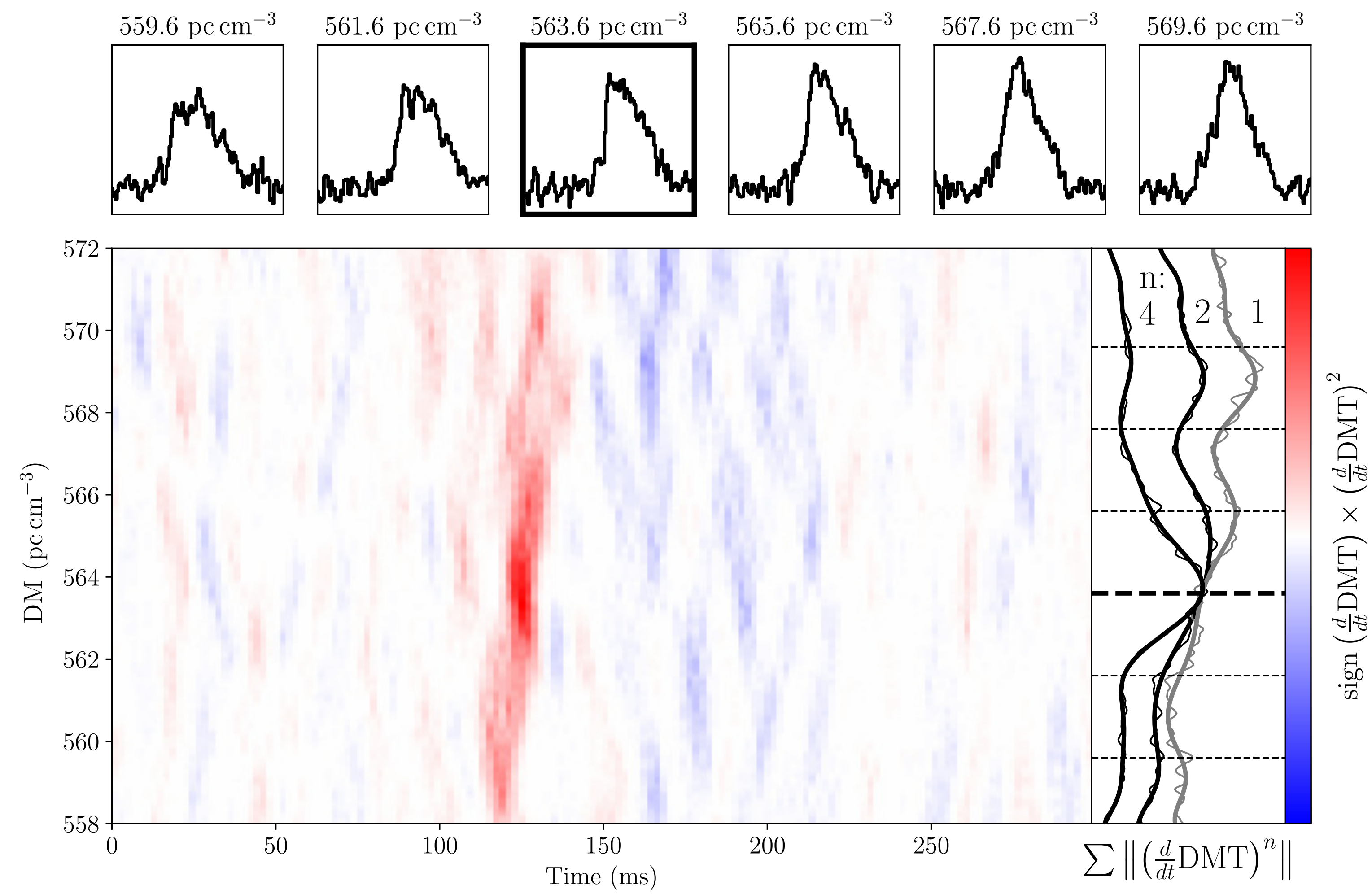
DM search for optimising the drift of sub-structures

Idea: make small structure more visible by playing with DM values around the detection DM value

Forward derivative of the dedispersed time series $\frac{d}{dt}\mathrm{DMT}$

Rising VS falling regions $\mathrm{sign}(\frac{d}{dt}\mathrm{DMT})$

Colour highlight the steepness



The order of n (4, 2, 1) allows to select sharp rises or multiple peaks → maximum gives DM structure optimised value

Structure optimised DM = 563.6 → ~1% higher than previous known DM for FRB121102 (ARECIBO)

Pulse shape fit

<u>Idea</u>: Fit the pulse components using the optimised DM

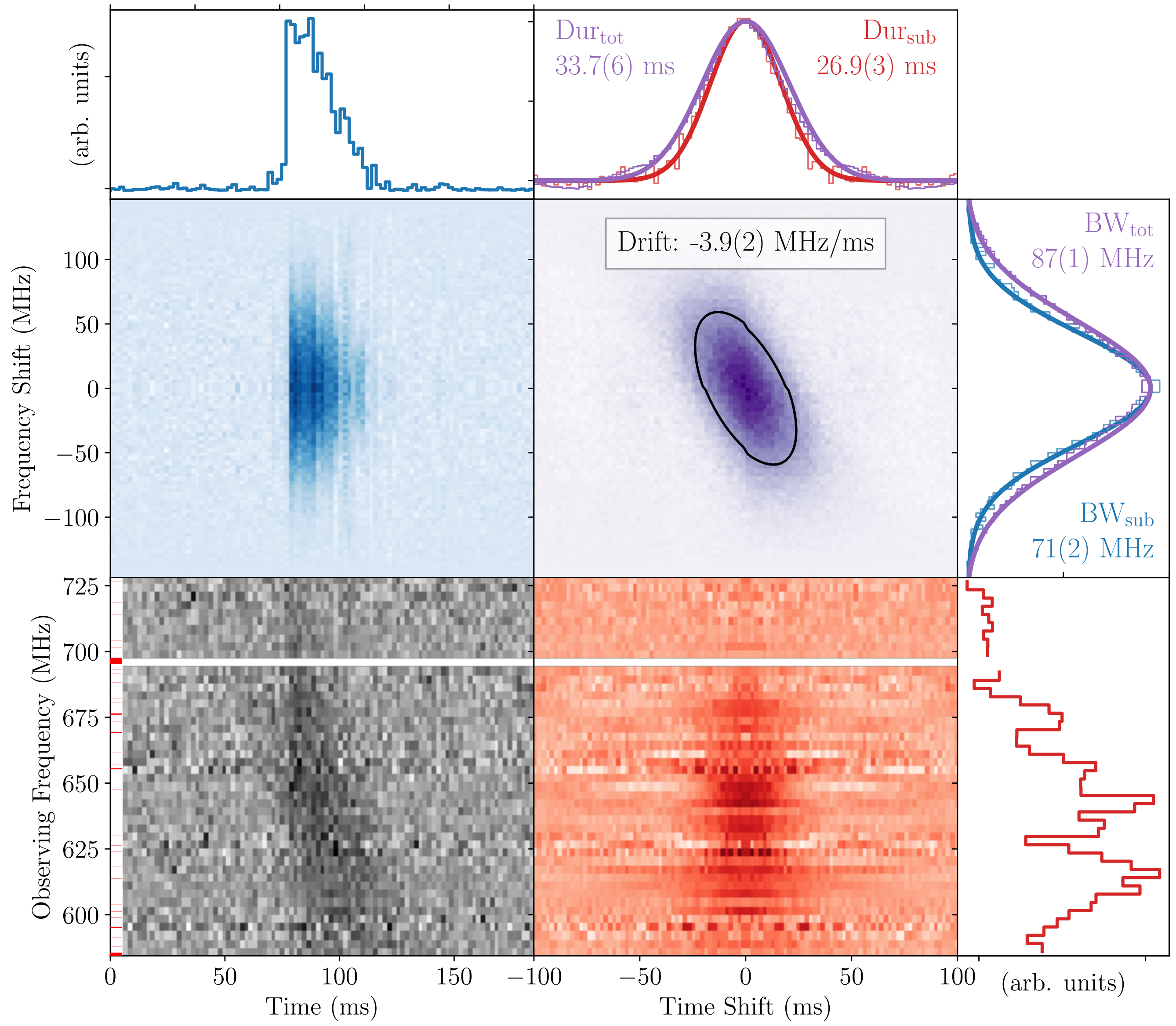
Dedispersed spectrum

Clean frequency band selected: 580-725MHz

Gaussian profiles assumed

2D autocorrelation:

- frequency drift ~-3.9MHz/ms
- burst envelope width~33.7 ms and frequency width ~87MHz
- sub-burst width~26.9 ms and frequency width ~71MHz



However excluded frequencies may hide more signal which can significantly changes these results in addition the bandpass correction is still under improvements…

Pulse shape fit second methods

Idea: Perform a SNR optimising search directly on raw data

Method: least-square algorithm from CHIME/FRB coll. 2019a

- fit gaussians spectral components against the 16k frequency channels
- Set DM and scattering time as global parameters $\propto \nu^{-2}$ and $\propto \nu^{-4}$

3 components are favoured with no significant scattering (3-sigma upper limit of 9.6 ms @500MHz)

Parameter	Global Parameters		
Dispersion Measure (pc cm^{-3})	563.6		
Dispersion Index	−2		
Scattering Timescale (ms; referenced to 1 GHz)	0.27(11)		
Scattering Index	−4		
Parameter	**Component 1**	**Component 2**	**Component 3**
Arrival time relative to first component (ms)	0(2)	8(2)	27(2)
Amplitude (Jy)	0.6(2)	2.4(3)	0.7(4)
Time Width (ms)	3.1(5)	10.1(9)	7(2)
Frequency Width (MHz)	26(4)	33(4)	18(8)
Frequency of Peak Emission	684(4)	644(6)	612(10)

A frequency drift rate of -2.1 MHz is found which is consistent with the previous methods

Burst fluence determination and burst rate in the 400-800MHz bandwidth

Burst fluence of ~12 Jy.ms (<1Jy for ARECIBO) measured over and effective bandwidth of 255MHz out of 400MHz-800MHz

Calibration done using the observations of 3C 48 which is within 0.1° declination of FRB121102 and uncertainty estimated using 9 other bright sources within 1° declination

From a total of 11.3h of observations with a 90% Poisson uncertainty on the single detected burst of 0.05-4.7 bursts → 0.1-10 burst per day

(since FRB121102 is non Poissonian, this is to consider as a rough approximation)

System sensitivity estimates (overview)

1) day-to-day instruments gain variations

→ monitor bright galactic pulsars within the beam location

2) changing source position within the synthesised beams

→ model the sensitivity variation across the beam (description of FFT formed beams + ray tracing computations)

3) different emission bandwidths and frequency centres within the instrument bandpass

→
- from calibration process, use the beam-former-to-jansky conversion
- simulate gaussian profiles with a SED summed over all the frequencies
- convolve the two above to get a relative SNR scale factor for different emission bandwidths and central frequencies
- draw from a Monte-Carlo simulation the fluence threshold for some possible burst taking into account the exposure at a given day and the sensitivity thanks to the pulsars study and the transit effects along the beams

Very schematic:

Generate events → Instrument response + exposure +sensitivity of the day / emission bandwidth +transit across the beam = fluence threshold

repeat 10^6 times

1) ~1, 2) ~0.7 and 3) ~0.9 Jy.ms

Low frequency observations:

→ Constraints on possible frequency cut-off: for exemple free-free absorption at the source must be below 720MHz (corrected for redshift)

DM measurements:

→ A 1% higher DM is inconsistent with any Milky-way electron column density enhancement (from pulsars measurements) and it is very unlikely that inter-galactic medium changes so much → local source change

Young compact object inside a super-nova remnant as predicted by *Piro&Gaensler 2018* expect much smaller changes in DM

The synchrotron-maser model (magnetar) from *Metzger et al 2019* predict stochastic DM variations but this kind of high DM changes are expected at higher frequencies

New constraints for theoretical models

Burst morphology:

→ FRB121102 shows burst with peaked spectral energy distributions exhibiting emission bandwidths that appear to be proportional to frequency ~0.15 (CHIME)

If this is true for all frequencies then we expect to have 12MHz bandwidth at 80MHz (NenuFAR FRB pilot program)

→
- Depending on the number of sub-bursts, the SNR VS DM curve can peak beyond reference values obtained with structure optimising methods
- In addition the curve will flatten as the number of sub-bursts and envelope width increases

flat curves are characteristics features of RFI → target search based on SNR in the DM-time plane gets more tricky

Fluence spectra:

→ If we compare measured fluence at 1.5GHz ~0.3 Jy.ms to fluence at 400MHz ~12Jy.ms

↳ we have a spectral index of -2.8 assuming a power law

↳ expected fluence at 80MHz ~1000Jy…

New constraints for observations at low frequency

Discussion

Linear drift rate:

→ might be explained by plasma gradient from the emitting region, e.g. from blast wave decelerations (*Metzger et al 2019*) or in the propagation from high to low curvature regions of bunches of charges particles (*Wang et al. 2019*)

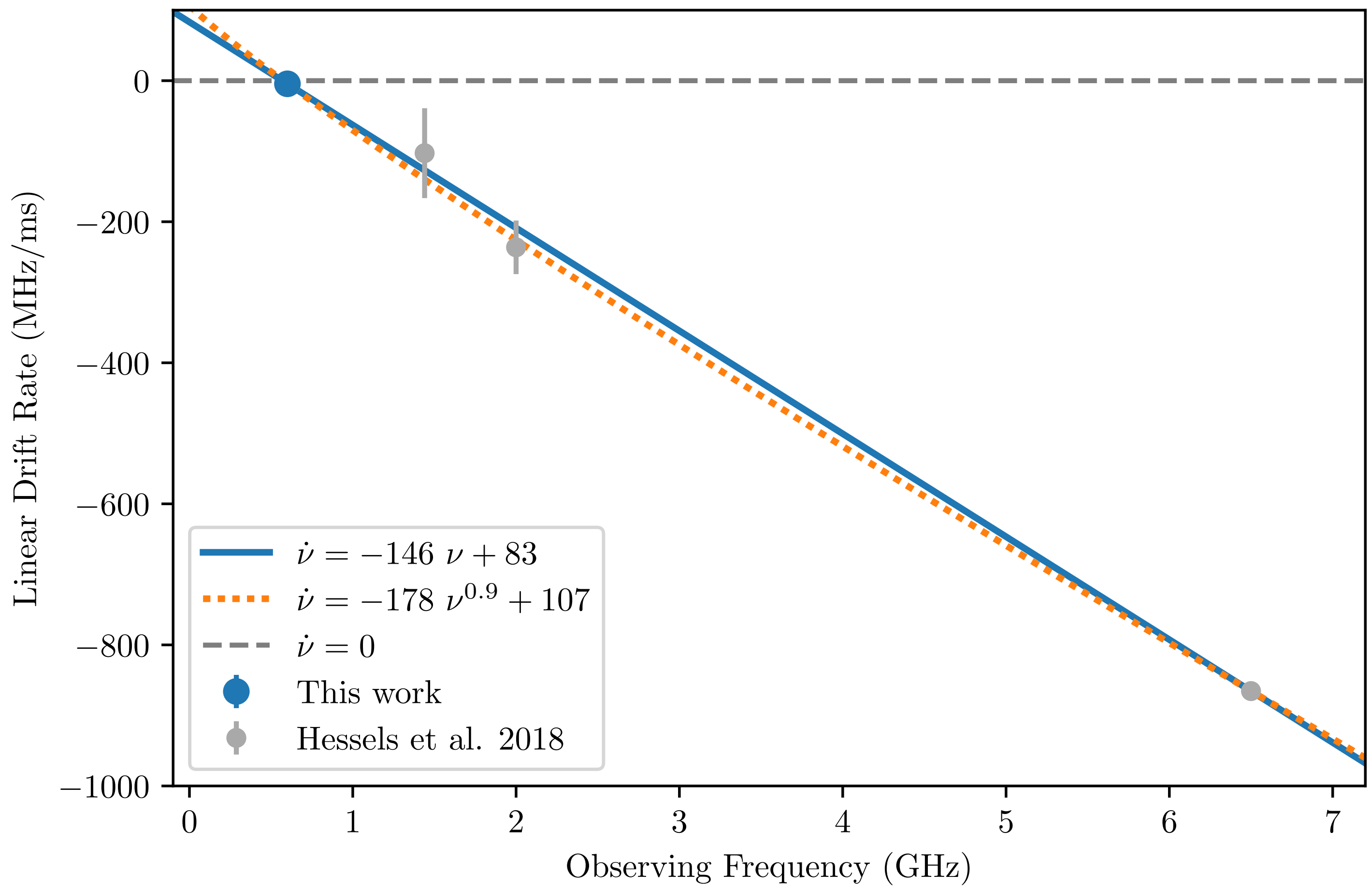
These models derive a relation between drift rates and frequency

$$\dot{\nu}_{\rm obs} \propto \nu_{\rm obs}^{\alpha}$$

α depends on the specific of the progenitor

↪ Here α ~1seems to fit the data

As a consequence around 80MHz we should expect a drift rate ~176MHz/ms



↪ Which makes it very difficult to observe in particular if we add the scattering effects

Finally scattering measurement provide no evidence of second screen as observed by *Masui et al 2015*

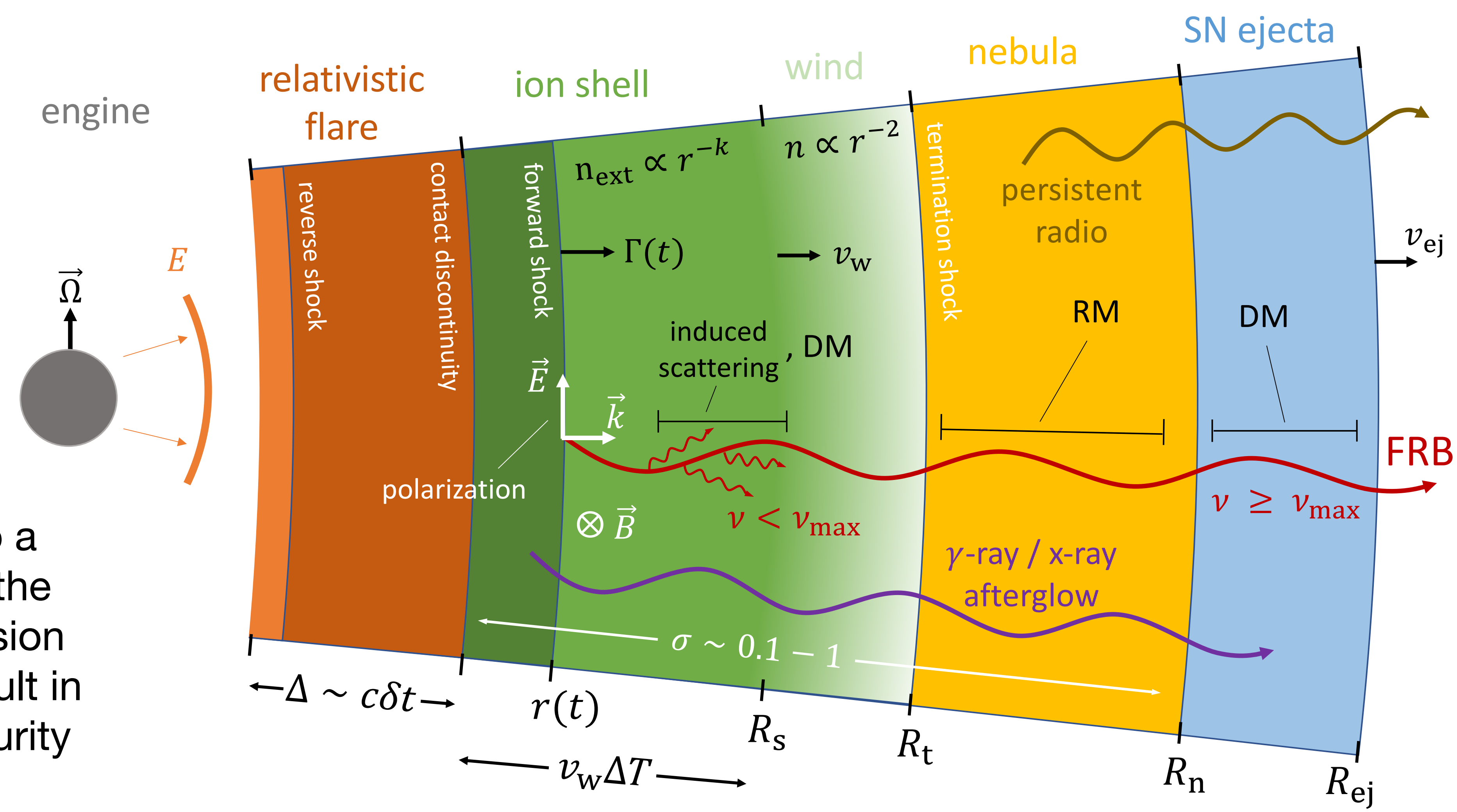
Brief discussion on FRB models

Fast radio burst as synchrotron maser emission from decelerating relativistic blast waves
- *Metzger et al. 2019*

Synchrotron maser emission at ultra-relativistic magnetised shocks, such as produced by flare ejecta from young magnetars.

Combine synchrotron maser emission with the dynamics of self-similar shock deceleration.

Deceleration of the blast wave, ad increasing transparency of the upstream medium, generates a temporal decay of the peak frequency, similar to the observed downward frequency drift seen in the sub-bursts.



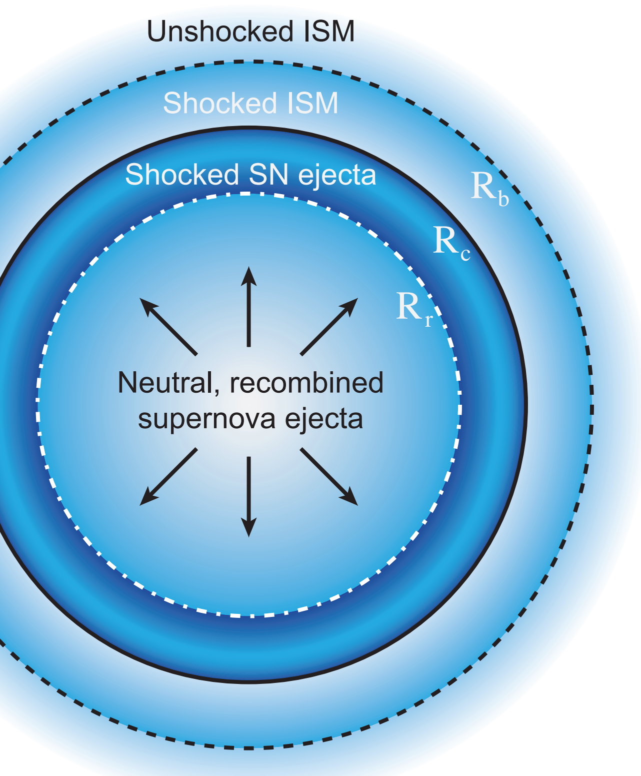
synchrotron emission "leads" to a population inversion in a part of the medium giving a maser like emission but the lack of resonant cavity result in a lack of spatial coherence and purity mode…

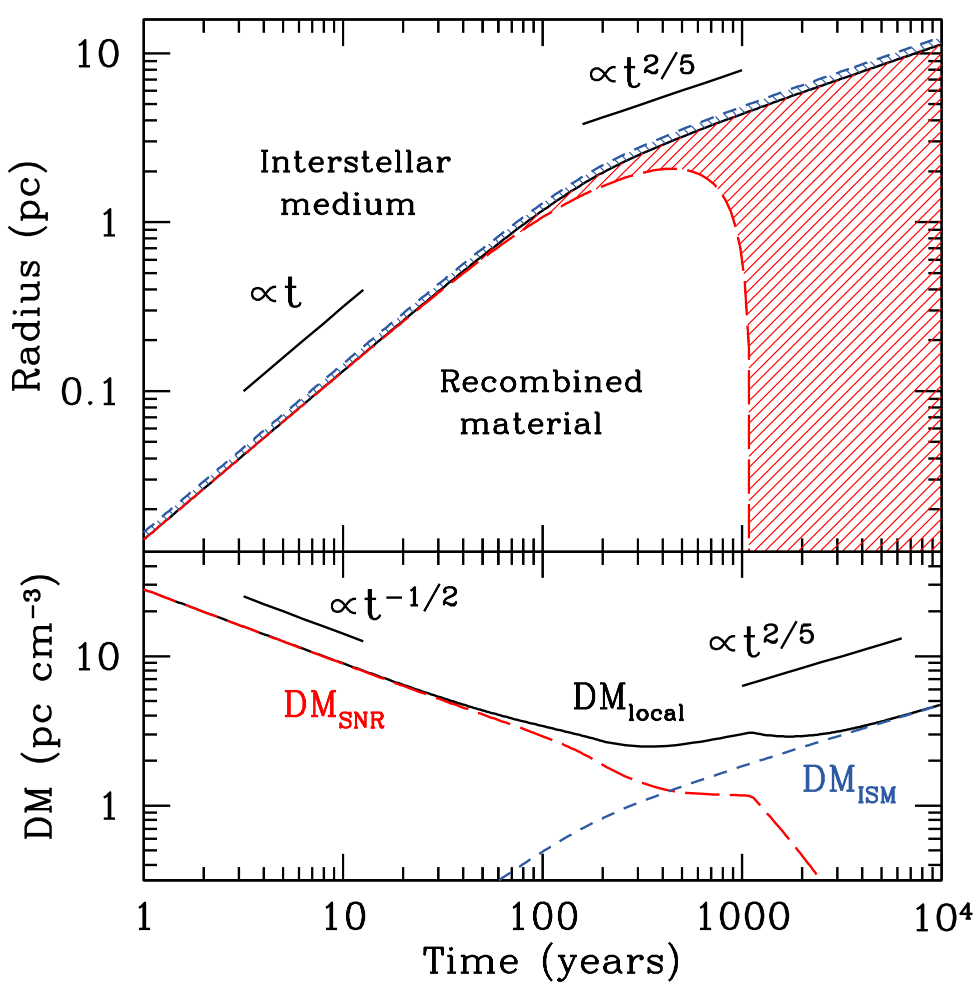
Brief discussion on FRB models

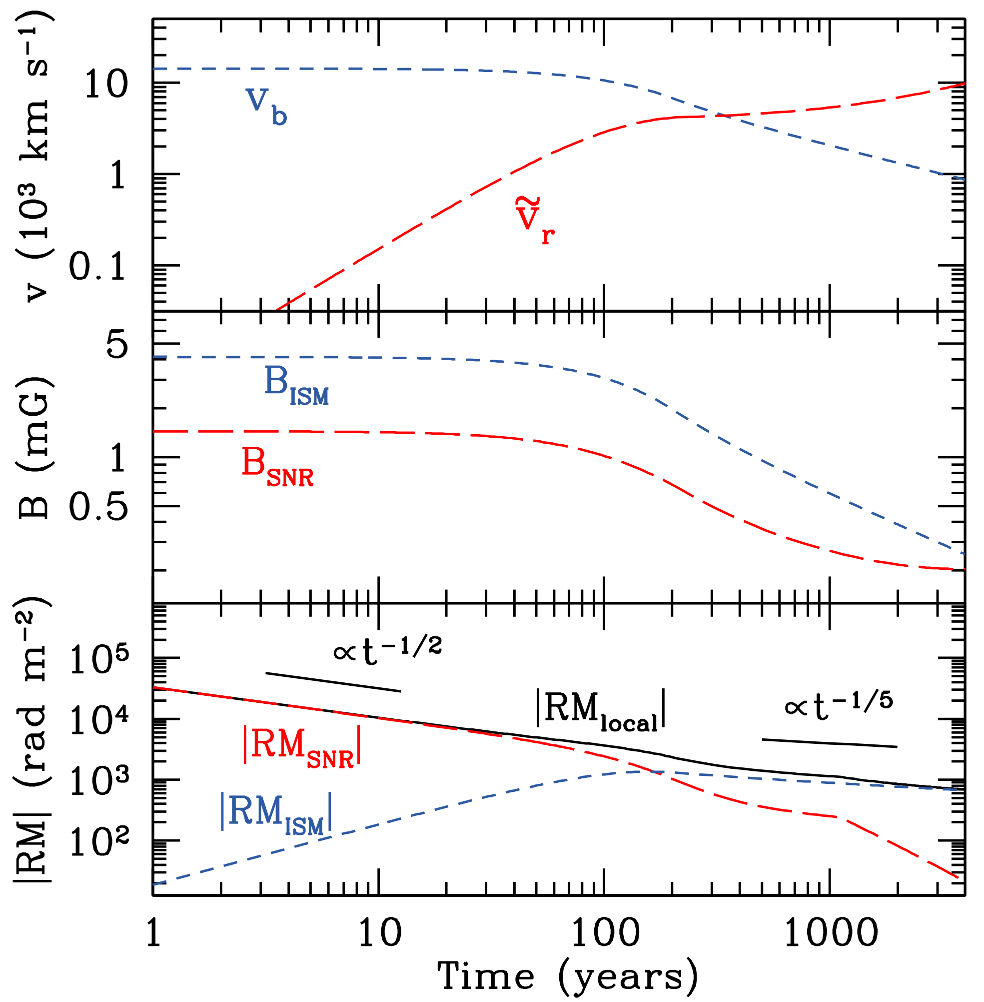
The dispersion and rotation measure of supernova remnants and magnetised stellar winds: application to fast radio burst - *Piro & Gaensler 2018*

In the context of young compact objects models of FRB the super nova ejecta and stellar winds provide a changing dispersion measure (DM) and rotation measure (RM) that can potentially probe the environments of FRB progenitors.

The amount of ionised material is controlled by the dynamics of the reverse shock → DM can be constant or even increase as the super-nova remnant sweeps up material.





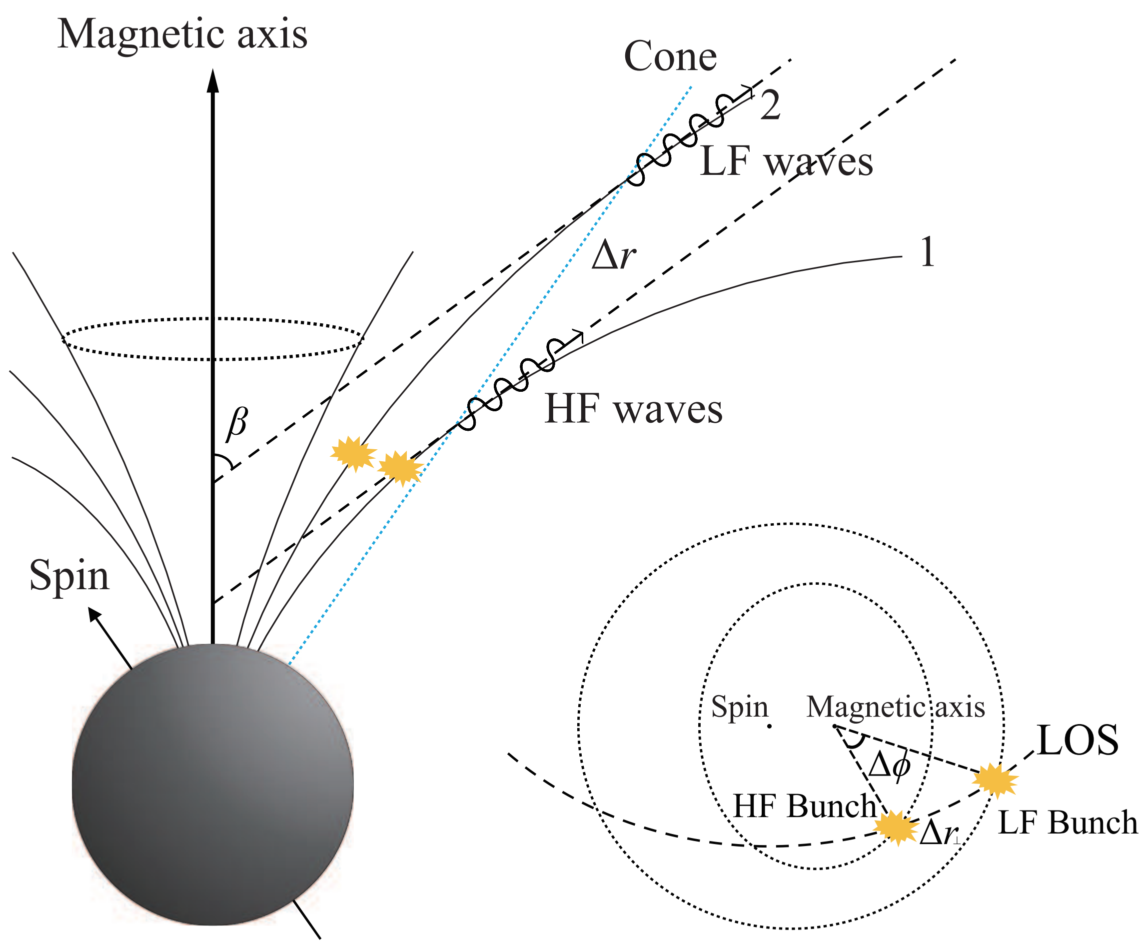


On the time-frequency downward drifting of repeating fast radio bursts - *Wang et al. 2019*

A generic geometric model

Bunches of electron-positron paires radiates through curvature radiation along the magnetic field lines of a neutron star magnetosphere

As the field lines sweep across the line of sight of the observer, bunches seen later have traveled farther into less curves part of the magnetic field lines, thus emitting at lower frequencies



2 scenarii:
- emission from the inner gap region of a slowly rotation NS
- externally trigger magnetosphere reconfiguration: cosmic comb

For the curious → https://frbtheorycat.org