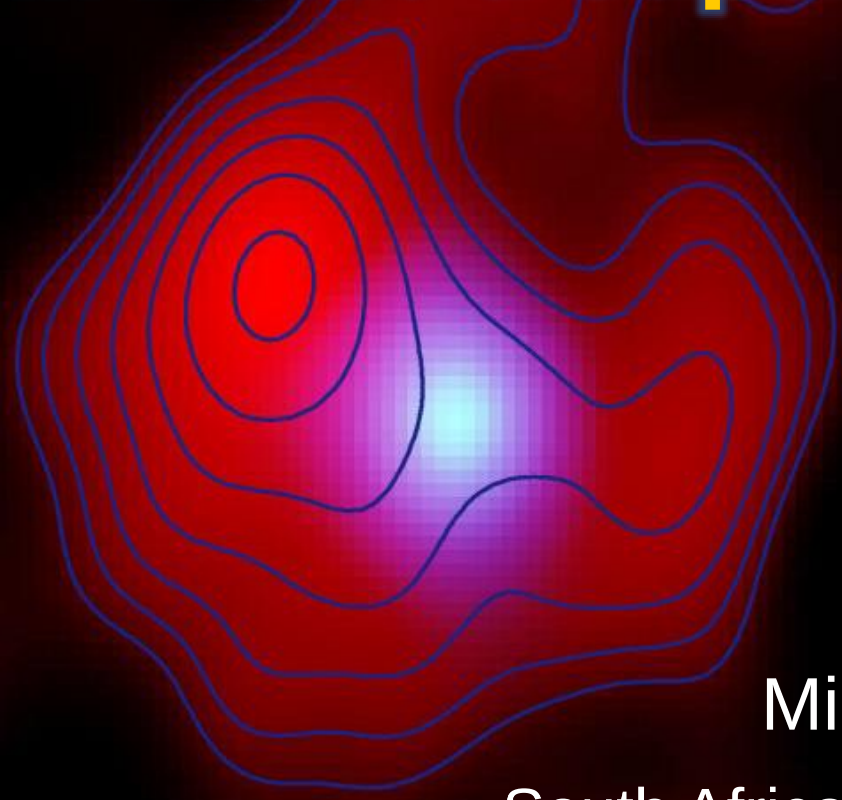
VLBI of SN 1986J and the Possibility of FRBs Originating from Inside a Supernova



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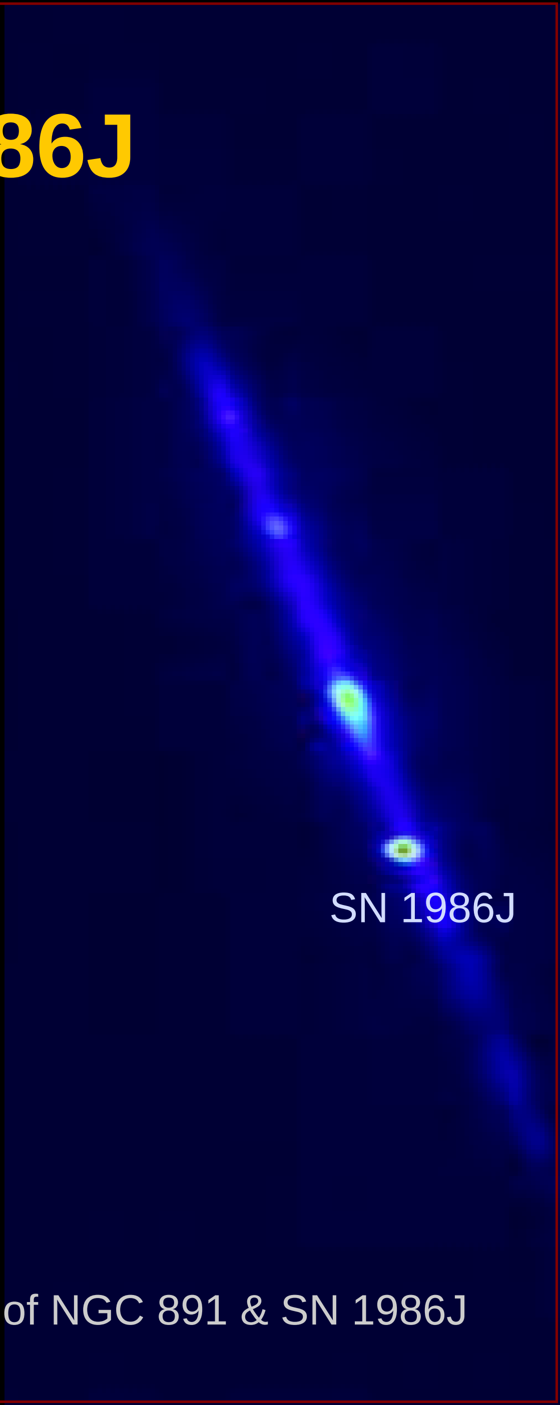
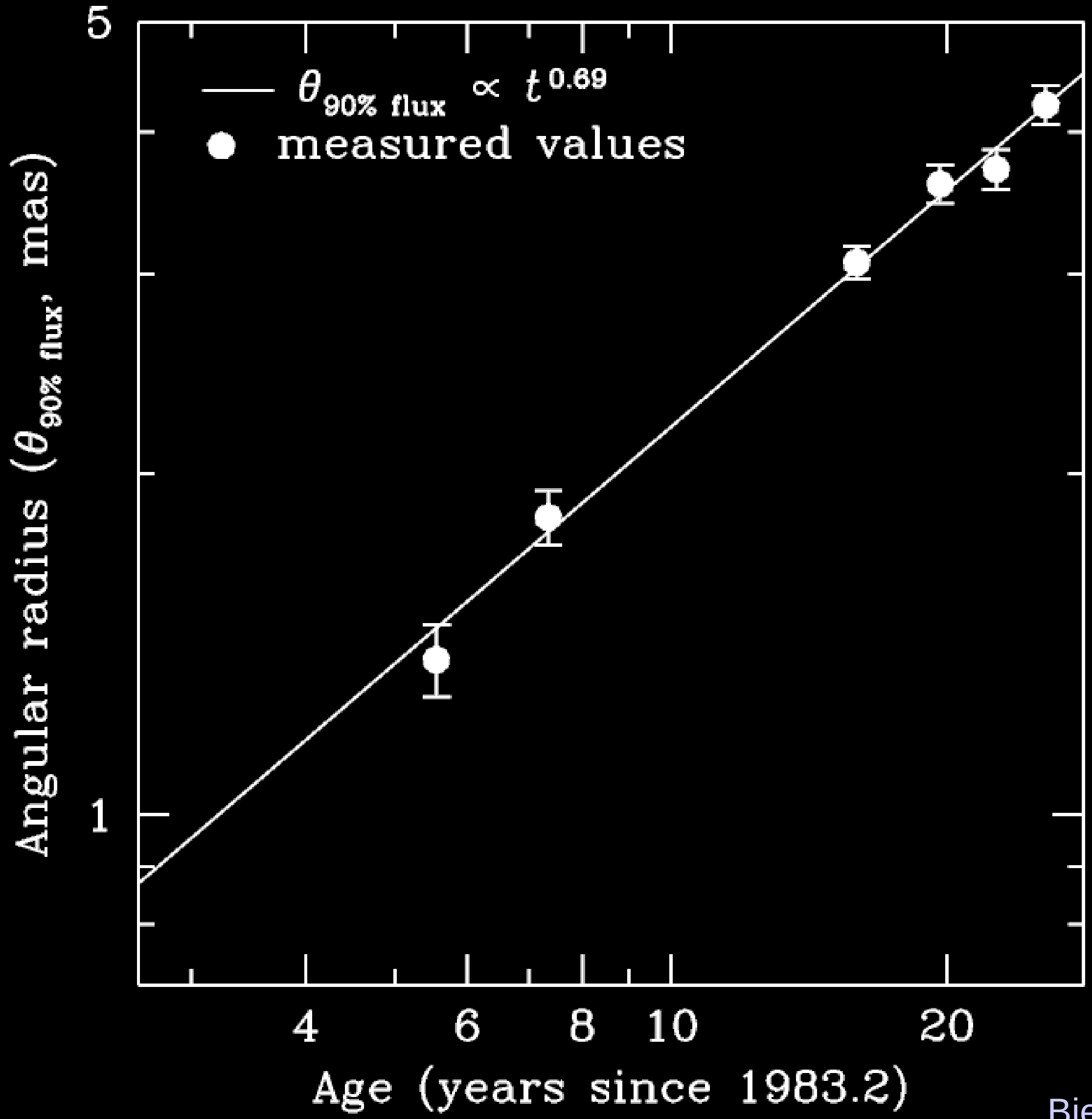
Introduction to SN 1986J

- SN 1986J discovered in the radio in 1986 (Rupen, van Gorkom et al.)
- In NGC 891, *D* = 10 Mpc (NED)
- Supernova happened in 1983.2 ± 1.1
- Massive progenitor (>20 Msol)
- Classified as a Type IIn SN (Rupen et al. 1987)
- Strong circumstellar medium (CSM) interaction
- Very radio luminous. One of the first SNe to be observed with Very Long Baseline Interferometry (Bartel et al 1987, 1991)
- Although it's fading, it's still radio-bright 30 years on



VLA image of NGC 891 & SN 1986J

Expansion of SN 1986J



- Evolution of the outer angular radius of SN 1986J
- Powerlaw evolution with angular radius, $\theta \propto t^{0.69}$
- Expected in case of powerlaw density profiles for ejecta and CSM (Chevalier)

$\theta_{90\%\ flux}$ is angular radius containing 90% of the flux density

Bietenholz, Bartel & Rupen 2010

- VLBI Images: 1987 to 2014 (and continuing…)
- Global VLBI images at 8.4 and 5 GHz

↔ 1 mas

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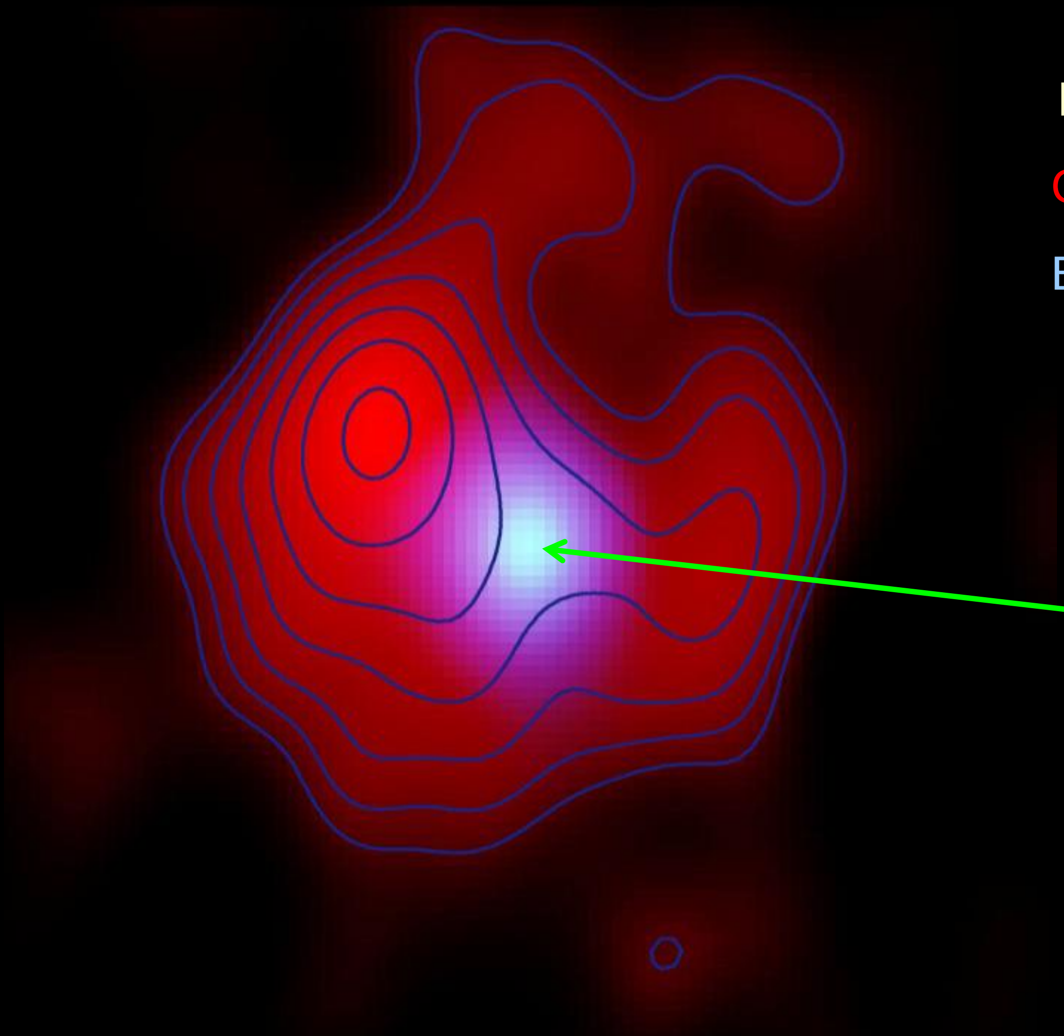
Central Component in SN1986J



Multi-frequency VLBI Image:

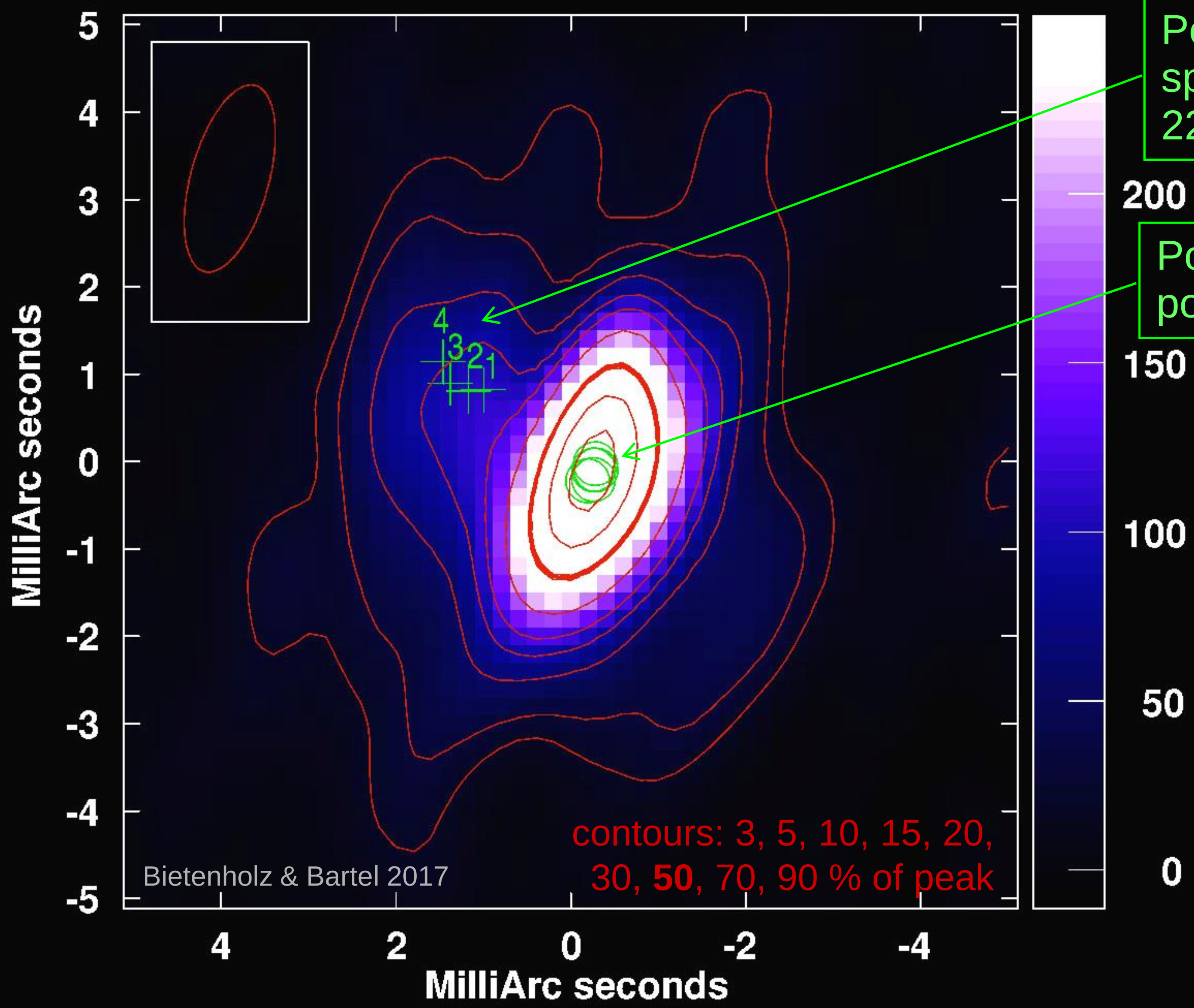
Contours, red: 5 GHz

Blue → white: 15 GHz

Youngest Neutron Star or Black Hole?

Bietenholz, Bartel & Rupen 2004

VLBI Image at 5 GHz in 2014

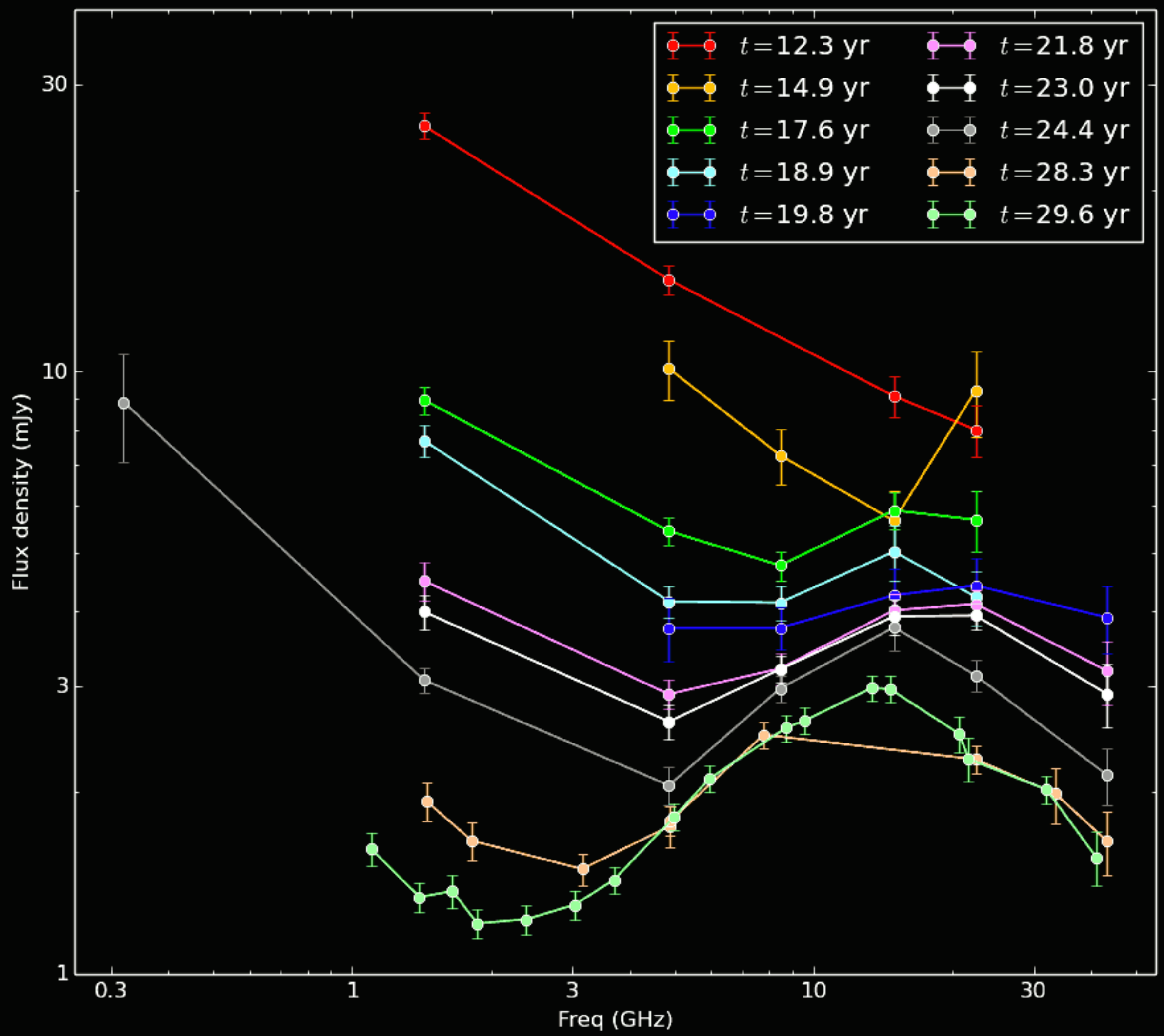


Positions of shell hot-spot at 15.9 ("1") 19.6, 22.6 and 25.6 ("4") yr

Posn. of central com-ponent 20.3 to 31.6 yr

- 2014 Oct. 23 (*t* = 31.6 yr)
- Global-array VLBI (EVN and NRAO antennas)
- Phase-referenced to 3C66A
- rms = 5.9 μJy beam^{-1}

Evolution of the Spectral Energy Distribution (SED)



- VLA measurements:
- Inversion in SED first appears at t = 14.9 yr
- both inflection point and high-frequency turnover evolve downward with time

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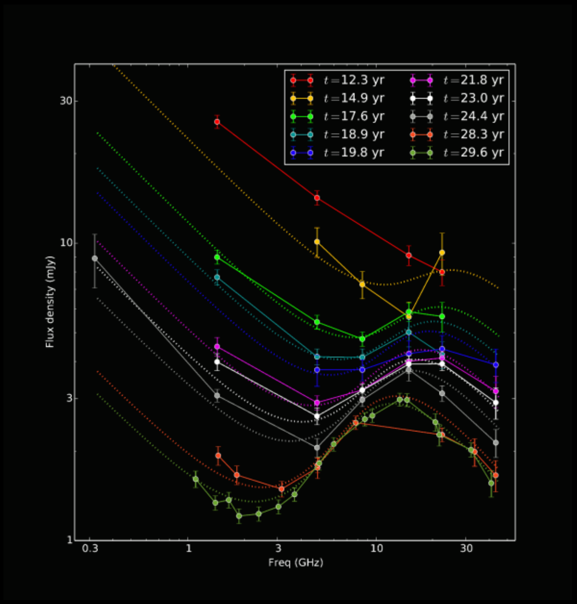
Fit to the Evolving SED

- Two-part model for evolving SEDs, with 1) a shell component and 2) a central component, which is partly absorbed (free-free), both with powerlaw spectra
- Both intrinsic flux densities of the components and the absorption (Emission Measure) evolve as power-laws, $\propto t^{\,b}$
- Bayesian fit wrt. the measured flux densities



$$S_{\rm shell} = S_{\rm 0,shell}\left(\frac{t}{20\ \rm yr}\right)^{b_{\rm shell}} \left(\frac{\nu}{1\ \rm GHz}\right)^{\alpha_{\rm shell}}$$

$$S_{\rm comp} = S_{\rm 0,comp}\left(\frac{t}{20\ \rm yr}\right)^{b_{\rm comp}} \left(\frac{\nu}{1\ \rm GHz}\right)^{\alpha_{\rm comp}}$$

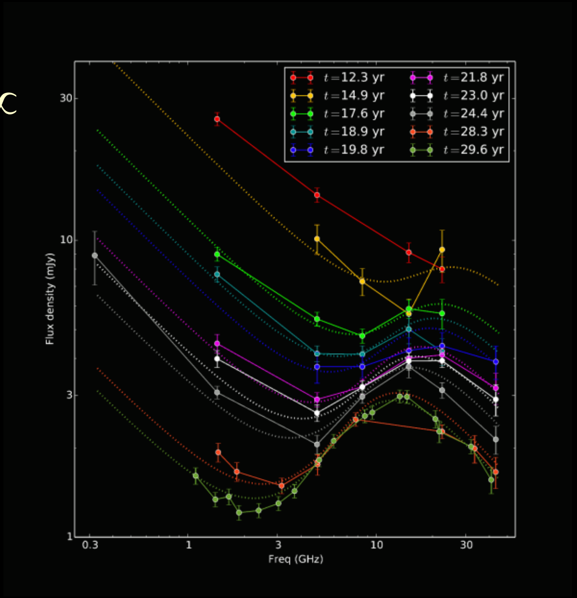
Results:

- S_{shell} = 7.1 ± 0.2 mJy
- b_{shell} = –3.92 ± 0.07
- α_{shell} = –0.63 ± 0.03

- S_{comp} = 61 ± 17 mJy
- b_{comp} = – 2.1 ± 0.2
- α_{comp} = – 0.76 ± 0.07
- EM_0 = (1.6 ± 0.2) $\times 10^9$ cm^{-6} pc
- b_{EM} = – 2.7 ± 0.3

Results of Fit to the SED

- Both central component and shell are declining in flux density with time, but shell more rapidly (shell $\propto t^{-3.92}$, central comp $\propto t^{-2.1}$)
- The spectral indices of the central component and the shell are almost the same within the uncertainties
- At t=20 yr, the intrinsic (unabsorbed) central component was 9 ± 3 times stronger than shell – and its dominance is increasing.
- EM (absorption) also declining with time $\propto t^{-2.7}$, consistent with constant number of electrons and a system expanding with $r \propto t^{-0.54}$



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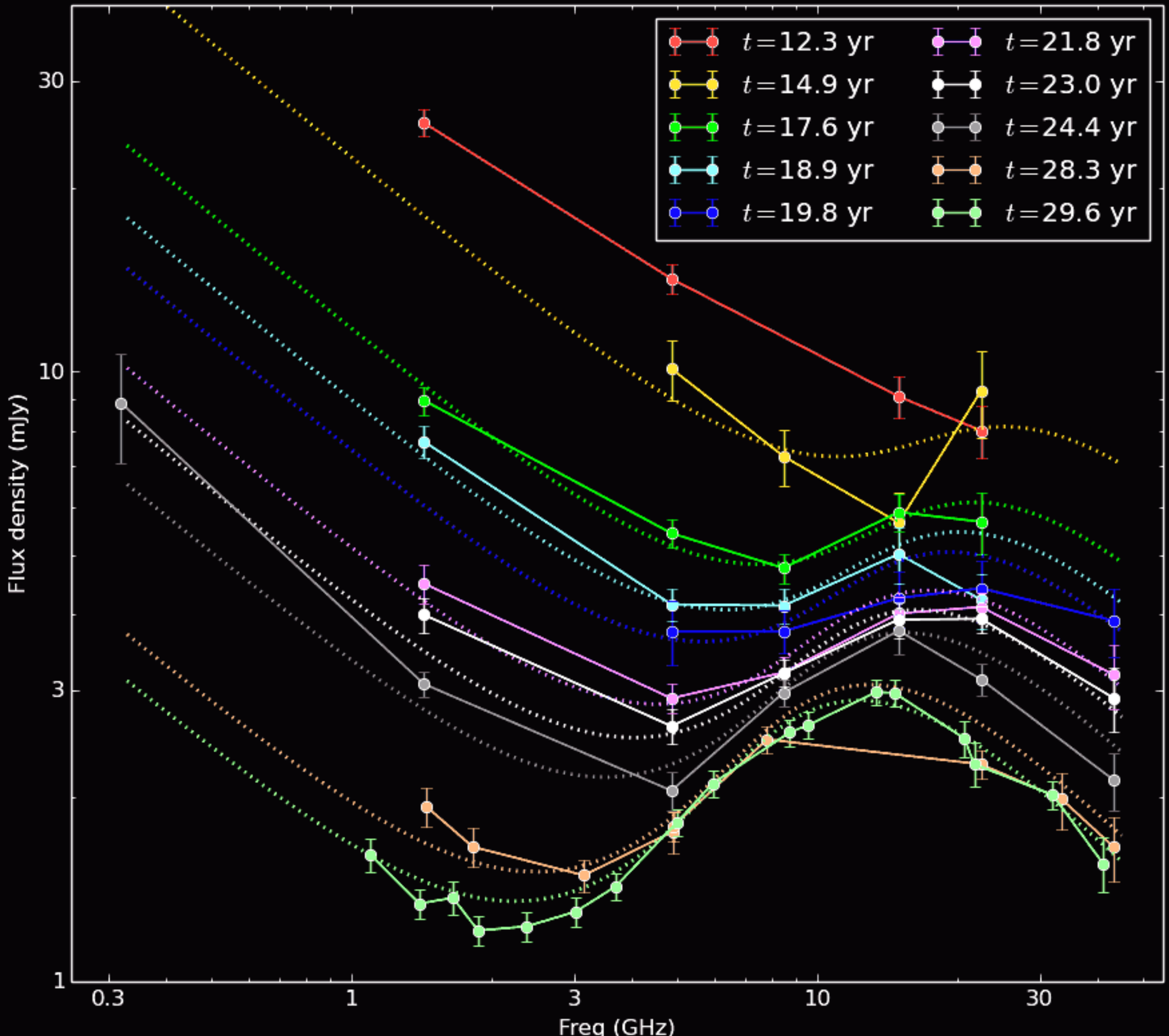
Evolution of the SED

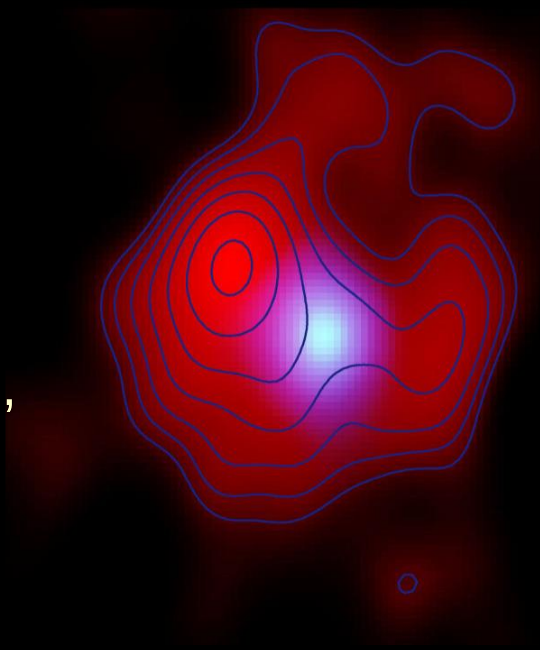


- thin dotted lines show the fitted shell + partly-absorbed central component model
- inflection point and high-frequency turnover move down with time

Bietenholz & Bartel 2017b

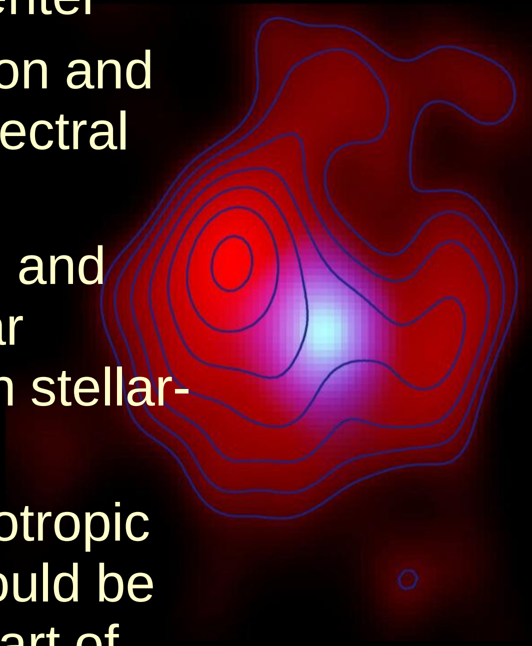
What Do We Know about the Central Component?

- Its intrinsically brighter than the shell, with much higher surface brightness. Currently its 5-GHz spectral luminosity is ~30× that of the Crab Nebula
- Its radio emission is partly absorbed, likely by free-free absorption in the intervening ejecta. Its unabsorbed spectral luminosity is ~9× that of the shell and around 120× that of the Crab nebula
- Its unabsorbed flux density is decreasing with time, $S \propto t^{-2.1}$ (shell $\propto t^{-3.92}$)
- Its spectral index is close to that of the shell
- The amount of absorption is decreasing with time
- It is stationary to within the uncertainties of 570 km/s (12 μarcsec/yr)
- It is marginally resolved, $r_{comp} = (6.7^{+0.7}_{-3.7}) \times 10^{17}$ cm
- if it originated in the SN explosion, it is expanding with ~680 km/s, ~9% the expansion speed of the shell.

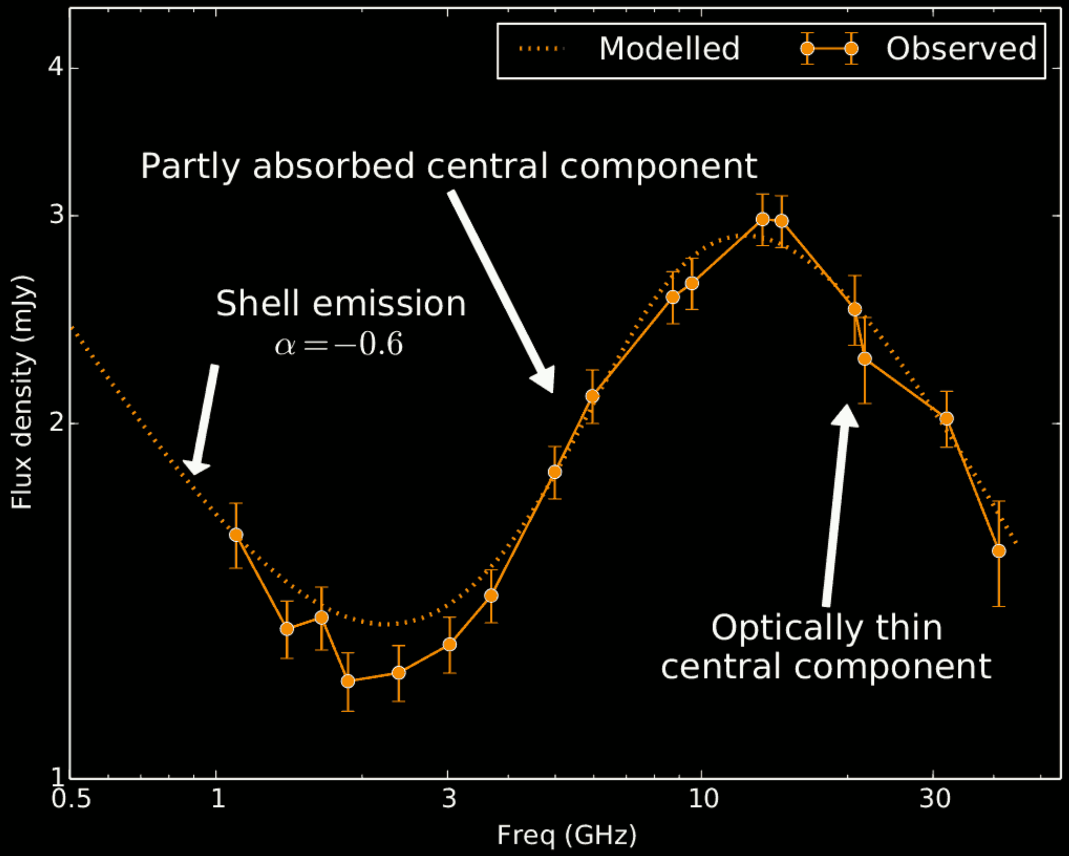


What is the Central Component?

- Central location, high brightness and stationarity suggest that central component *is* near the 3-dimensional center
- 1) A newly-born pulsar wind nebula. Central location and stationarity are expected, but the relatively steep spectral index and the decline with time are not.
- 2) An accreting black-hole system. Central location and stationarity are expected, but central comp. has a far higher radio luminosity, and L_{radio}/L_X than any known stellar-mass black hole systems.
- 3) The interaction of the SN shock with a very anisotropic ISM, with a very dense equatorial region. Shock would be hour-glass shaped. The central component is the part of the shock propagating in equatorial region (see e.g., Chevalier 2012)



Characterizing the Absorbing Material



- Spectrum of central component shows absorption below ~10 GHz at t = 30 yr
- Any 1-GHz would be strongly absorbed
- Emission measure (EM) is decreasing in time - we can extrapolate time of transparency at 1 GHz to be 60 ~ 200 yr after the explosion

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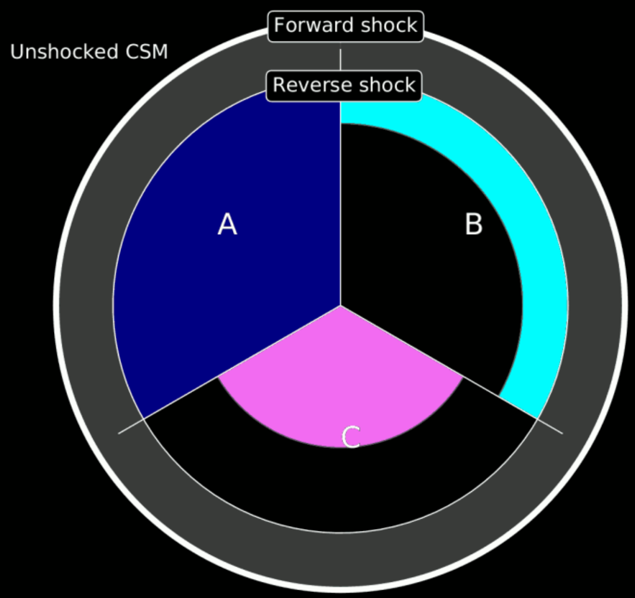
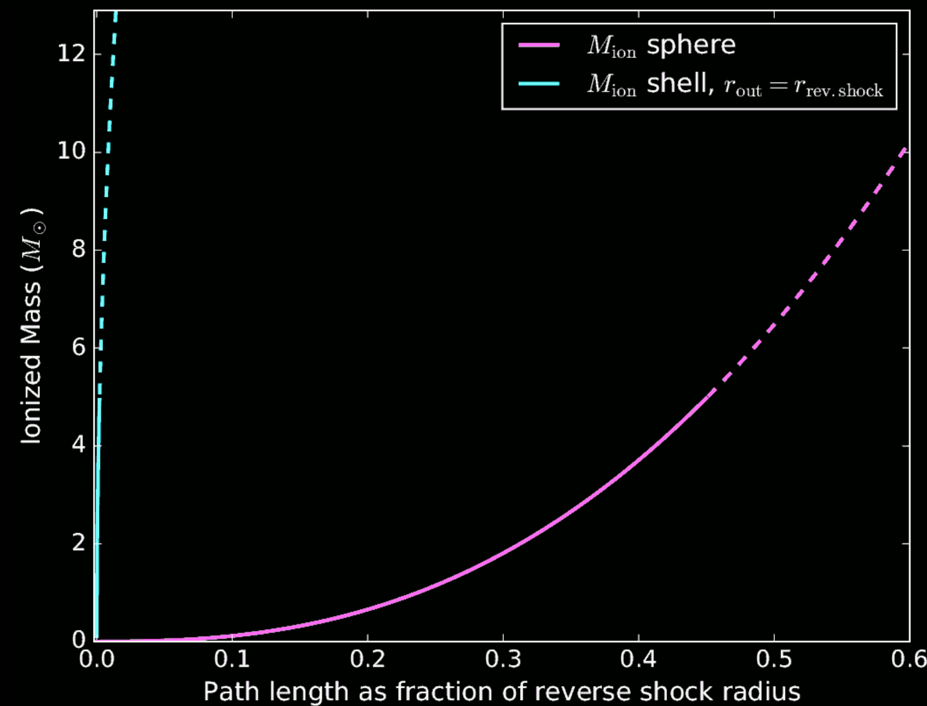
Mass of Ionized (Absorbing) Material





- Mass of ionized material required to produce the observed EM at t = 20 yr (EM = $1{:}63 \times 10^{9}$ cm^{-6} pc) for three different distributions of ionized matter
- A: uniform - requires 40 Msol ionized matter - *too much*
- B: material ionized from the outside: for values of the total ionized mass, of say, < 5 Msol, the ionized region must very thin: <0.002 pc
- C: material ionized from the inside: for < 5 Msol, must be at r < 45% of the forward shock radius
- To get the observed amount of absorption requires a small, dense ionized region in the ejecta

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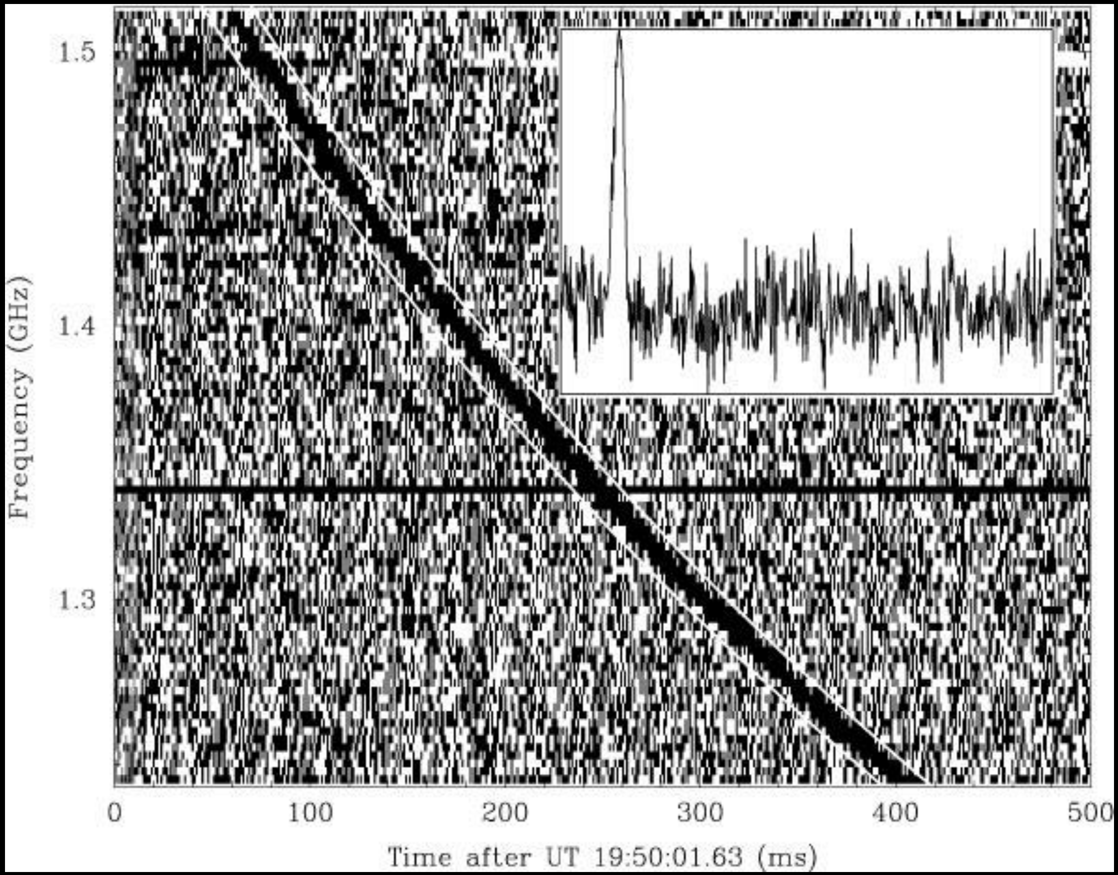
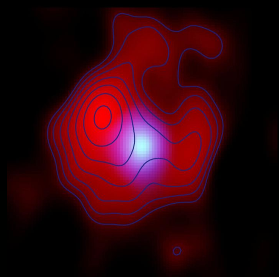
FRB's from Inside a Supernova



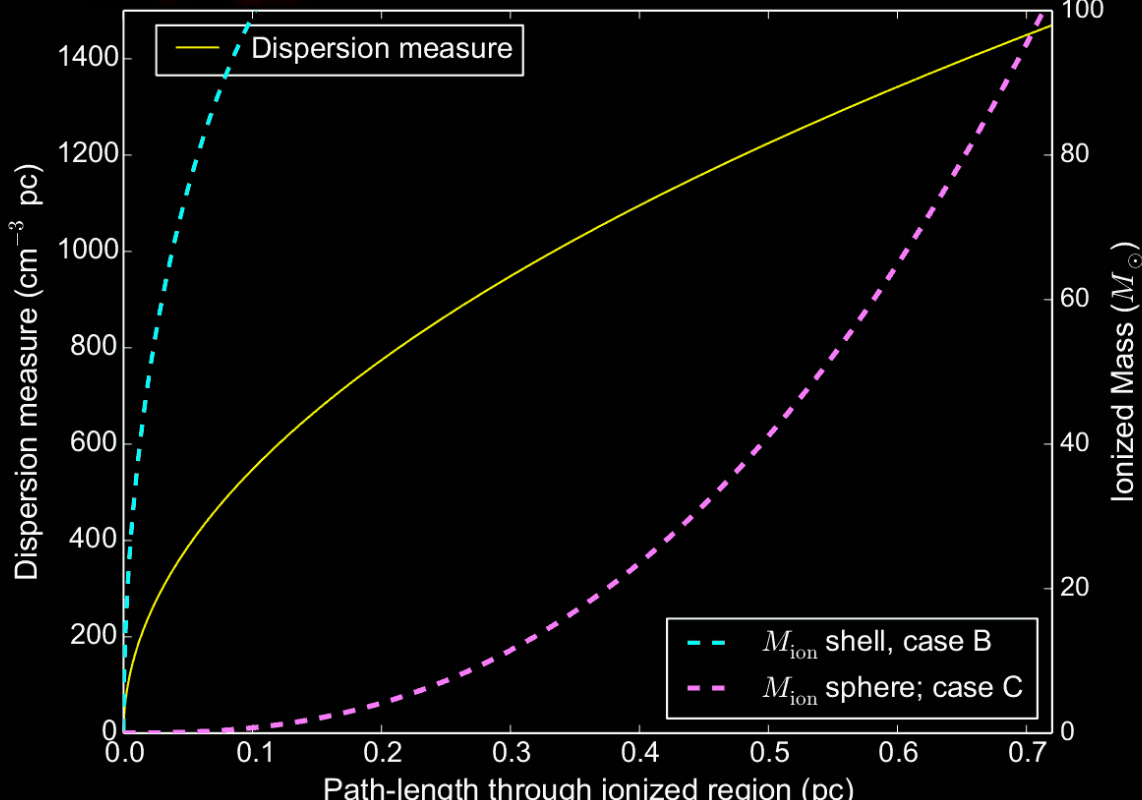
Lorimer et al

- •The origin of Fast Radio Bursts (RFBs) remains obscure
- •They are characterized by very high dispersion measures (DM),
- •Short timescales (ms) suggest a very compact source such as a neutron star (magnetar?) or stellar-mass black hole
- •could they be from young NS/BH, and dispersion measure be due to the propagating through the ionized SN ejecta?

Dispersion Measure and FRBs



SN 1986J is the only case where we can actually *see* radio emission from *inside* a SN



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- At present (t ~ 30 yr), ejecta are still optically thick at 1 GHz
- Extrapolated time of transparency at 1 GHz: 60 ~ 200 yr
- So to get a FRB from a young NS (or BH) you have to wait several decades after the SN
- Hard to get FRB dispersion from SN ejecta of > 500 cm^{-3} pc

SKA VLBI for GRBs and SNe

SKA VLBI for GRBs and SNe:

Why Image SNe and GRBs with VLBI?

- **Resolution:** we can resolve the explosive outflows.
- Normal supernova: 20000 km/s = 0.4 mas/yr at 10 Mpc, relativistic supernova or GRB, *c* = 0.6 mas/yr at 100 Mpc
- Determine ejecta speed, nature and geometry of the ejecta – jets? Clumpiness? Bipolar ejections?
- Radio emission is usually due to the interaction of the ejecta with the surrounding material: from interaction we can learn about both ejecta and the surrounding material
- Evolution of SN shells, shock acceleration, eventual merging with ISM, compact remnant of a core-collapse SN?
- Gravitational wave events, kilonovae
- Supernova rates, especially in dusty environments
- Direct distances with the expanding shock front method – out to Virgo cluster

SKA-VLBI Sensitivity

SKA Band	SKA-Core SEFD	Bandwidth	Remote Telescope SEFD	Baseline sensitivity 60s	Image sensitivity 1hr
	(Jy)	(MHz)	(Jy)	(μJy)	(μJy)
50% SKA1-mid	5.2	256	20	82	9
SKA1-mid	2.6	1024	20	29	3
Full SKA	0.26	2048	20	3	0.05

Expected 1σ sensitivities of various SKA-VLBI configurations at 3 to 8 GHz with the inner 4 km of SKA core phased up. 50% SKA1-MID (early operations): assuming five 25–30m class dishes and a 100m-class antenna. SKA1-MID – same configuration. Note at ~1–3 GHz and including SKA1-SUR as well will provide a similar sensitivity. Full SKA: 10× more sensitive than SKA1-MID. All the baseline sensitivities are given for a 100m-class remote telescope (Paragi et al 2015)

SN VLBI with SKA

- Higher sensitivity – detect faint SNe
- Follow SNe till late times - resolve older, more distant supernovae: Cas A would be 1 μJy and 6 mas at 170 Mpc - fill in the gap between supernovae and supernova remnants
- High signal-to-noise may allow more accurate size measurements well below resolution
- Astrometric and flux-density accuracy
- detect radio-only SNe
- wide-field VLBI – census of SNe in dusty star-forming galaxies