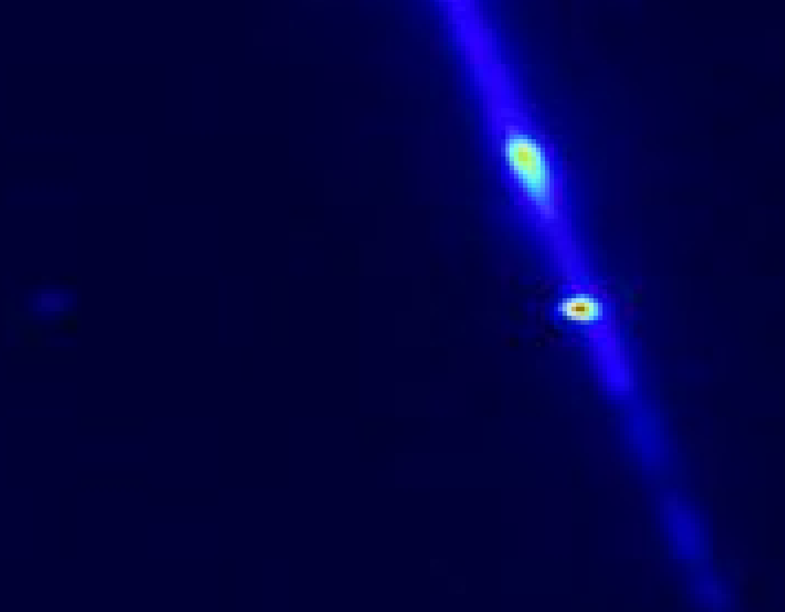
SN 1986J: a Neutron Star or a Black Hole in the Center?

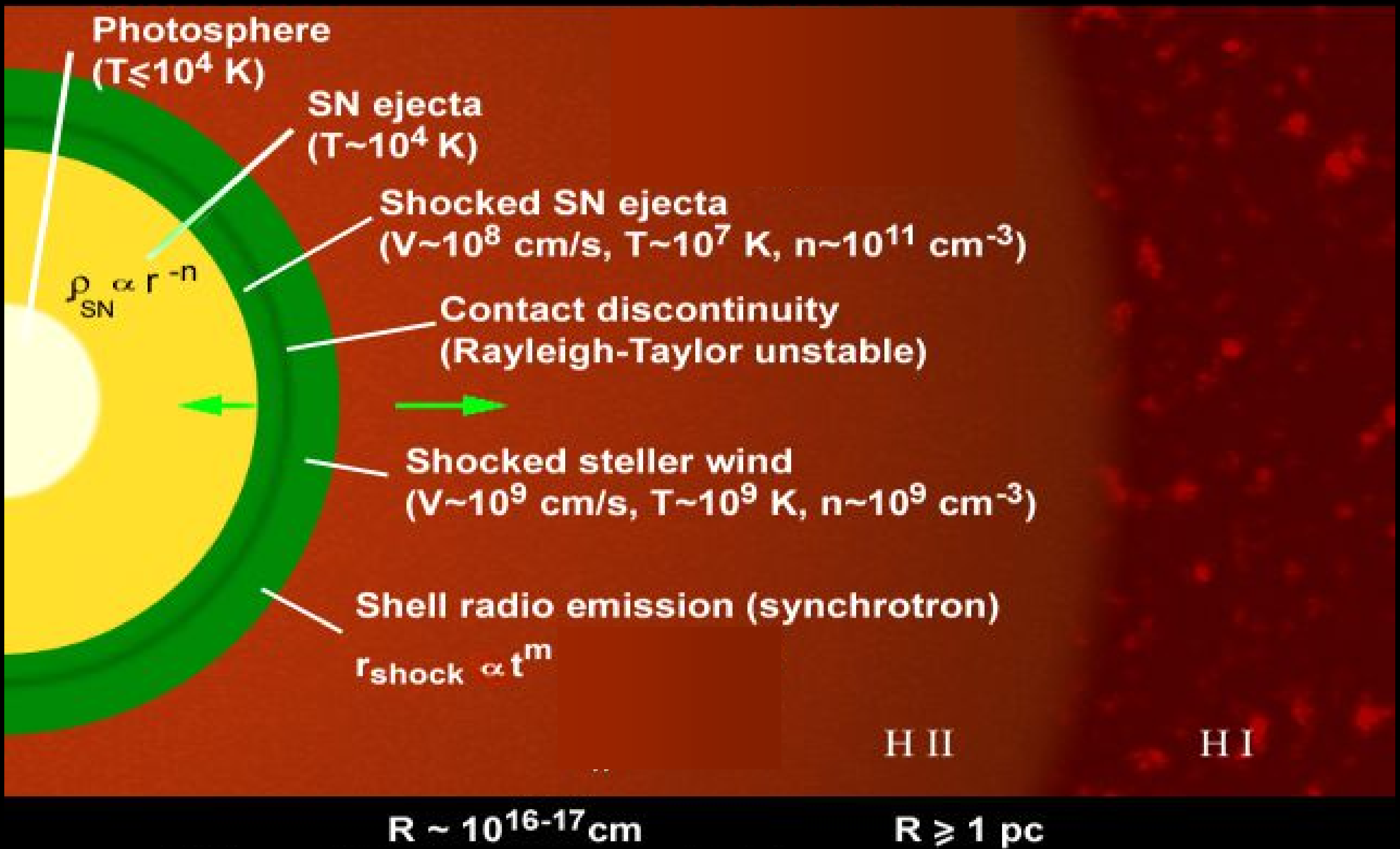


Michael Bietenholz, Hartebeesthoek Radio Observatory, South Africa *also* York University, Canada
Norbert Bartel, York University, Canada

Radio Observations of SNe

- Optical: ~1000 SNe are detected each year, both Type I and Type II
- Radio: Only core-collapse (Type II, Type I b/c) detected in radio to date. Only a few SNe detected each year in radio; total radio detections to date ~100
- Except for Magellanic clouds (i.e. SN 1987A), the ***only*** way to resolve the ejecta in the first ~century is VLBI
- Only a handful have been resolved with VLBI (radio bright and < 30 Mpc)

Standard Model of SN Radio Emission

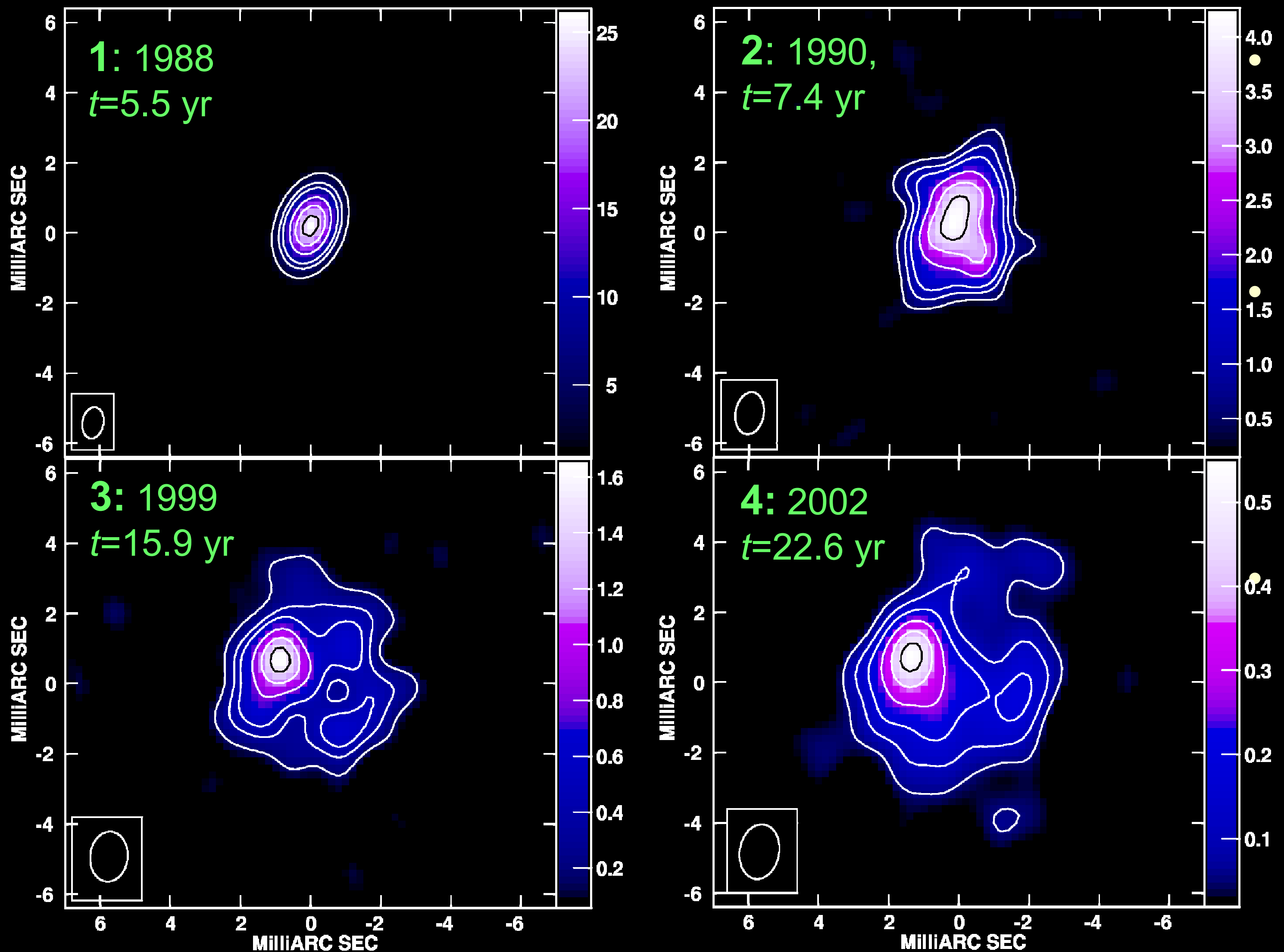


Chevalier, 1982

Introduction to SN 1986J

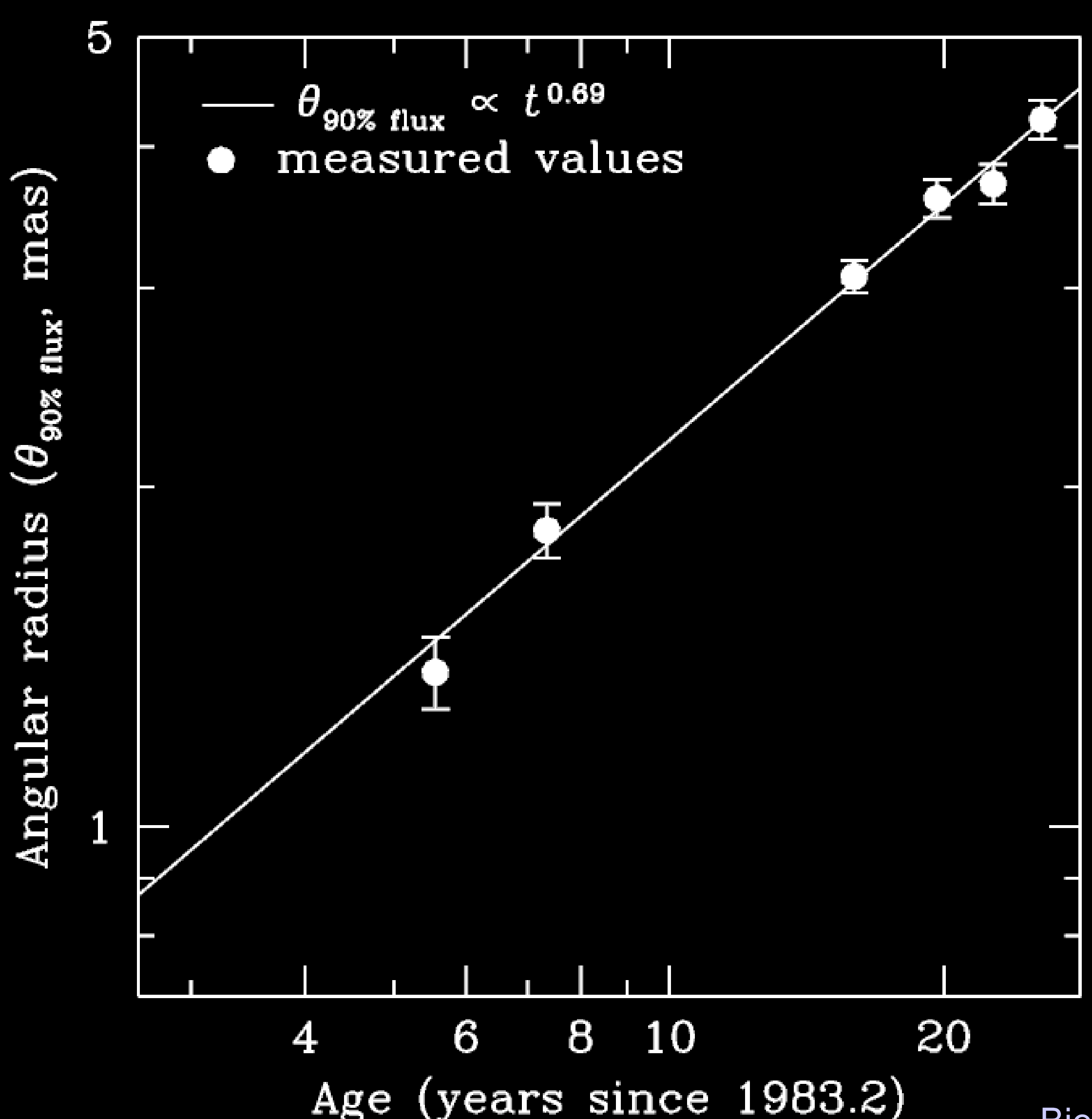
- SN 1986J discovered in the radio in 1986
- In NGC 891, *D* = 10 Mpc (NED)
- Supernova happened in 1983.2 ± 1.1
- Massive progenitor (>20 Msol)
- Optical spectrum was unusual: prominent Hα lines but narrow linewidths → classified as a Type IIn SN (Rupen et al. 1987)
- Very radio luminous. One of the 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

Evolution of SN1986J



- VLBI images at 8.4 or 5 GHz
- Contours and color-scale both show radio brightness
- FWHM resolution indicated at lower left

Expansion of SN 1986J

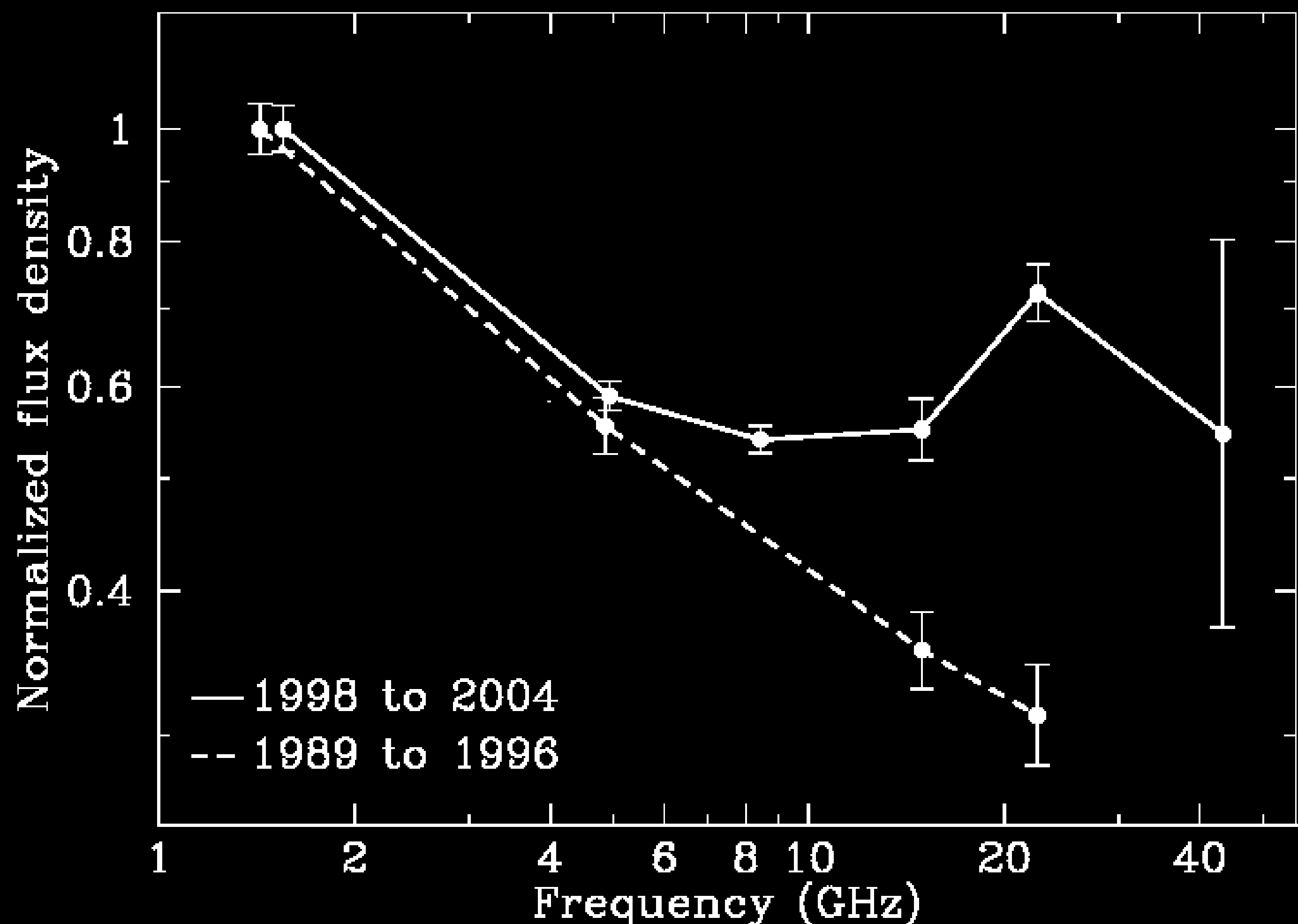


- Evolution of the outer angular radius of SN 1986J
- Powerlaw evolution with angular radius, $\theta \propto t^{0.69}$
- Expected in case of powerlaw density profiles for ejecta and CSM (Chevalier)

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

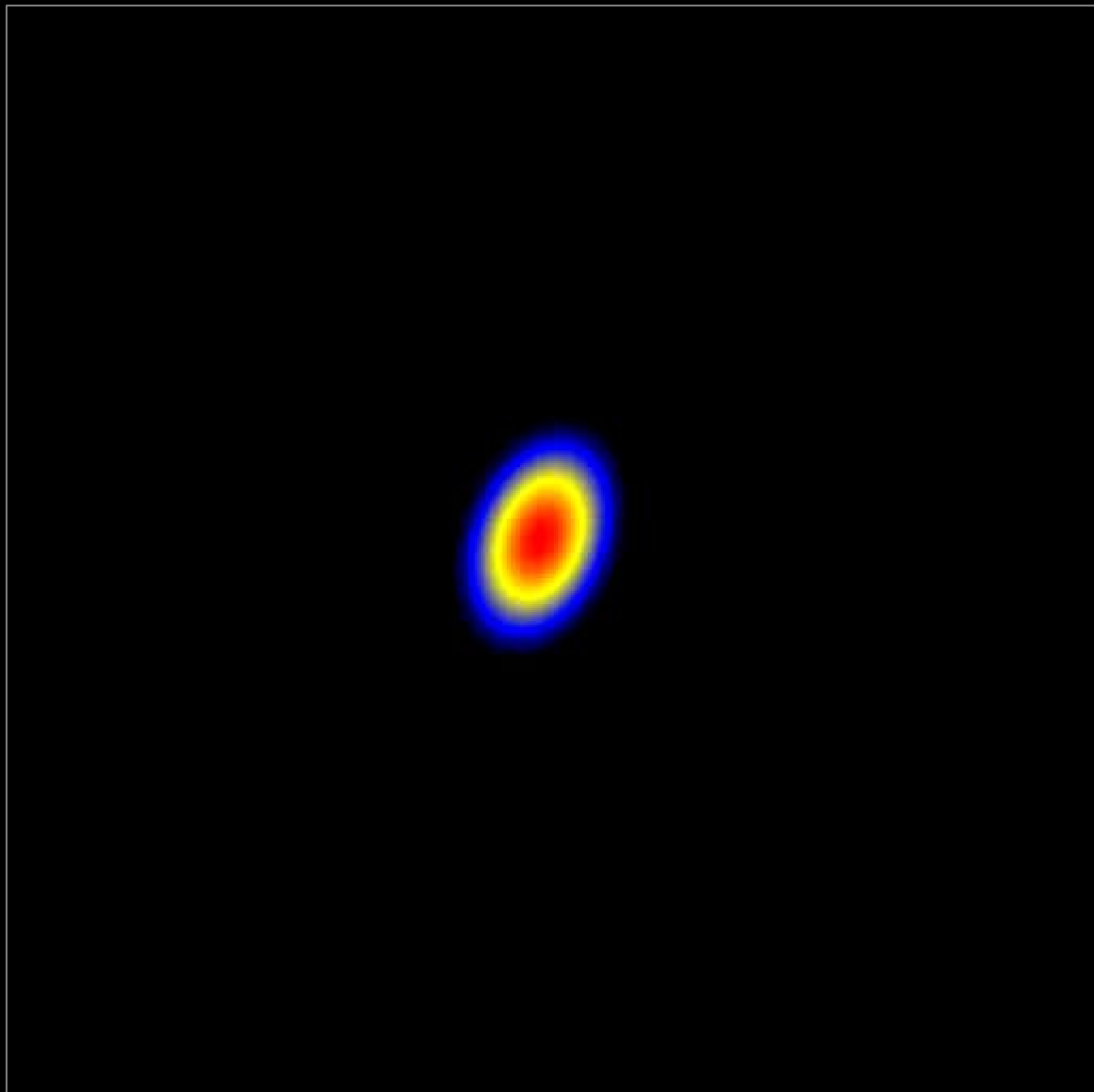
Bietenholz, Bartel & Rupenl 2010

Radio Spectrum of SN 1986J



VLA total flux density measurements

Bietenholz, Bartel, & Rupen, 2004, Science, 304, 1947

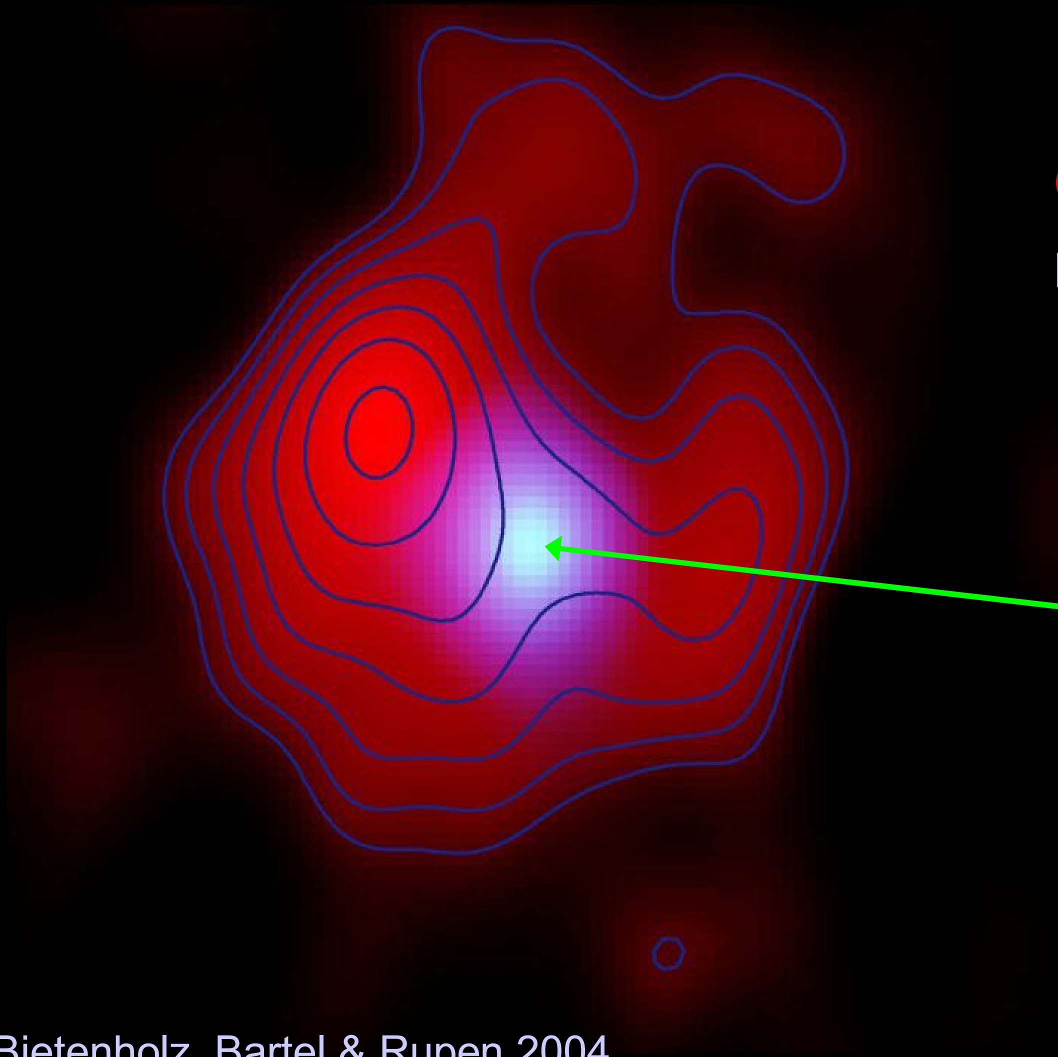


1 mas

Bietenholz & Bartel 2017

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

Central Component in SN1986J



Multi-frequency VLBI Image:

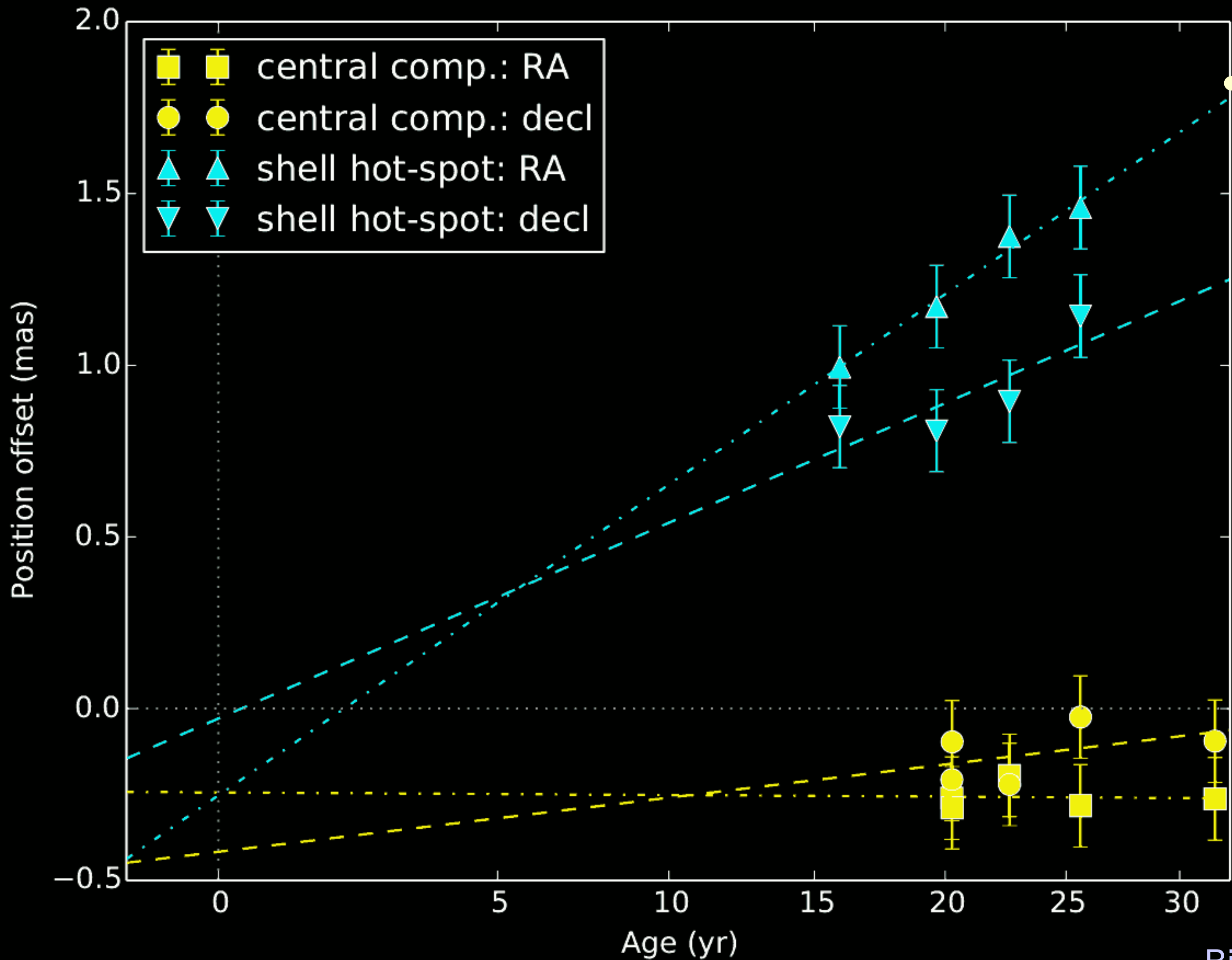
Contours, red: 5 GHz

Blue → white: 15 GHz

Youngest Neutron Star or Black Hole?

Bietenholz, Bartel & Rupen 2004

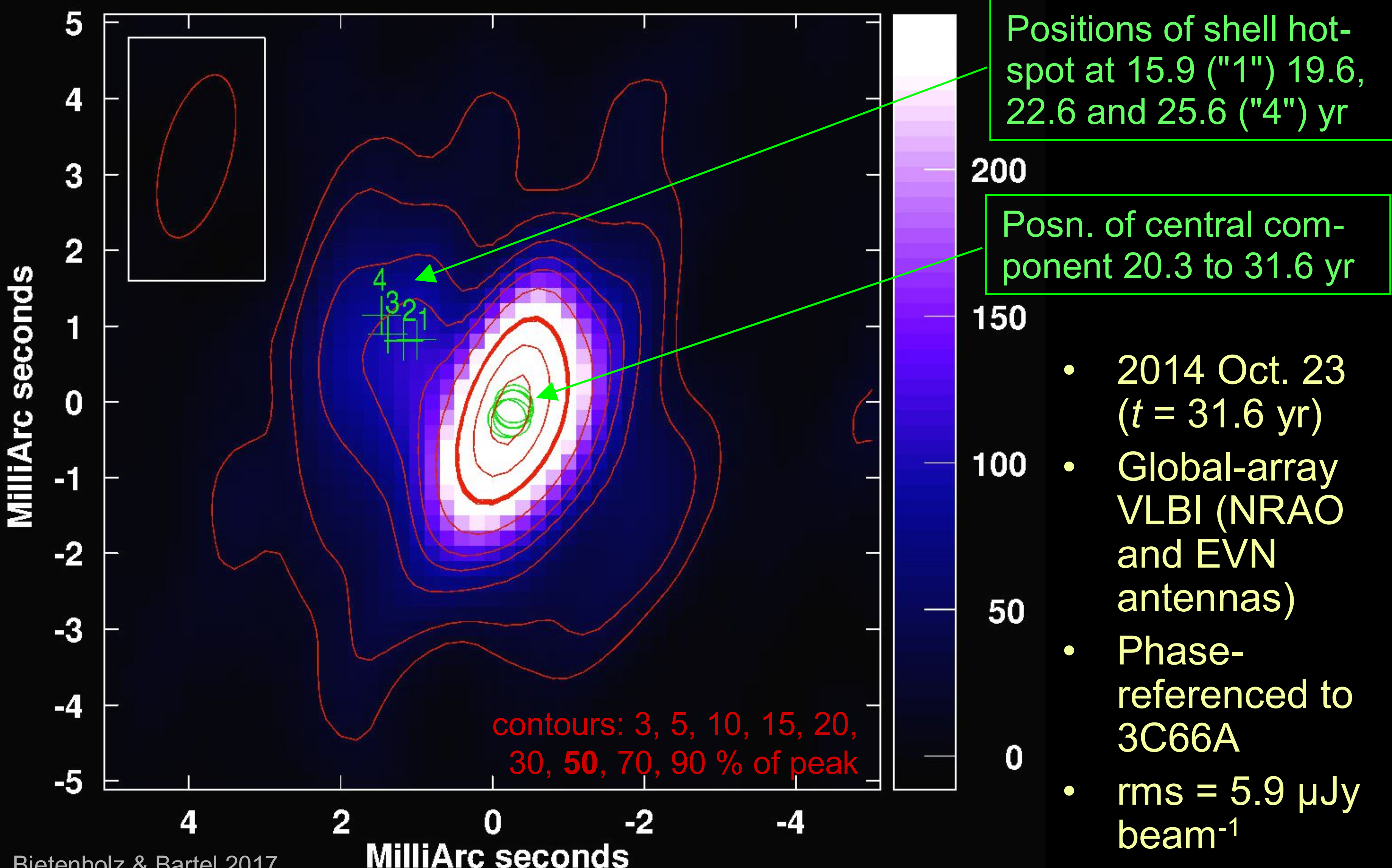
Motion of the Two Hotspots



- Time axis is non-linear, so $x \propto t^{0.69}$, similar to outer radius, $\theta_{out} \propto t^{0.69}$

Bietenholz & Bartel 2017

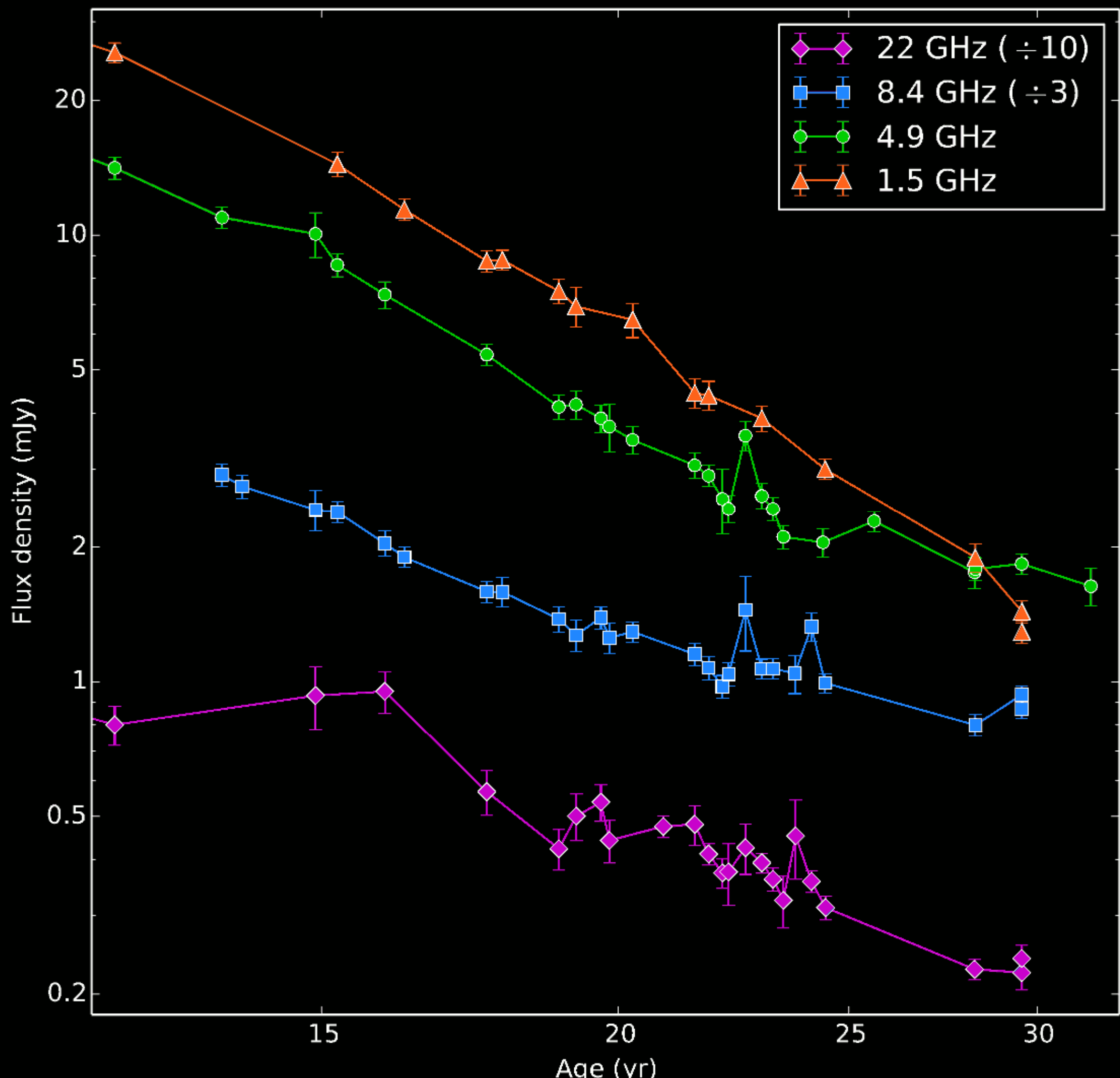
VLBI Image at 5 GHz in 2014



Bietenholz & Bartel 2017

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

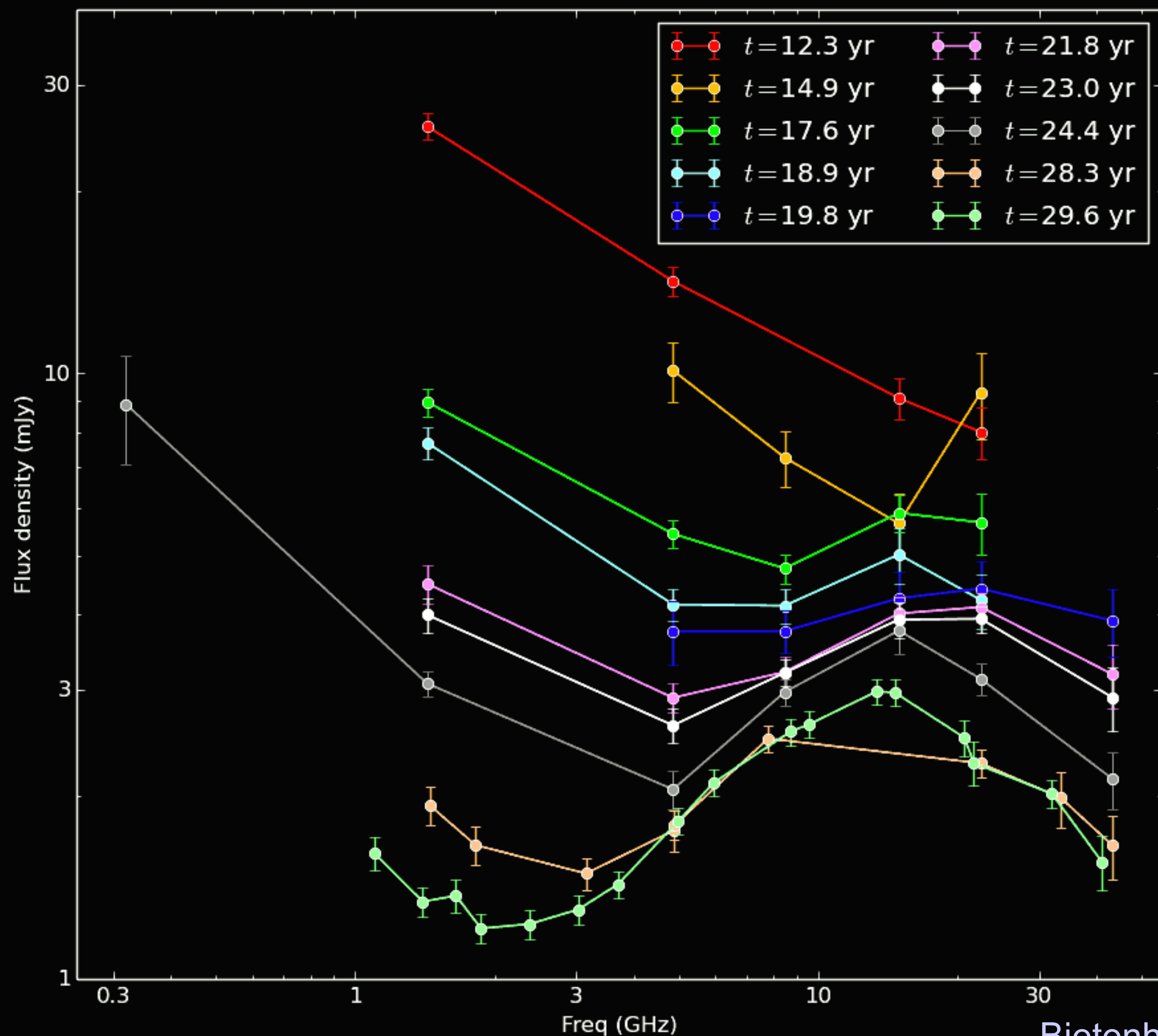
Multi-frequency Radio Lightcurve



- The radio lightcurves of SN 1986J at several different frequencies, as measured with the Very Large Array
- The slope of the decay is different at different frequencies

Bietenholz & Bartel 2017 *in prep.*

Evolution of the Spectral Energy Distribution (SED)

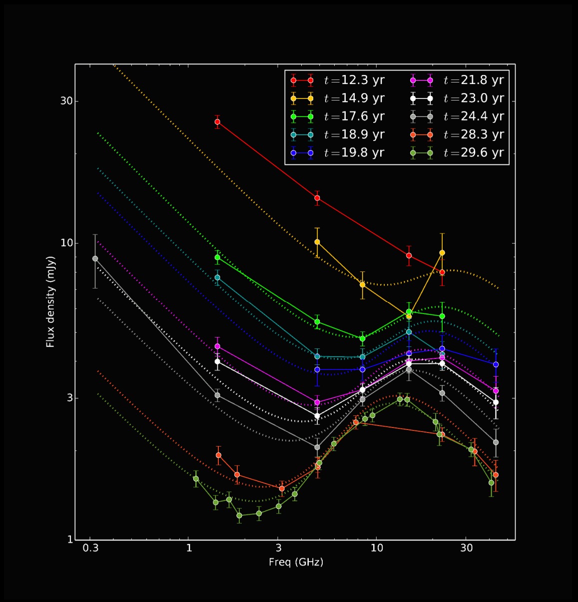


- VLA measurements:
- Inversion in SED first appears at *t* = 14.9 yr
- both inflection point and high-frequency turnover evolve downward with time

Bietenholz & Bartel 2017 *in prep.*

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



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

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

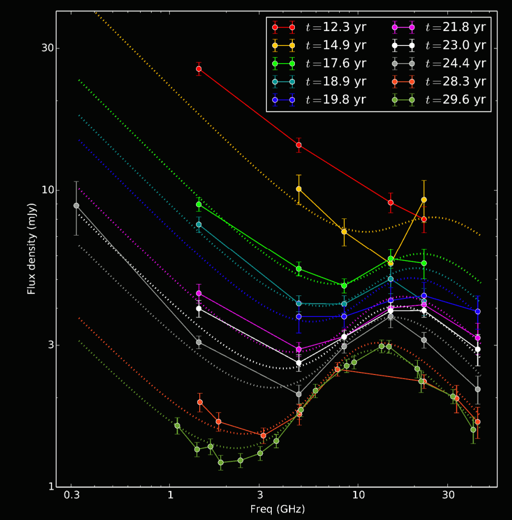
Results:

- $S_{\rm shell}$ = 7.1 ± 0.2 mJy
- $b_{\rm shell}$ = –3.92 ± 0.07
- $\alpha_{\rm shell}$ = –0.63 ± 0.03

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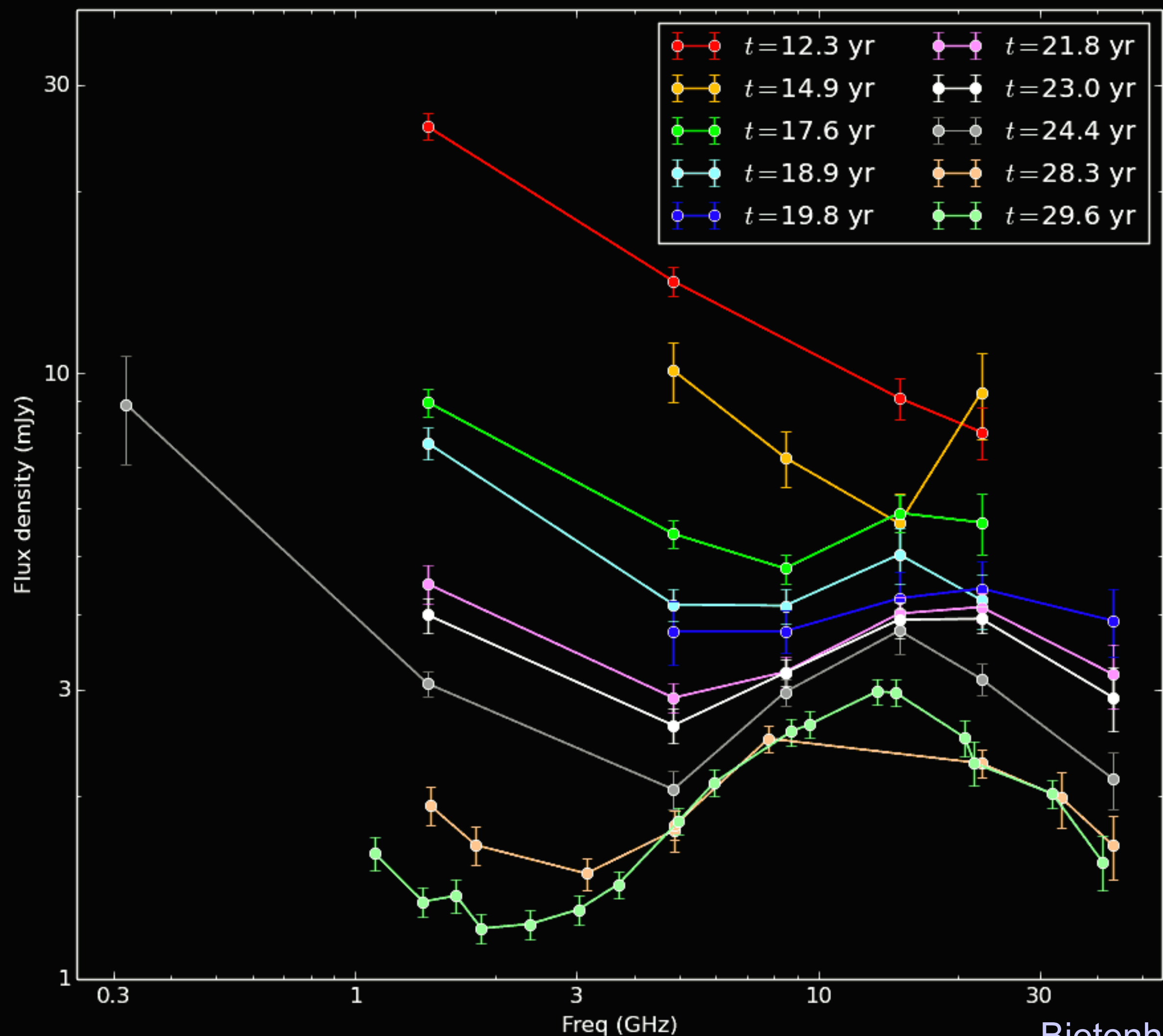

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Bietenholz & Bartel 2017 *in prep.*

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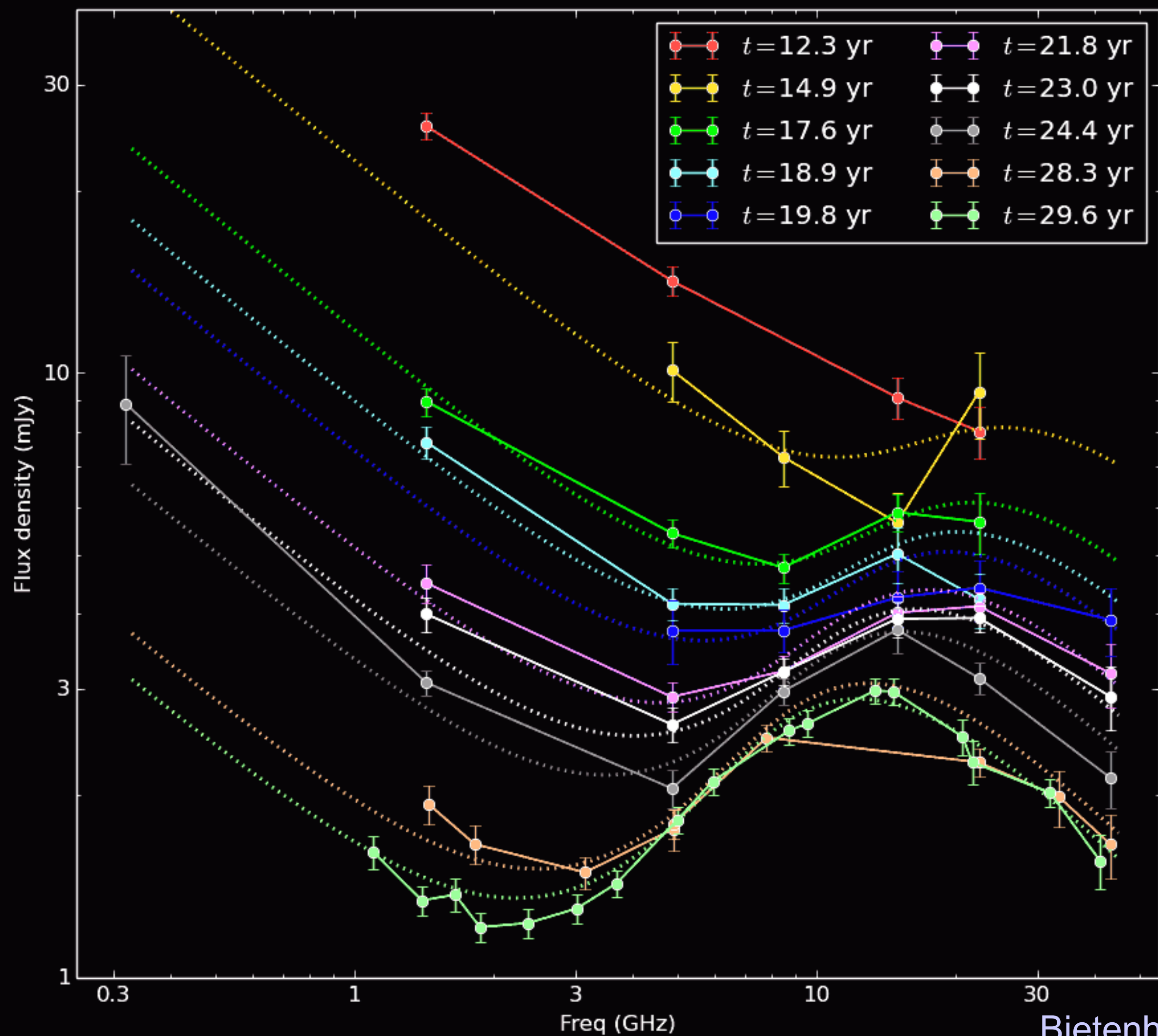
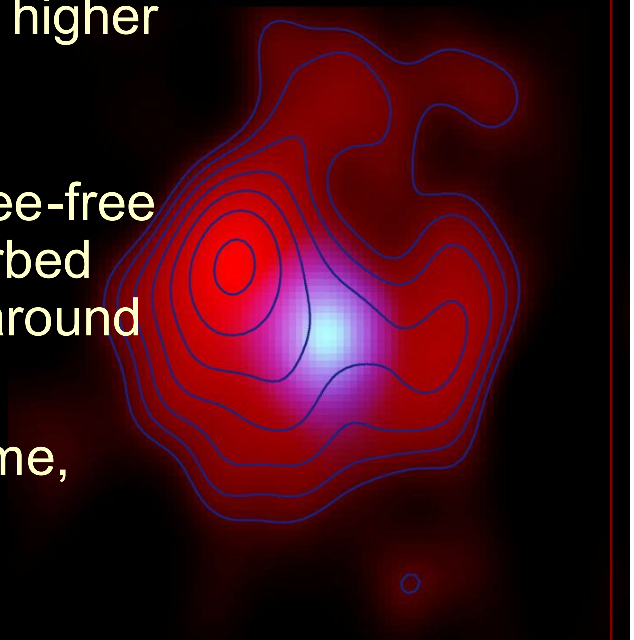


- thin dotted lines show the fitted shell + partly-absorbed central component model
- inflection point and high-frequency turnover move down with time

Bietenholz & Bartel 2017 *in prep.*

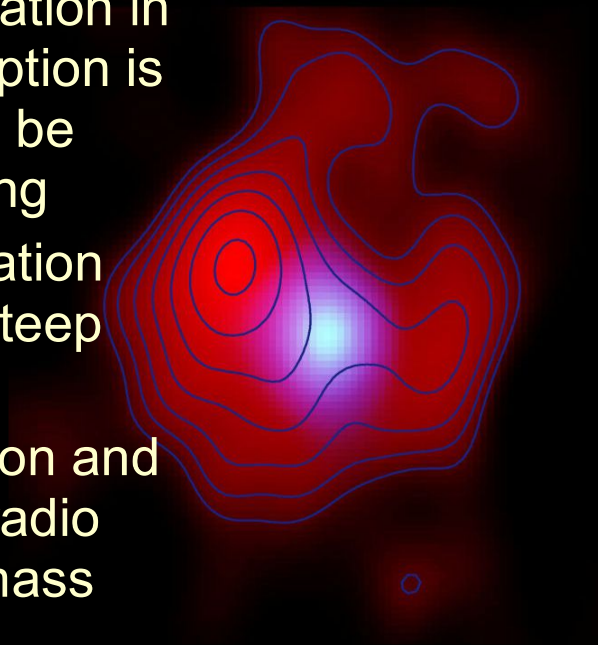
What Do We Know about the Central Component?

- 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?

- 1) Interaction of the shock with a dense condensation in the CSM, by chance central in projection. Absorption is due to the CSM clump itself, not the ejecta. Can be ruled out: Its too stationary, bright, and long lasting
- 2) 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.
- 3) An accreting black-hole system. Central location and stationarity are expected, but it has a far higher radio luminosity, and L_{radio}/L_X than any known stellar-mass black hole systems.
- 4) 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)



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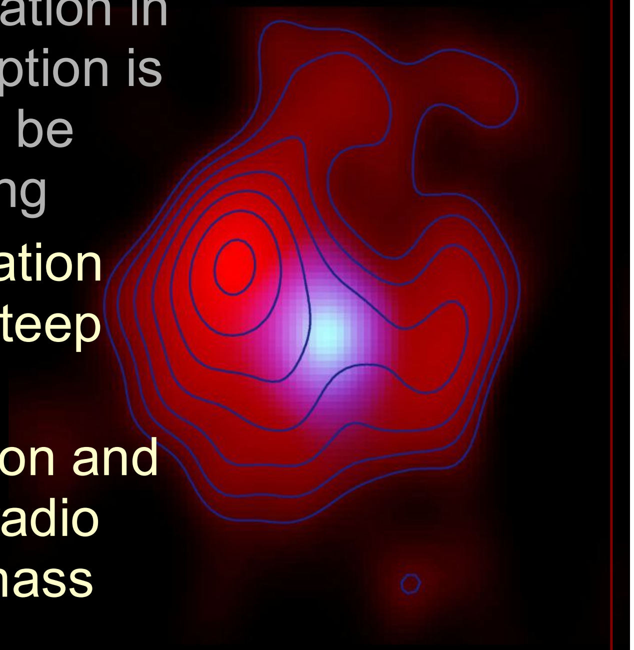

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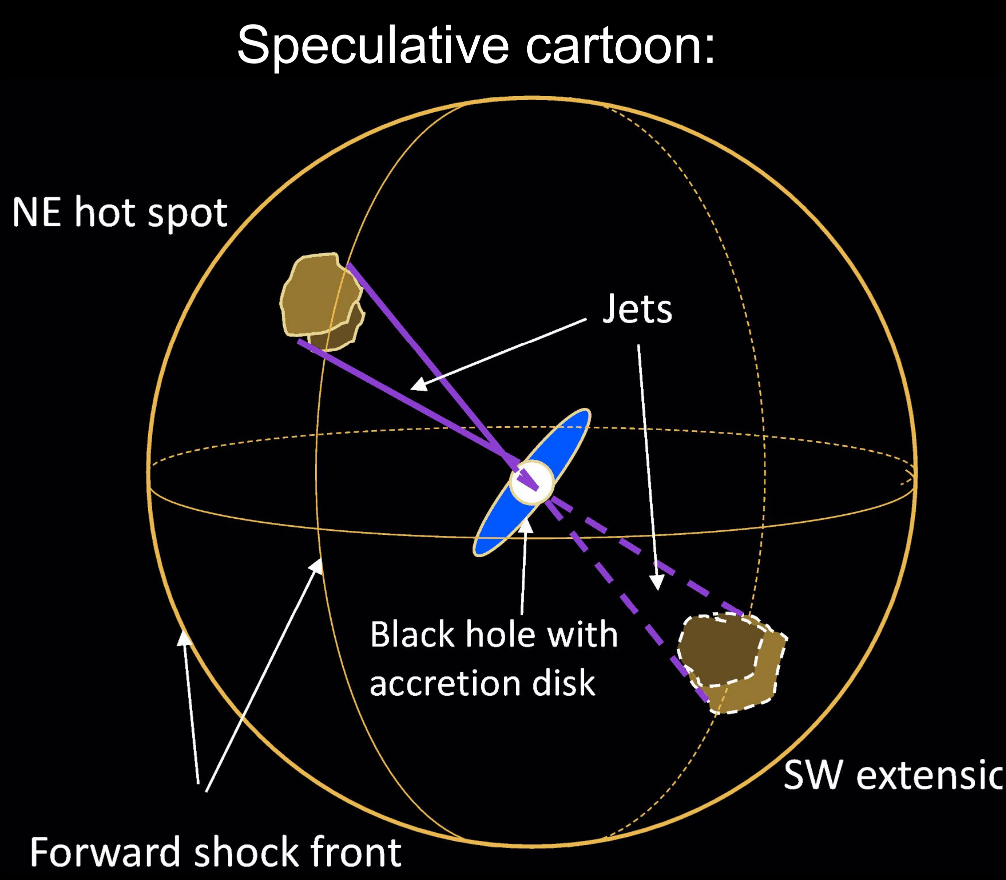
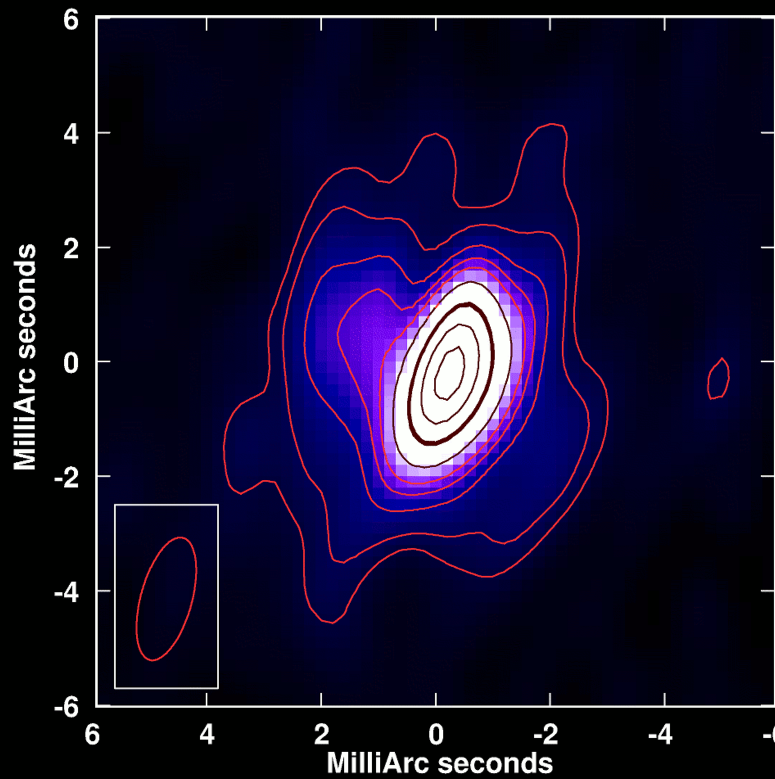
Black Hole with Jets???





- Could SN 1986J host an accreting black hole with jets, where the jets produce the NE hot-spot and the faint SW extension?