How small can you get?

reducing data volume, retaining good imaging

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thanks to Crystal Brogan and all ALMA colleagues,

Nick Wrigley and all e-MERLIN colleagues

ALMA

EUROPEAN ARC

ALMA Regional Centre || UK

eMERLIN

IVOA

EUROPEAN VLBI NETWORK

RadioNet

MANCHESTER 1824

UNIVERSITY OF OXFORD

UNIVERSITY OF CAMBRIDGE

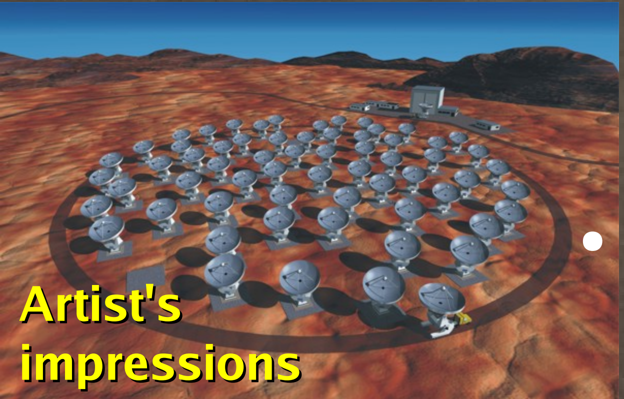
UK Astronomy Technology Centre

Rutherford Appleton Laboratory

Science & Technology Facilities Council

ALMA

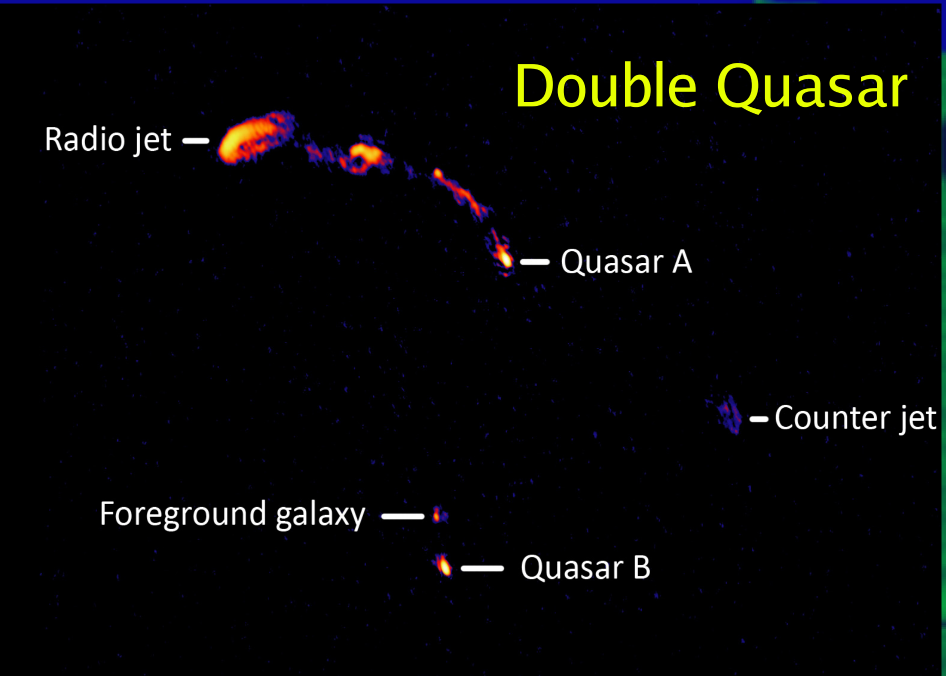
- Main array 50x12-m dishes
  - Compact array 12x7-m, plus 4x12-m total power
- 25m to ~15 km baselines in full operation
  - 0.8 –6 arcsec @ λ0.4 - 3 mm, 0.1-km baseline
  - 0.005 - 0.04 arcsec @ λ0.4 –3 mm, 15-km baseline
- Eventually 10 bands between 30 to ~950 GHz
- FoV 7 –50 arcsec @ λ0.4 - 3 mm, 12-m dishes
  - Mosaicing, single dish fill-in



- Closest pads 15-m separation
  - Nearly filled aperture at asec resolution

e-MERLIN

- 5 x 25-m dishes, 1x32-m, sometimes Lovell 75-m
  - Baselines 10 –217 km
- Broadband 1.2-1.7, 4-8, 21-26 GHz receivers
  - Optical fibres, broadband electronics (2 GHz/pol)
  - New WIDAR correlator
- First images: 0.5 GHz bandwidth at 6 GHz



High resolution imaging arrays

- ALMA <1300 $\theta_{synthesised}$ (<7000 pixels) per $\Theta_{PrimaryBeam}$
  - Up to 8 GHz bandwidth, max. 4 x 4096 channels (2 pols)
- e-MERLIN <8000 $\theta_{synthesised}$ (<40000 pixels) per Θ_{PB}
  - 2 GHz bw, 16 IFs, ~32000 channels (not all IFs at once)
- Early stages of ALMA (8-16 ants), e-MERLIN (5-6 ants)
  - Pipelines not yet operational, testing on desktops
- Even in full ops, users will want to tweak image resolution, averaging etc.
  - More extensive manual processing of innovations
  - Teaching radio interferometry
- Typical raw datasets tens-100s Gb already

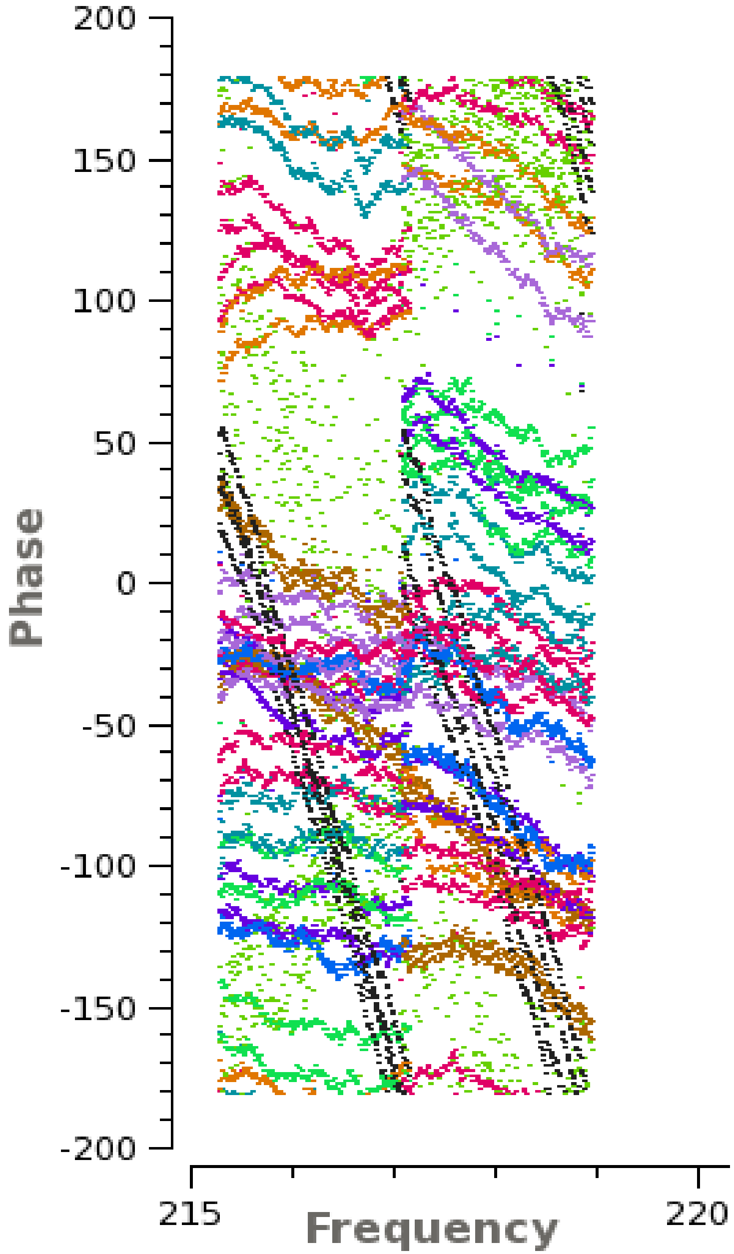
Limited issues considered

- No significant beam-squint nor anisoplanaticism
- Do need to image full field of view
  - Confusion issues for e-MERLIN at full sensitivity
  - Many ALMA sources will fill (many) primary beams
- Both will have heterogenous antennas
  - But full mix not yet being used
- Post-correlation only
  - Limited configurations in comissioning
  - Implementable in CASA
  - Intelligible to average user with some experience
- Incremental averaging depending on data and science

Science target constraints

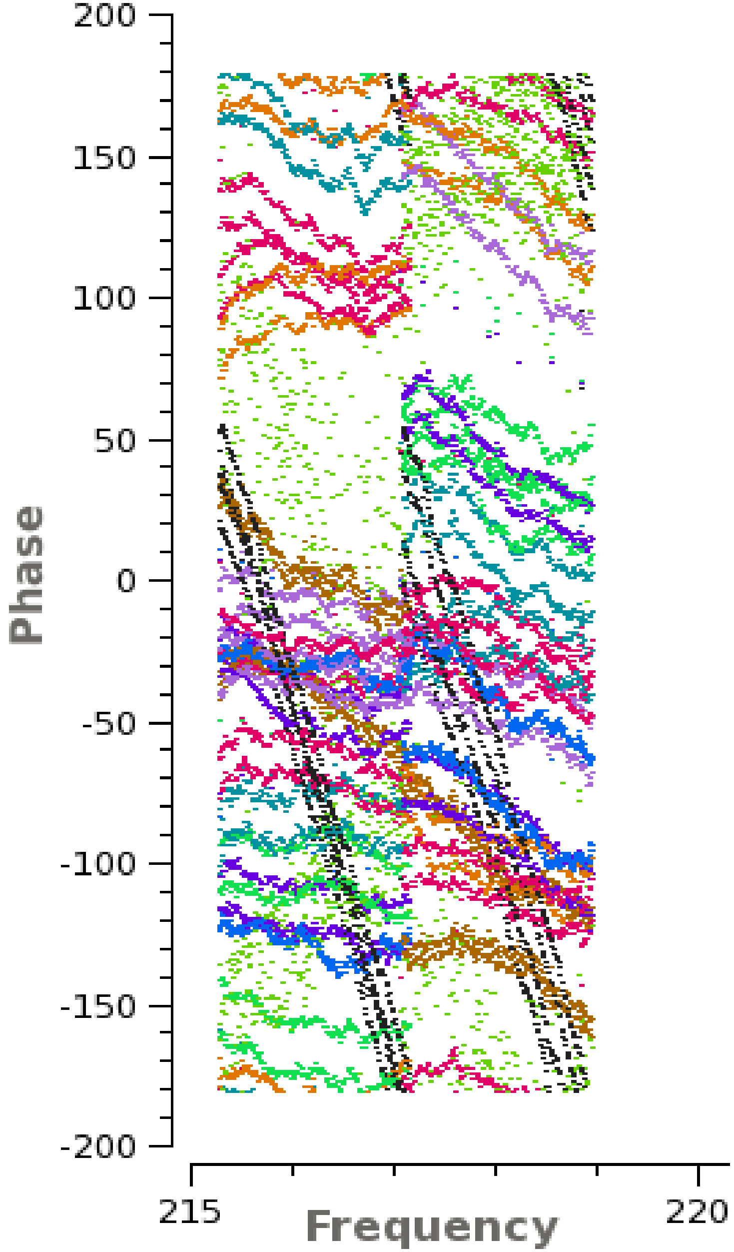
- These will override anything later in this talk
- milli-sec source variability or rapid Doppler tracking
    - PSR, solar, radar, spacecraft tracking, SETI etc.
- At least 3, ideally ~10 chans per spectral line
    - Spectral resolution >10^7 for <1 km s^{-1} lines
        - Even higher for e.g. maser physics/polarization
    - Factorizable channelization if want to combine arrays
- Shortest spacing constrains largest spatial scale
    - e-MERLIN <20x θ_{synth} (max:min baseline 217:20 m)
        - Snap-shots only for bright point-like sources
        - MFS helps fill aperture in long tracks ($\Delta\nu/\nu \leqslant \frac{1}{2}$)
    - Unwise to smooth to larger resolution

First post-correlation issues



- Spectral resolution for rfi excision
  - or avoiding ALMA lines
- Delay error $(\delta\phi/2\pi)/\delta\nu$ on continuum point at phase centre
  - e.g. $\delta\phi=100^o$ (0.55π), $\delta\nu=1$ GHz $\Rightarrow$ 0.278 ns delay
    - Can be ~100 ns: need $\delta\nu\leqslant2.5$ MHz for $\delta\phi/2\pi$/chan$\leqslant1/4$
      - Spectral resolution $>10^5$
      - Talk by Bourke
    - No instrumental delay errors when fully commissioned

First post-correlation issues



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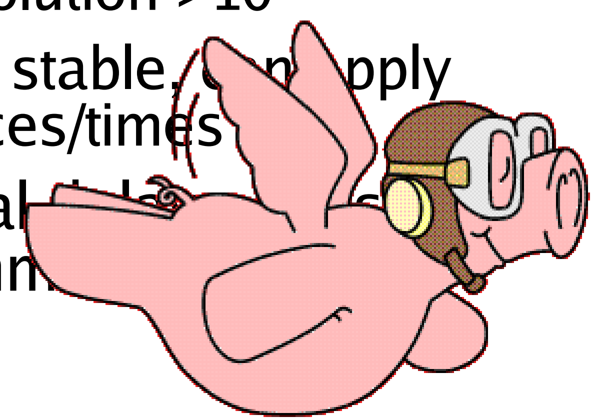
    - Can be ~100 ns: need $\delta\nu\leqslant2.5$ MHz for $\delta\phi/2\pi$/chan$\leqslant1/4$
      - Spectral resolution $>10^{5}$
      - Usually very stable, c n pply across sources/times
    - No instrumental when fully comm



Time-variable atmospheric errors

- Want to sample at better than $d\phi/dt < \pi/6$
  - cm-λ phase-rate: few min Solar min; few sec active $\odot$
  - mm-λ: few min short baselines (at ALMA site);
    - sub-mm-λ and/or km baselines: (few) sec
  - ALMA Water Vapour Radiometry every (few) sec
    - Model phase corrections
  - T_{sys} amp corrections few min, eventually more rapid
  - ALMA astrophysical phase ref cycles down to 20:2 sec
- Strongest time constraints will *tend* to be:
  - e-MERLIN wide-field imaging
  - ALMA calibration
    - Maybe also mosaicing

Imaging constraints on time/channel averaging

- Assume all editing and external calibration applied
  - Their constraints can hereafter be ignorred
  - In comissioning, keep unaveraged data just in case ...
- Typical current correlator outputs:
  - ALMA 4 x ⩽2 GHz spw, dual polarization
    - TDM t_{int} ⩽1 s, channel dν 15.625 MHz
    - FDM t_{int} ⩾1 s, channel dν ⩽ 0.488 MHz
  - e-MERLIN 4 (eventually 16) x 128-MHz IFs
    - t_{int} 1 s, dν 0.25 MHz per pol. at present
- Eventually ~ infinite variety of configurations....

Wide-band, wide field continuum

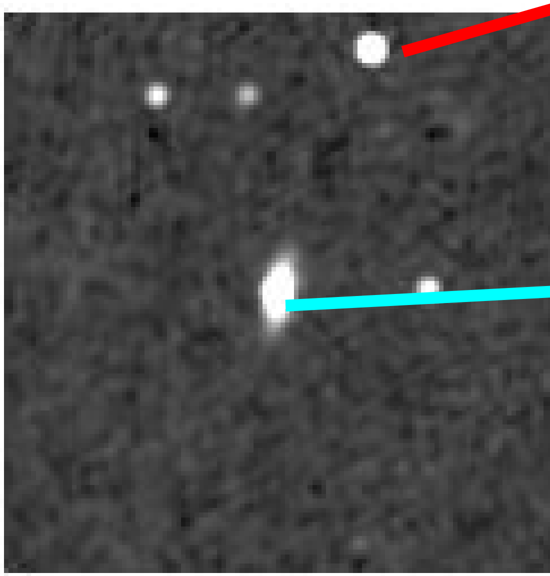
- Frequency-dependent
  - Bandwidth amplitude smearing
  - Source spectral index
    - Assume good MFS imaging at order ⩾1
  - Rotation Measure synthesis (not considered here)
- Time-dependent
  - Time amplitude smearing
  - Phase rate
  - Dynamic range
- Effective array $PB = \lambda / \Sigma W_{ij\nu} D_{ij} / \Sigma W_{ij\nu}$ (*Strom04; Wrigley*)
  - e.g. 0.05/27 or 6.3 arcmin for e-MERLIN at 6 GHz

Bandwidth smearing

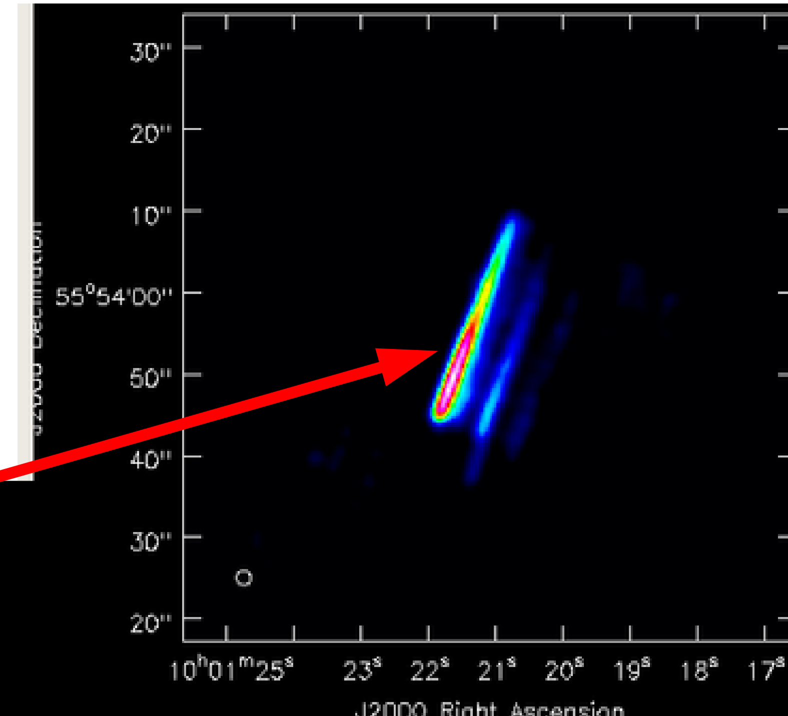
- Simplistic concept:
  - Resolution $\theta_B \sim \lambda/B$ where B is longest baseline
    - within a factor ~2 depending on weighting, *uv* coverage
    - ignor direction-dependent projection effects for non-circular *uv* coverage
  - Source component position θ depends on $\Sigma\lambda/B_{ij}$
    - i.e. scaling in *uv* plane
  - The flux will be smeared when λ changes enough for θ to change by an appreciable fraction of θ_B
- NRAO Summer School 1999 Taylor, Carilli & Perley
  - (NRAO99) ⁋ 18 Bridle & Schwab
  - Use their expressions to derive convenient relationships

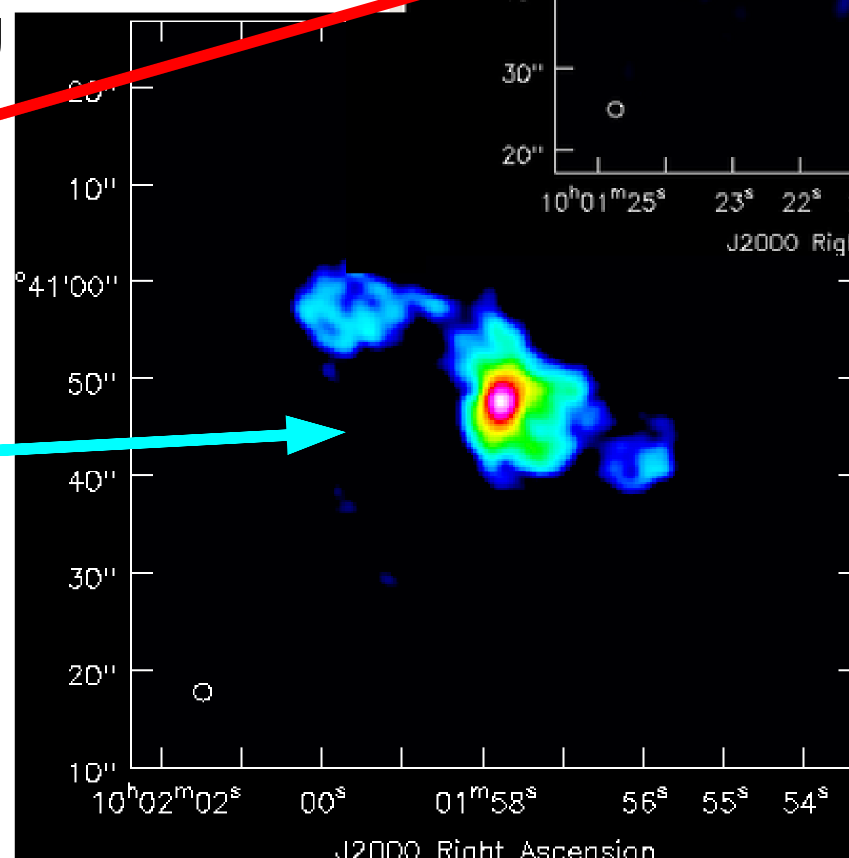
VLA Bandwidth smearing

- ν 1.4 GHz, dν 50 MHz
- Radial smearing
  - Relatively easy to subtract
  - Possible to reconstruct (*Cornwell*)?
    - Could be volume saving
    - Time-expensive



NVSS

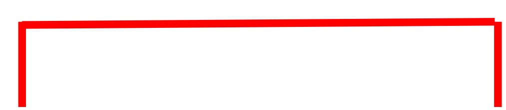




Bandwidth Smearing

- Parameterized using $\beta = d\nu/\nu\ \theta/\theta_B$
- Apparent/real flux density *R* of source θ from pointing centre when channels are averaged to $d\nu$
- 'Tapered Gaussian' distribution of *uv* plane samples
  - Reasonable for ALMA ES, e-MERLIN, most EVLA
    - Uniform coverage also considered by B&S but not here
- Case 1.4 Gaussian shape of $d\nu$

  - Suitable for few channels with e.g. Hanning smoothing
- Case 1.3 $d\nu$ square profile



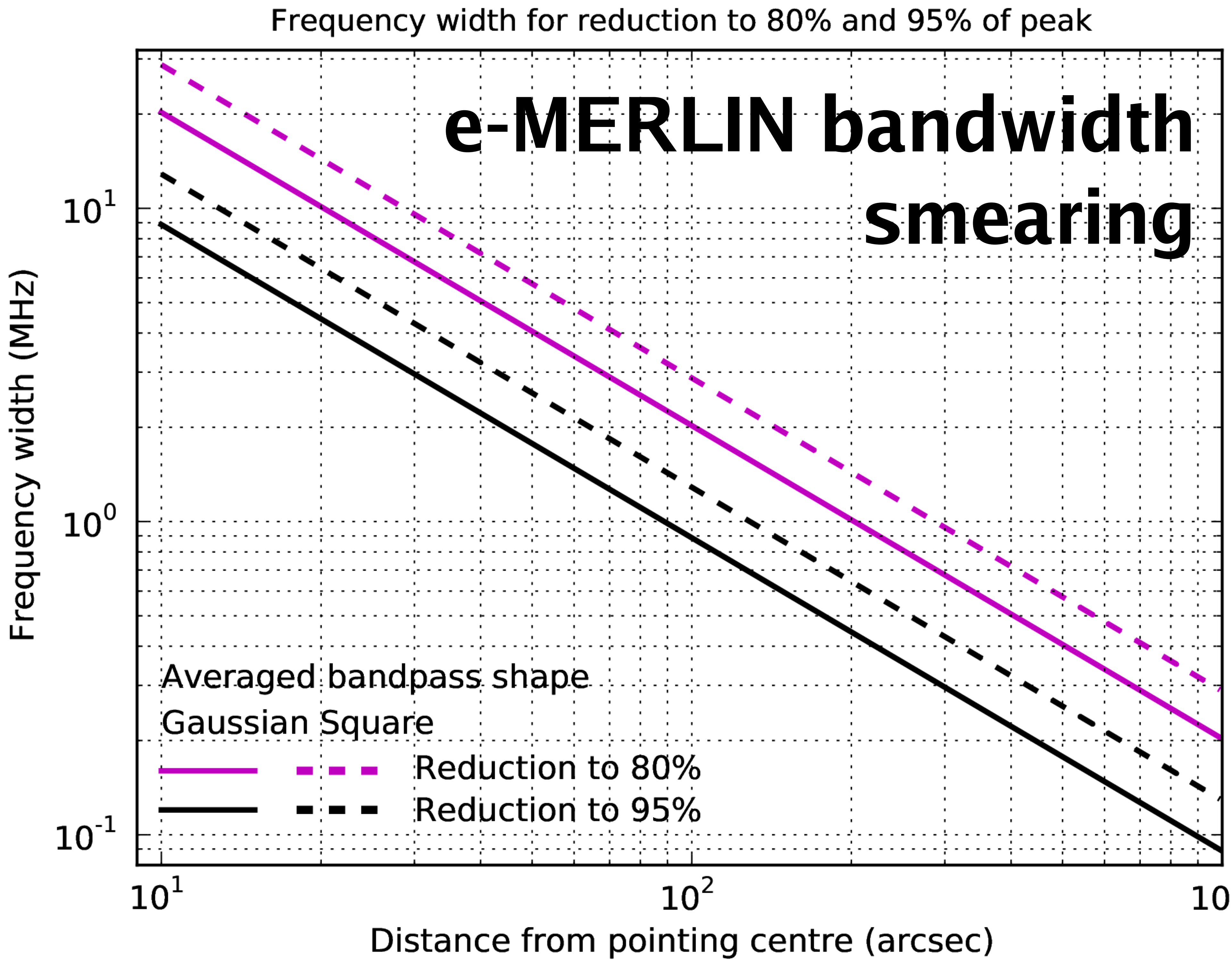
  - Suitable for many channels, well-behaved bandpass

Gaussian *uv*, Gaussian bandpass

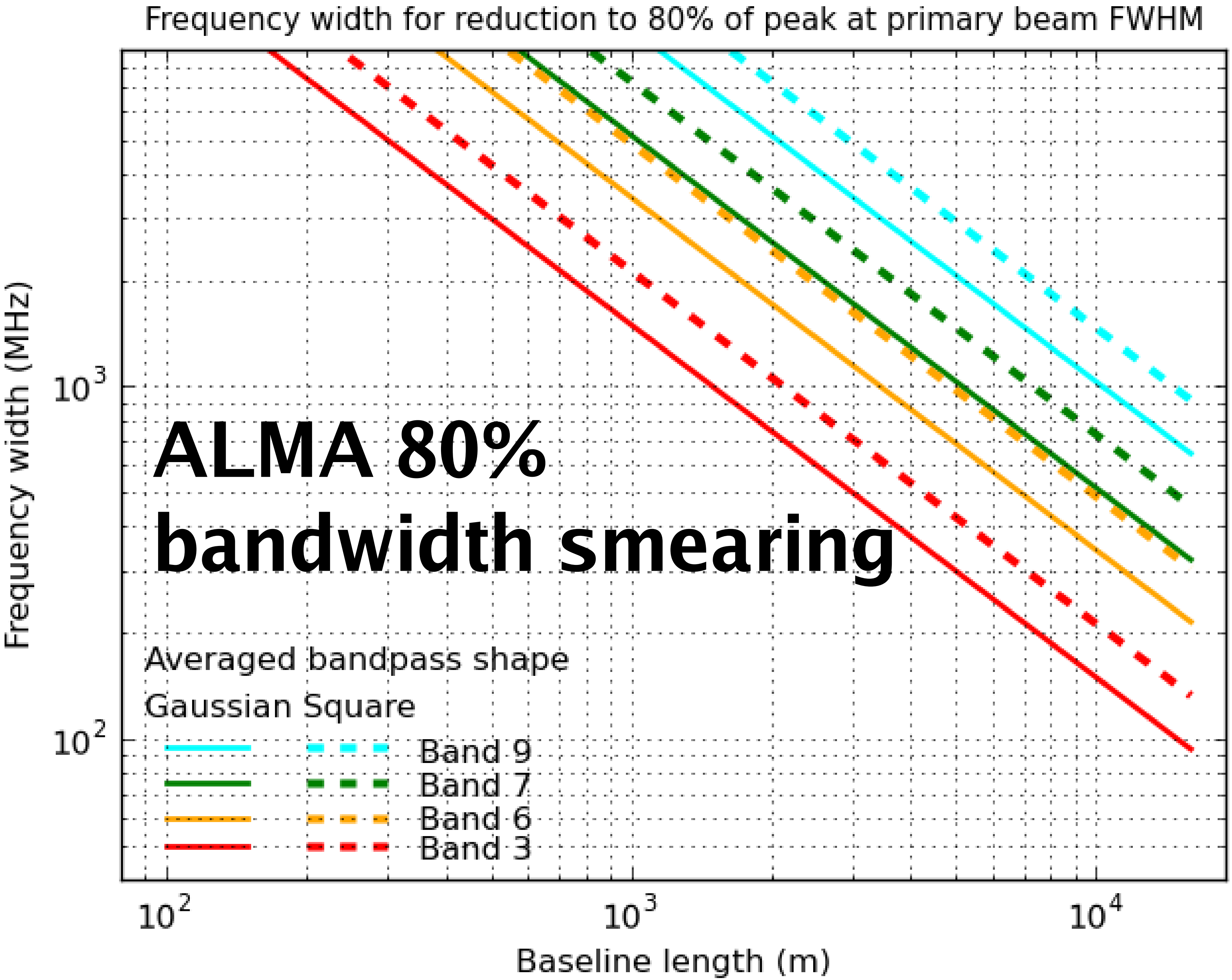
- $\beta = d\nu/\nu \ \theta/\theta_B$
- $R = 1/\sqrt{(1 + \beta_{GG}^2)}$
- Approximate predictions for easy use
  - e-MERLIN: Limited range of ν; fixed *B*; large span of θ
    - Ready reckoner: $d\nu_{GG} = \beta_{GG}\, \nu\, (\theta_B/\theta)$ x *consts*
      - User inputs *R*, ν, θ, θ_B
  - ALMA: Wide ranges of ν and *B*; often image to θ_{PB}
    - Ready reckoner: $d\nu_{GG} = \beta_{GG}\, c\, (1/B\, \theta)$ x *consts*
      - User inputs *R*, θ, *B*
  - *consts* converts from user units (asec, MHz etc.) to SI

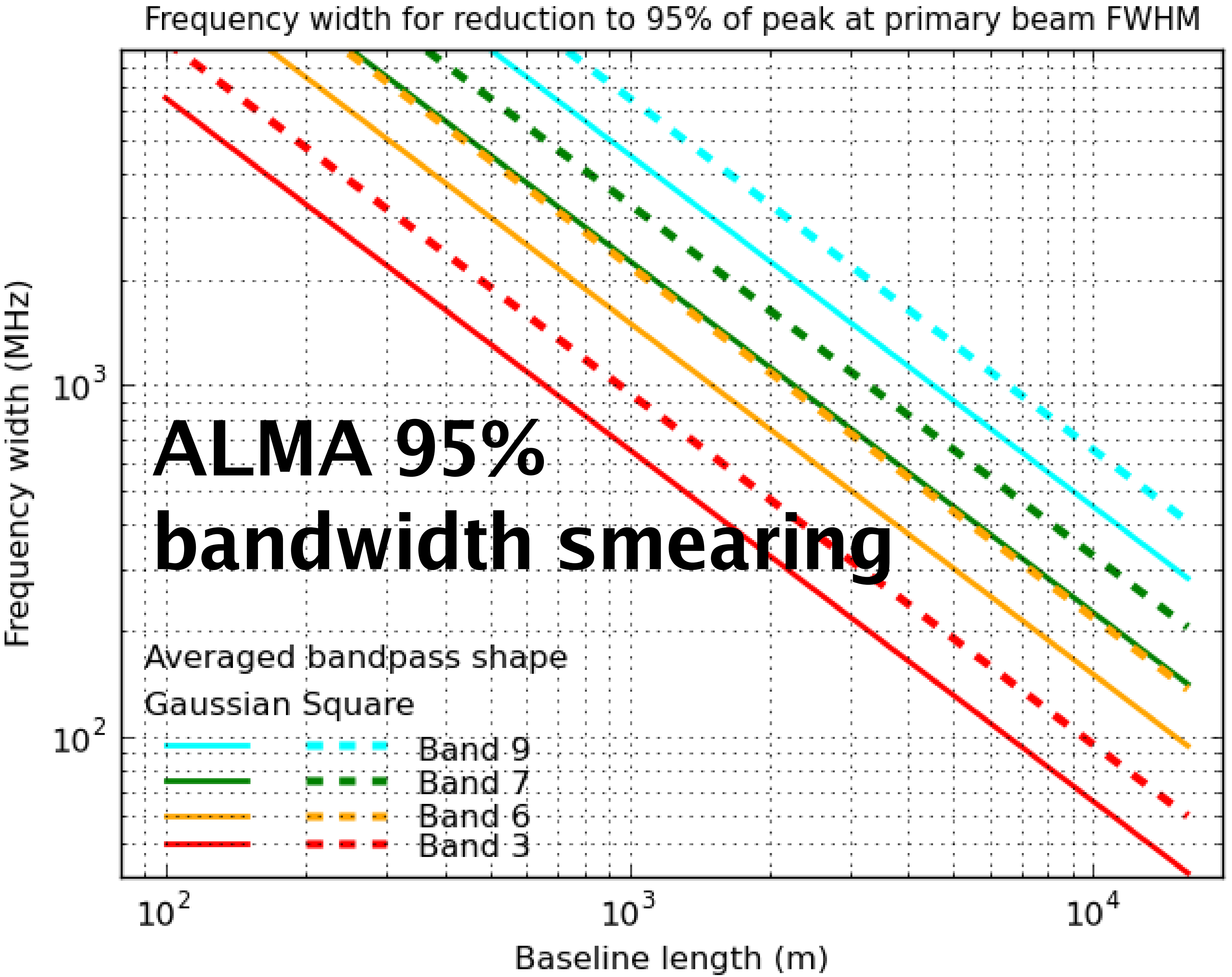
Gaussian *uv*, Square bandpass

- $\beta = d\nu/\nu\ \theta/\theta_B$
- $R = \sqrt{\pi}/(2\sqrt{\ln 2}\ \beta)$ x erf $(2\sqrt{\ln 2}\ \beta/2)$
- Approximate erf using first 3 terms of Maclaurin series
  - $R = \sqrt{\pi}/(2\sqrt{\ln 2}\ \beta)$ x $2/\sqrt{\pi}\ (z - z^3/3 + z^5/10)$
    - where $z = 2\sqrt{\ln 2}\ \beta/2$
  - This cancels to a quadratic equation in z^2, giving
  - $\beta = 2/2\sqrt{\ln 2}\ \sqrt{[(10 - \sqrt{(360R - 260)})]/6}$
    - real roots for $R>13/18$
    - accurate to few % for $R>0.8$
  - Ready reckoners for $d\nu_{GS}$ as before



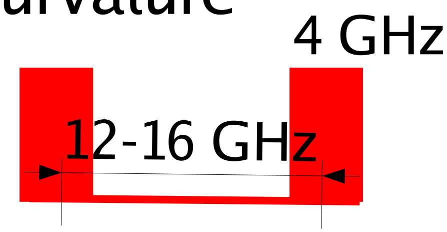
Frequency width for reduction to 80% and 95% of peak
e-MERLIN bandwidth smearing
Frequency width (MHz)
10^{1}
10^{0}
10^{-1}
10^{1}
10^{2}
10^{3}
Distance from pointing centre (arcsec)
Averaged bandpass shape
Gaussian Square
Reduction to 80%
Reduction to 95%


Frequency width for reduction to 80% of peak at primary beam FWHM
Frequency width (MHz)
Baseline length (m)
ALMA 80%
bandwidth smearing
Averaged bandpass shape
Gaussian Square
Band 9
Band 7
Band 6
Band 3
10^2
10^3
10^4

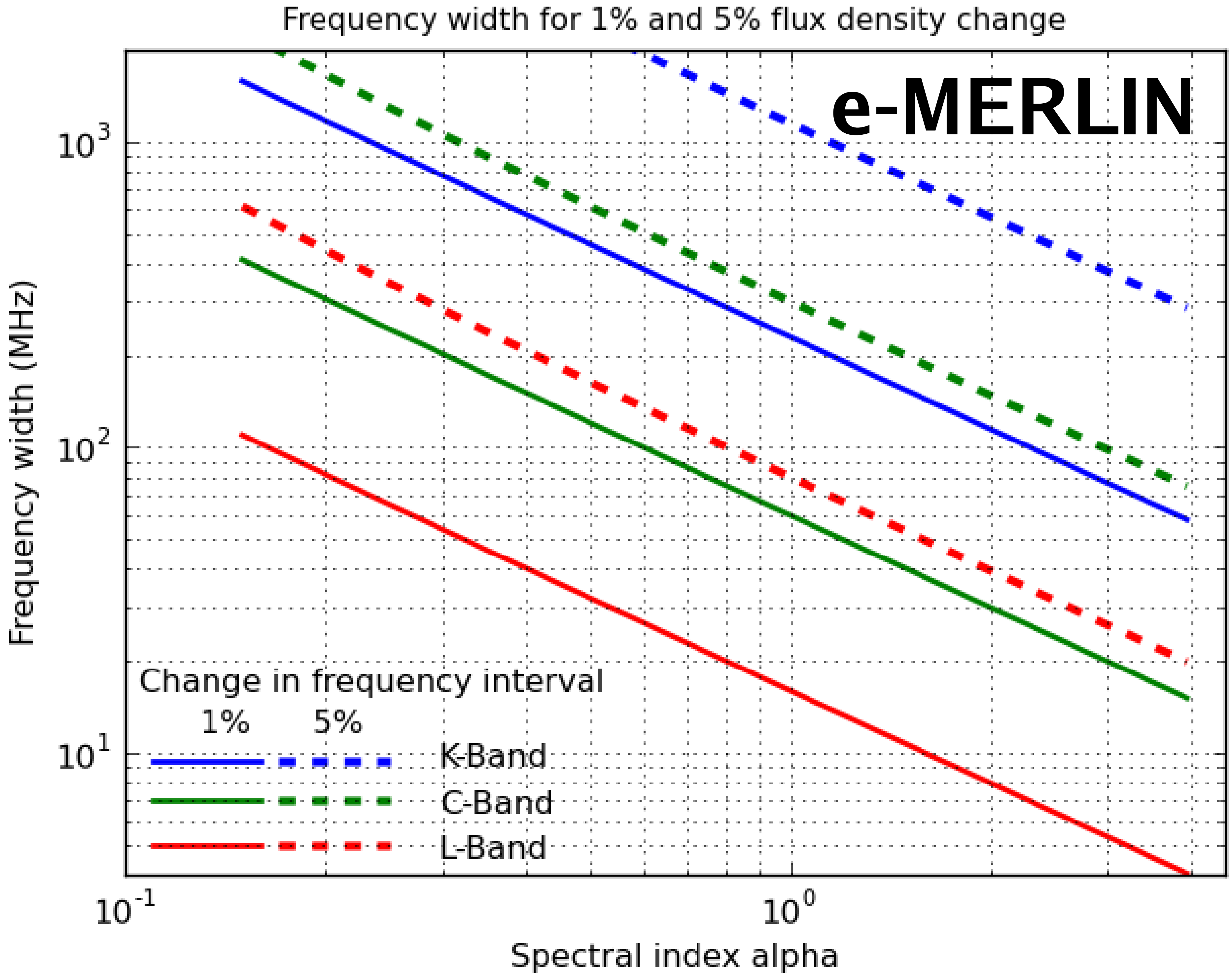

Frequency width for reduction to 95% of peak at primary beam FWHM
Frequency width (MHz)
10^3
10^2
10^2
10^3
10^4
Baseline length (m)
Averaged bandpass shape
Gaussian Square
Band 9
Band 7
Band 6
Band 3
ALMA 95%
bandwidth smearing

Spectral index

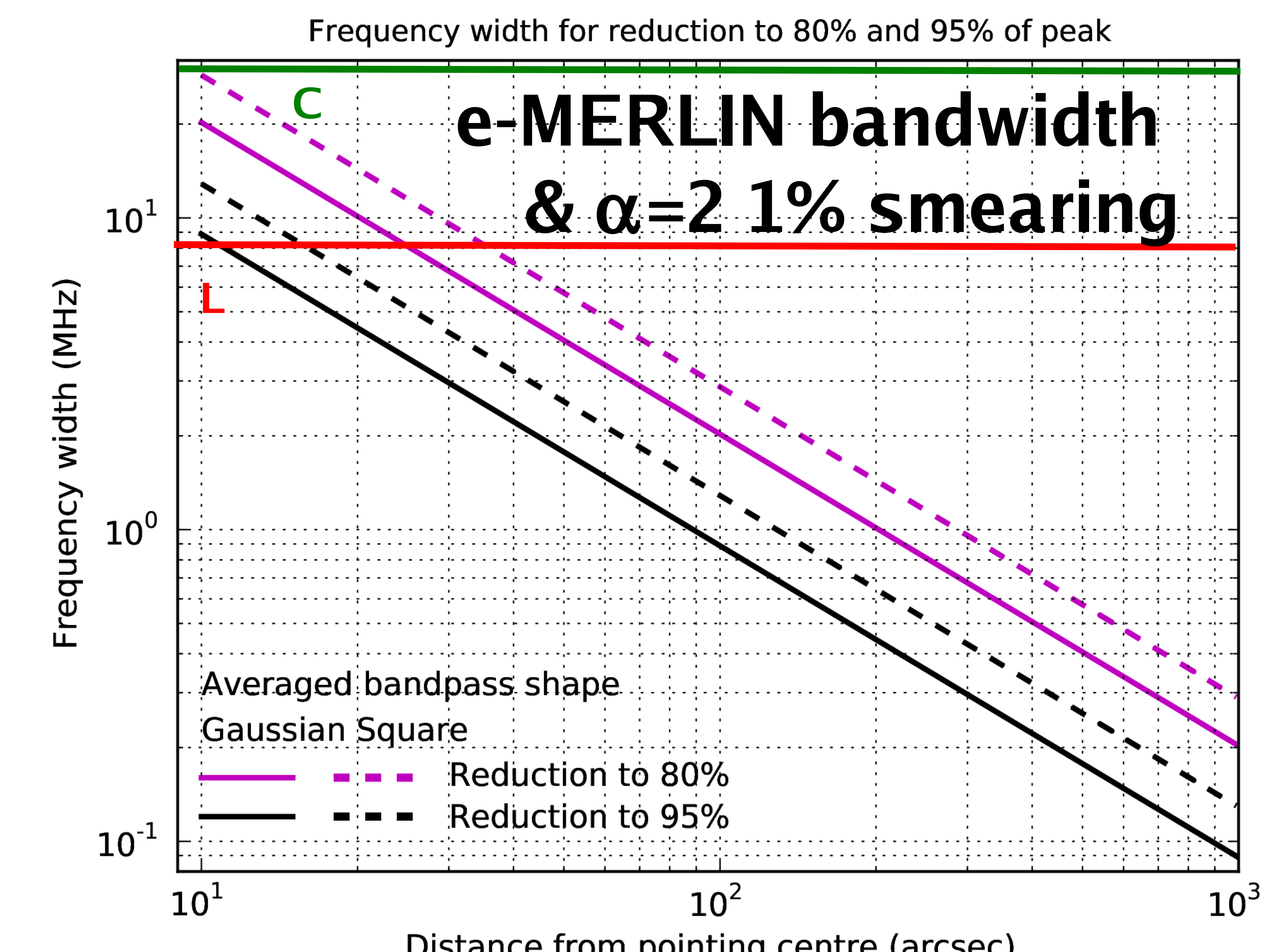
- Bandwidth averaging also limited by spectral index α
- Flux density S at frequency ν
- Max fractional change f_S, requiring frequency width
  - $d\nu = \nu[(1+f_S)^{1/|\alpha|} - 1]$
    - Smearing width is independent of sign convention
    - Relatively weak constraint, ignor spectral curvature
  - User inputs α, f_S, ν



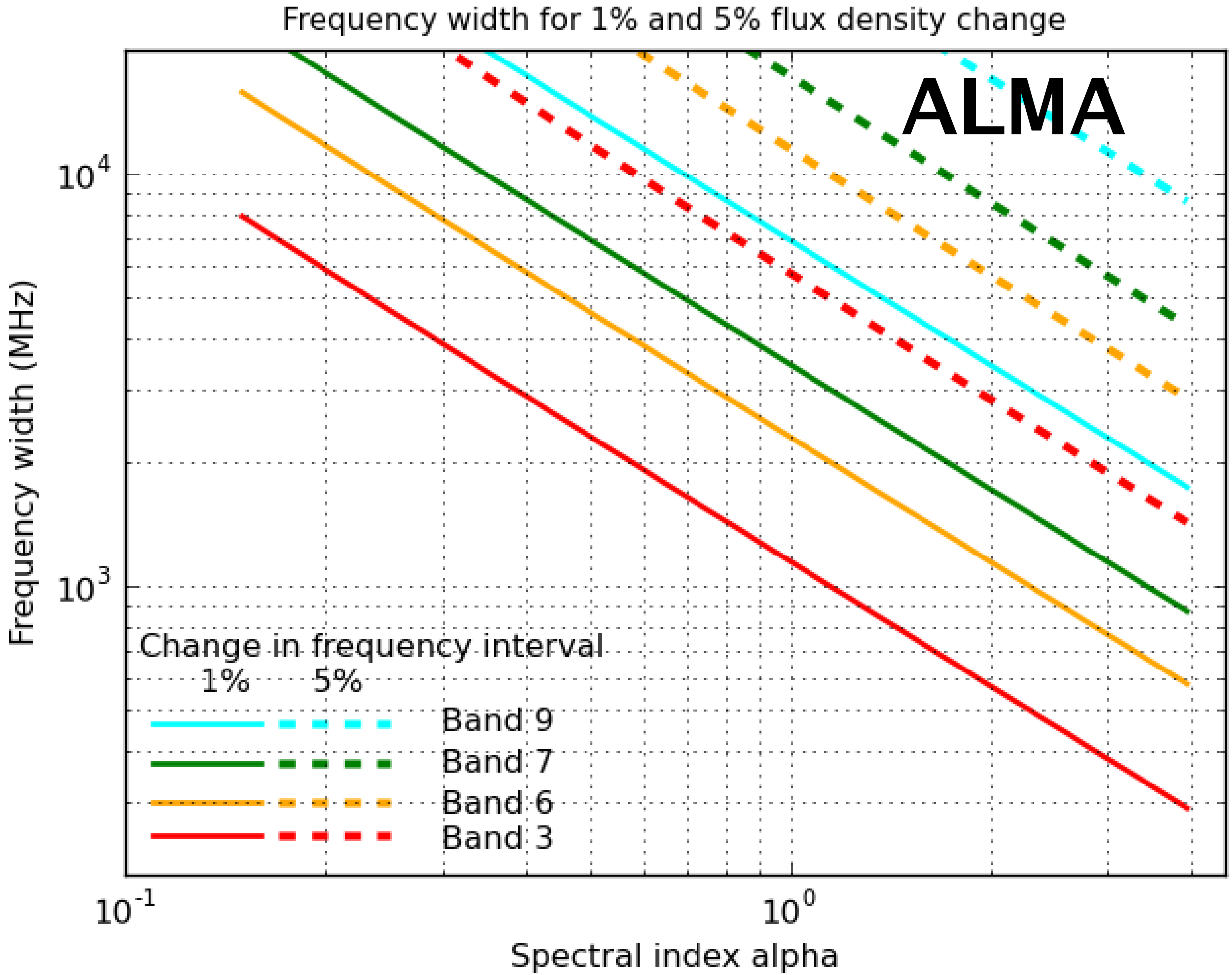
- Image ALMA sidebands separately
  - If spectral curvature is an issue
- Similar considerations for RM synthesis imaging



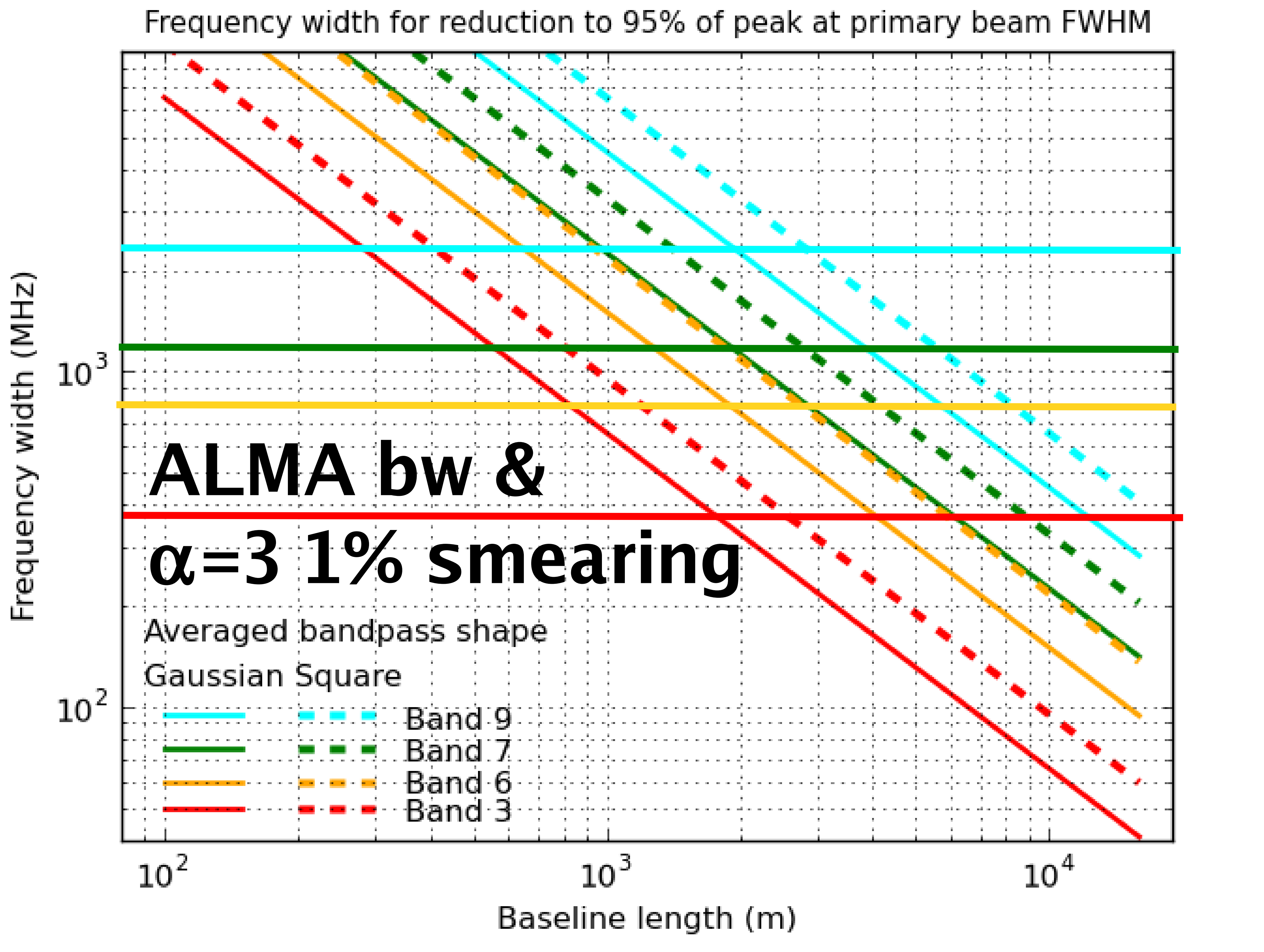
Frequency width for 1% and 5% flux density change
e-MERLIN
Frequency width (MHz)
10^3
10^2
10^1
10^{-1}
10^0
Spectral index alpha
Change in frequency interval
1%
5%
K-Band
C-Band
L-Band



Frequency width for reduction to 80% and 95% of peak
e-MERLIN bandwidth
& α=2 1% smearing
C
L
Frequency width (MHz)
10^1
10^0
10^-1
10^1
10^2
10^3
Distance from pointing centre (arcsec)
Averaged bandpass shape
Gaussian Square
Reduction to 80%
Reduction to 95%



Frequency width for 1% and 5% flux density change
ALMA
Frequency width (MHz)
10^4
10^3
Change in frequency interval
1%
5%
Band 9
Band 7
Band 6
Band 3
10^{-1}
10^0
Spectral index alpha



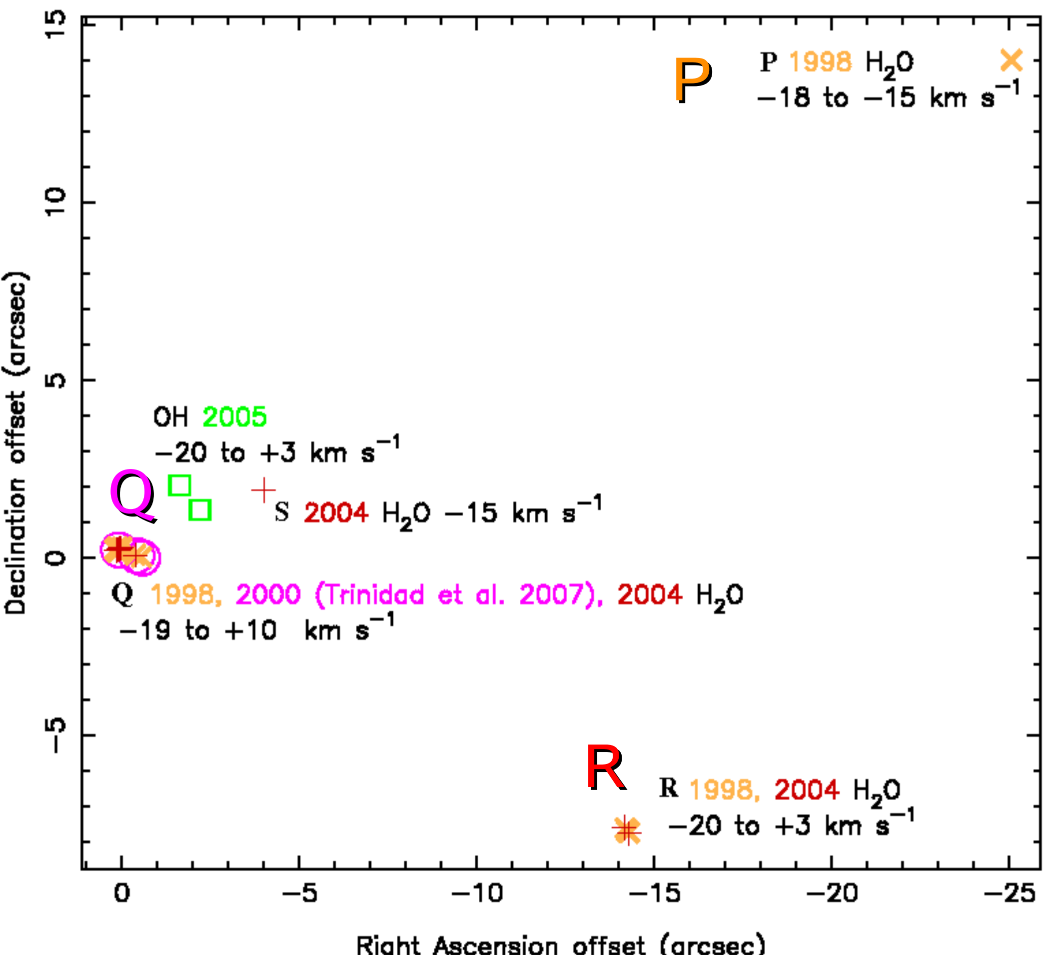
Frequency width for reduction to 95% of peak at primary beam FWHM
Frequency width (MHz)
Baseline length (m)
10^2
10^3
10^4
ALMA bw &
α=3 1% smearing
Averaged bandpass shape
Gaussian Square
Band 9
Band 7
Band 6
Band 3

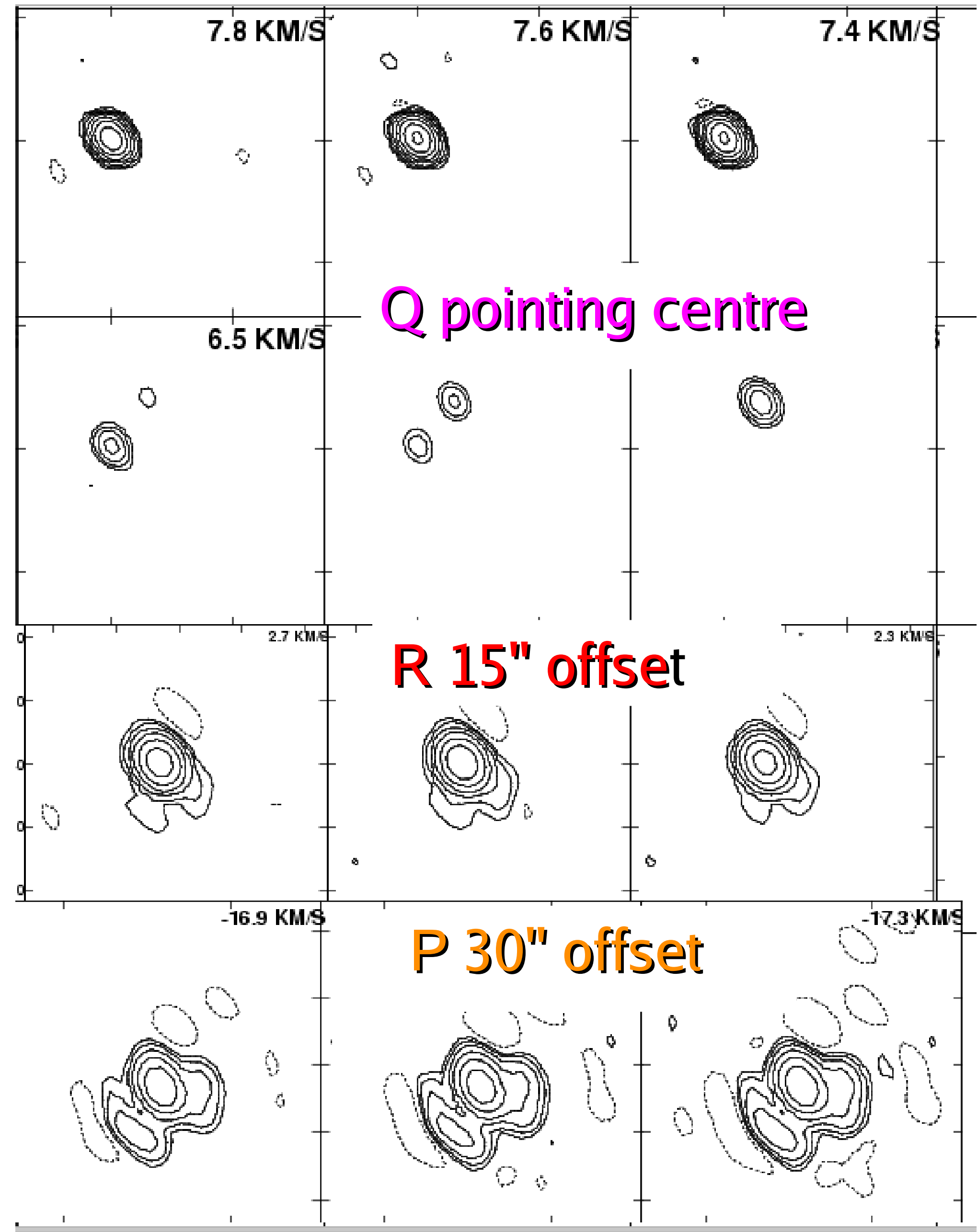
Time smearing

- Crude description: sky rotates during averaging time dt
- Reduced amplitude $R = 1 - C\,(\theta/\theta_B)^2\,\mathrm{d}t^2$ (NRAO99 ¶18)
  - C=1.08 10^{-9} uniform *uv* coverage, 1.22 10^{-9} Gaussian
    - $\mathrm{d}t = \sqrt{[(1-R)/C]}\ \times\ \theta/\theta_B$
      - User inputs R, θ, θ_B
- Phase rate $\mathrm{d}\phi/\mathrm{d}t_1 = 2\pi(\theta/\theta_B)\ /(24 \times 3600)$ in 1 sec
  - Corresponding reduction in amplitude to
    - $R_\phi = \mathrm{sinc}[(\mathrm{d}\phi/\mathrm{d}t_1)(\mathrm{d}t)/2\pi]$ (NRAO99 ¶13 Perley)
      - $= \mathrm{sinc}\{\sqrt{[(1-R)/C]}\ /\ (24\mathrm{x}3600)\}$
      - $R_\phi > R$ for all values of R
  - But further self-calibration required $(\mathrm{d}\phi/\mathrm{d}t_1)\mathrm{d}t \lesssim \pi/6$
    - Only an issue if small θ/θ_B , large dt (hundreds s): unlikely

MERLIN spectral time smearing

- ν 22 GHz, dν 0.016 MHz, d*t* 4s
- Smearing mimics multiplicity
  - Complex non-radial patterns

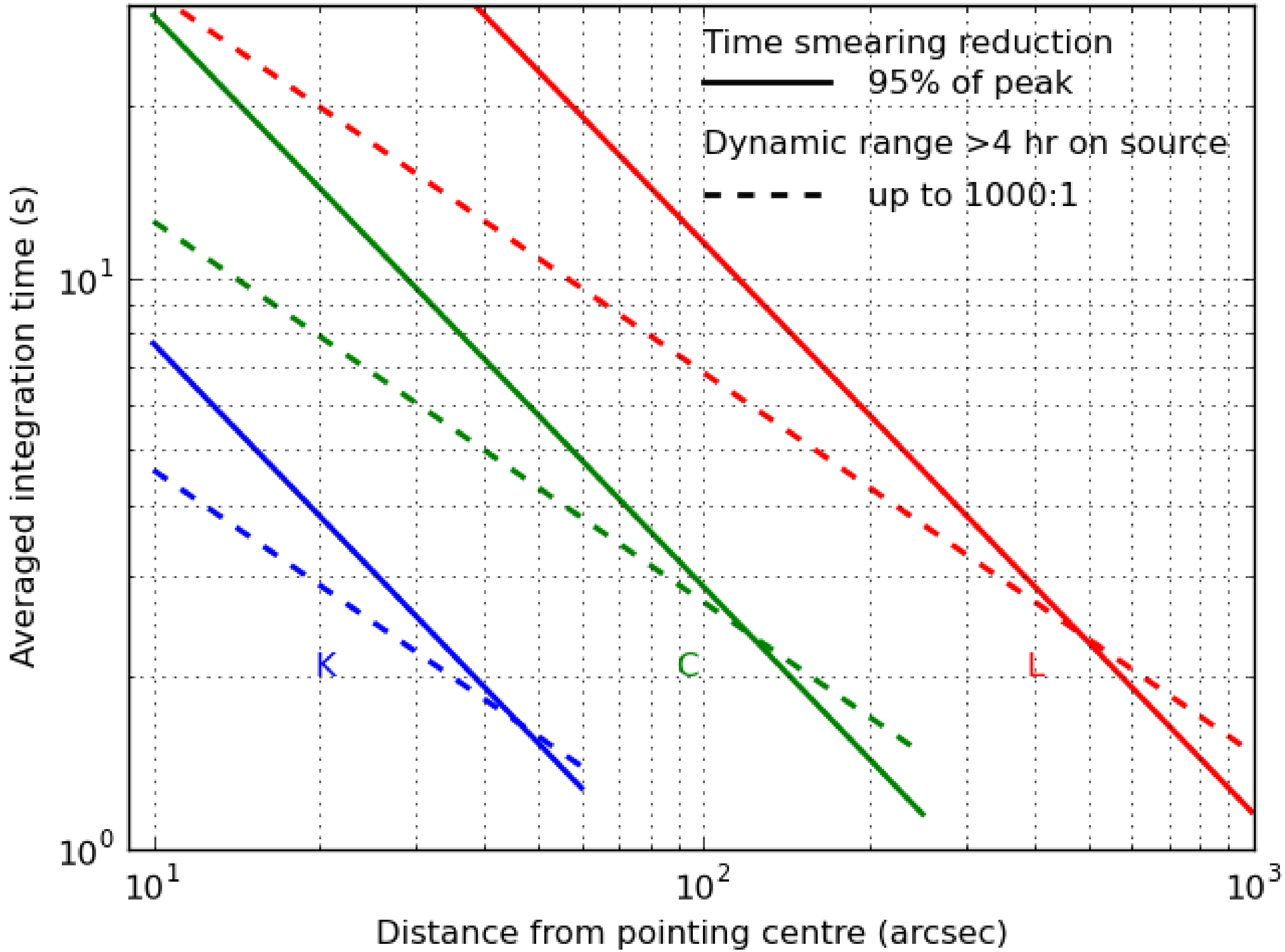




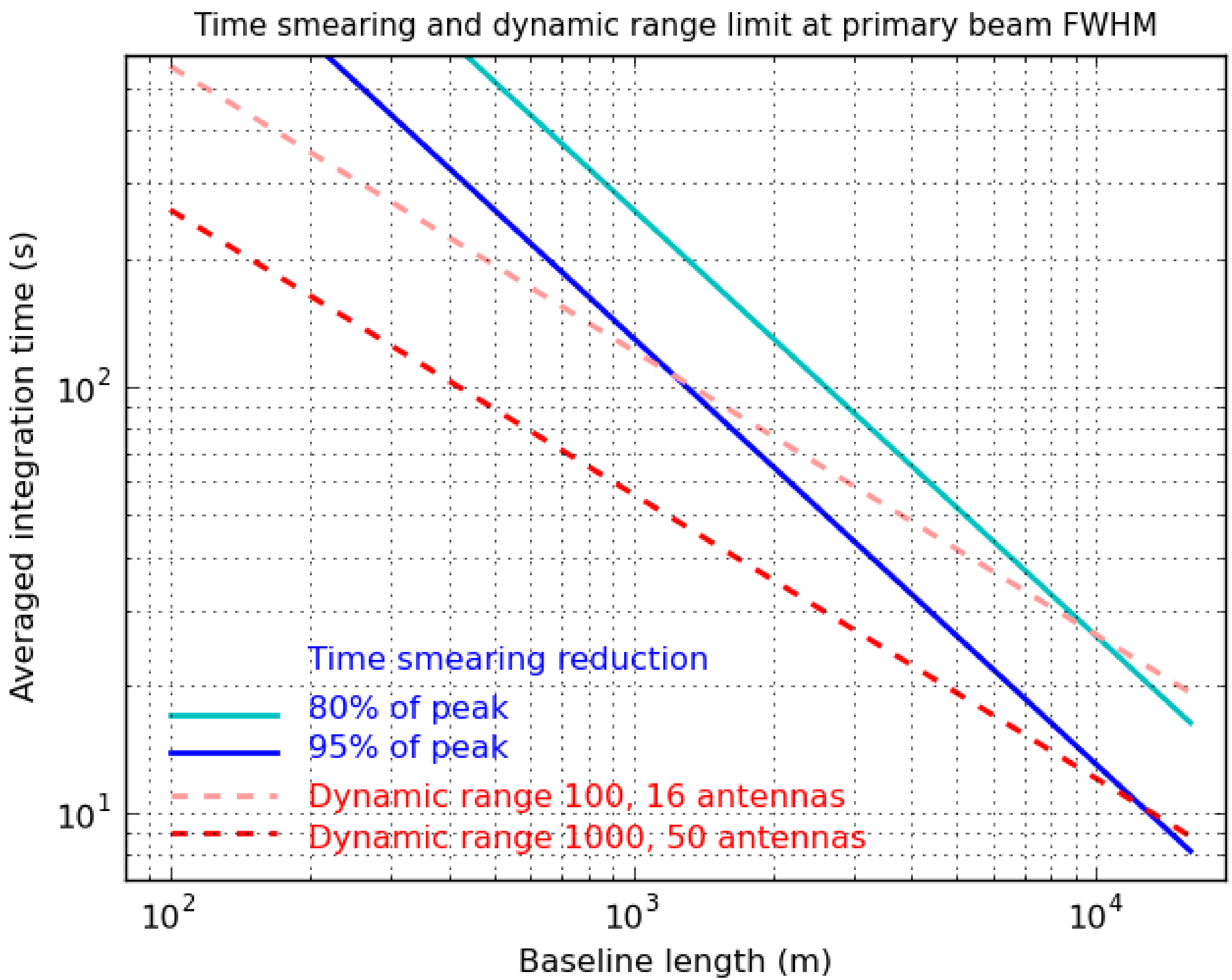
Dynamic Range

- Limitations due to phase errors NRAO99 ⁋13
  - Surmise that phase winding has similar effect
- Dynamic range limited to $D = (\surd M) N \,/\, (\mathrm{d}\phi/\mathrm{d}t_1)\mathrm{d}t$
  - N antennas, M independent samples
    - Is dt the duration of an 'independent sample'?
      - OK for ALMA if dt is similar to snapshot duration
      - May be (much) too low for eMERLIN or ALMA on long baselines, for very high dynamic ranges
    - If this is the case then for observations duration H hr
      - $M = H/\mathrm{d}t$
    - $\mathrm{d}t = [3600 H N^2 / (D \times \mathrm{d}\phi/\mathrm{d}t_1)^2]^{1/3}$

e-MERLIN time smearing/ dynamic range limits



ALMA *t* smearing/dynamic range



Other sources of error

- Acceptably aberrated FoV may be more strictly limited
  - Pointing errors (seem not to be effectively correctable)
  - Antenna position errors (correctable?)
  - Imperfect primary beam models
- 3D sky/non-coplanar array (*Cornwell et al. 2005*)
  - Significant if Fresnel ratio $F_R > \lambda B_{max} / PB^2$
  - e-MERLIN $F_R \sim 4 - 80$ depending on λ, Lovell or not
    - *w*-projection faster than faceting
      - But wasteful/excessive image size for large, sparse fields
        - find the trade-off point?
  - ALMA ~ 1.1 for band 1, longest baseline, otherwise <<1
    - But what about far-out emission in mosaicing?

e-MERLIN and ALMA constraints

- Flag rfi, then imaging tightest e-MERLIN constraint
- Subtract confusing sources
- Continuum dν 0.0625 MHz at L-band
  - Sufficient to image θ~1° (>4x*PB* FWHM) at L to *R* 0.95
    - Would need d*t* 0.35 s to keep time-smearing to 0.95
  - dν 0.25 MHz C- & K-bands allows ~8' (>2x*PB* FWHM)
    - But default 1 s integration reduces this to 6'.5
- Phase winding less strict unless high dynamic range
- ALMA calibration may be most demanding
  - Imaging phase-rates on 15 km baselines
  - Wide-field mosaicing

Progressive averaging e-MERLIN

- Potential volume savings for restricted FoV
  - 1000" only at lower frequencies
- Smearing <0.95 in frequency interval dν, time dt
- Dynamic range D 1000 (probably worse for short dt)
- Default chan width 0.0625/0.25 MHz at L/C&K; t_{int} 1s

Band	θ_{beam} (mas)	dν@1"		@10"		@100"		@1000"	
All		*125* MHz		12.5 MHz		0.75 MHz		0.0625 MHz	
		sec @1"		@10"		@100"		@1000"	
		dt	D	dt	D	dt	D	dt	D
L	200	*1280*	150	125	33	12	7	1	1
C	50	*320*	60	32	12	3	2	0.3	0.6
K	12	75	24	7	5	0.75	1		

Progressive averaging ALMA

- Potential volume savings for restricted FoV
  - Smearing <0.95 in frequency interval dν, time dt
    - Dynamic range up to 1000 reached in 1 hr
    - 1% change for $|\alpha| = 3$
  - Default chan width 15.625 MHz in TDM

Band (GHz)	θ/θ_{beam}	100	750	2000	all
		dν (MHz)	dν (MHz)	dν (MHz)	dν $\|\alpha\|$=3
3 (115)		540	70	15	380
6 (230)		*1090*	140	35	760
7 (345)		*1640*	210	55	*1140*
9 (690)		*3280*	430	160	*2290*
All	dt (s)	60	8	3	

Source Subtraction

- Why subtract outliers and average up?
  - Pro:
    - Speed-up in imaging if you might have to repeat it
      - Smaller input data set
      - May be able to image smaller area
      - May be essential for mosaicing
  - Con:
    - Subtraction and splitting is time-consuming
    - Subtracted sources can get 'lost'
    - If channels/times have been flagged, need
      - either to reject enough data to ensure equal-sized bins
      - or apply suitable weights - how?
      - MFS and RM imaging artefacts if samples irregularly spaced –can this be mitigated? Anna Scaife talk!

Progressive averaging possible

- Single fields:
  - Target may extend far out, or confusion
    - Time and bw constraints for line and continuum
    - Can subtract outliers to allow further averaging
- Mosaicing: effective FoV many x *PB* FWHM
  - Parts of target will be in remote parts of beam
  - Impractical to sample fast enough to avoid all smearing
    - What is limit for subtracting smeared sources v. adding the regions together with appropriate sensitivity weight?
- Frequency-dependent/heterogenous primary beams
  - Sanjay's talk –assess sensitivity outside FWHM
    - e-MERLIN with Lovell especially complicated (*Wrigley+*)
    - ALMA combining different frequency intervals

Next steps

- These calculations are approximations for data averaging
  - *Not* for deriving corrections to over-averaged data!
- Test on real data in CASA
  - Investigate time consumed in SPLIT v. saved in CLEAN
  - Realistic limits? (improve dynamic range understanding)
- CASA guide for manual specification of averaging
- Develop CASA task or switches in SPLIT
  - Obtain frequency, typical resolution etc. from MS metadata
  - User inputs FoV, smearing limit, dynamic range, α
    - Sensible defaults
  - Retain options to set dt &/or dν averaging manually
    - Spectral line and time-variable sources!