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Tianlai and the Foreground Removal Problem

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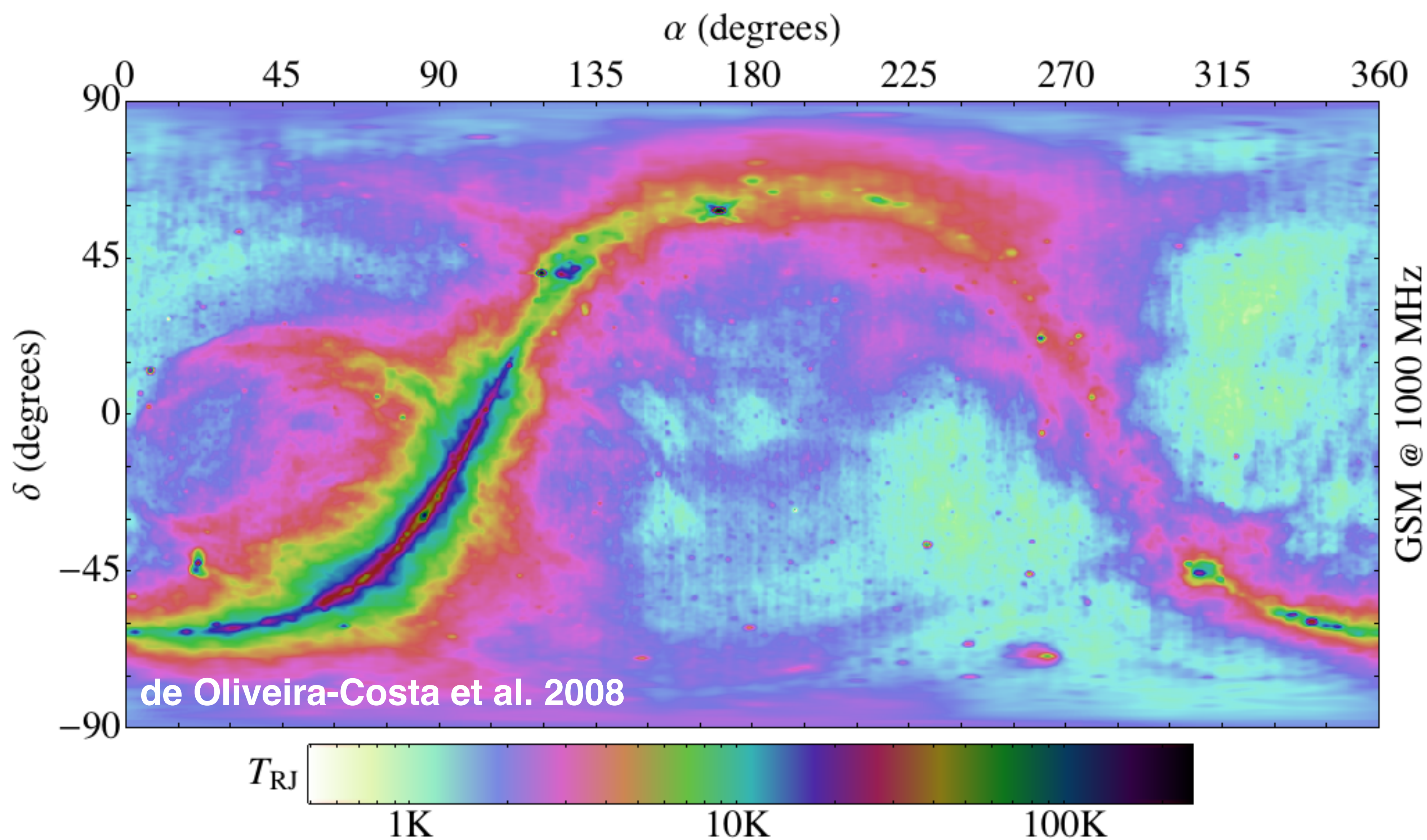
2015 Tianlai 21cm Workshop

Balikun, Xinjiang, China

9 September 2015

Foreground removal efficacy remains a significant issue



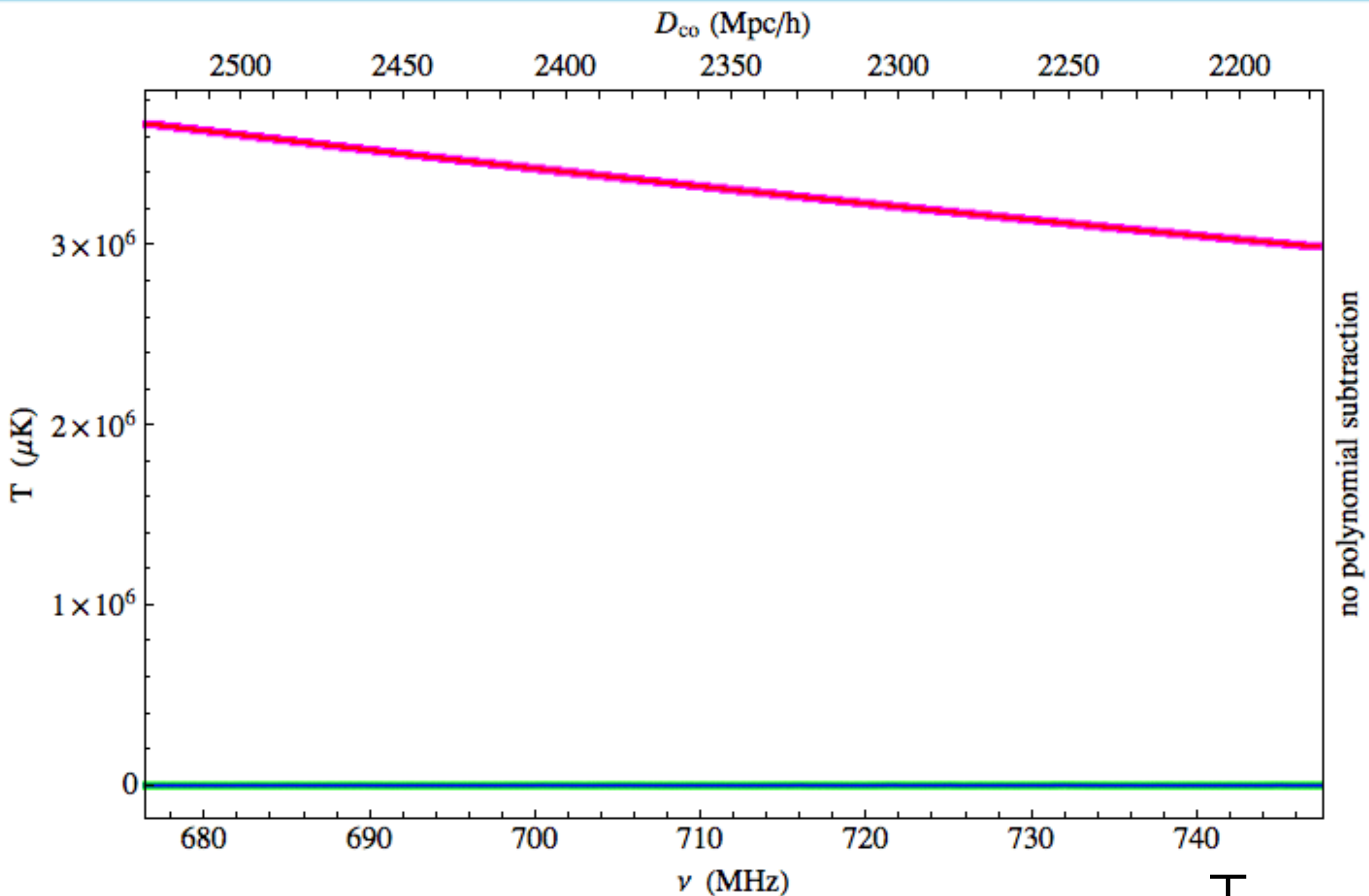
Even for dark radio sky ~1K foreground is ~10^4 larger than ~100μK signal

Foregrounds are expected to be smooth in frequency
… but are they?

Non-Smooth Spectrum Foregrounds

- While it is true that optically thin free-free or synchrotron emission is smooth in the optically thin limit for any electron energy distribute - yet it need not be so when self-absorption is present.
- There is evidence for synchrotron self-absorption in gigahertz peaked sources (GPS).
- Faraday rotation linearly polarized light can cause the linearly polarization to have oscillatory behavior which can leak into the inferred intensity.
- Peter Timbie presented evidence yesterday for this effect in the GBT data.
- It is unlikely that these could have spectral features as sharp as those expected in 21cm spectrum it can contaminate the low k modes which are important for measuring quantities like f_{NL}.

Ideally Smooth foreground subtraction should work well



$T_{fit} = \sum_p a_p \ln[v]^p$

- Many algorithms proposed to take advantage of this
- See excellent overview yesterday by Yichao Li
- Would like to get noise down to ~50μK level to see real non-linear structures

Mode Mixing

- An interferometer with a finite number of elements will only "see" a finite number of "beams" on the sky.
- The Hilbert space of all linear combinations of beams we call the space of beams.
- This space of beams generally depends frequency. This frequency dependence of the Hilbert spaces is called mode mixing because it mixes frequency dependence and angle dependence.
- If we could remove mode mixing one can directly measure the angular average spectrum with no assumption about angular structure.
- For this filtering smooth spectrum foregrounds is better when the amount of mode mixing is minimized.

Beam Projection and Purity

- Given a metric, $\cdot$, on the space of beam define the beam projection operator:

  $$\mathfrak{B}[\nu] \equiv \sum_{i,j} \mathbf{B}_i[\nu]\cdot(\mathbf{B}_i[\nu]\cdot\mathbf{B}_j[\nu])^{-1}\cdot\mathbf{B}_j[\nu]$$

  where $\mathbf{B}_i[\nu]$ are the frequency dependent beam in the Stokes parameter space.

- $\mathfrak{B}[\nu]$ has n_{beam} (number of beams) unit eigenvalues and the rest zero.

- Define the purity operator by

  $$\mathcal{P} \equiv \int d\nu\, W[\nu]\, \mathfrak{B}[\nu] = \sum_a p_a\ \boldsymbol{\wp}_a \otimes \boldsymbol{\wp}_a$$

  where $W[\nu]$ is a ν weight function (or purity band) such that: $\int d\nu\, W[\nu] = 1$

  the $\boldsymbol{\wp}_a$ (eigenvectors) are purity eigenbeams: $\boldsymbol{\wp}_i \cdot \boldsymbol{\wp}_j = \delta_{ij}$

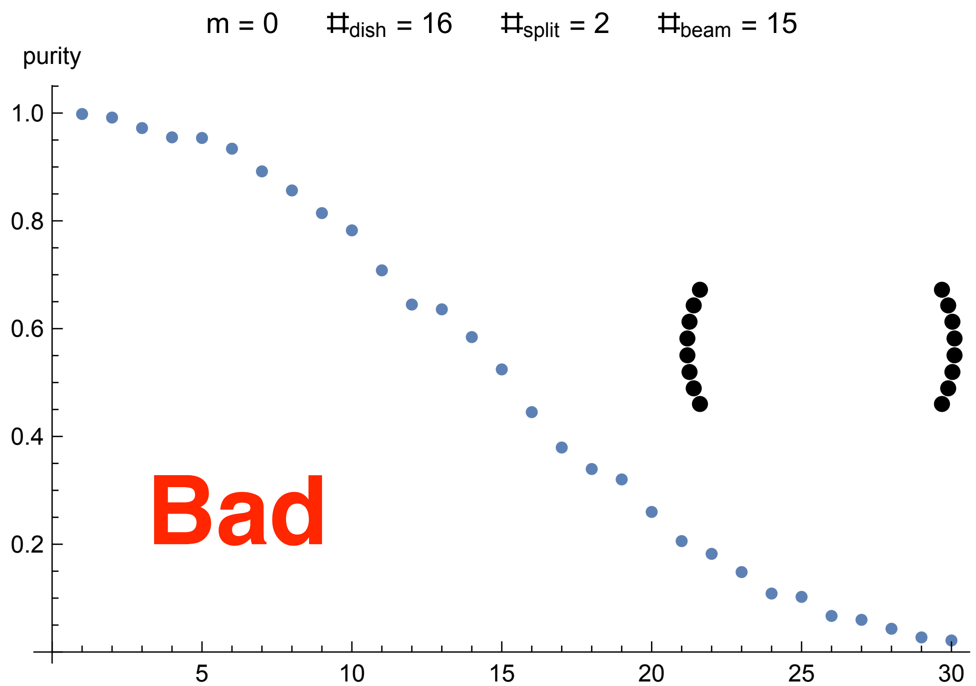
  the p_a (eigenvalues) are purities: $0 \leq p_a \leq 1$ and $\sum_a p_a = 1$

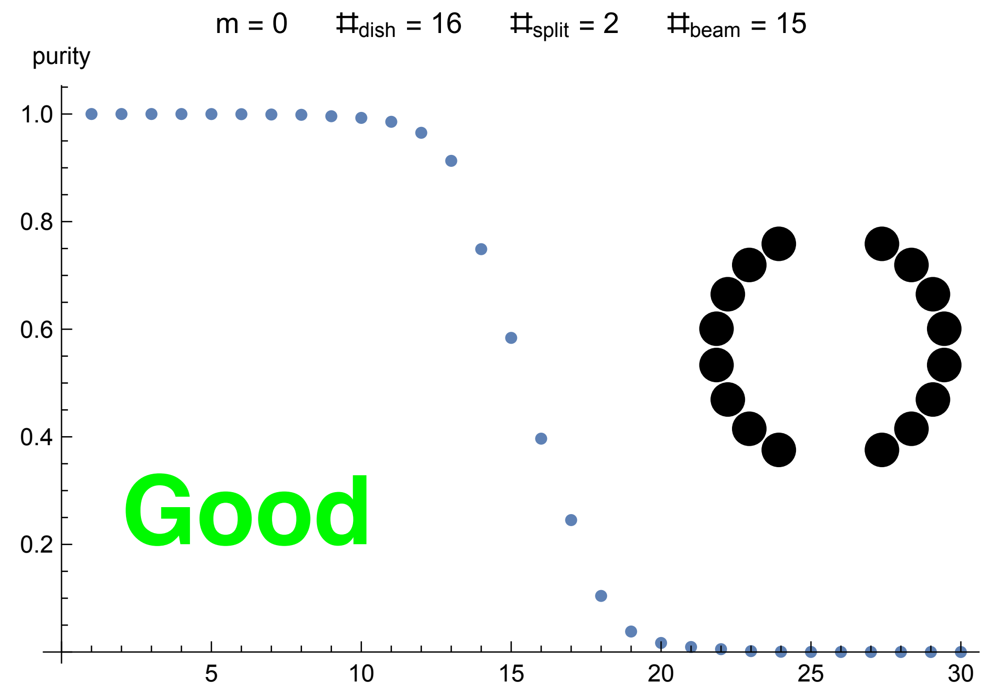
- The $\boldsymbol{\wp}_a$ with the largest purity have the least mode mixing!

- The $\boldsymbol{\wp}_a$ with $p_a \ll 1$ have large amounts of mode mixing and high pass filtering is less effective at removing smooth but highly anisotropic foregrounds.

Purity and Telescope Design

- There are at most n_{beam} very pure ($p_a \cong 1$) modes $\boldsymbol{p}_a$.
- N.B. $p_a \to 1$ in the limit of zero bandwidth: $W[\nu] \to \delta[\nu - \nu_0]$
- A high purity interferometer is an one which for a given bandwidth has close to n_{beam} very pure modes. They are useful for understanding the underlying spectra of the emission.





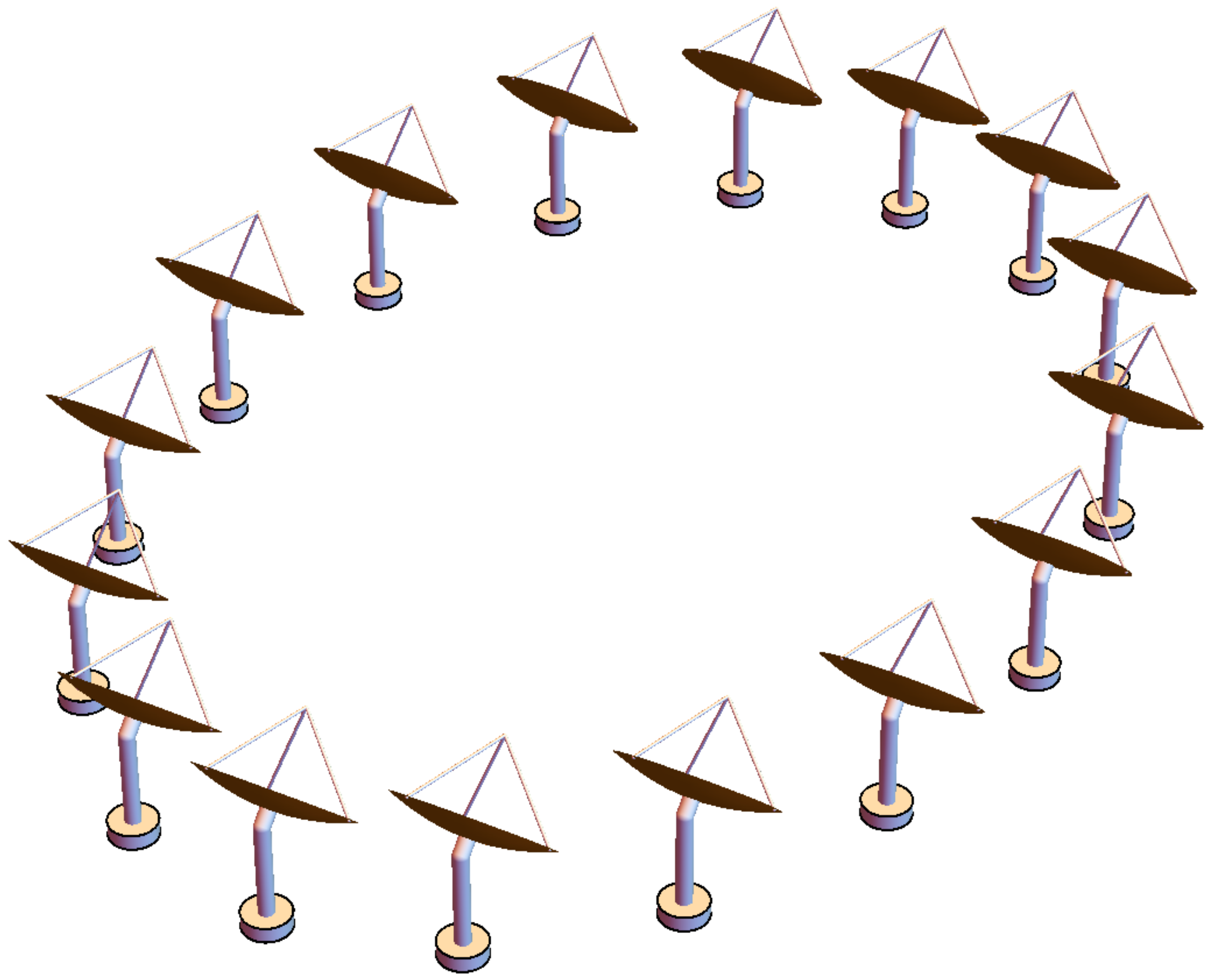
- Define the purity number $= -\ln[1-p_a]$ which is large for very pure modes
- Dense arrays with large overlap, $\mathbf{B}_i[\nu]\cdot\mathbf{B}_j[\nu]$, do better than sparse arrays (see Reza's talk).
- One never does worse by adding an additional element to an existing array (but ¥ $)

Purity and Telescope Design and Tianlai

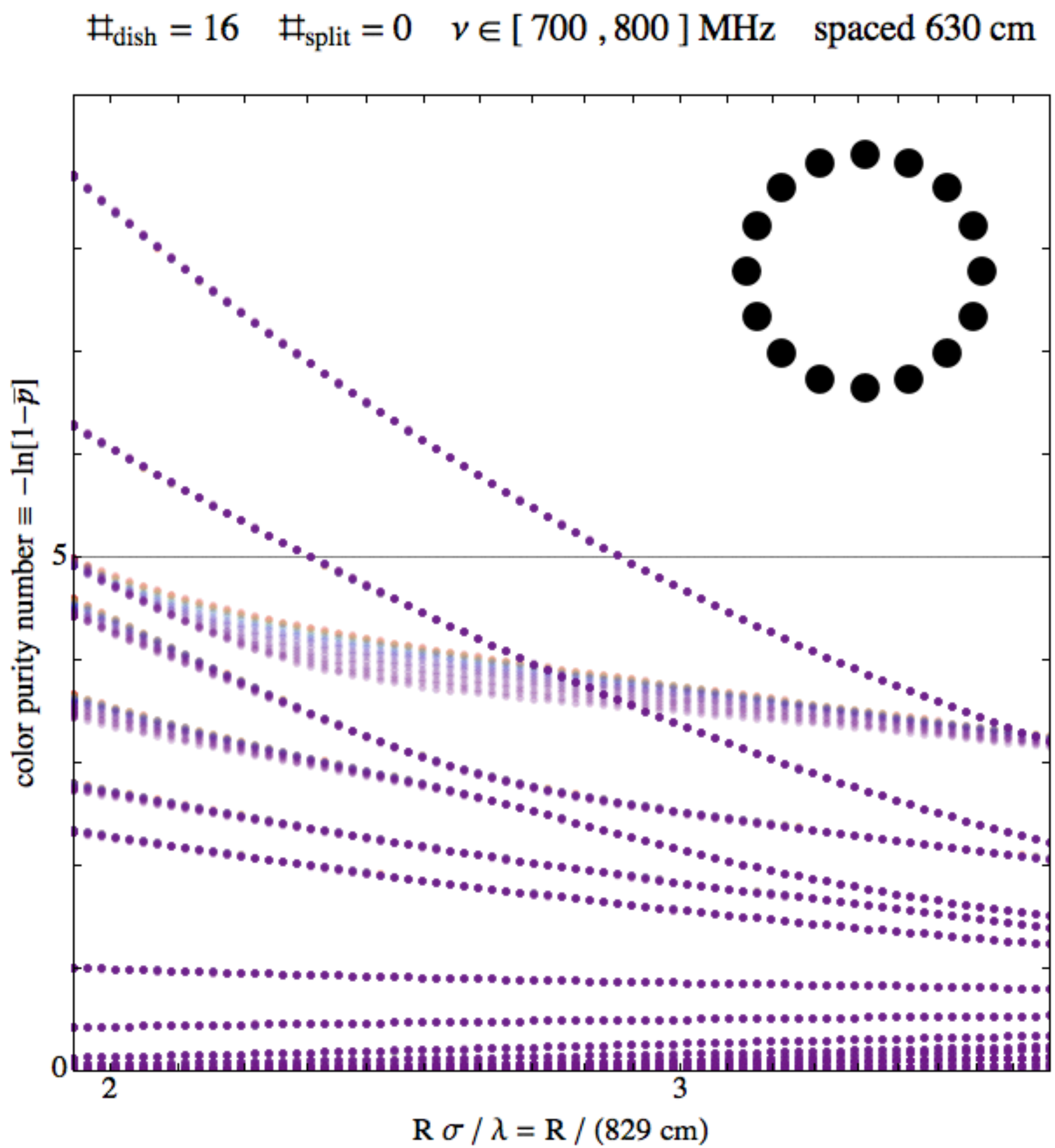
Polarscope

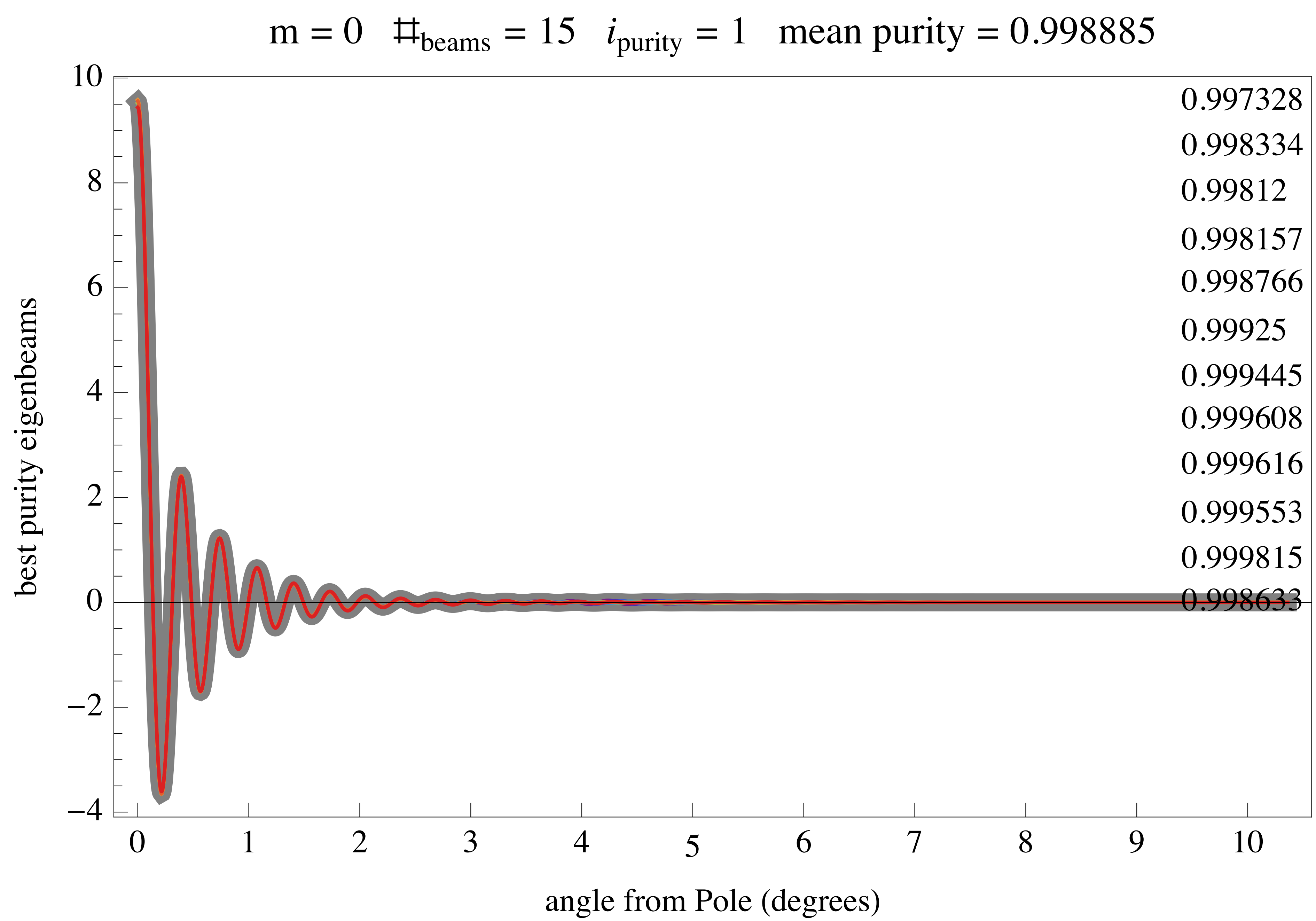
A polarscope is a transit interferometer consisting of a number antenna each pointing directly at a Celestial Pole, North or South.

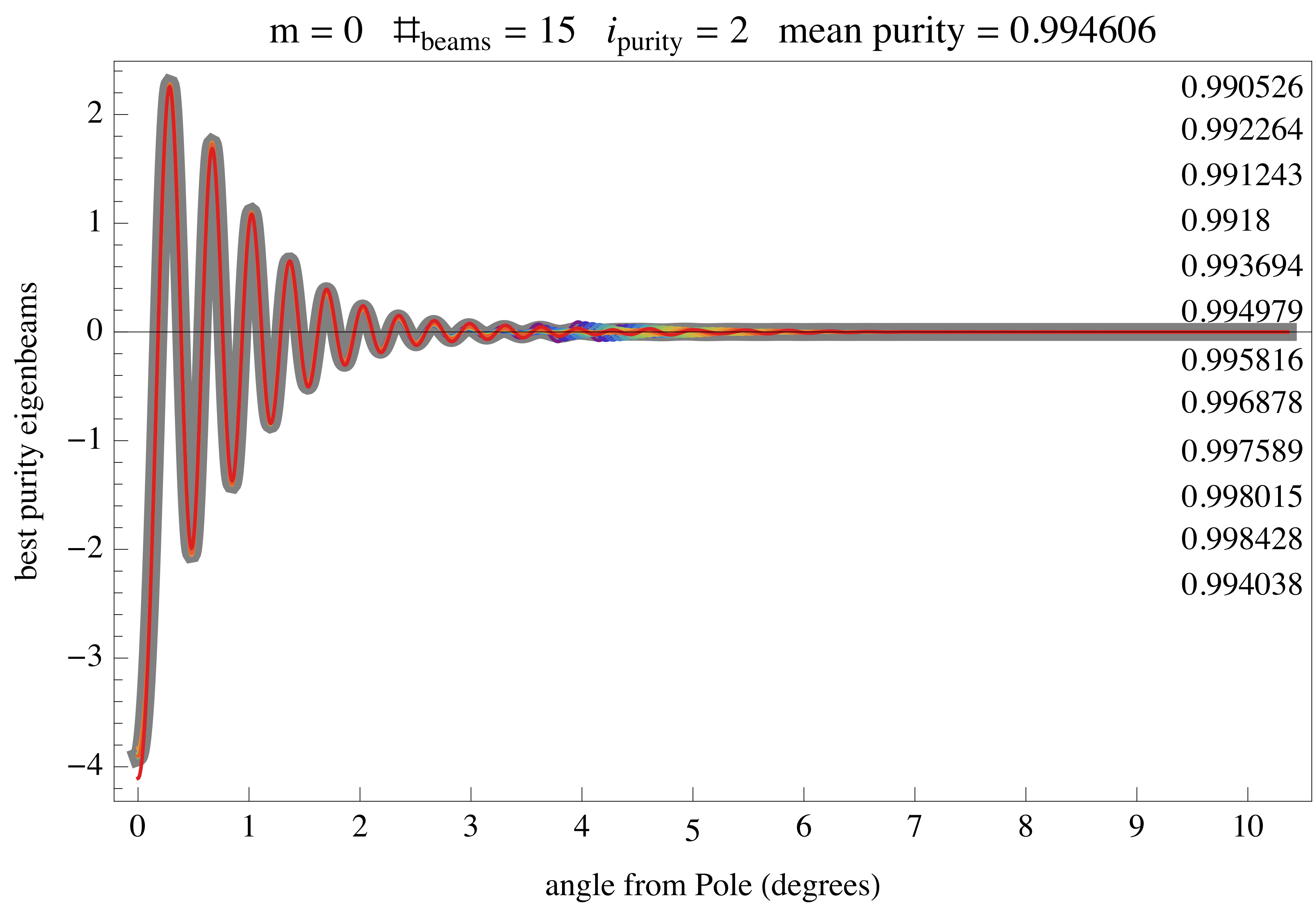
Since it always points at same spot it integrates to low noise very rapidly



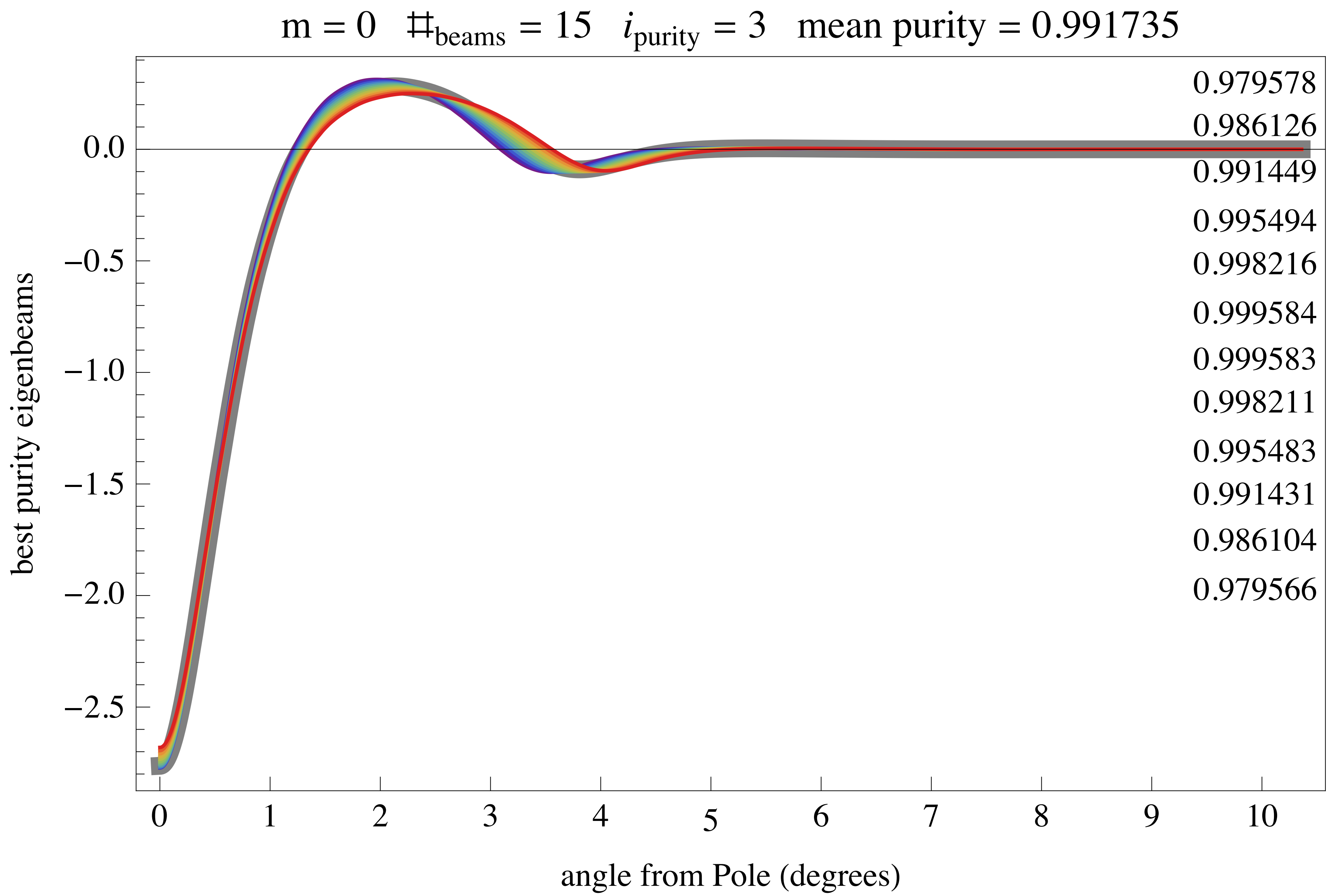
DISCLAIMER: Celestial sources near poles move slowly so a polarscope has very little handle on day timescale transients, *e.g.* ground pickup. N.B. Signals repeat every half day not every day.


♯dish = 16 ♯split = 0 ν ∈ [700 , 800] MHz spaced 630 cm
color purity number ≡ −ln[1−p̄]
5
0
2
3
R σ / λ = R / (829 cm)

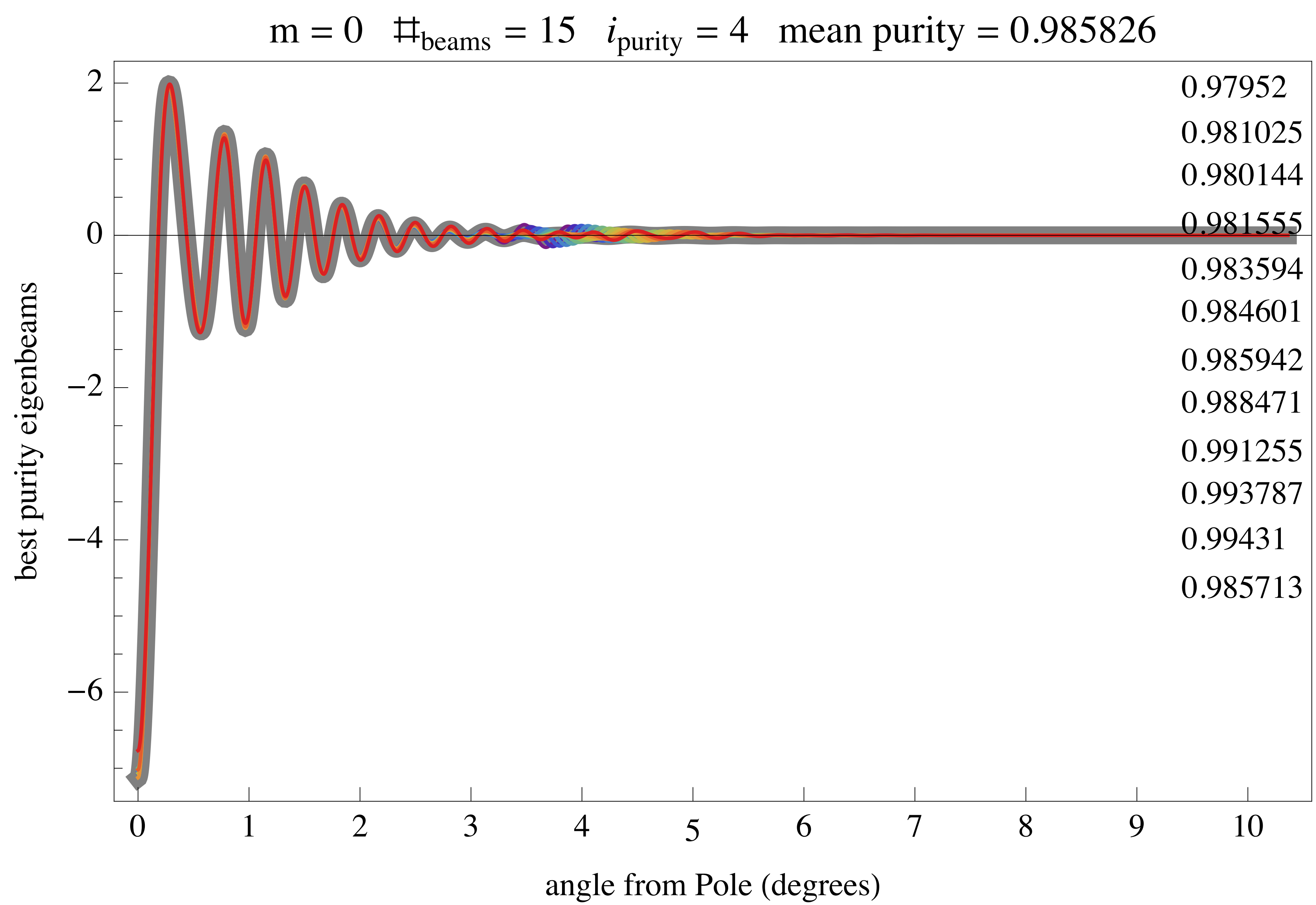

m = 0 ♯beams = 15 ipurity = 1 mean purity = 0.998885
best purity eigenbeams
angle from Pole (degrees)
0.997328
0.998334
0.99812
0.998157
0.998766
0.99925
0.999445
0.999608
0.999616
0.999553
0.999815
0.998633
10
8
6
4
2
0
−2
−4
0
1
2
3
4
5
6
7
8
9
10



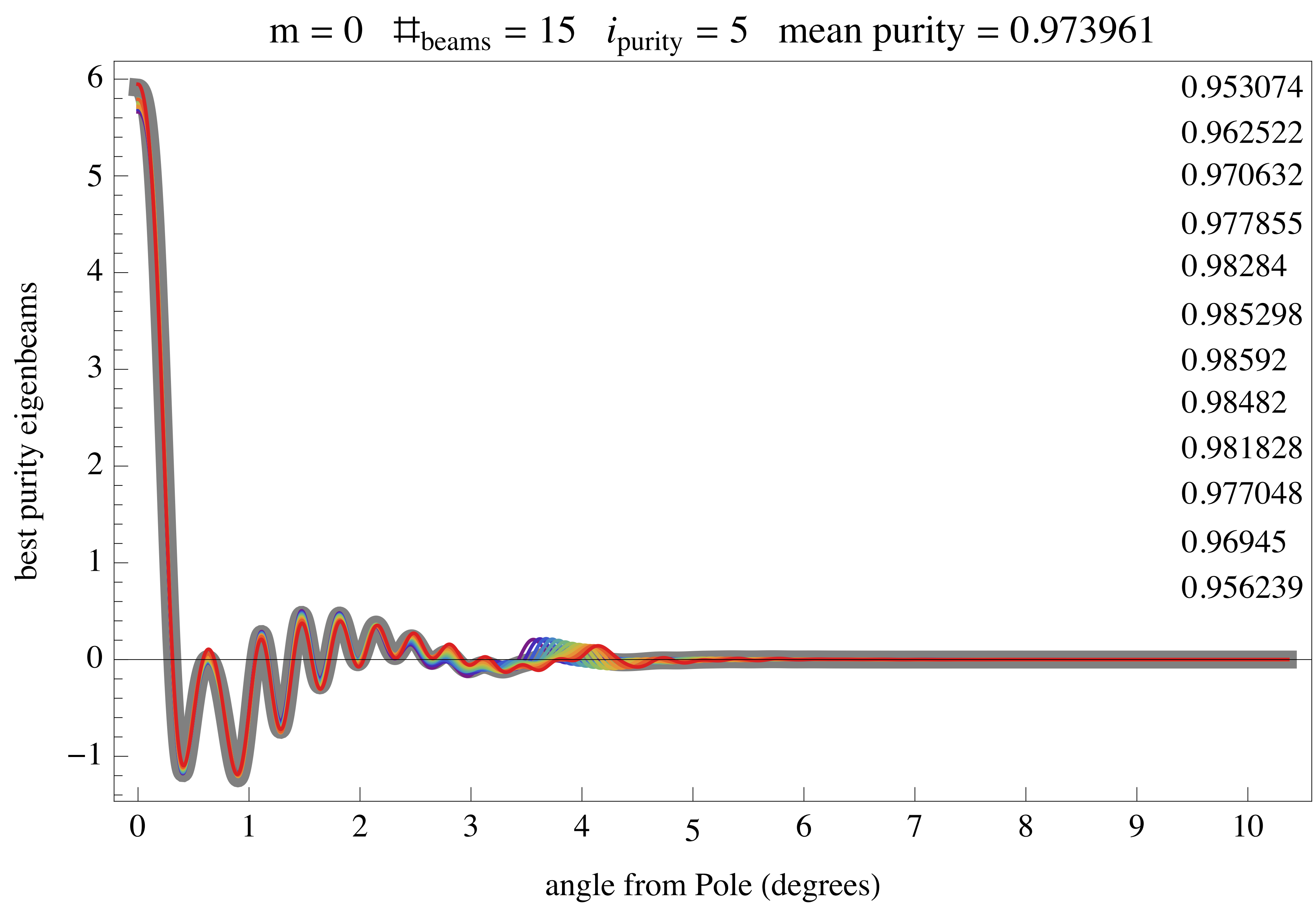
m = 0 ⌗beams = 15 ipurity = 2 mean purity = 0.994606
0.990526
0.992264
0.991243
0.9918
0.993694
0.994979
0.995816
0.996878
0.997589
0.998015
0.998428
0.994038
best purity eigenbeams
angle from Pole (degrees)
2
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
7
8
9
10



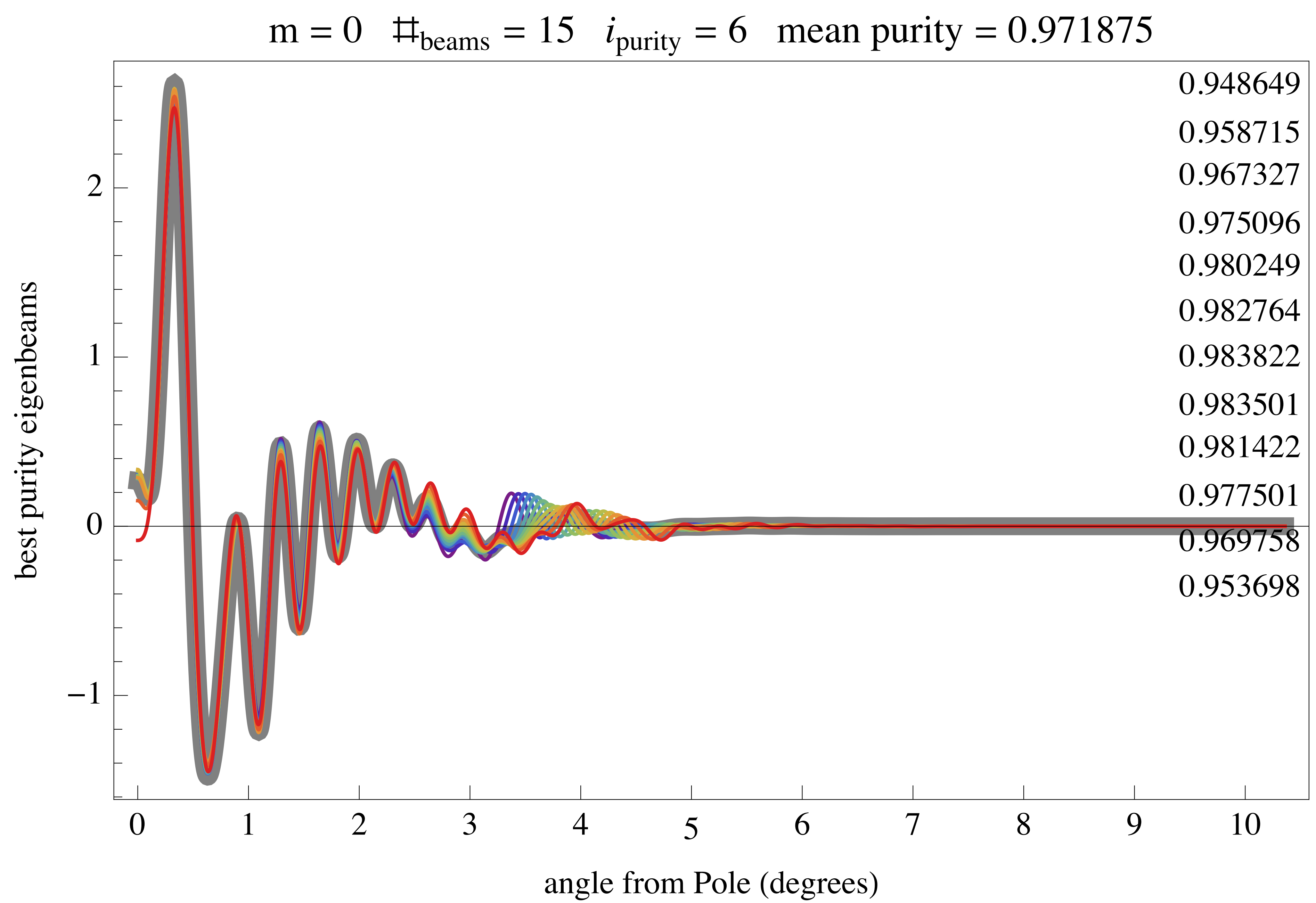
m = 0 ♯beams = 15 ipurity = 3 mean purity = 0.991735
0.979578
0.986126
0.991449
0.995494
0.998216
0.999584
0.999583
0.998211
0.995483
0.991431
0.986104
0.979566
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
best purity eigenbeams
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)

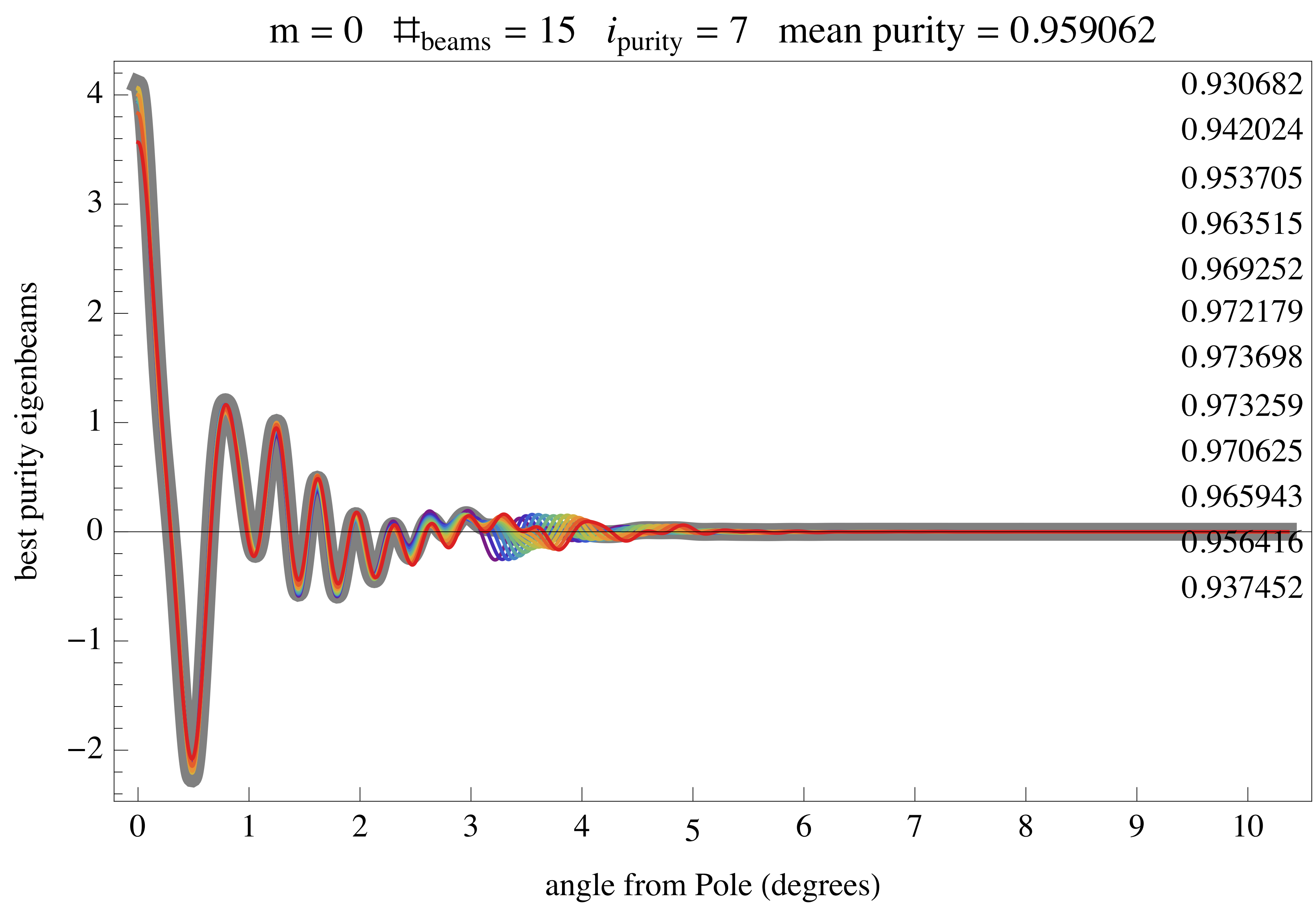


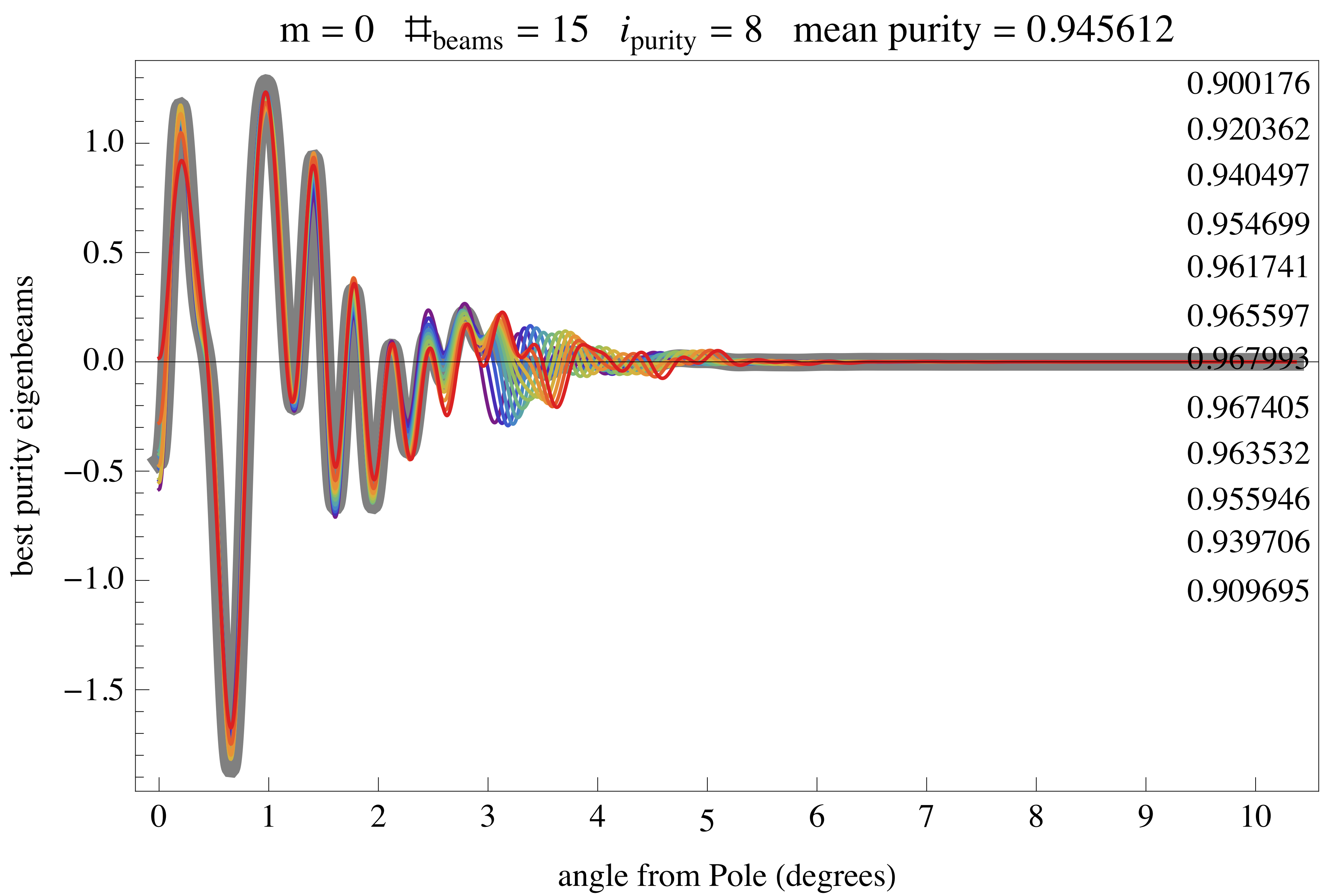
m = 0 ♯beams = 15 ipurity = 4 mean purity = 0.985826
2
0
−2
−4
−6
best purity eigenbeams
0.97952
0.981025
0.980144
0.981555
0.983594
0.984601
0.985942
0.988471
0.991255
0.993787
0.99431
0.985713
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)

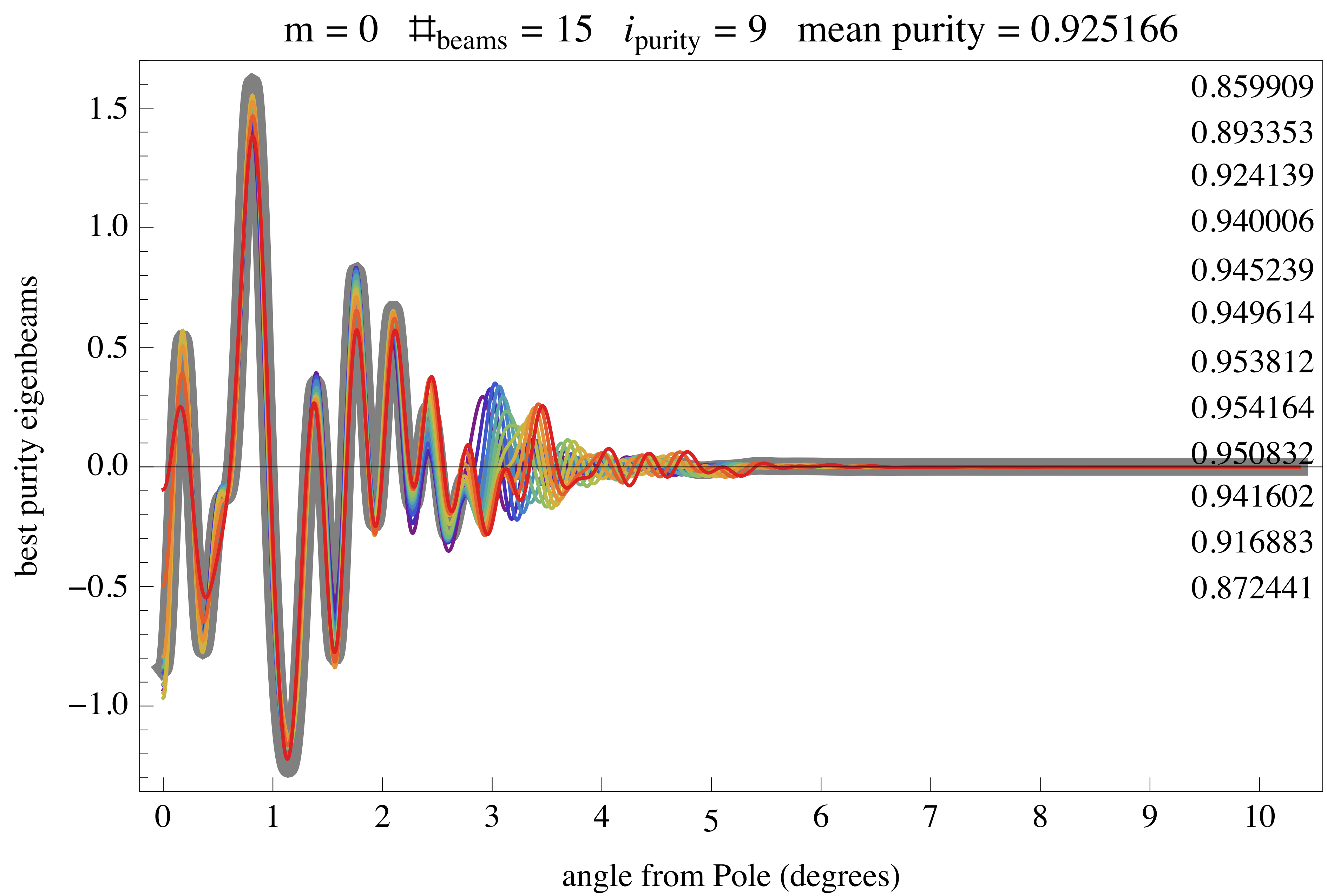


m = 0 ♯beams = 15 i purity = 5 mean purity = 0.973961
best purity eigenbeams
angle from Pole (degrees)
6
5
4
3
2
1
0
−1
0
1
2
3
4
5
6
7
8
9
10
0.953074
0.962522
0.970632
0.977855
0.98284
0.985298
0.98592
0.98482
0.981828
0.977048
0.96945
0.956239

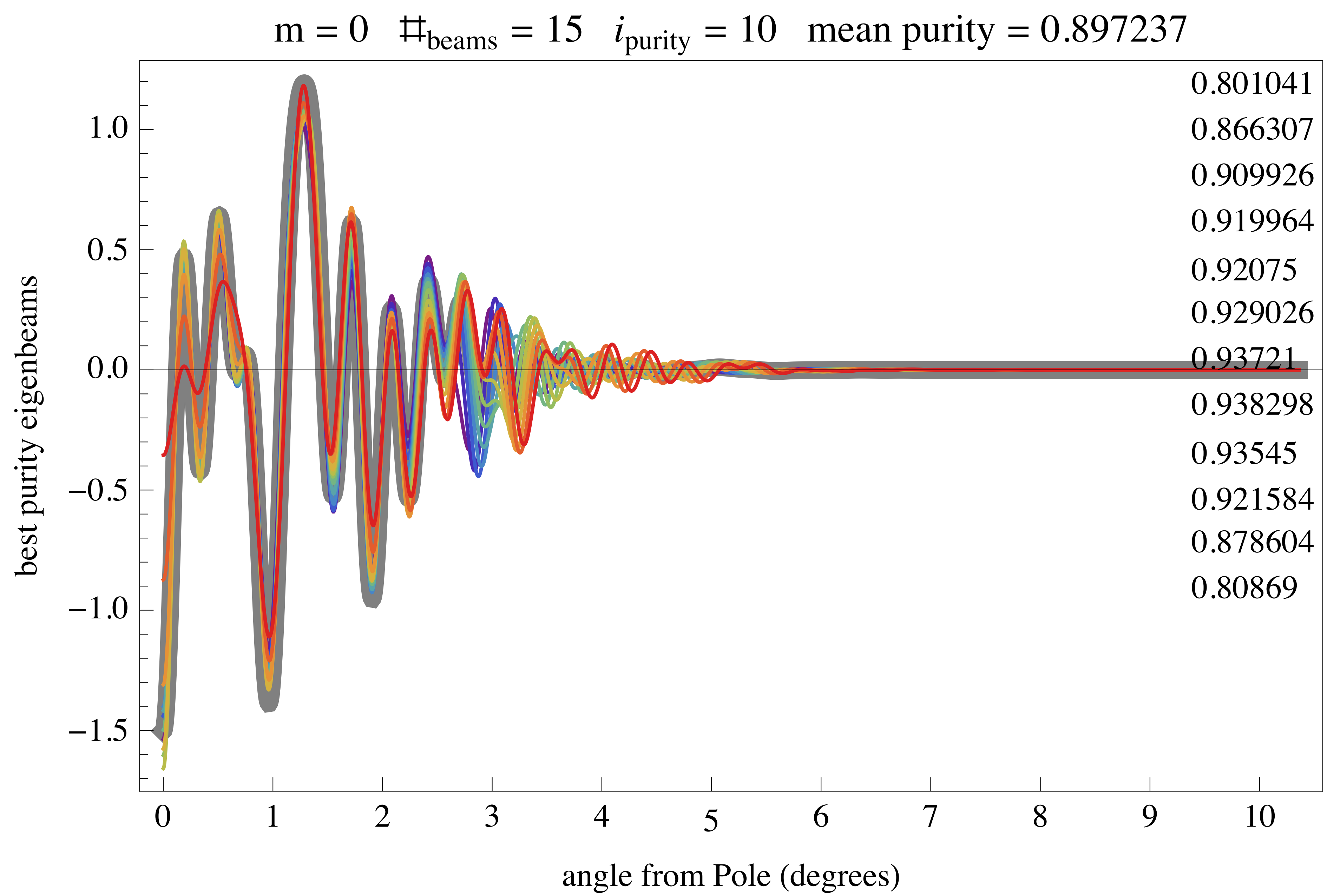

m = 0   ♯beams = 15   ipurity = 6   mean purity = 0.971875
best purity eigenbeams
angle from Pole (degrees)
0.948649
0.958715
0.967327
0.975096
0.980249
0.982764
0.983822
0.983501
0.981422
0.977501
0.969758
0.953698
2
1
0
−1
0
1
2
3
4
5
6
7
8
9
10

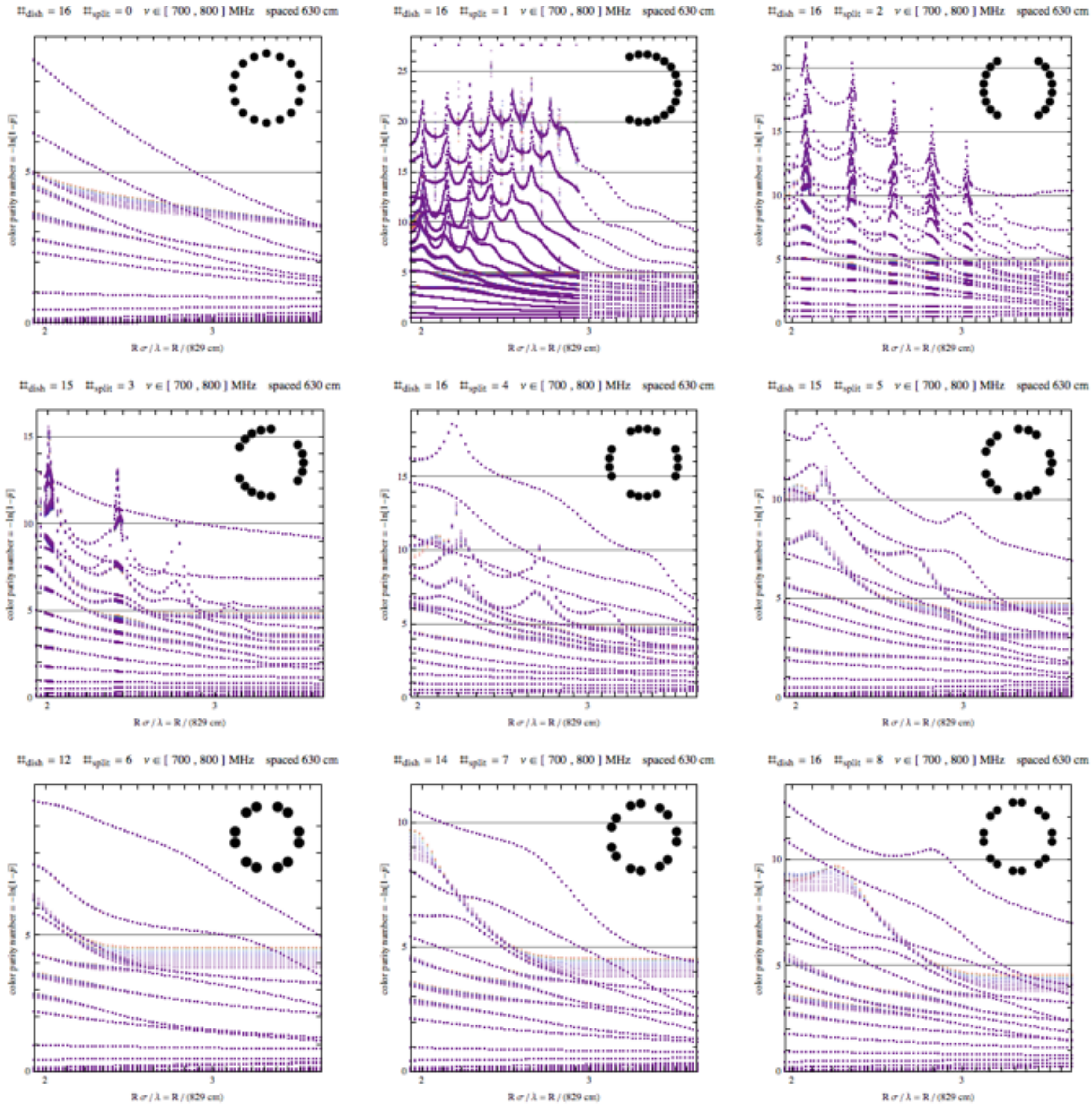

m = 0 ♯beams = 15 ipurity = 7 mean purity = 0.959062
best purity eigenbeams
angle from Pole (degrees)
4
3
2
1
0
−1
−2
0
1
2
3
4
5
6
7
8
9
10
0.930682
0.942024
0.953705
0.963515
0.969252
0.972179
0.973698
0.973259
0.970625
0.965943
0.956416
0.937452


m = 0 ♯beams = 15 ipurity = 8 mean purity = 0.945612
best purity eigenbeams
angle from Pole (degrees)
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
1
2
3
4
5
6
7
8
9
10
0.900176
0.920362
0.940497
0.954699
0.961741
0.965597
0.967993
0.967405
0.963532
0.955946
0.939706
0.909695



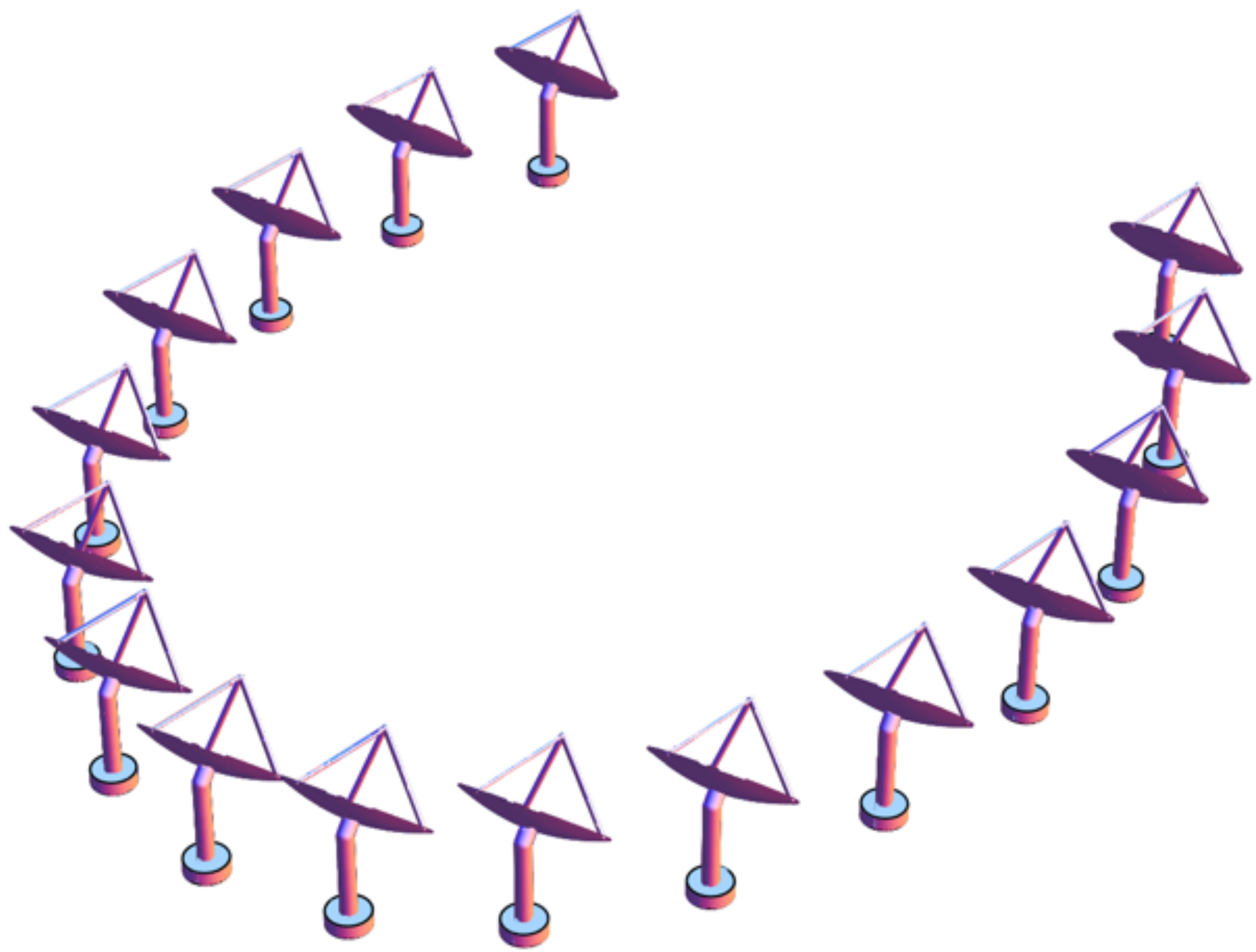
m = 0 ♯beams = 15 ipurity = 9 mean purity = 0.925166
best purity eigenbeams
angle from Pole (degrees)
1.5
1.0
0.5
0.0
−0.5
−1.0
0 1 2 3 4 5 6 7 8 9 10
0.859909
0.893353
0.924139
0.940006
0.945239
0.949614
0.953812
0.954164
0.950832
0.941602
0.916883
0.872441

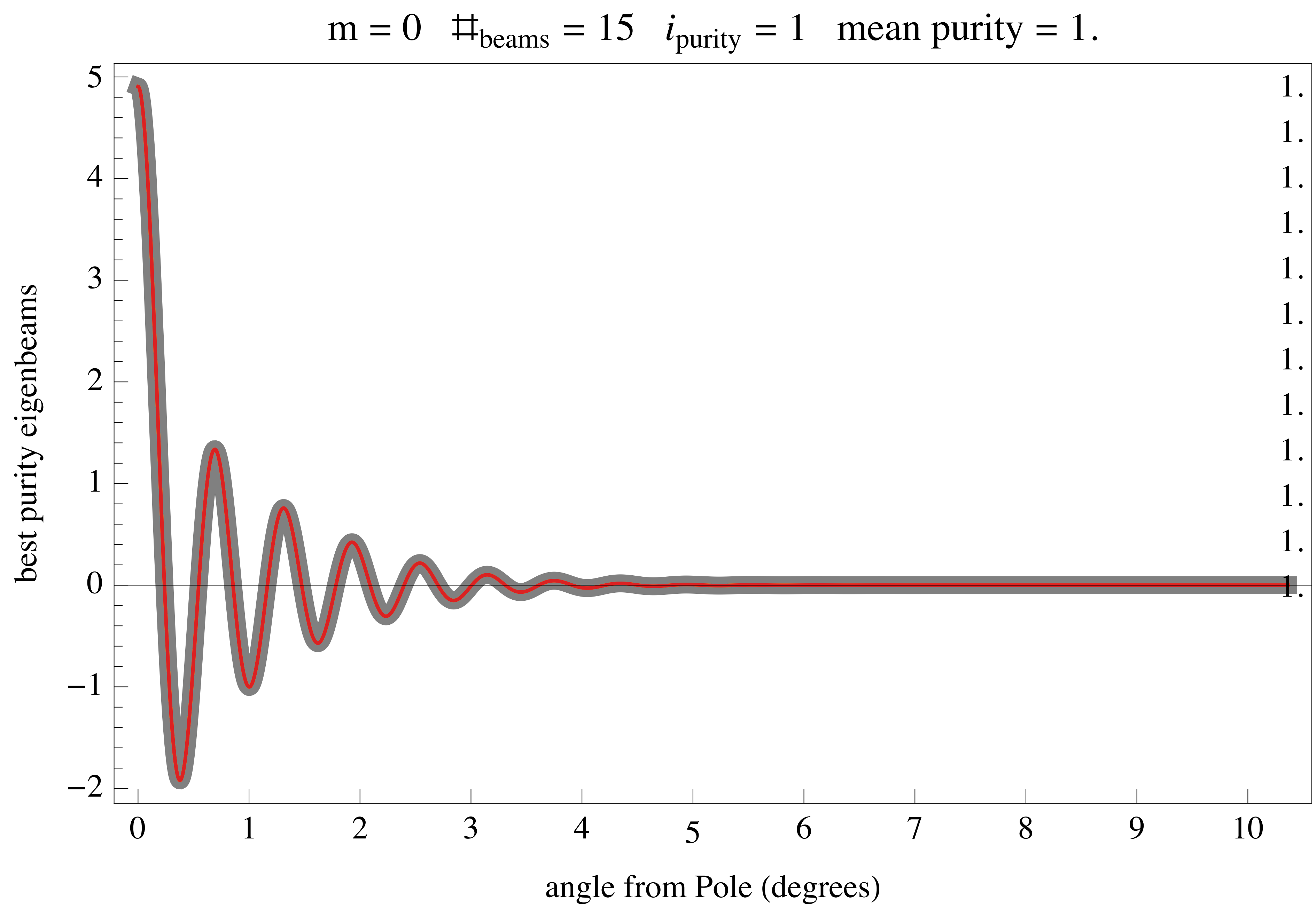

m = 0 ♯beams = 15 ipurity = 10 mean purity = 0.897237
best purity eigenbeams
angle from Pole (degrees)
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
1
2
3
4
5
6
7
8
9
10
0.801041
0.866307
0.909926
0.919964
0.92075
0.929026
0.93721
0.938298
0.93545
0.921584
0.878604
0.80869



$\#_{dish} = 16$ $\#_{split} = 0$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 16$ $\#_{split} = 1$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 16$ $\#_{split} = 2$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 15$ $\#_{split} = 3$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 16$ $\#_{split} = 4$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 15$ $\#_{split} = 5$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 12$ $\#_{split} = 6$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 14$ $\#_{split} = 7$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
$\#_{dish} = 16$ $\#_{split} = 8$ $\nu \in [\,700\,,800\,]$ MHz spaced 630 cm
color parity number $= -\ln[1-\rho]$
$R\,\sigma / \lambda = R\,/\,(829\text{ cm})$

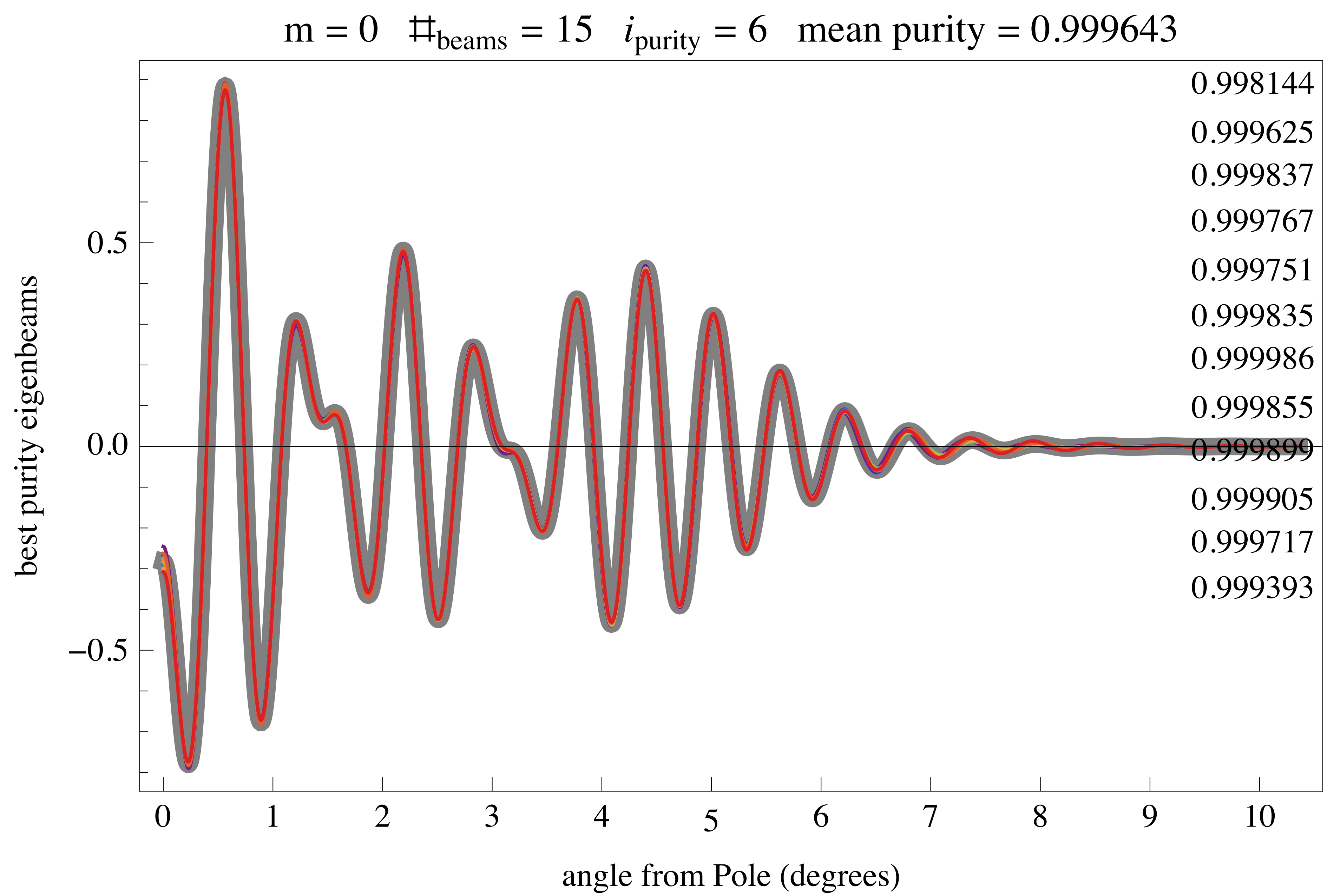
A Very Pure Polarscope



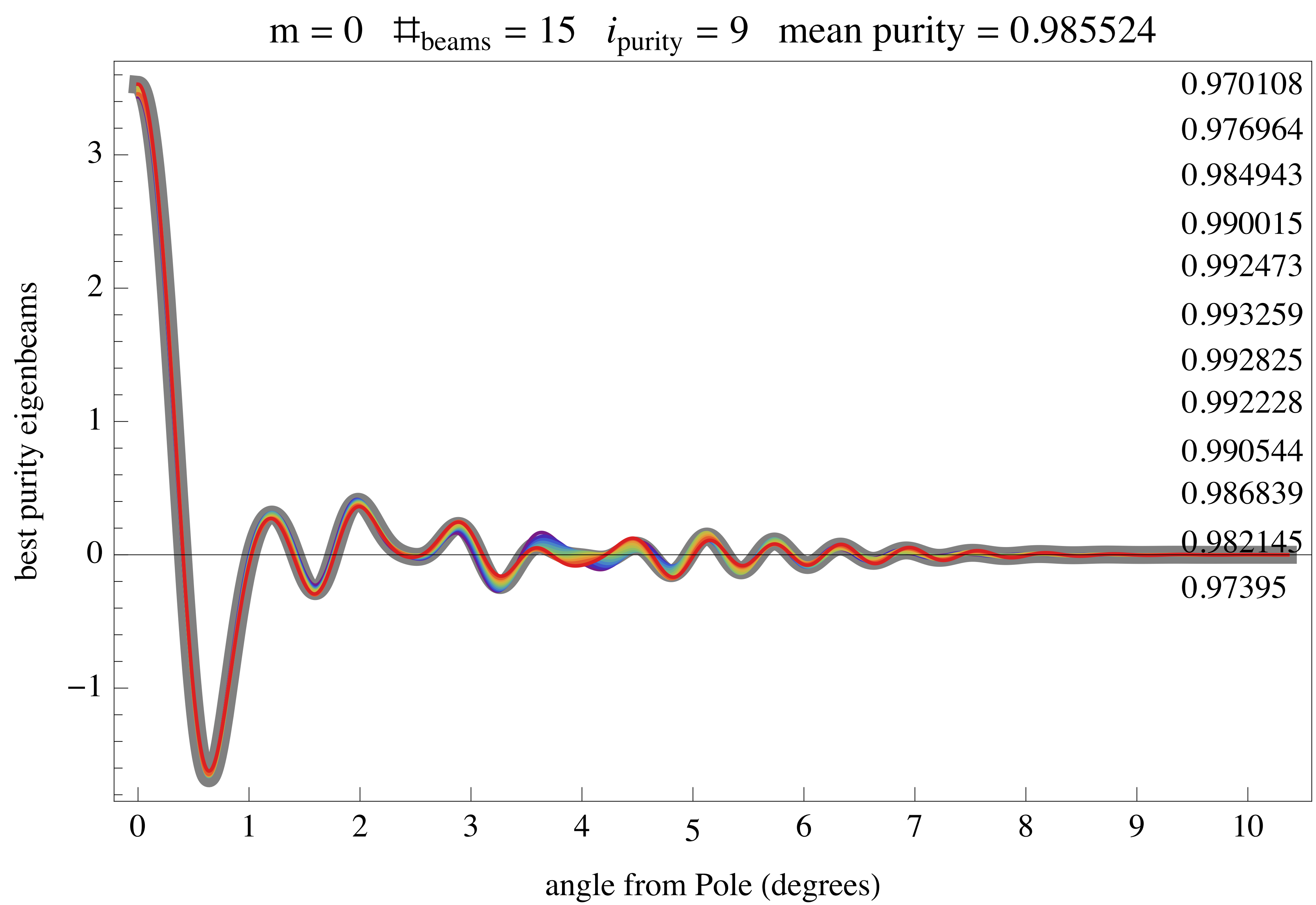


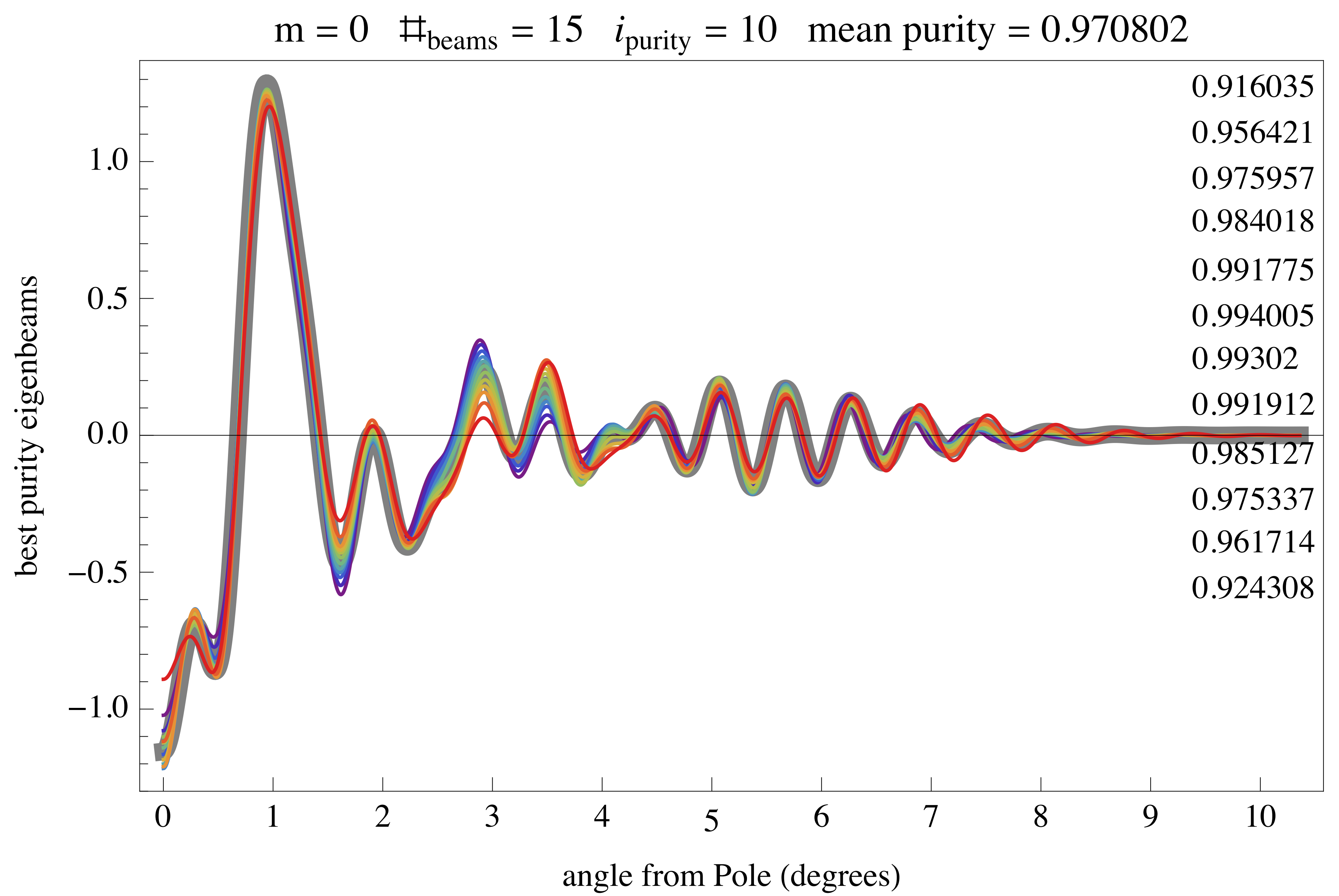
m = 0 ♯beams = 15 ipurity = 1 mean purity = 1.
best purity eigenbeams
angle from Pole (degrees)
5
4
3
2
1
0
−1
−2
0
1
2
3
4
5
6
7
8
9
10
1.
1.
1.
1.
1.
1.
1.
1.
1.
1.
1.
1.

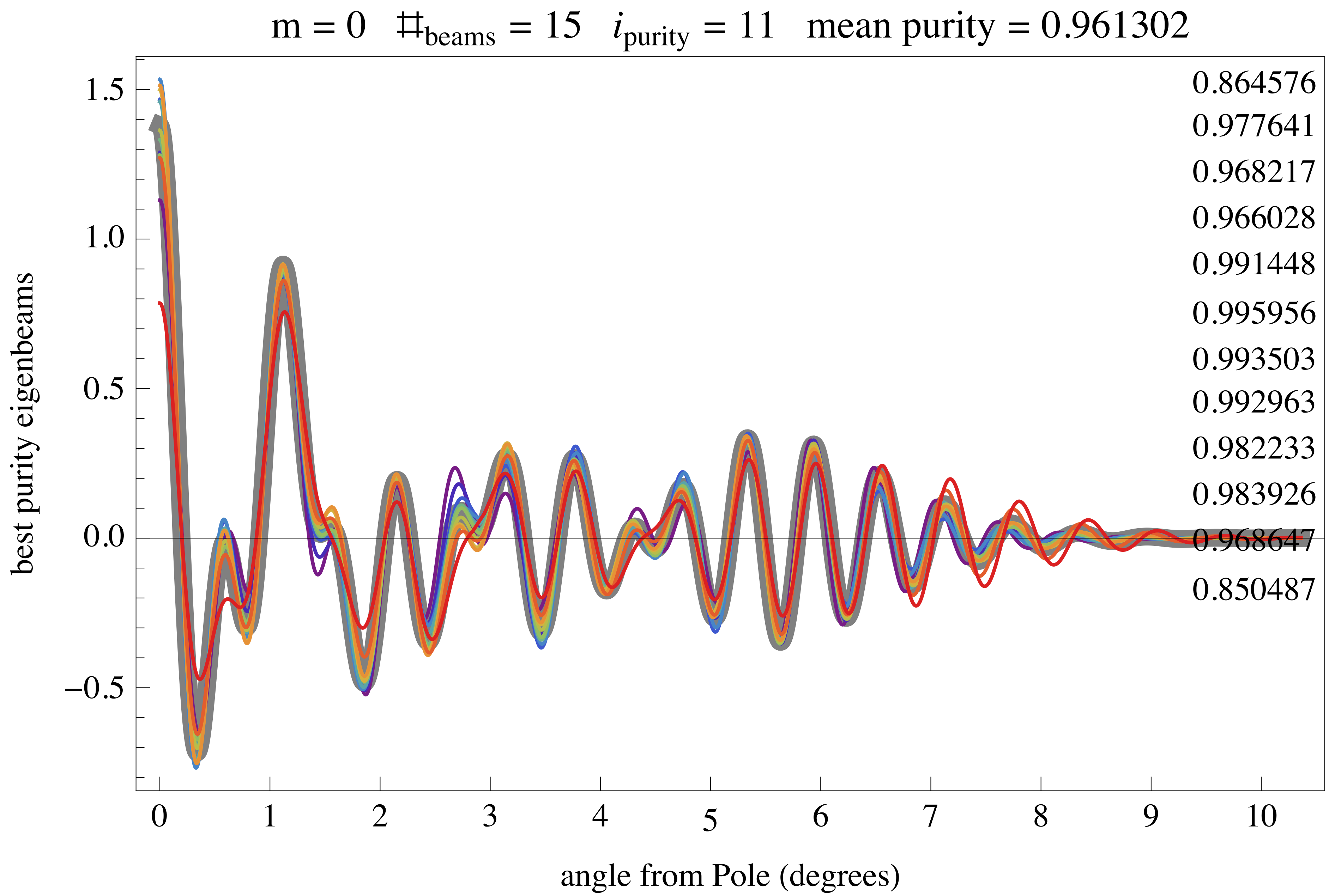
Skip to 6th purity eigenmode



Skip to 9th purity eigenmode




m = 0 ♯beams = 15 ipurity = 10 mean purity = 0.970802
best purity eigenbeams
angle from Pole (degrees)
1.0
0.5
0.0
−0.5
−1.0
0
1
2
3
4
5
6
7
8
9
10
0.916035
0.956421
0.975957
0.984018
0.991775
0.994005
0.99302
0.991912
0.985127
0.975337
0.961714
0.924308



m = 0 ♯beams = 15 ipurity = 11 mean purity = 0.961302
0.864576
0.977641
0.968217
0.966028
0.991448
0.995956
0.993503
0.992963
0.982233
0.983926
0.968647
0.850487
1.5
1.0
0.5
0.0
−0.5
0
1
2
3
4
5
6
7
8
9
10
best purity eigenbeams
angle from Pole (degrees)

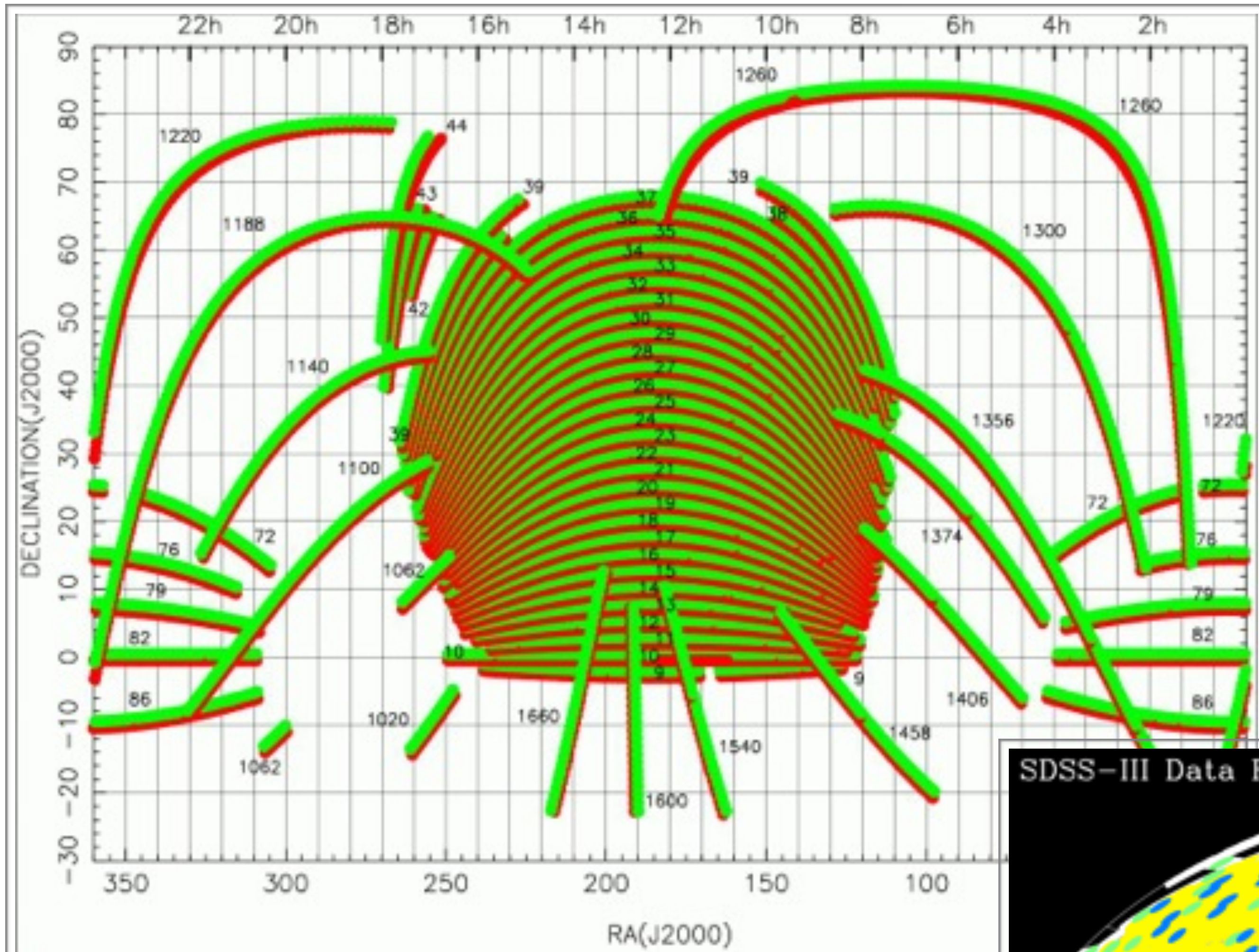
Suggestion for Next Tianlai-16 Configuration

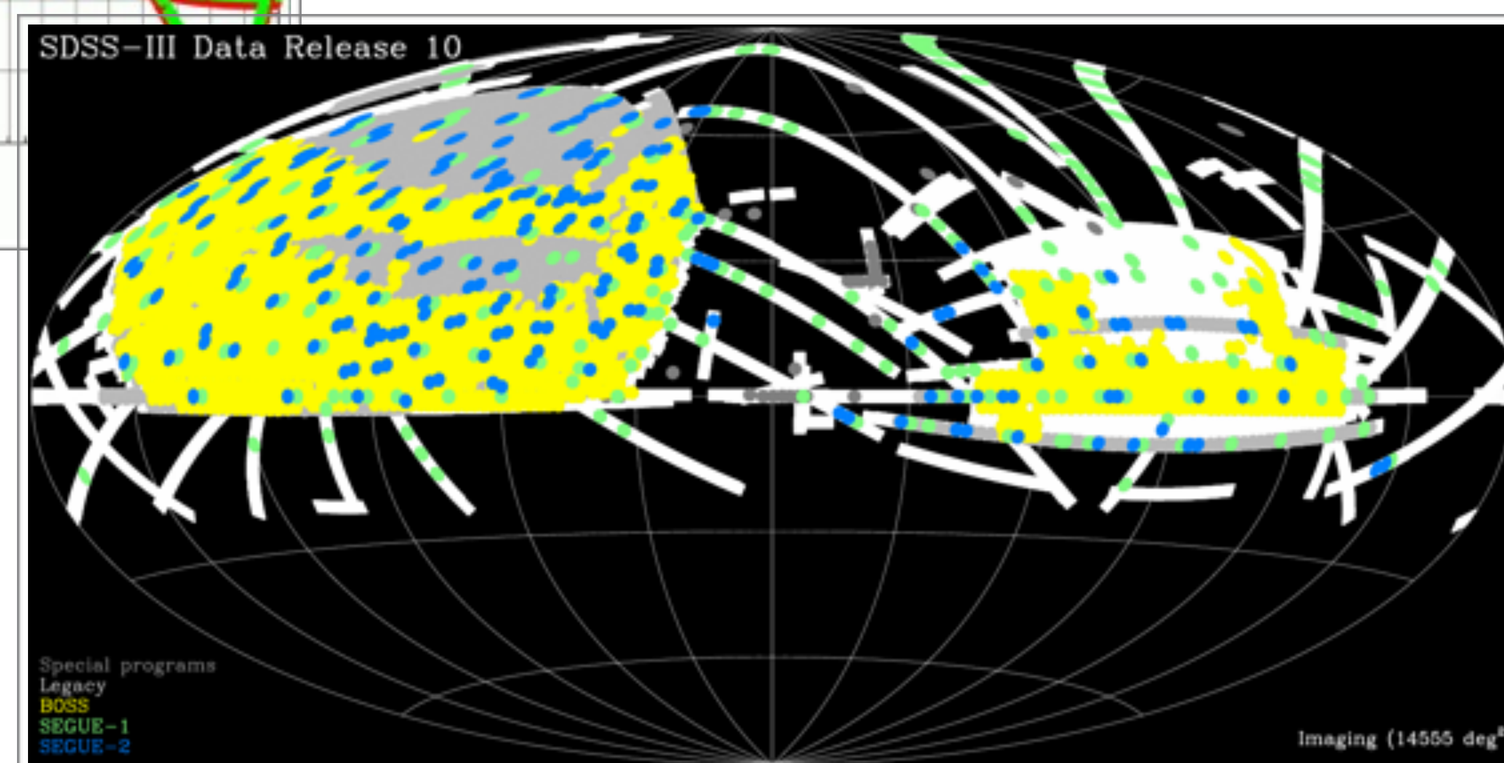
The Tianlai-16 dish array allows us the opportunity to

- by pointing toward the NCP (a polarscope or close to one) to integrate down rapidly to low noise levels
- experiment with array configuration to try to demonstrate a high purity interferometer
- in so doing rapidly test the efficacy of smooth spectrum foreground subtraction
- look for more concrete evidence of non-smooth foreground components

These results will have important implications for Tianlai cylinder and 21cm intensity mapping more generally.

Unfortunately Other Surveys Have Avoided NCP





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