Fermilab

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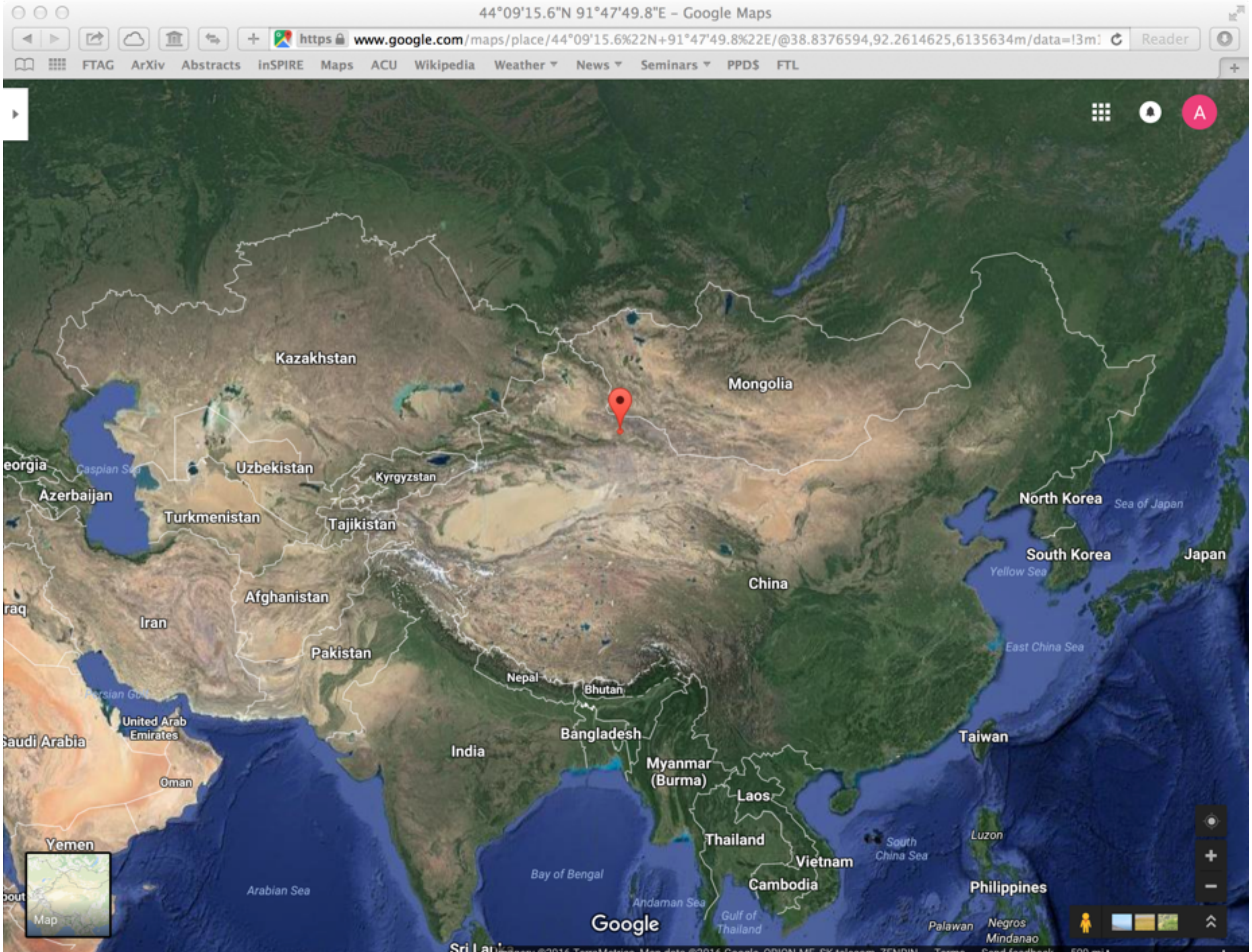
Tianlai Cosmic Vision

Albert Stebbins

Cosmic Visions Workshop

Berkeley, USA

14 November 2017



44°09'15.6"N 91°47'49.8"E - Google Maps
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Yellow Sea
China
Afghanistan
Iran
Pakistan
East China Sea
Nepal
Bhutan
United Arab Emirates
Saudi Arabia
Bangladesh
Taiwan
India
Myanmar (Burma)
Oman
Laos
Yemen
Thailand
South China Sea
Luzon
Vietnam
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Arabian Sea
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Gulf of Thailand
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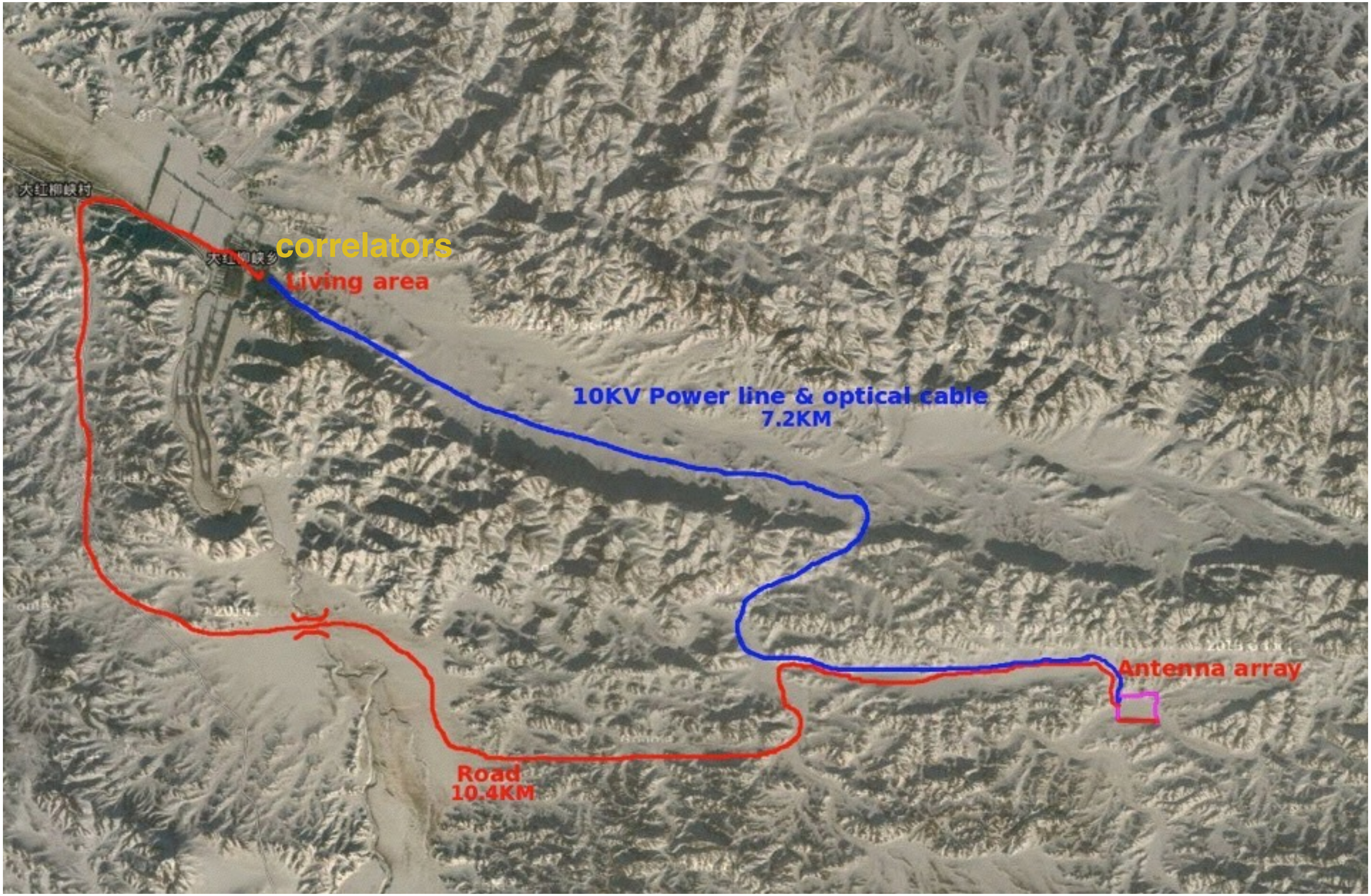
Tianlai Facility


大红柳峡村
correlators
大红柳峡乡
Living area
10KV Power line & optical cable
7.2KM
Antenna array
Road
10.4KM

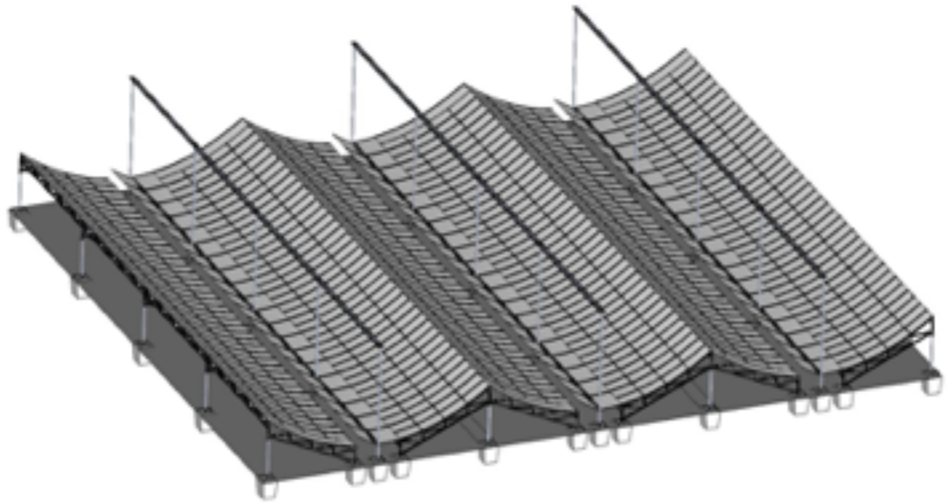
U.S. Participation in Tianlai

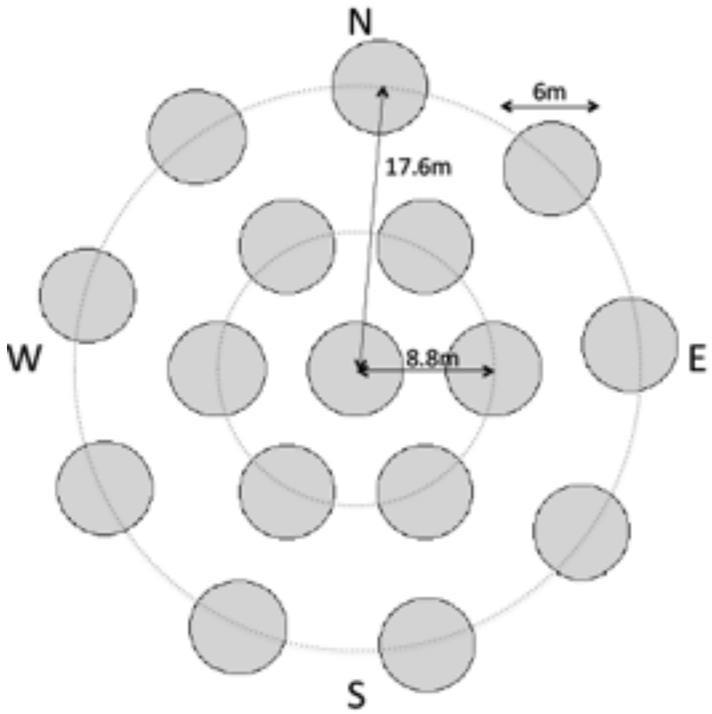
- In addition to large Chinese / French participation
  - Timbie / Das + students - University of Wisconsin
  - Stebbins / Marriner - Fermilab
  - Tucker + student - Brown
  - Peterson - Carnegie Mellon
  - open to new participants
- NSF grant: reduce/analyze 1st 3 years of data
  - Timbie (PI) / AS received NSF-AAG Grant (2016 - 2019)
  - **Tianlai Analysis Center**
    - computing/storage @ FNAL & Open Science Grid
- Manpower limited

Tianlai Configuration(s)

Pathfinders to demonstrate basic principle and encounter all issues rapidly

- **Band** 700-800MHz (0.77<z<1.3)
  1024 frequency channels
  ($\delta\nu$=100kHz δz=0.0002)
  tunable in 600-1420MHz
- **Cylinder Array** 3 x 15m x 40m cylinders
  96 dual polarization feeds
  4 sec sampling
- **Dish Array** 16 x 6m dishes
  16 dual polarization feeds
  1 sec sampling
- **Pathfinder+ Cylinder Array**
  216 dual polarization feeds
  4 sec sampling
- **Full Cylinder Array** 8 x 15m x 120m
  2048 dual polarization feeds
  400-1420MHz





Pathfinder Highly Configurable Transit Telescope

- Tuneable:
  - 600 < ν < 1420Mhz (0<z<1.36) [fixed 100 Mhz bandwidth]

- Cylinders:
  - equal/unequal spacing of feeds on cylinder
  - feed placement on cylinders may be same or different
    - redundancy vs broader u-v coverage (less mode mixing)

- Dishes:
  - pointable / tracking
  - arrangeable in any ground configuration

R&D: plan to play with all the knobs

Tianlai Long Term Goals

with **lessons learned** from current pathfinder array fill out and expand (cylinder) array

- expand (cylinder) array to do lower noise / higher resolution imaging of Northern sky.
- make HI maps, $P_{HI}[k]$ for cosmological parameters e.g. BAO/DE.

Table 2
Telescope Configurations Used in This Paper

Bull et al. 2014

		Experiments	$T_{\rm inst}$ [K]	$N_{\rm d} \times N_{\rm b}$	$D_{\rm dish}$ [m]	$D_{\rm min}$ [m]	$D_{\rm max}$ [m]	$\nu_{\rm crit}$ [MHz]	$\nu_{\rm max}^{\rm IM}$ [MHz]	$\nu_{\rm min}^{\rm IM}$ [MHz]	$\Delta\nu^{\rm IM}$ [MHz]	$z_{\rm min}$	$z_{\rm max}$	$S_{\rm area}$ [deg^2]
Targeted IM	•	BAOBAB-128	40	128 × 1	1.6	1.6	26.0	···	900	600	300	0.58	1.37	1,000
		BINGO	50	1 × 50	25.0	···	···	···	1260	960	300	0.13	0.48	5,000
	◊	CHIME	50	1280 × 1	20.0	···	···	···	800	400	400	0.77	2.55	25,000
		FAST	20	1 × 20	500.0	···	···	···	1000	400	600	0.42	2.55	2,000
	•	MFAA	50	3100 × 1	2.4	0.1	250.0	950	950	450	500	0.49	2.16	5,000
	◊	Tianlai	50	2048 × 1	15.0	···	···	···	950	550	400	0.49	1.58	25,000

Table 4
1D Marginal Constraints (68% CL) on the Extended ΛCDM Model, Including the Planck Prior

Experiments	A / 10^{-2}	h / 10^{-3}	Ω_K / 10^{-4}	$\Omega_{\rm DE}$ / 10^{-3}	n_s / 10^{-4}	σ_8 / 10^{-3}	γ / 10^{-2}	w_0 / 10^{-2}	w_a / 10^{-2}	FOM
BAOBAB-128	24.3	50.2	71.3	36.6	38.5	8.1	9.0	33.3	71.4	8.0
BINGO	25.8	30.8	90.0	16.1	38.5	8.2	2.8	44.1	172.5	7.8
CHIME	3.0	8.7	9.7	7.1	30.2	5.2	3.4	5.0	15.1	288.1
FAST	7.5	13.5	16.0	10.1	33.5	6.4	3.2	7.1	18.5	144.7
MFAA	5.7	11.9	14.1	9.1	32.2	6.0	3.1	6.3	17.2	165.7
Tianlai	3.6	8.0	11.9	6.3	28.7	4.9	2.4	4.0	12.0	383.3

Tianlai Pathfinder Goals

- Implement large interferometric **arrays** in a quiet site in western China to obtain a high fidelity 3D image of Northern Sky w/ 100MHz bandwidth. Accurate **beam calibration** is essential.
- Compare cylinder arrays with dish arrays (also cross correlate dish/cylinder)
- Experiment with cylinder feed arrangements / dish placements.
- Experiment with different calibration schemes: artificial calibration sources on ground and in air; natural calibrations sources: Sun and other bright sources, pulsars, holography; numerical modeling of beam.
- Deep imaging of North Celestial Cap (NCC) with dish array.
- Optimize algorithms **and** telescope arrangement for best foreground removal.
- Construct redshift space HI emission maps especially in NCC.
- Vary frequency band up to 1.4GHz (lo-z 21cm) so as to make maps to compare with LSS with optical redshift surveys SDSS and NCCRS.

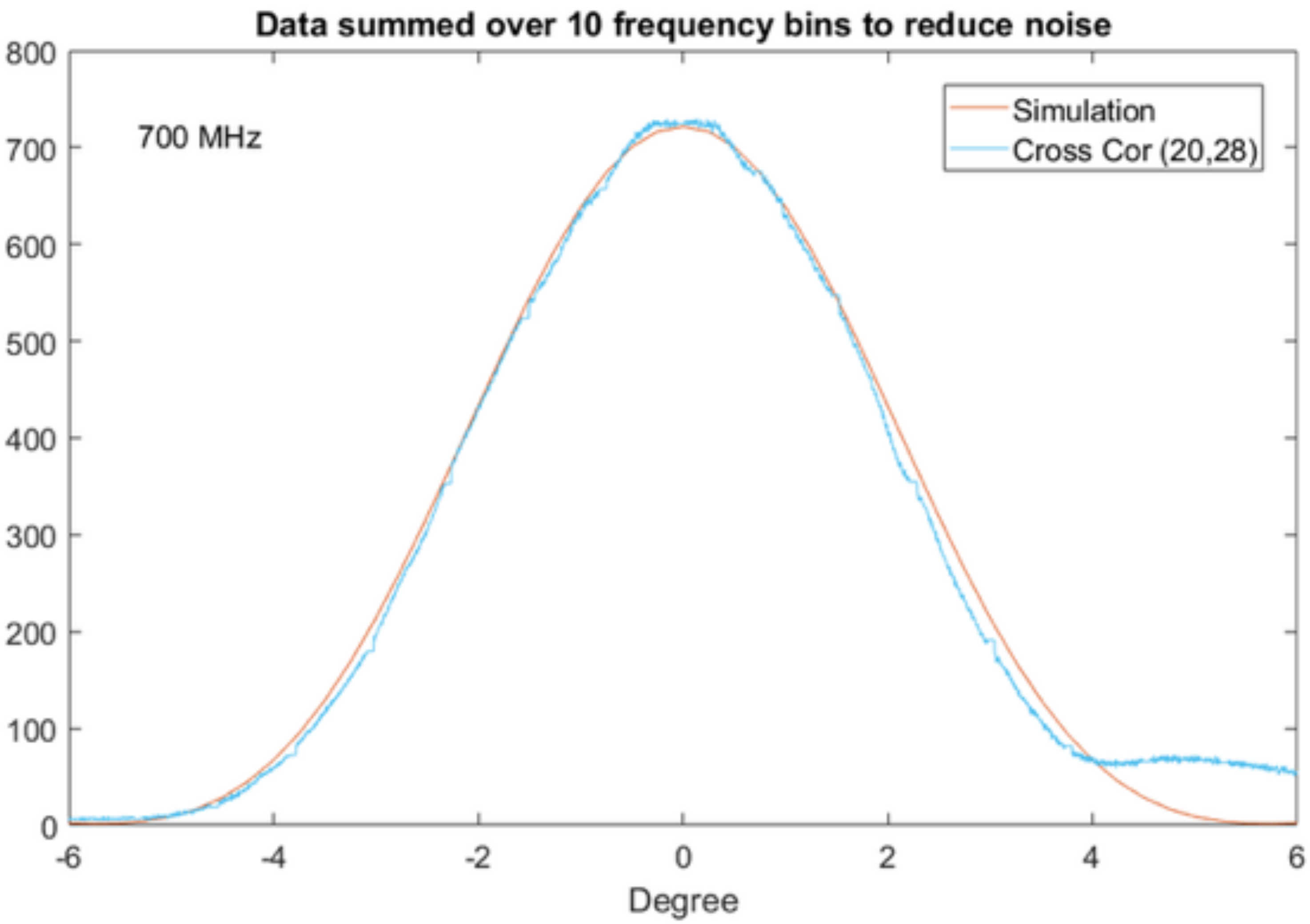
Timeline

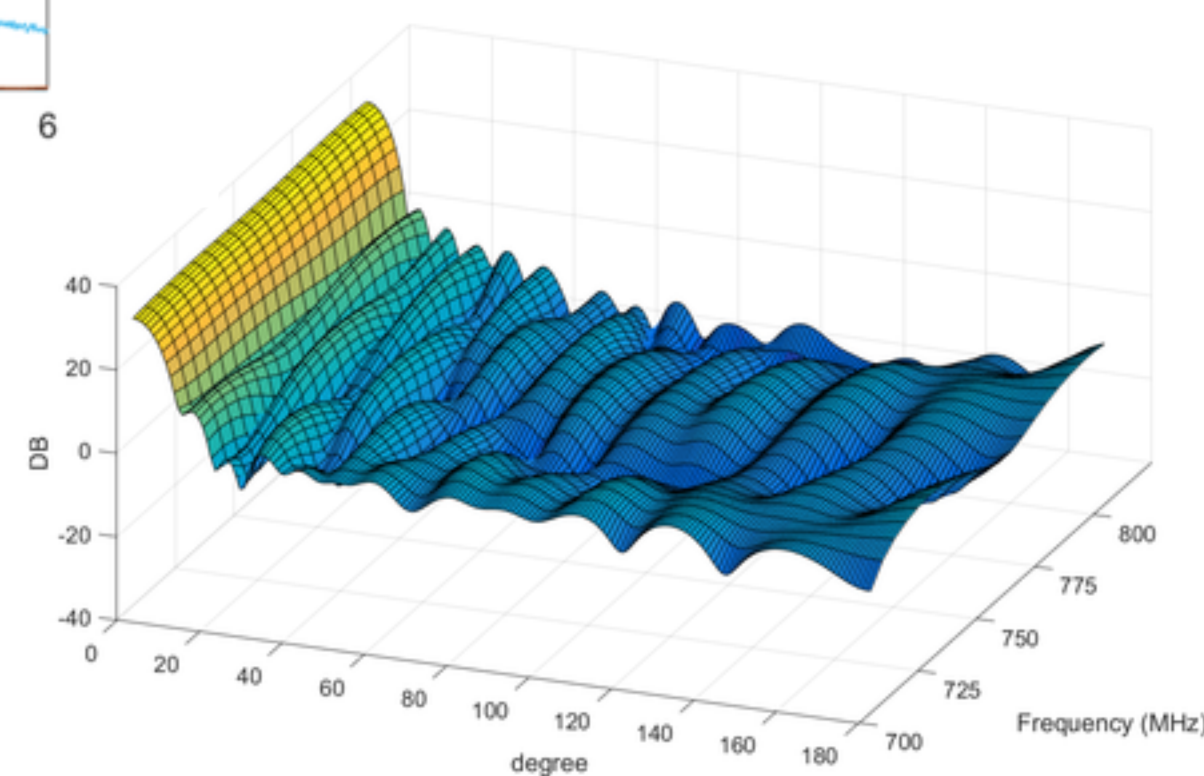
- 2014:
  - basic infrastructure: roads, buildings, power, optical fibers
  - electronics design
- 2015:
  - scientific infrastructure: reflectors finished
  - much of electronics installed
  - first fringe
  - engineering / debugging
- 2016:
  - engineering / debugging
  - astronomical imaging of bright sources
  - several runs with dish array : mostly NCC
  - 1 run with with cylinders
- 2017:
  - fix hardware issues (some down time)
  - develop test calibration methods (mostly offline analysis development while taking data)
  - cylinder+dish runs
- 2018:
  - production runs
  - transient backend / outriggers?
- 2019:
  - production runs
  - tune dishes to lo-z
  - transient backend / outriggers?

Tianlai Analysis Center

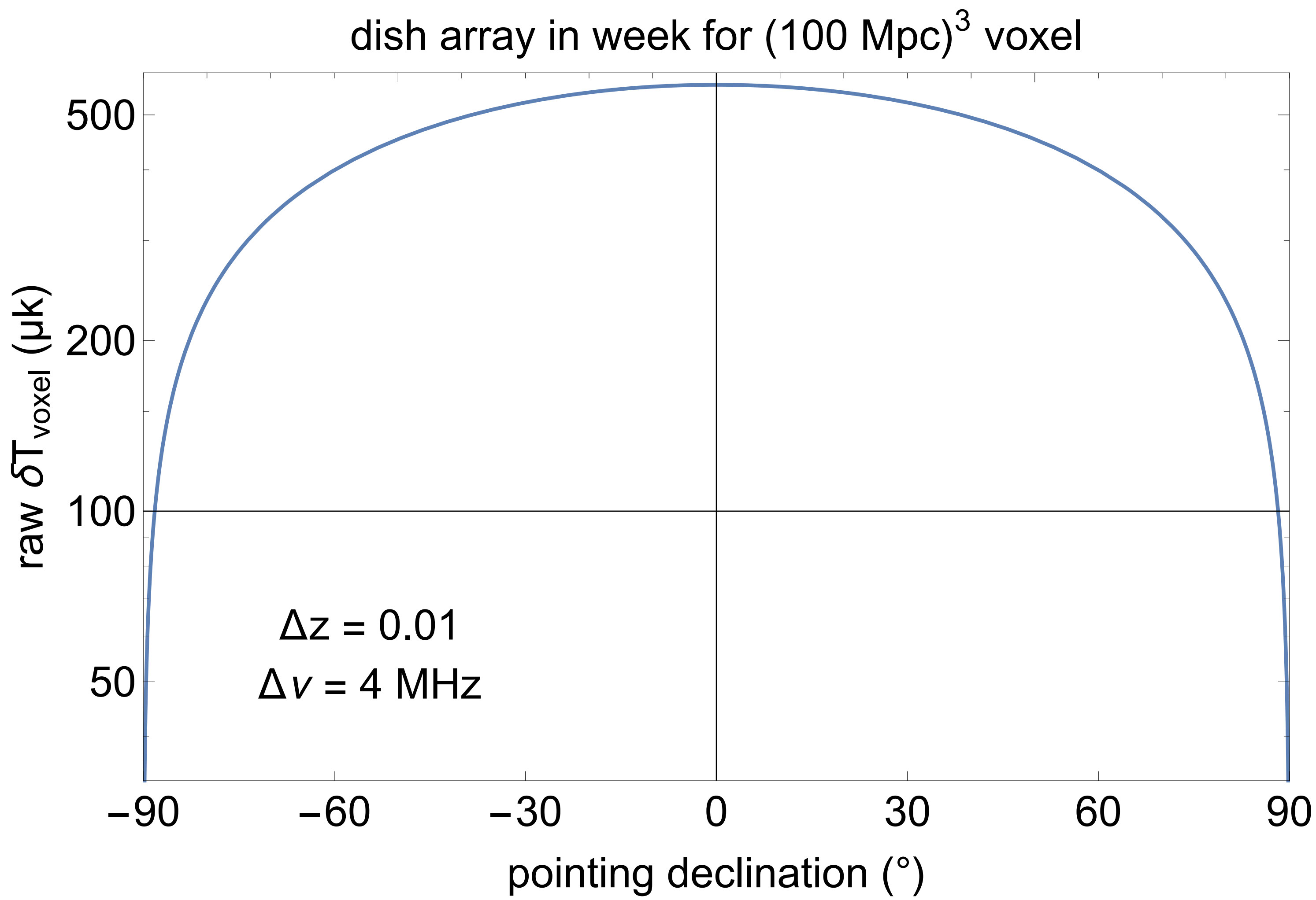
- software development
- computer resources / data storage
- data reduction
- data visualization tools/repository
- feedback for instrumentation / observational strategy
- EM simulations and modeling of beams
- beam calibration techniques
- transient detections

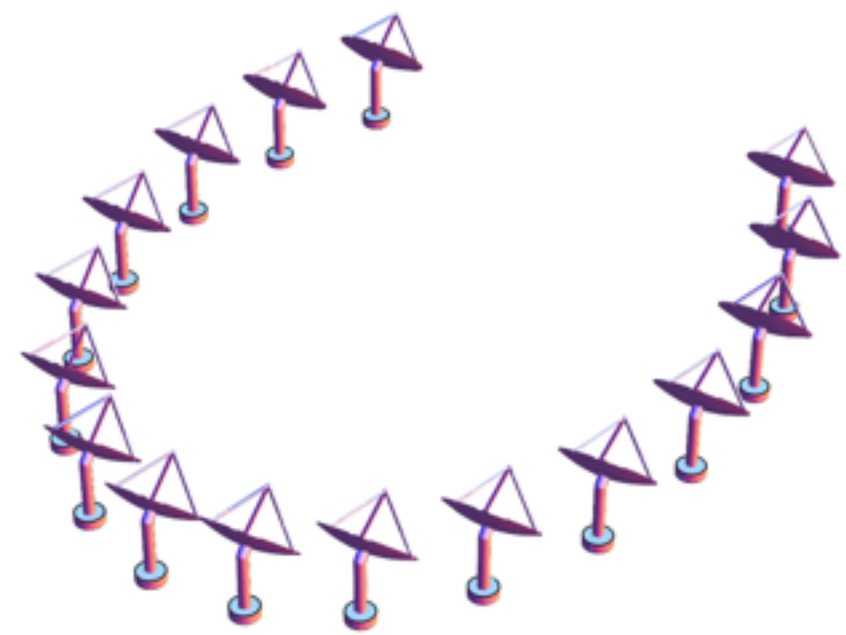
EM Simulations





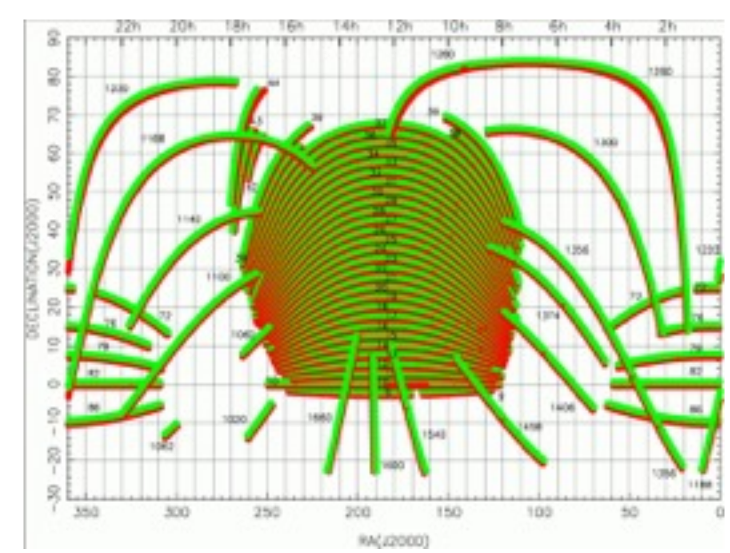
Dish Array as Polarscope



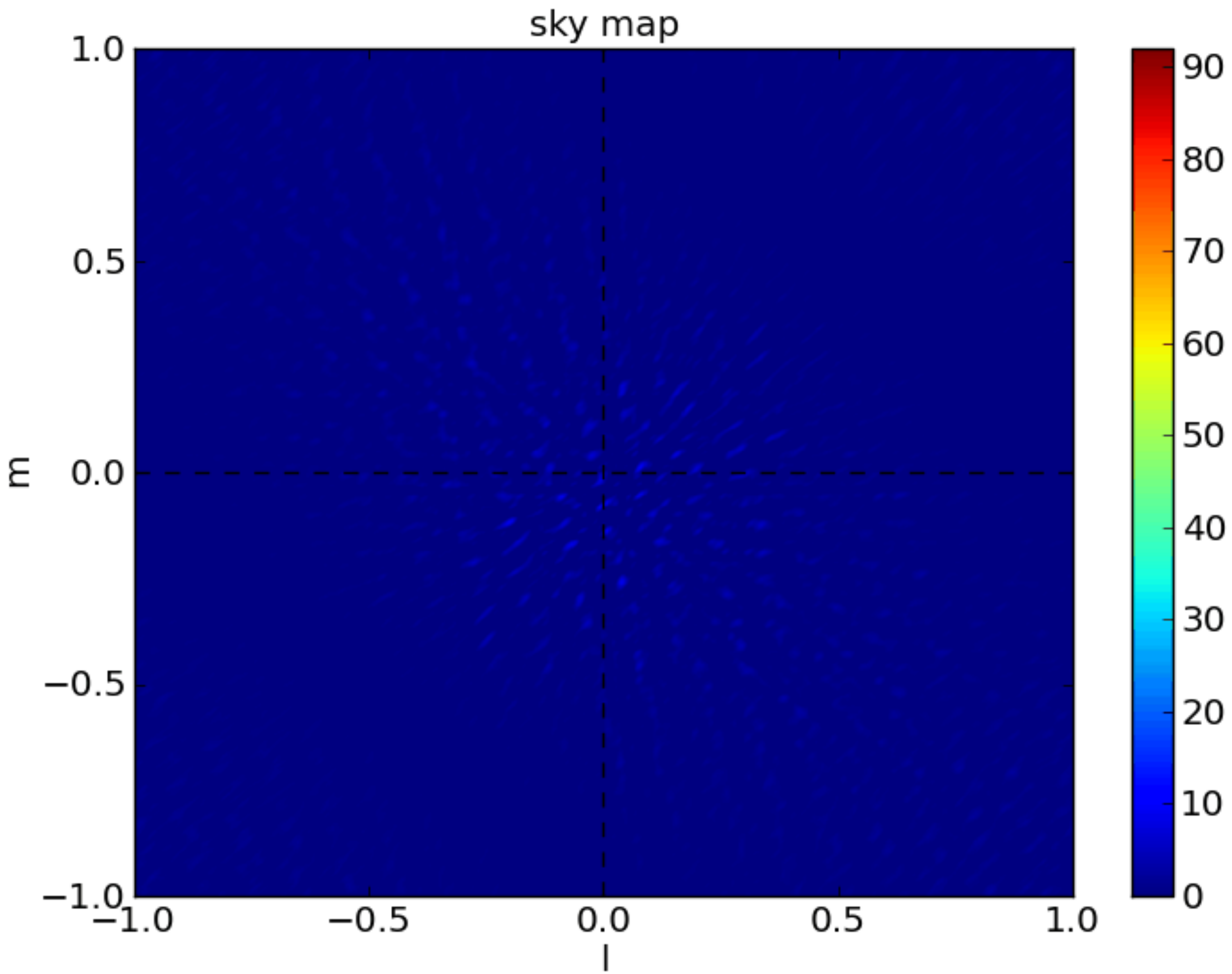


- By pointing disk array toward pole will integrate down to low map noise temperature rapidly.

- **WANTED**: NCC optical spectroscopic survey of <u>existing</u> photometric survey to compare to



Transients

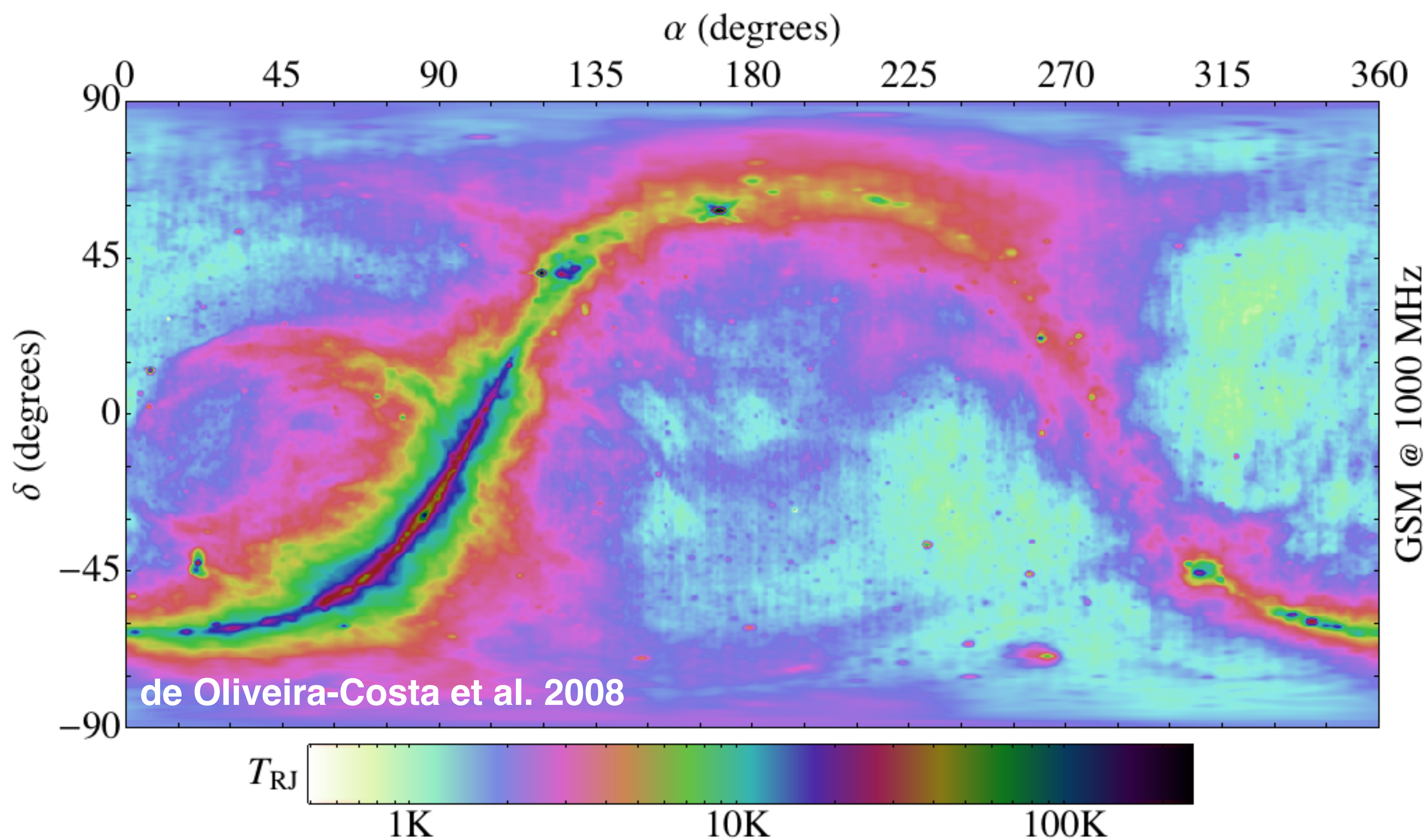


Tianlai Target Of Opportunity

- Tianlai Analysis Center NSF Grant ends in 2019!
- **but** Tianlai will continue and expand.
- continued/expanded US participation after 2019?
- most flexible developmental machine for HI intensity mapping
- excellent site wrt RFI.
- Tianlai buildout $\gtrsim$ CHIME
- low entry costs relative to a new scope
- Chinese lead in funding

Additional Slides

Foreground removal efficacy remains a significant issue

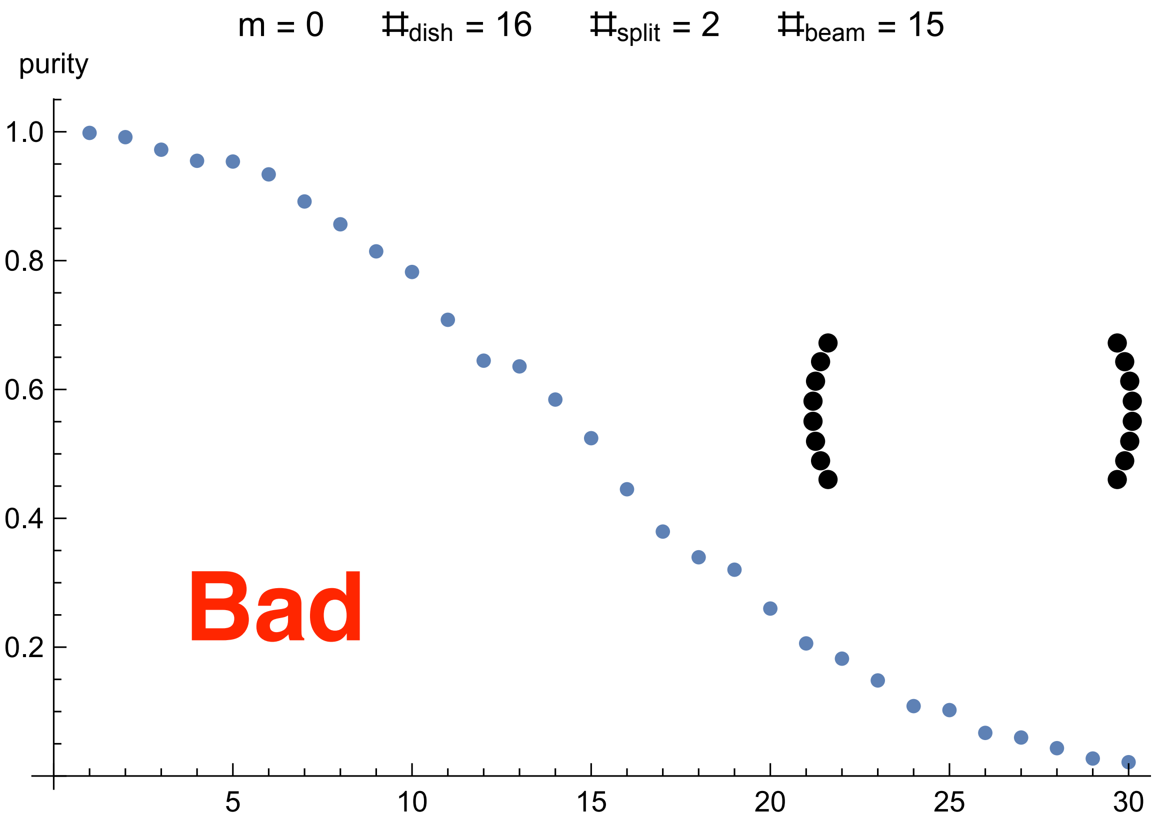


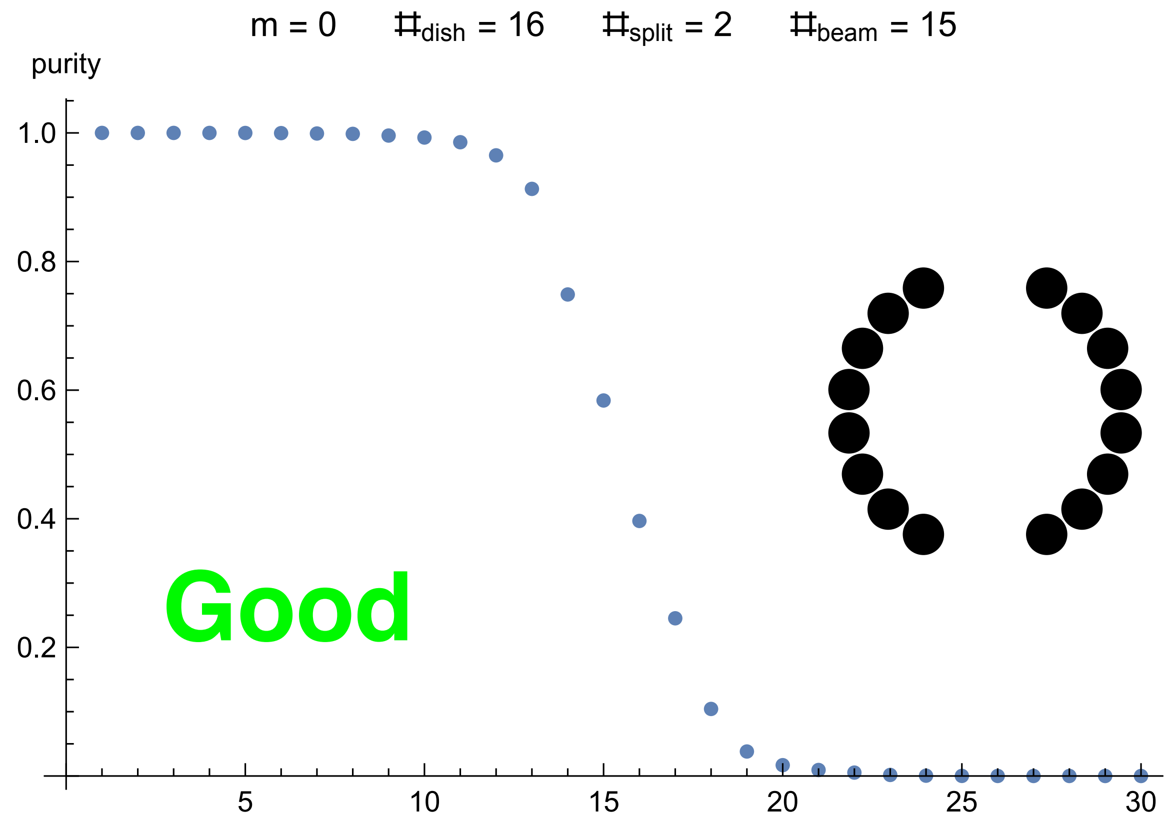
Even for dark radio sky ~1K foreground is ~10^4 larger than ~100μK signal

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

Purity and Telescope Design

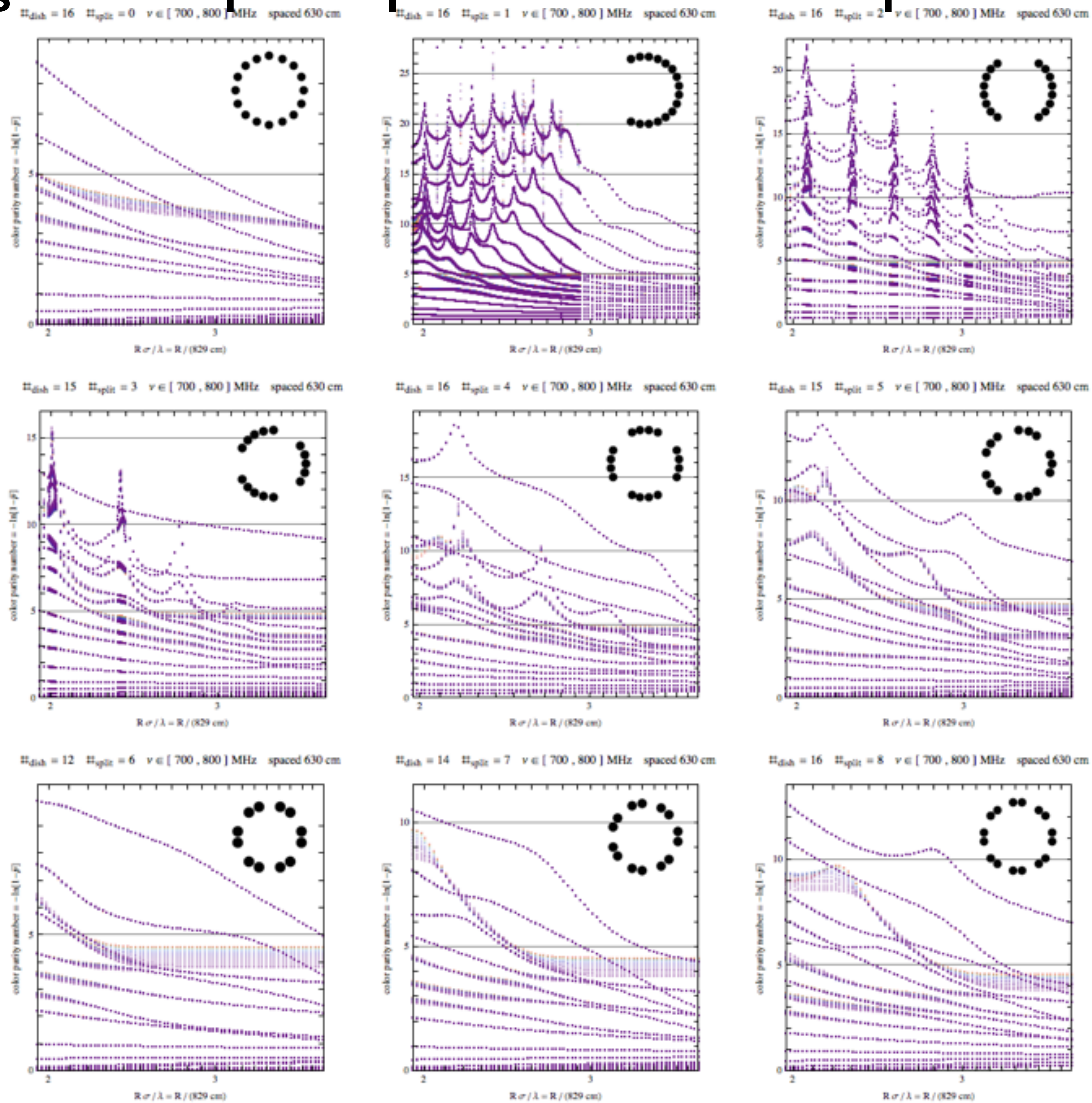
- A high purity interferometer is an one which for a given bandwidth has close to n_{beam} very "pure" synthetic beams.



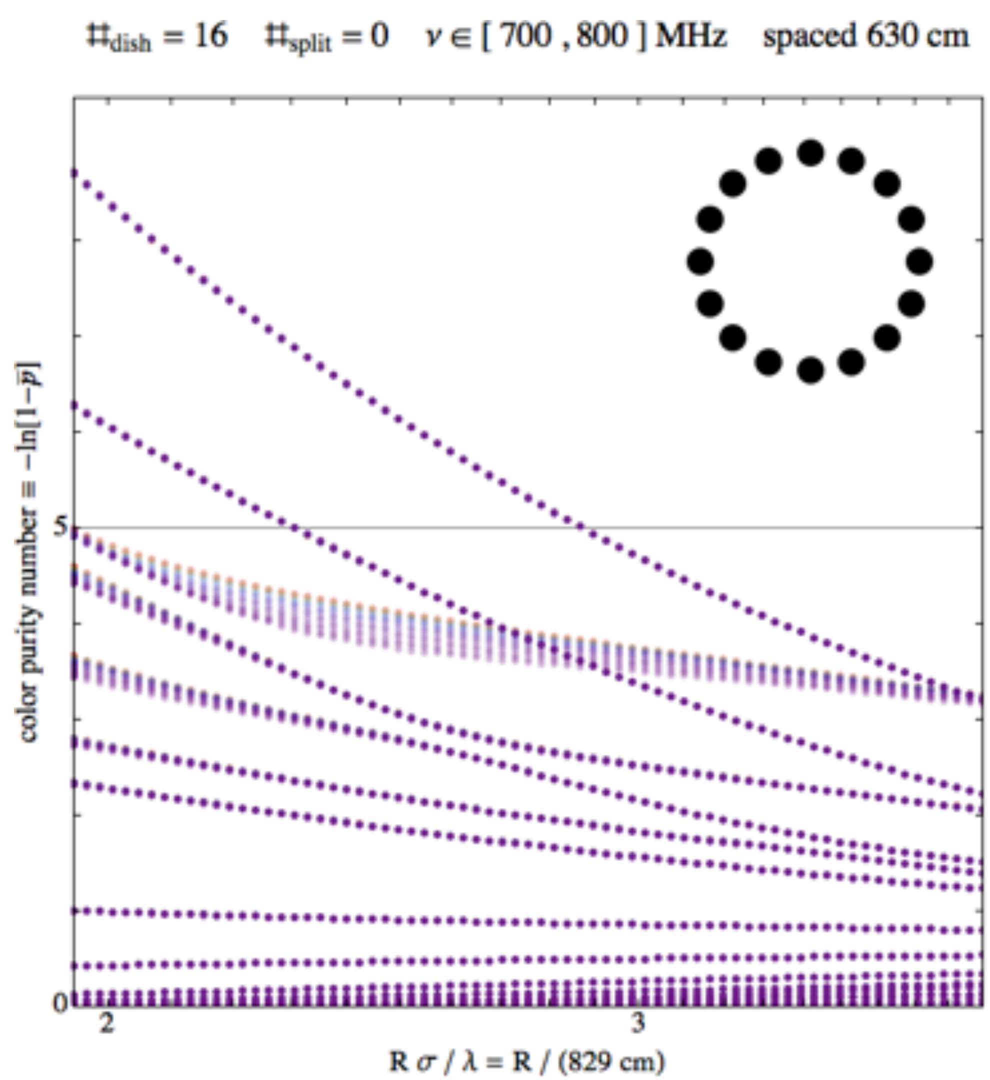


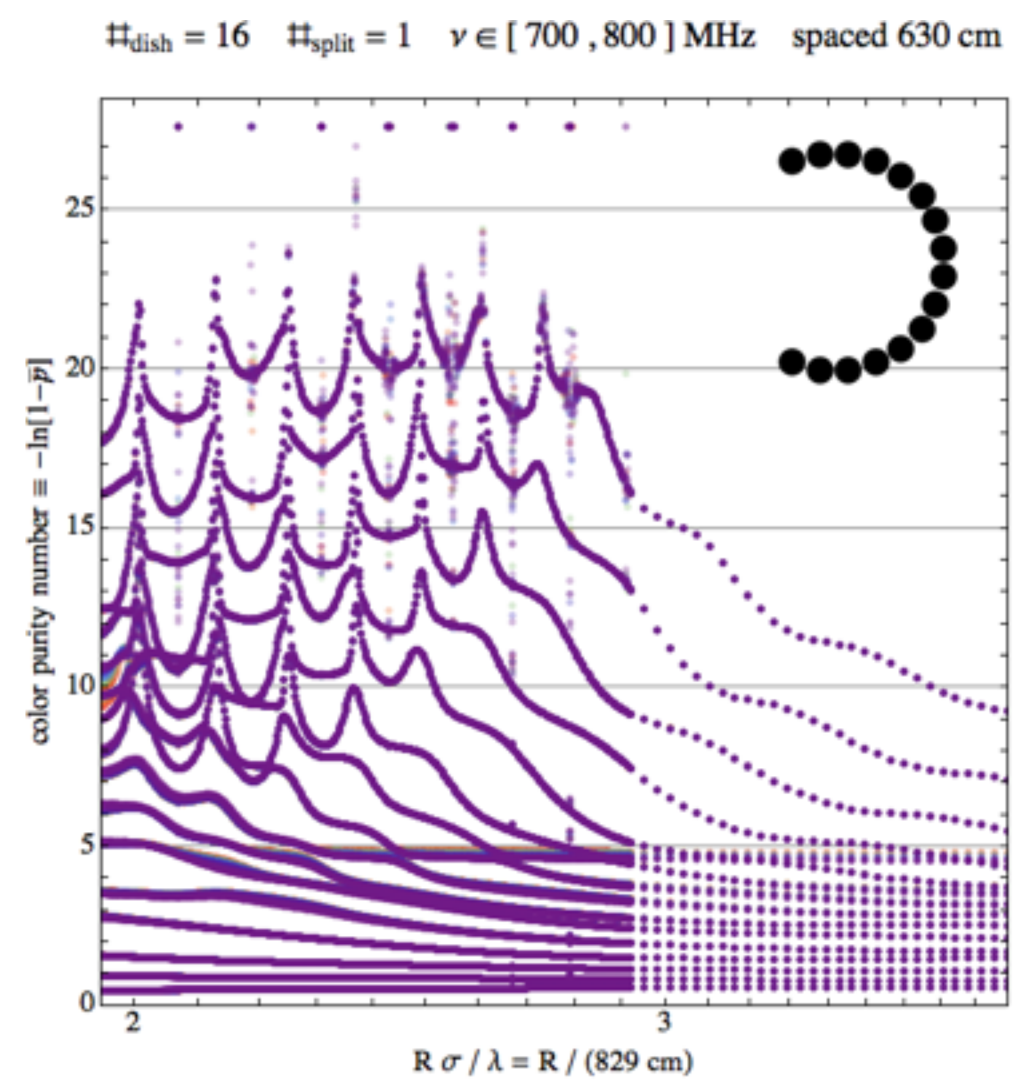
- Purity number: $-\ln[1-p_a]$ is large for very pure modes

configuration space: split circle into *n* compact subarrays



Optimizing Dish Array Design

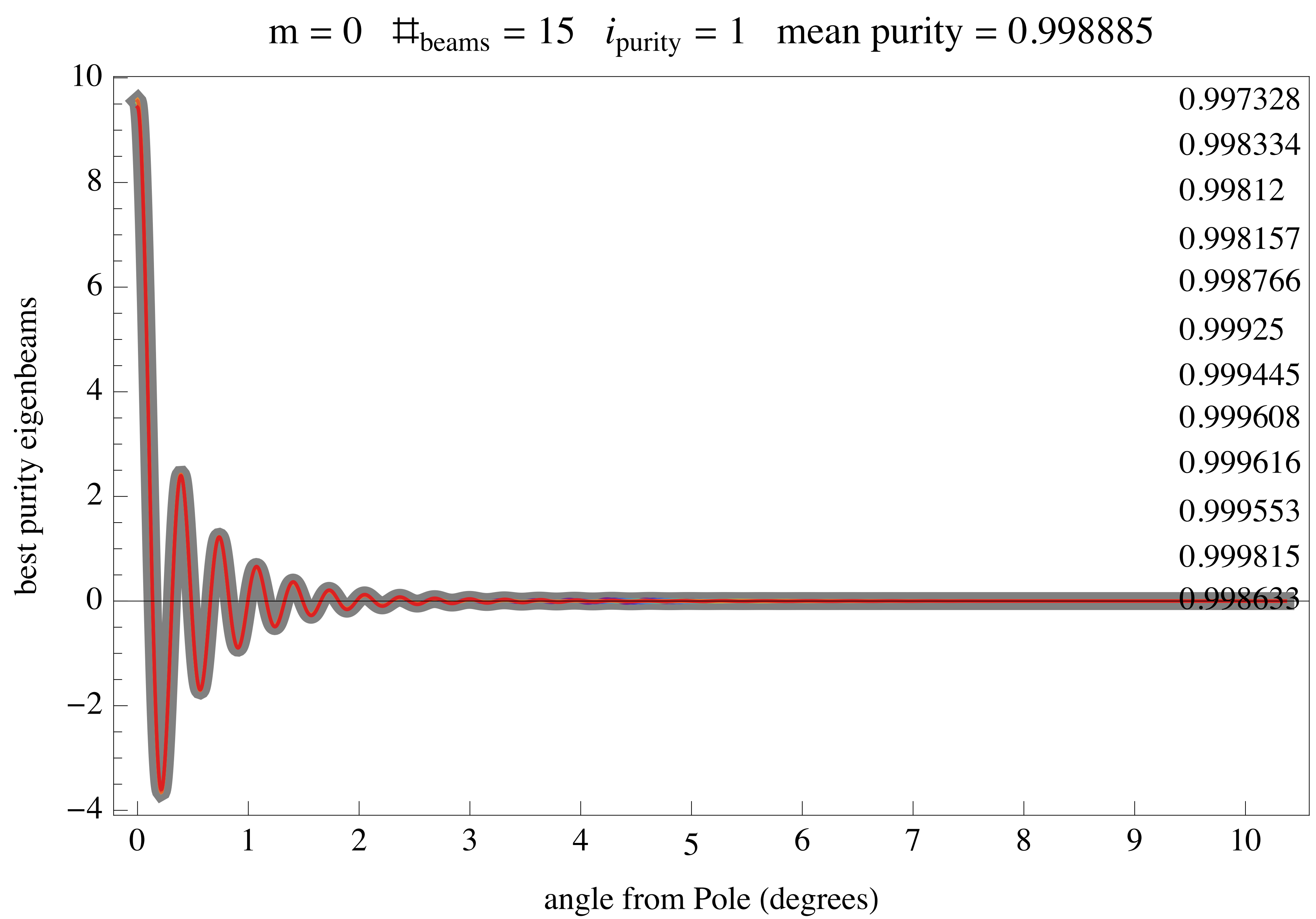




- By rearranging dish array elements (to within a fraction of λ) one can decrease the amount of mode mixing in synthetic beams by a large amount.

- mode mixing - aliasing of angular modes into frequency modes - which effects degree one can remove foreground

declination dependence of purity eigenbeams

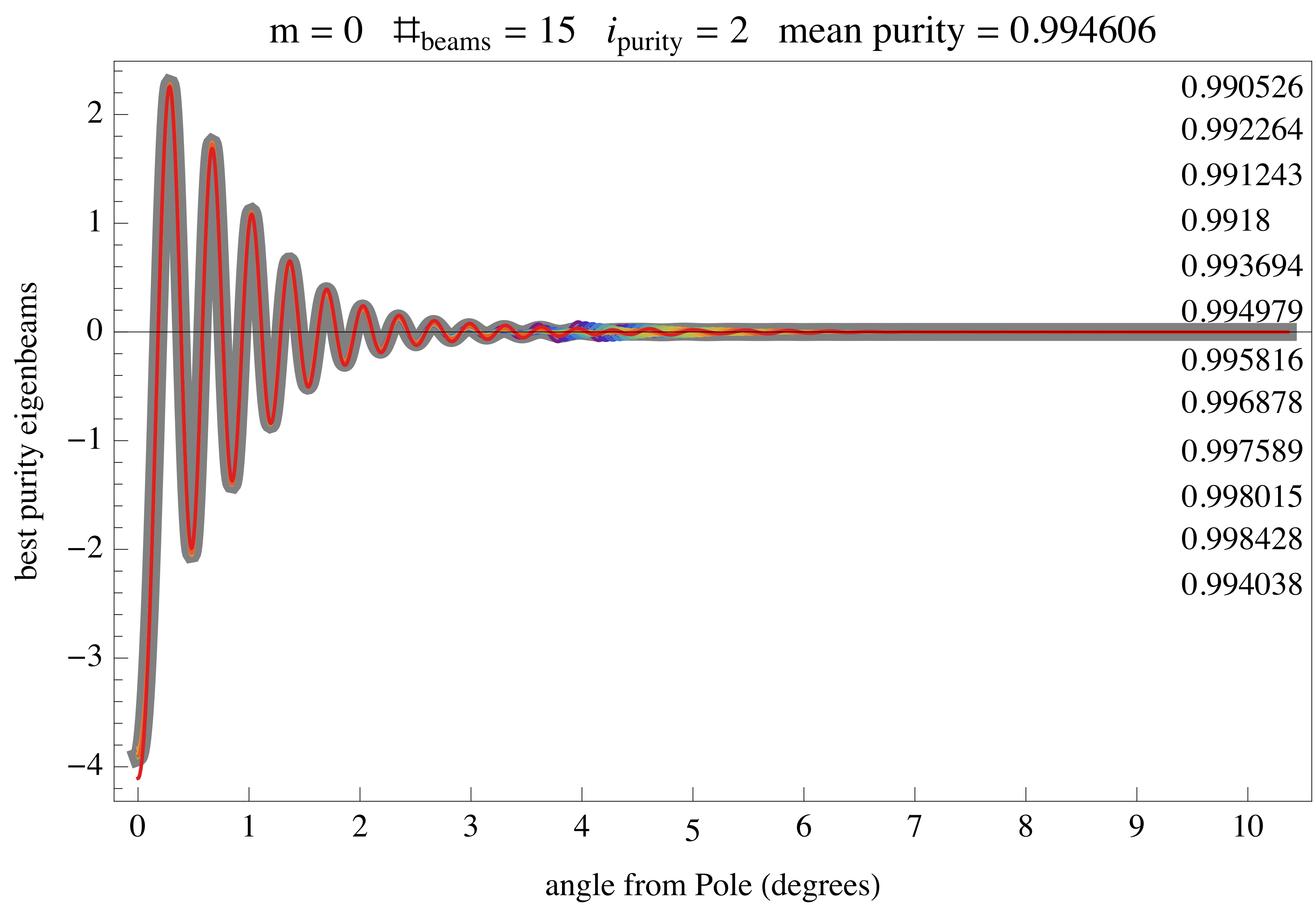


brown curve gives the eigenbeam in the full (full bandwidth) space of beams.

colored curves are projection of a single channel space of beams for 12 different frequency channels.

different channels are colored differently

however for this purest eigenbeam the patterns are largely identical so only see one channel (red)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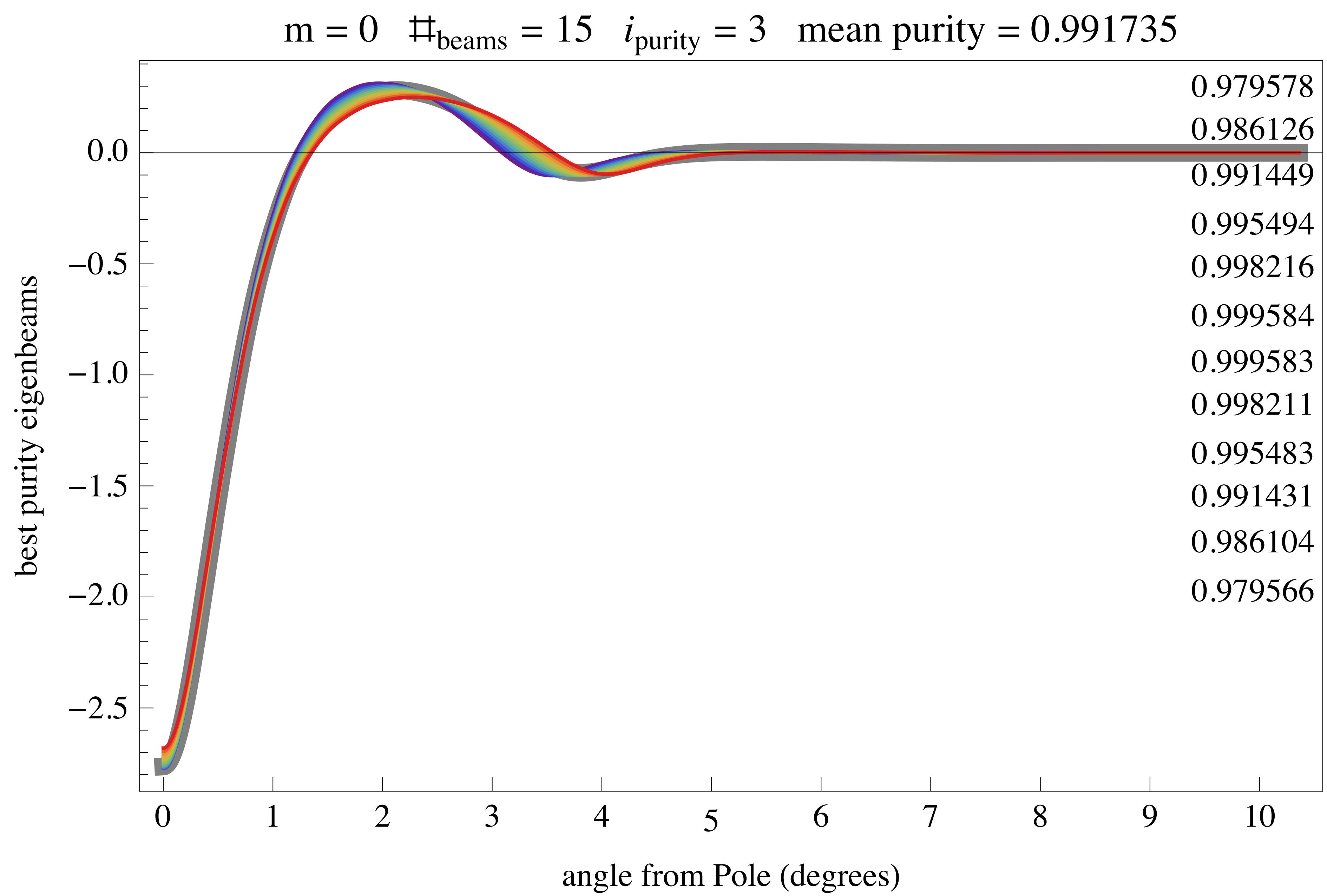
0.990526
0.992264
0.991243
0.9918
0.993694
0.994979
0.995816
0.996878
0.997589
0.998015
0.998428
0.994038
best purity eigenbeams
angle from Pole (degrees)
2
1
0
−1
−2
−3
−4
0
1
2
3
4
5
6
7
8
9
10



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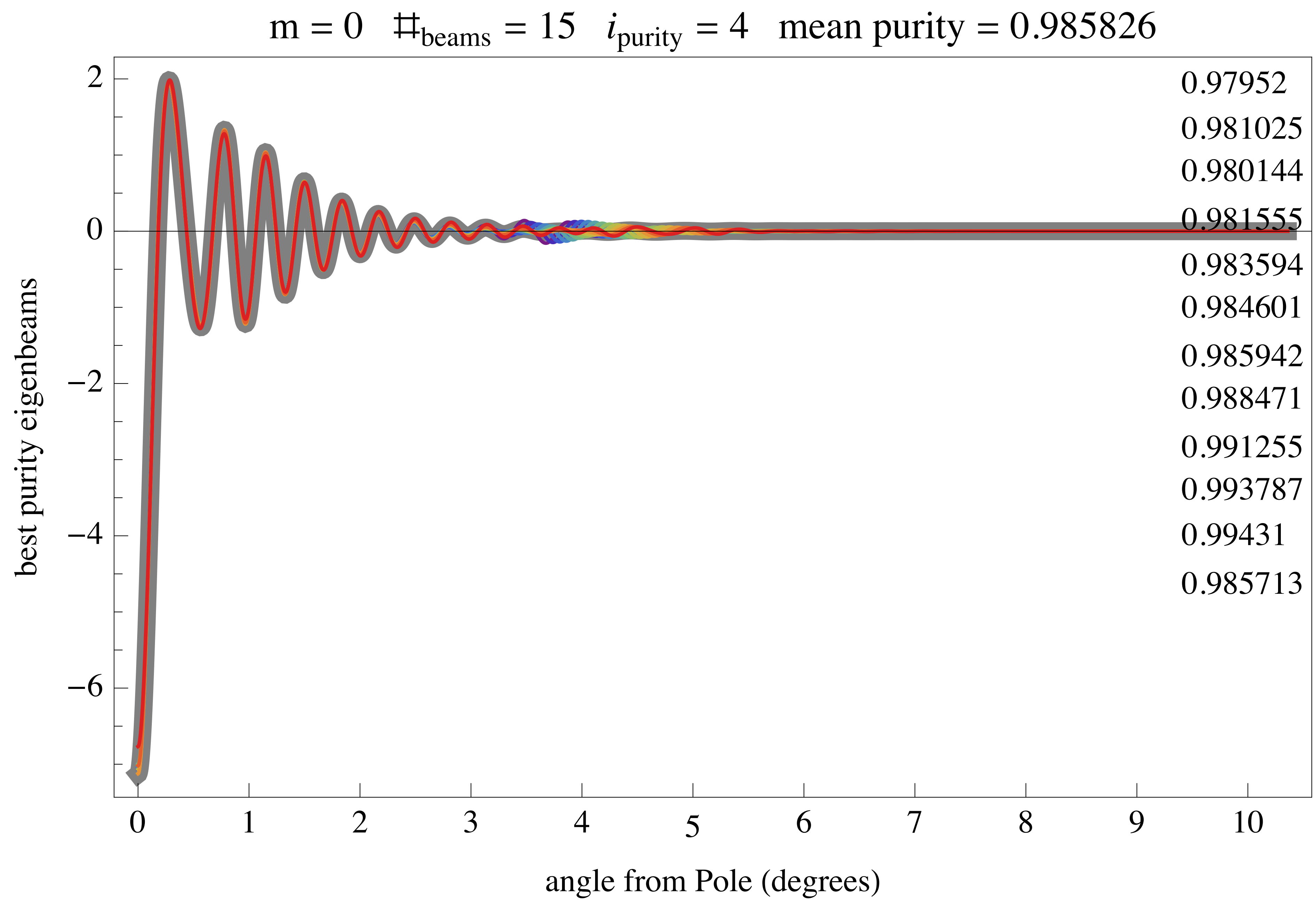
0.986126
0.991449
0.995494
0.998216
0.999584
0.999583
0.998211
0.995483
0.991431
0.986104
0.979566
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
best purity eigenbeams
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)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0.980144
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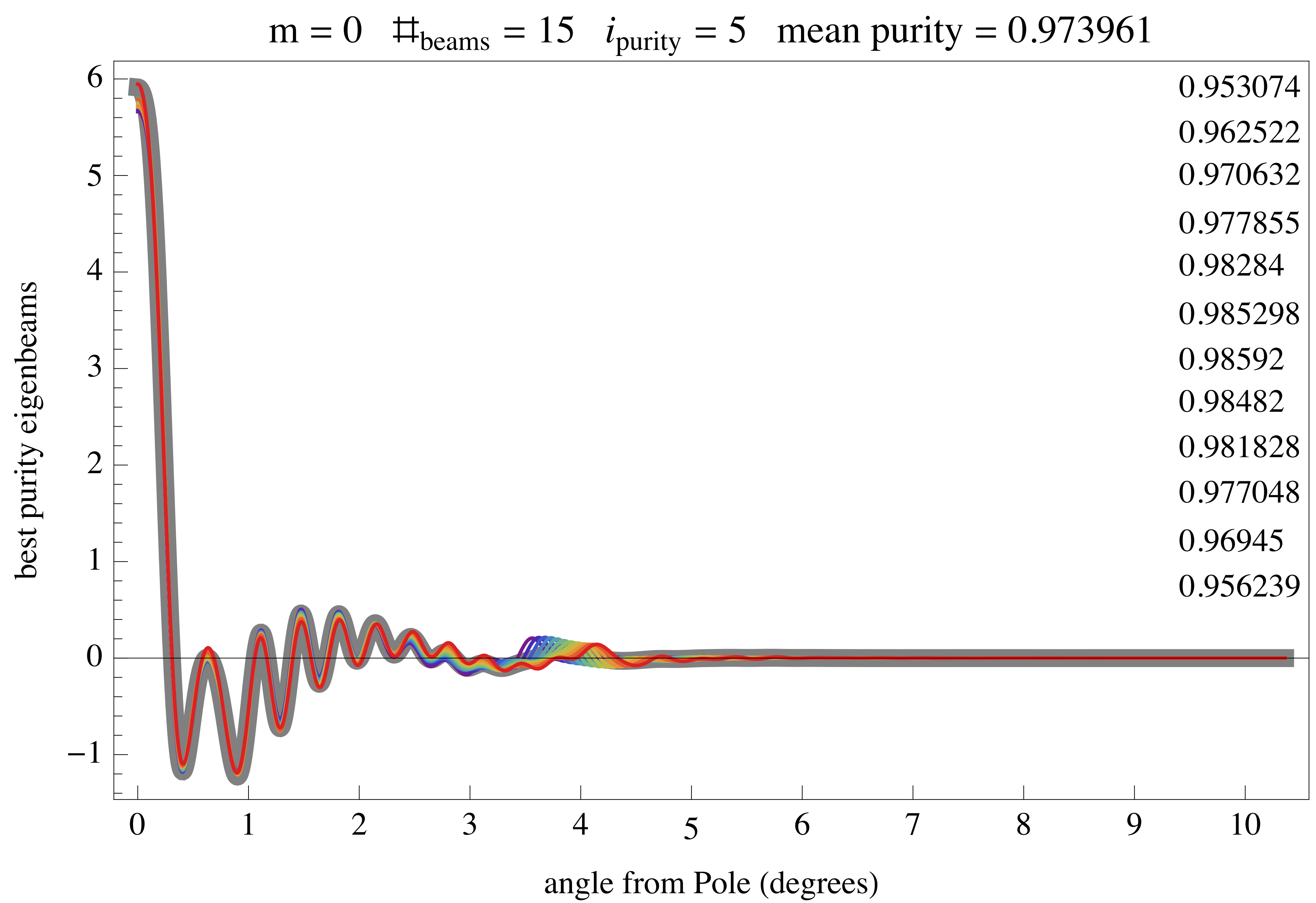
0.983594
0.984601
0.985942
0.988471
0.991255
0.993787
0.99431
0.985713
2
0
−2
−4
−6
best purity eigenbeams
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)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angle from Pole (degrees)
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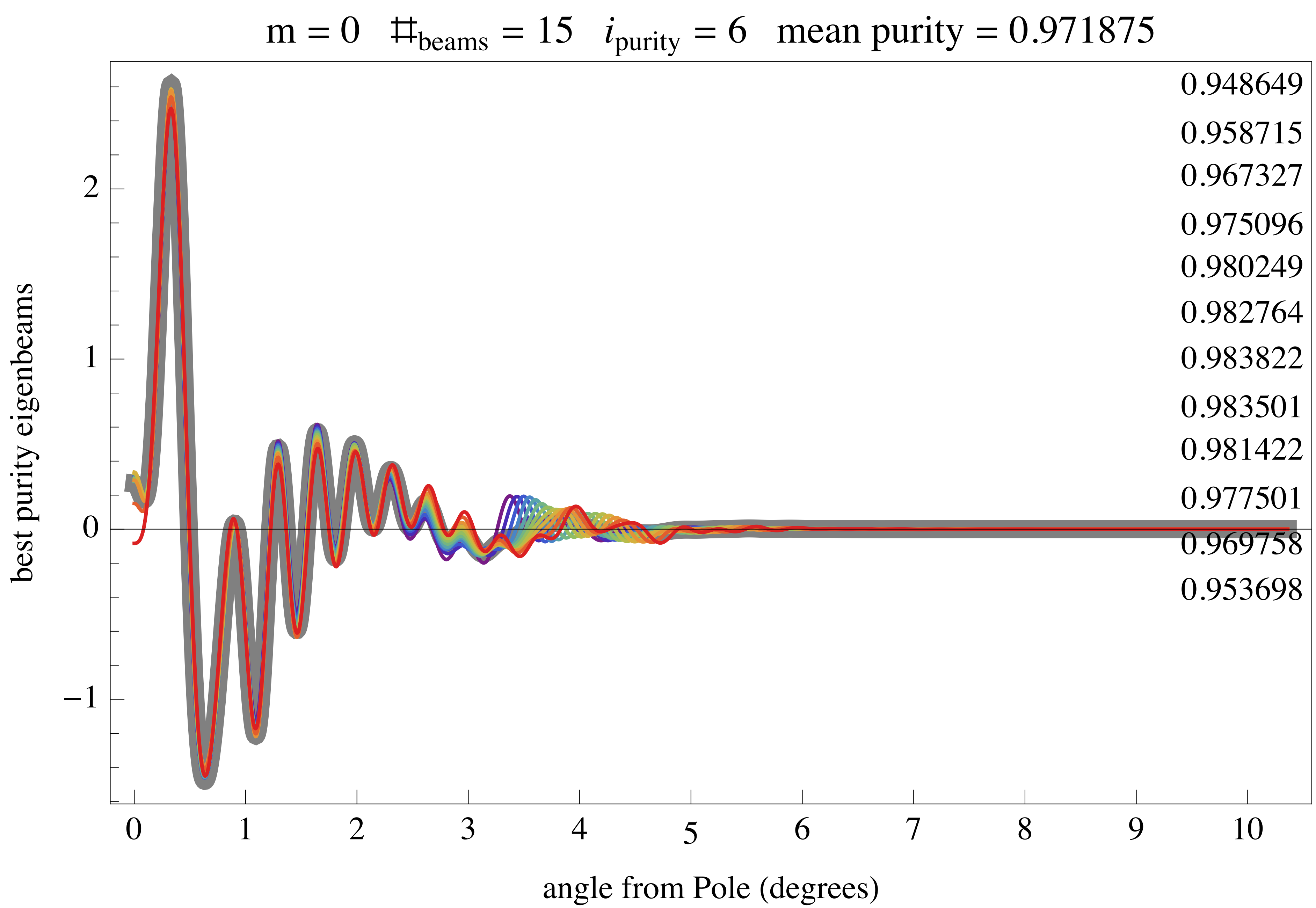
0.962522
0.970632
0.977855
0.98284
0.985298
0.98592
0.98482
0.981828
0.977048
0.96945
0.956239
6
5
4
3
2
1
0
−1
0
1
2
3
4
5
6
7
8
9
10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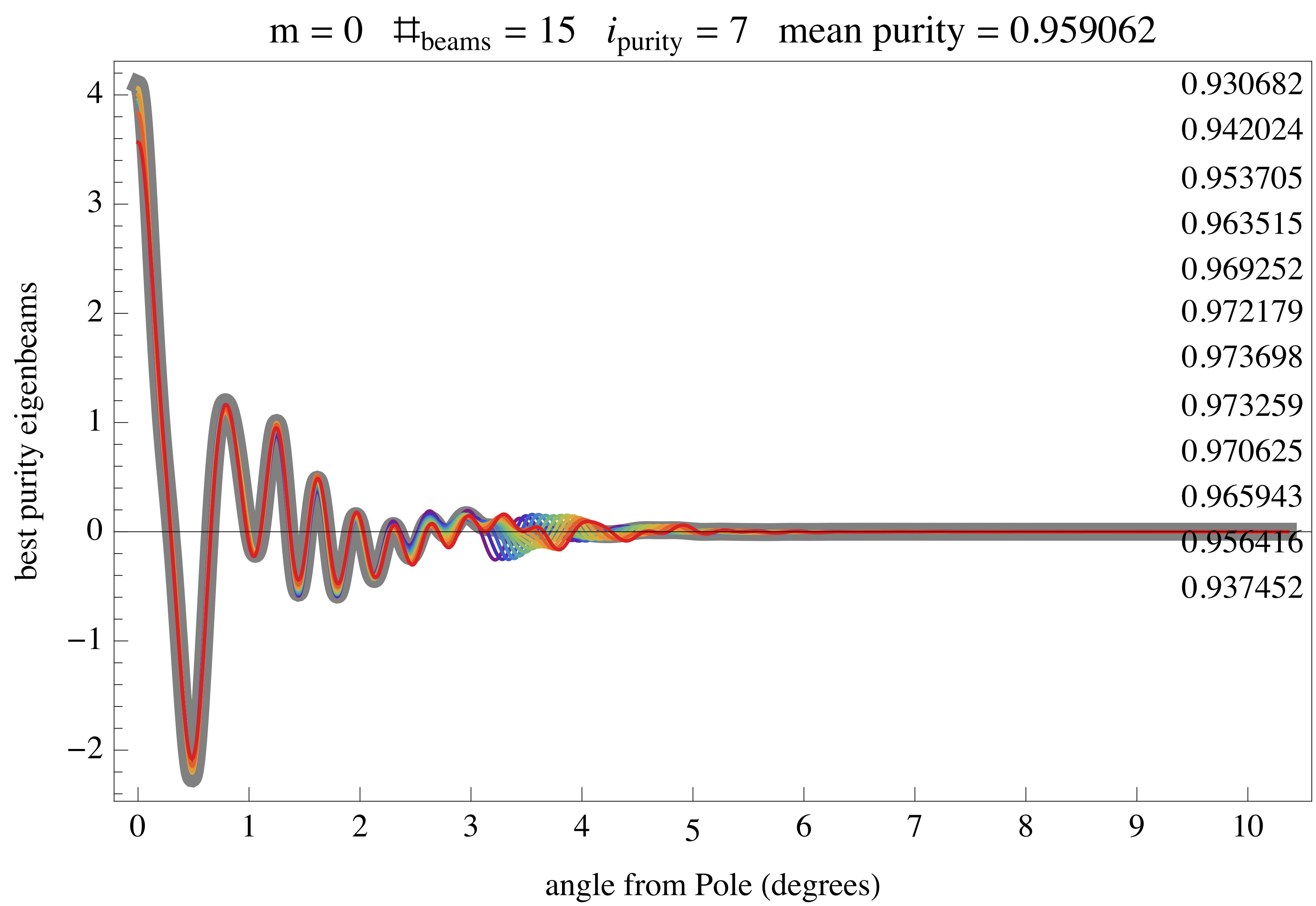
0.948649
0.958715
0.967327
0.975096
0.980249
0.982764
0.983822
0.983501
0.981422
0.977501
0.969758
0.953698
2
1
0
−1
best purity eigenbeams
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)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best purity eigenbeams
angle from Pole (degrees)
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0.942024
0.953705
0.963515
0.969252
0.972179
0.973698
0.973259
0.970625
0.965943
0.956416
0.937452
4
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0
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−2
0
1
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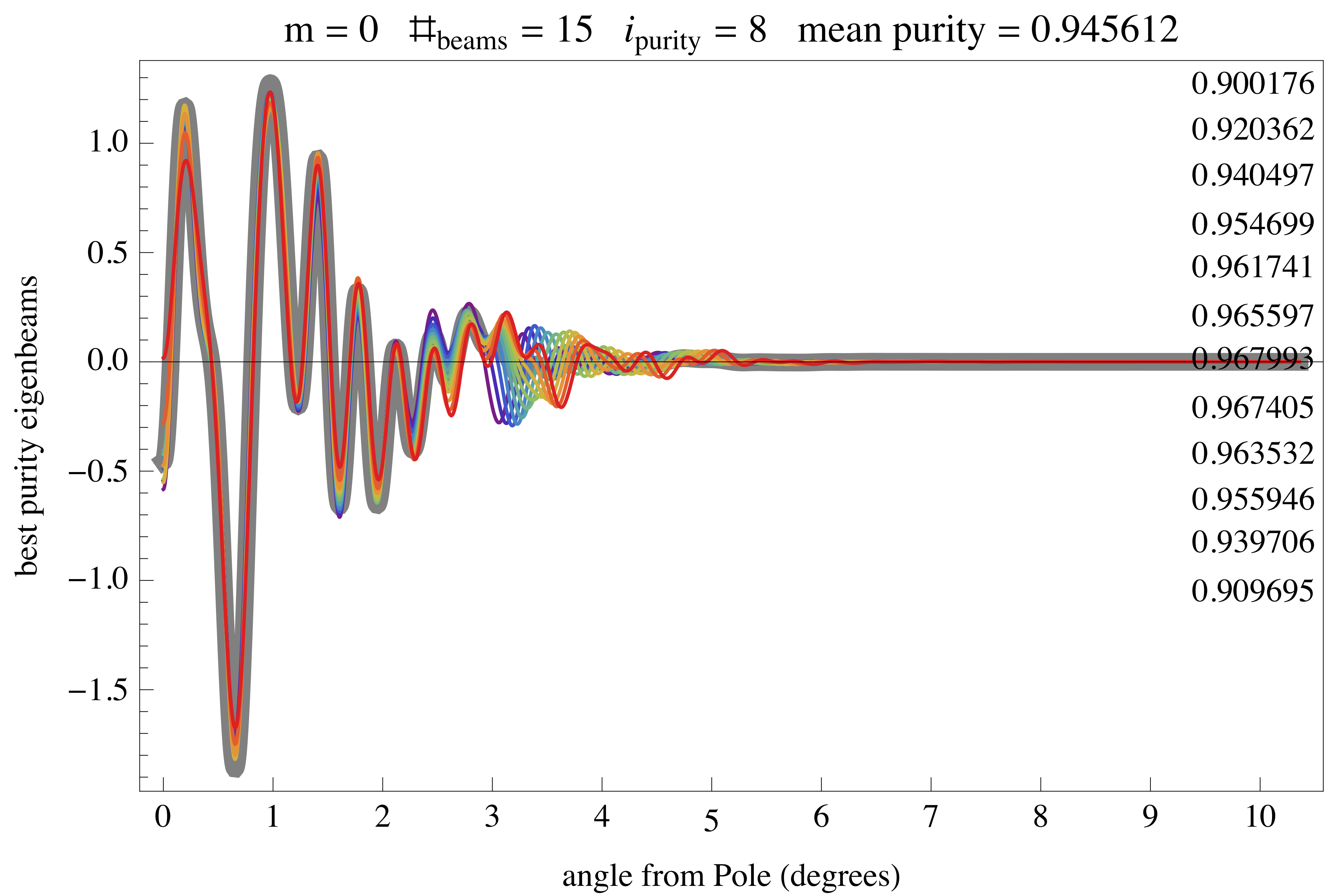
3
4
5
6
7
8
9
10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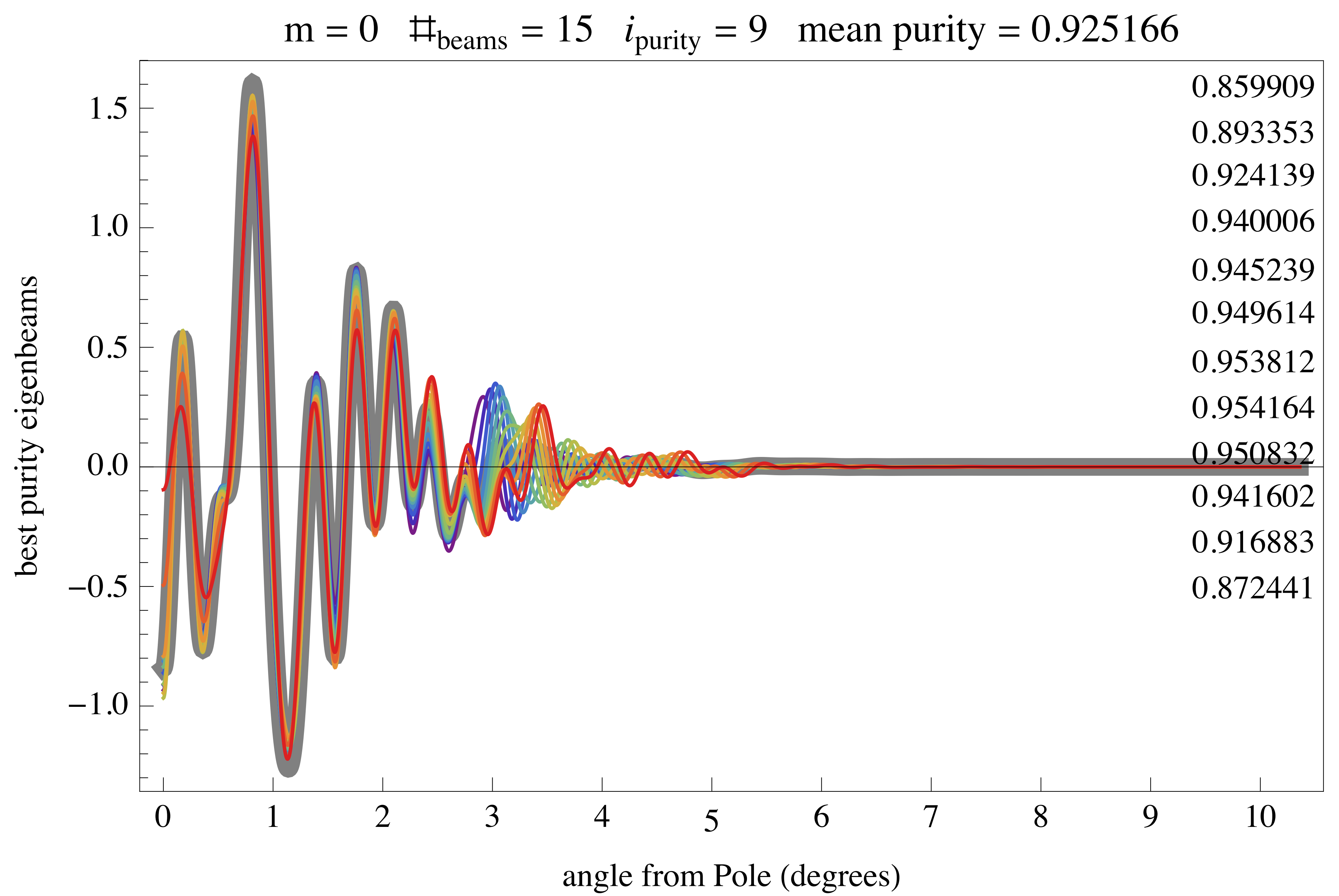
0.920362
0.940497
0.954699
0.961741
0.965597
0.967993
0.967405
0.963532
0.955946
0.939706
0.909695
best purity eigenbeams
1.0
0.5
0.0
−0.5
−1.0
−1.5
0 1 2 3 4 5 6 7 8 9 10
angle from Pole (degrees)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best purity eigenbeams
angle from Pole (degrees)
1.5
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
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0.949614
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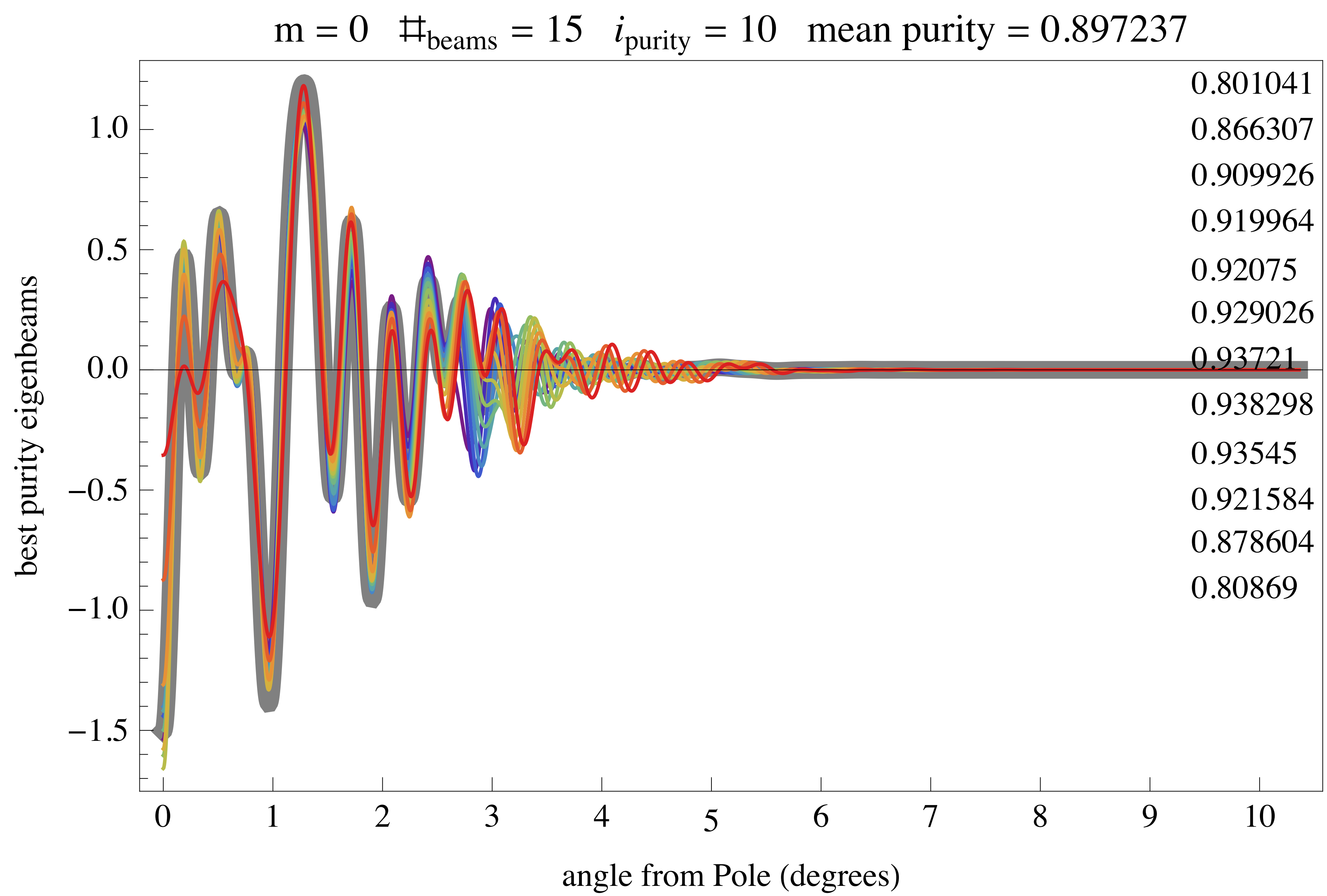
0.941602
0.916883
0.872441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0.866307
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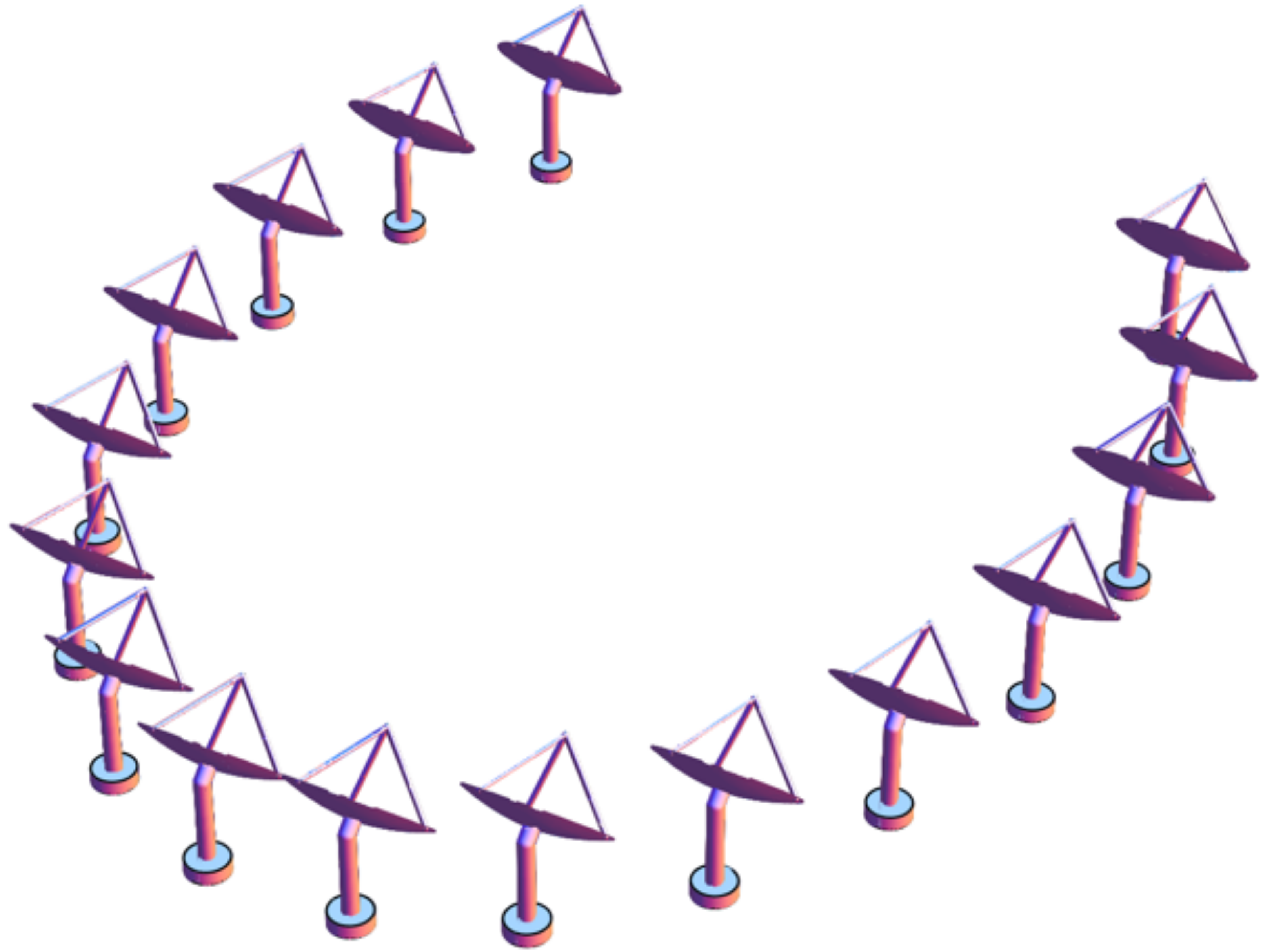
0.919964
0.92075
0.929026
0.93721
0.938298
0.93545
0.921584
0.878604
0.80869
best purity eigenbeams
1.0
0.5
0.0
−0.5
−1.0
−1.5
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)

A Very Pure Polarscope



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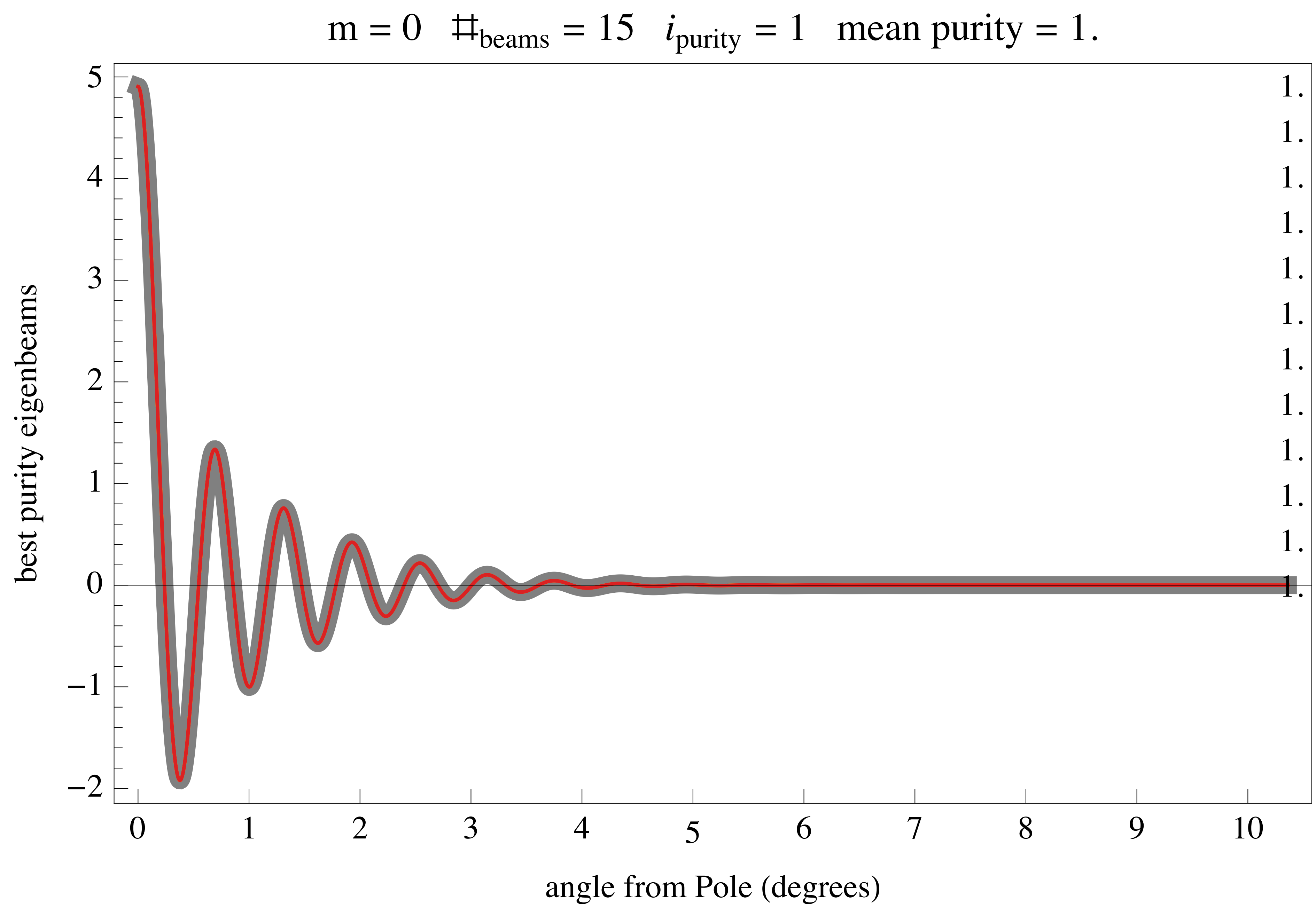
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best purity eigenbeams
angle from Pole (degrees)
5
4
3
2
1
0
−1
−2
0
1
2
3
4
5
6
7
8
9
10
1.
1.
1.
1.
1.
1.
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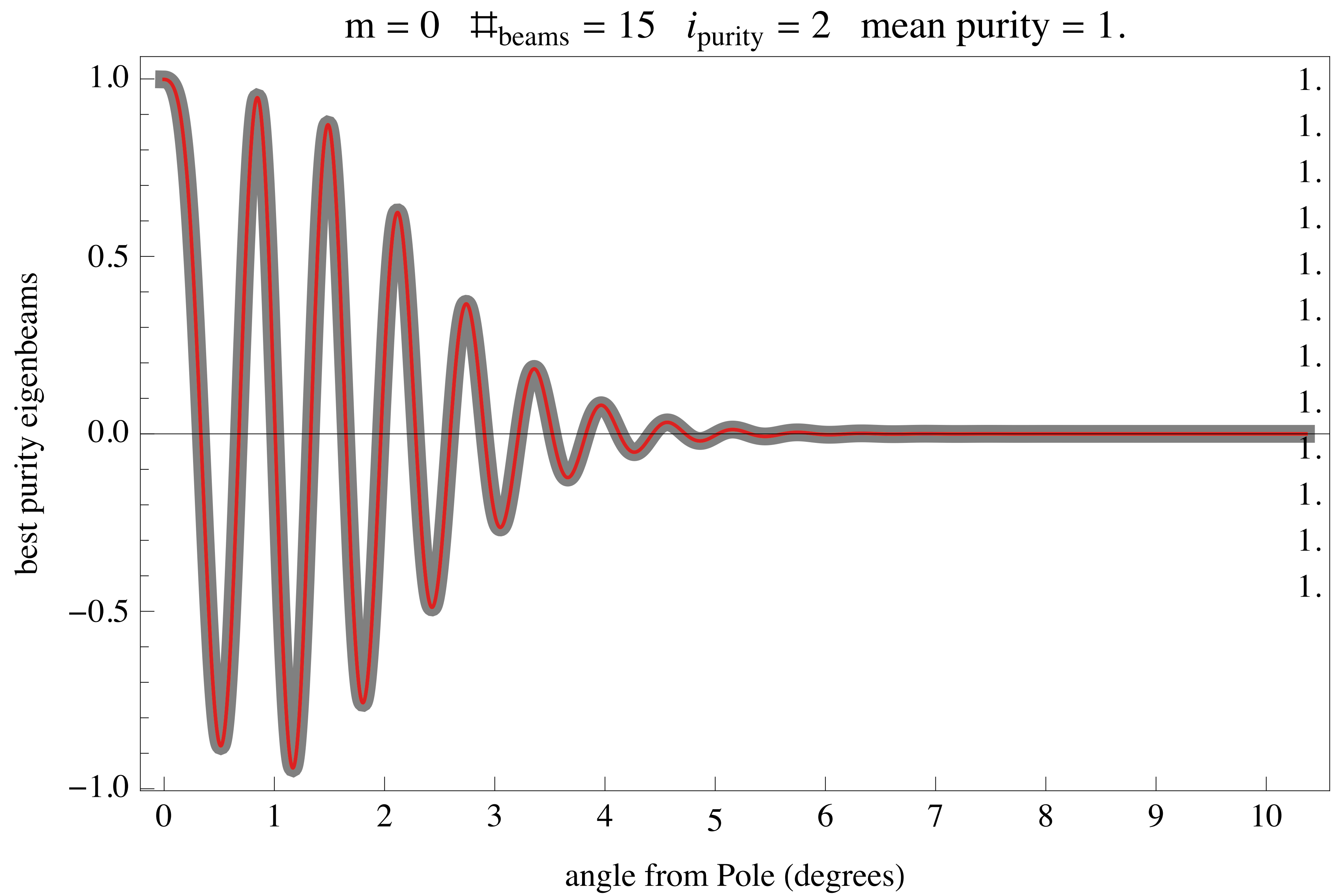
1.
1.
1.
1.



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best purity eigenbeams
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0.5
0.0
−0.5
−1.0
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)
1.
1.
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1.
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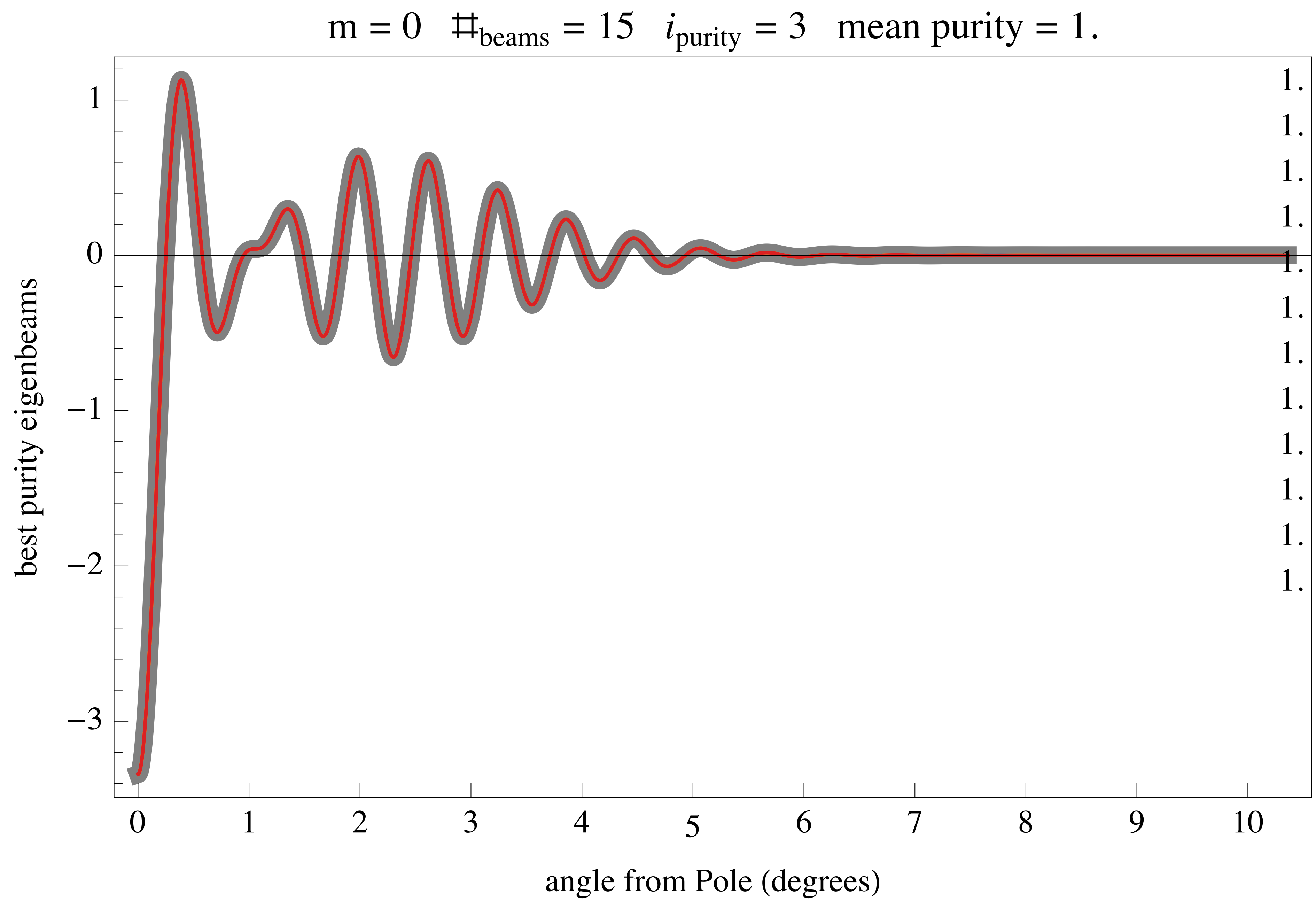
1.
1.
1.
1.



$m = 0 \quad \sharp_{beams} = 15 \quad i_{purity} = 3 \quad$ mean purity = 1.
best purity eigenbeams
angle from Pole (degrees)
1
0
−1
−2
−3
0
1
2
3
4
5
6
7
8
9
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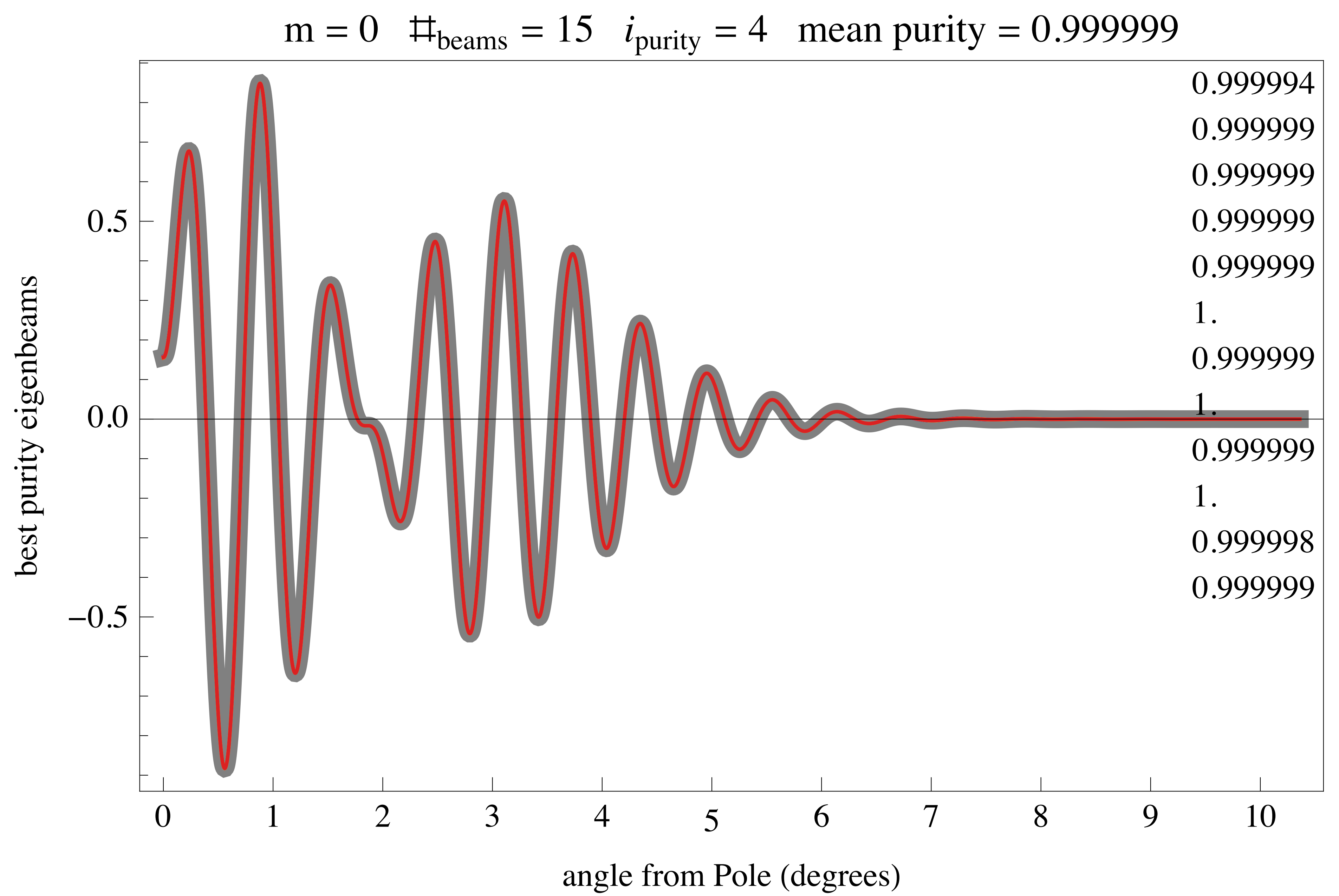
1.
1.
1.
1.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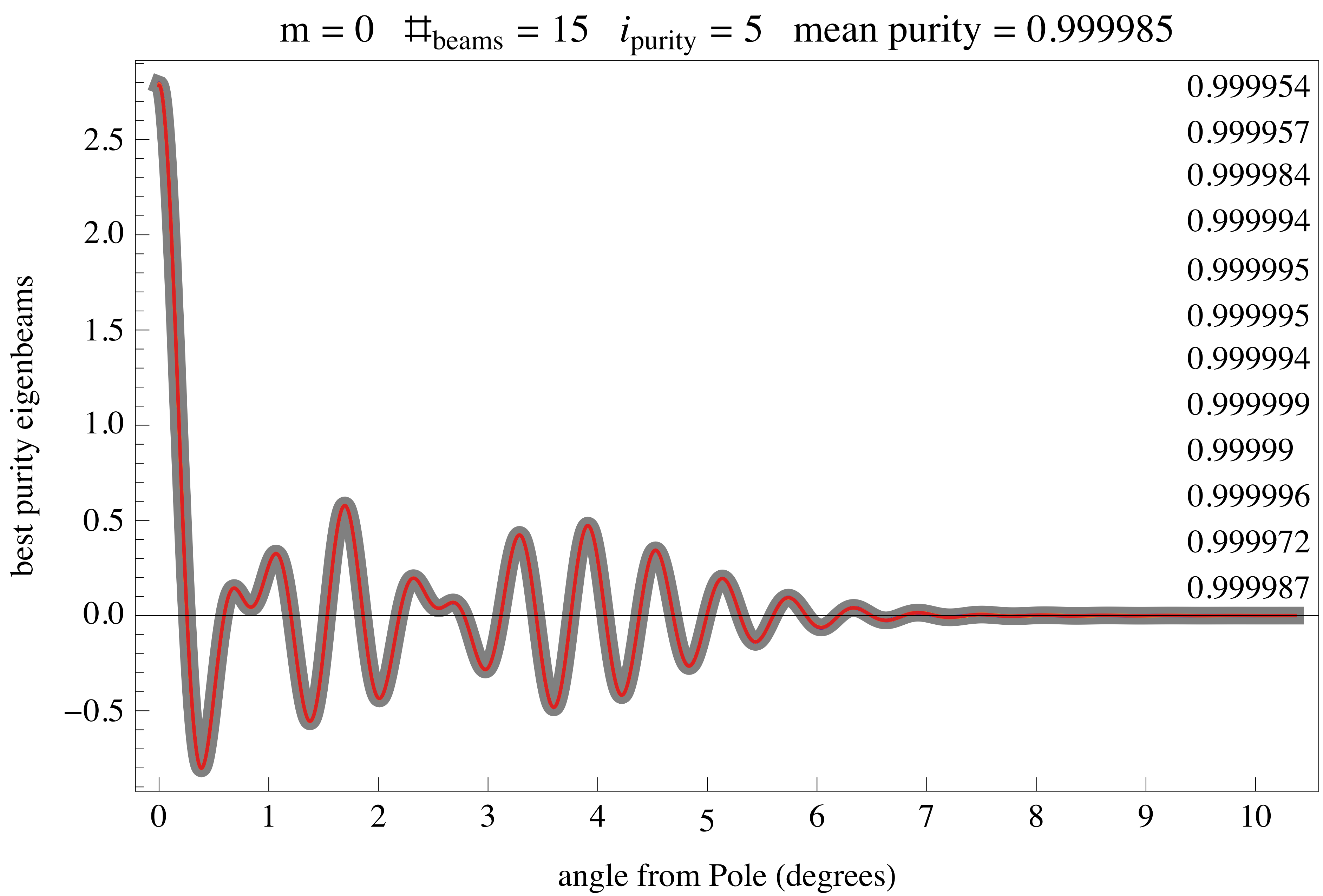
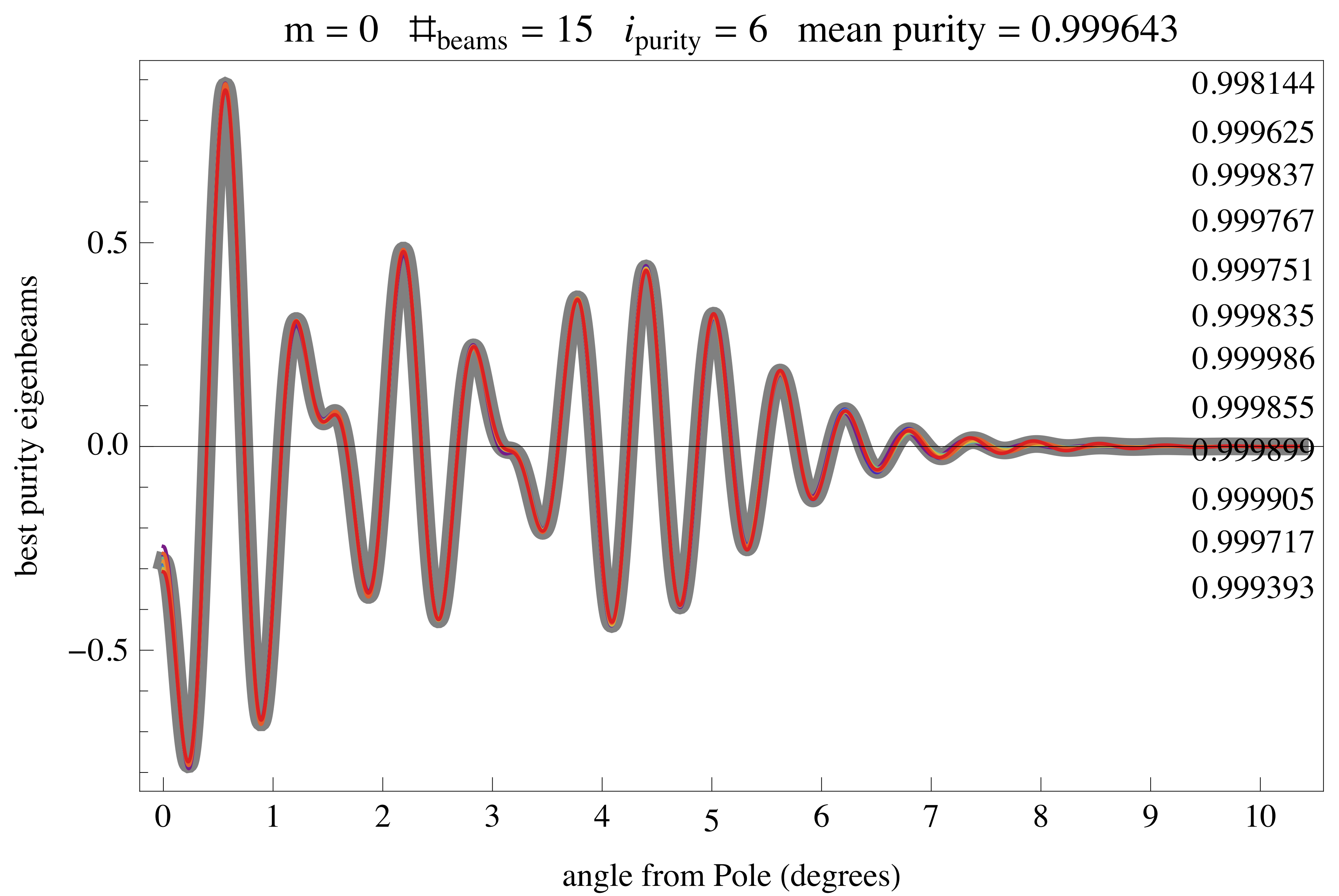
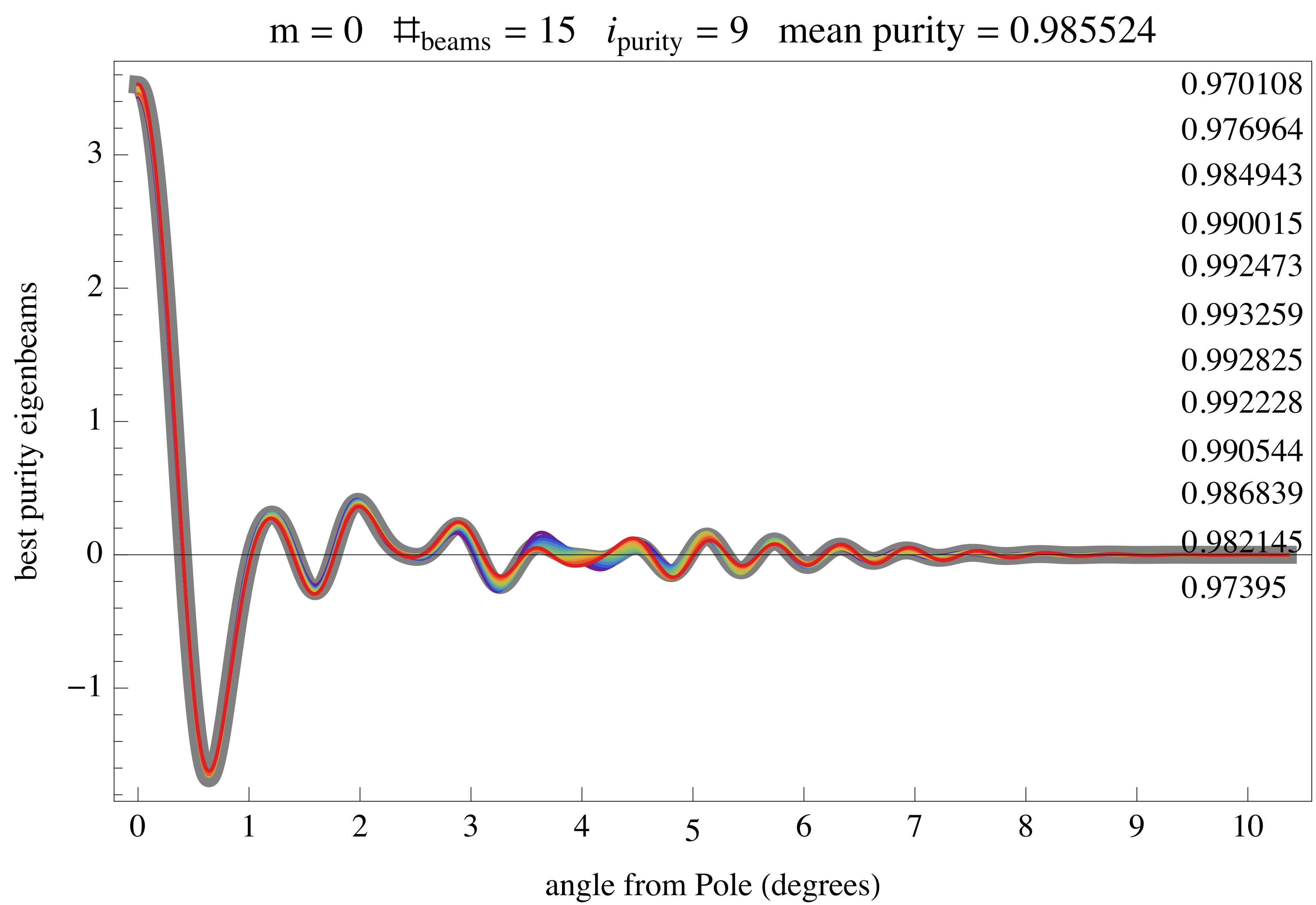
0.999999
0.999999
0.999999
0.999999
1.
0.999999
1.
0.999999
1.
0.999998
0.999999
0.5
0.0
−0.5
best purity eigenbeams
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)

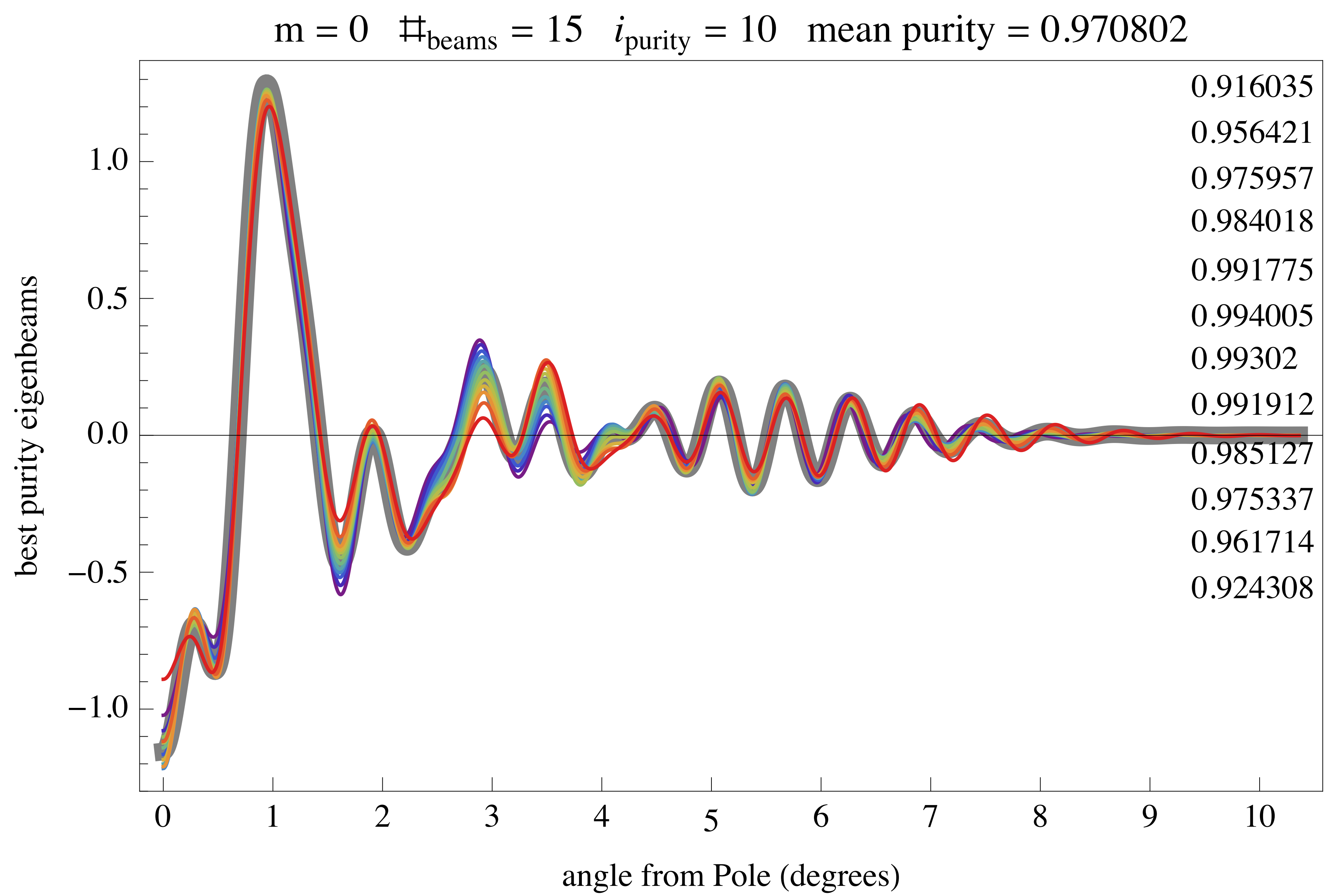


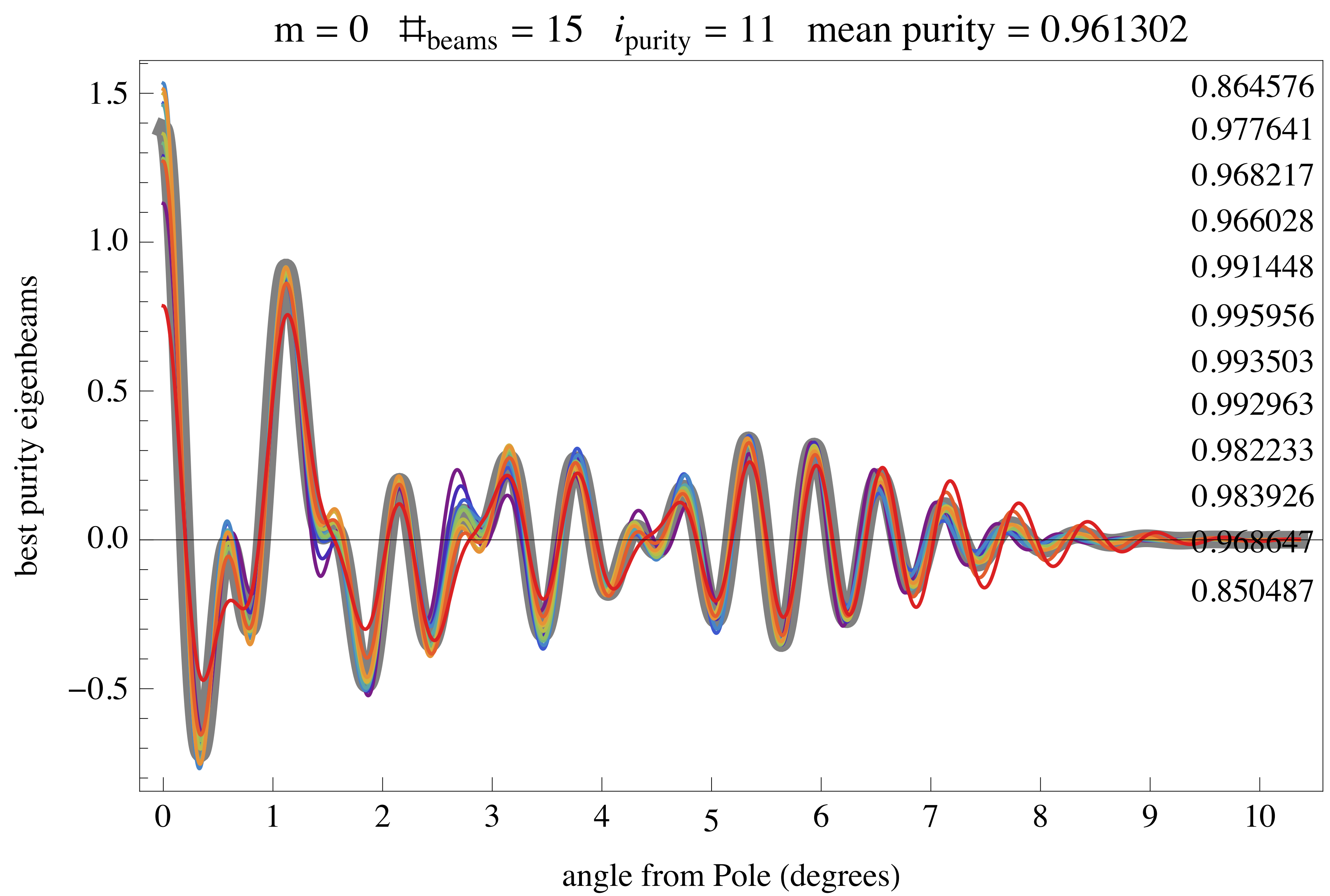
m = 0 ♯beams = 15 ipurity = 5 mean purity = 0.999985
best purity eigenbeams
angle from Pole (degrees)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
0
1
2
3
4
5
6
7
8
9
10
0.999954
0.999957
0.999984
0.999994
0.999995
0.999995
0.999994
0.999999
0.99999
0.999996
0.999972
0.999987


m = 0 ♯beams = 15 ipurity = 6 mean purity = 0.999643
0.998144
0.999625
0.999837
0.999767
0.999751
0.999835
0.999986
0.999855
0.999899
0.999905
0.999717
0.999393
0.5
0.0
–0.5
best purity eigenbeams
0
1
2
3
4
5
6
7
8
9
10
angle from Pole (degrees)

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

best performance: split into two compact subarrays

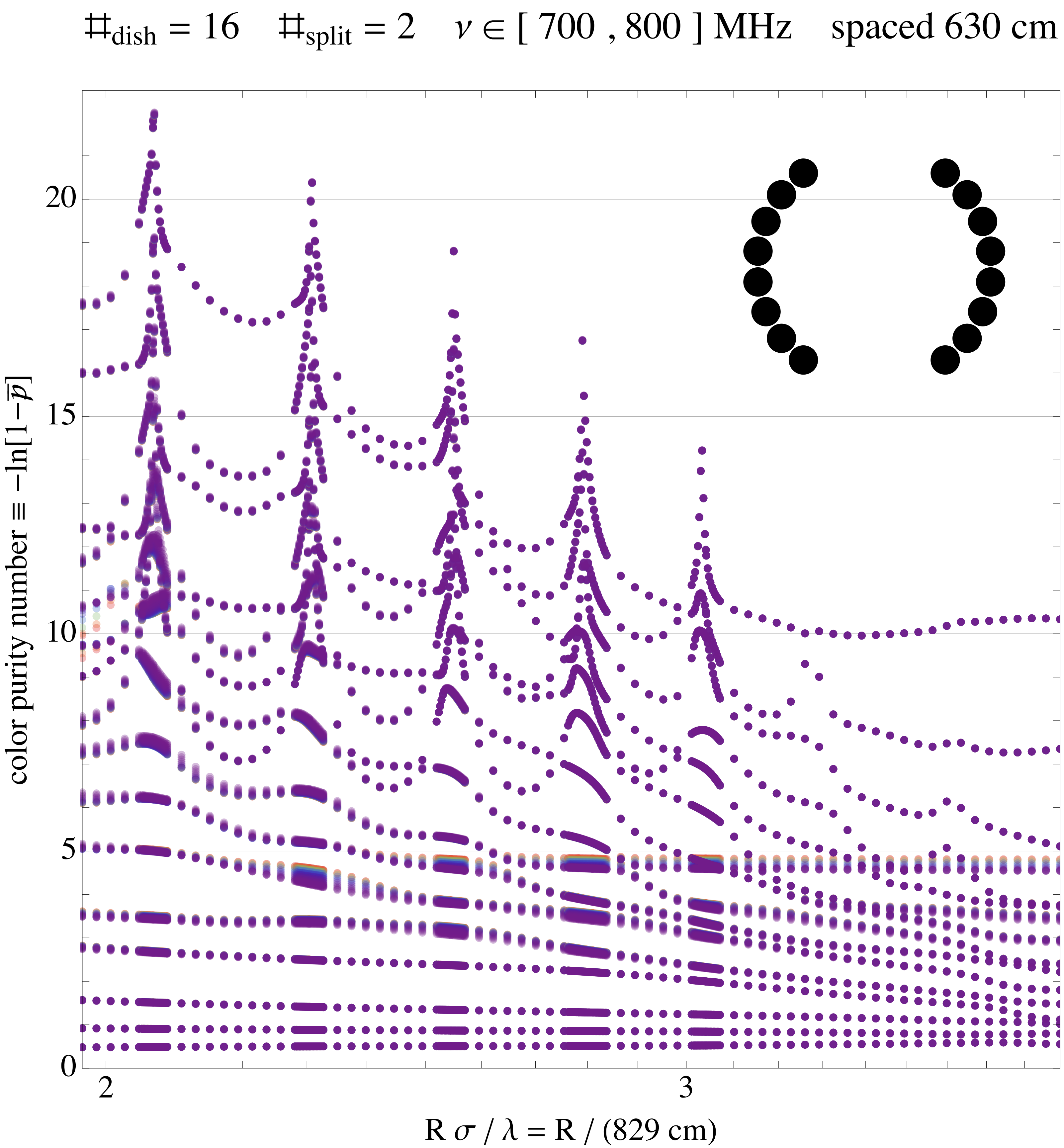
there exist purity “resonances” where astounding purity is attained.

resonances are “narrow” w/ few cm tolerance

lowest purity attained near “singularities”

singularities are array configurations where two baselines become equal and the number of independent beams decreases.

resonances are not the most compact configuration



Forecasting and Simulations

Sky reconstruction from transit visibilities: PAON-4 and Tianlai Dish Array

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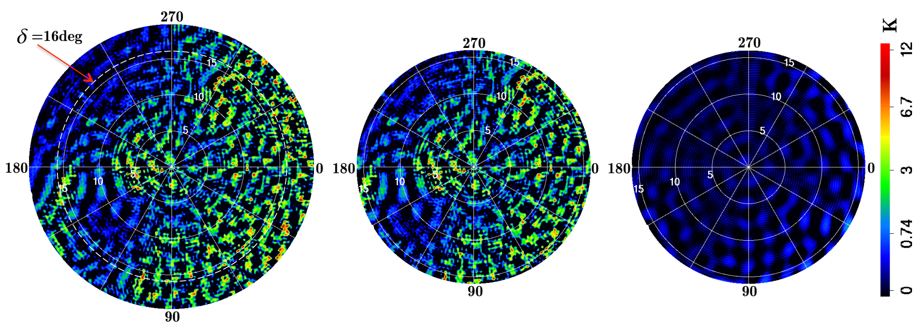

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FORECASTS ON THE DARK ENERGY AND PRIMORDIAL NON-GAUSSIANITY OBSERVATIONS WITH THE TIANLAI CYLINDER ARRAY

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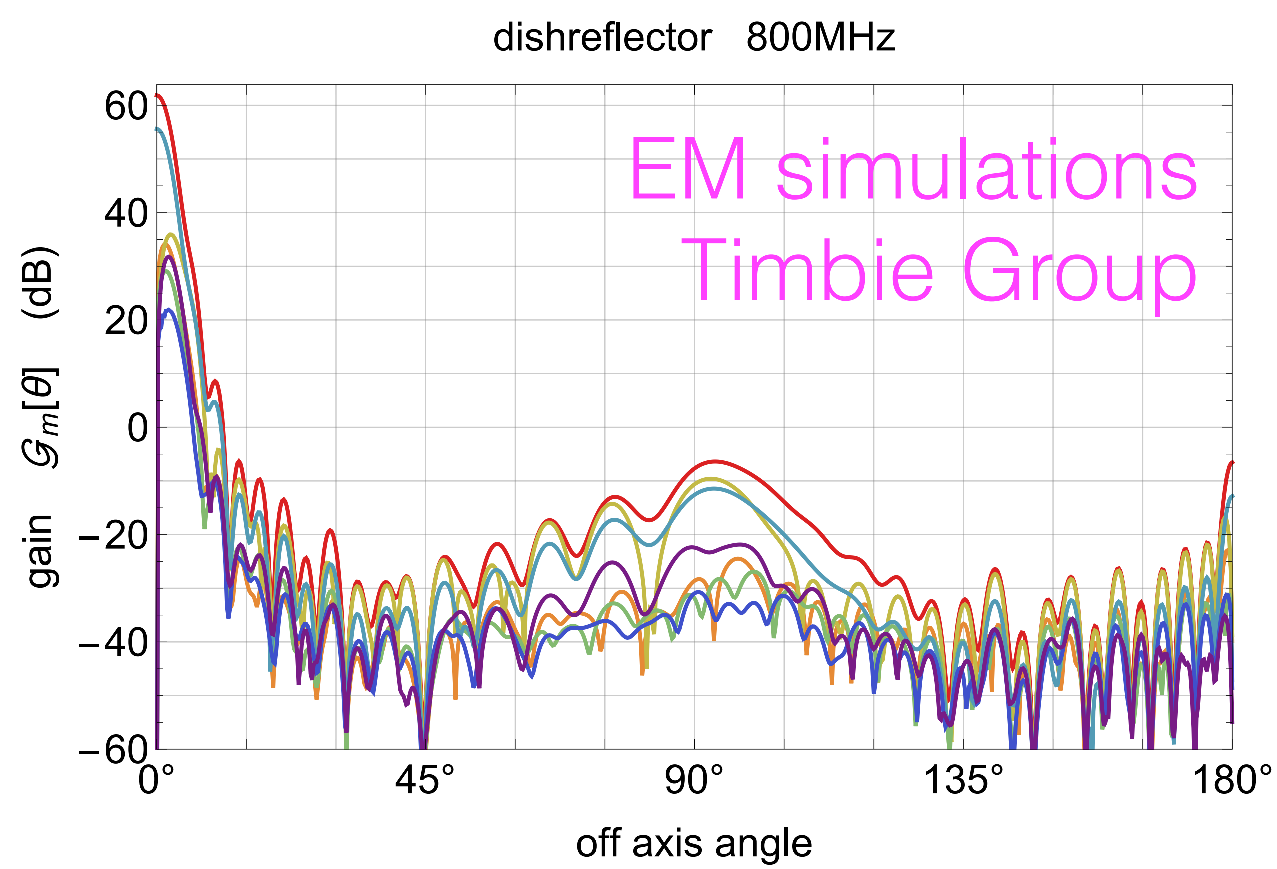


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