# Spectral templates of Type Ia Supernovae

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with directions from Chris Pritchet,
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# building a “mean uberspectrum”

- old uberspectrum
  - based on 1 spectrum per epoch per wavelength
  - not necessarily representative
  - for example, 92A (s=0.8) and 94D (s=0.8) were heavily used
  - larger epoch intervals
- should use the average of many spectra per epoch per wavelength
- averaging fluxes
  - washes out features
  - sensitive to noise
- weighted average of narrow band colours

# recipe

1. collect sample of spectra

# 500 spectra
# 84 supernovae

| | |
|---|---|
| 04D3nq | 9 |
| 05D3kx | -1 |
| 05D3mq | 8 |
| 81b | 0,17,20,26,35,49,58,64 |
| 86g | -5,-4,-3,-2,<br>-1,0,1,21,22,23,32,34,41,44,50,52,54,56,89,90,102,103 |
| 89b | -7,-5,-3,-2,<br>-1,0,3,5,6,8,9,11,12,13,14,16,17,18,19,21,51 |
| 90af | -3 |
| 90g | 40 |
| 90m | 34 |
| 90n | -14,-7,2,3,7,14,17,38 |
| 90o | -8,-7,-6,-1,19,20 |
| 90r | 60,74,131 |
| 90t | 16,37 |
| 91ad | 40 |
| 91ag | 7,8 |
| 91bc | 100 |
| 91bd | 18 |
| 91bg | 0,1,2,13,16,18,23,29,30,32,34,44,<br>46,50,52,53,55,74,79,87,88,105,117 |
| 91bj | 40 |
| 91f | 85114 |
| 91m | 3,28,81 |
| 91s | 15,19 |
| 91t | -12,-11,-10,-9,-8,-7,-6,0,10,15,22,24,41,45,67 |
| 91u | 11 |
| 91x | 30 |
| 92a | -5,-1,3,5,6,7,9,11,16,17,24,28,37,46,76 |
| 92ac | 22,31 |
| 92ae | 3 |
| 92ag | -1 |
| 92ah | 30 |
| 92al | -6,3 |
| 92aq | 1 |
| 92au | 65 |
| 92bc | -11,10,37 |
| 92bg | 8 |
| 92bh | 2 |
| 92bk | 8,9 |
| 92bl | 1 |
| 92bo | 1 |
| 92bp | 7 |
| 92br | 6 |
| 92bs | 2 |
| 92g | 15,97,106,128 |
| 92j | 14,15 |
| 92k | 41 |
| 92p | -1 |
| 93b | 11 |
| 93h | 0,2,5 |
| 93o | -5,1 |
| 94ae | -1,0,1,2,3,4,5,8,9,10,29,35,39,63,69,87 |
| 94d | -11,-10,-9,-8,-7,-5,-4,<br>-2,2,3,4,5,7,8,10,11,12,13,14,15,16,17,18,19,20,24,25,26,48,50,54,106 |
| 94m | 36 |
| 94q | 10,41 |
| 94s | 22 |
| 94u | 6 |
| 96x | -4,-2,-1,0,1,2,3,7,12,22,23,24,31,32,57,87 |
| 97br | -9,-8,-7,-6,-4,8,24,51,67 |
| 98aq | -9,-8,-3,0,1,2,3,4,5,6,7,19,21,24,31,32,36,51,55,58,60,63,66,79,82,91 |
| 98bu | -4,-3,<br>[illegible],27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,56 |
| 99aa | [illegible],19,25,28,33,40,47,51,58 |
| 99ac | -15,-11,-9,0,2,8,11,16,24,28,31,33,39,42 |
| 99ao | 5,7,10,13,18,29,34,40 |
| 99aw | [illegible],59,81 |
| 99aw | [illegible] |
| 99be | 14,19,26,33,37,44 |
| 99bi | 12 |
| 99bk | 4,7,9,10 |
| 99bm | 3,6,21 |
| 99bn | 2,22,27 |
| 99bp | -2,0,1,6,17,23 |
| 99by | 1,6,16,27,34 |
| 99ee | -9,-8,-7,-6,-2,-1,0,2,3,7,8,9,11,12,16,17,19,20,22,23,27,28,32,33,41,42 |
| 00cx | -4,-3,-2,-1,0,1,5,6,7,11,14,19,22,24,26,28,30,31,41,61,71,89,97,125 |
| 00e | -6,-3,-2,8,122 |
| 01ay | 0,1,9,16,21,26 |
| 01ba | -3,13,22 |
| 01bf | 3,12 |
| 01bt | -7 |
| 01cn | 2,10 |
| 01el | 9,14,22,31,53 |
| 01hc | 0 |
| 02bo | -14,-13,-11,-6,-5,-4,-3,-2,-1,4,28,38,43,82 |
| 02iu | 2 |
| 03du | -11,-7,13,37,87,138 |

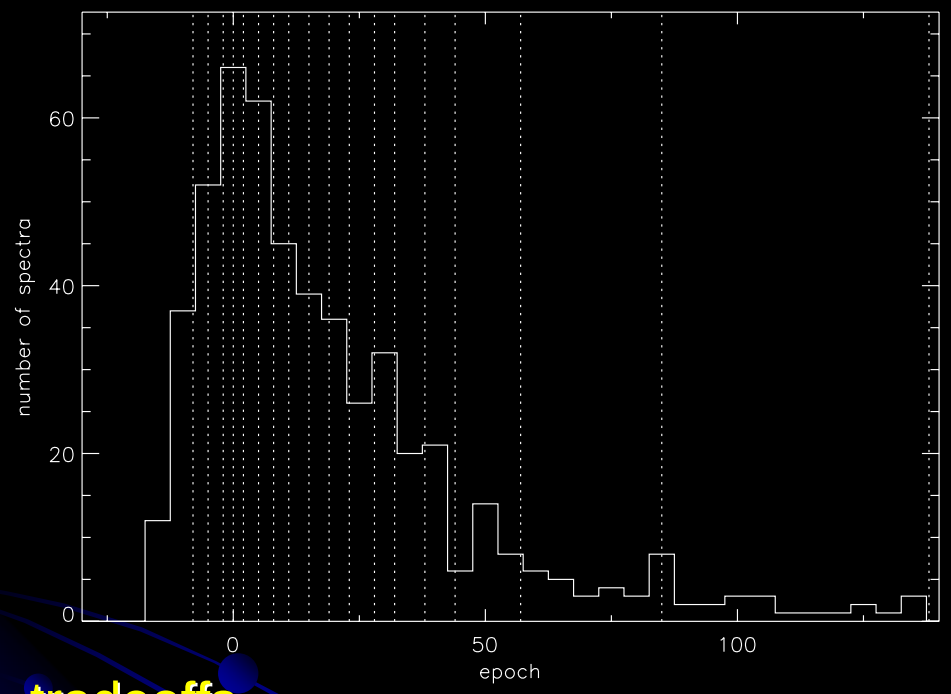


uberspectrum – k-correction errors – intrinsic scatter

# recipe

1. collect sample of spectra
2. define epoch intervals

# epoch intervals




| lower | upper | weighted | stretch | no. of spec |
|---|---|---|---|---|
| -15 | -8 | -10.9 | 1.014 | 30 |
| -7 | -5 | -6.3 | 0.969 | 24 |
| -4 | -2 | -2.5 | 1.006 | 29 |
| -1 | 0 | -0.5 | 0.985 | 30 |
| 1 | 2 | 1.7 | 0.988 | 29 |
| 3 | 5 | 3.5 | 0.984 | 33 |
| 6 | 8 | 7.2 | 0.989 | 33 |
| 9 | 11 | 10.1 | 1.008 | 32 |
| 12 | 15 | 13.3 | 1.023 | 28 |
| 16 | 19 | 17.3 | 1.014 | 32 |
| 20 | 23 | 21.9 | 1.001 | 25 |
| 24 | 28 | 26.1 | 0.989 | 28 |
| 29 | 32 | 30.9 | 1.020 | 24 |
| 33 | 38 | 35.3 | 1.011 | 27 |
| 39 | 44 | 41.0 | 1.033 | 24 |
| 45 | 57 | 51.6 | 0.953 | 24 |
| 58 | 85 | 71.7 | 0.957 | 24 |

tradeoffs

large intervals:

large spectral variations

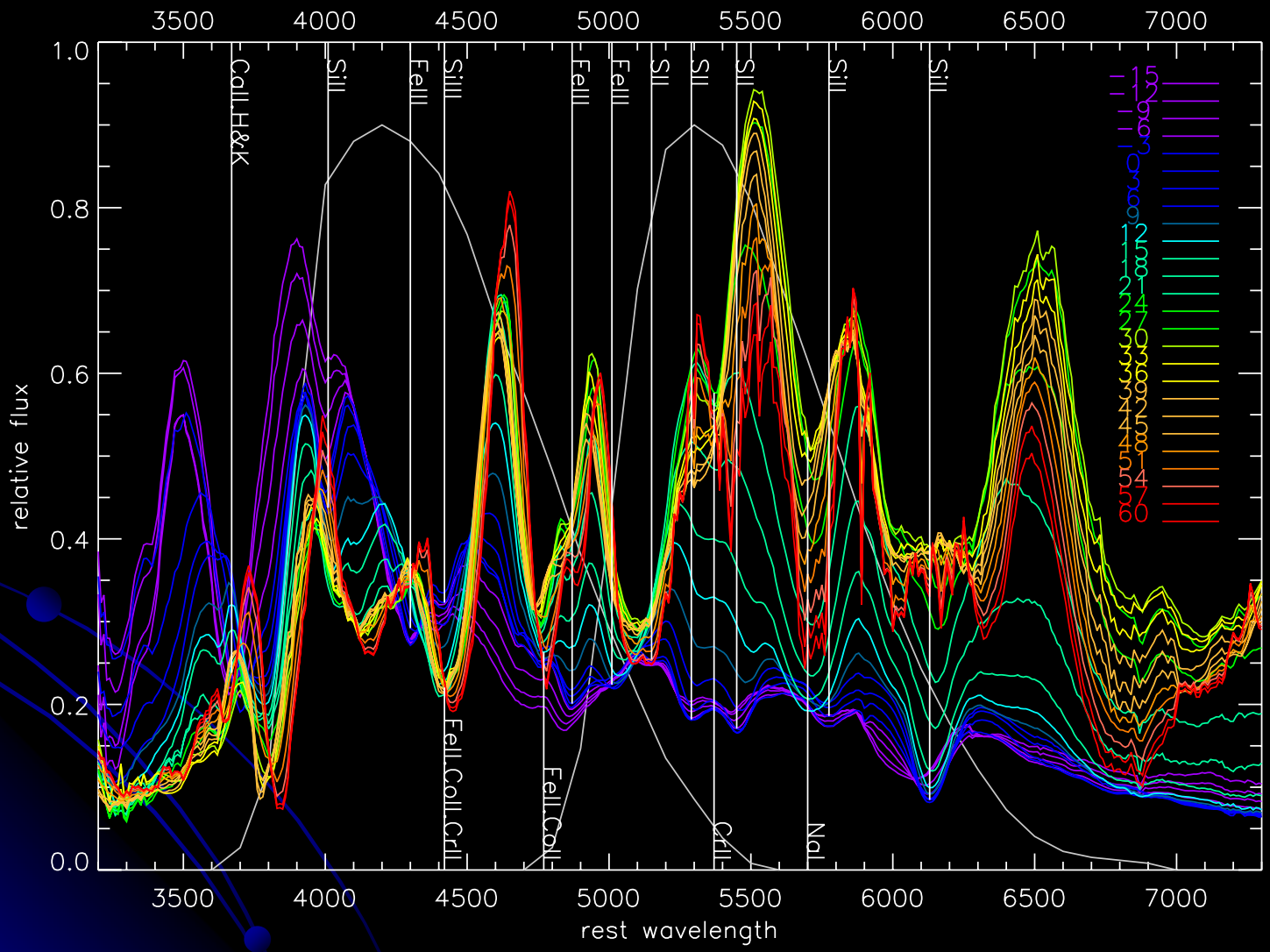
small intervals:

small number of spectra



uberspectrum – k-correction errors – intrinsic scatter

# epoch intervals

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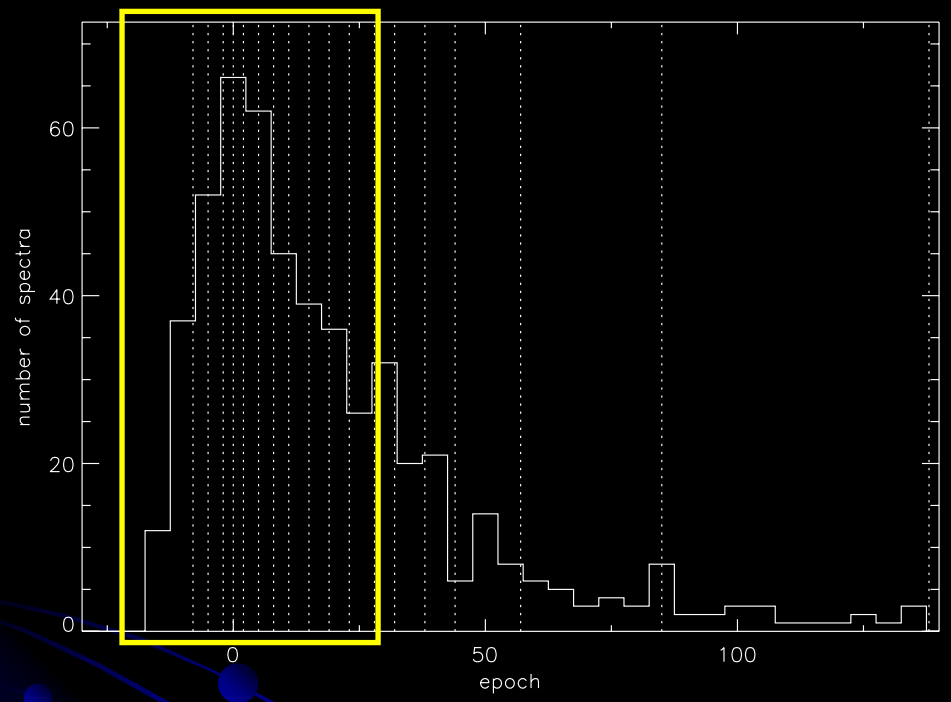
# epoch intervals




| lower | upper | weighted | stretch | no. of spec |
|---|---|---|---|---|
| -15 | -8 | -10.9 | 1.014 | 30 |
| -7 | -5 | -6.3 | 0.969 | 24 |
| -4 | -2 | -2.5 | 1.006 | 29 |
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| 33 | 38 | 35.3 | 1.011 | 27 |
| 39 | 44 | 41.0 | 1.033 | 24 |
| 45 | 57 | 51.6 | 0.953 | 24 |
| 58 | 85 | 71.7 | 0.957 | 24 |

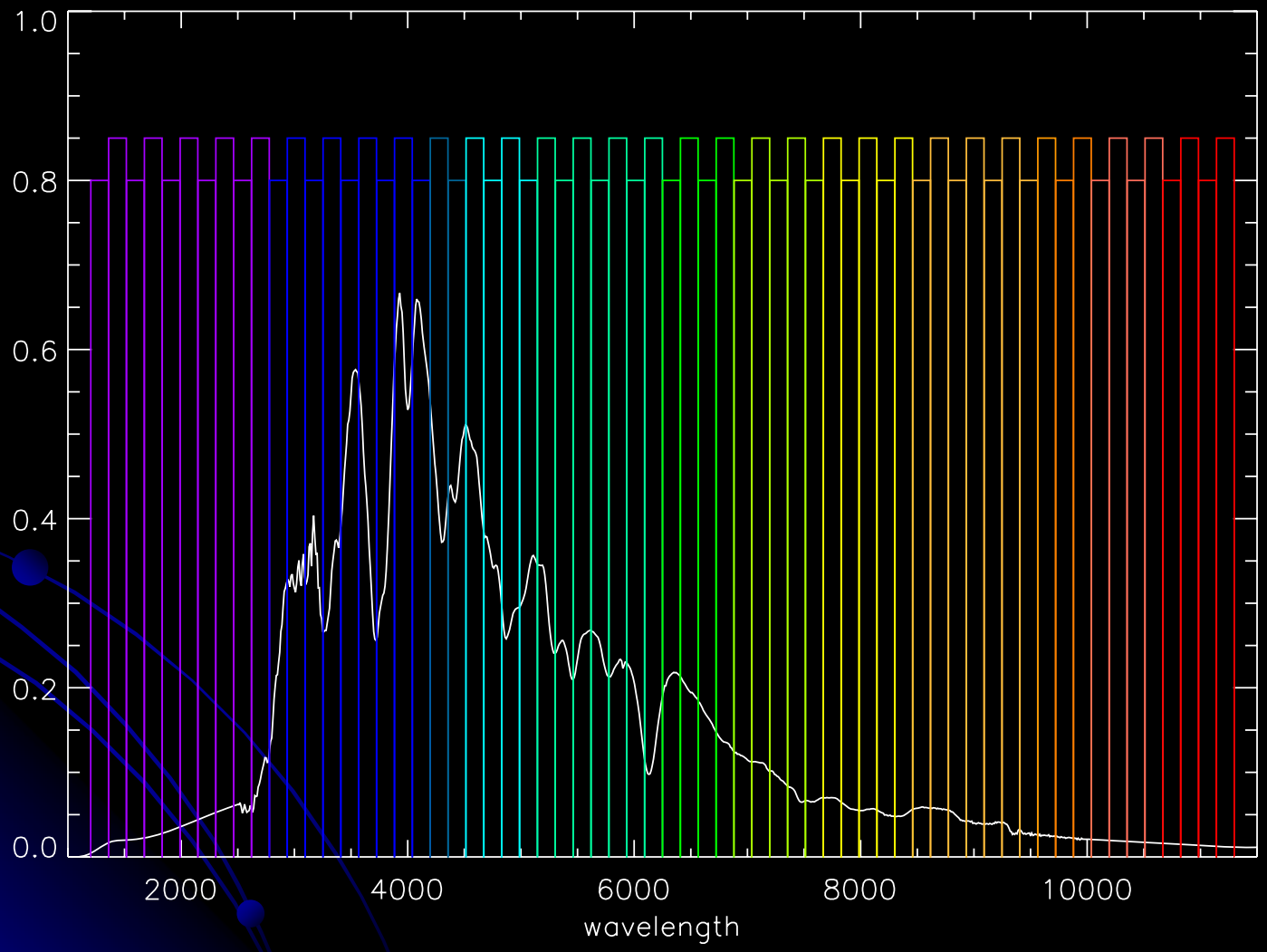
epochs with the most rapid change in spectral features

few spectra before t = -8

# recipe

1. collect sample of spectra
2. define epoch intervals
3. define narrow filters

# narrow band filters






uberspectrum – k-correction errors – intrinsic scatter

# recipe

1. collect (hopefully representative) sample of spectra
2. define epoch intervals
3. define narrow filters
4. calculated narrow colours and weights
   for each spectrum at each wavelength interval

# weighting scheme

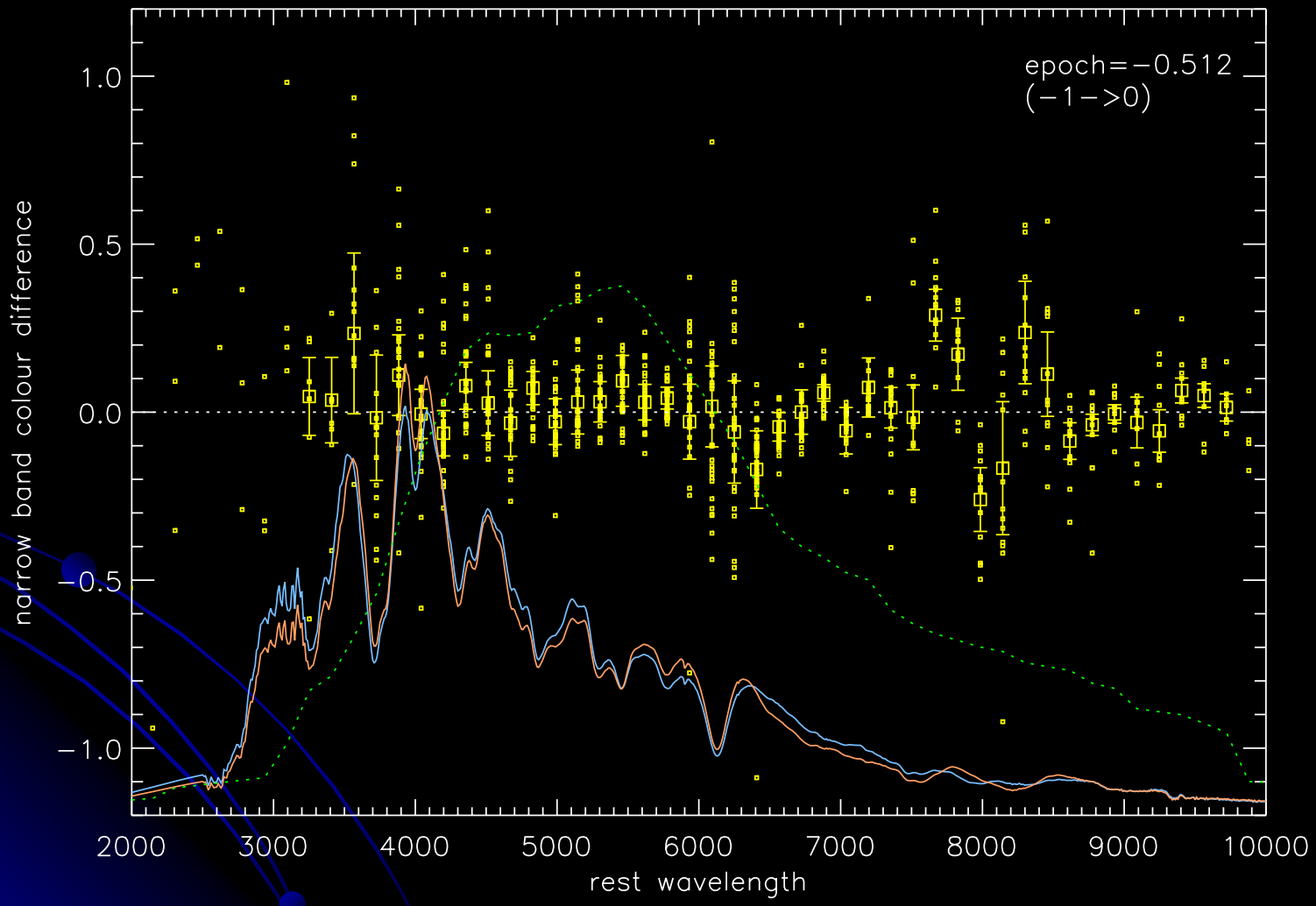
simple weighting by:

- epoch
- stretch
- type: normal vs 91bg-like/91T-like
- wavelength coverage: edges vs middle
- number of spectra from the same SN

# recipe

1. collect sample of spectra
2. define epoch intervals
3. define narrow filters
4. calculated narrow colours and weights for each spectrum at each wavelength interval
5. calculated weighted narrow colour per epoch per wavelength interval

# narrow band colours



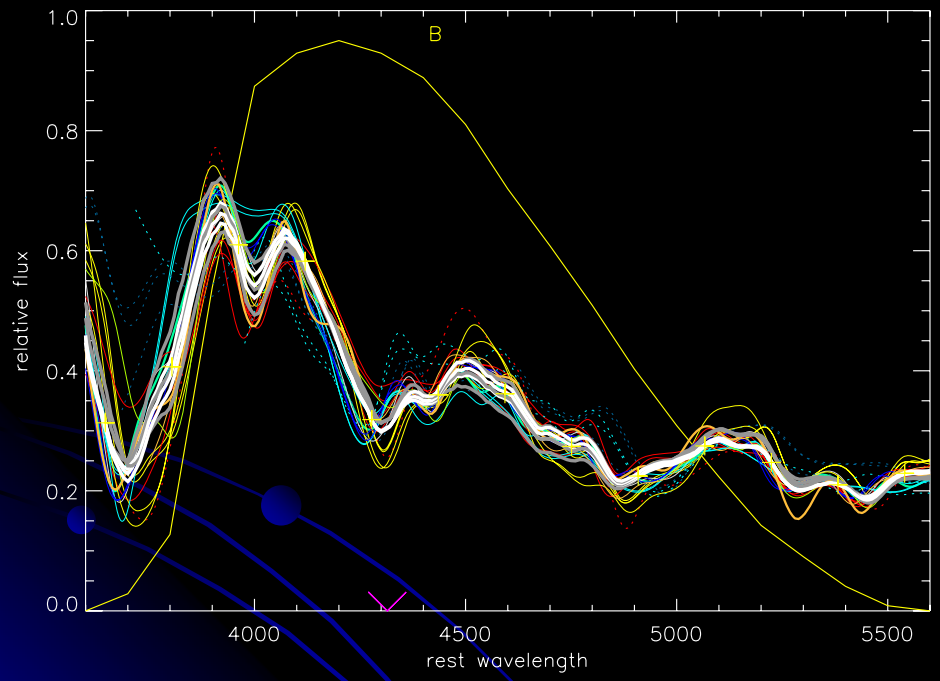

uberspectrum – k-correction errors – intrinsic scatter

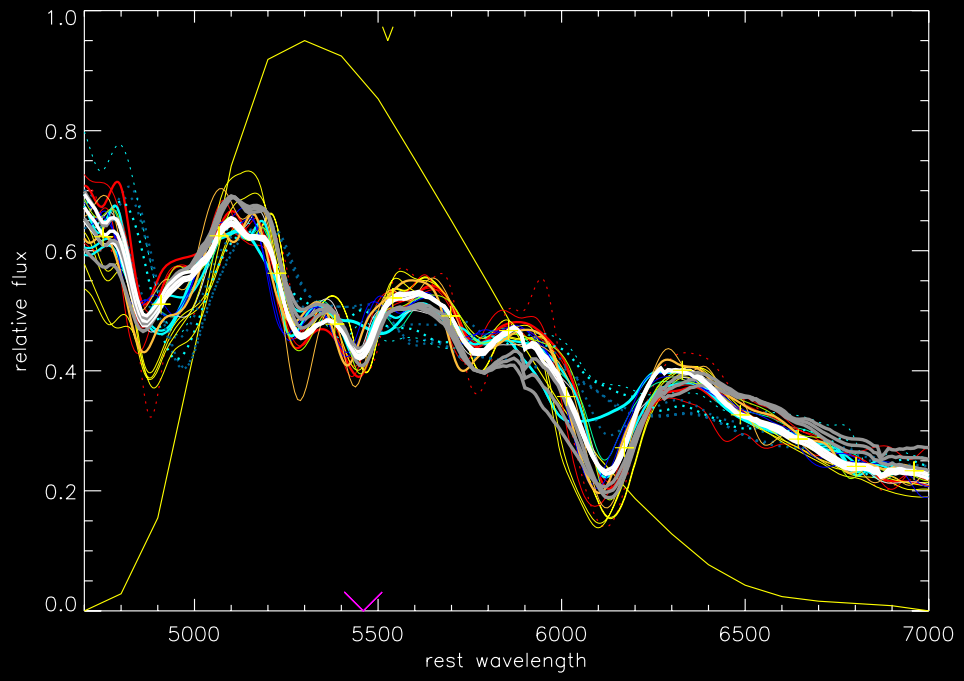
# recipe

1. collect sample of spectra
2. define epoch intervals
3. define narrow filters
4. calculated narrow colours and weights
   for each spectrum at each wavelength interval
5. calculated weighted narrow colour
   per epoch per wavelength interval
6. adjust template spectral features with weighted colours
   adjust template broadband colours to s=1 colours

# adjusted uberspectrum

**epoch = -6.3 (-7~-5)**



s=0.7 s=1.2

new uberspectrum

old uberspectrum

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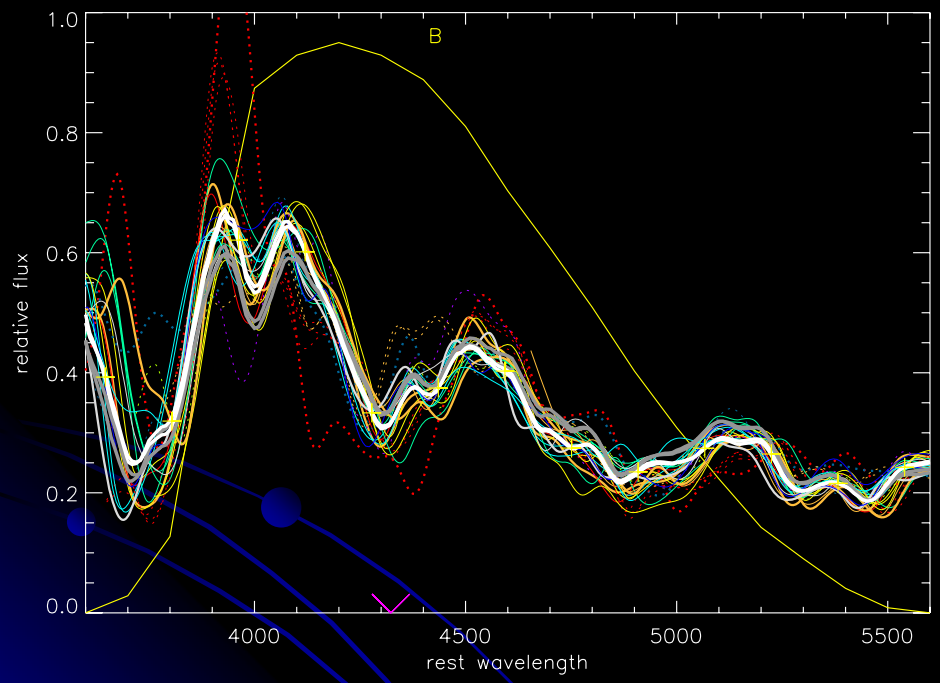
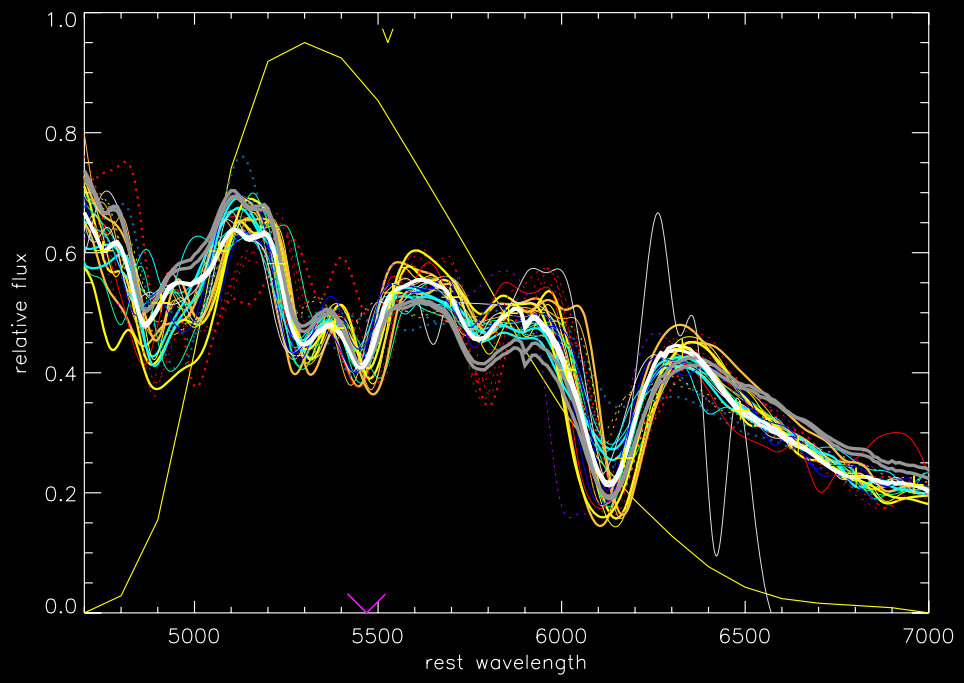
# adjusted uberspectrum

**epoch = 1.7 (1~2)**




s=0.7 s=1.2

new uberspectrum

old uberspectrum



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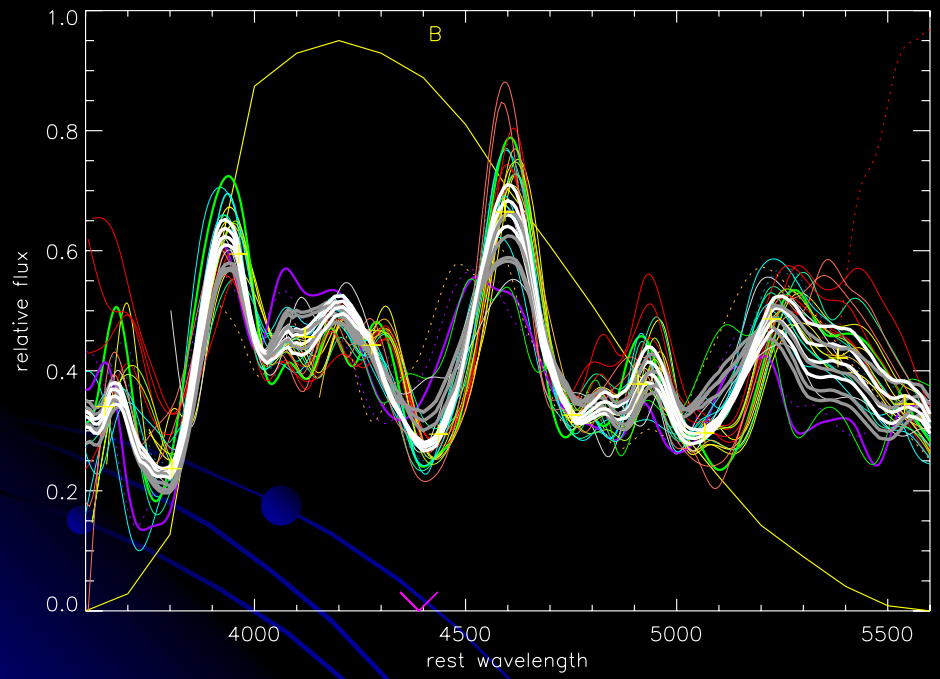
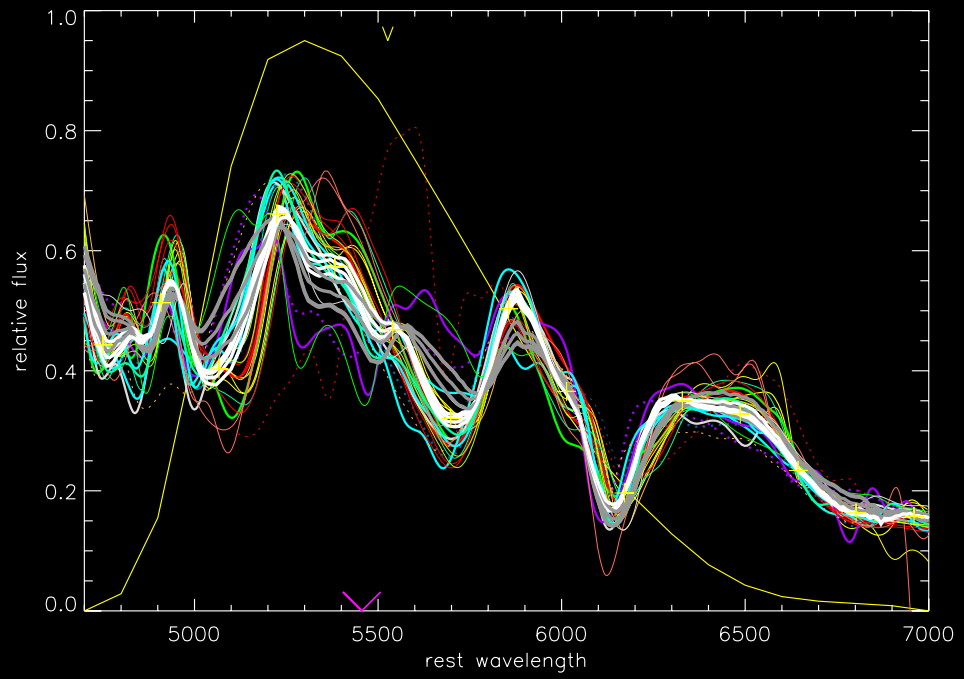
# adjusted uberspectrum

**epoch = 13.3 (12~15)**



s=0.7 s=1.2

new uberspectrum

old uberspectrum



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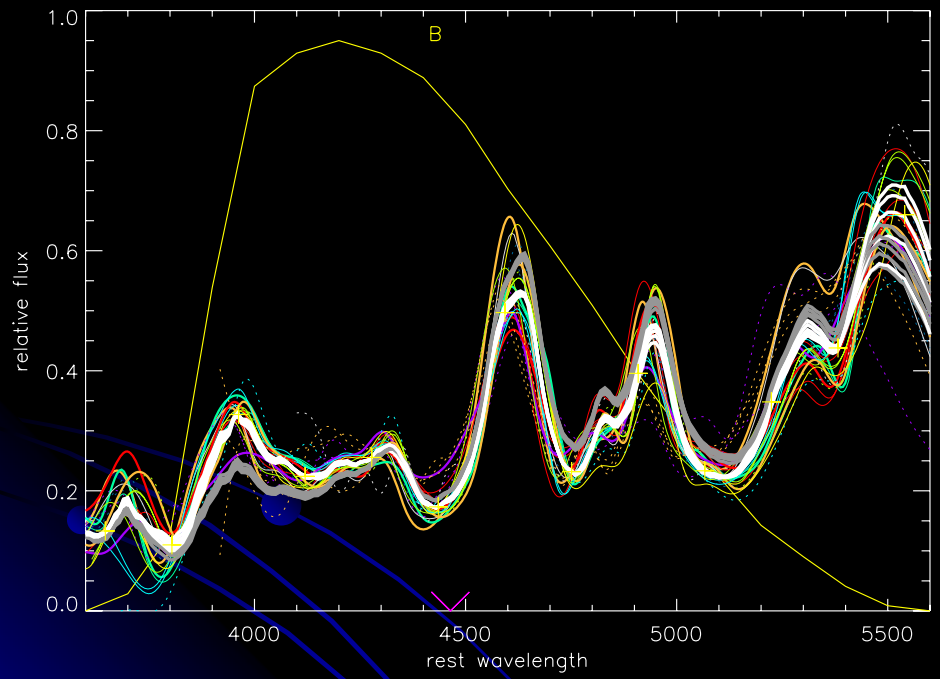
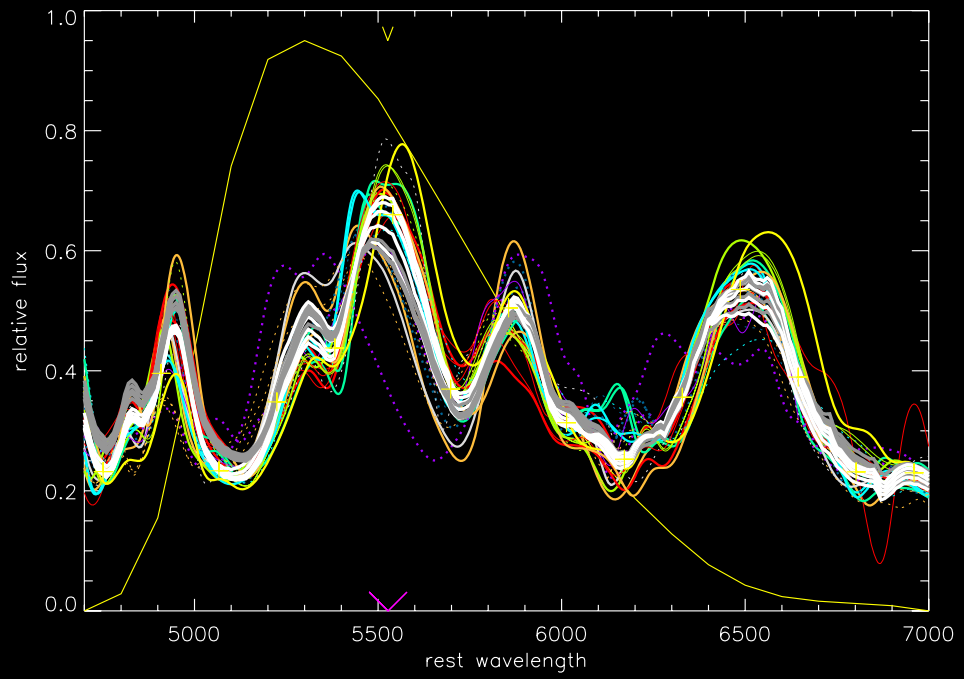
# epoch = 26.1 (24~28)



s=0.7 s=1.2

new uberspectrum

old uberspectrum

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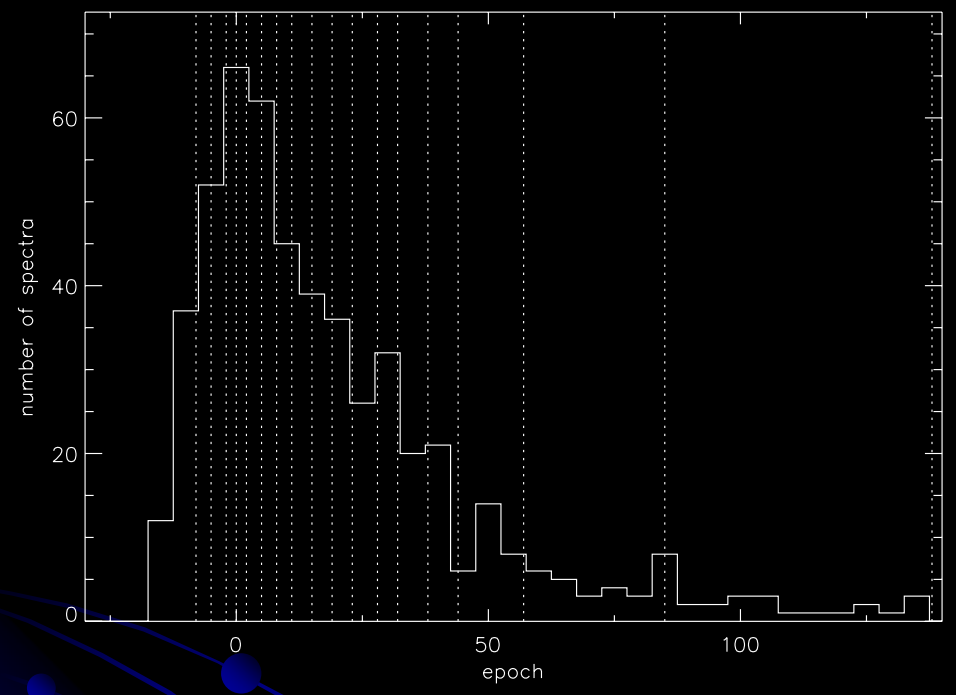
# epoch intervals




| lower | upper | weighted | stretch | no. of spec |
|---|---|---|---|---|
| -15 | -8 | -10.9 | 1.014 | 30 |
| -7 | -5 | -6.3 | 0.969 | 24 |
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| -1 | 0 | -0.5 | 0.985 | 30 |
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| 9 | 11 | 10.1 | 1.008 | 32 |
| 12 | 15 | 13.3 | 1.023 | 28 |
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| 20 | 23 | 21.9 | 1.001 | 25 |
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| 45 | 57 | 51.6 | 0.953 | 24 |
| 58 | 85 | 71.7 | 0.957 | 24 |



uberspectrum – k-correction errors – intrinsic scatter

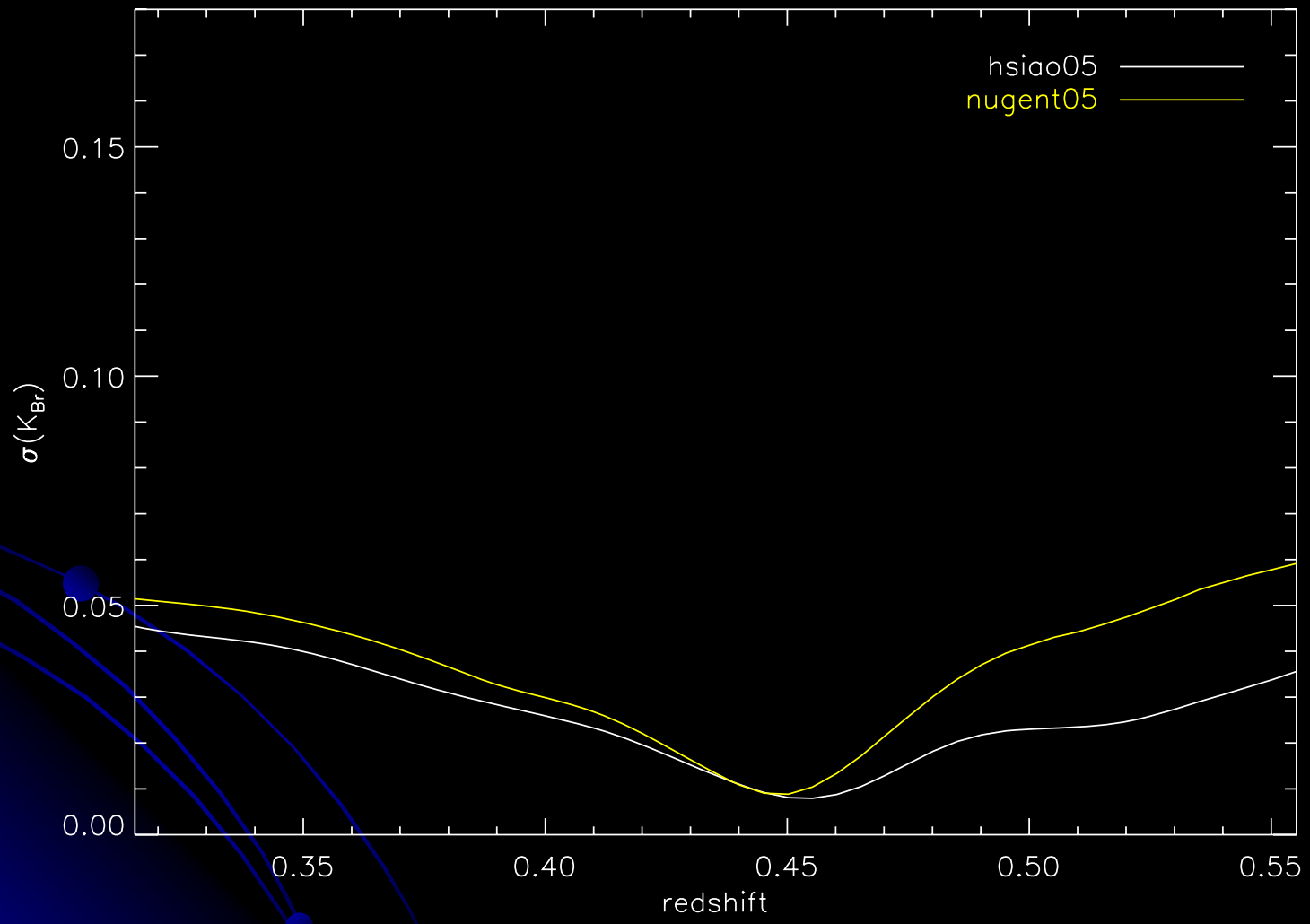
# recipe

1. collect sample of spectra
2. define epoch intervals
3. define narrow filters
4. calculated narrow colours and weights
   for each spectrum at each wavelength interval
5. calculated weighted narrow colour
   per epoch per wavelength interval
6. adjust template spectral features with weighted colours
   adjust template broadband colours to s=1 colours
7. interpolate between weighted epochs
   adjust template broadband colours to s=1 colours

# k-correction errors

- errors defined by difference between k-correction calculated with uberspectrum and actual spectra
- compare different methods of k-correction
- include 81B, 89B, 90N, 90T, 91T, 91bg, 92A from epoch = -14 ~ 37

# hsiao05 vs nugent05



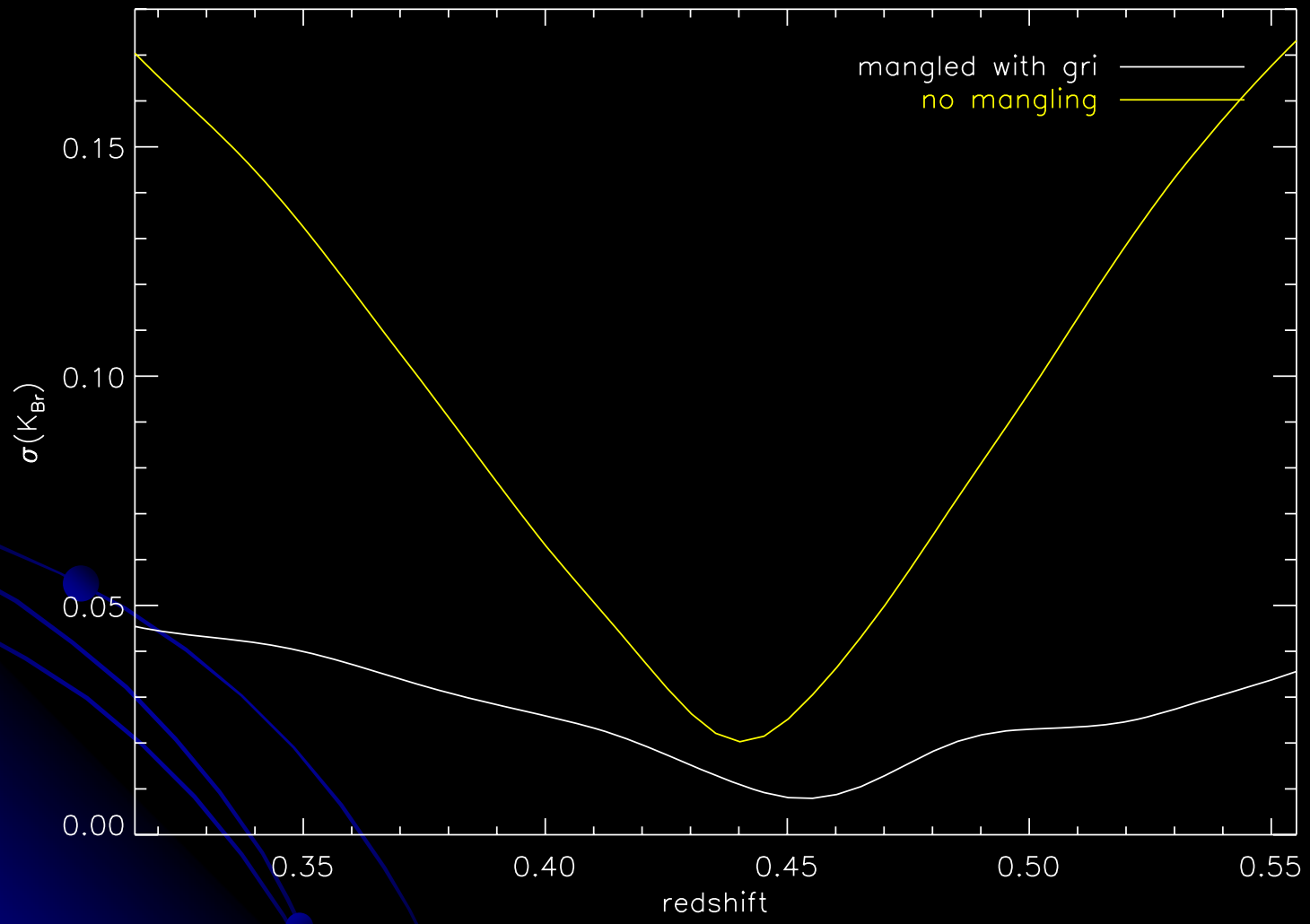



uberspectrum – k-correction errors – intrinsic scatter

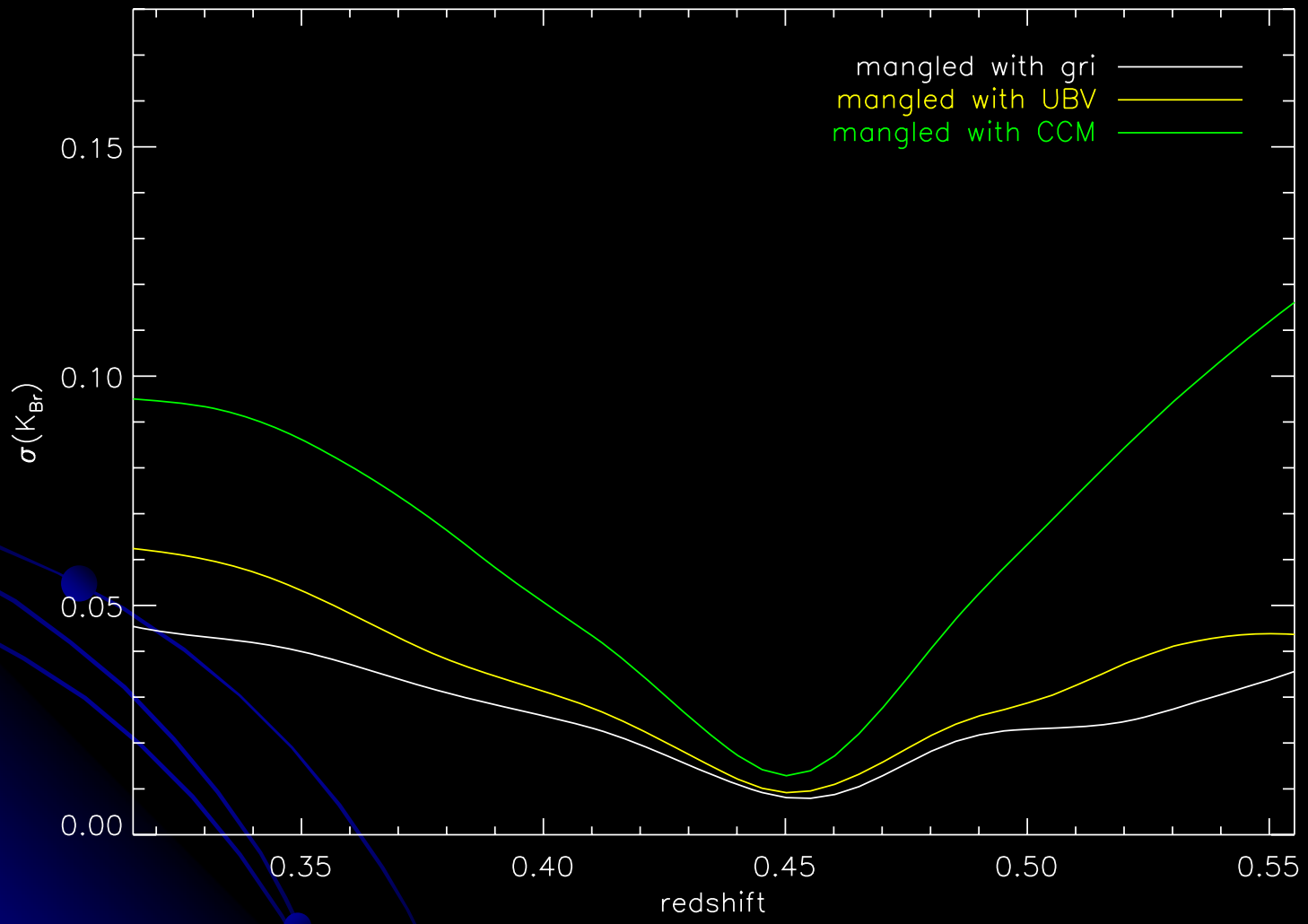
# colour correcting uberspectrum

- by E(B-V) and CCM_UNRED
  - constraints B-V but guess the other colours
- by MANGLE_SPECTRUM2 (written by Mark Sullivan)
  - least square minimiser
  - constraints multiple colours

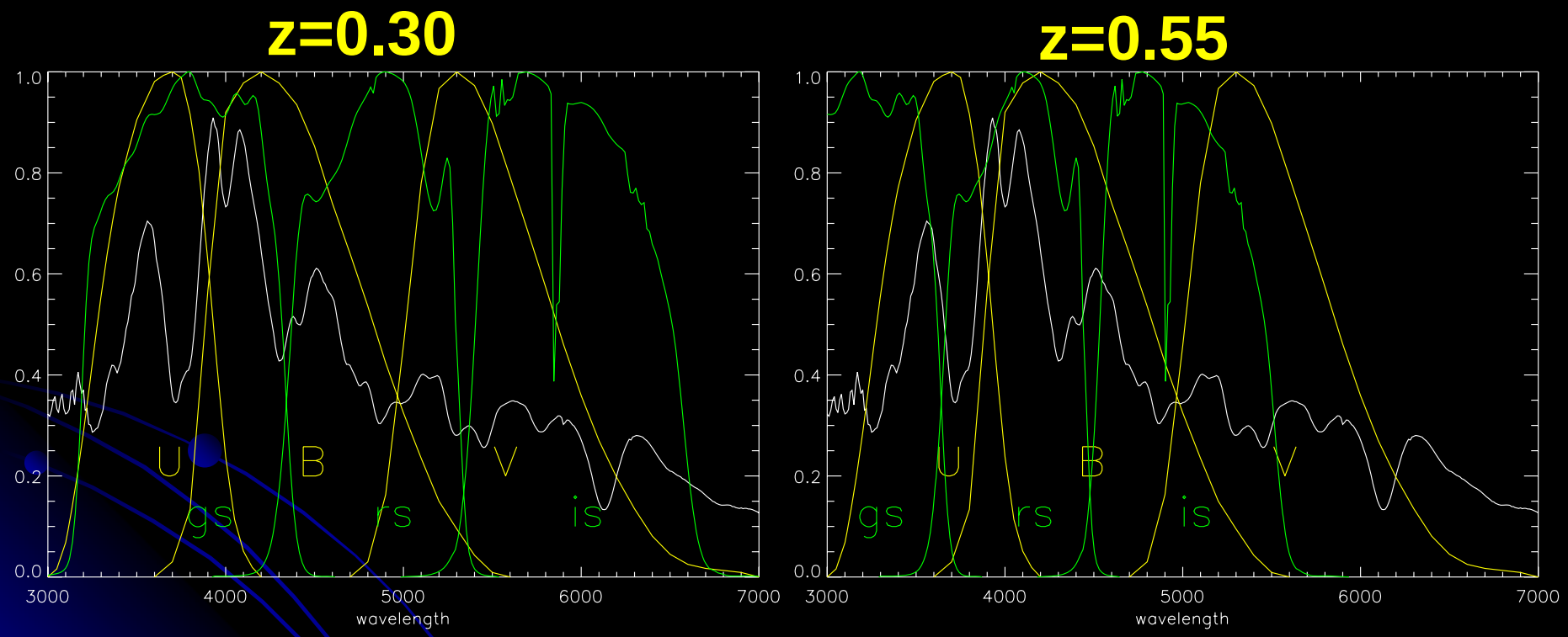
# mangled vs unmangled



# mangled with rest vs observed colours



# mangled with rest vs observed colours

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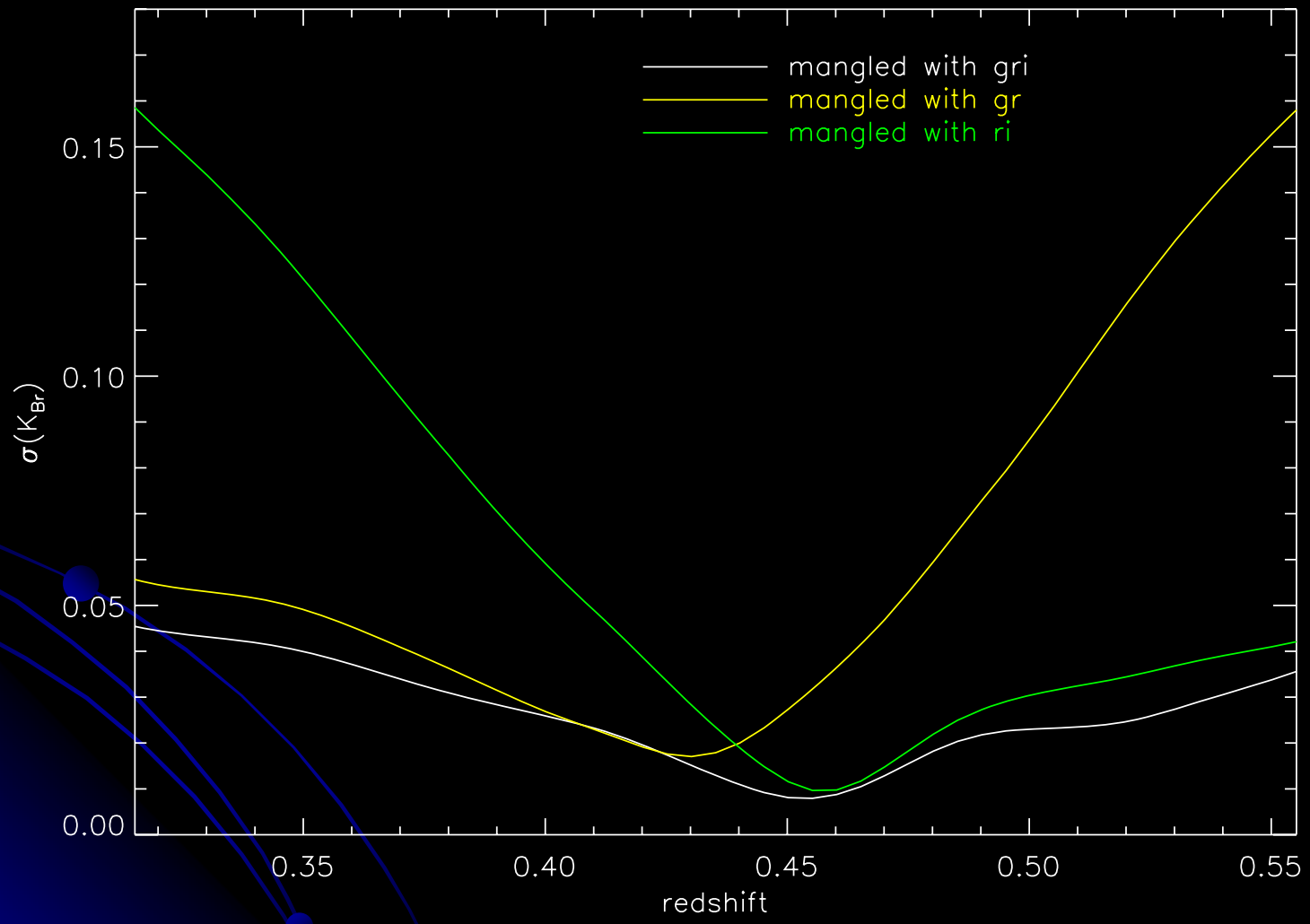
# mangled with 2 colours vs 1 colour

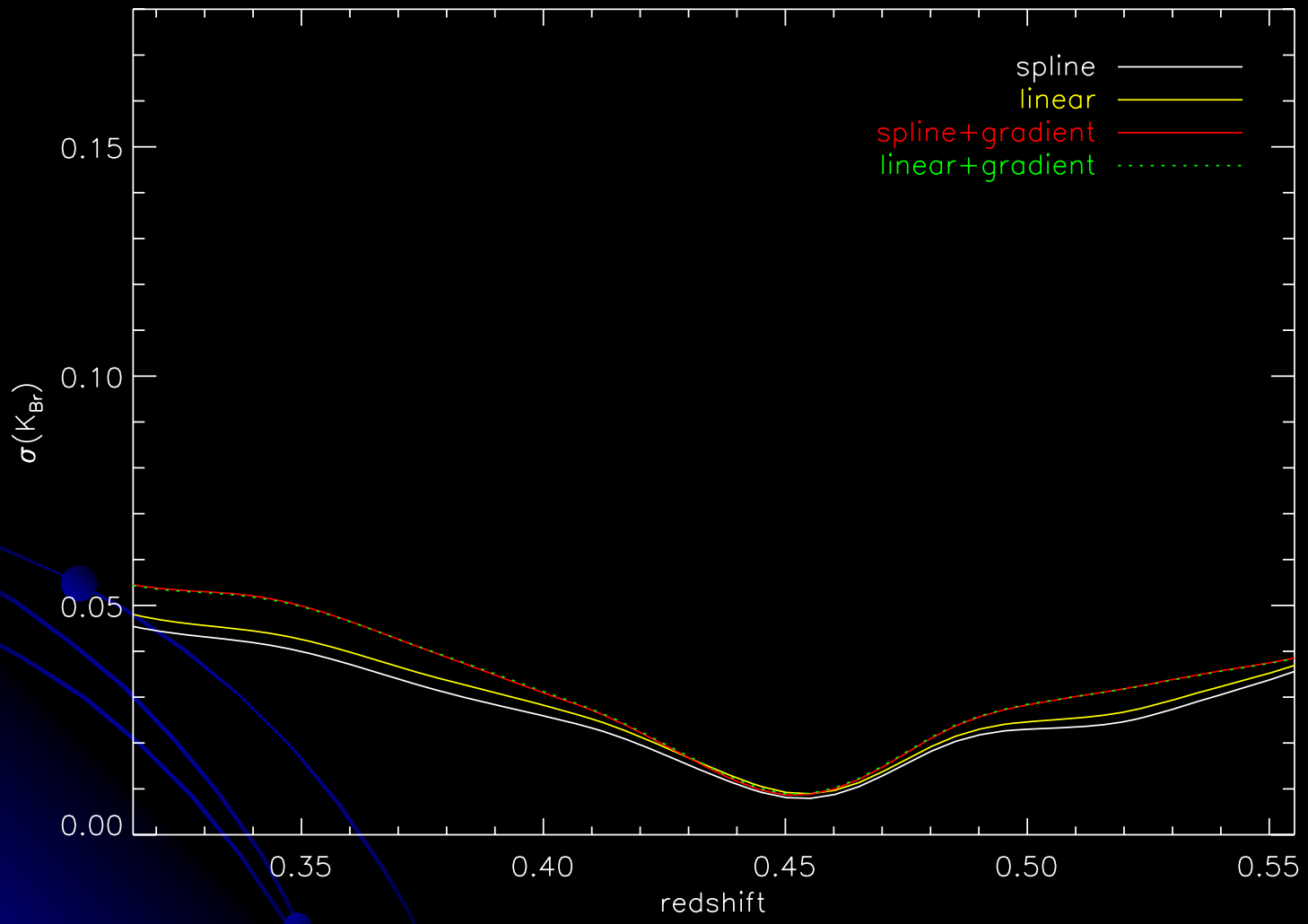


# colour correcting uberspectrum

- by E(B-V) and CCM_UNRED
  - constraints B-V but guesses the other colours
- by MANGLE_SPECTRUM2 (written by Mark Sullivan)
  - least square minimiser
  - constraints multiple colours
  - leaves the rest unchanged

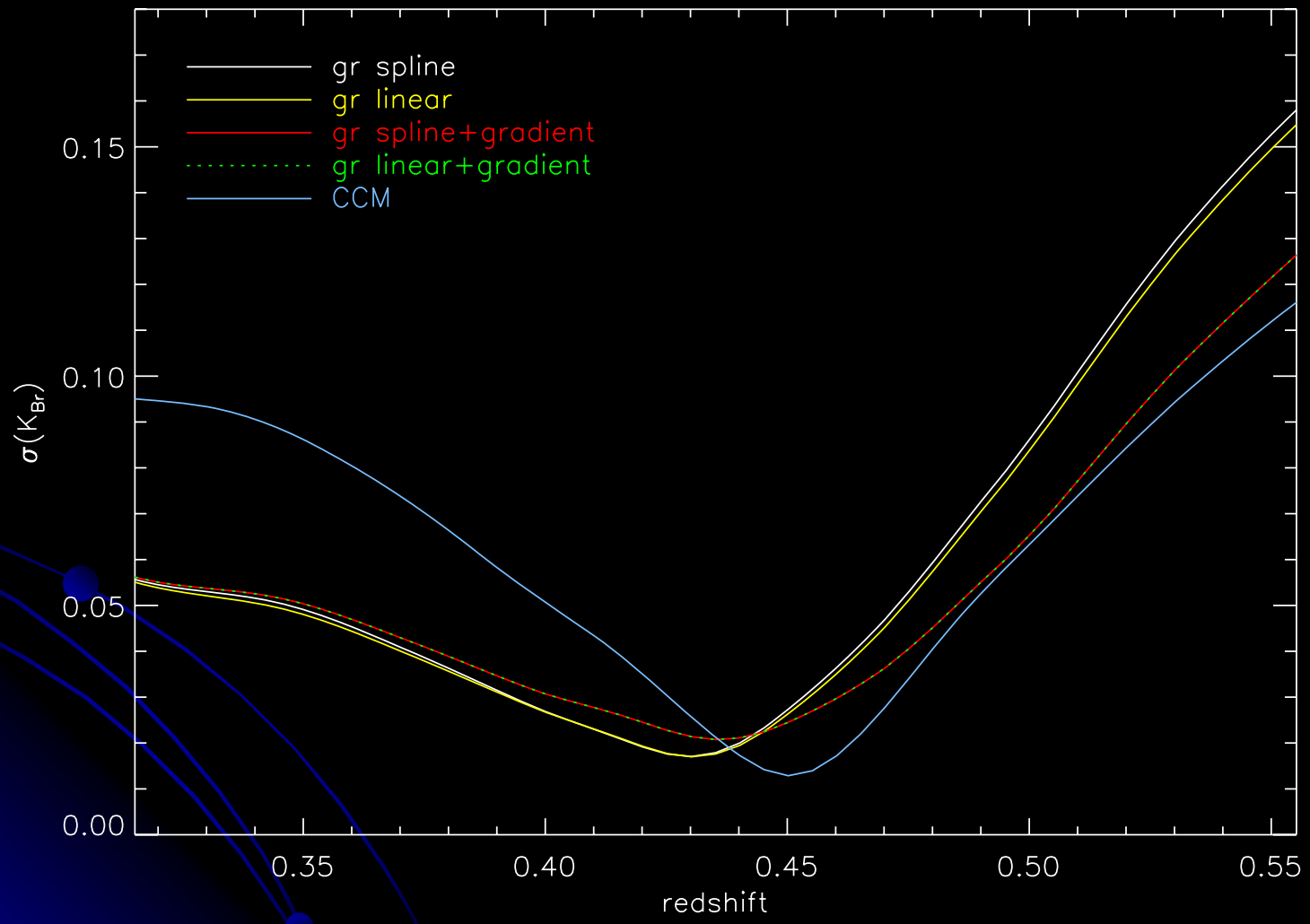
  - option SPLINE
  - option LINEAR
  - option GRADIENT

# 2-colour-mangling with various techniques




uberspectrum – k-correction errors – intrinsic scatter

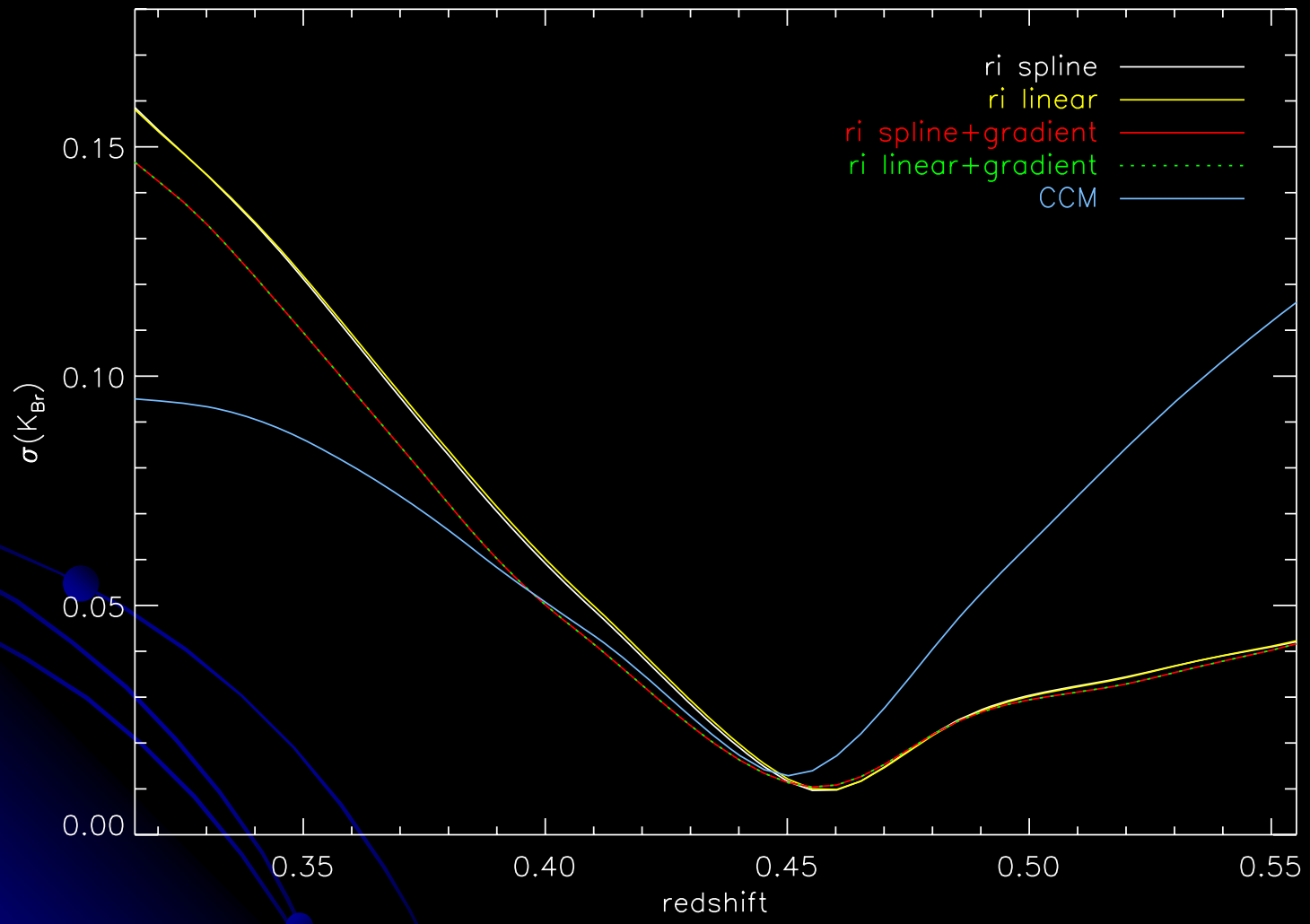
# 1-colour-mangling with various techniques






uberspectrum – k-correction errors – intrinsic scatter

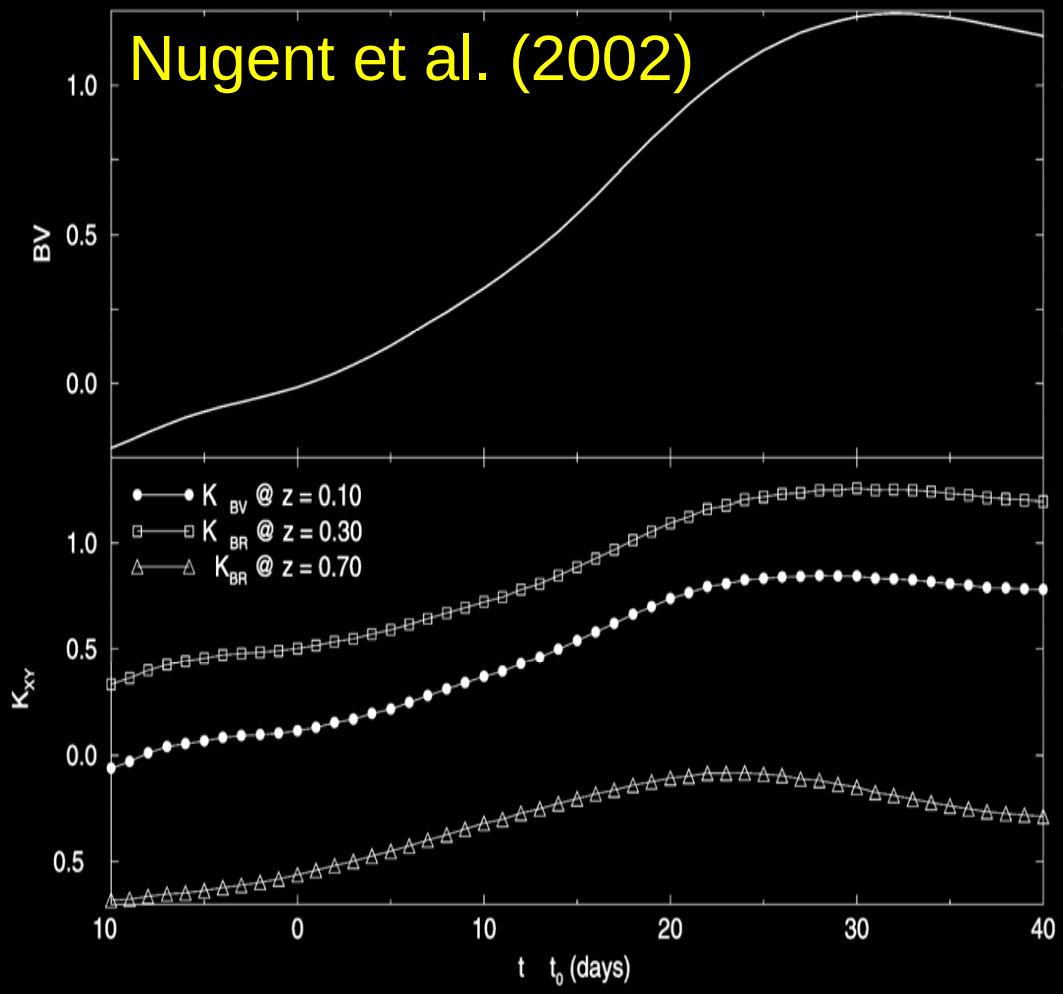
# 1-colour-mangling with various techniques





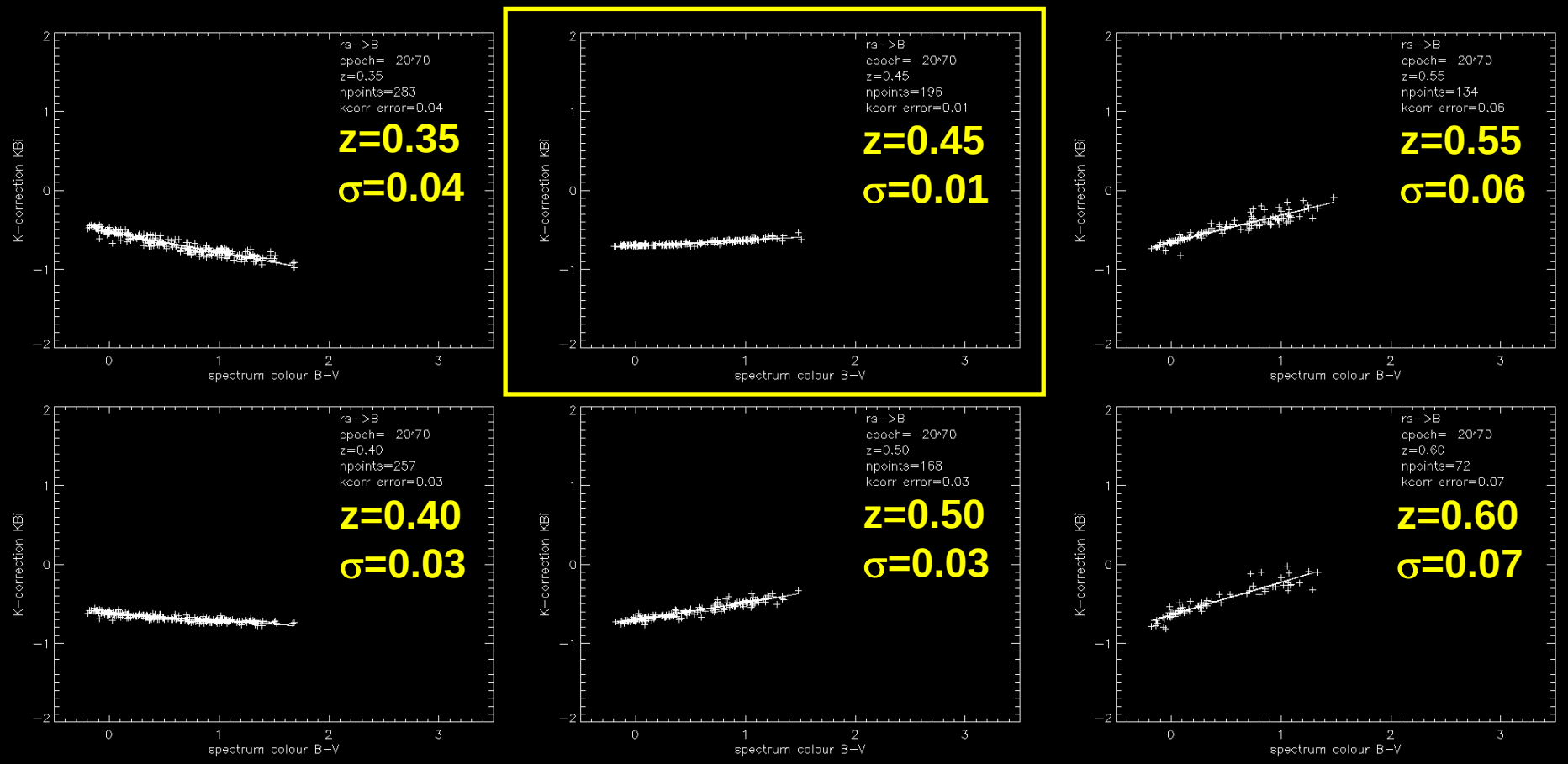

uberspectrum – k-correction errors – intrinsic scatter

# variation in spectral features

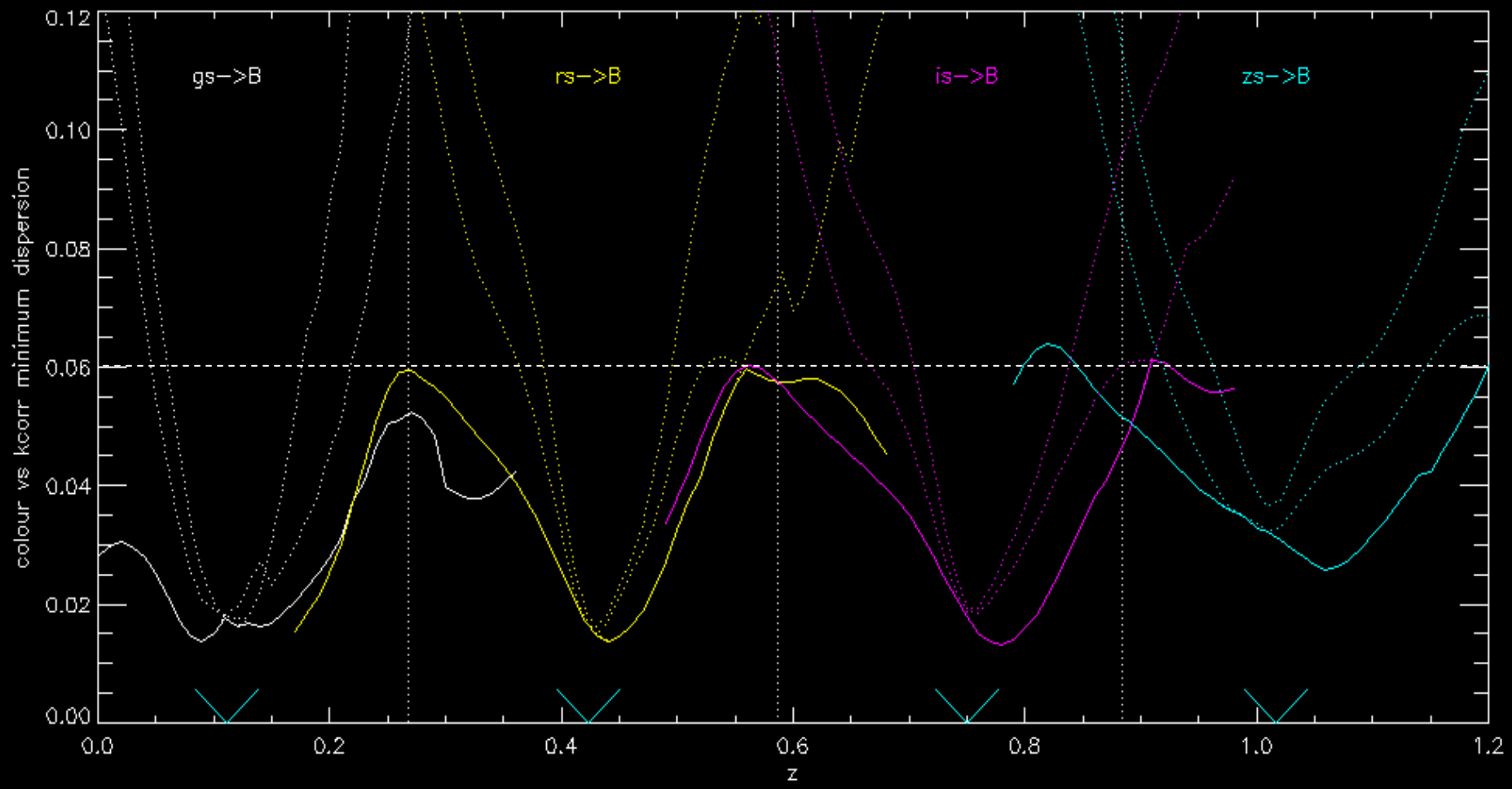



- k-correction largely driven by broadband colours
- use the scatter of k-correction vs colour plots to determine scatter caused by variations in spectral features

- plot KBi vs B-V at each redshift for each spectrucm
- independent of uberspectrum



# variation in spectral features

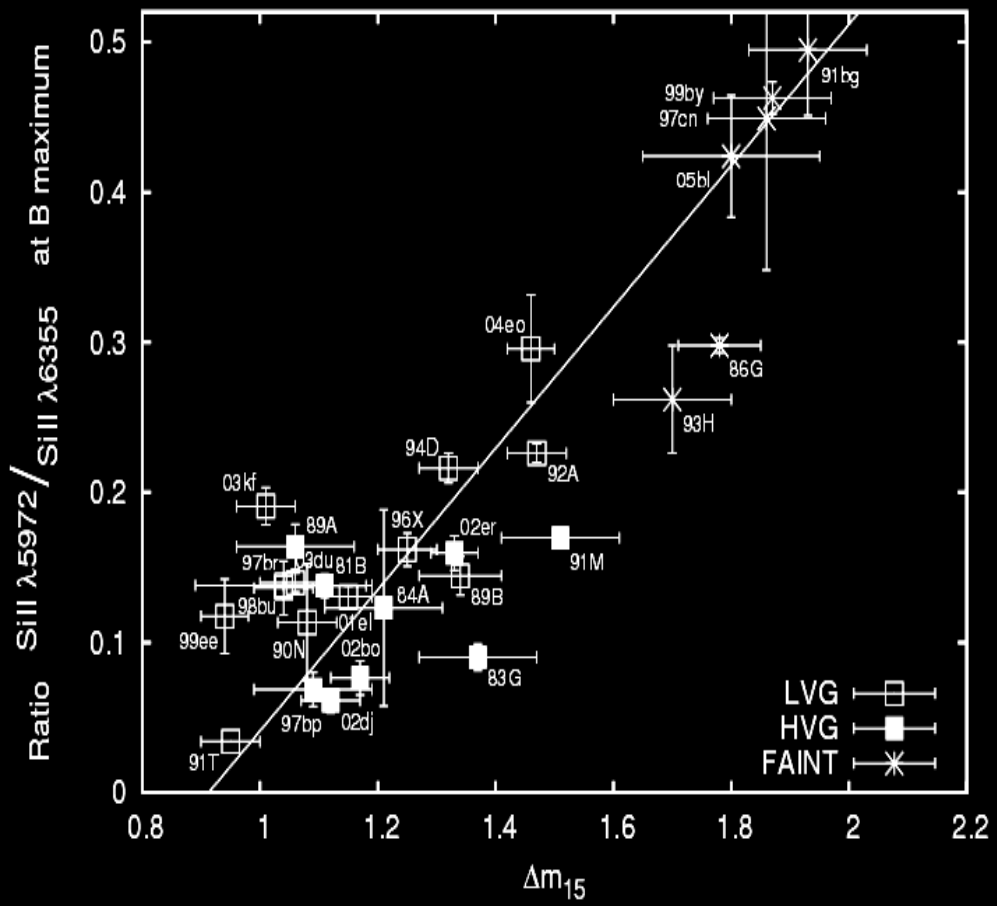


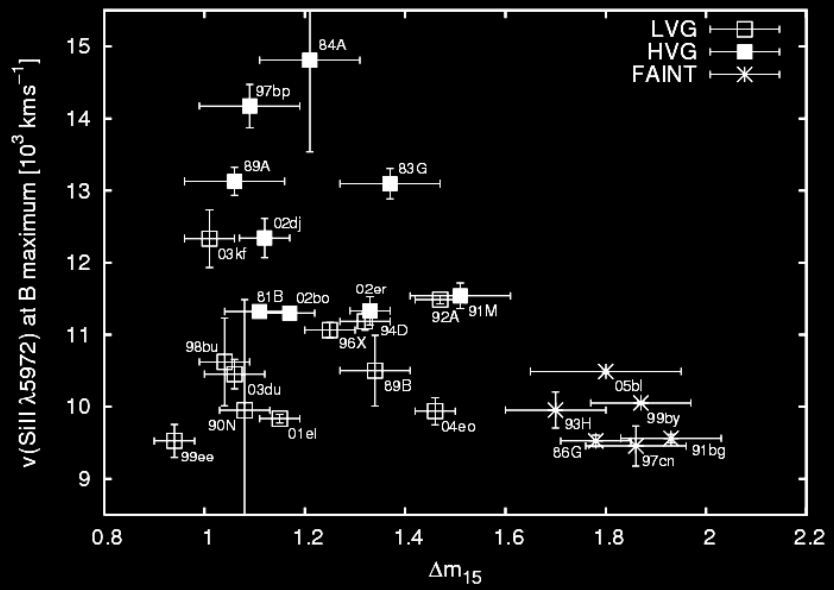


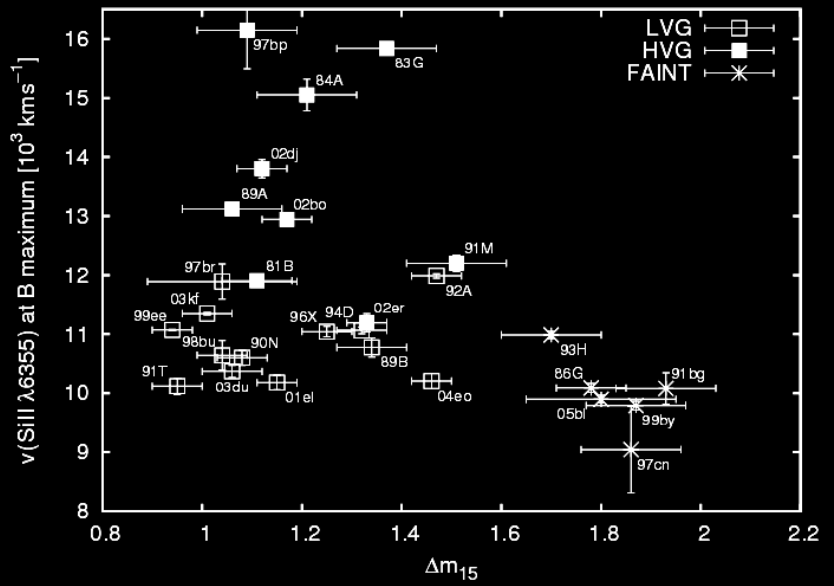

uberspectrum – k-correction errors – intrinsic scatter

# spectroscopic sequence in stretch

- mean template: 2 dimensional
  (epoch, wavelength)
- ideal spectroscopic sequence: 3 dimensional
  (epoch, wavelength, stretch)
- difficult to find features which vary with stretch
- try with the most well known:
  SiII 5972/6355 ratio

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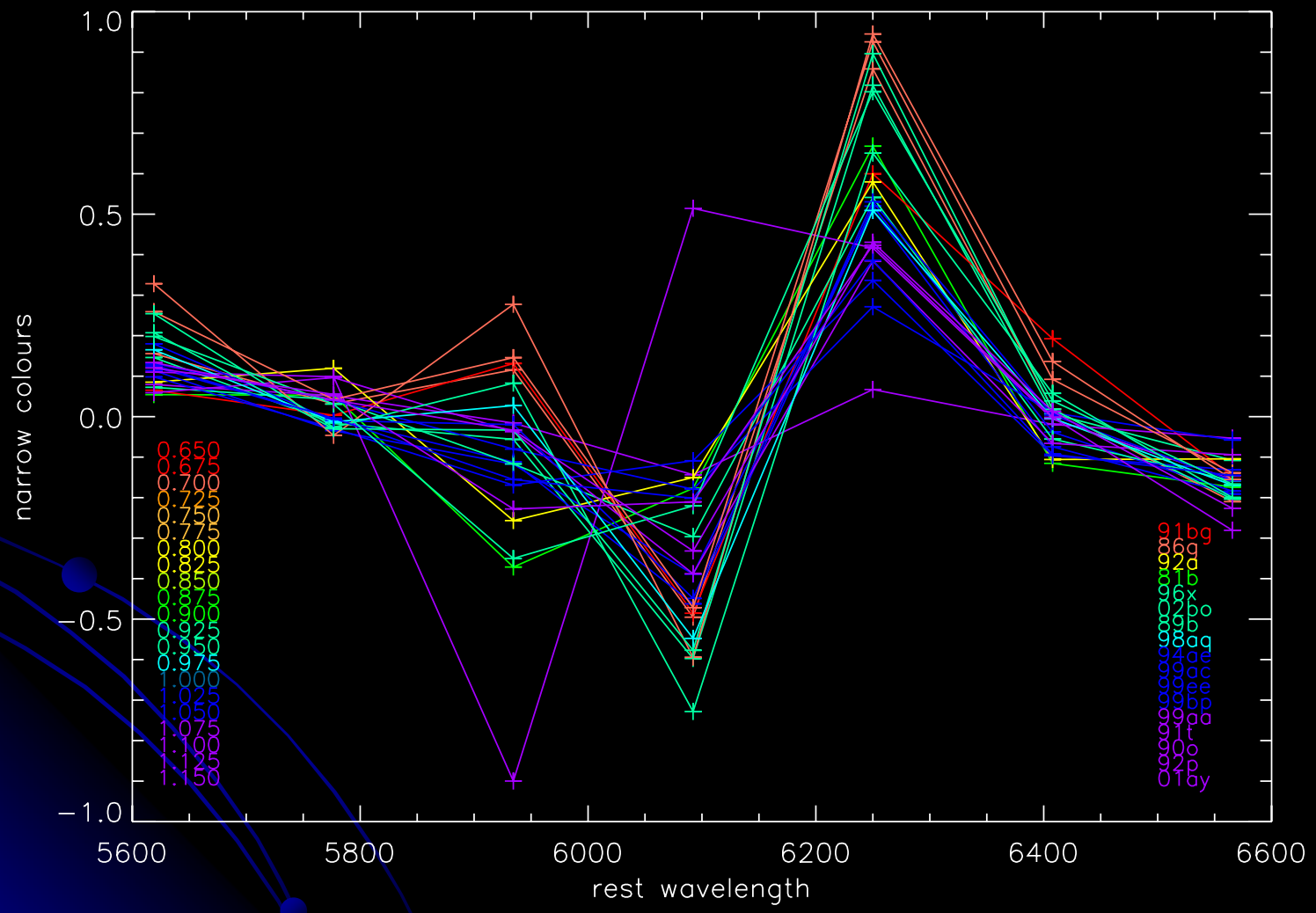
# narrow band colours





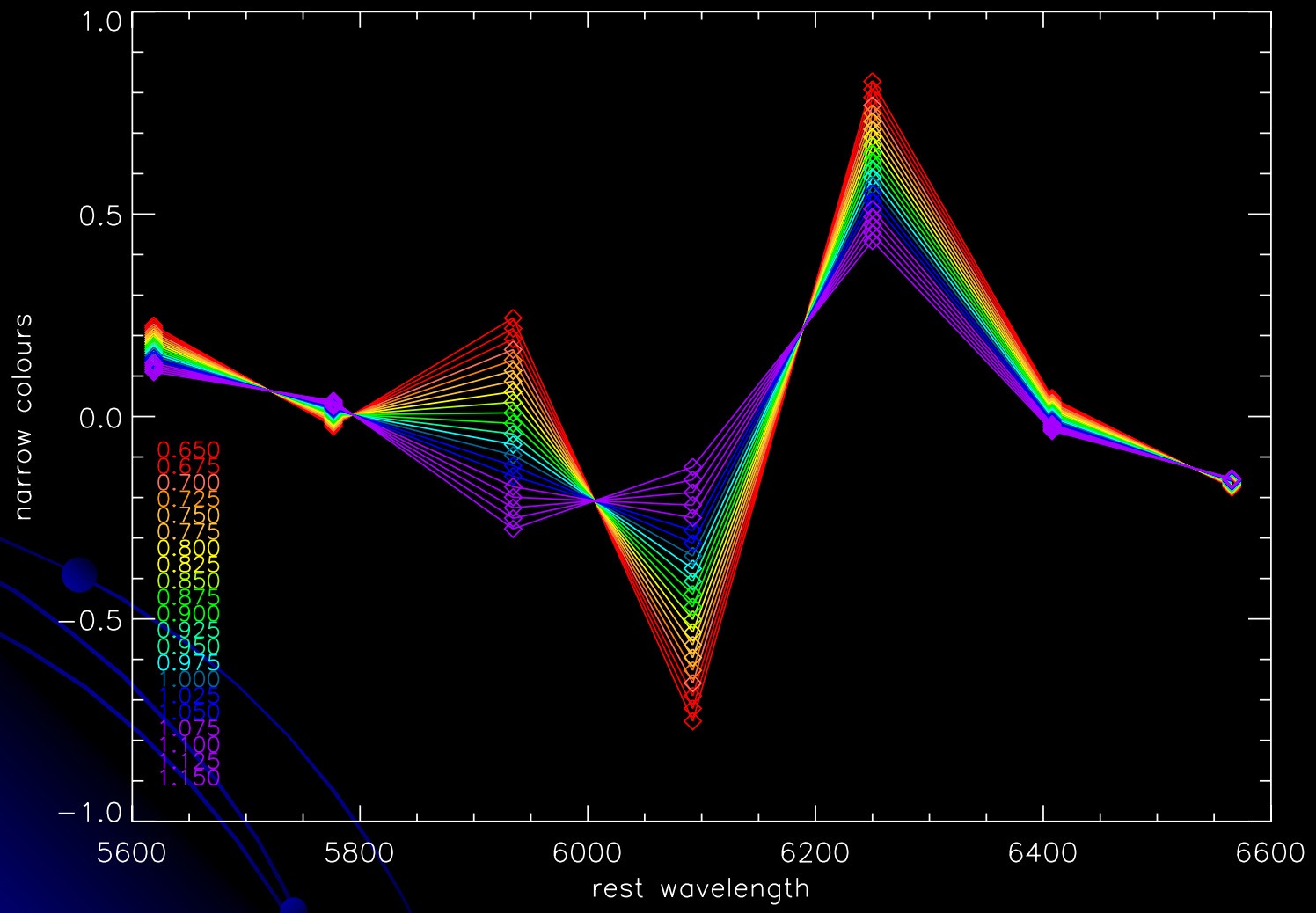

uberspectrum – k-correction errors – intrinsic scatter

# PCA of narrow colours

| mode | eigenvalue | percent |
|---|---|---|
| 1 | 0.138 | 70.4 |
| 2 | 0.043 | 22.0 |
| 3 | 0.008 | 4.2 |
| 4 | 0.003 | 1.6 |

stretch?

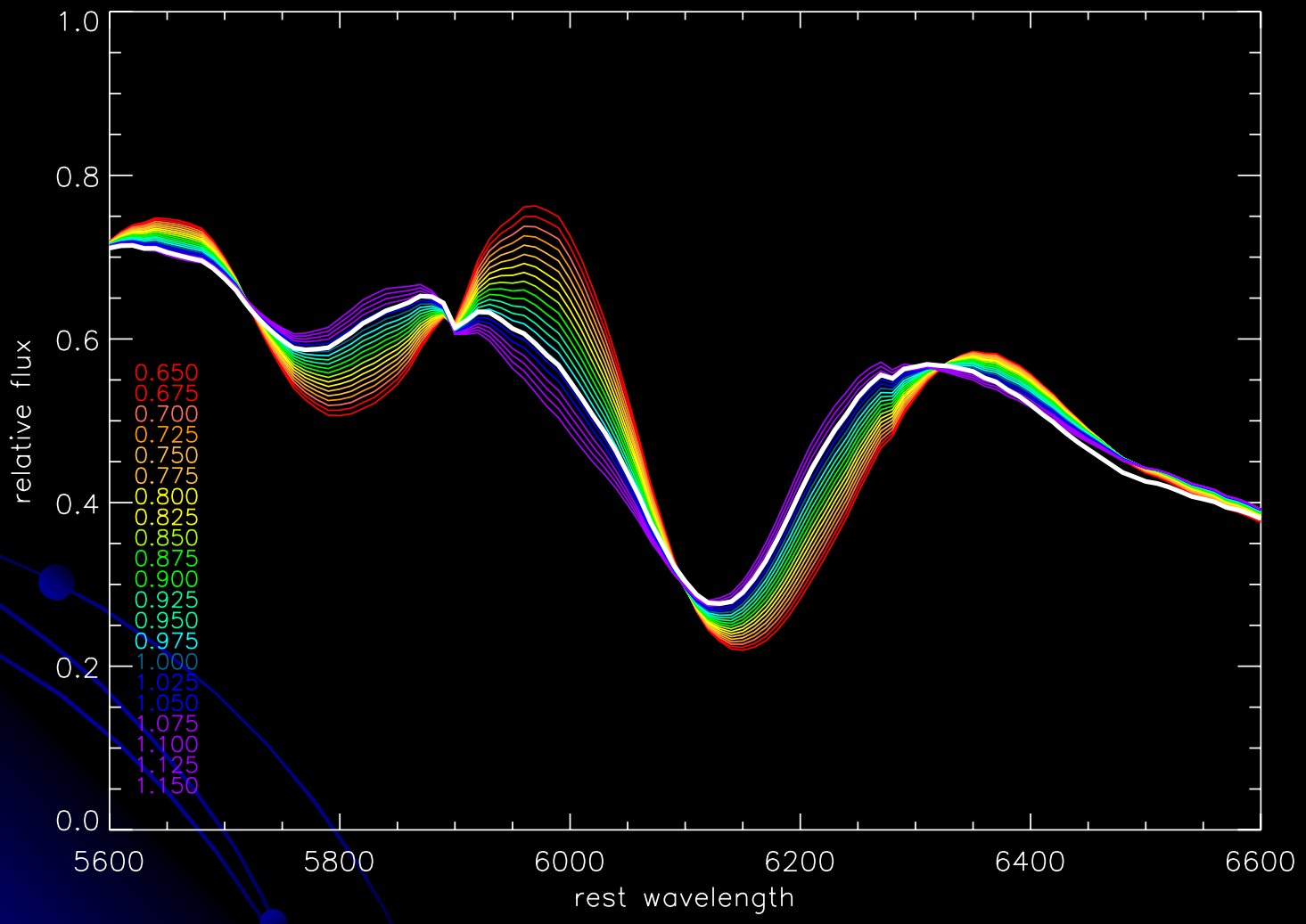
# spectroscopic sequence in stretch






uberspectrum – k-correction errors – intrinsic scatter

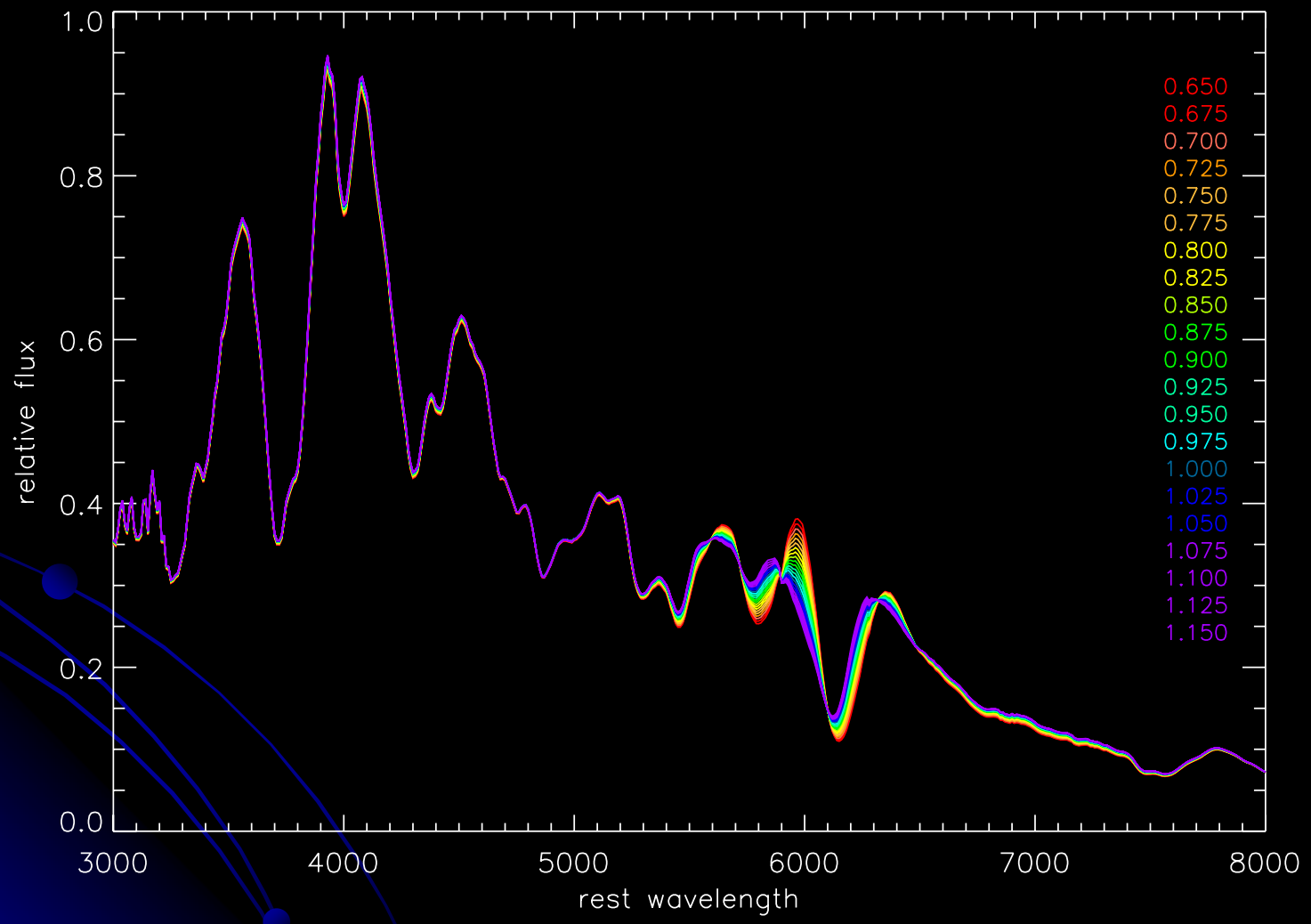
# spectroscopic sequence in stretch






uberspectrum – k-correction errors – intrinsic scatter

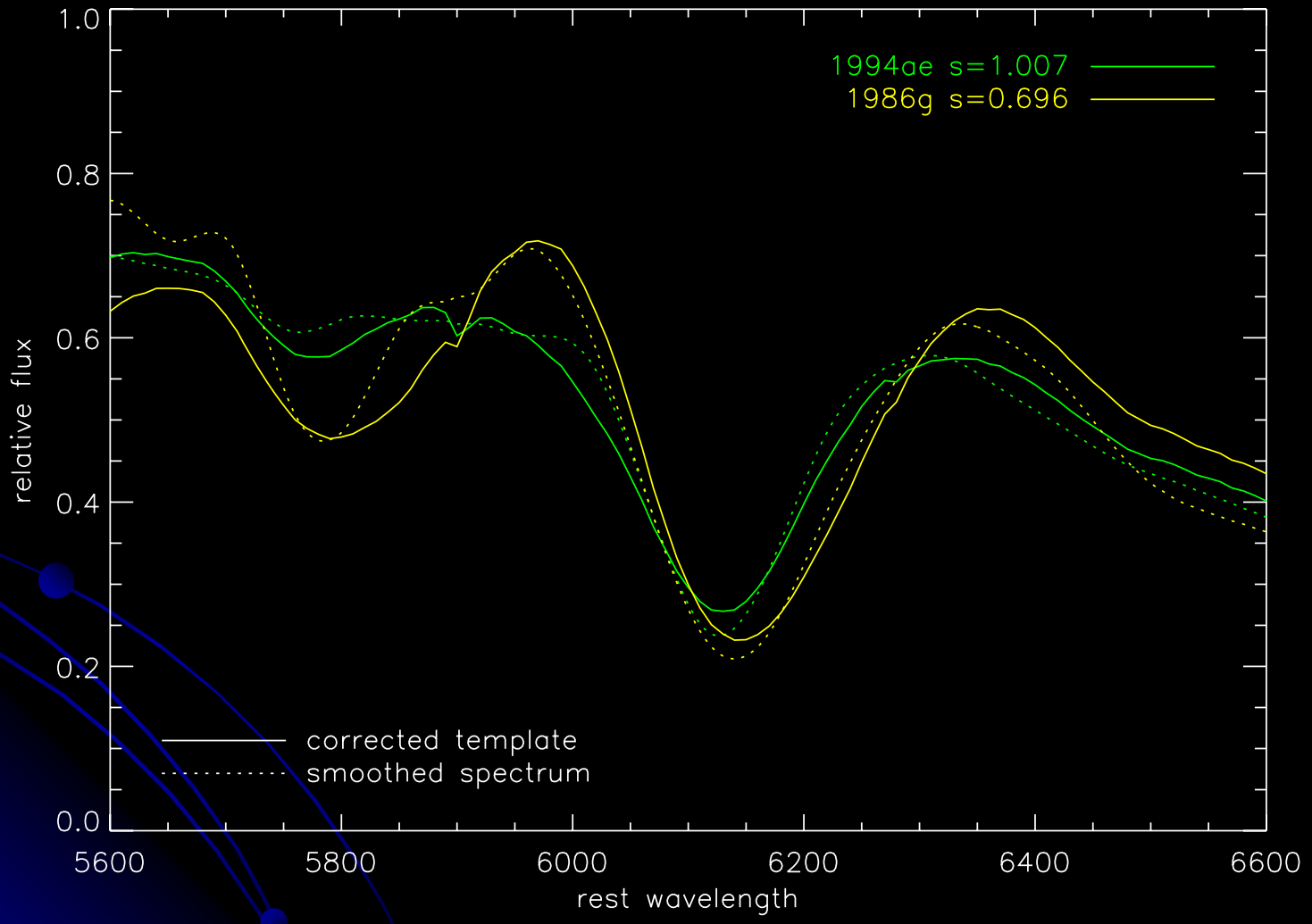
# spectroscopic sequence in stretch






uberspectrum – k-correction errors – intrinsic scatter

# spectroscopic sequence in stretch






uberspectrum – k-correction errors – intrinsic scatter

# conclusions

- to eliminate systematic errors in k-correction
  build “mean uberspectrum” from a representative sample
- mangling using observed colours
  better than using rest colours
- uberspectrum unconstrained by colour(s)
  can cause large errors
- variations in spectral features causes
  sizeable k-correction scatter at misaligned redshifts