The Rotation Rate and its Evolution Derived from Improved Mode Fitting and Inversion Methodology

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The Data: Some 13 Years of It

- GONG *pipe-line* (Anderson *et al*, 1990) `1995.06.29 -- 2009.09.07`
  - ⋆ 147 GONG *months* (36 days),
  - ⋆ fitted in *overlapping* 108-day long segments,
  - ⋆ *individually & independently* fitted,
  - ⋆ no leakage matrix information, symmetric profile.

- MDI *pipe-line* (Schou, 1992) `1996.05.01 -- 2009.12.07`
  - ⋆ 67 MDI non-overlapping epochs (72 days),
  - ⋆ polynomial expansion in m,
  - ⋆ incl. leakage matrix information, symmetric profile.

- MDI Larson/Schou improvements
  - ⋆ spatial decomposition: plate scale and image distortion
  - ⋆ leakage matrix: distortion by differential rotation
  - ⋆ symmetric *and* asymmetric profile (62 & 57 epochs)

YAOPBM

- SGK fit (Korzennik 2005, 2008)
  - ⋆ Method
    - ∗ simultaneous fit of indiv. modes w/ sanity rejection,
    - ∗ incl. leakage matrix,
    - ∗ asymmetric profile,
    - ∗ *optimal* multi-tapered spectral estimator,
    - ∗ use time-series of varying lengths.
  - ⋆ *pipe-line* SHC time-series `1996.05.01 -- 2002.01.17`
    - ∗ 2088-day long time-series
    - ∗ 728-, 364-, 182-day long, overlapping, time-series
  - ⋆ *improved* SHC time-series `1996.05.01 -- 2009.07.16`
    - ∗ incl. distortion by diff. rotation
    - ∗ 64×72, 32×72, 16×72-day long, overlapping, time-series

Yet An Other Peak Bagging Method

The Problems: Foreword

- Inverse Theory

$$y_i = \int K_i \, x(p) \, dp$$

  - ⋆ Inverse problems are singular,
  - ⋆ require regularization to lift singularity (smoothness),
  - ⋆ produce an *estimate* of the solution $\hat{x} = x \otimes R$
  - ⋆ R resolution kernels – depend on the input set

- Solar Rotation

$$\delta\nu_{n,\ell,m} = \iint K_{n,\ell,m}(r,\theta) \, \Omega(r,\theta) \, dr \, d\theta$$

  - ⋆ input set is defined by $\{n, \ell, m\}$ or $\{n, \ell, a_i\}$
  - ⋆ temporal changes in the input set affect R, hence $\hat{x}$

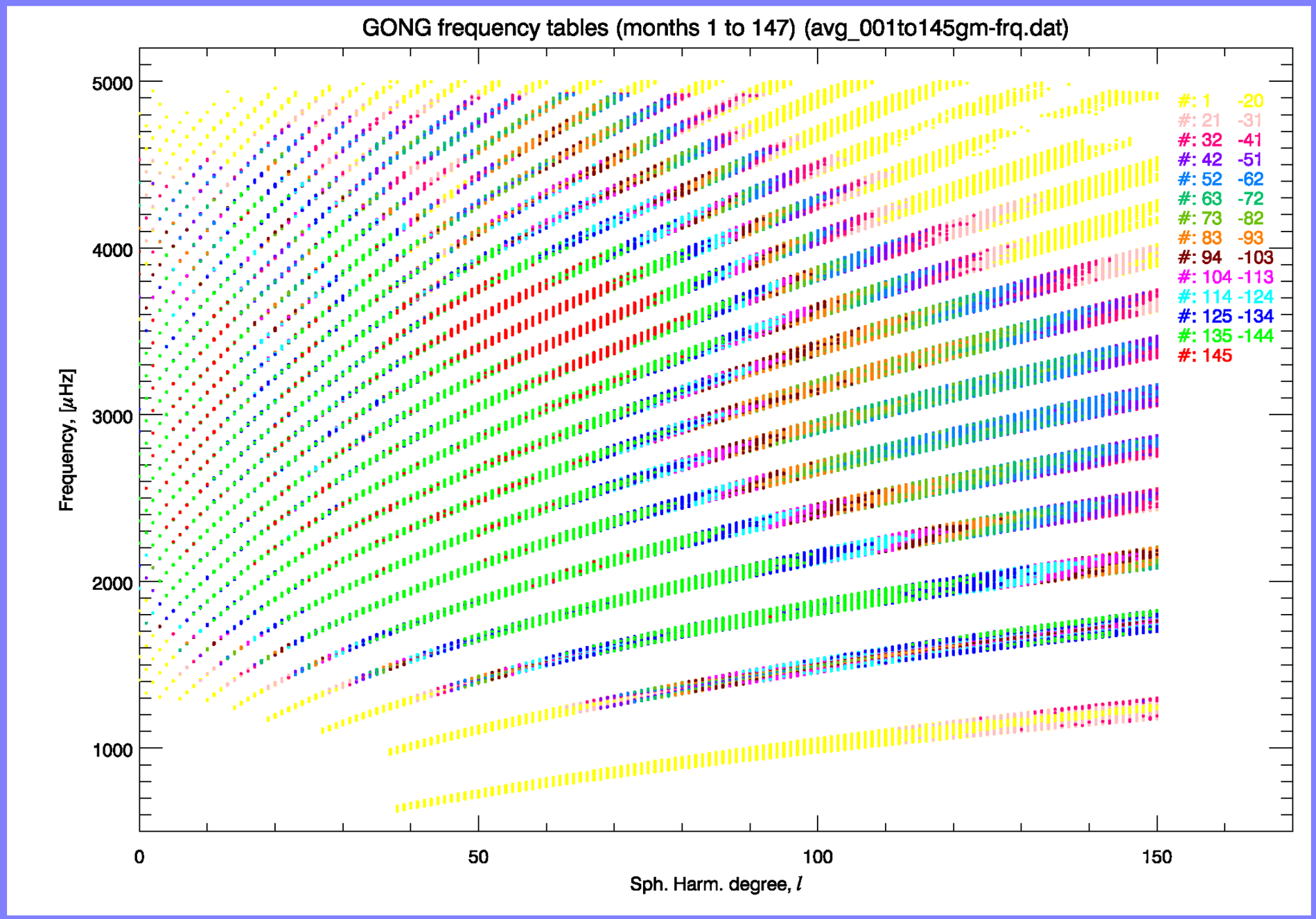
$\Rightarrow$ chose to invert a constant input set

GONG & MDI

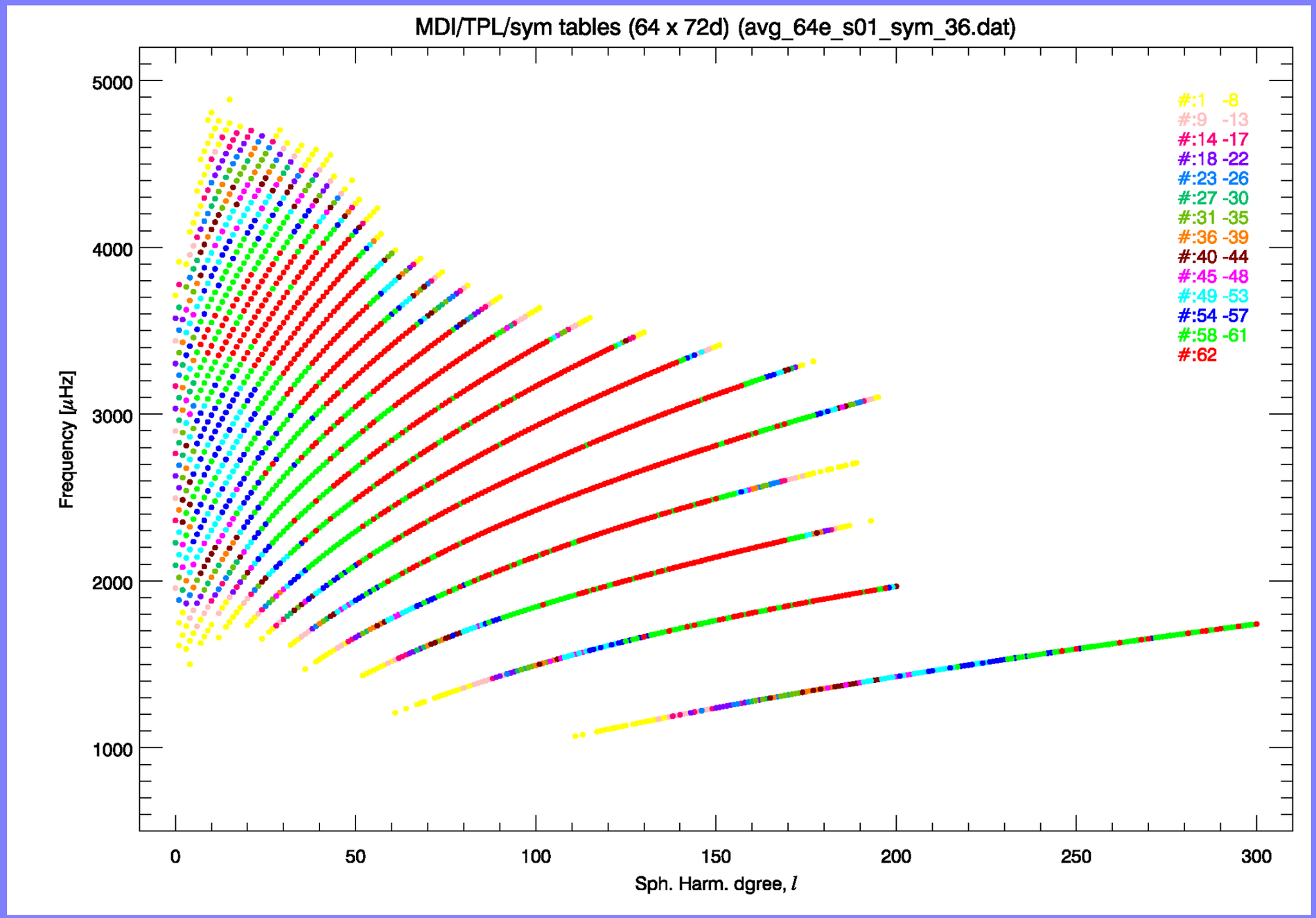
qui aime bien, châtie bien

- Frequencies or polynomial expansion?
  - ⋆ GONG *pipe-line*
    - ∗ Would like to use ν, not a_i
    - ∗ a_i computed from $\nu_{n,\ell,m}$
  - ⋆ MDI *pipe-line*
    - ∗ Produces only a_i, independent of mode visibility
- Mode attrition when reducing to a unique input set
- Fill factor not constant with time
- Error bars estimate

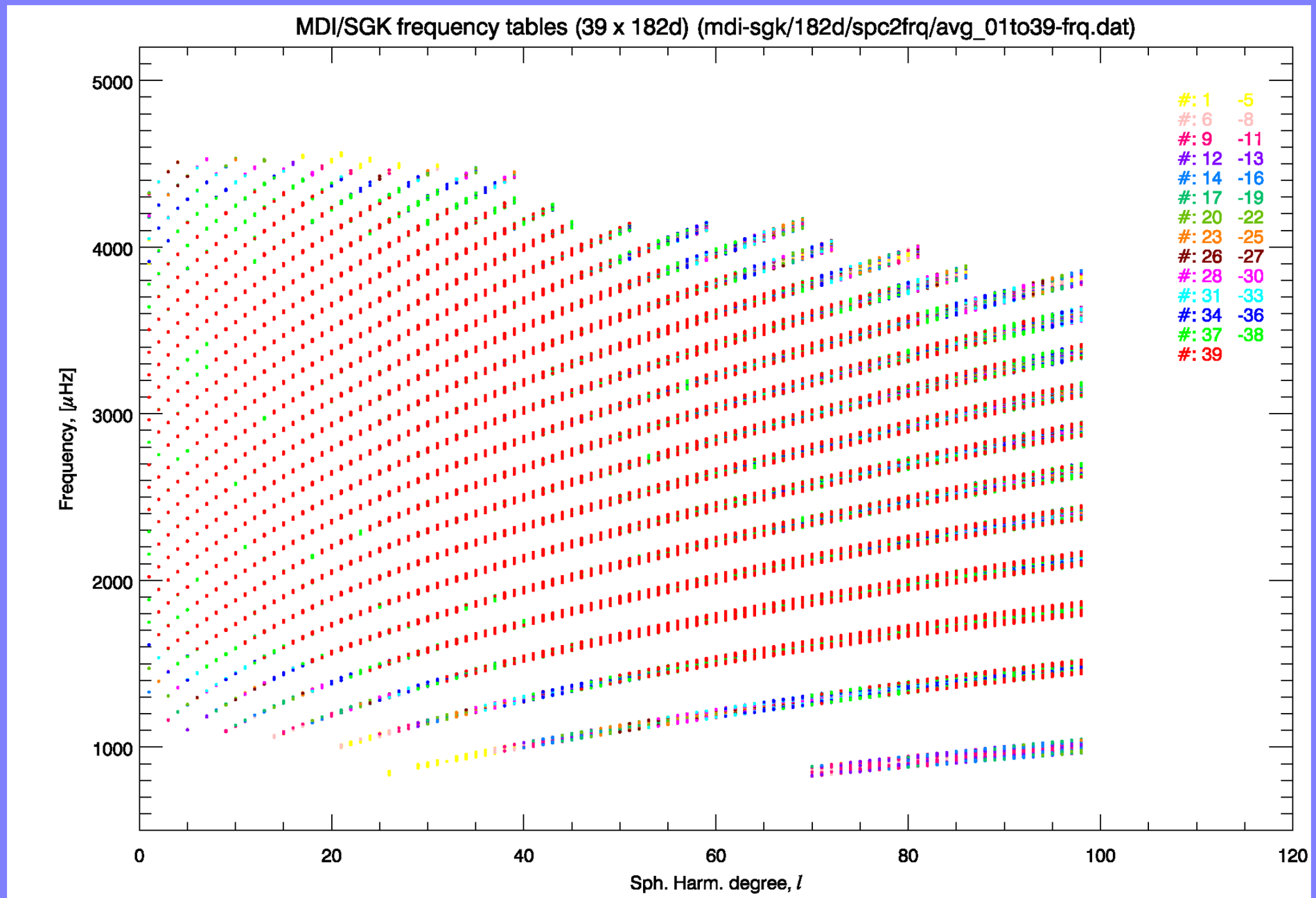
Attrition – GONG Tables



Attrition – MDI Tables



SGK Fitting ($YAOPBM$/MDI) – Attrition



More Problems

- Leakage matrix
  - ⋆ closest leaks – $\Delta\nu_{\delta m=2,\delta\ell=0}$ – are *rarely* resolved
    - ∗ $\Delta\nu \gg \Gamma$, $\Delta\nu \simeq 2 \times \frac{\Omega}{2\pi} \simeq 0.8\,\mu$Hz
  - ⋆ plate scale, distortions, B_0
    - ∗ new MDI Sph. Harm. Coefs accounts for plate scale and image distortion
    - ∗ distortion by differential rotation (Woodard 1989) 1 – 6% effect
    - ∗ $B_0 = B_0(t)$ 3 – 15% effect
    - ∗ other geometric variations negligible

  $\Rightarrow$ very long time-series indicate remaining mismatch for f-mode

- Independent leakage computation

Leakage Matrix – Refinements I

Leakage Matrix – Distortion by Differential Rotation

Leakage Matrix – Refinements II

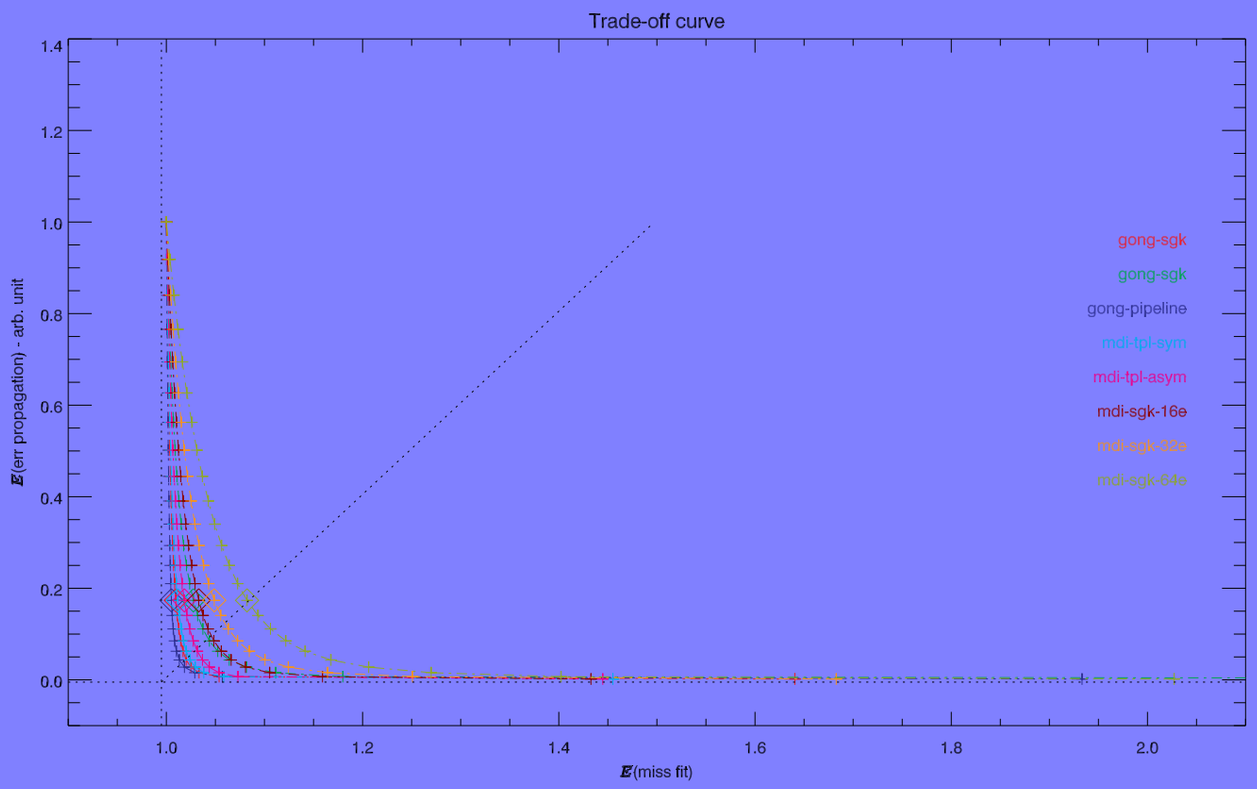
Leakage Matrix – Bo effect

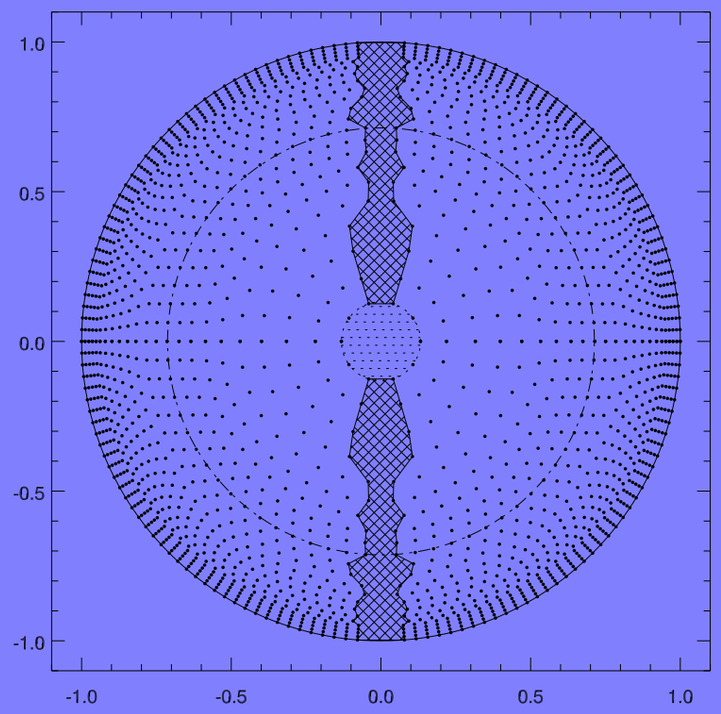
Leakage Matrix – f & p-modes

f, p_1, p_2, & p_3 modes, $\ell = 20, (5), 200$, 64x72d

The Inversion Methodology

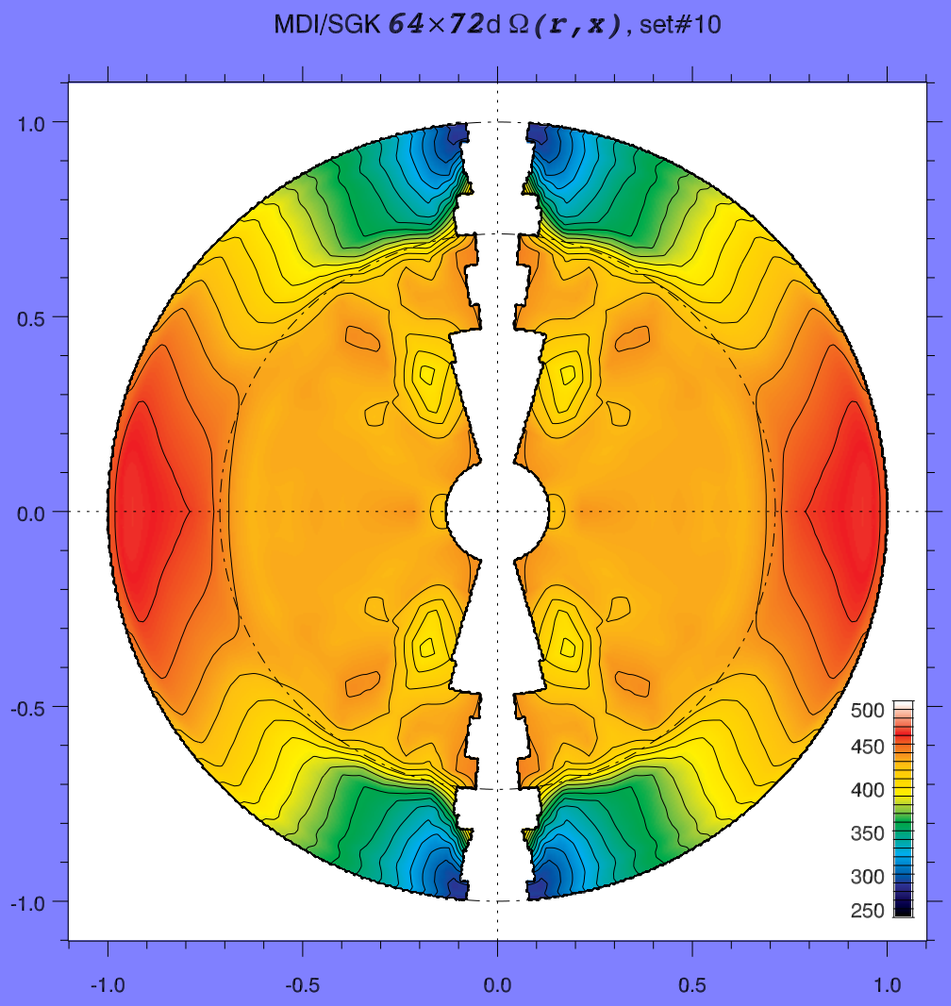
- Modified RLS (Eff-Darwich & Korzennik, 2007)
  - ⋆ Iterative approach
  - ⋆ *optimal* model grid, based on input set
  - ⋆ *non-uniform* model grid

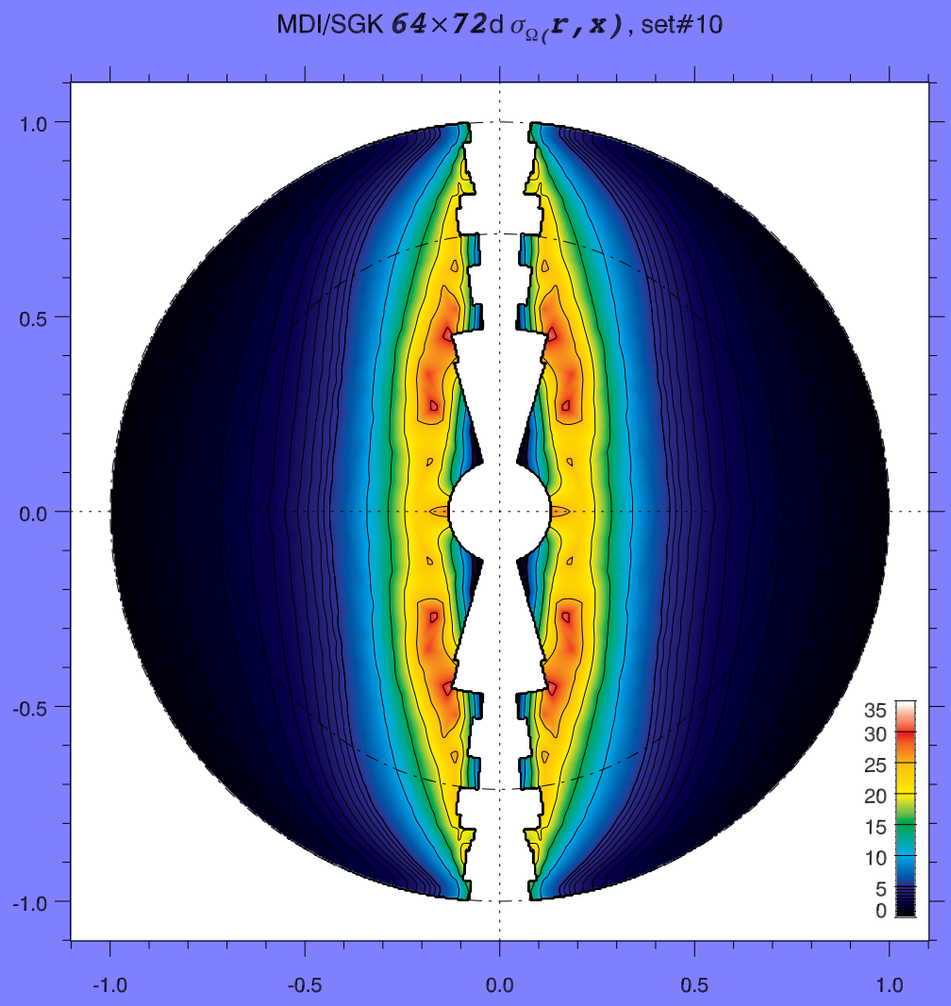




- $\Omega(r, \theta)$, 64×72d, change with trade-off

Mean Rotation Rate & Precision – MDI 64×72 days (12.6 yr)



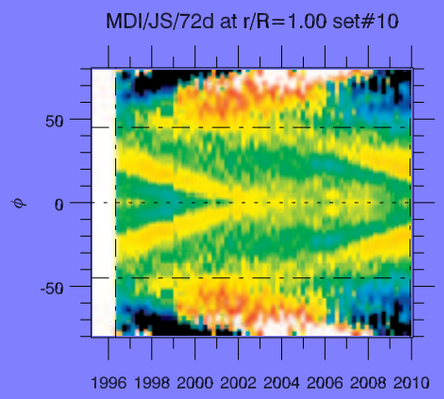


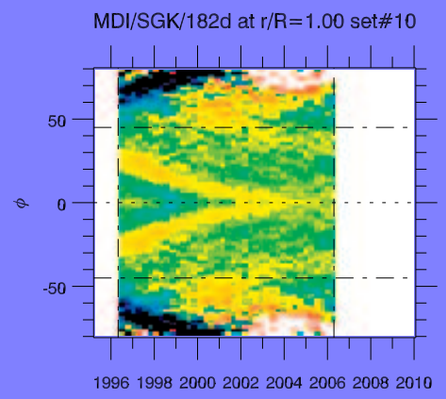
Rotation Rate – Changes with time, $6 \times 16 \times 72$d

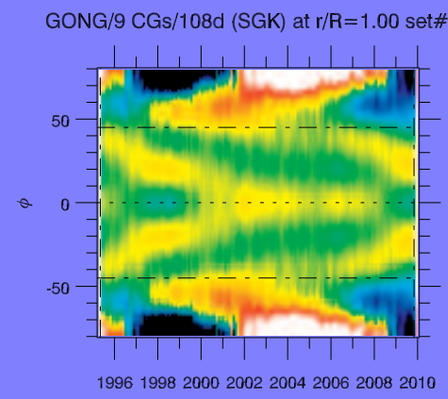
$\Omega(r, \theta)$, 6×16×72d, change with time

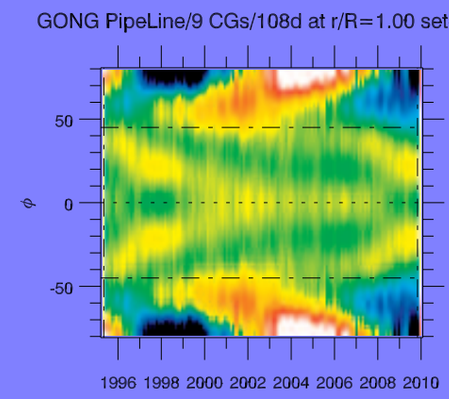
- $\Omega(r, \theta)$, $6 \times 16 \times 72$d, change with time

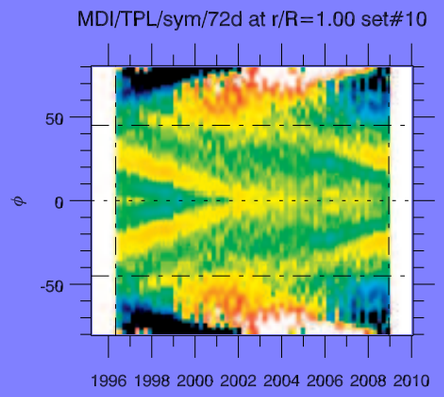
Rotation Rate Changes – $r/R = 1.00$

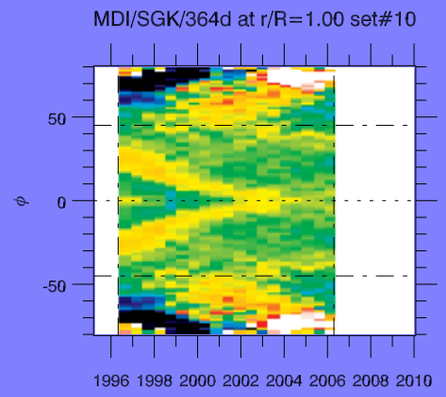


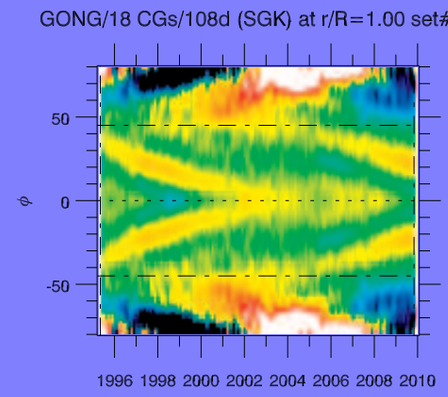


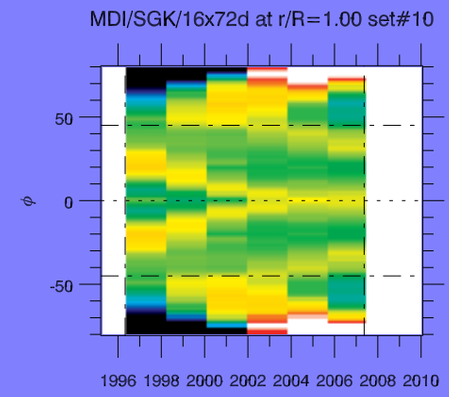


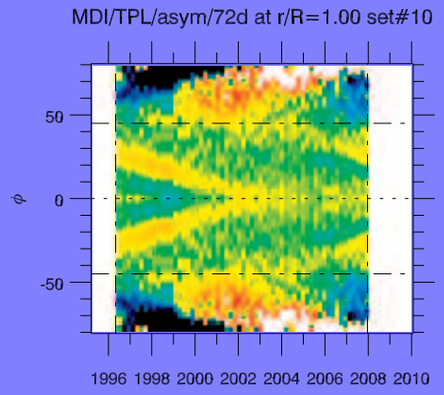


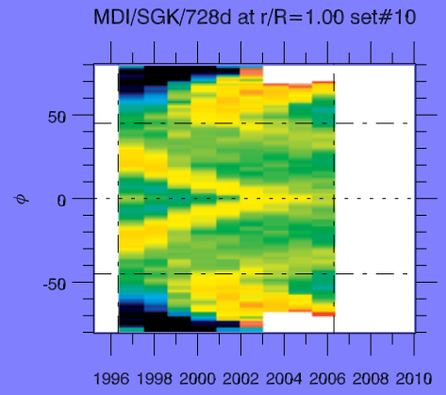


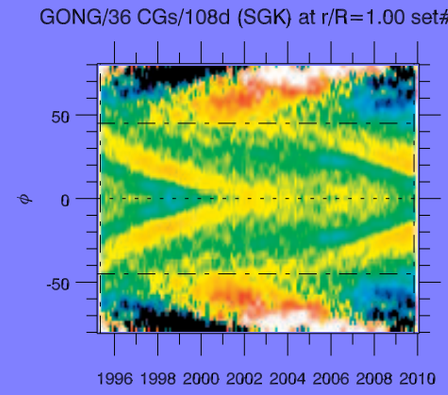












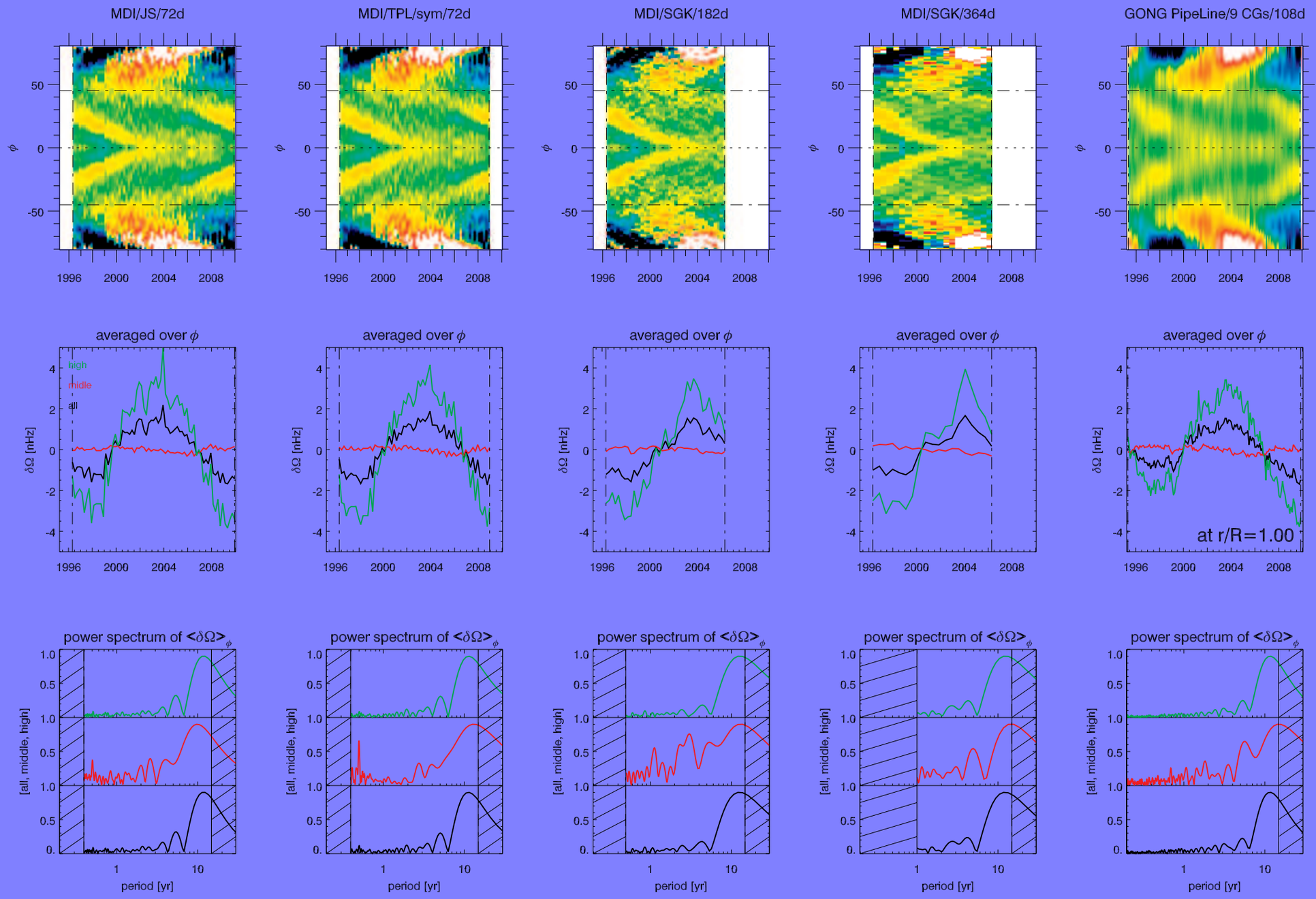
Rotation Rate Changes – GONG $r/R = 1.00 - 0.47$

$\Omega(r, \theta)$, GONG – change with time at various depths

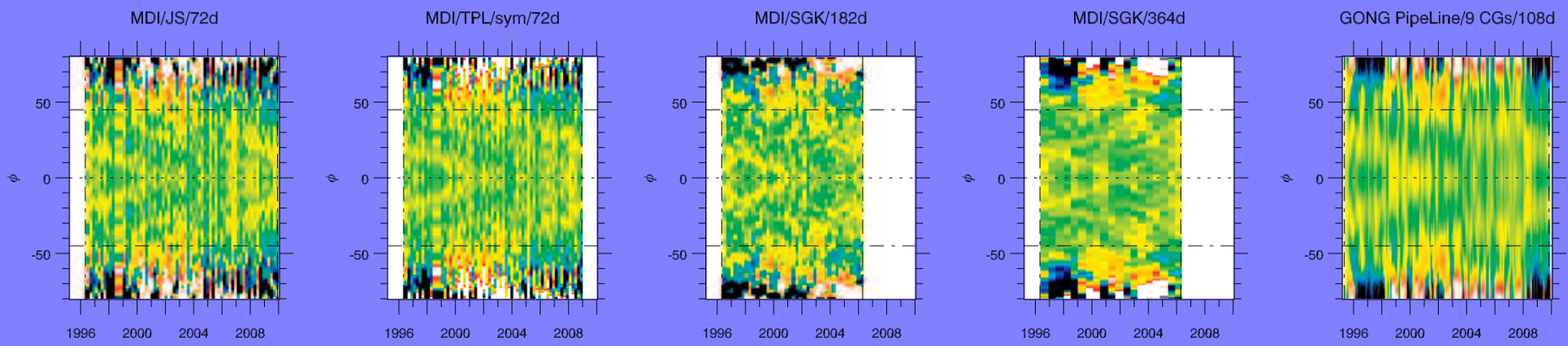
Rotation Rate Changes – MDI $r/R = 1.00 - 0.47$

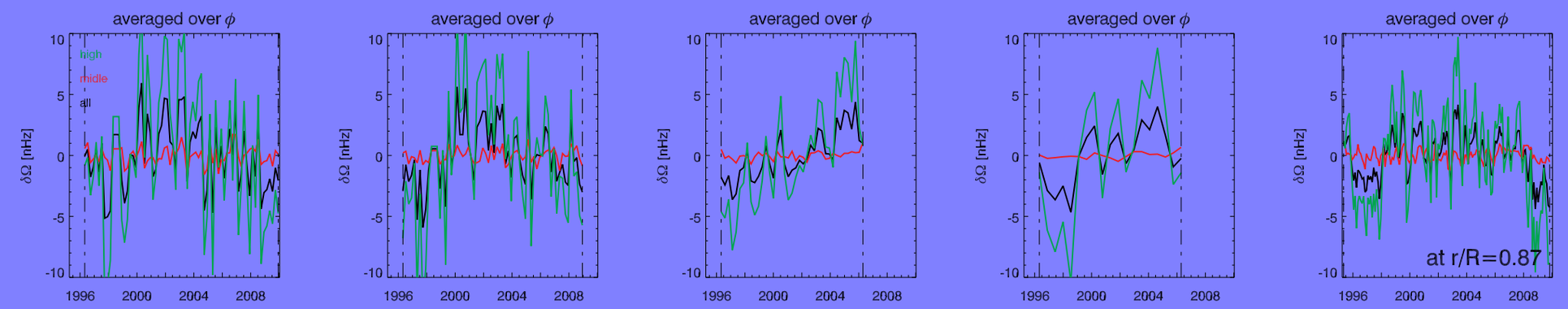
$\Omega(r, \theta)$, MDI – change with time at various depths

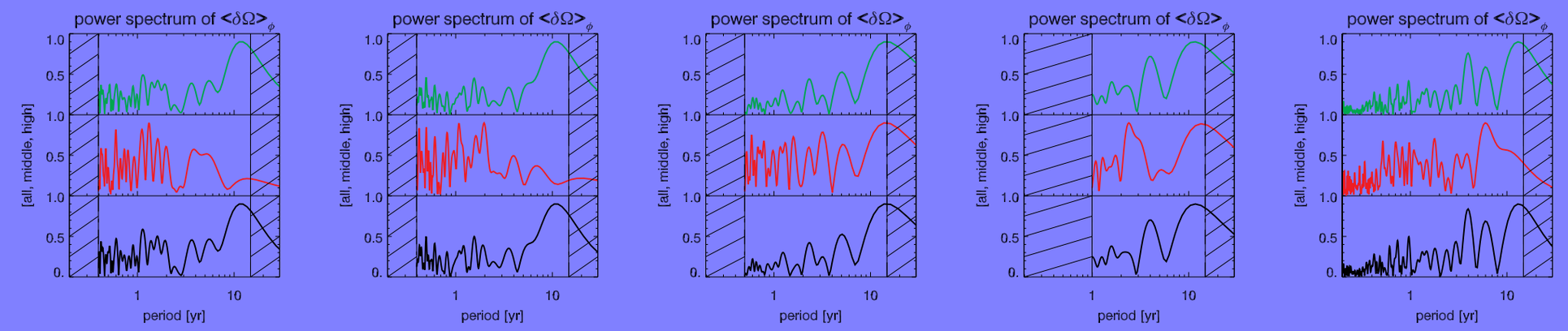
Rotation Rate Changes – $r/R = 1.00$ (selection)



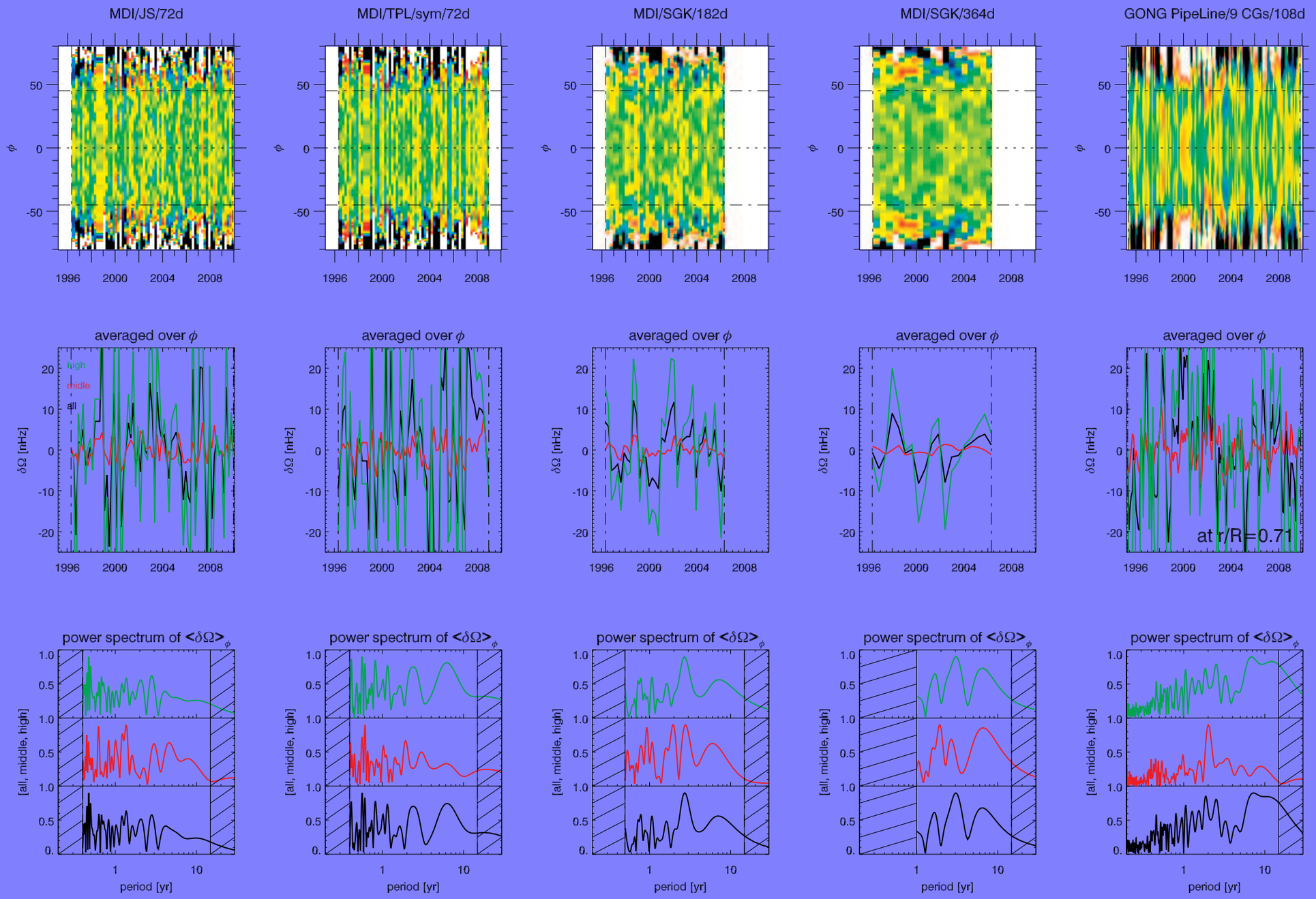
Rotation Rate Changes – $r/R = 0.87$ (selection)







Rotation Rate Changes – $r/R = 0.71$ (selection)



Conclusions

- Fitting remains an *issue*
  - ⋆ attrition
  - ⋆ f-mode leakage mismatch:
    - ∗ high ℓ (MTF) or horizontal component ($\beta = 1$)
  - ⋆ plan to complete MDI analysis on shorter epochs
  - ⋆ expect to apply it on GONG and HMI

- Mean rotation
  - ⋆ long time-series
  - ⋆ dip at $(0.4, 63^\circ)$ – 1σ, rising branch of cycle

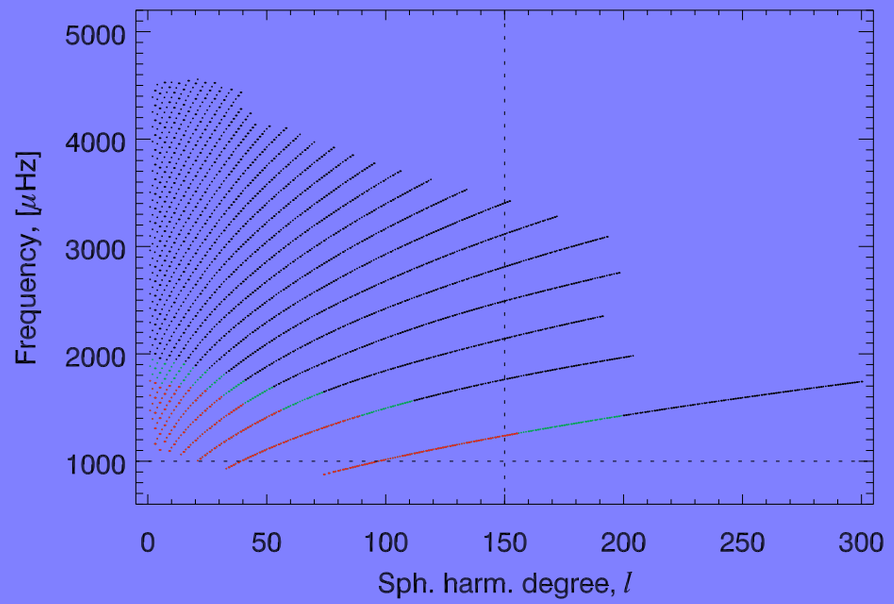
- Evolution
  - ⋆ *easy* at the surface
  - ⋆ remains challenging down to base of CZ
  - ⋆ difficult below CZ

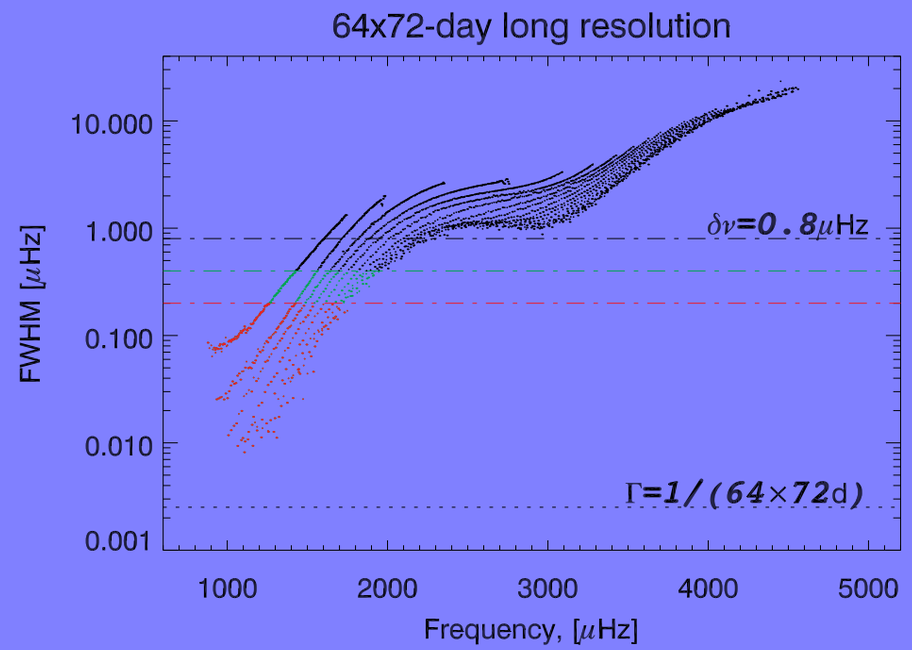
That's all folks!

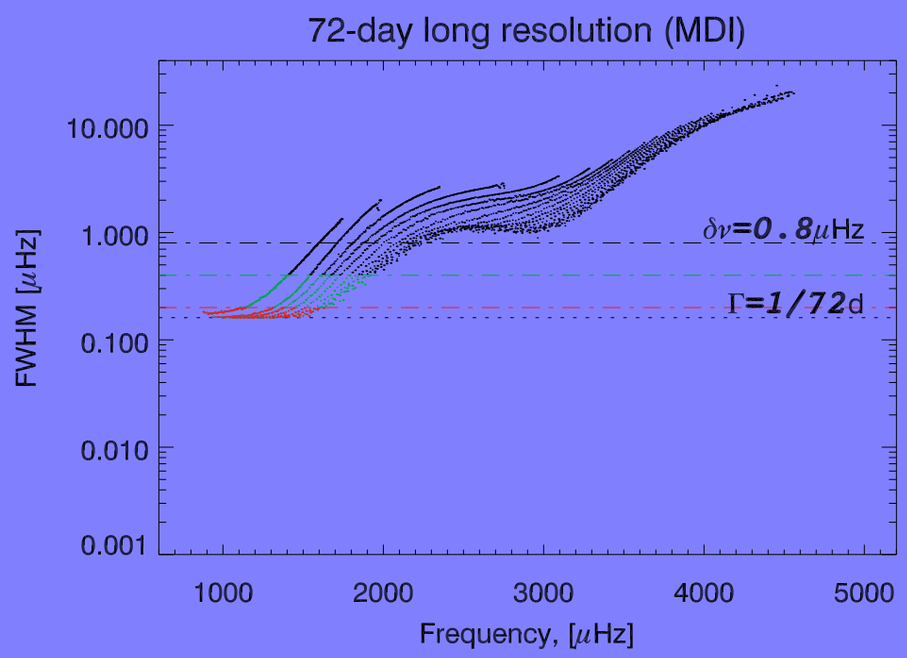
ADV – See Also Posters:

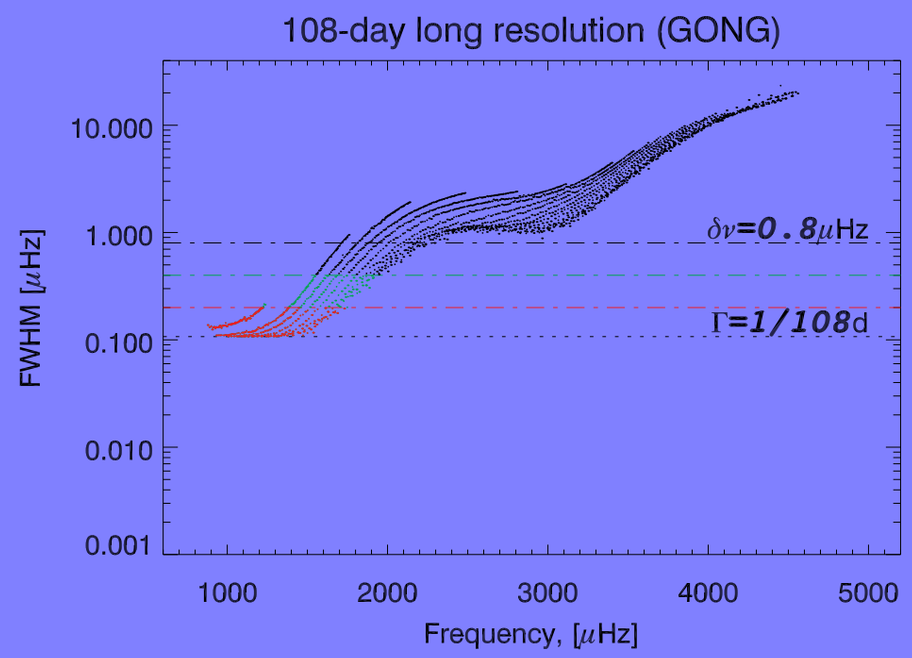
- CDF–4 Antia & Basu
- CDF–6 Howe & *al*
- CDF–7 Howe & *al*
- CDF–9 Komm & *al*
- CDF–10 Eff-Darwich & Korzennik
- M–9 Eff-Darwich & Korzennik

Leakage Matrix – Resolution









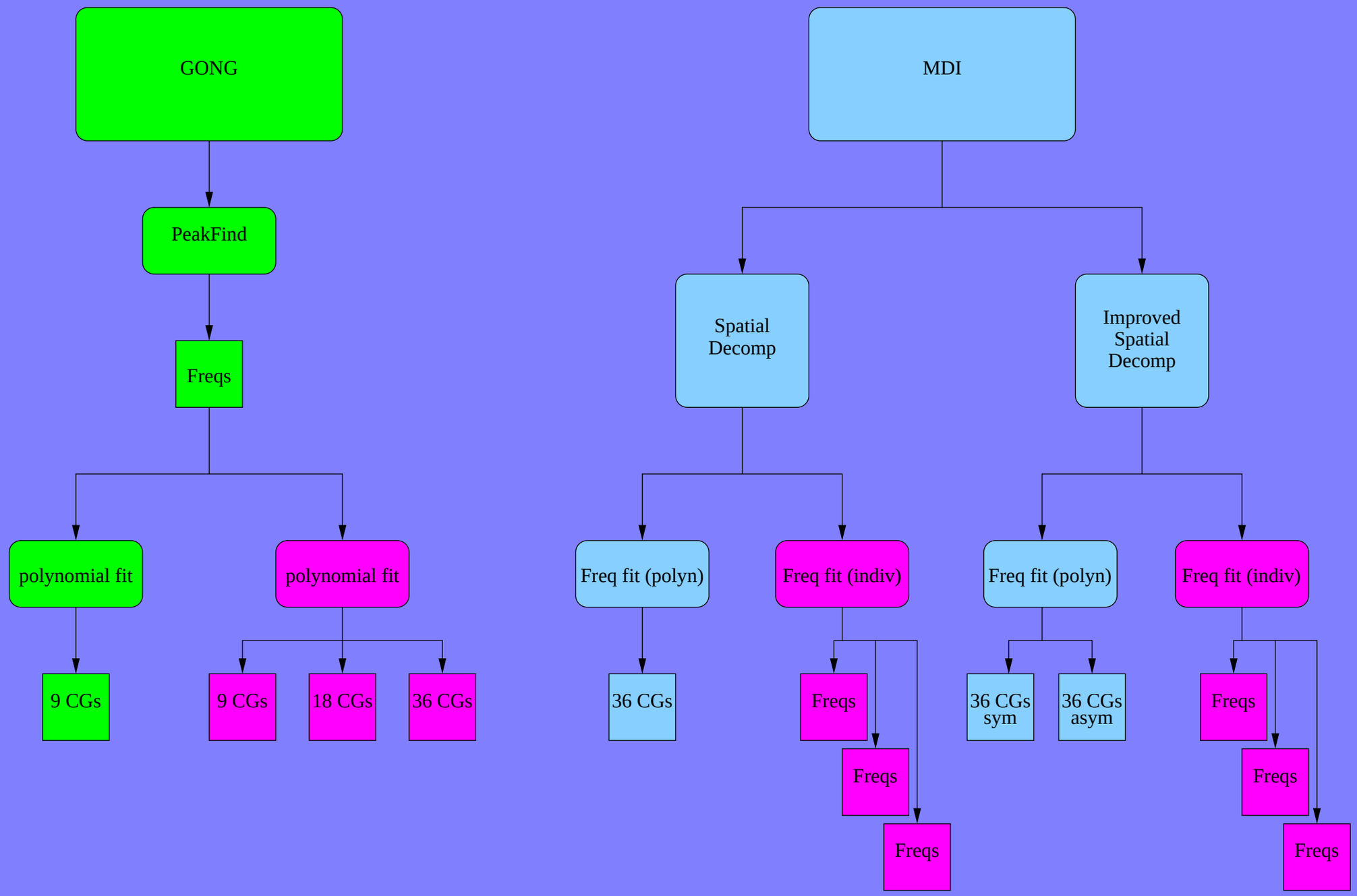
Leakage Matrix – The f-mode

f-mode – 64 $\times$ 72d & 2 $\times$ 72d – $\ell = 120, (2), 300$

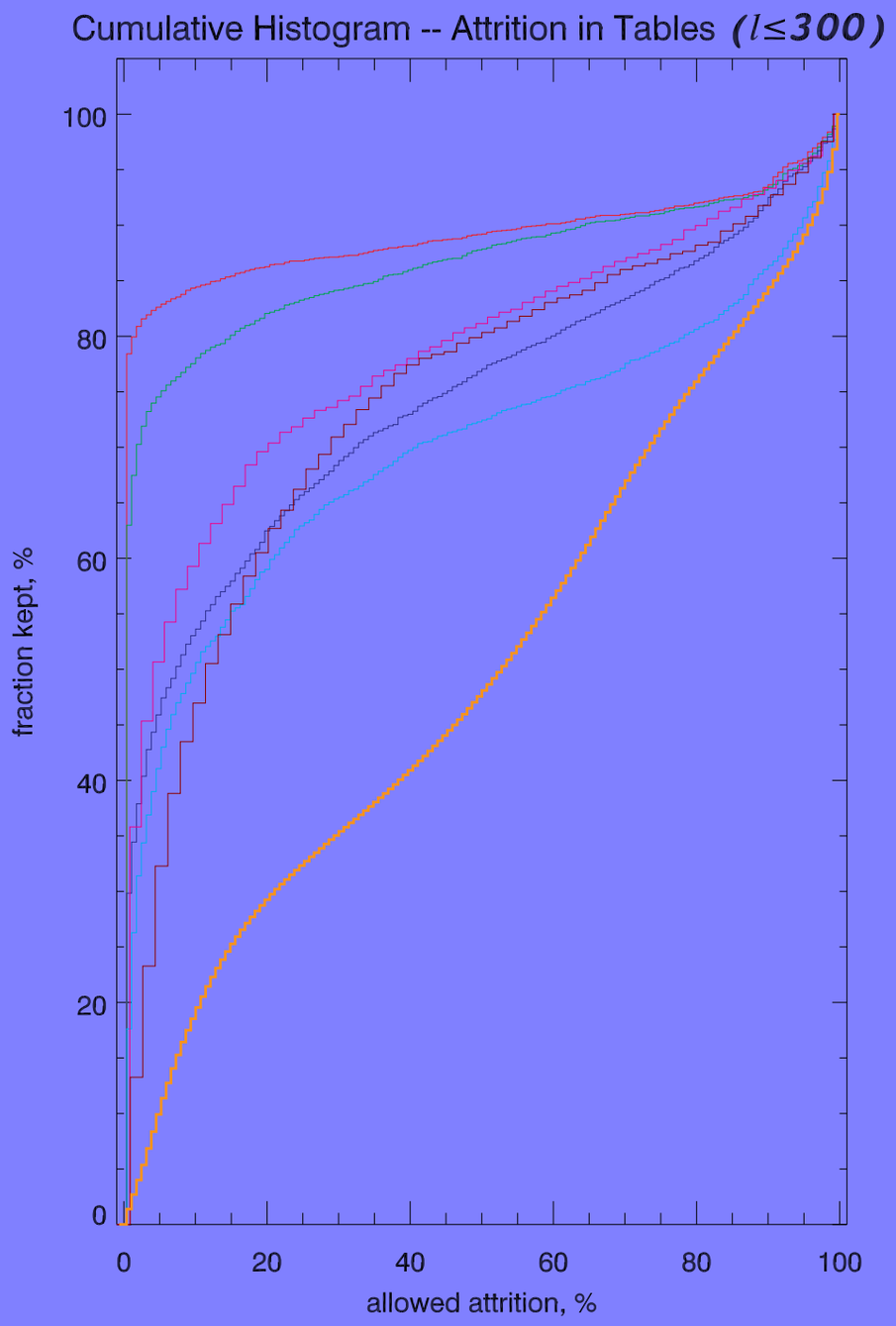
Leakage Matrix – f-mode Mismatch

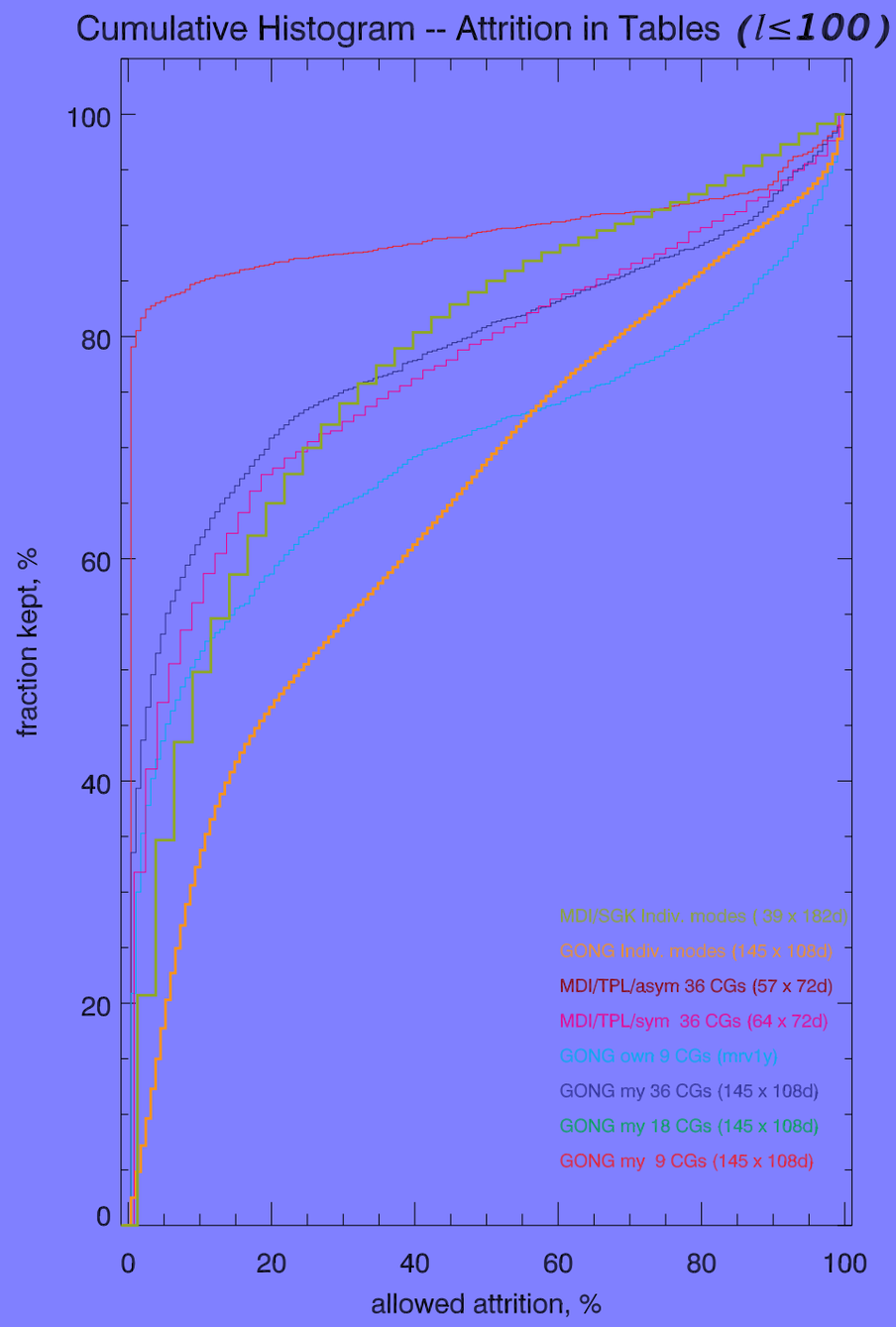
f-mode – 64×72d – $\ell = 120, (2), 300$

The Data

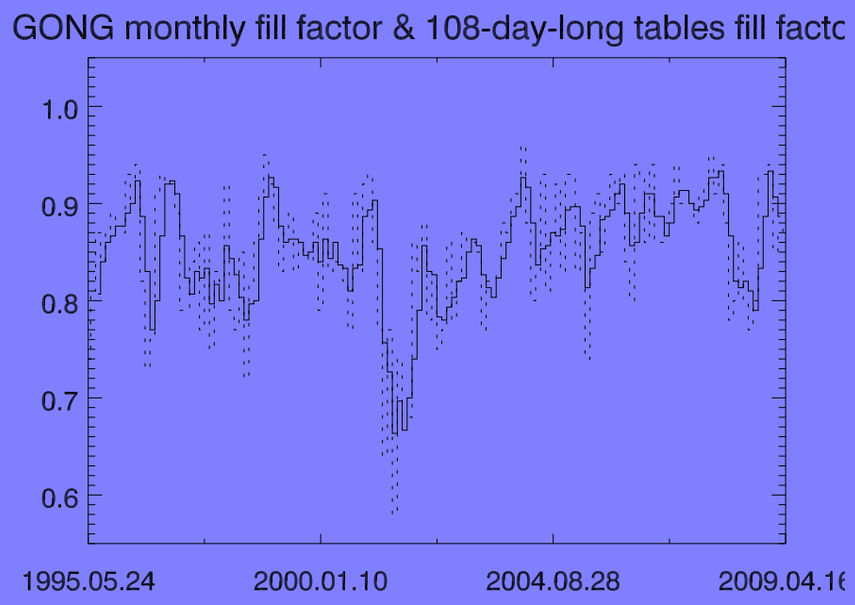

GONG
PeakFind
Freqs
polynomial fit
polynomial fit
9 CGs
9 CGs
18 CGs
36 CGs
MDI
Spatial Decomp
Improved Spatial Decomp
Freq fit (polyn)
Freq fit (indiv)
Freq fit (polyn)
Freq fit (indiv)
36 CGs
Freqs
Freqs
Freqs
36 CGs sym
36 CGs asym
Freqs
Freqs
Freqs

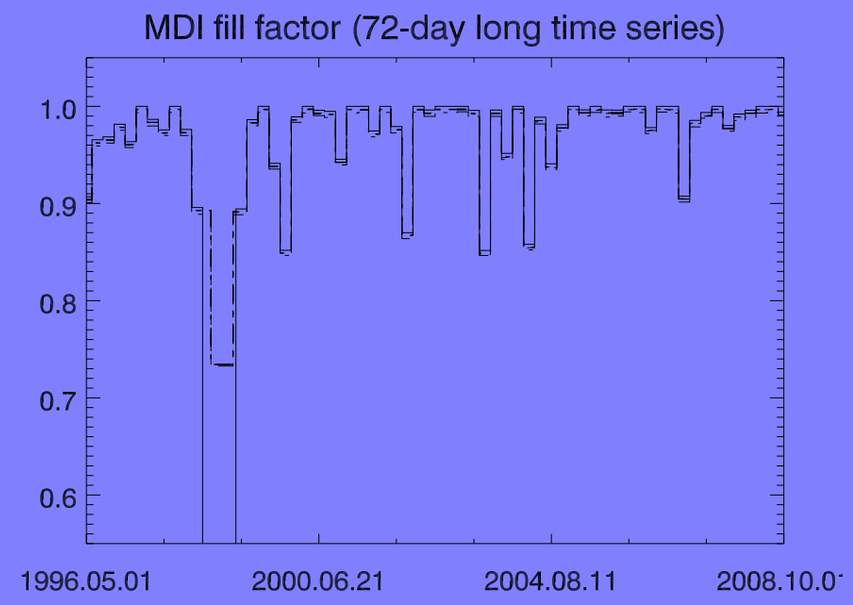
Attrition – Summary

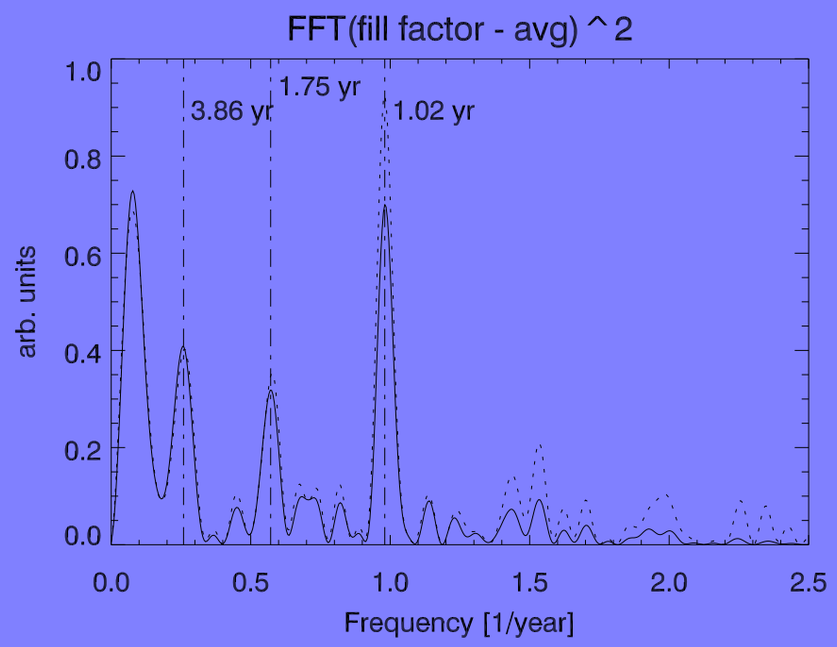


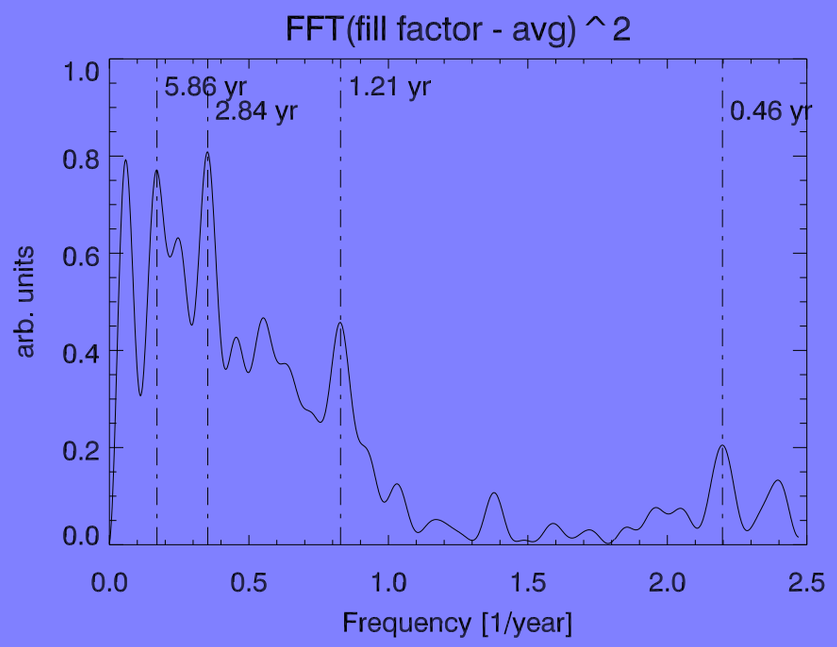


Fill factors, GONG & MDI





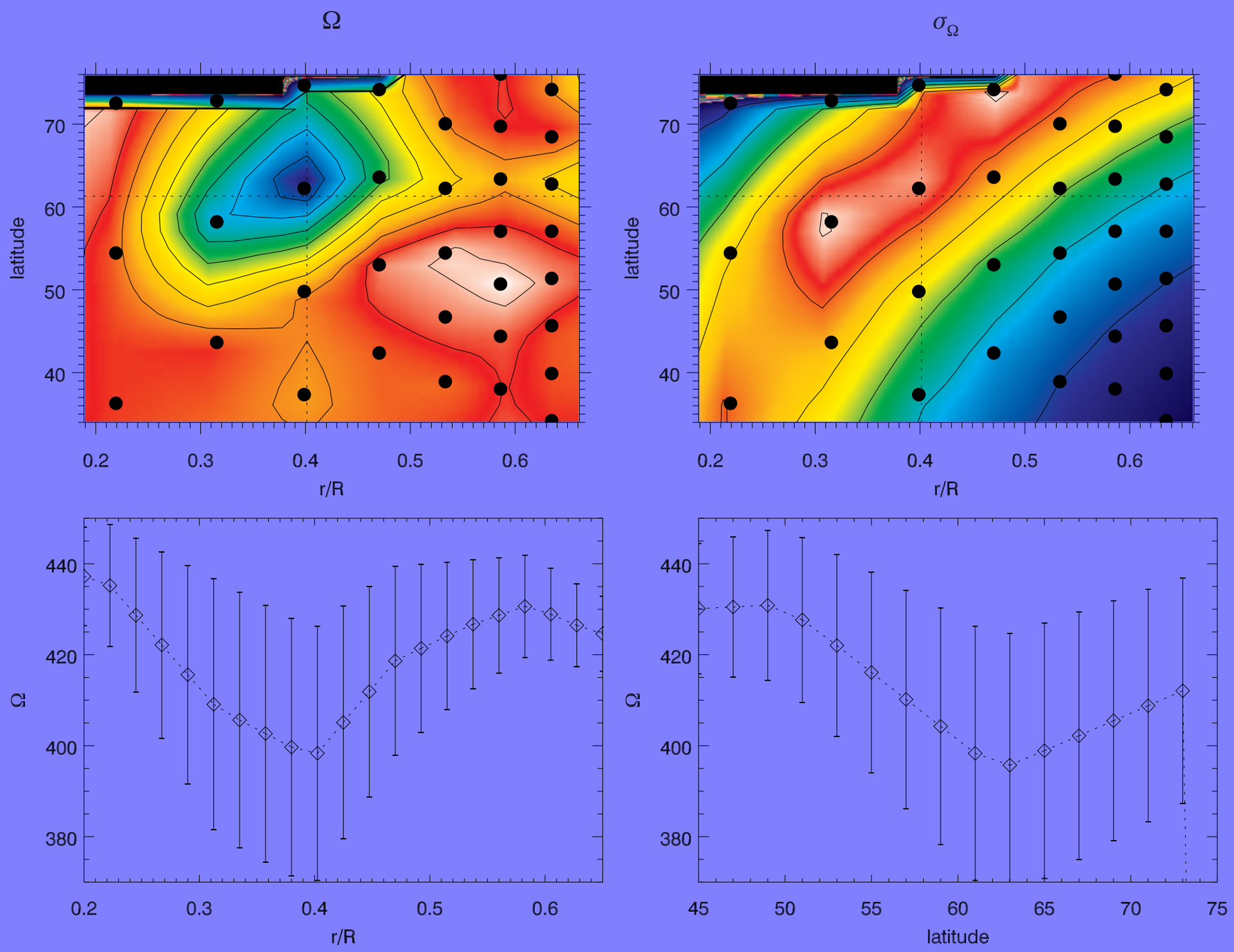




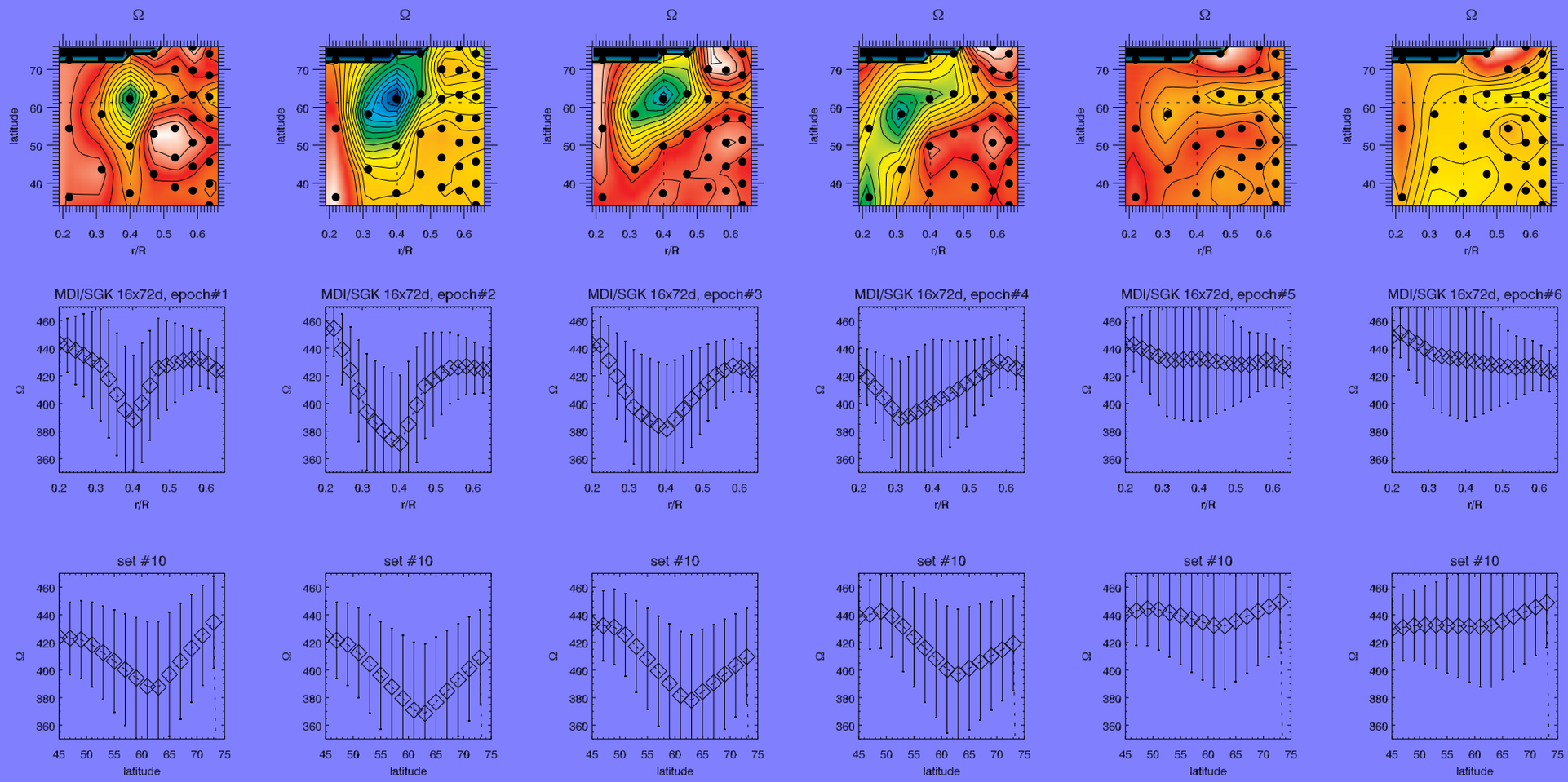
Mean Rotation Rate – 12.6 yr – MDI

$\Omega(r, \theta)$, 64×72d, change with trade-off

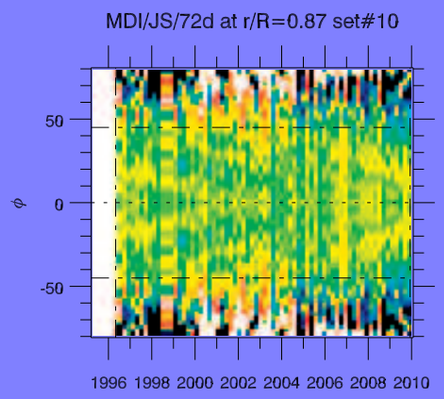
Dip at $r/R = 0.4, \theta = 63^{\circ}$ – MDI 64×72d

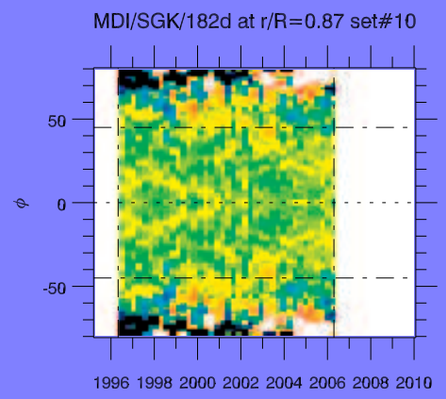


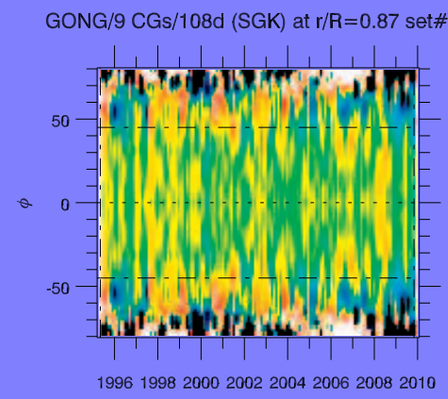
Dip at $r/R = 0.4, \theta = 63^{\circ}$ – MDI 16×72d

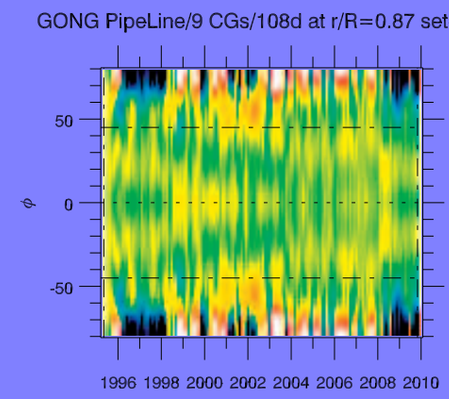


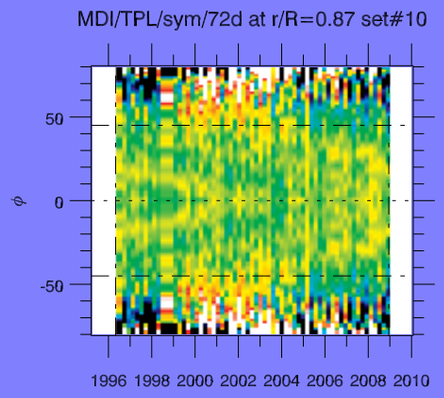
Rotation Rate Changes – $r/R = 0.87$

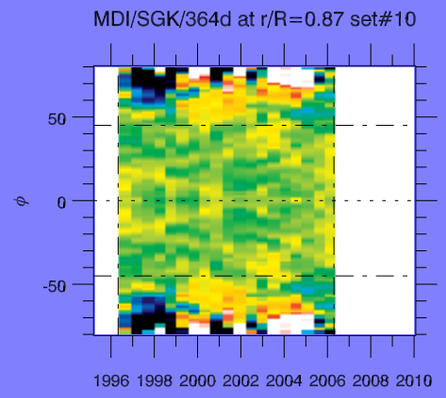


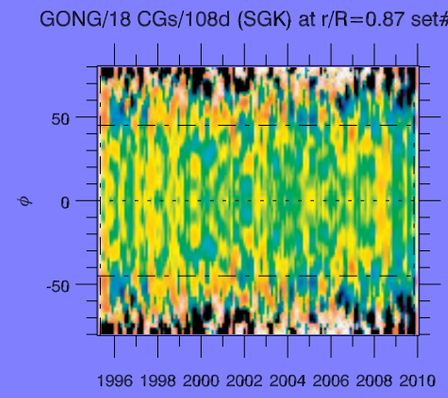


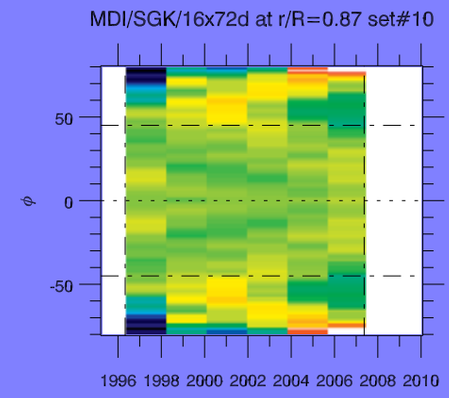


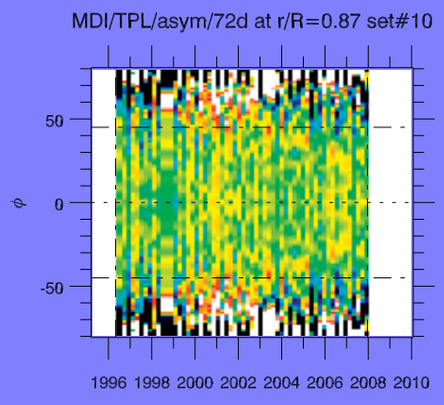


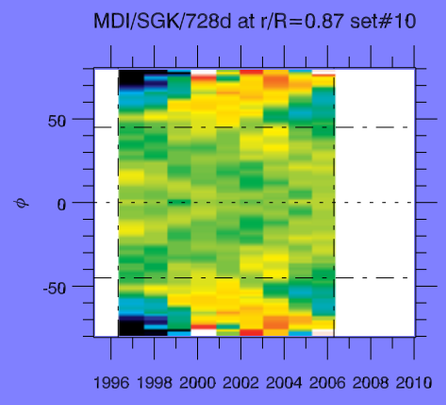


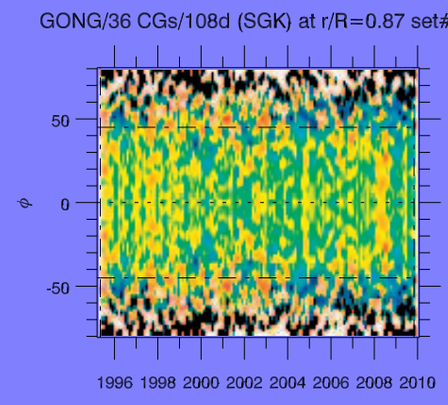




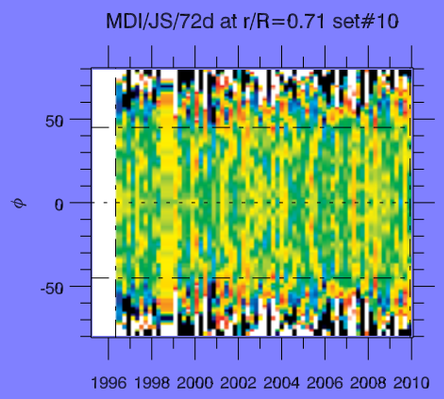


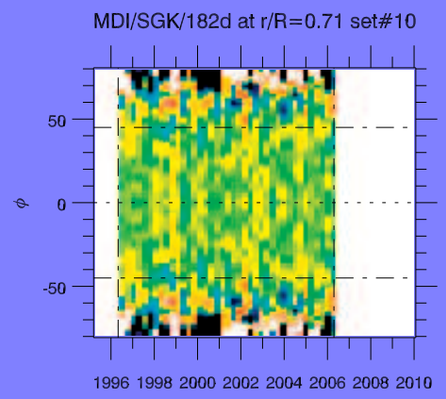


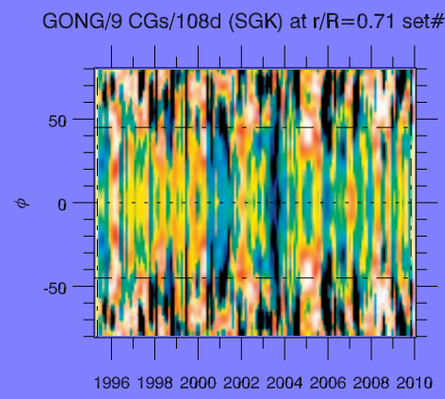


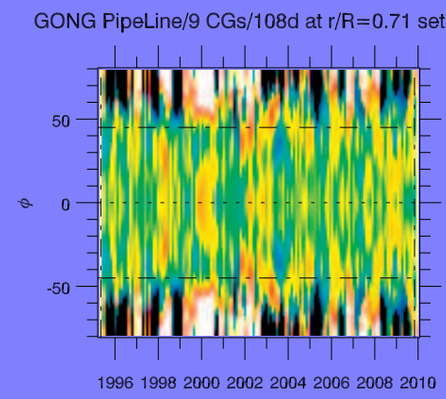


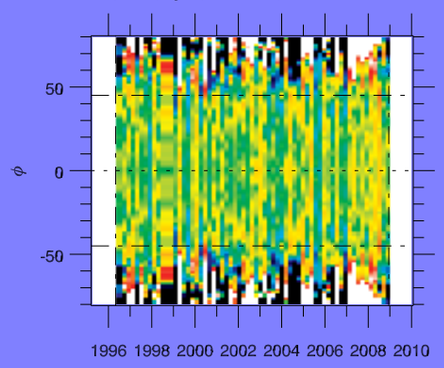
Rotation Rate Changes – $r/R = 0.71$

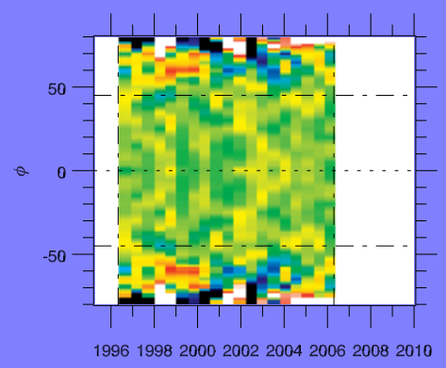


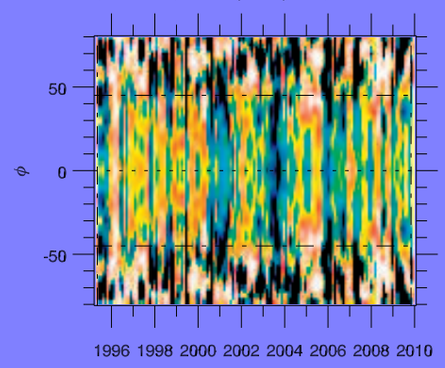


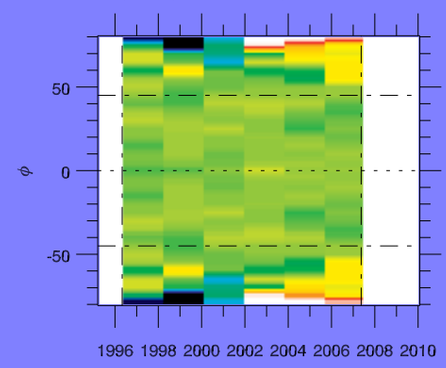


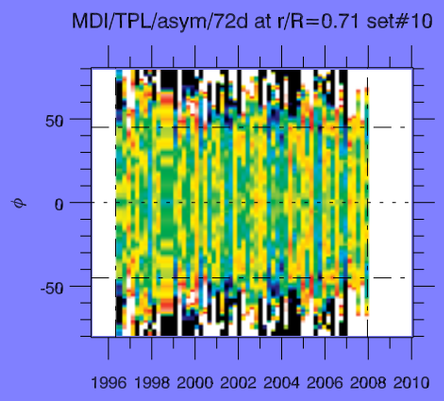


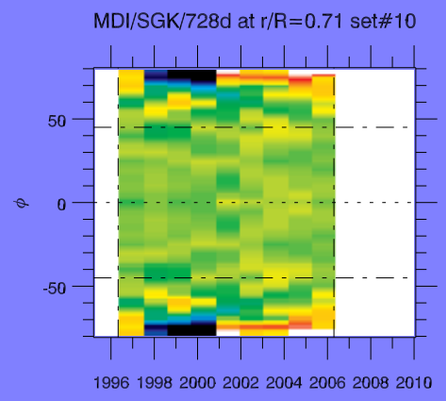


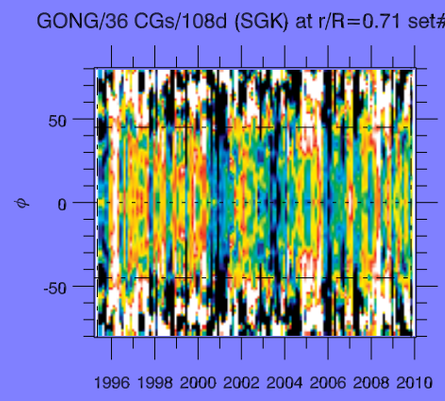












The End

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