PTA Observing Strategies for Gravitational-wave Detection

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What is Strategy?

- A *plan of action* to achieve a *vision*
- What is the vision?
- What actions can you take to realize it?
- Deploy resources to enable actions that achieve your vision

Goals, Actions & Resources

- Goals
  - Greatest expected number of sources?
  - Greatest ability to localize sources detected?
  - Greatest ability to measure wave polarization?
- Actions
  - Timing existing pulsars
  - Searching for new timers
- Resources
  - Pulsars
  - Telescopes
  - Observing time

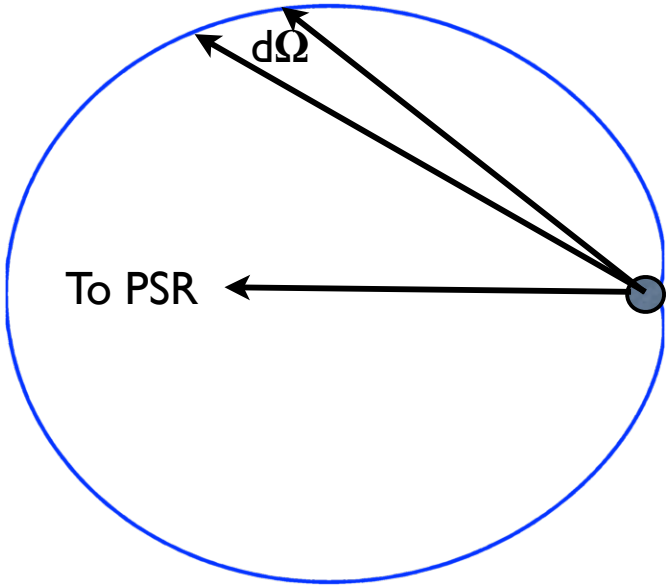
If we're going to prioritize, we're going to need some priorities.

Identify Your Resources

- Pulsars
  - Which should we time?
- Observing time
  - How should we allocate it among pulsars?
- Telescopes
  - Are there advantages to timing particular pulsars with particular telescopes?

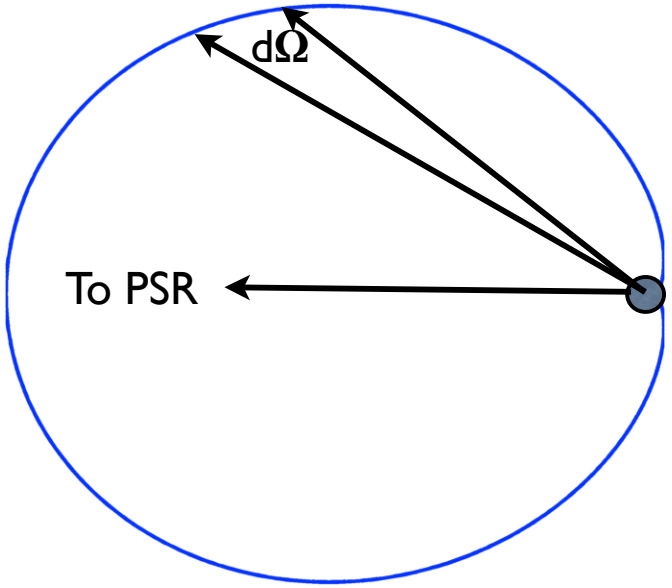
Goal: Greatest expected *number* of sources?

- Antenna patterns add in quadrature
  - If sources are homogeneously and isotropically distributed, greatest number of sources corresponds to greatest volume of space observable
  - Conclusion: want all pulsars are in same direction ...
  - But, what is sources are not isotropically distributed . . .



Goal: Greatest ability to localize *observed* sources?

- Ability to localize associated with change in response when wave propagation direction changes
  - Large change in response: greatest ability to localize
  - Occurs when angle between pulsar line of sight and wave propagation direction is 90 deg.
- Conclusions:
  - pulsar distribution that maximizes number has poor localization capability
  - Want pulsars orthogonal to each other on sky



Goal: Greatest ability to measure observed source polarization

- Polarization tells us about source
  - Axisymmetric or non-axisymmetric; orientation; internal dynamics
- Stokes parameters describe polarization in terms of measured field intensities
  - Why intensities? Intensities explain interference phenomena that fields cannot
- For transverse (traceless) fields, four intensities and four Stokes parameters
  - I: Specific intensity
  - Q, U: linear polarization
  - V: Circular polarization

Analytic signal: strip off negative frequencies

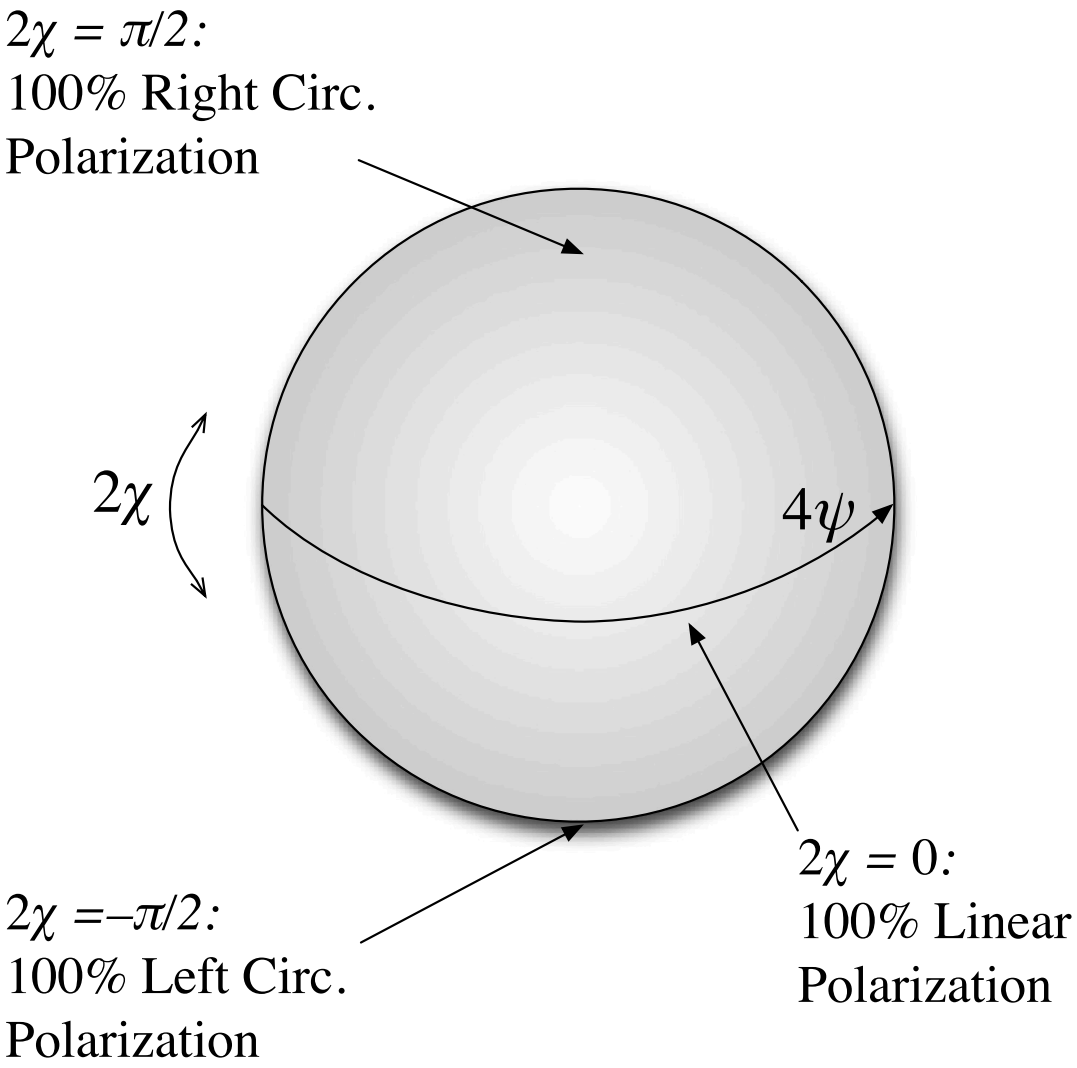
$$\mathcal{E}_{+,\times} = -\frac{1}{2}\ddot{h}_{+,\times}$$

$$\tilde{\mathcal{E}}_T = \int_0^T e^{2\pi i f t}\mathcal{E}\,dt$$

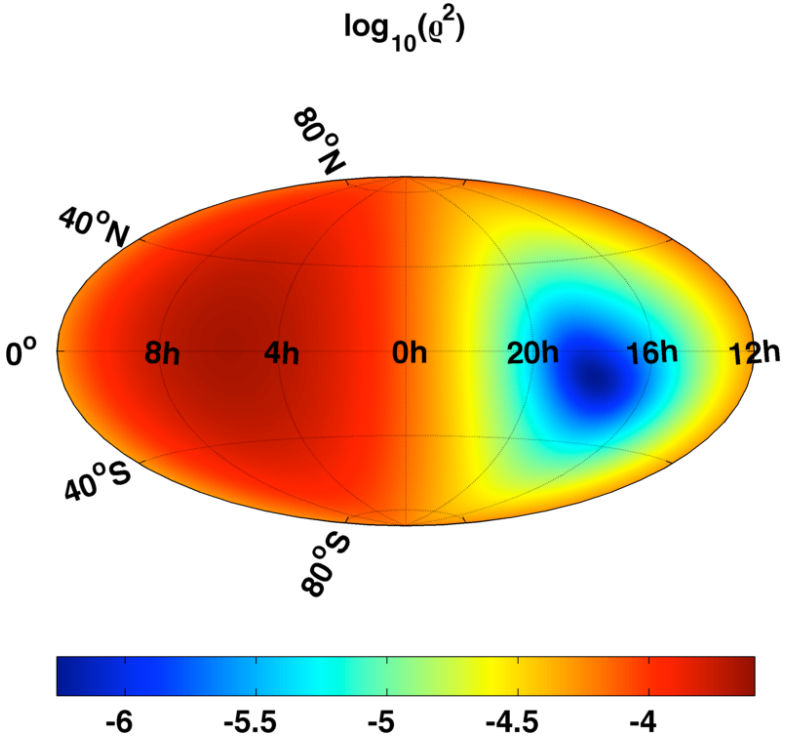
$$\begin{pmatrix} I_f \\ Q_f \\ U_f \\ V_f \end{pmatrix} = \frac{1}{8\pi\left(2\pi f\right)^2 T}\begin{pmatrix} \left|\tilde{\mathcal{E}}_+\right|^2 + \left|\tilde{\mathcal{E}}_\times\right|^2 \\ \left|\tilde{\mathcal{E}}_+\right|^2 - \left|\tilde{\mathcal{E}}_\times\right|^2 \\ 2\Re\left(\tilde{\mathcal{E}}_+\tilde{\mathcal{E}}_\times^\dagger\right) \\ 2\Im\left(\tilde{\mathcal{E}}_+\tilde{\mathcal{E}}_\times^\dagger\right) \end{pmatrix}$$

Polarization and the Poincare Sphere

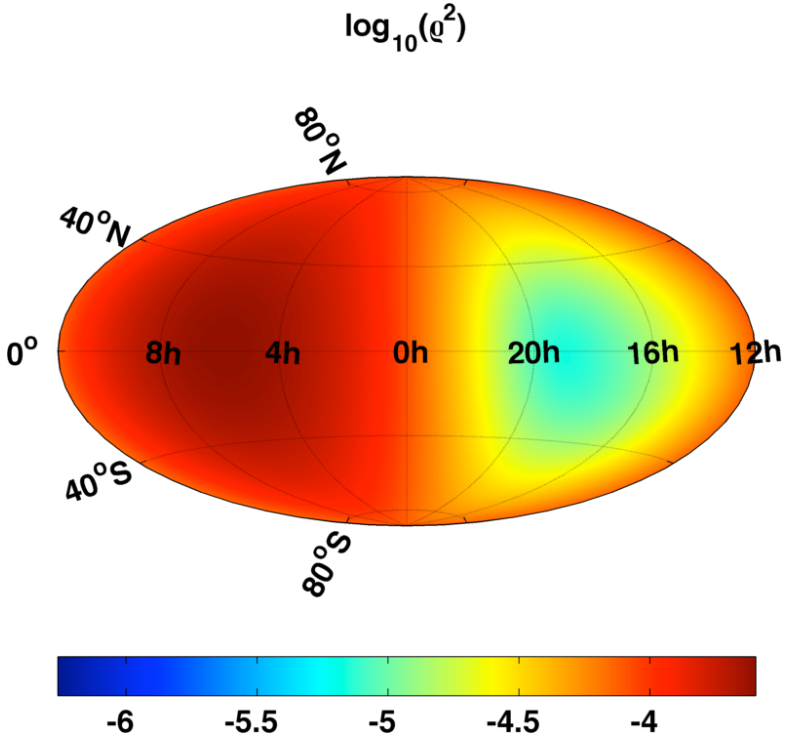
- Fully-polarized radiation: $I^2=Q^2+U^2+V^2$
  - Q, U, V represent points on radius I *Poincare Sphere*
- Polarization described by two angles: χ and ψ
  - χ measures circular polarization
  - ψ measures linear polarization angle



Mean Power SNR as function sky location for fixed Stokes I wave

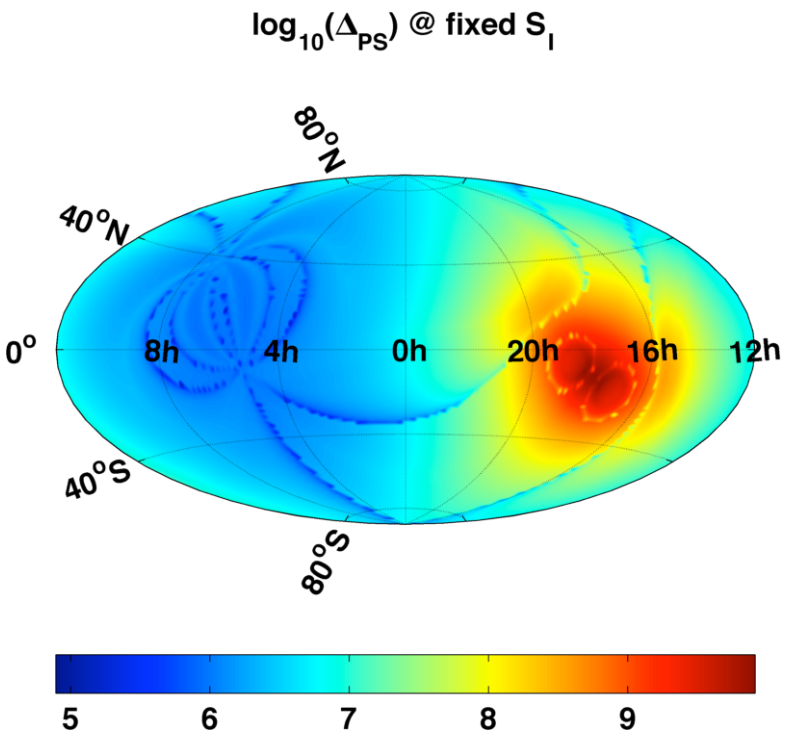


1713 & 1909



All 17 NANOGrav PSRs

Median Poincare sphere error-box volume for fixed S_l wave



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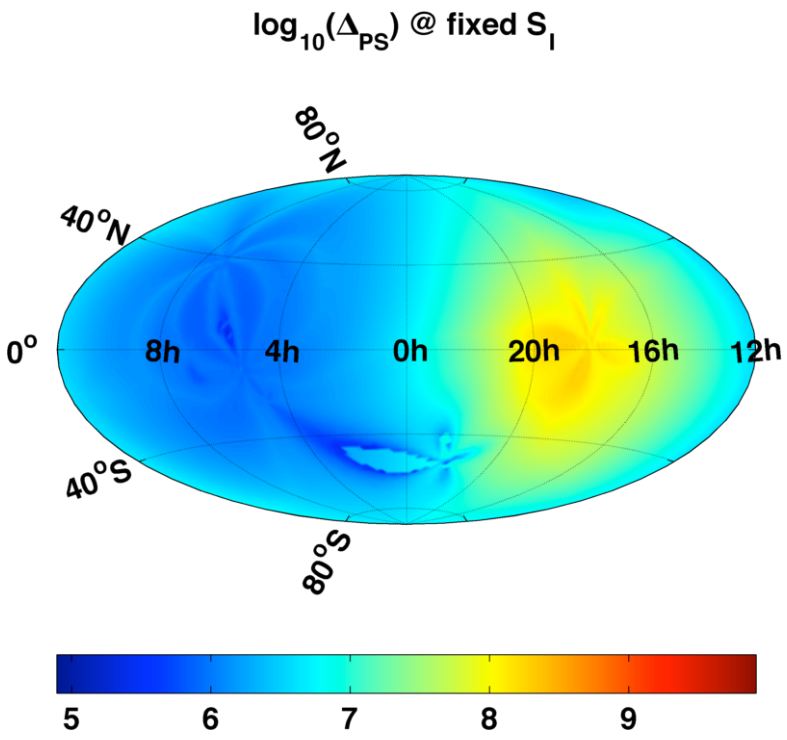

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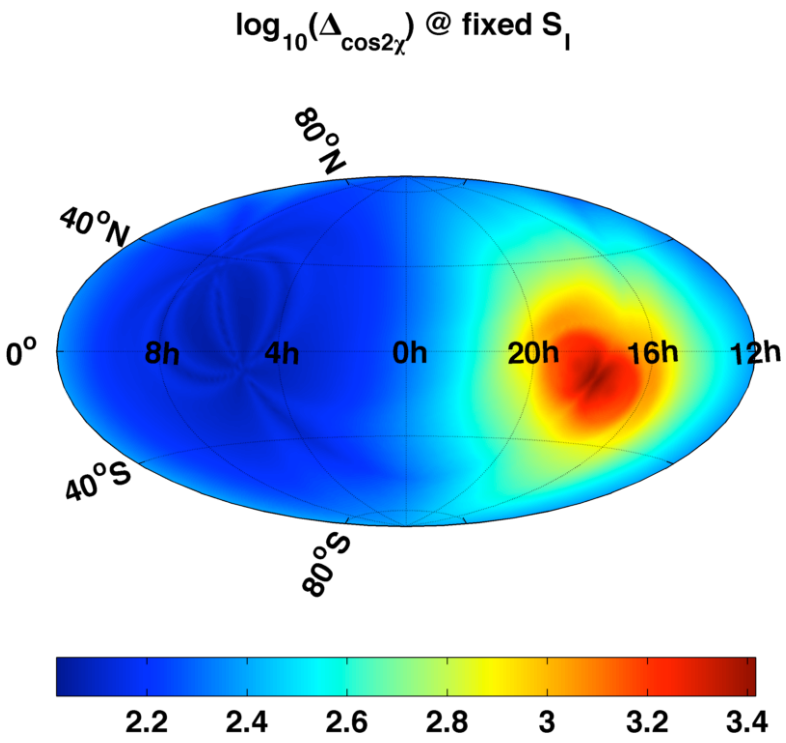
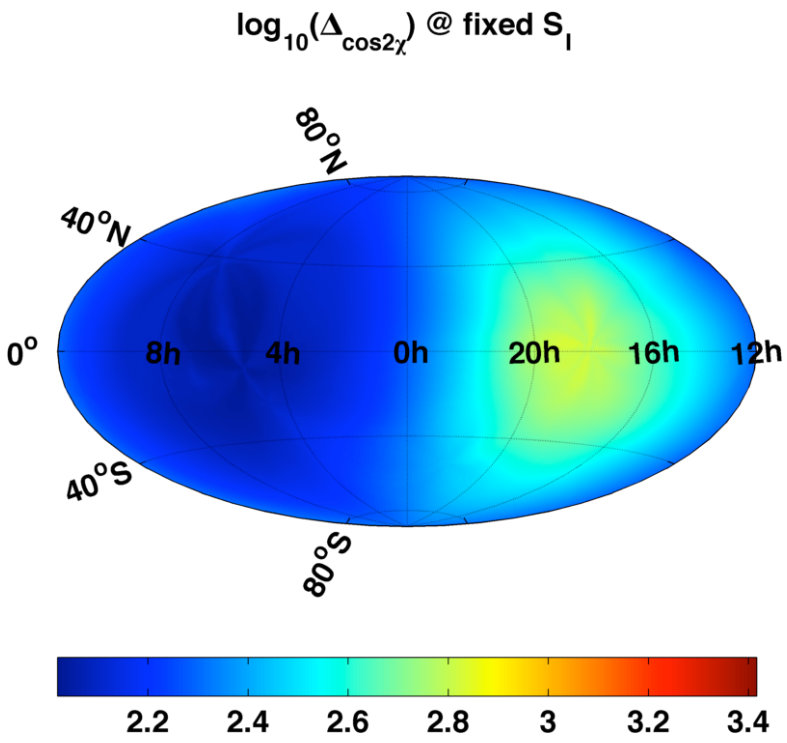
Median error in measured S_V for fixed S_I wave



1713 & 1909



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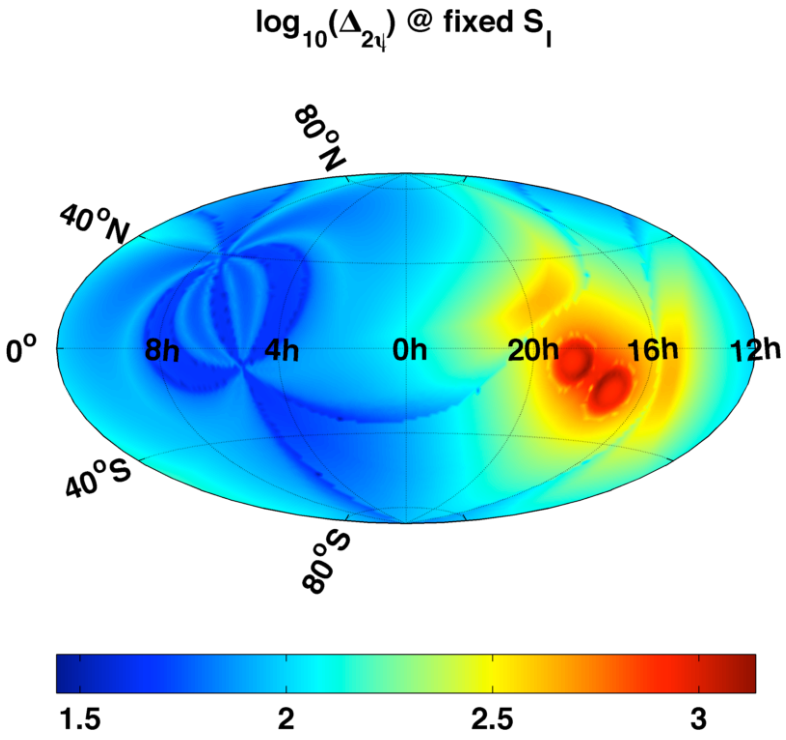
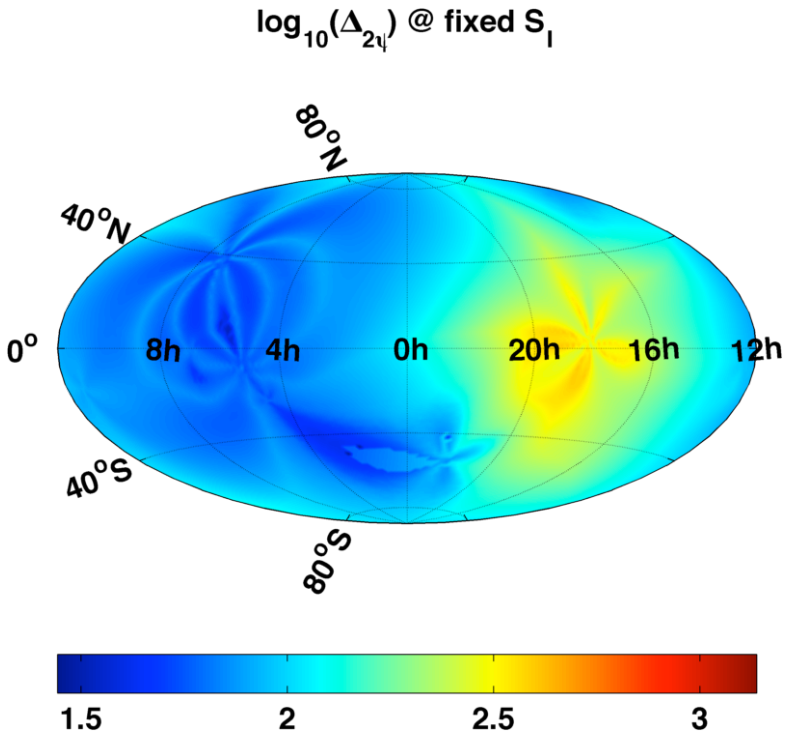
Median error in measured linear polarization angle for fixed S_l wave



1713 & 1909



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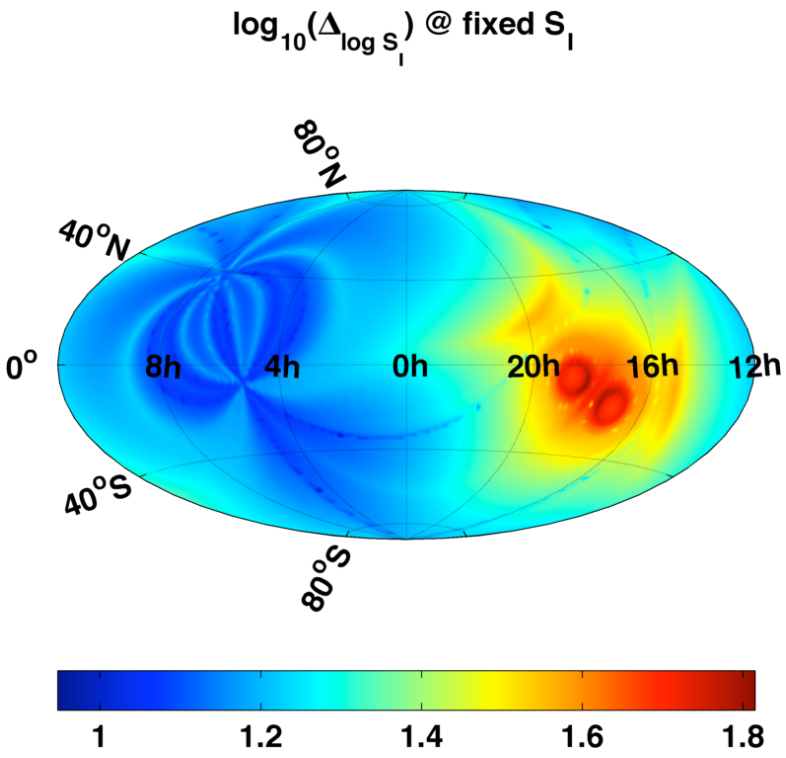
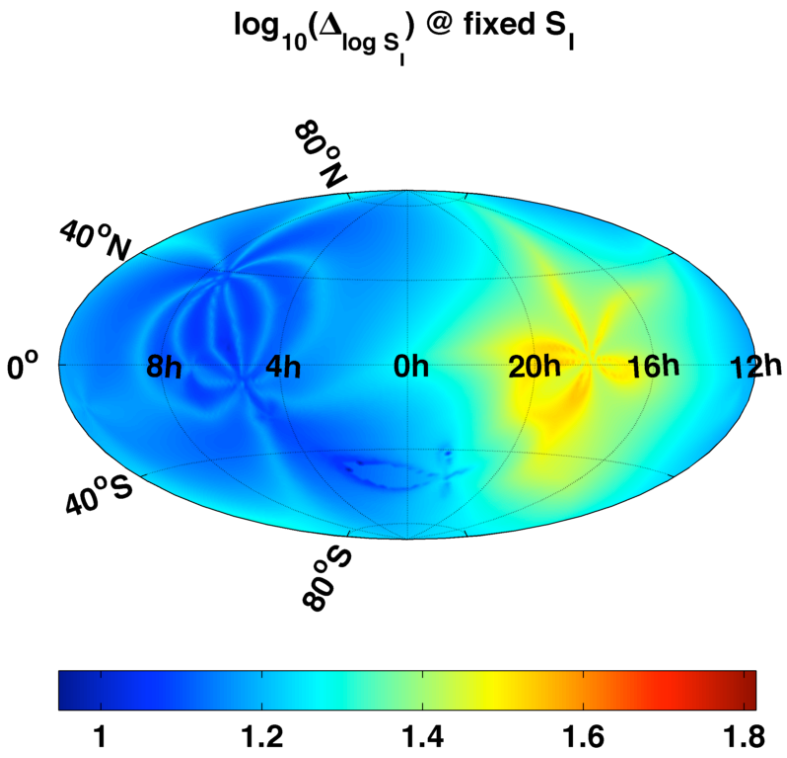
Median error in Stokes S_I for fixed S_I wave



1713 & 1909



All 17 NANOGrav PSRs

Which pulsars should we time?

- Mean contribution of a pulsar to (power) signal-to-noise in a PTA observation is proportional to τ_n^{-2}
  - At present, on average 84% of SNR contributed by 1713 & 1909
  - Add next two most important (1855 & 0030) and you have 90% of SNR!
- Conclusion: need more 1713's, 1909's
  - Improve timing of existing PSRs and/or find new ones

Pulsar	% SNR
J0030+0451	2.14
J0613-0200	1.48
J1012+5307	0.62
J1455-3330	0.08
J1600-3053	1.77
J1640+2224	0.28
J1643–1224	0.02
J1713+0747	52.19
J1744–1134	1.20
J1853+1308	0.72
B1855+09	3.81
J1909–3744	32.53
J1910+1256	0.09
J1918–0642	1.14
B1953+29	0.02
J2145–0750	1.15
J2317+1439	0.75

How should we allocate observing time?

- Timing noise involves a component that can be averaged down and a component that is intrinsic
  - Longer integrations can improve timing noise, up to a point ...
- Allocate observing time to
  - Increase number of pulsars with residuals within factor few of best pulsar
  - Observe only pulsars with residuals with factor few of pulsar

Lessons:

1. It matters what you want

2. It matters where you look (for new pulsars)

3. It matters who you time

4. It matters how you time