Studying the Sun with SNO

Searching for High-Frequency Variations in the Solar Neutrino Flux

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Astrophysics-Cosmology Seminar
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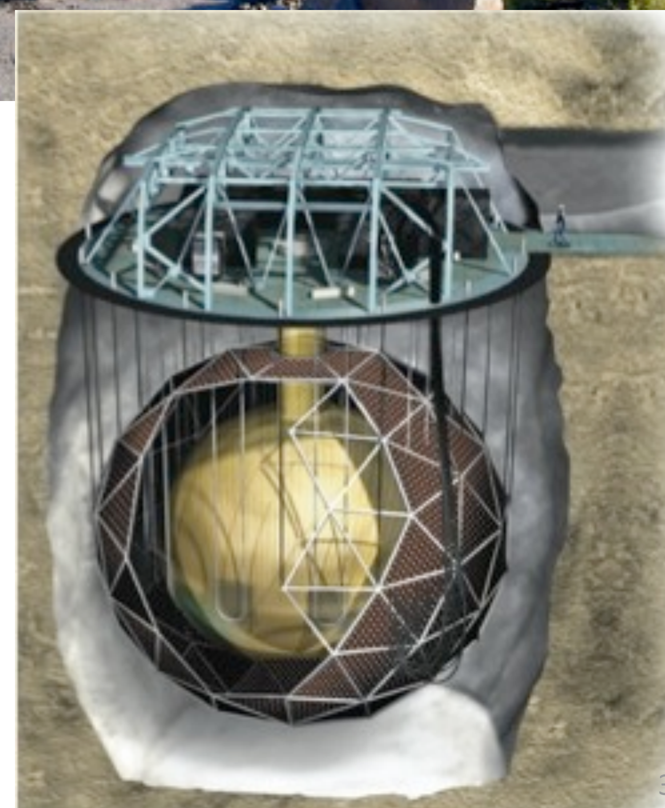
Overview

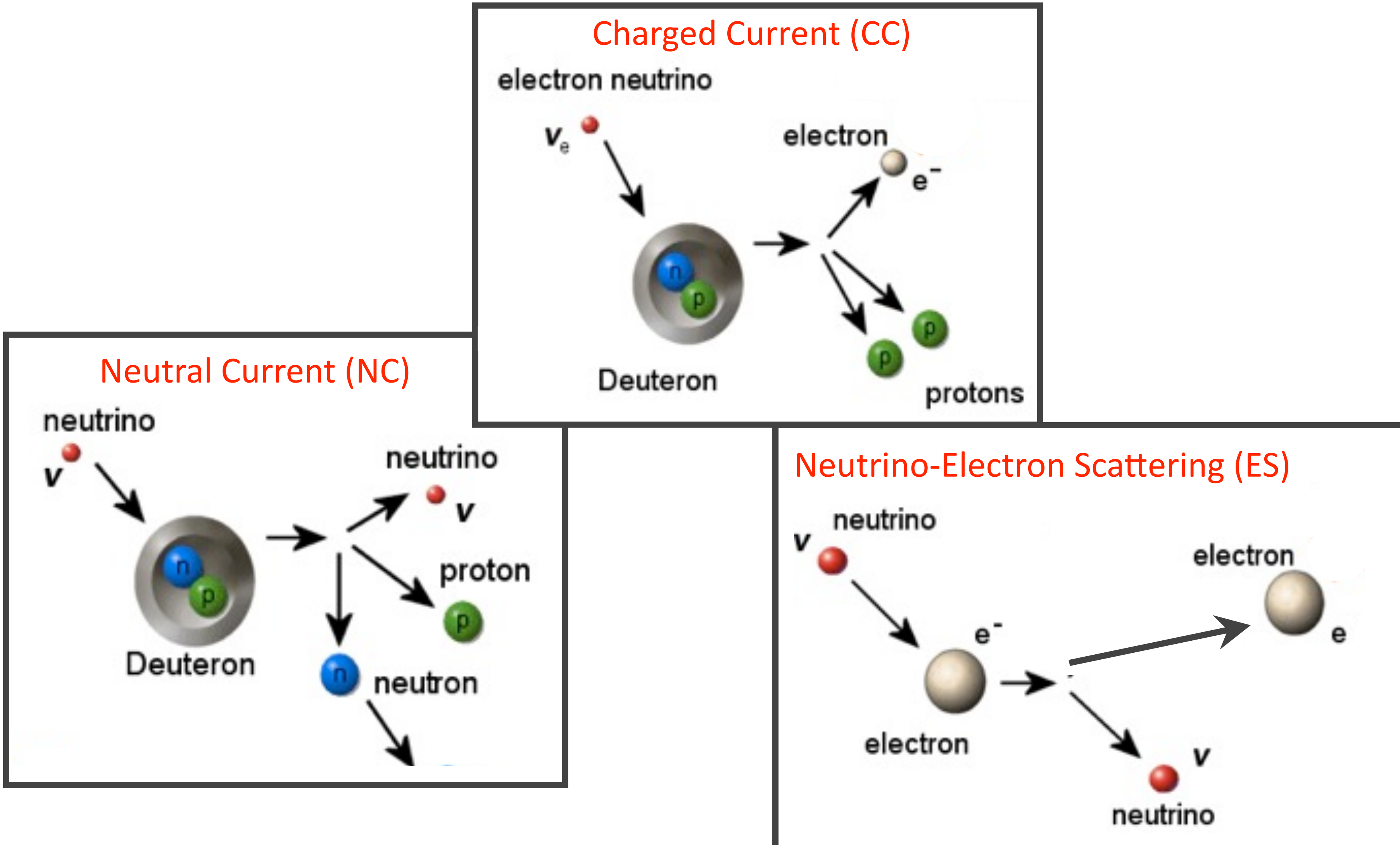
- The Sudbury Neutrino Observatory
- High-frequency search: motivations
- Methodology of search
  - General
  - Directed
  - Broadband
- Results

The Sudbury Neutrino Observatory

- Nov. 1999 - Dec. 2006
- Located in Sudbury, Ontario
- 6,800 ft underground in Vale INCO's Creighton #9 Mine (~6,000 m.w.e.)
- 1,000 tonnes D_2O
- 3 phases:
  - D_2O (clean measurement, poor n sensitivity)
  - D_2O + NaCl (better neutron sensitivity)
  - D_2O + ^{3}He proportional counters (n sensitivity)



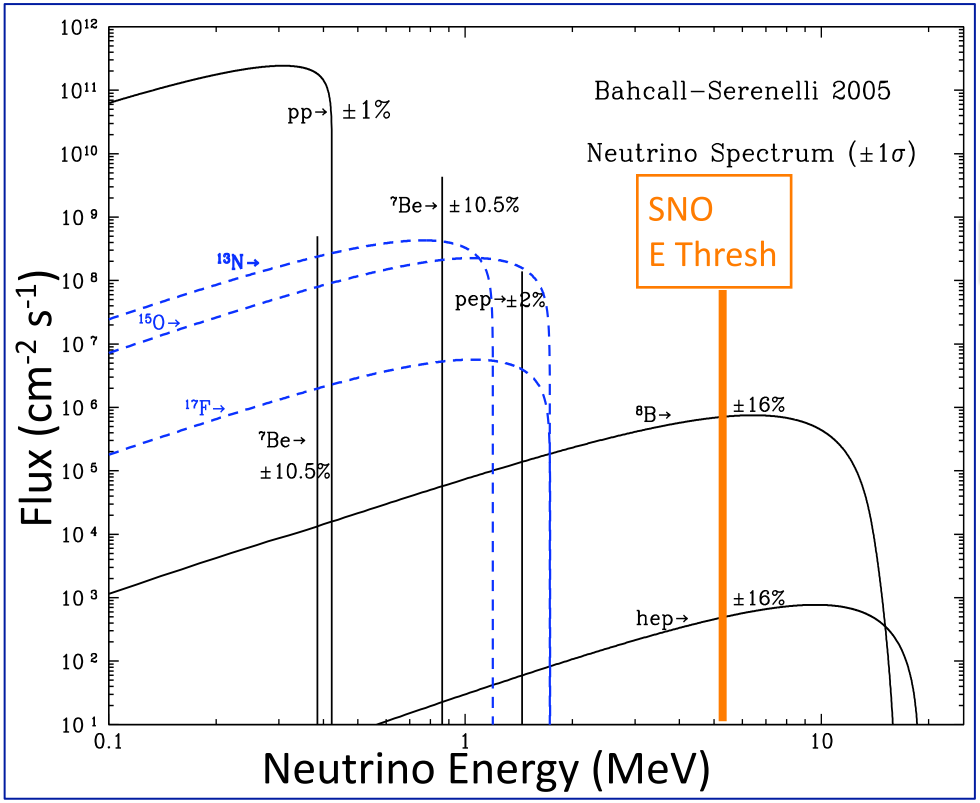
Neutrino Interactions in SNO

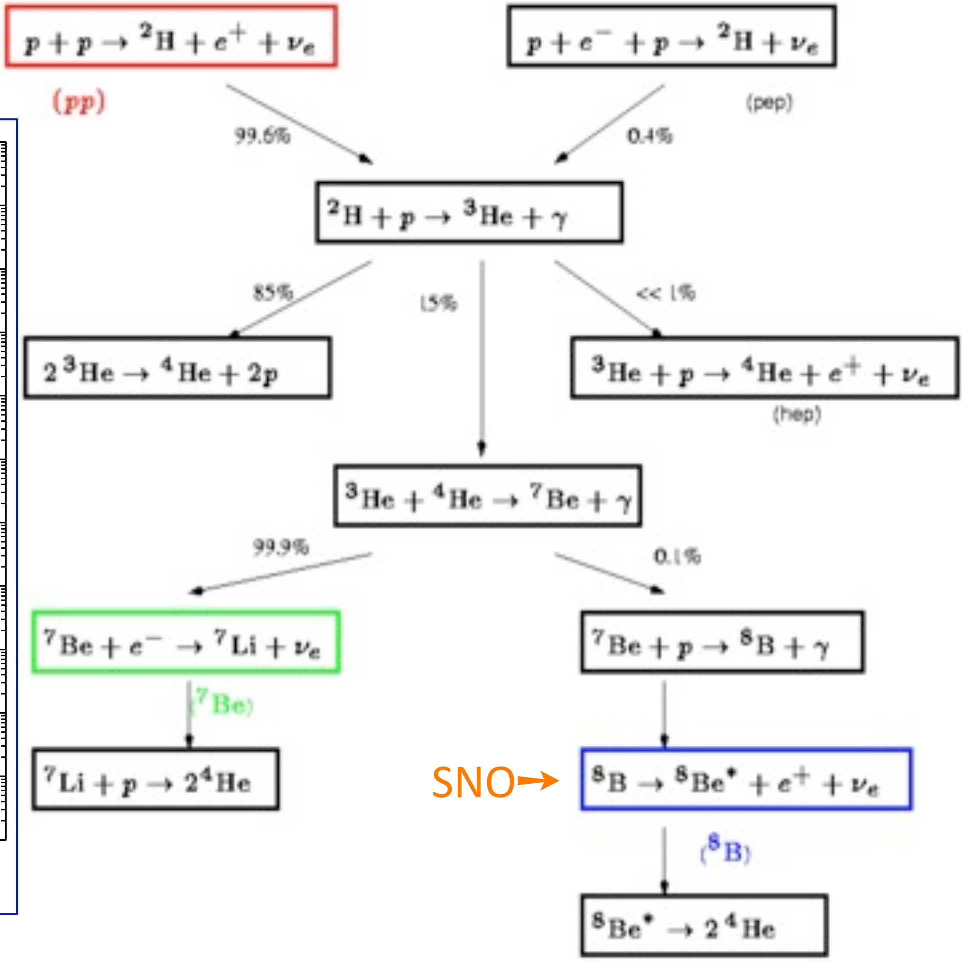


Heavy Water Cherenkov detector → 3 interactions possible

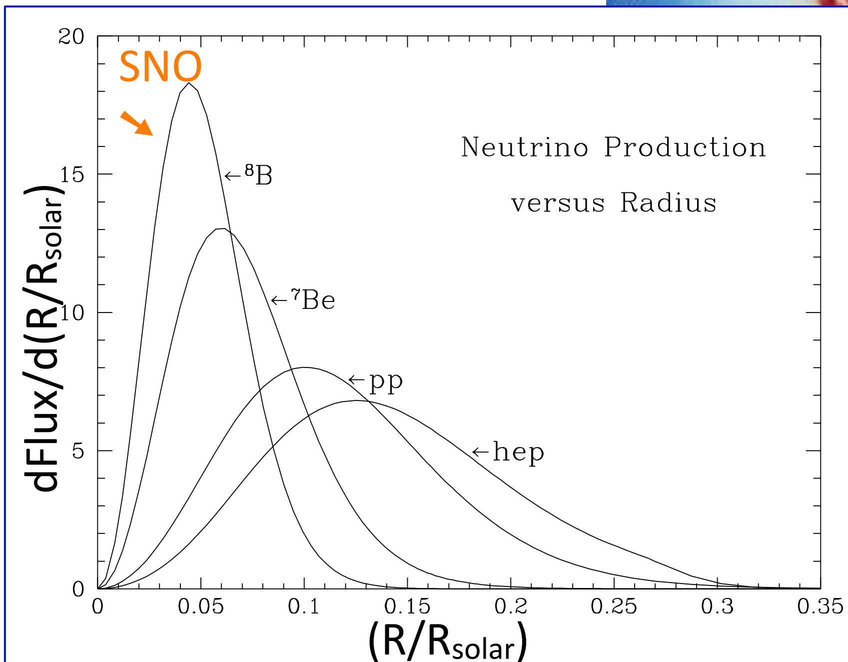
CC, NC cross sections ~ 10x ES cross section

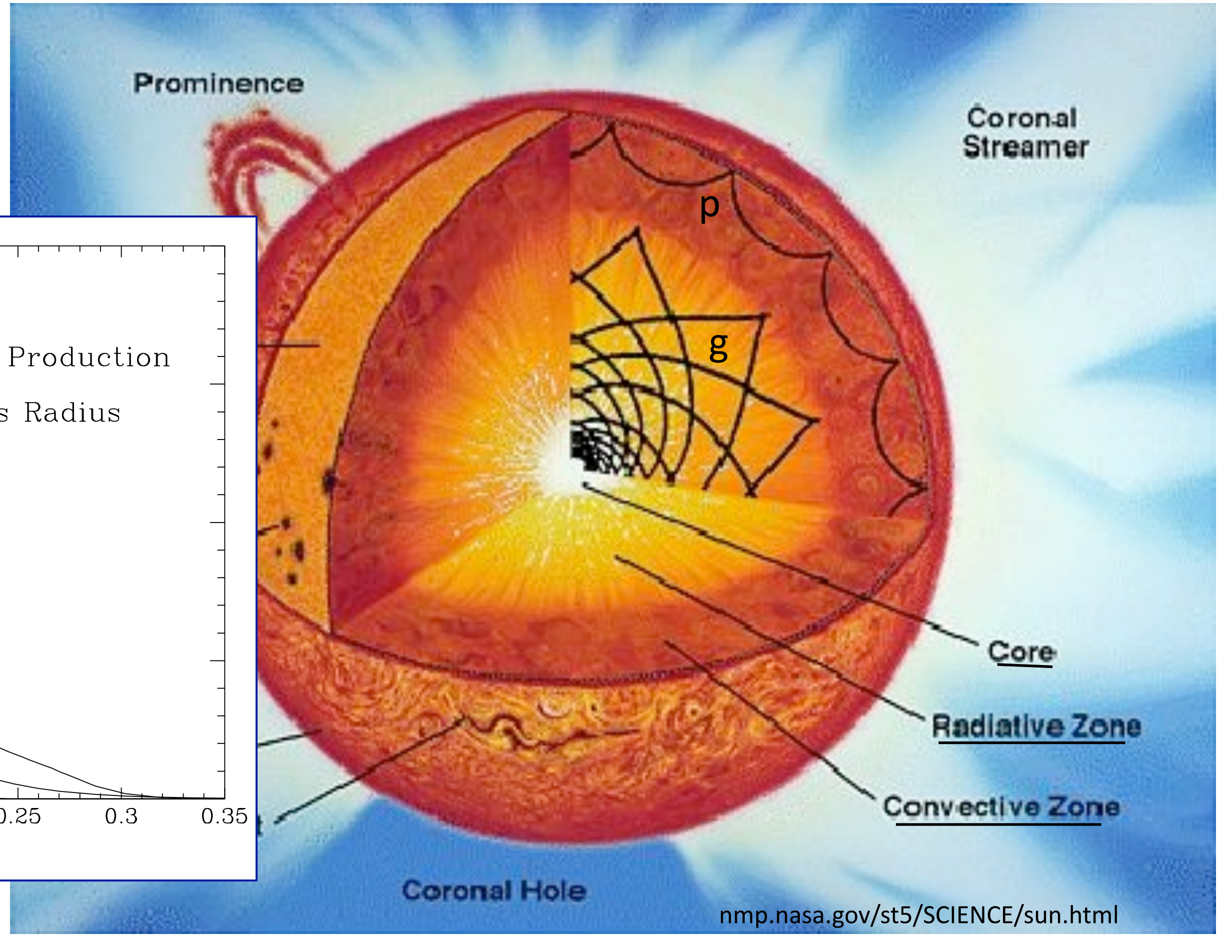
Standard Solar Model





Standard Solar Model: solar oscillations

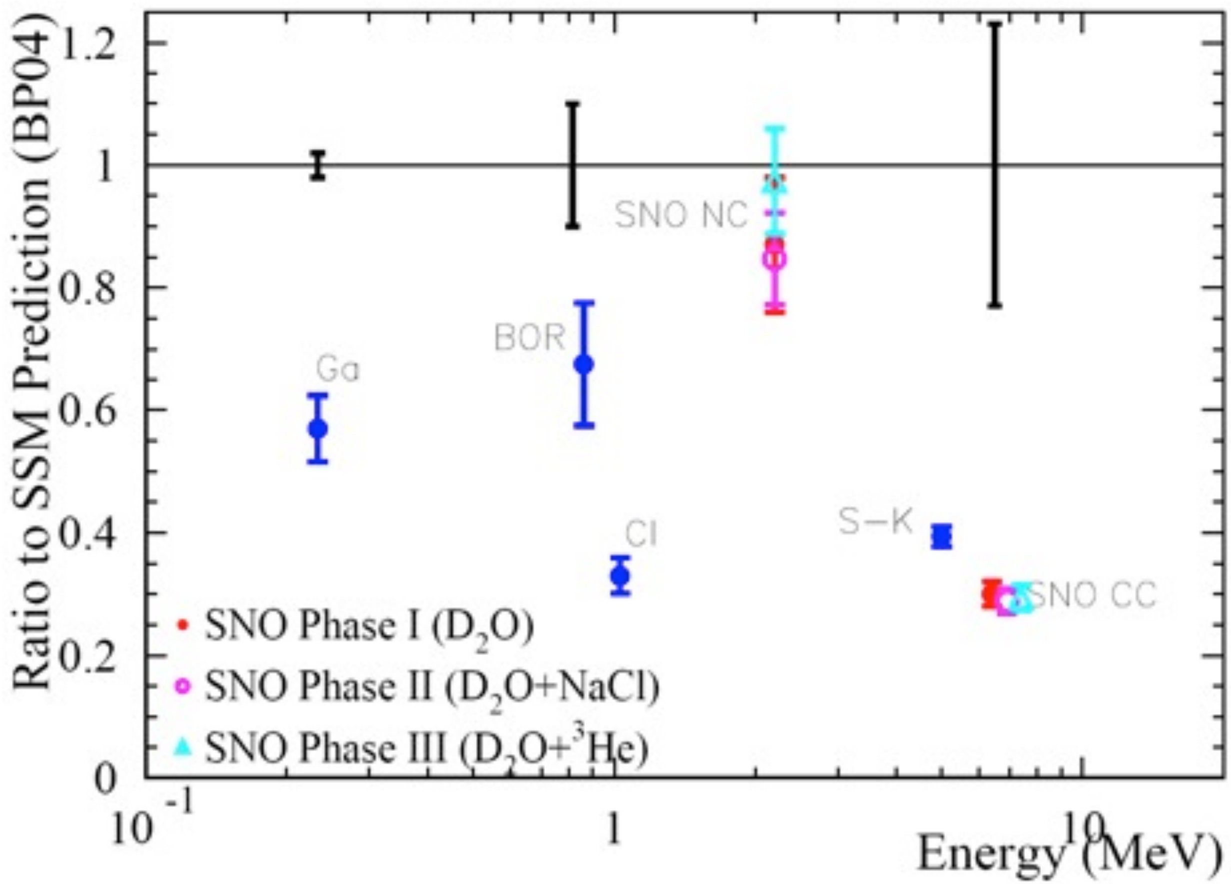




Neutrino production: core
p-mode (acoustic) oscillations: largely convective zone
g-mode (gravity) waves: core and radiative zone

The Solar Neutrino Problem

Deficit of ν_e's from sun

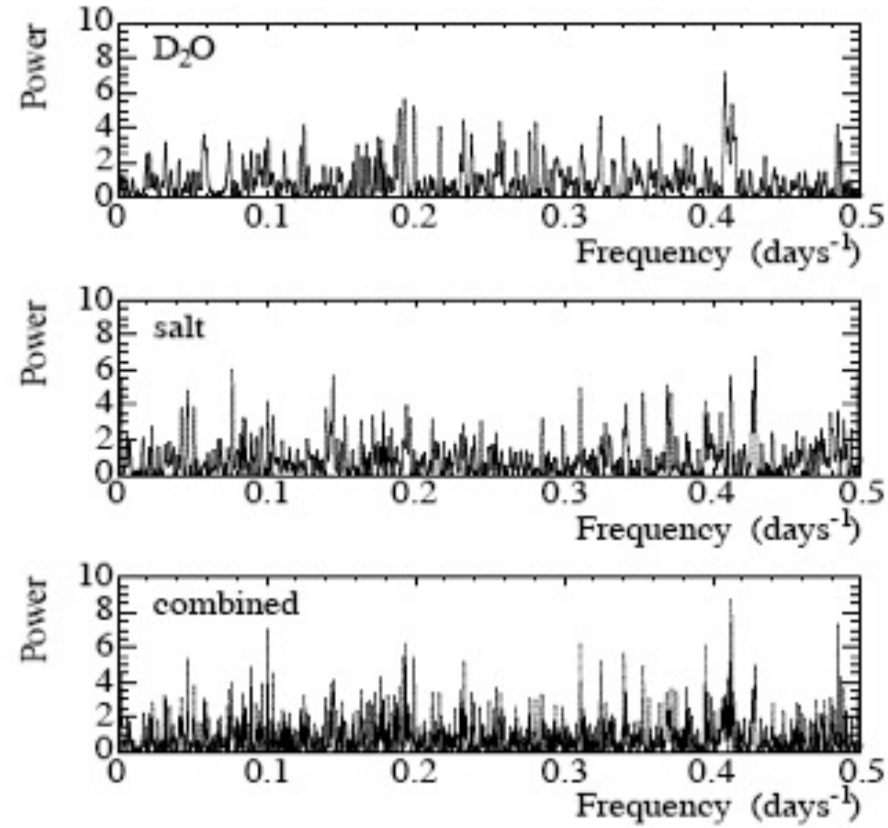


theory

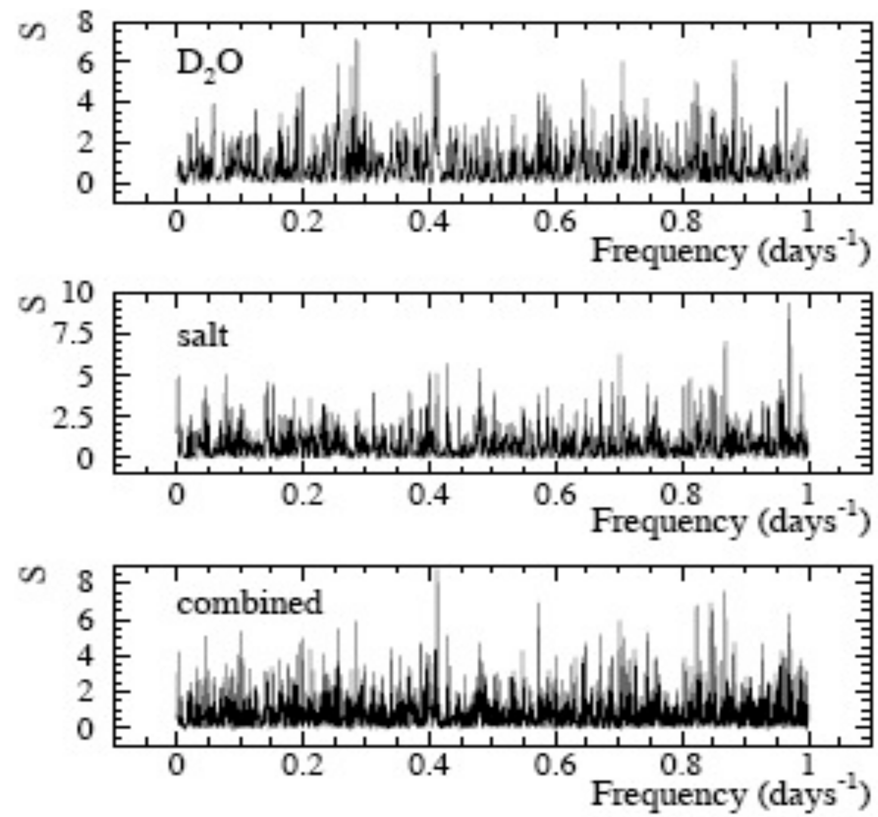
experiment

SNO is unique → first inclusive appearance experiment; showed that flux of three flavors *combined* (NC) agreed with predicted flux of ν_es *only* (CC) → neutrino oscillations

SNO Low-Frequency Periodicity Search[1]



Lomb-Scargle (Binned)

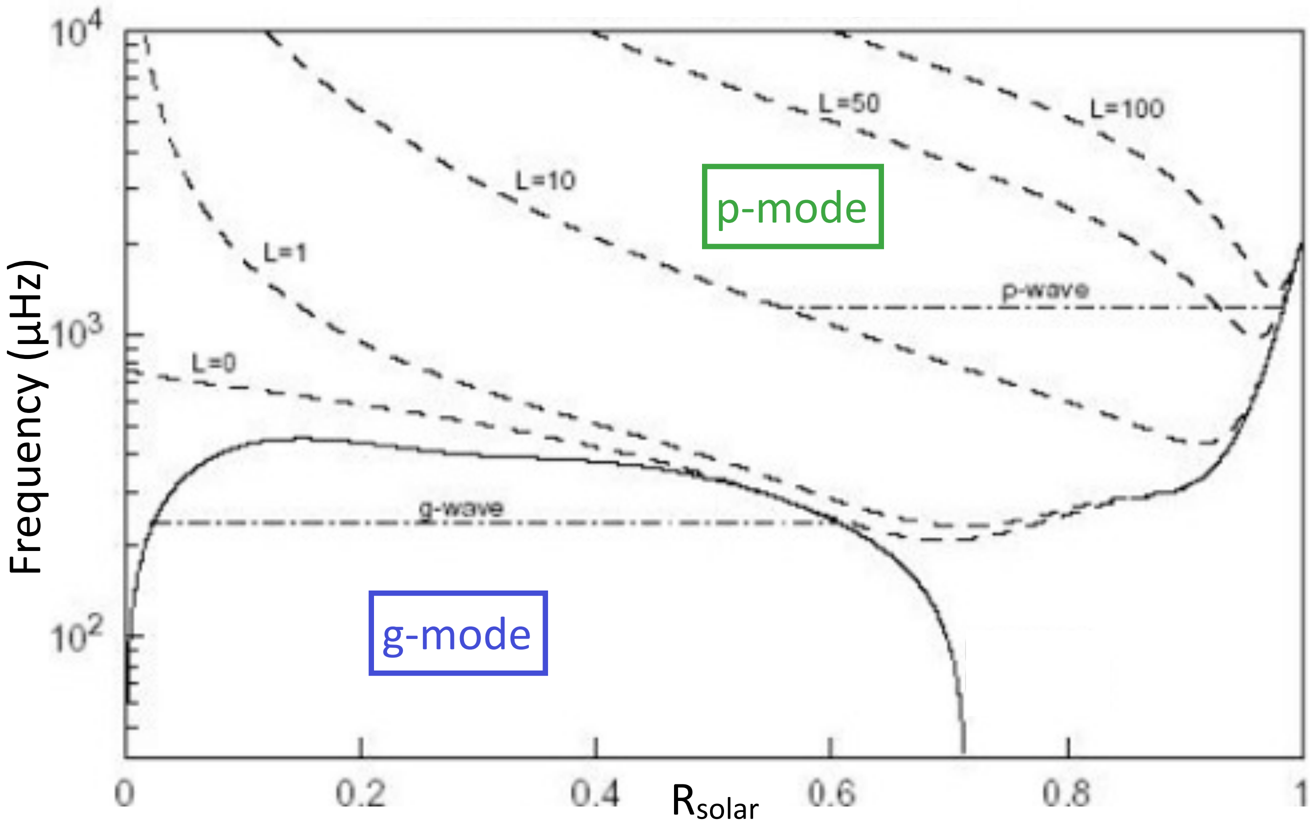


Maximum Likelihood (Unbinned)

⇒ No periodicities detected over range of periods, 1 day to 10 years

[1] *A Search for Periodicities in the ^{8}B Solar Neutrino Flux Measured by the Sudbury Neutrino Observatory*, Phys. Rev. D 72 (2005) 052010

High Frequency Periodicity Search
Motivation: *g*-modes



Solar g-mode oscillations:

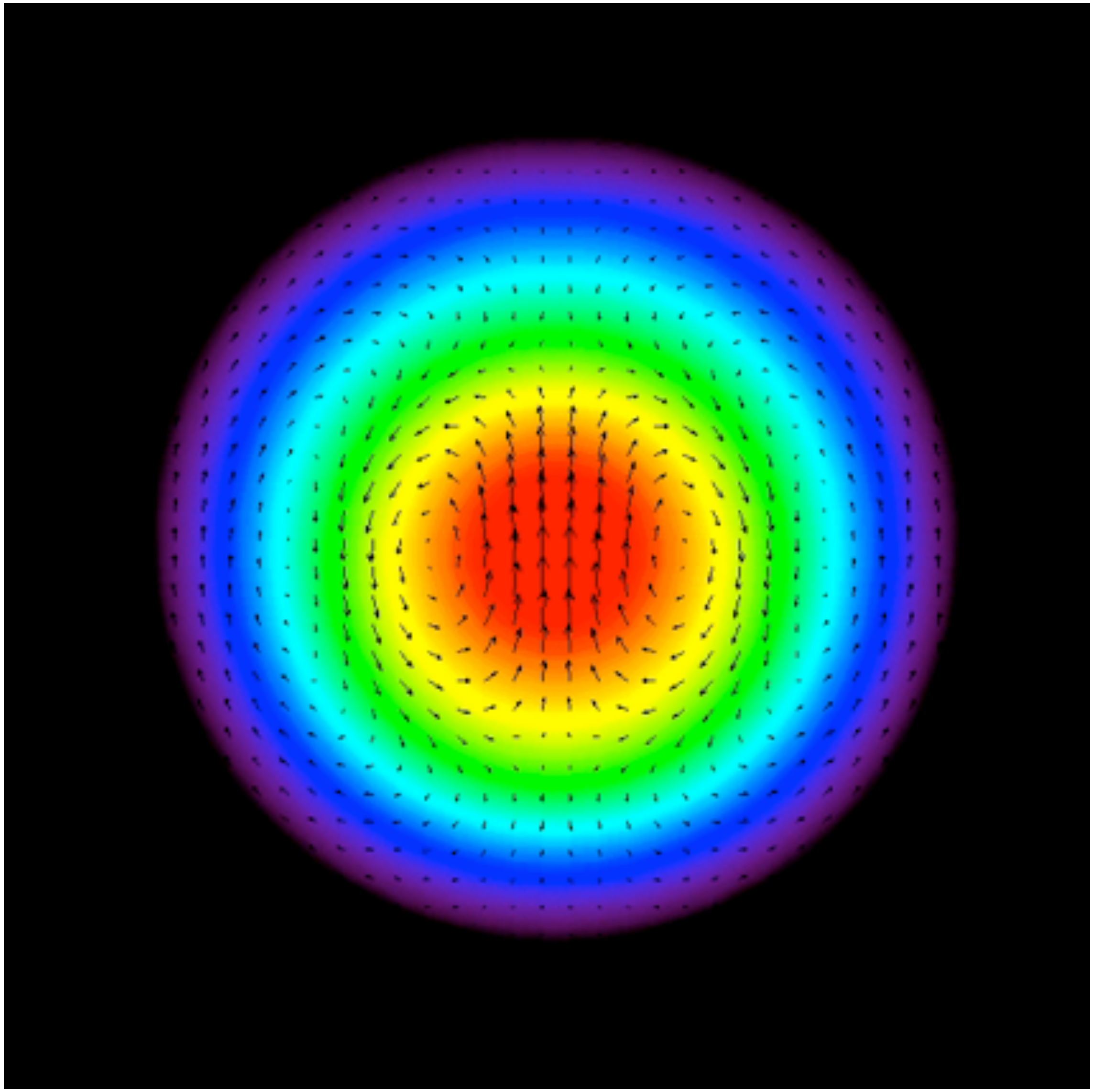
- High-frequency, non-radial
- Gravity is restoring force
- Trapped; evanescent in convection zone, so difficult to observe with conventional methods

Solar p-mode oscillations:

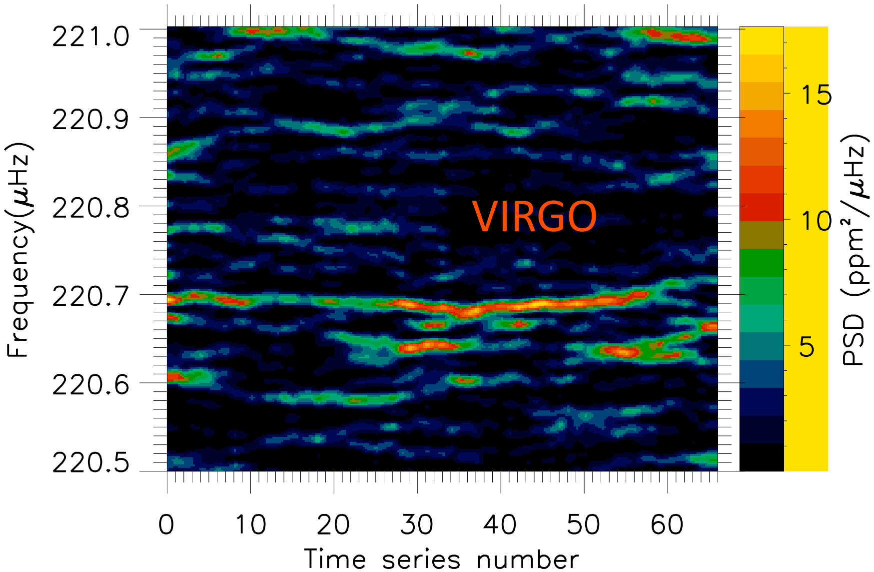
- High-frequency, radial and non-radial
- Pressure is restoring force
- Only truly able to probe down to ~0.2R_{solar} (increase in sound-speed velocity with depth, so p modes spend more time in convection zone than radiative zone)

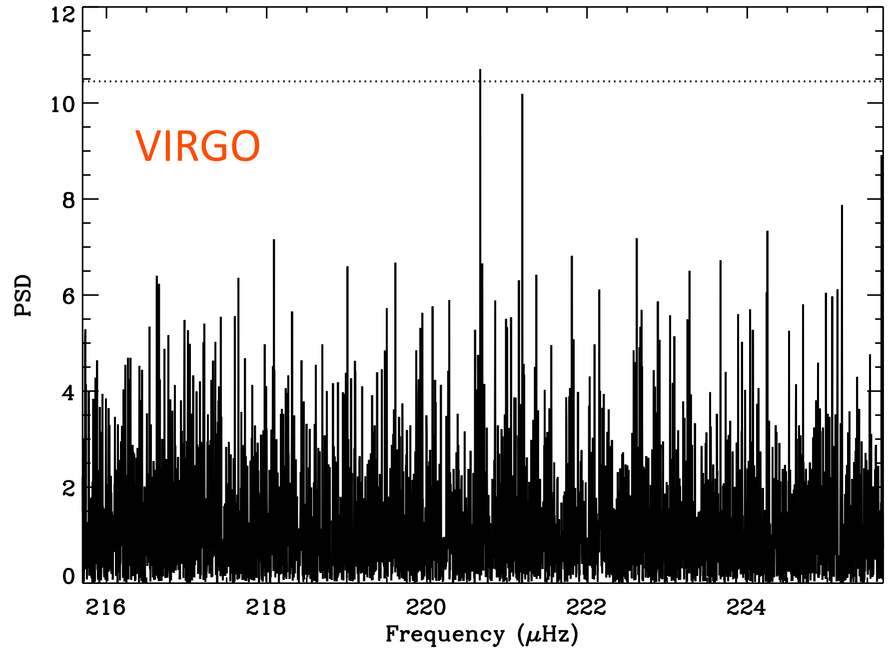
g-mode Oscillations: A Visualization

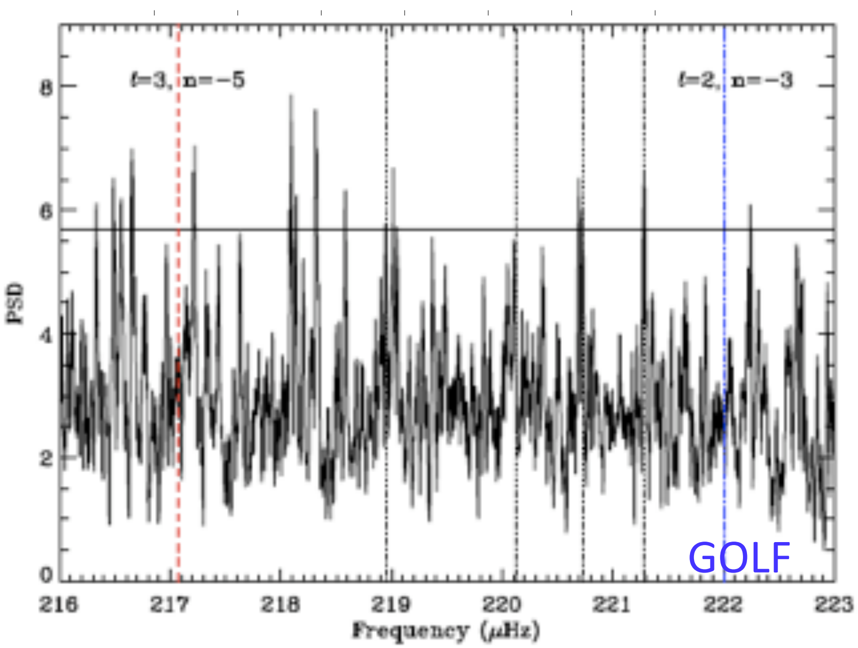
g-mode Oscillations: A Visualization



High Frequency Periodicity Search: Motivation - SoHO







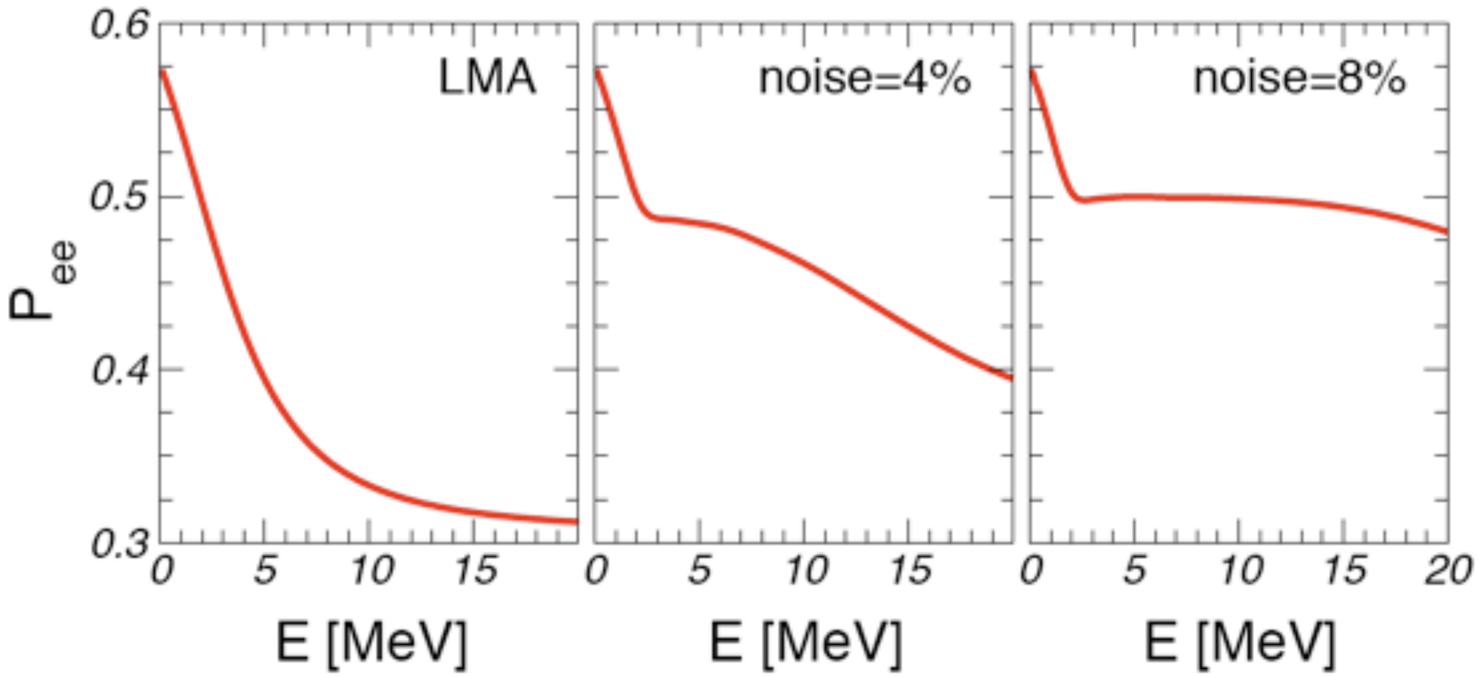
- VIRGO data corroborate GOLF signal at 220.7 uHz

- Claimed to be persistent over 10-year period

On the solar origin of the signal at 220.7 uHz, A. Jimenez, R. Garcia; arXiv:0908.0562v1 4 Aug 2009

Update on g-mode Research, R. Garcia et al., AN 999, No. 88, 1-9 (2006)

High Frequency Periodicity Search: Motivation



Burgess *et al*. (and others) have shown possible effects of solar core density fluctuations, or "noise", on solar neutrino survival probability (MSW effect)

If density profile is noisy, could see time-dependent effects in the solar neutrino flux (different electron densities could affect neutrino's propagation)

Large-amplitude noise (shown here) ruled out; but small amplitudes?

High Frequency Periodicity Search: Motivation

- SNO: Low Backgrounds, real-time detector → good platform for testing for high frequency periodicity in sun

- Phenomenological predictions (“noise”) and experimental (helioseismology) detection claims could be explored, verified

- Never been done!

- Novel approach, Rayleigh power test → Allows faster processing and analysis, opening up larger frequency region

High-Frequency Method of Periodicity Analysis:
The Rayleigh Power Test

Typically used in directional statistics:
- -pigeon homing
- -stopping position of a roulette wheel

Equal probability of landing on any of the available numbers = isotropic distribution of ‘events’

High-Frequency Method of Periodicity Analysis: The Rayleigh Power Test

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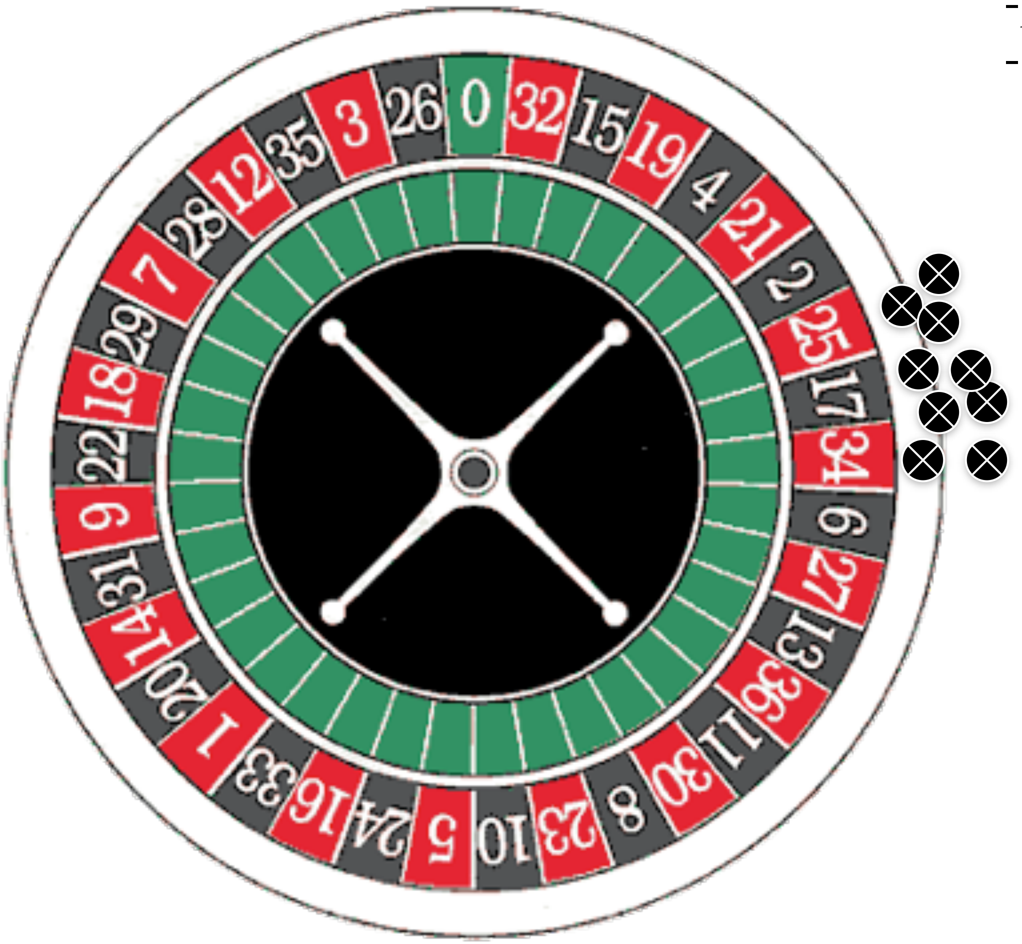
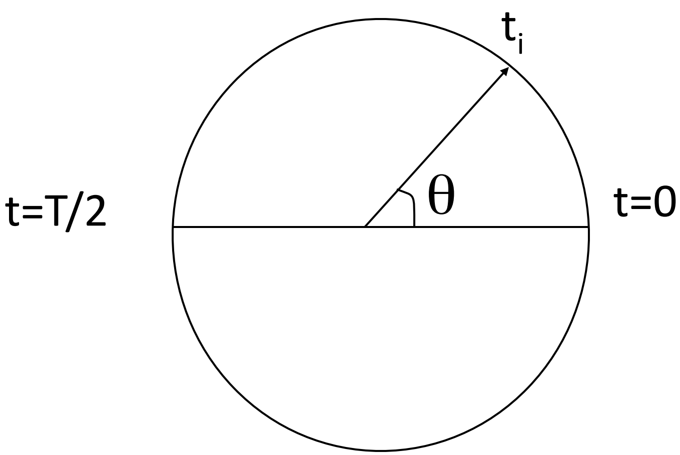


Uneven probability of landing on any of the available numbers = highly directional/non-isotropic distribution of ‘events’

The Rayleigh Power Test



• Unbinned Analysis

• Less CPU-intense

→ Faster processing time: opens up higher-frequency regions

Rayleigh Power, *z*:

$$\boxed{z = \frac{U^2}{N} = \frac{1}{N}\left[\left(\sum_{i=1}^{N}\cos\theta_i\right)^2 + \left(\sum_{i=1}^{N}\sin\theta_i\right)^2\right]}$$

$$\text{where } \theta_i = 2\pi\nu t_i$$

$$\vec{U} = \sum_{i=1}^{N}\cos\theta_i\ \hat{e}_x + \sum_{i=1}^{N}\sin\theta_i\ \hat{e}_y$$

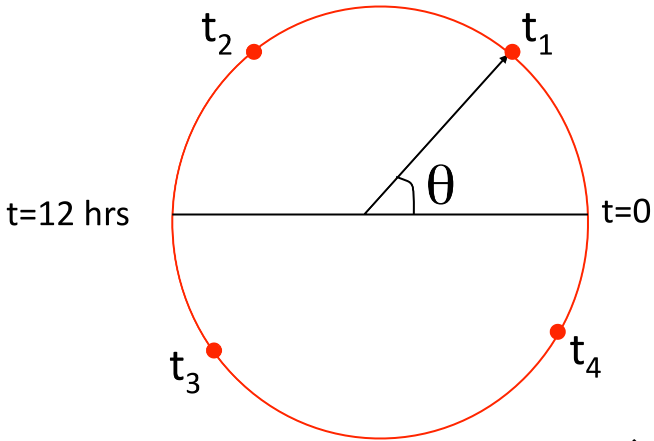
• ***U*** measures deviation from true 'randomness'

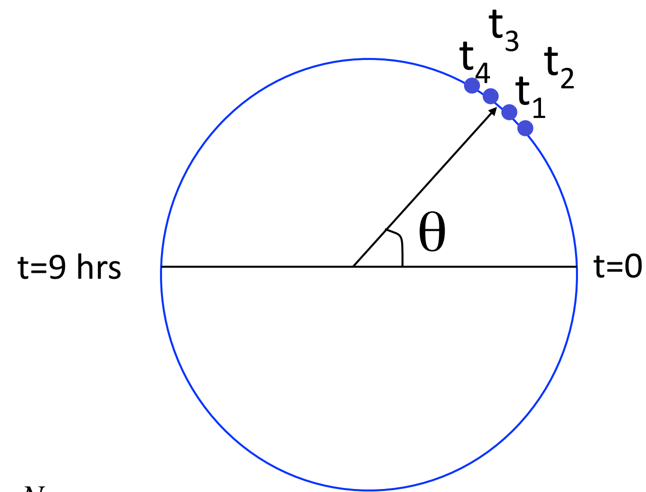
• Isotropic signal gives low Rayleigh power, z

Probability of seeing signal of strength greater than K :

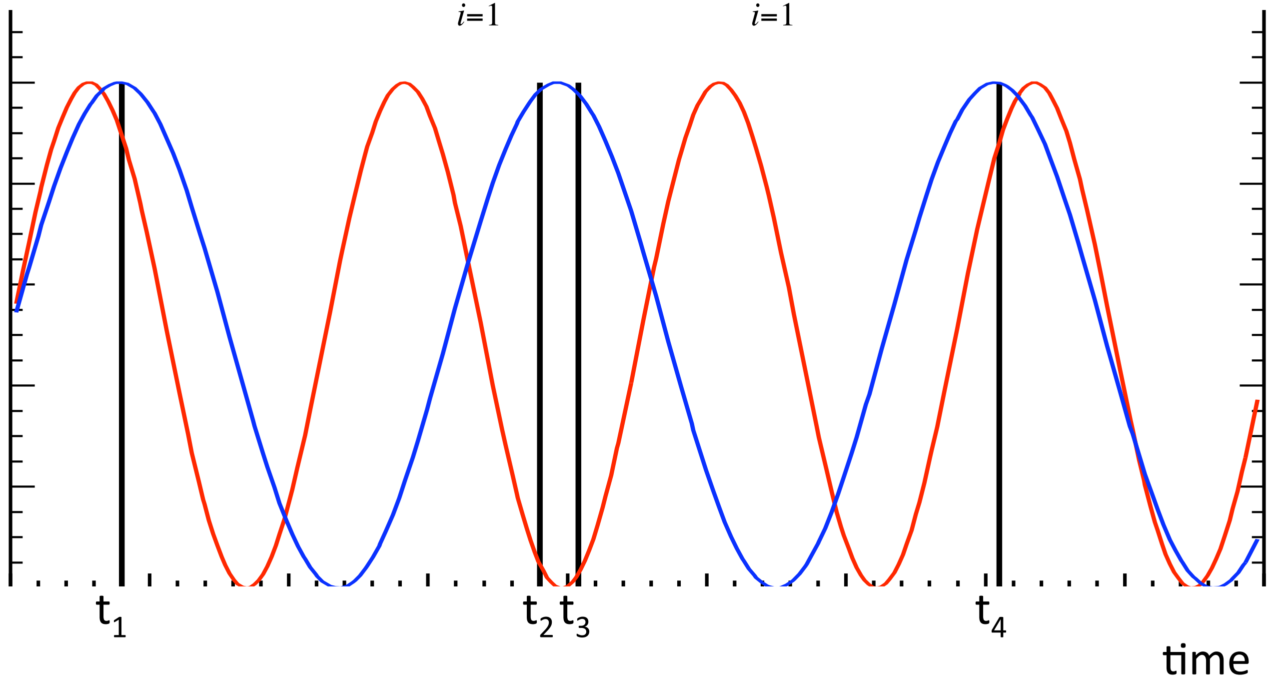
$$P(z > K) = e^{-K}$$

The Rayleigh Power Test



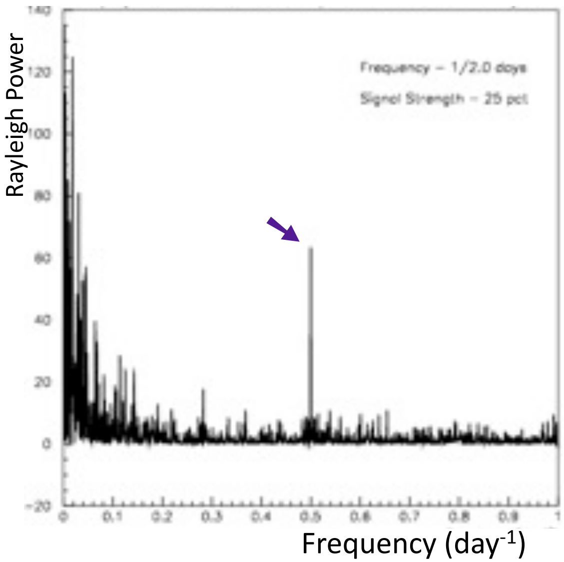


$$\vec{U} = \sum_{i=1}^{N} \cos\theta_i \ \hat{e}_x + \sum_{i=1}^{N} \sin\theta_i \ \hat{e}_y$$



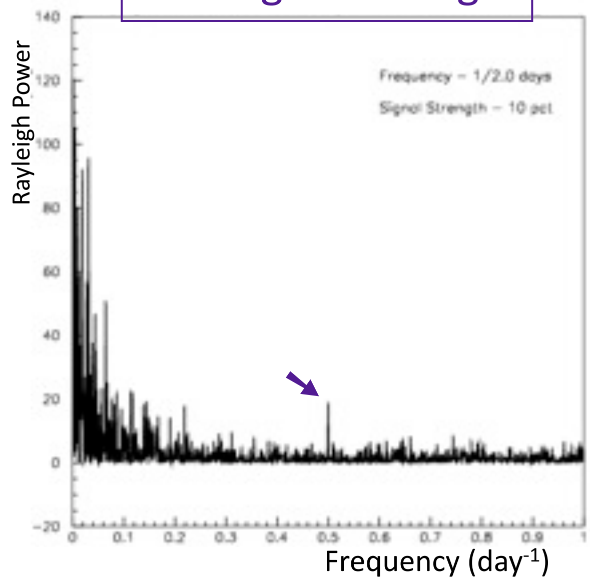
Signal Sensitivity of Rayleigh Power Test

Power Spectra of SNO Monte Carlo files with periodic signal built in

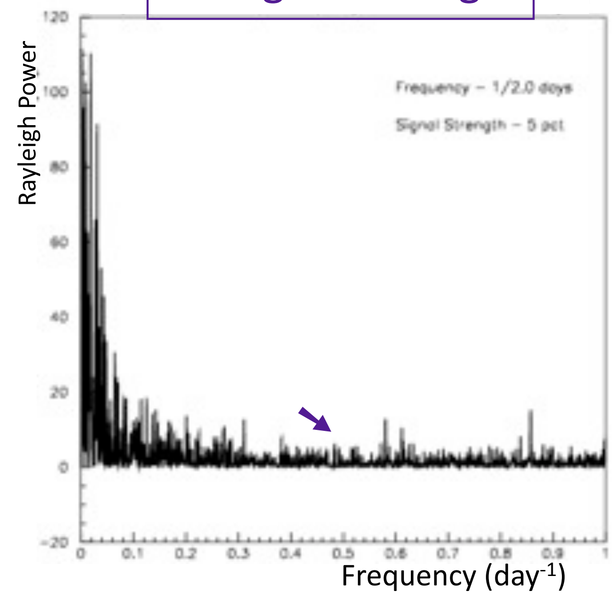


25% Signal Strength

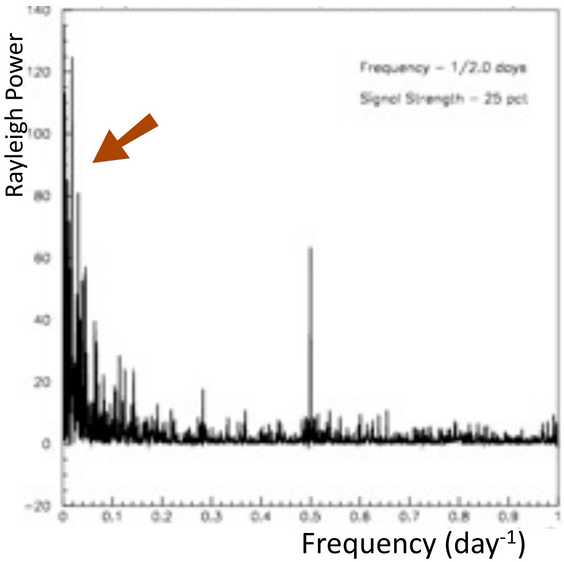
10% Signal Strength



5% Signal Strength



Signal Sensitivity of Rayleigh Power Test



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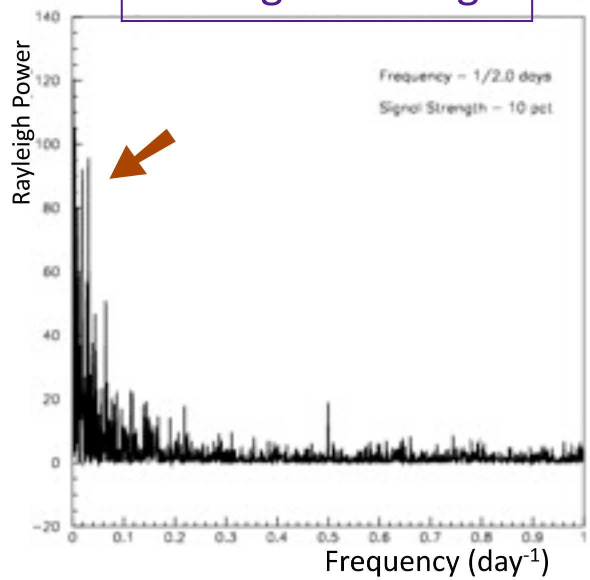

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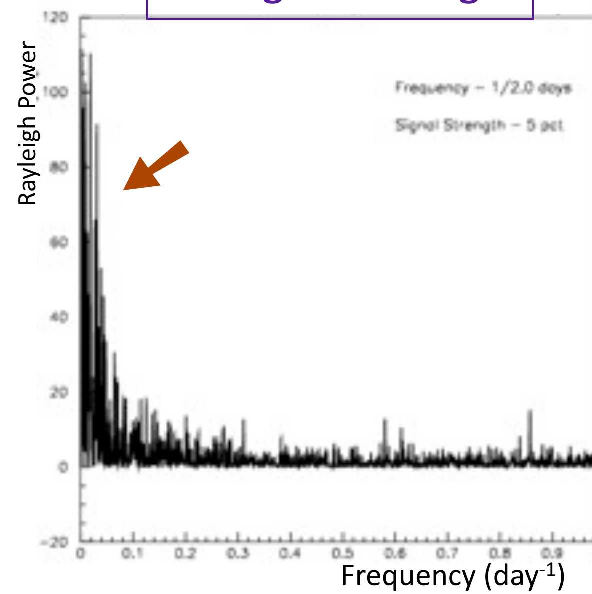
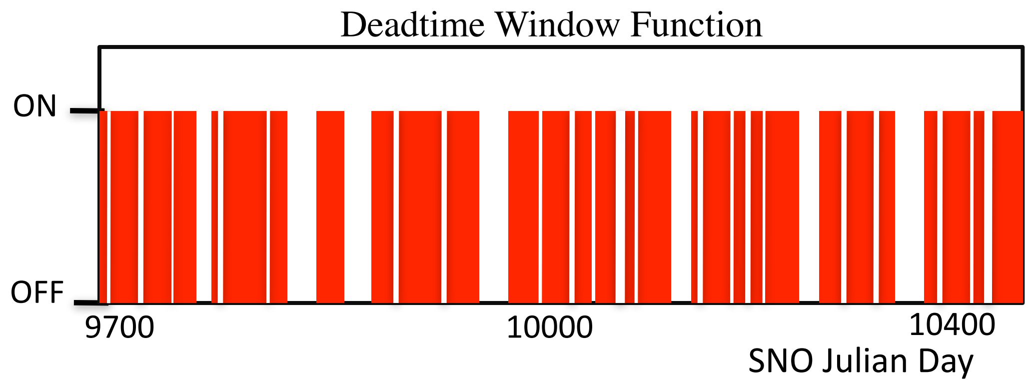


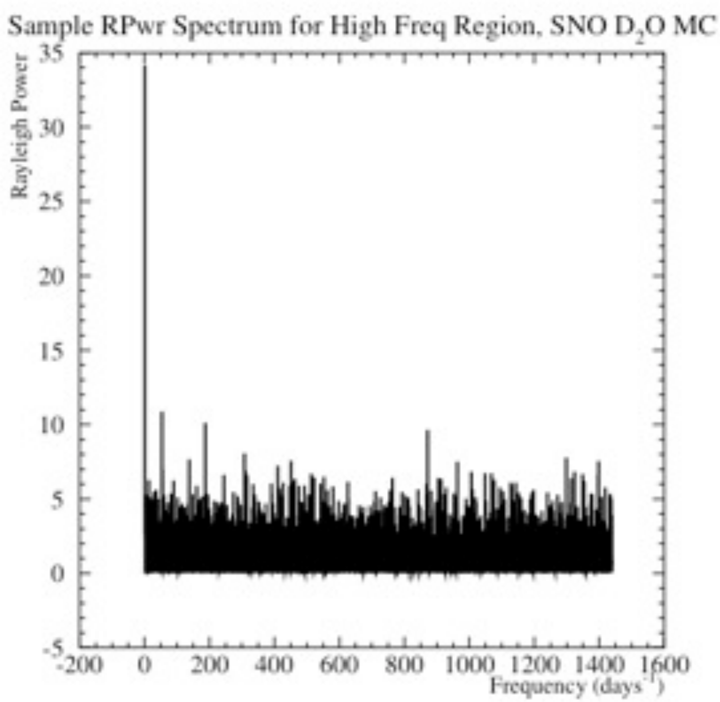
- Obvious underlying structure
- Structure due to deadtime

→ changes significance of each peak

Rayleigh Power Structure



SNO MC with NO periodic signal built in,
ONLY deadtime window function

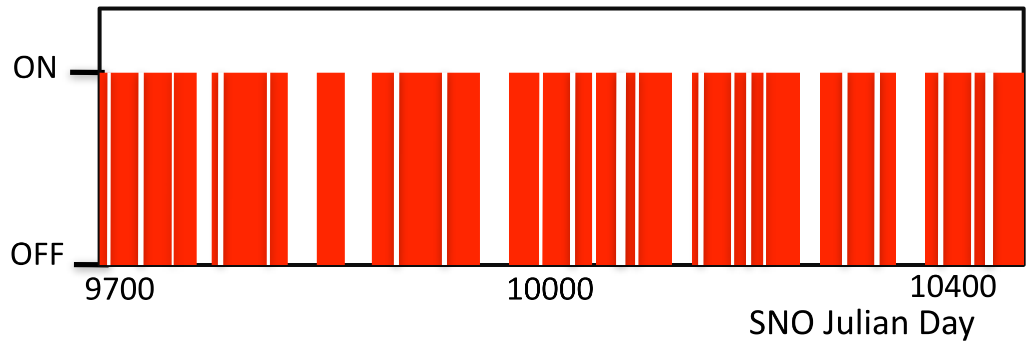


Sources of SNO Deadtime

- Background Removal
  - -Muons
  - -Muon Followers
  - -Bursts
  - -Instrumentals
- Calibration Running
- Detector Shutdown/ Maintenance

Rayleigh Power Structure

Deadtime Window Function



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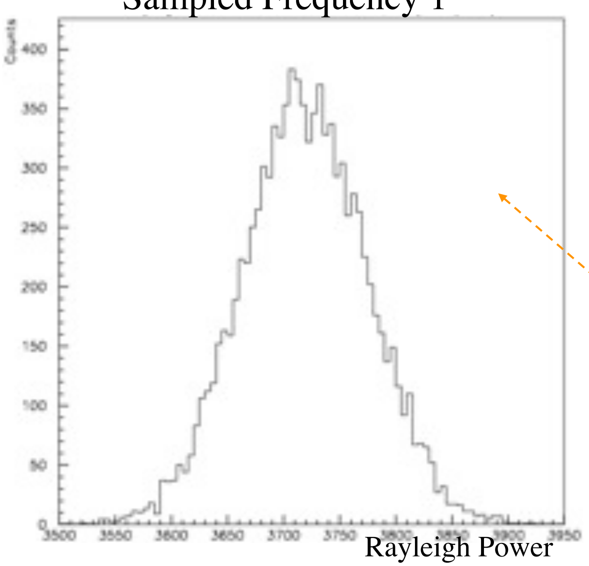
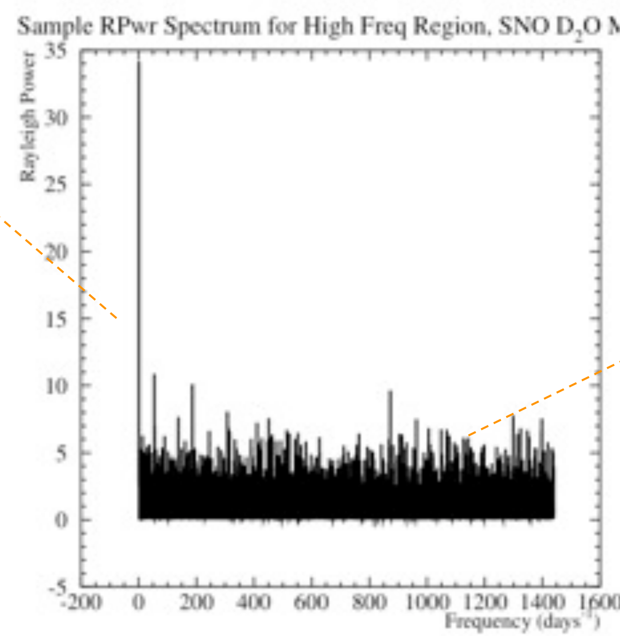
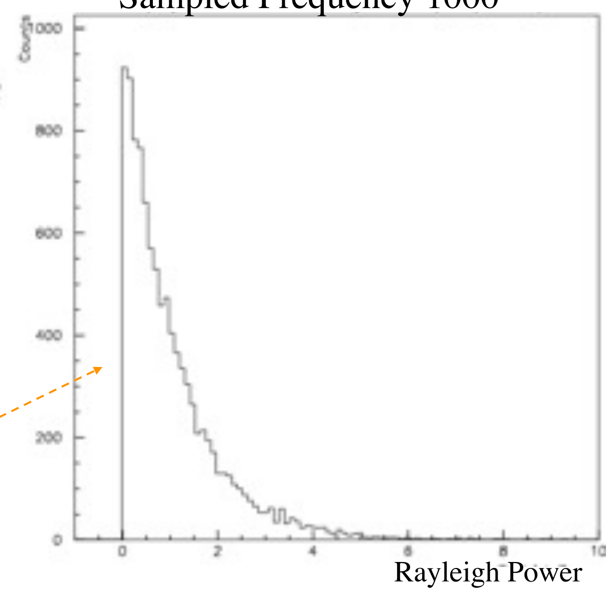
Sampled Frequency 1





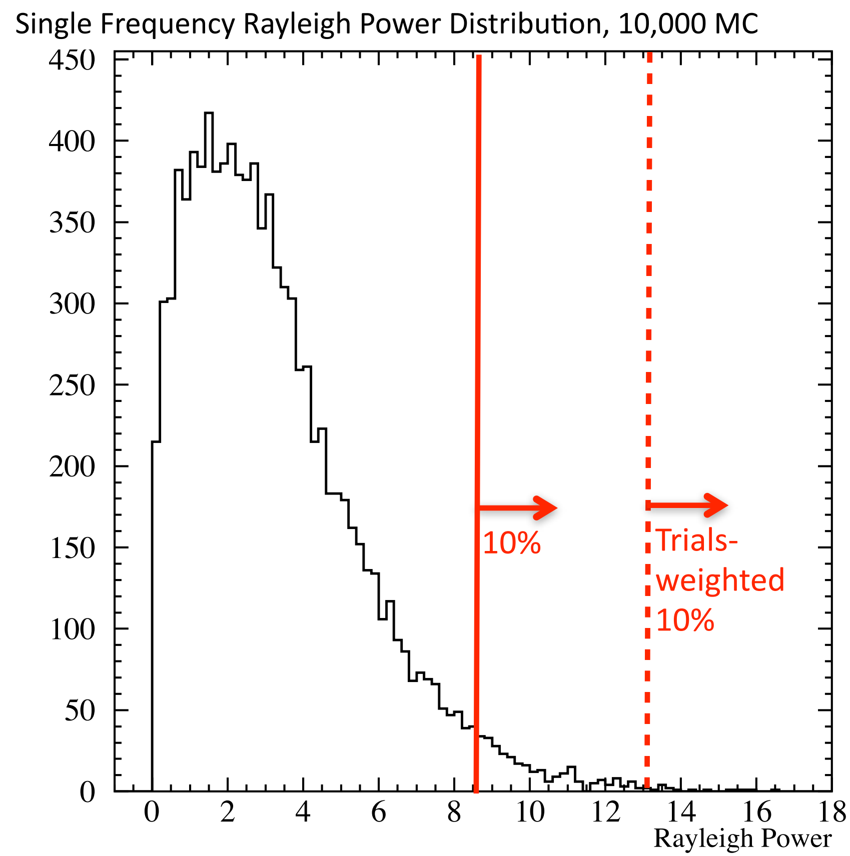
Sampled Frequency 1000



Analyzing Rayleigh Power Spectra

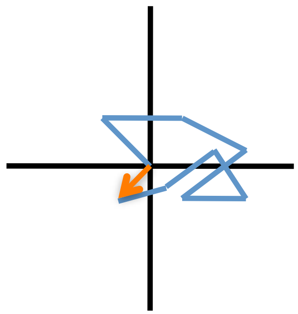
- 1.6 million frequencies sampled (1/day to 1/10 min)
- Each frequency: unique distribution
- To obtain high confidence level value, sit at tail
- Trials Penalty!
- No longer possible to achieve necessary precision with Monte Carlo simulations alone

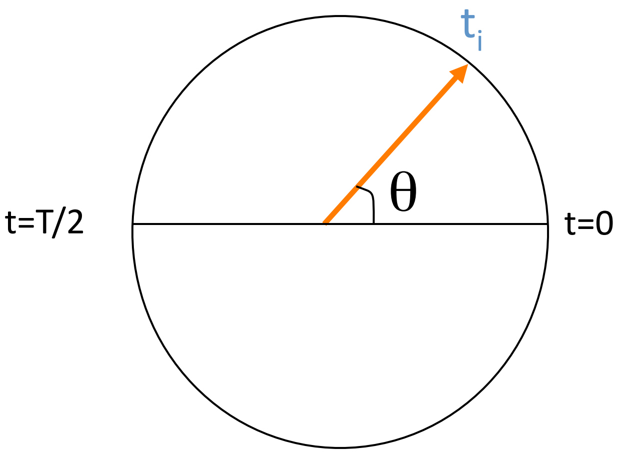
➢ Must develop predictive analytic form



The Rayleigh Power and The Random Walk

Resultant vector which determines value of Rayleigh power can be modeled by Random Walk





Each step corresponding to an event time, t_i

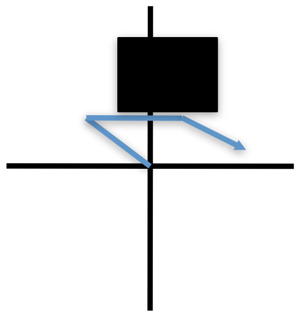
Central Limit Theorem in 2D predicts Gaussian distribution of resultant vectors

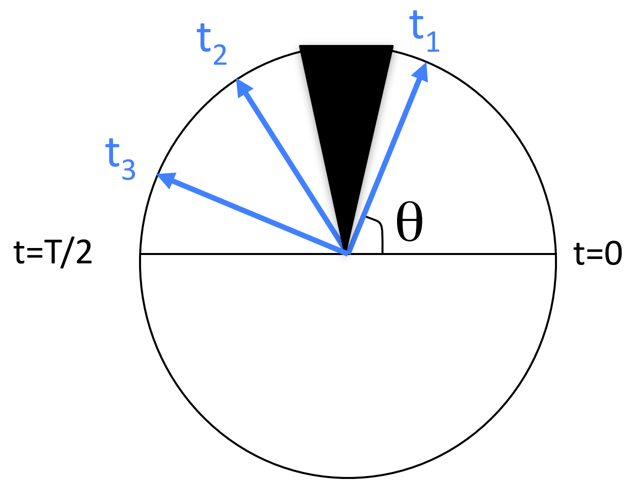
We can analytically calculate means, variances, etc. of these distributions, for instance:

$$\mu_x = \frac{1}{2\pi}\int_0^{2\pi} d\theta \cos\theta$$

Random Walk: Non-uniform Phase Coverage

Resultant vector which determines value of Rayleigh power can be modeled by Random Walk





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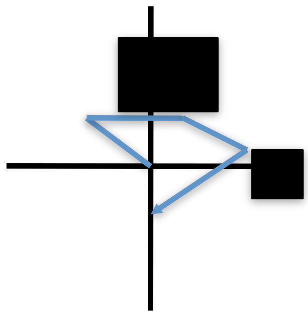

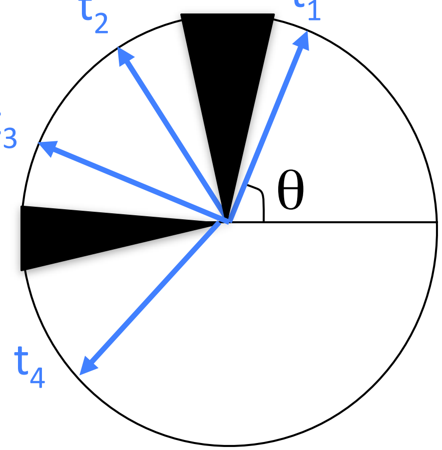

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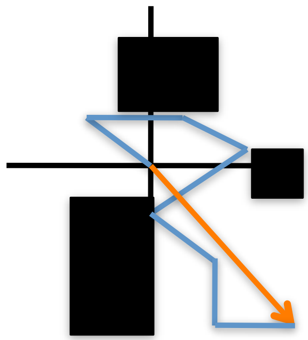
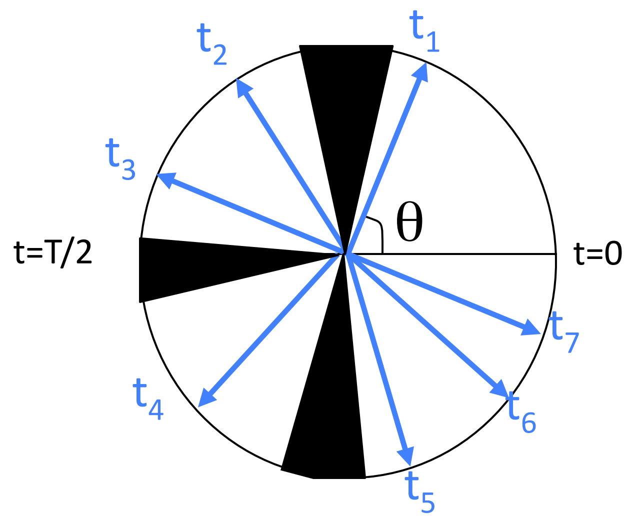




Each step corresponding to an event time, t_i

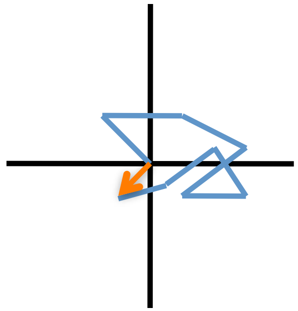
→ Nonuniform phase coverage must be included in Random Walk model (deadtime restricts allowed event occurrence)

→ Design Gaussian parameters to account for nonuniform phase coverage ($g(\theta)$), for instance:

$$\mu_x = \int_0^{2\pi} g(\theta) d\theta \cos\theta \qquad \text{or, more specifically:} \qquad \mu_x = \frac{1}{T} \sum_{j=1}^{runs} \int_{t_{start,j}}^{t_{stop,j}} dt \cos \omega t$$

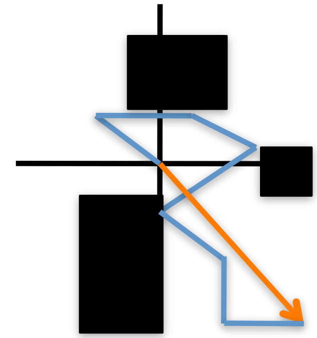
The Rayleigh Power and The Random Walk

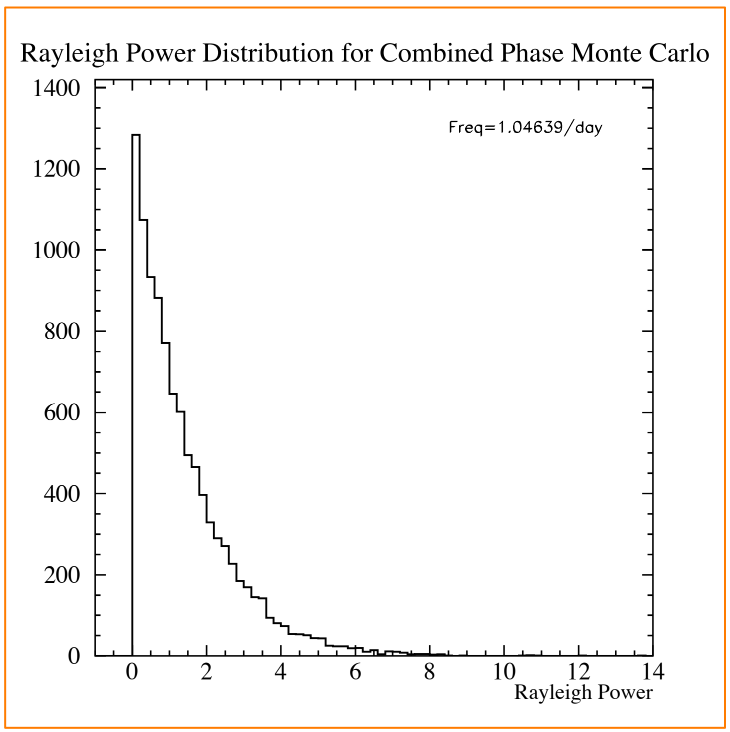
No Deadtime

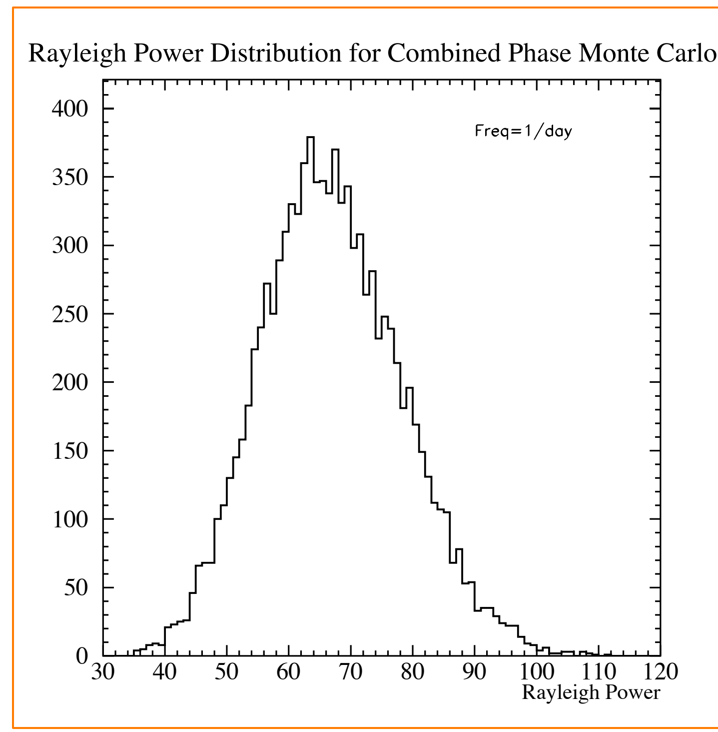


Distribution of
Resultant Vectors
Follows
$e^{-\chi^2}$

Deadtime







The Rayleigh Power Analytic Form

Based on 'Random Walk' model applied to unit circle

$$\chi^2(X,Y) = (X - N\mu_x, Y - N\mu_y)\begin{pmatrix} N{\sigma_x}^2 & N\,cov\,(x,y) \\ N\,cov\,(x,y) & N{\sigma_y}^2 \end{pmatrix}^{-1}\begin{pmatrix} X - N\mu_x \\ Y - N\mu_y \end{pmatrix}$$

$$= \frac{(X - N\mu_x)^2{\sigma_y}^2}{N{\sigma_x}^2{\sigma_y}^2 - N\,cov^2(x,y)} + \frac{(Y - N\mu_y)^2{\sigma_x}^2}{N{\sigma_x}^2{\sigma_y}^2 - N\,cov^2(x,y)} - \frac{2(X - N\mu_y)(Y - N\mu_y)cov(x,y)}{N{\sigma_x}^2{\sigma_y}^2 - N\,cov^2(x,y)}$$

Here, μ_x is the average x-component, μ_y the average y-component, $\sigma_x{}^2$ is the variance in x, and $\sigma_y{}^2$ is the variance in y.

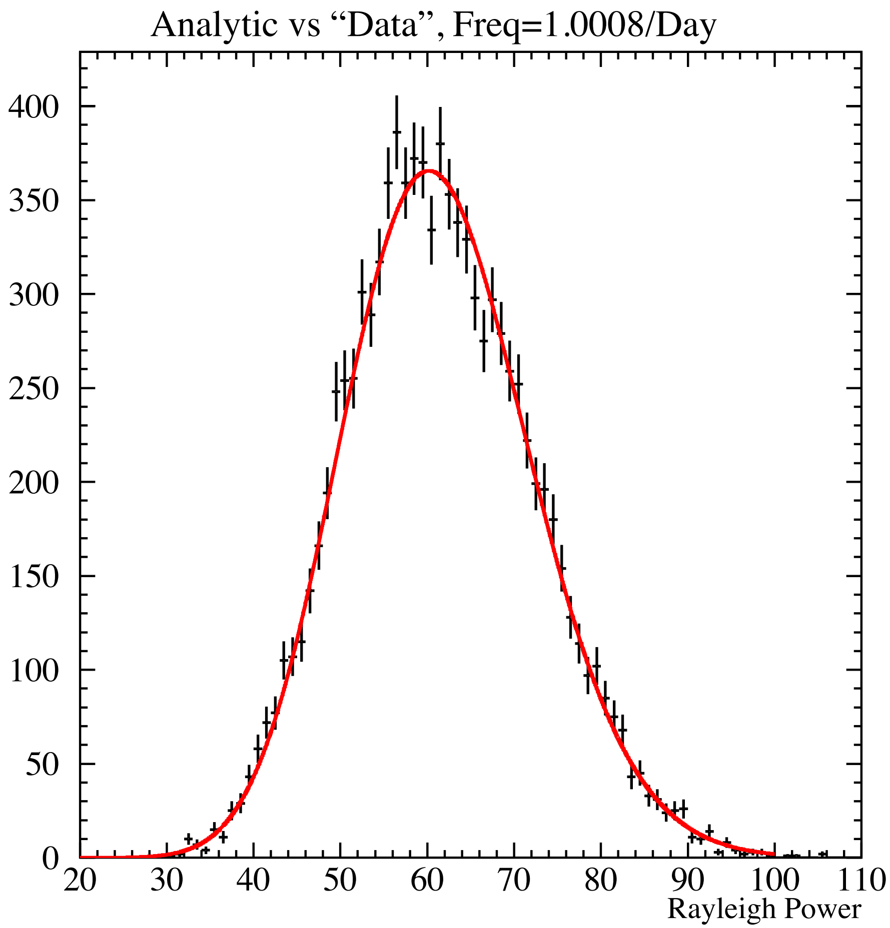
Again, $X = \Sigma_i \cos\theta_i$, $Y = \Sigma_i \sin\theta_i$, where $\theta_i = wt_i$

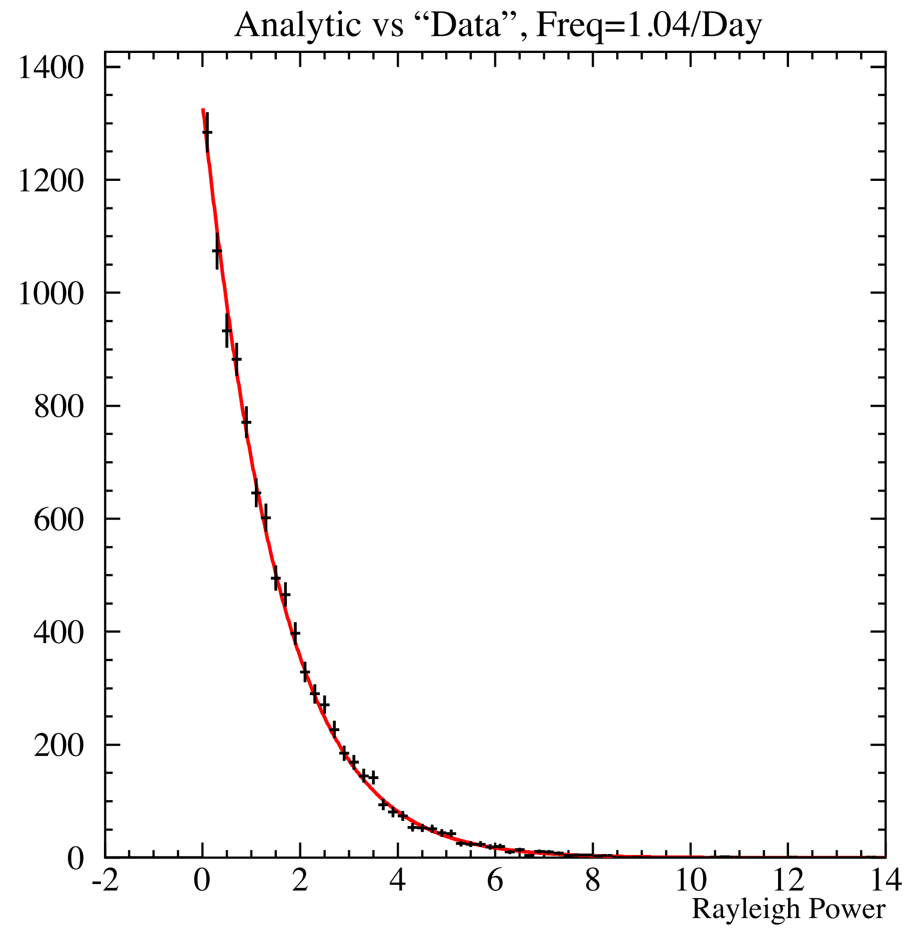
$$\mu_x = \frac{1}{2\pi}\int_0^{2\pi} g(\theta)d\theta\cos\theta \qquad \mu_y = \frac{1}{2\pi}\int_0^{2\pi} g(\theta)d\theta\sin\theta$$

$$\sigma_x^2 = \frac{1}{2\pi}\int_0^{2\pi} g(\theta)d\theta(\cos\theta - \mu_x)^2 \qquad \sigma_y^2 = \frac{1}{2\pi}\int_0^{2\pi} g(\theta)d\theta(\sin\theta - \mu_y)^2$$

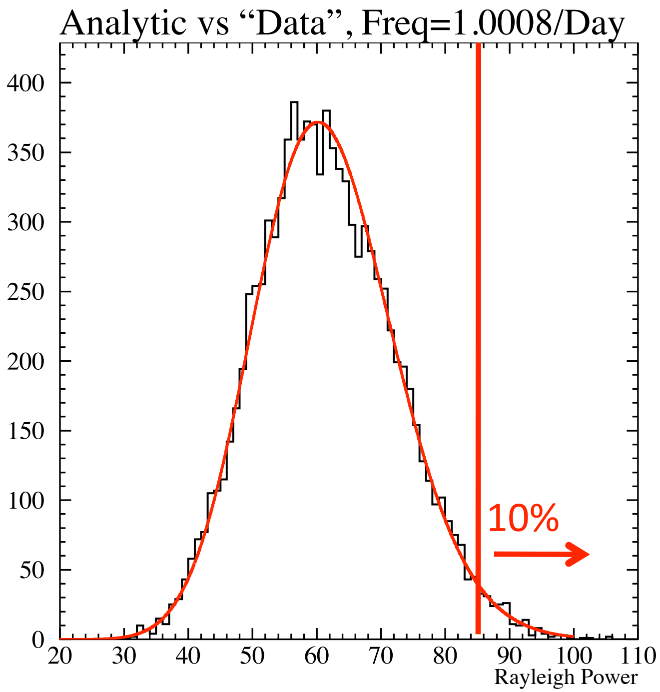
$$\mathrm{cov}(x,y) = \frac{1}{2\pi}\int_0^{2\pi} g(\theta)d\theta(\cos\theta - \mu_x)(\sin\theta - \mu_y)$$

Analytic Rayleigh Power Form in High Frequency Region

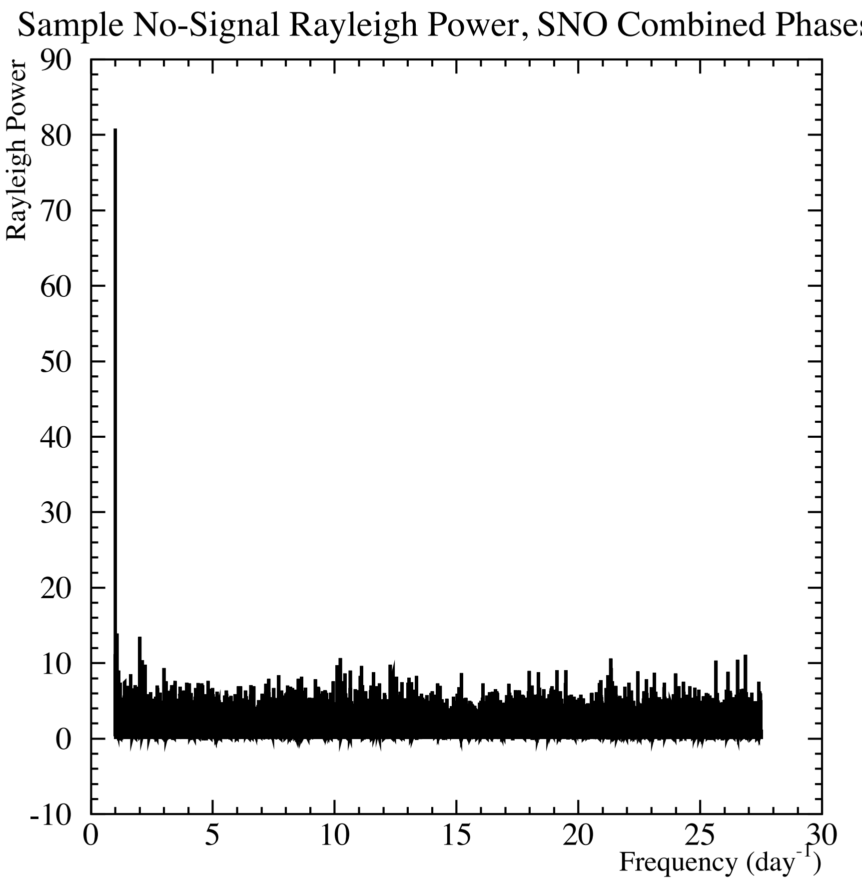




Determination of Confidence Levels



Using analytic form for each frequency, find CL for each frequency sampled in 10,000 MC "data" sets



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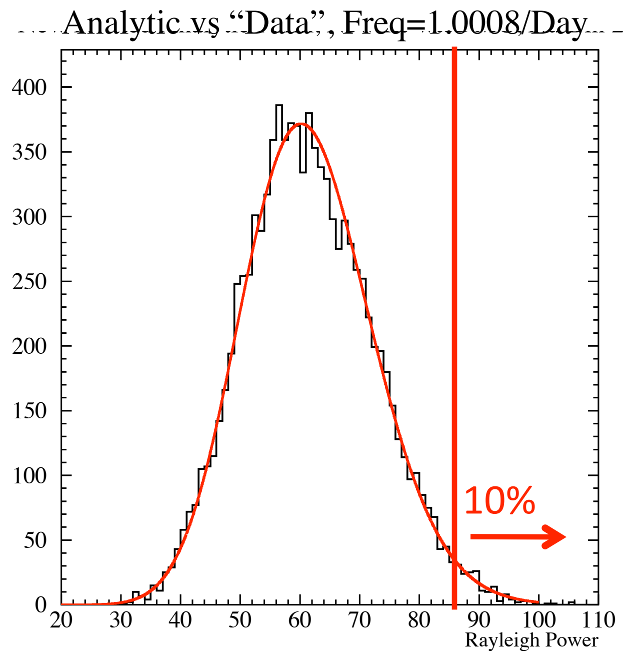
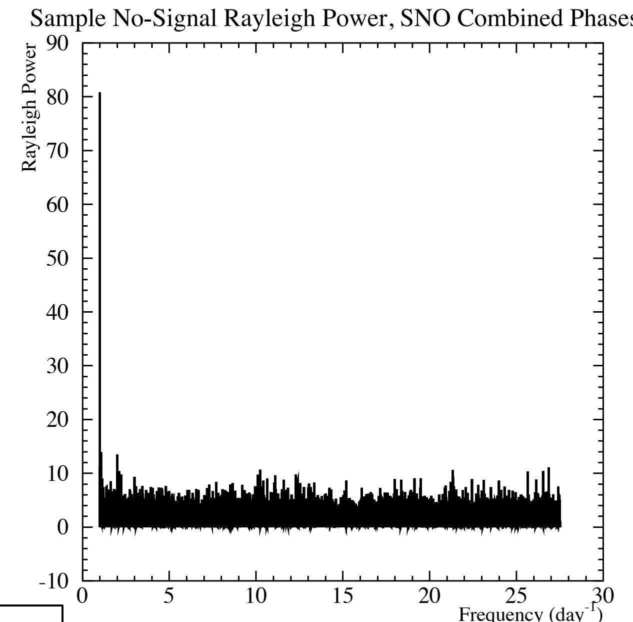
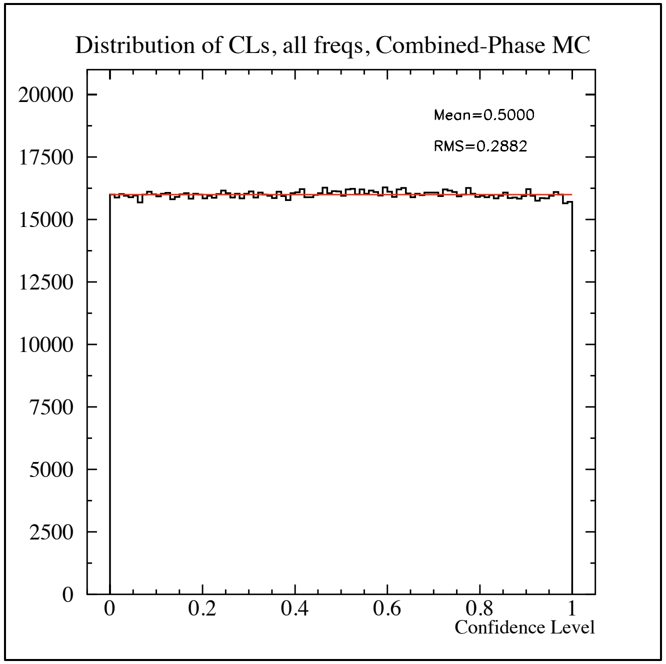
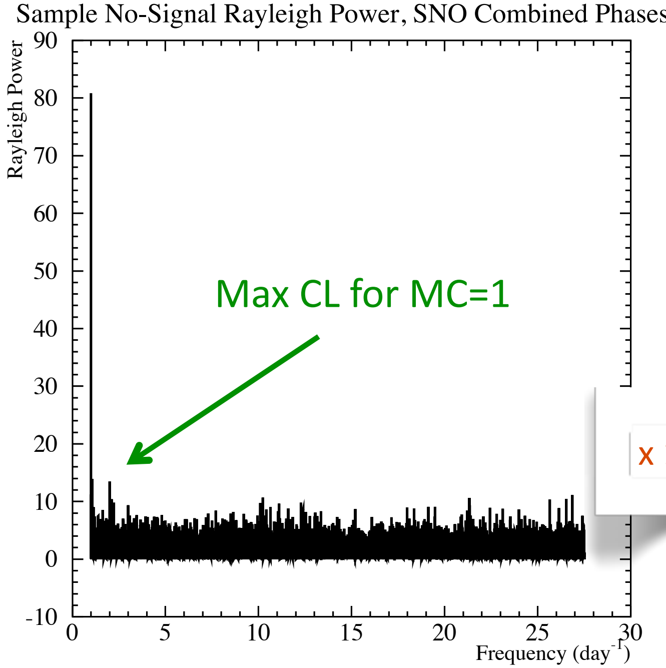


Analytic Form gives expected distribution of confidence levels for all frequencies of no-signal Monte Carlo: mean=0.5000



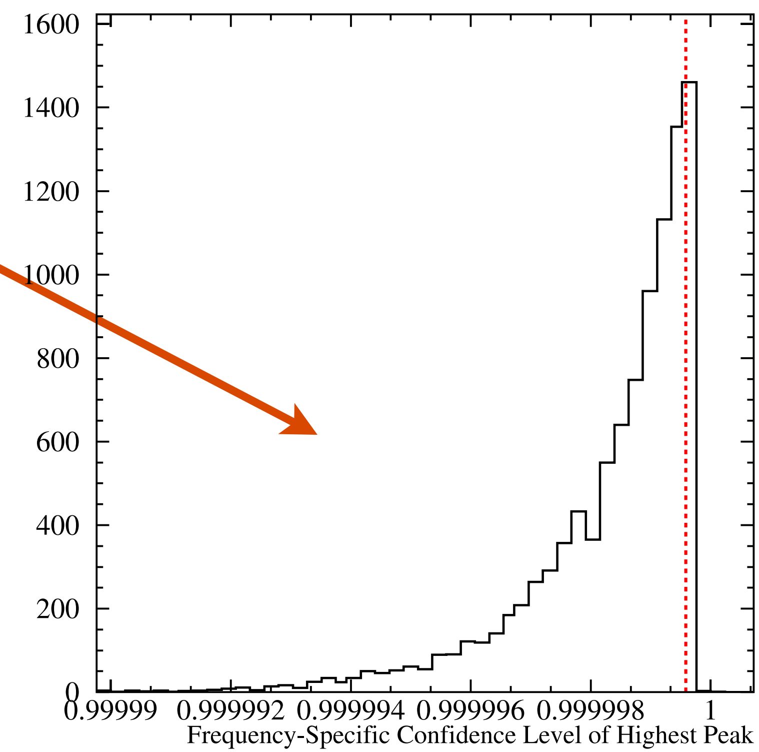


Determination of Confidence Levels



x 10,000

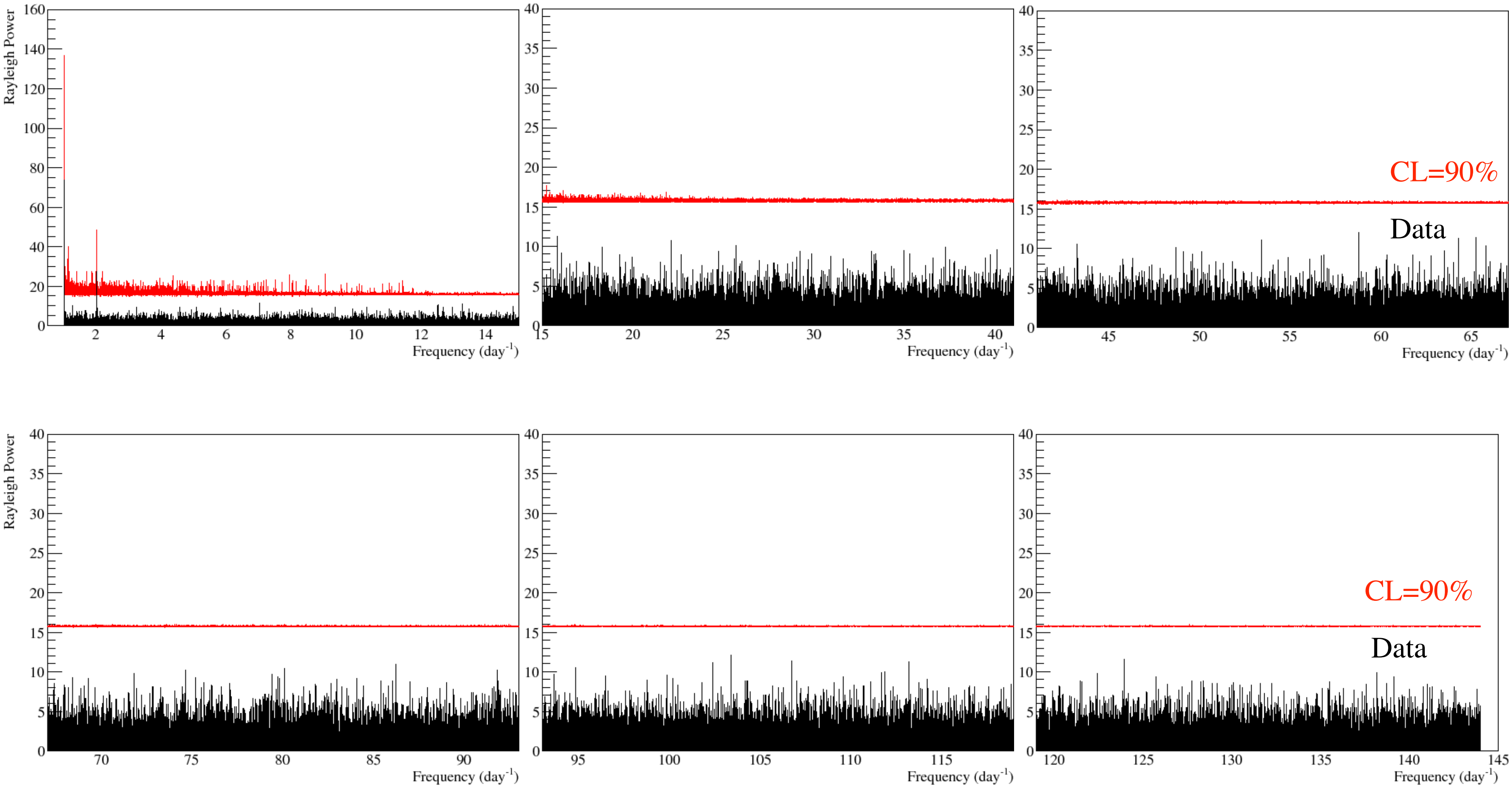
Collect maximum confidence level value for each of 10,000 MC data sets, to obtain a "CL of CLs":



Using analytic form for each frequency:

- Find CL for each frequency sampled in each MC data set (power spectrum for 1 MC data set -> 1.6 million sampled frequencies)
- In each of 10,000 MC data sets, find 'local maximum' CL
- Compile all 10,000 'local maximum' CL values

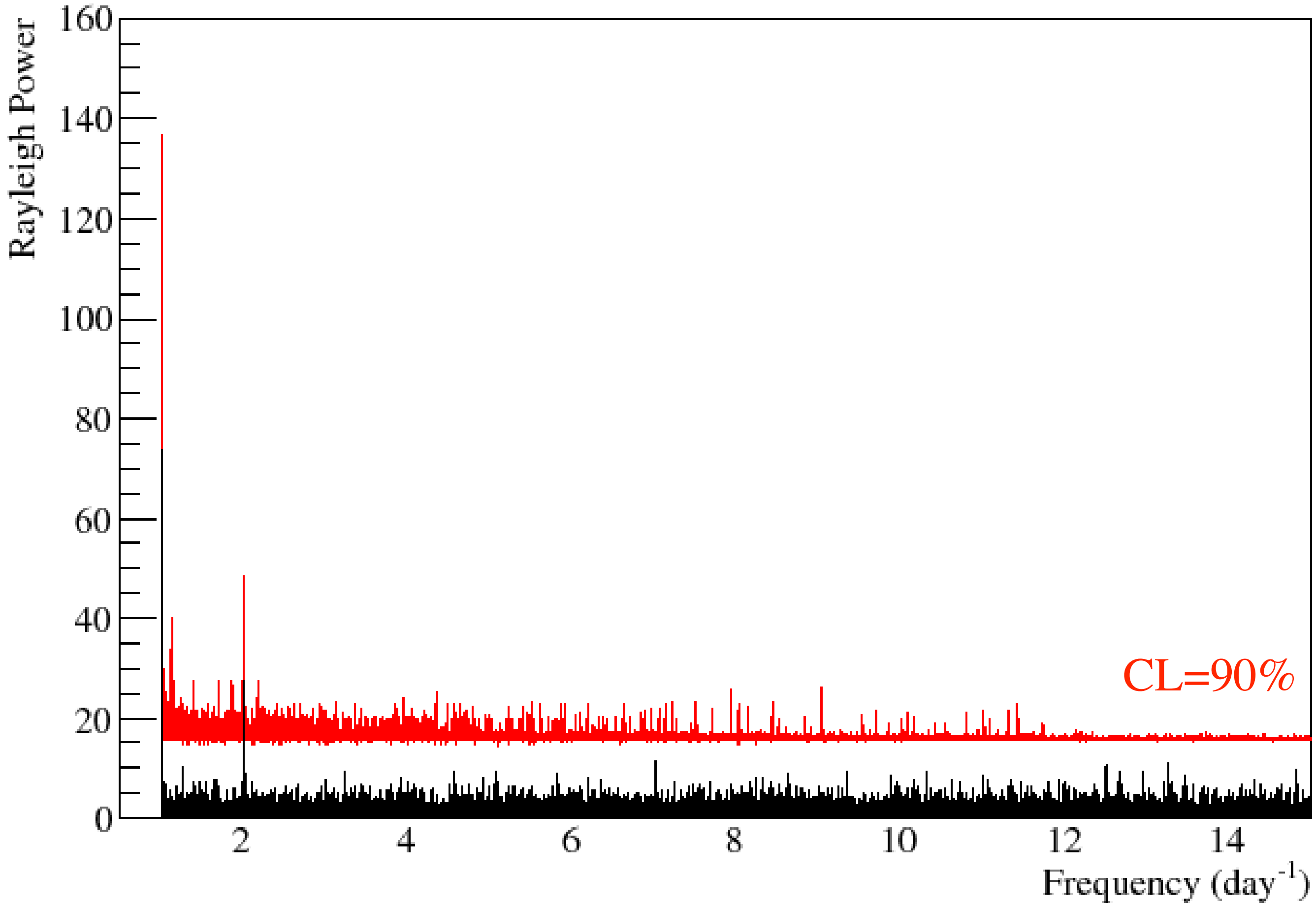
High Frequency Periodicity Results



Highest-Confidence Level Peak: 103.385/day at 2% CL

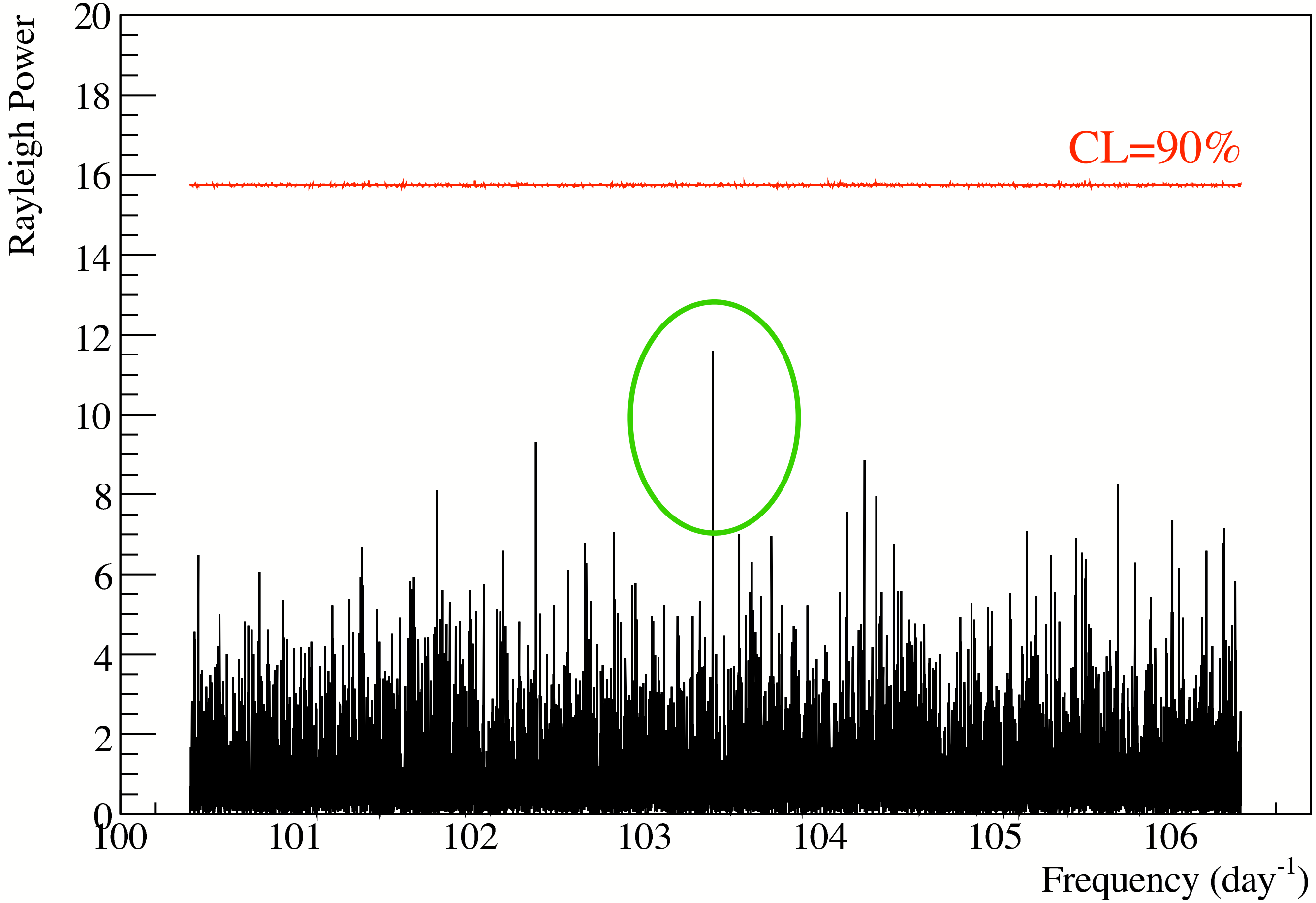
→ No high-frequency periodicity in SNO dataset!!

High Frequency Periodicity Results



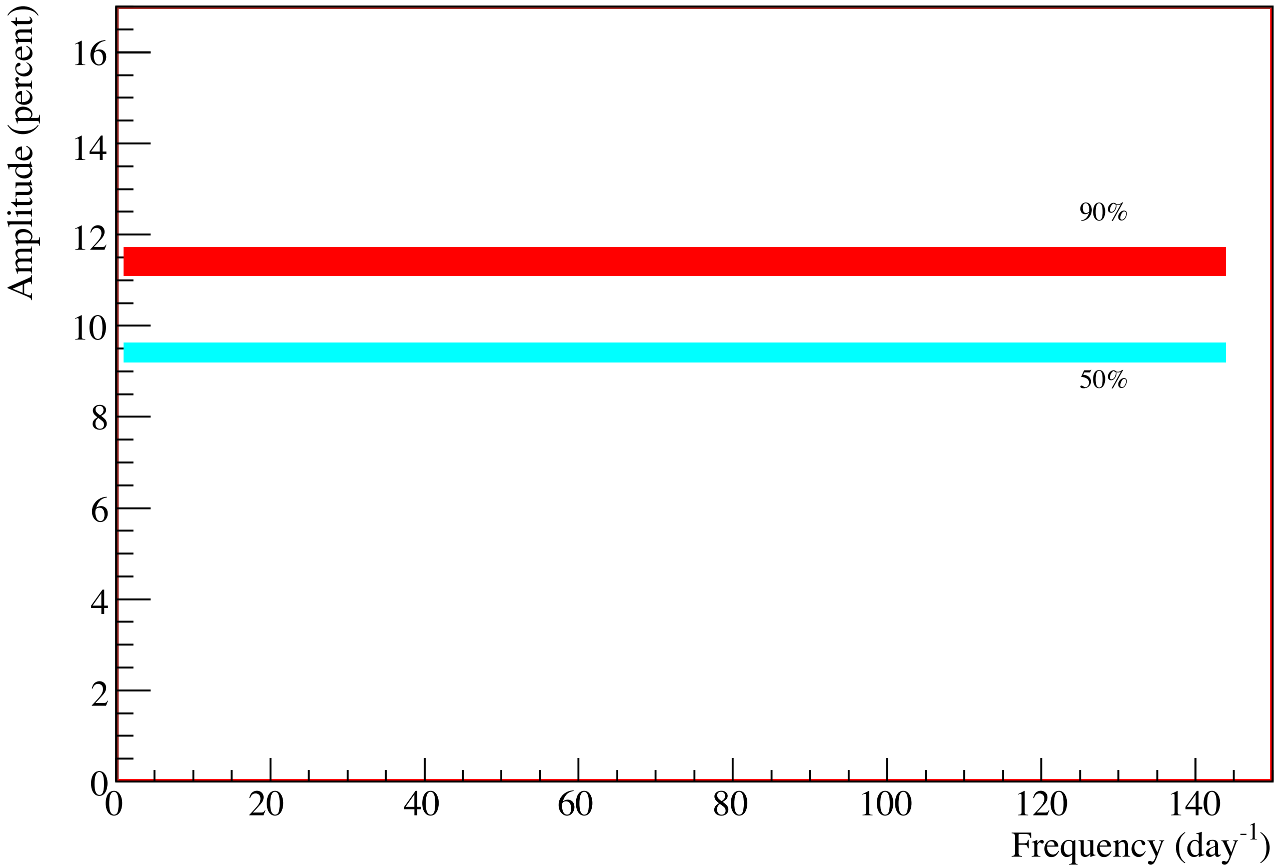
Zoomed-in View of Low-frequency Region of High-frequency Search

High Frequency Periodicity Results



Zoomed-in View of Highest Peak in SNO dataset
Frequency=103.38/day   Rayleigh Power=12.06

High Frequency Rayleigh Power Sensitivity



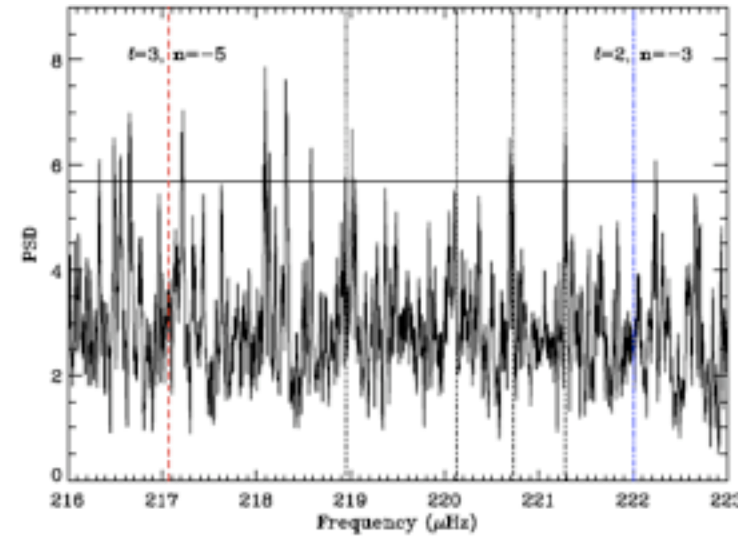
Demonstrates the strength of signal that would be necessary for SNO to be able to claim 99%-confidence detection with 50% chance, and with 90% chance

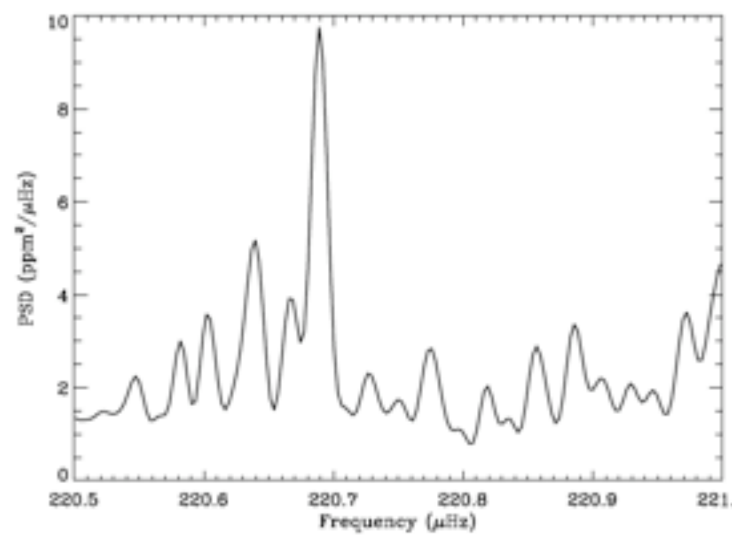
SNO and SoHO

- GOLF experiment (aboard SoHO) recently claimed discovery of signal at 220.7 μHz, or ~19.07/day
- Signal corroborated by VIRGO (also aboard SoHO)
- Searching for a specific signal: can afford to sample smaller range of frequencies
- Directed region of frequency – SNO can sample, reduce Trials penalty

➡ Run "Directed" Search:

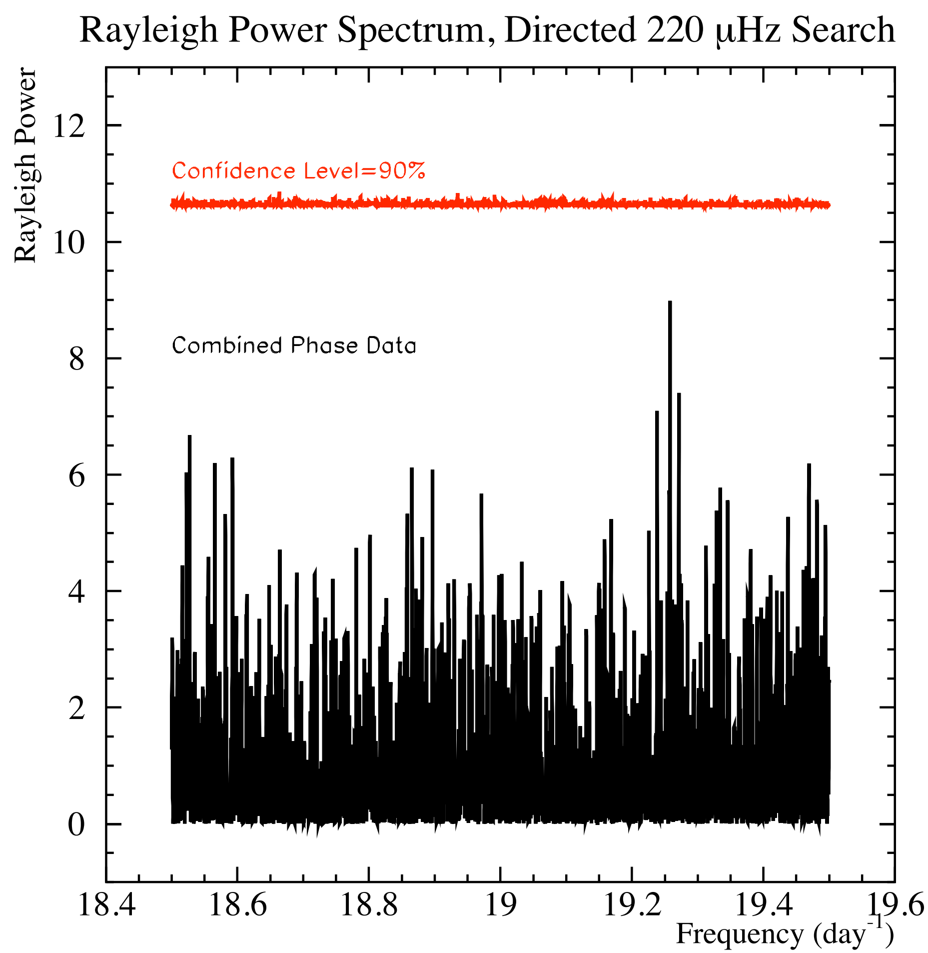
  - ✦ No-signal MC
  - ✦ Confidence Level Generation
  - ✦ CL of CL's
  - ✦ Signal MC
  - ✦ Sensitivity Contours





Update on g-mode Research, R. Garcia et al., AN 999, No. 88, 1-9 (2006)

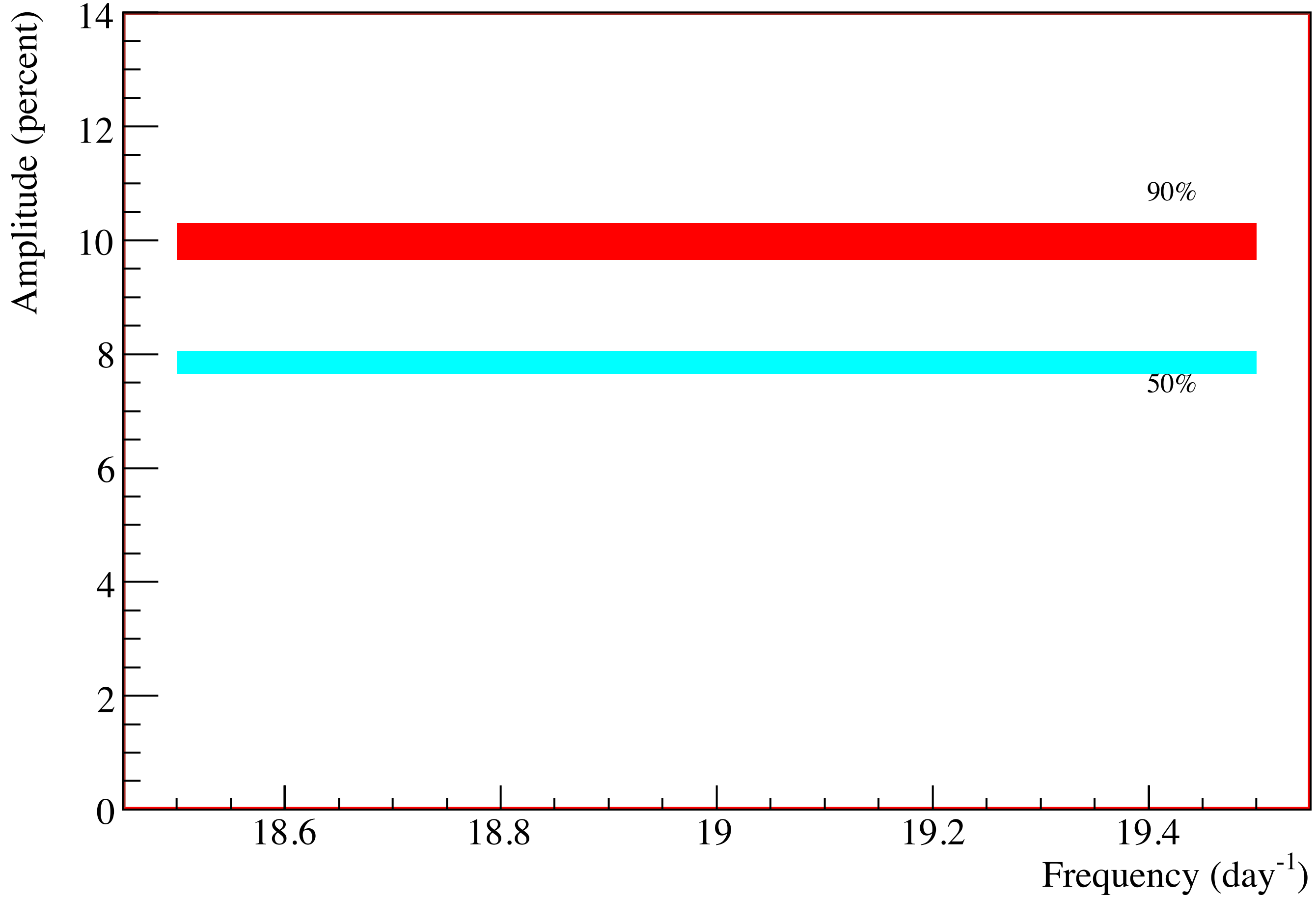
Directed Search Results



Highest-Confidence Level Peak: 19.2579/day at 58% CL

→ No High-frequency periodicity in SNO directed dataset!

Directed Search Sensitivity



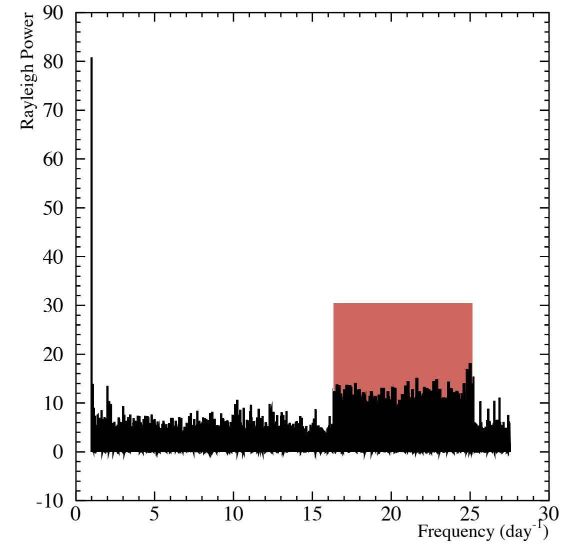
Sensitivities better for directed-search region than full-search region due to improvement on Trials penalty

High-Frequency "Noise" Search: Method

• Single-peak detection replaced by multiple-peak detection

• Individual Rayleigh powers likely to be insignificant in single-peak search, but collectively significant

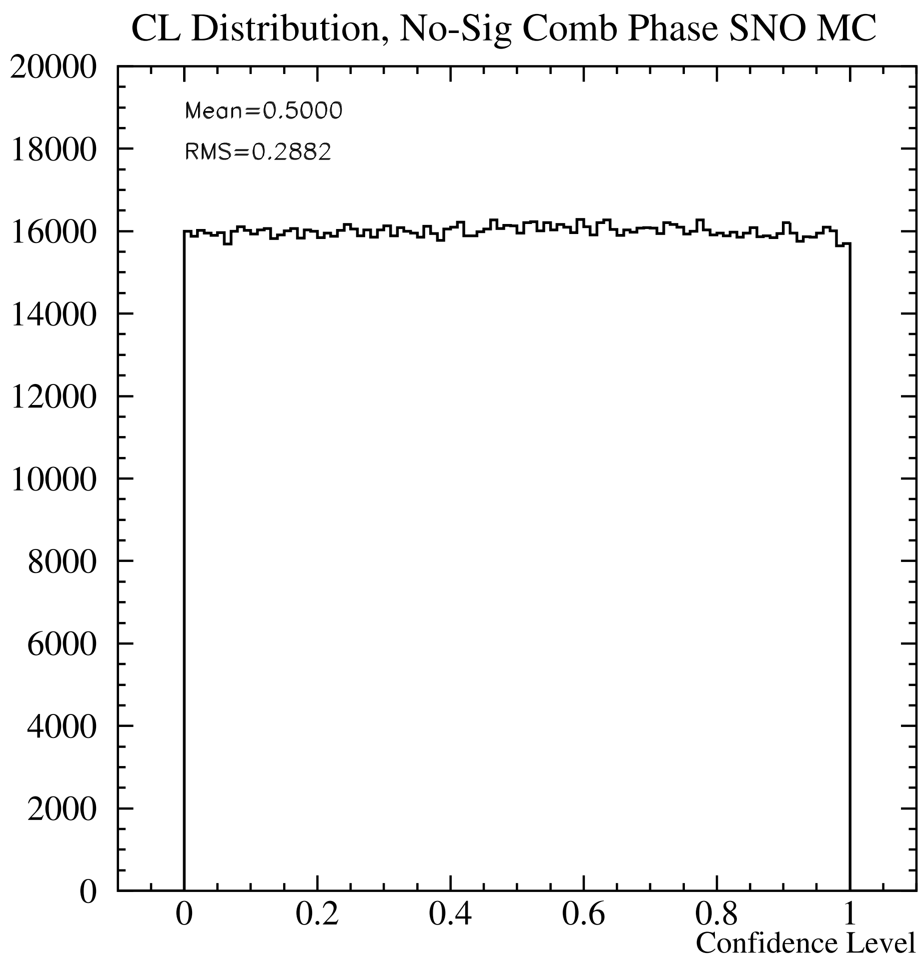
• Overall power spectrum will be distorted if multiple peaks deviate from null-hypothesis distributions



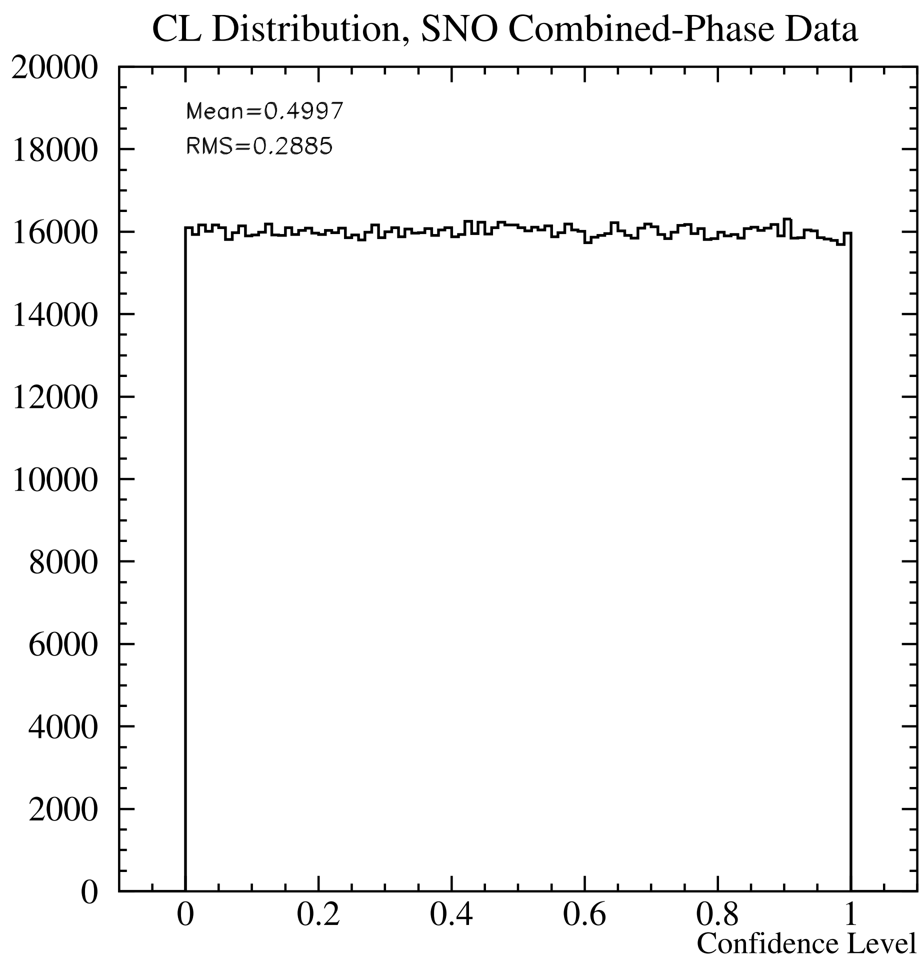
→ Search for noise by looking at distribution of Rayleigh powers' confidence levels

High-Frequency "Noise" Search:

Null-Hypothesis Monte Carlo

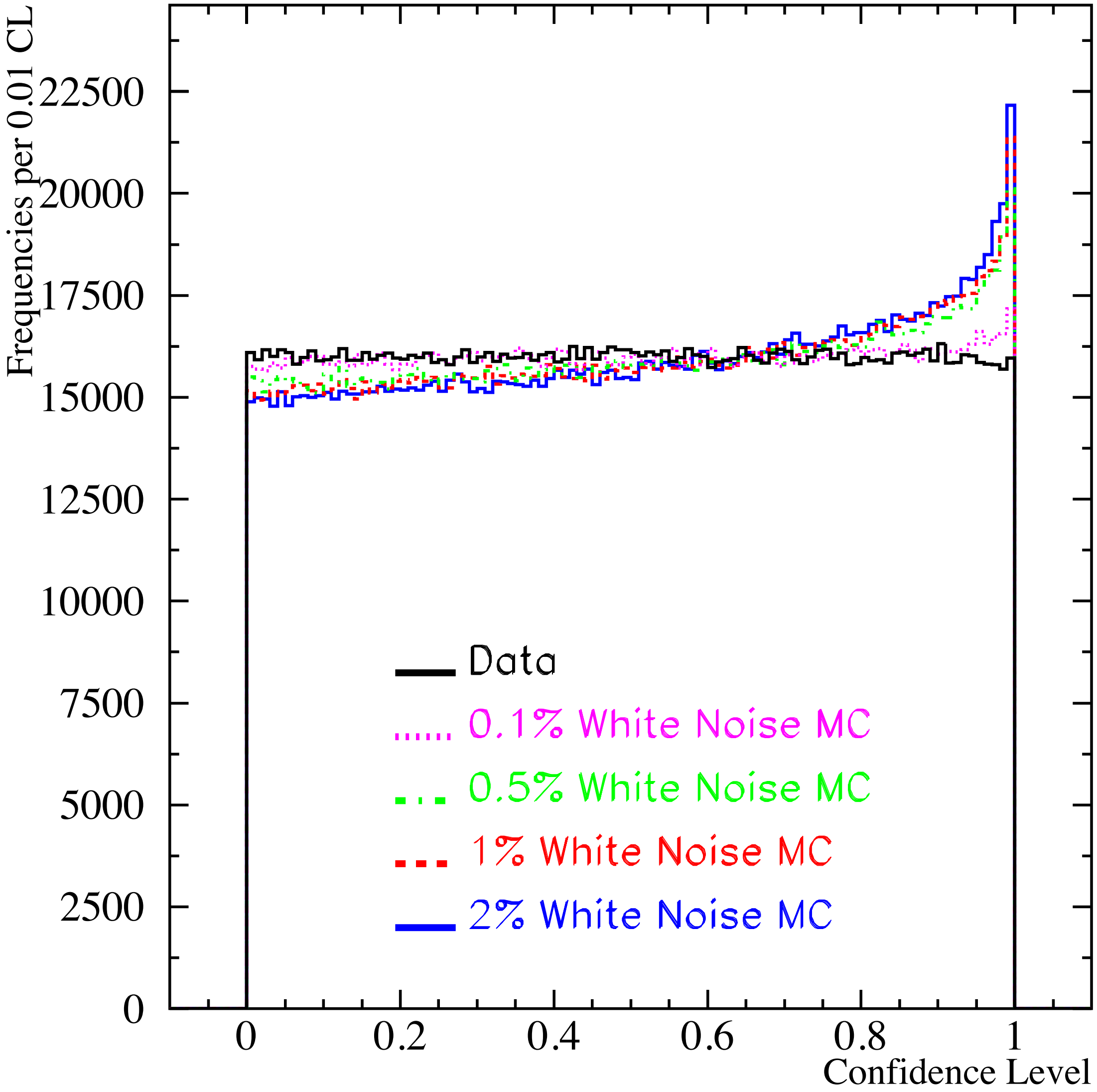


High-Frequency "Noise" Search:
SNO Combined-Phase Data



High-Frequency "Noise" Search:

White Noise Signal Monte Carlo



Conclusion

- Theoretical and experimental motivations for high frequency signal: *g*-modes, density fluctuations could affect neutrino production or neutrino propagation
- Used modified Rayleigh power approach to determine power and significance at 1.6 million frequencies
- No high-frequency signal detected in SNO solar neutrino flux, for general (g-mode), directed (GOLF-motivated), or broadband ("noise") search
- Findings published in February 10 issue of ApJ: *Searches for high-frequency variations in the ^{8}B solar neutrino flux at the Sudbury Neutrino Observatory* ApJ **710** (2010) 540-548.