Determinantal Expansions in Random Matrix Theory and Number Theory

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Random Matrix Theory - Number Theory Connection

Measures of Spacings: n-Level Density and Families

Let ϕ_i be even Schwartz functions whose Fourier Transform is compactly supported, $L(s, f)$ an L-function with zeros $\frac{1}{2} + i\gamma_f$ and conductor Q_f:

$$D_{n,f}(\phi) = \sum_{\substack{j_1,\dots,j_n \\ j_i \neq \pm j_k}} \phi_1\left(\gamma_{j_1;f}\frac{\log Q_f}{2\pi}\right)\cdots\phi_n\left(\gamma_{j_n;f}\frac{\log Q_f}{2\pi}\right)$$

Measures of Spacings: *n*-Level Density and Families

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- Properties of *n*-level density:
  - ◇ Individual zeros contribute in limit
  - ◇ Most of contribution is from low zeros
  - ◇ Average over similar *L*-functions (family)

n-Level Density

n-level density: $\mathcal{F} = \cup \mathcal{F}_N$ a family of L-functions ordered by conductors, ϕ_k an even Schwartz function: $D_{n,\mathcal{F}}(\phi) =$

$$\lim_{N\to\infty} \frac{1}{|\mathcal{F}_N|} \sum_{f \in \mathcal{F}_N} \sum_{\substack{j_1,\dots,j_n \\ j_i \neq \pm j_k}} \phi_1\left(\gamma_{j_1;f}\frac{\log Q_f}{2\pi}\right)\cdots\phi_n\left(\gamma_{j_n;f}\frac{\log Q_f}{2\pi}\right)$$

As $N \to \infty$, n-level density converges to

$$\int \phi(\overrightarrow{x})\rho_{n,\mathcal{G}(\mathcal{F})}(\overrightarrow{x})d\overrightarrow{x} \quad = \quad \int \widehat{\phi}(\overrightarrow{u})\widehat{\rho}_{n,\mathcal{G}(\mathcal{F})}(\overrightarrow{u})d\overrightarrow{u}.$$

Conjecture (Katz-Sarnak)

Scaled distribution of zeros near central point agrees with scaled distribution of eigenvalues near 1 of a classical compact group (in the limit).

Number Theory: Extending the Support

Goal:

Prove n-level densities agree for $\text{supp}(\widehat{\phi}) \subset \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$.

Philosophy:

Number theory harder - adapt tools to get an answer.
Random matrix theory easier - manipulate known answer.

Theorem (ILS)

Let Ψ *be an even Schwartz function with* $\text{supp}(\widehat{\Psi}) \subset (-2, 2)$. *Then*

$$\sum_{m \le N^\epsilon} \frac{1}{m^2} \sum_{(b,N)=1} \frac{R(m^2, b) R(1, b)}{\varphi(b)} \int_{y=0}^{\infty} J_{k-1}(y) \widehat{\Psi}\left(\frac{2 \log(by\sqrt{N}/4\pi m)}{\log R}\right) \frac{\mathrm{d}y}{\log R}$$
$$= -\frac{1}{2}\left[\int_{-\infty}^{\infty} \Psi(x) \frac{\sin 2\pi x}{2\pi x} \mathrm{d}x - \frac{1}{2}\Psi(0)\right] + O\left(\frac{k \log\log kN}{\log kN}\right),$$

where $R = k^2 N$, φ *is Euler's totient function, and* $R(n, q)$ *is a Ramanujan sum.*

2-Level Density

$$\int_{x_1=2}^{R^\sigma}\int_{x_2=2}^{R^\sigma}\widehat{\phi}\left(\frac{\log x_1}{\log R}\right)\widehat{\phi}\left(\frac{\log x_2}{\log R}\right)J_{k-1}\left(\frac{4\pi\sqrt{m^2x_1x_2N}}{c}\right)\frac{dx_1dx_2}{\sqrt{x_1x_2}}$$

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Change of variables and Jacobean:

$$\begin{aligned} u_2 &= x_1 x_2 & \qquad x_2 &= \tfrac{u_2}{u_1} \\ u_1 &= x_1 & \qquad x_1 &= u_1 \end{aligned}$$

$$\left|\frac{\partial x}{\partial u}\right| = \left|\begin{matrix} 1 & 0 \\ -\frac{u_2}{u_1^2} & \frac{1}{u_1} \end{matrix}\right| = \frac{1}{u_1}.$$

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Left with

$$\int\int\widehat{\phi}\left(\frac{\log u_1}{\log R}\right)\widehat{\phi}\left(\frac{\log\left(\frac{u_2}{u_1}\right)}{\log R}\right)\frac{1}{\sqrt{u_2}}J_{k-1}\left(\frac{4\pi\sqrt{m^2u_2N}}{c}\right)\frac{du_1du_2}{u_1}$$

2-Level Density (continued)

Changing variables, u_1-integral is

$$\int_{w_1=\frac{\log u_2}{\log R}-\sigma}^{\sigma} \widehat{\phi}(w_1)\,\widehat{\phi}\left(\frac{\log u_2}{\log R}-w_1\right)dw_1.$$

2-Level Density (continued)

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$$\int_{w_1=\frac{\log u_2}{\log R}-\sigma}^{\sigma} \widehat{\phi}(w_1)\,\widehat{\phi}\left(\frac{\log u_2}{\log R}-w_1\right)dw_1.$$

Support conditions imply

$$\Psi_2\left(\frac{\log u_2}{\log R}\right) = \int_{w_1=-\infty}^{\infty} \widehat{\phi}(w_1)\,\widehat{\phi}\left(\frac{\log u_2}{\log R}-w_1\right)dw_1.$$

2-Level Density (continued)

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Substituting gives

$$\int_{u_2=0}^{\infty} J_{k-1}\left(\frac{4\pi\sqrt{m^2u_2N}}{c}\right)\Psi_2\left(\frac{\log u_2}{\log R}\right)\frac{du_2}{\sqrt{u_2}}$$

Number Theory Side: Hughes-Miller: $\text{supp}(\widehat{\phi}) \subset (-\frac{1}{n-1}, \frac{1}{n-1})$

Sequence of Lemmas

1. Apply Petersson Formula

Theorem (Modified Petersson Formula - ILS)

If N is prime and $(n, N^2)|N$, then

$$\sum_{f \in H_k^\sigma(N)} \lambda_f(n) = \frac{(k-1)N}{12\sqrt{n}} \delta_{n,\square Y} + \Delta_{k,N}^\infty(n)$$

$$+ \frac{(k-1)N}{12} \sum_{\substack{(m,N)=1 \\ m \le Y}} \frac{2\pi i^k}{m} \sum_{\substack{c \equiv 0 \bmod N \\ c \ge N}} \frac{S(m^2, n; c)}{c} J_{k-1}\left(4\pi \frac{\sqrt{m^2 n}}{c}\right),$$

where $\delta_{n,\square Y} = 1$ if $n = a^2$ for $a \le Y$ and 0 otherwise.

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Sequence of Lemmas

1. Apply Petersson Formula

2. Restrict Certain Sums

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Sequence of Lemmas

1. Apply Petersson Formula
2. Restrict Certain Sums
3. Convert Kloosterman Sums to Gauss Sums

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Sequence of Lemmas

1. Apply Petersson Formula
2. Restrict Certain Sums
3. Convert Kloosterman Sums to Gauss Sums
4. Remove Non-Principal Characters

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1. Apply Petersson Formula
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5. Convert Sums to Integrals

New Results: Iyer-Miller-Triantafillou: $\text{supp}(\widehat{\phi}) \subset (-\frac{1}{n-2}, \frac{1}{n-2})$

Sequence of Lemmas - New Contributions Arise

1. Apply Petersson Formula
2. Restrict Certain Sums
3. Convert Kloosterman Sums to Gauss Sums
4. Remove Non-Principal Characters
5. Convert Sums to Integrals

New Results: Number Theory Side: Iyer-Miller-Triantafillou: $\text{supp}(\widehat{\phi}) \subset \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$

Typical Argument

If any prime is 'special', bound error terms

$$\ll \frac{1}{\sqrt{N}} \sum_{p_1,\dots,p_n \le N^\sigma} \sum_{m \le N^\epsilon} \sum_{r=1}^{\infty} \frac{m^2 r}{r p_1} \frac{\sqrt{p_1 \cdots p_n}}{r p_1 \sqrt{N}} \frac{1}{\sqrt{p_1 \cdots p_n}}$$

$$\ll N^{-1+\epsilon'} \left(\sum_{p \le N^\sigma} 1 \right)^{n-1} \ll N^{-1+(n-1)\sigma+\epsilon'}$$

Bounds fail for large support - new terms arise.

Converting Sums to Integrals - Hughes-Miller: $\mathrm{supp}(\widehat{\phi}) \subset (-\frac{1}{n-1}, \frac{1}{n-1})$

We want to evaluate

$$\sum_{n_1,\dots,n_n} \left[\prod_{i=1}^{n} \hat{\phi}\left(\frac{\log n_i}{\log R}\right) \frac{\chi_0(n_i)\Lambda(n_i)}{\sqrt{n_i}\log R}\right] J_{k-1}\left(\frac{4\pi m\sqrt{n_1\cdots n_n}}{b\sqrt{N}}\right)$$

$$= \frac{1}{2\pi i}\int_{\mathfrak{Re}(s)=1} \left[\prod_{i=1}^{n}\sum_{n_i} \hat{\phi}\left(\frac{\log n_i}{\log R}\right) \frac{\chi_0(n_i)\Lambda(n_i)}{\sqrt{n_i}\log R}\right] \times \left(\frac{4\pi m\sqrt{n_1\cdots n_n}}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds$$

Converting Sums to Integrals - Hughes-Miller: $\mathrm{supp}(\widehat{\phi}) \subset (-\frac{1}{n-1}, \frac{1}{n-1})$

Important Observation

$$\sum_{r=1}^{\infty} \hat{\phi}\left(\frac{\log r}{\log R}\right) \frac{\chi_0(r)\Lambda(r)}{r^{(1+s)/2}\log R} = \phi\left(\frac{1-s}{4\pi i}\log R\right) + \mathcal{E}(s),$$

where

$$\mathcal{E}(s) = -\frac{1}{2\pi i}\int_{\mathfrak{Re}(z)=c} \phi\left(\frac{(2z-1-s)\log R}{4\pi i}\right)\frac{L'}{L}(z,\chi_0)dz.$$

For convenience, rename expressions, $X = Y + Z$.

Converting Sums to Integrals - Hughes-Miller: $\text{supp}(\widehat{\phi}) \subset (-\frac{1}{n-1}, \frac{1}{n-1})$

Important Observation

By the binomial theorem,

$$\begin{aligned}
&\frac{1}{2\pi i}\int_{\Re\mathfrak{e}(s)=1} X^n \left(\frac{4\pi m}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds \\
=&\frac{1}{2\pi i}\int_{\Re\mathfrak{e}(s)=1} (Y+Z)^n \left(\frac{4\pi m}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds \\
=&\sum_{j=0}^{n}\binom{n}{j}\frac{1}{2\pi i}\int_{\Re\mathfrak{e}(s)=1} Y^{n-j}Z^j \left(\frac{4\pi m}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds.
\end{aligned}$$

Converting Sums to Integrals - Hughes-Miller: $\mathrm{supp}(\widehat{\phi}) \subset (-\frac{1}{n-1}, \frac{1}{n-1})$

$Z = \mathcal{E}(s)$ is easy to bound (shift coutours), get

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$$\ll N^{(n-j)\sigma/2+\epsilon''}$$

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For $\sigma < \frac{1}{n-1}$, only $j = 0$ term is non-negligible.

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Unfortunately, $Z = \mathcal{E}(s)$ is hard to compute with.

Converting Sums to Integrals - Iyer-Miller-Triantafillou: $\mathrm{supp}(\widehat{\phi}) \subset (-\frac{1}{n-2}, \frac{1}{n-2})$

Key idea: Recall $X = Y + Z$, write $Z = X - Y$.

Converting Sums to Integrals - Iyer-Miller-Triantafillou: $\text{supp}(\widehat{\phi}) \subset (-\frac{1}{n-2}, \frac{1}{n-2})$

Key idea: Recall $X = Y + Z$, write $Z = X - Y$.

$$\begin{aligned} &\frac{n}{2\pi i}\int_{\Re\mathfrak{e}(s)=1} Y^{n-1}Z\left(\frac{4\pi m}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds \\ = &\frac{n}{2\pi i}\int_{\Re\mathfrak{e}(s)=1} XY^{n-1}\left(\frac{4\pi m}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds \\ - &\frac{n}{2\pi i}\int_{\Re\mathfrak{e}(s)=1} Y^{n}\left(\frac{4\pi m}{b\sqrt{N}}\right)^{-s} G_{k-1}(s)ds. \end{aligned}$$

Hughes-Miller handle Y^n term, XY^{n-1} term is similar.

Converting Sums to Integrals - Iyer-Miller-Triantafillou: $\mathrm{supp}(\widehat{\phi}) \subset (-\frac{1}{n-2}, \frac{1}{n-2})$

When the dust clears, we see

$$\begin{aligned}
&\sum_{n_1,\dots,n_n} \left[\prod_{i=1}^{n} \hat{\phi}\left(\frac{\log n_i}{\log R}\right) \frac{\chi_0(n_i)\Lambda(n_i)}{\sqrt{n_i}\log R}\right] J_{k-1}\left(\frac{4\pi m\sqrt{n_1\cdots n_n}}{b\sqrt{N}}\right) \\
=&(1-n)\left(\int_{-\infty}^{\infty} \phi(x)^n \frac{\sin 2\pi x}{2\pi x} dx - \frac{1}{2}\phi(0)^n\right) \\
&+ n\left(\int_{-\infty}^{\infty} \hat{\phi}(x_2) \int_{-\infty}^{\infty} \phi^{n-1}(x_1) \frac{\sin(2\pi x_1(1-|x_2|))}{2\pi x_1} dx_1 dx_2 \right. \\
&\left. - \frac{1}{2}\phi^n(0)\right) + o(1)
\end{aligned}$$

New Results: Number Theory Side: Iyer-Miller-Triantafillou: $\text{supp}(\widehat{\phi}) \subset (-\frac{1}{n-2}, \frac{1}{n-2})$

Theorem

Fix $n \geq 4$ and let ϕ be an even Schwartz function with $\text{supp}(\widehat{\phi}) \subset \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$. Then, the nth centered moment of the 1-level density for holomorphic cusp forms is

$$\frac{1+(-1)^n}{2}(-1)^n(n-1)!!\left(2\int_{-\infty}^{\infty}\hat{\phi}(y)^2|y|dy\right)^{n/2}$$
$$\pm(-2)^{n-1}\left(\int_{-\infty}^{\infty}\phi(x)^n\frac{\sin 2\pi x}{2\pi x}dx - \frac{1}{2}\phi(0)^n\right)$$
$$\mp(-2)^{n-1}n\left(\int_{-\infty}^{\infty}\hat{\phi}(x_2)\int_{-\infty}^{\infty}\phi^{n-1}(x_1)\frac{\sin(2\pi x_1(1+|x_2|))}{2\pi x_1}dx_1dx_2 - \frac{1}{2}\phi^n(0)\right).$$

Compare to ...

Random Matrix Theory: New Combinatorial Vantage

n-Level Density: Katz-Sarnak Determinant Expansions

Example: SO(even)

$$\int_{-\infty}^{\infty} \cdots \int_{-\infty}^{\infty} \widehat{\phi}(x_1) \cdots \widehat{\phi}(x_n) \det\left(K_1(x_j, x_k)\right)_{1 \le j,k \le n} dx_1 \cdots dx_n,$$

where

$$K_1(x, y) = \frac{\sin\left(\pi(x-y)\right)}{\pi(x-y)} + \frac{\sin\left(\pi(x+y)\right)}{\pi(x+y)}.$$

n-Level Density: Katz-Sarnak Determinant Expansions

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Problem: n-dimensional integral - looks very different.

Preliminaries

Easier to work with cumulants.

$$\sum_{n=1}^{\infty} C_n \frac{(it)^n}{n!} = \log \widehat{P}(t),$$

where P is the probability density function.

$$\mu'_n = C_n + \sum_{m=1}^{n-1} \binom{n-1}{m-1} C_m \mu'_{n-m},$$

where μ'_n is uncentered moment.

Preliminaries

Manipulating determinant expansions leads to analysis of

$$K(y_1,\dots,y_n) = \sum_{m=1}^{n} \sum_{\substack{\lambda_1+\dots+\lambda_m=n \\ \lambda_j\geq 1}} \frac{(-1)^{m+1}}{m} \frac{n!}{\lambda_1!\cdots\lambda_m!}$$
$$\sum_{\epsilon_1,\dots,\epsilon_n=\pm 1} \prod_{\ell=1}^{m} \chi_{\left\{\left|\sum_{j=1}^{n} \eta(\ell,j)\epsilon_j y_j\right|\leq 1\right\}},$$

where

$$\eta(\ell,j) = \begin{cases} +1 & \text{if } j \leq \sum_{k=1}^{\ell} \lambda_k \\ -1 & \text{if } j > \sum_{k=1}^{\ell} \lambda_k. \end{cases}$$

New Result: Iyer-Miller-Triantafillou: Large Support: $\text{supp}(\widehat{\phi}) \subseteq \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$

Hughes-Miller solved for $\text{supp}(\widehat{\phi}) \subseteq (-\frac{1}{n-1}, \frac{1}{n-1})$.

New Complications: If $\text{supp}(\widehat{\phi}) \subseteq (-\frac{1}{n-2}, \frac{1}{n-2})$,

1. $\eta(\ell, j)\epsilon_j y_j$ need not have same sign (at most one can differ);
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Solution: Double count terms and subtract a correcting term ρ_j.

Generating Function Identity - $\lambda_i \geq 1$

$$\sum_{n=0}^{\infty} \frac{(-1)^n}{n!} x^n = e^{-x} = \frac{1}{1-(1-e^x)} = \sum_{m=0}^{\infty} (1-e^x)^m$$

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$$= \sum_{m=0}^{\infty} (-1)^m \left(\sum_{\lambda=1}^{\infty} \frac{1}{\lambda!} x^{\lambda} \right)^m = \sum_{n=0}^{\infty} \left(\sum_{m=1}^{\infty} \sum_{\lambda_1+\cdots+\lambda_m=n} \frac{(-1)^m}{\lambda_1!\cdots\lambda_m!} \right) x^n$$

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$$\Rightarrow (-1)^n = \sum_{m=1}^{\infty} \sum_{\lambda_1+\cdots+\lambda_m=n} \frac{(-1)^m n!}{\lambda_1! \cdots \lambda_m!}.$$

New Result: Dealing With 'ρ_j's

All $\lambda_i, \lambda_i' \geq 1$.

$$\rho_j = \sum_{m=1}^{n} \sum_{l=1}^{m} \sum_{\substack{\lambda_1+\cdots+\lambda_{\ell-1}=j-1 \\ \lambda_\ell=1 \\ \lambda_{\ell+1}+\cdots+\lambda_m=n-j}} \frac{(-1)^m}{m} \frac{n!}{\lambda_1!\cdots\lambda_m!}$$

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$$= n \sum_{m=1}^{n} \sum_{\ell=1}^{m} \sum_{\lambda_1'+\cdots+\lambda_{m-1}'=n-1} \frac{(-1)^m}{m} \frac{(n-1)!}{\lambda_1'!\cdots\lambda_{m-1}'!}$$

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$$\sum_{j=1}^{n} \rho_j = \sum_{j=1}^{n}\sum_{m=1}^{n}\sum_{\ell=1}^{m} \sum_{\substack{\lambda_1+\cdots+\lambda_{\ell-1}=j-1 \\ \lambda_\ell=1 \\ \lambda_{\ell+1}+\cdots+\lambda_m=n-j}} \frac{(-1)^m}{m} \frac{n!}{\lambda_1!\cdots\lambda_m!}$$

$$= n\sum_{m=1}^{n}\sum_{\ell=1}^{m} \sum_{\lambda_1'+\cdots+\lambda_{m-1}'=n-1} \frac{(-1)^m}{m} \frac{(n-1)!}{\lambda_1'!\cdots\lambda_{m-1}'!}$$

$$= n\sum_{m=1}^{n} \sum_{\lambda_1'+\cdots+\lambda_{m-1}'=n-1} (-1)\frac{(-1)^{m-1}(n-1)!}{\lambda_1'!\cdots\lambda_{m-1}'!}$$

New Result: Dealing With 'ρ_j's

All $\lambda_i, \lambda_i' \geq 1$.

$$\sum_{j=1}^{n} \rho_j = \sum_{j=1}^{n} \sum_{m=1}^{n} \sum_{\ell=1}^{m} \sum_{\substack{\lambda_1+\cdots+\lambda_{\ell-1}=j-1 \\ \lambda_\ell=1 \\ \lambda_{\ell+1}+\cdots+\lambda_m=n-j}} \frac{(-1)^m}{m} \frac{n!}{\lambda_1!\cdots\lambda_m!}$$

$$= n \sum_{m=1}^{n} \sum_{\ell=1}^{m} \sum_{\lambda_1'+\cdots+\lambda_{m-1}'=n-1} \frac{(-1)^m}{m} \frac{(n-1)!}{\lambda_1'!\cdots\lambda_{m-1}'!}$$

$$= n \sum_{m=1}^{n} \sum_{\lambda_1'+\cdots+\lambda_{m-1}'=n-1} (-1) \frac{(-1)^{m-1}(n-1)!}{\lambda_1'!\cdots\lambda_{m-1}'!}$$

$$= n(-1)^n.$$

New Result: Iyer-Miller-Triantafillou: Large Support: $\mathrm{supp}(\widehat{\phi}) \subseteq \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$

After Fourier transform identities:

New Result: Iyer-Miller-Triantafillou: Large Support: $\text{supp}(\widehat{\phi}) \subseteq \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$

After Fourier transform identities:

$$\begin{aligned} C_n^{\mathrm{SO}}(\phi) &= \frac{(-1)^{n-1}}{2}\left(\int_{-\infty}^{\infty} \phi(x)^n \frac{\sin 2\pi x}{2\pi x} dx - \frac{1}{2}\phi(0)^n\right) \\ &\quad + \frac{n(-1)^n}{2}\left(\int_{-\infty}^{\infty} \hat{\phi}(x_2) \int_{-\infty}^{\infty} \phi^{n-1}(x_1)\right. \\ &\quad\quad \left.\frac{\sin(2\pi x_1(1+|x_2|))}{2\pi x_1} dx_1 dx_2 - \frac{1}{2}\phi^n(0)\right). \end{aligned}$$

New Result: Iyer-Miller-Triantafillou: Large Support: $\mathrm{supp}(\widehat{\phi}) \subseteq \left(-\frac{1}{n-2}, \frac{1}{n-2}\right)$

After Fourier transform identities:

$$C_n^{\mathrm{SO}}(\phi) = \frac{(-1)^{n-1}}{2}\left(\int_{-\infty}^{\infty} \phi(x)^n \frac{\sin 2\pi x}{2\pi x} dx - \frac{1}{2}\phi(0)^n\right) + \frac{n(-1)^n}{2}\left(\int_{-\infty}^{\infty} \hat{\phi}(x_2) \int_{-\infty}^{\infty} \phi^{n-1}(x_1) \frac{\sin(2\pi x_1(1+|x_2|))}{2\pi x_1} dx_1 dx_2 - \frac{1}{2}\phi^n(0)\right).$$

Agrees with number theory!

Recap

Recap

1. Difficult to compare n-dimensional integral from RMT with NT in general. Harder combinatorics worthwhile to appeal to result from ILS.
2. Solve combinatorics by using cumulants; support restrictions translate to which terms can contribute.
3. Extend number theory results by bounding Bessel functions, Kloosterman sums, etc. New terms arise and match random matrix theory prediction.
4. Better bounds on percent of forms vanishing to large order at the center point.

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