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# MOMENT ZETA FUNCTIONS FOR TORIC CALABI-YAU HYPERSURFACES

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## 1. INTRODUCTION

Let  $n \geq 2$  be a positive integer. We consider the following family

$$X_\lambda : x_1 + \cdots + x_n + \frac{1}{x_1 \cdots x_n} = \lambda$$

of  $(n - 1)$ -dimensional toric Calabi-Yau hypersurfaces in  $\mathbb{G}_m^n$  parameterized by  $\lambda \in \mathbb{A}^1$ . Let  $\mathbb{P}_\Delta$  be the projective toric variety associated to the Newton polytope of the above Laurent polynomial. The projective closure  $Y_\lambda$  of  $X_\lambda$  in  $\mathbb{P}_\Delta$  is simply the quotient by  $G = (\mathbb{Z}/(n + 1)\mathbb{Z})^{n-1}$  of the following Dwork family of projective Calabi-Yau hypersurfaces in  $\mathbb{P}^n$ :

$$W_\lambda : x_0^{n+1} + \cdots + x_n^{n+1} = \lambda x_0 \cdots x_n.$$

The crepant resolution of the family  $Y_\lambda$  is the mirror family of  $W_\lambda$ .

Let  $\mathbb{F}_q$  be a finite field of  $q$  elements with characteristic  $p$ . In this paper, we are interested in the moment zeta function which measures the arithmetic variation of the zeta function of  $X_\lambda$  over  $\mathbb{F}_q$  as  $\lambda$  varies in  $\mathbb{F}_q$ . The moment zeta function grew out of the second author's study [28][29][30] of Dwork's unit root conjecture. Its general properties were studied in Fu-Wan [11] and Wan [26][31]. Note that the zeta function of  $Y_\lambda$  differs from the zeta function of  $X_\lambda$  by some trivial factors.

The zeta function of the Dwork family  $W_\lambda$  over finite fields had been studied extensively in the literature, first by Dwork [9] and Katz [17], and more recently in connection with arithmetic mirror symmetry by Candelas, de la Ossa and Rodriques-Villegas [3][4], and by Wan [33][34] and Fu-Wan [14]. By [33][34], the zeta function of  $X_\lambda$  is the most primitive piece of the zeta function of  $W_\lambda$ . Thus, we shall restrict ourself to the family  $X_\lambda$ . The Hasse-Weil zeta function (but not its higher moment zeta function which would seem to be too hard at the moment) in a similar number field example is studied in a recent paper by Harris, Shepherd-Barron and Taylor [16].

More precisely, for a positive integer  $d$ , let  $N_d(k)$  denote the number of points on the family  $X_\lambda$  such that  $x_i \in \mathbb{F}_{q^{dk}}$  for all  $1 \leq i \leq n$  and

$\lambda \in \mathbb{F}_{q^k}$ . The  $d$ -th moment zeta function of the morphism  $X_\lambda \rightarrow \lambda \in \mathbb{A}^1$  is defined to be

$$Z_d(\mathbb{A}^1, X_\lambda) = \exp\left(\sum_{k=1}^{\infty} \frac{N_d(k)}{k} T^k\right) \in 1 + T\mathbb{Z}[[T]].$$

This sequence  $Z_d(\mathbb{A}^1, X_\lambda)$  ( $d = 1, 2, \dots$ ) of power series gives a simple diophantine reformulation on the arithmetic variation of the zeta function of the family  $X_\lambda$ . It is a rational function in  $T$  for each  $d$ . In the special case  $n = 2$ ,  $X_\lambda$  is a family of elliptic curves and the moment zeta function  $Z_d(\mathbb{A}^1, X_\lambda)$  is closely related to arithmetic of modular forms. In general, Dwork's unit root zeta functions [10] attached to this family are the  $p$ -adic limits of this sequence of moment zeta functions. They are thus infinite  $p$ -adic moment zeta functions in some sense. Our aim of this paper is to give a precise study of this sequence  $Z_d(\mathbb{A}^1, X_\lambda)$  and their  $p$ -adic variation as  $d$  varies  $p$ -adically. One main consequence of our results is a complete determination of the purity decomposition and the trivial factors for the moment zeta function  $Z_d(\mathbb{A}^1, X_\lambda)$  for all  $d$ , all  $n$  and all  $p$  not dividing  $n + 1$ . This provides the first higher dimensional example for which all higher moment zeta functions are determined.

**Theorem 1.1.** *Assume that  $p$  does not divide  $n + 1$ . Then, the  $d$ -th moment zeta function has the following factorization*

$$Z_d(\mathbb{A}^1, X_\lambda)^{(-1)^{n-1}} = P_d(T)Q_d(T),$$

where  $Q_d(T)$  is the trivial factor given explicitly by

$$\frac{(1 - q^{\frac{d(n-1)}{2}} T)^{\frac{1+(-1)^{d+n}}{2}} \prod_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1 - q^{dk} T}{1 - q^{dk+1} T} \prod_{i=0}^{n-1} (1 - q^{di+1} T)^{(-1)^{i+1} \binom{n}{i+1}}}{(1 - q^{\frac{d(n-1)}{2} + 1} T)^{\frac{-(-1)^n - (-1)^{n+d}}{2}}}$$

and  $P_d(T)$  is the non-trivial factor which has the form

$$P_d(T) = \prod_{a+b=d, 0 \leq b \leq n} P_{a,b}(T)^{(-1)^{b-1}(b-1)},$$

where each  $P_{a,b}(T)$  is a polynomial in  $1 + T\mathbb{Z}[T]$ , pure of weight  $d(n-1) + 1$ , whose degree is given explicitly in Theorem 3.10.

**Corollary 1.2.** *Assume that  $p$  does not divide  $n + 1$ . Let  $N_d(k)$  denote the number of points on the family  $X_\lambda$  such that  $x_i \in \mathbb{F}_{q^{dk}}$  for all  $1 \leq i \leq n$  and  $\lambda \in \mathbb{F}_{q^k}$ . Then for every positive integer  $k$ , we have the estimate*

$$|N_d(k) - \left(\frac{q^{kd} - 1}{q^{k(d-1)}} + \frac{1}{2}(1 + (-1)^d)q^{k(\frac{d(n-1)}{2} + 1)}\right)| \leq (D + 2)q^{k(\frac{d(n-1)}{2})},$$

where  $D$  is the total degree of the rational function  $P_d(T)$ .

Since the first Hodge number  $h^{0,n-1}(X_\lambda) = 1$ , the zeta function of each fibre  $X_\lambda$  has at most one non-trivial  $p$ -adic unit root. One deduces the  $p$ -adic continuity result: If  $nm + 1 \leq d_1 \leq d_2$  are positive integers such that

$$d_1 \equiv d_2 \pmod{(p-1)p^m},$$

then

$$Z_{d_1}(\mathbb{A}^1, X_\lambda) \equiv Z_{d_2}(\mathbb{A}^1, X_\lambda) \pmod{p^{m+1}}.$$

For a  $p$ -adic integer  $s \in \mathbb{Z}_p$  and a residue class  $r \in \mathbb{Z}/(p-1)\mathbb{Z}$ , let  $\{d_i\}_{i=1}^\infty$  be a sequence of positive integers in the residue class  $r \pmod{p-1}$ , going to infinity as complex numbers but approaching to  $s$  as  $p$ -adic numbers, then the limit

$$\zeta_{r,s}(\mathbb{A}^1, X_\lambda) = \lim_{i \rightarrow \infty} Z_{d_i}(\mathbb{A}^1, X_\lambda) \in 1 + T\mathbb{Z}_p[[T]]$$

exists as a formal  $p$ -adic power series. This limit depends only on  $s$  and  $r$ , not on the particular chosen sequence  $\{d_i\}_{i=1}^\infty$ . The limit  $\zeta_{r,s}(\mathbb{A}^1, X_\lambda)$  is precisely Dwork's unit root zeta function attached to the family  $X_\lambda$ . It is a  $p$ -adic meromorphic function in  $T$  for every  $s \in \mathbb{Z}_p$  and  $r \in \mathbb{Z}/(p-1)\mathbb{Z}$ , as conjectured by Dwork [10] and proven by Wan [30]. It should be viewed as a two variable  $p$ -adic zeta function in  $(s, T)$ . Similarly, combining  $p$ -adic methods in [30] and  $\ell$ -adic methods, we show the limit

$$\mathcal{P}_{r,s,b}(T) = \lim_{i \rightarrow \infty} P_{d_i,b}(T) \in 1 + T\mathbb{Z}_p[[T]]$$

exists and is in fact a  $p$ -adic entire function for each  $r, s$  and  $b$ . Taking the limit of the previous theorem, we obtain the following result for Dwork's unit root zeta function.

**Theorem 1.3.** *Assume that  $p$  does not divide  $n + 1$ . Then, Dwork's unit root zeta function is given by*

$$\zeta_{r,s}(\mathbb{A}^1, X_\lambda)^{(-1)^{n-1}} = \frac{1-T}{(1-qT)^{n+1}} \prod_{b=0}^n \mathcal{P}_{r,s,b}(T)^{(-1)^{b-1}(b-1)}.$$

In the elliptic family case, the  $p$ -adic entire function  $\mathcal{P}_{r,s,0}(T)$  ( $b = 0$ ) is the characteristic power series of the  $U_p$ -operator acting on the space of overconvergent  $p$ -adic modular forms. It would be interesting but apparently difficult to get precise information on the slopes for the entire function  $\mathcal{P}_{r,s,b}(T)$ . Buzzard [2] had a complicated but explicit conjecture in some elliptic modular cases.

We now briefly explain the ideas in proving the above theorems. For a prime  $\ell \neq p$ , let  $\mathcal{H}^j(K)$  denote the relative  $\ell$ -adic cohomology with

compact support of the family  $X_\lambda$ . Then,  $Z_d(\mathbb{A}^1, X_\lambda)$  can be expressed in terms of the L-function over  $\mathbb{A}^1$  of the  $d$ -th Adams operation of the sheaf  $\mathcal{H}^j(K)$ :

$$Z_d(\mathbb{A}^1, X_\lambda) = \prod_{j=0}^{2(n-1)} L(\mathbb{A}^1, [\mathcal{H}^j(K)]^d)^{(-1)^j}.$$

It is thus a rational function in  $T$  for each positive integer  $d$ .

For a prime number  $\ell$  which may be equal to  $p$ , let  $\mathcal{F}_\ell$  be the non-trivial part of the relative  $\ell$ -adic cohomology with compact support of the family  $X_\lambda$  parameterized by  $\lambda \in \mathbb{A}^1$ . If  $\ell \neq p$ , then  $\mathcal{F}_\ell$  is the non-trivial part of the middle dimensional relative cohomology  $\mathcal{H}^{n-1}(K)$  and the generic rank of  $\mathcal{F}_\ell$  is  $n$ . If  $\ell = p$ , then the generic rank of  $\mathcal{F}_p$  is 1 as the first Hodge number  $h^{0,n-1}(X_\lambda) = 1$  and the family  $X_\lambda$  is generically ordinary [32]. The  $d$ -th moment zeta function is then given up to trivial factors, by the  $d$ -th moment L-function:

$$Z_d(\mathbb{A}^1, X_\lambda) \sim L(\mathbb{A}^1, [\mathcal{F}_\ell]^d)^{(-1)^{n-1}},$$

where  $[\mathcal{F}_\ell]^d$  denotes the  $d$ -th Adams operation of the sheaf  $\mathcal{F}_\ell$  on  $\mathbb{A}^1$ . Similarly, the unit root zeta function  $\zeta_{r,s}(\mathbb{A}^1, X_\lambda)$  is given up to trivial factors by the unit root L-function:

$$\zeta_{r,s}(\mathbb{A}^1, X_\lambda) \sim L(\mathbb{A}^1, \omega(\mathcal{F}_p)^r \otimes (\mathcal{F}_p \otimes \omega(\mathcal{F}_p)^{-1})^s)^{(-1)^{n-1}},$$

where  $\omega(\mathcal{F}_p)$  denotes the Teichmüller lifting of the reduction  $\mathcal{F}_p \otimes \mathbb{F}_p$ .

Fix a prime number  $\ell \neq p$ , let  $\mathcal{F}$  denote the  $\ell$ -adic sheaf  $\mathcal{F}_\ell$ . For non-negative integers  $a$  and  $b$ , let

$$\mathcal{G}_{a,b} := \text{Sym}^a \mathcal{F} \otimes \wedge^b \mathcal{F},$$

which is an  $\ell$ -adic sheaf on  $\mathbb{A}^1$ , vanishing if  $b > n$ . Thus, we shall assume that  $0 \leq b \leq n$  from now on. The generic rank of  $\mathcal{G}_{a,b}$  is  $\binom{n+a-1}{a} \binom{n}{b}$ , which goes to infinity as  $a$  goes to infinity. The  $d$ -th moment L-function is then given [28] by the formula

$$L(\mathbb{A}^1, [\mathcal{F}_\ell]^d) = \prod_{b=0}^n L(\mathbb{A}^1, \mathcal{G}_{d-b,b})^{(-1)^{b-1}(b-1)}.$$

Thus, to a large extent, the moment zeta functions are reduced to the study of the L-function  $L(\mathbb{A}^1, \mathcal{G}_{a,b})$  of the sheaf  $\mathcal{G}_{a,b}$  for all non-negative integers  $a$  and  $b$ . To understand the purity decomposition and the trivial factors of this last L-function, the key is to determine the local and global monodromy of the sheaf  $\mathcal{F}$ . This is accomplished in Section 2. As a consequence, we obtain

**Theorem 1.4.** *Assume that  $p$  does not divide  $n + 1$ . Let  $a$  and  $b$  be non-negative integers with  $0 \leq b \leq n$ . Then, we have the formula*

$$L(\mathbb{A}^1, \mathcal{G}_{a,b}) = \frac{P_{a,b}(T) \prod_{k=0}^{[(a+b)(n-1)/2]} (1 - q^k T)^{\alpha_{a,b}(k)}}{(1 - q^{(a+b)(n-1)/2} T)^{\delta_{a,b}} (1 - q^{(a+b)(n-1)/2+1} T)^{\delta_{a,b}}},$$

where  $P_{a,b}(T) \in 1 + T\mathbb{Z}[T]$  is a polynomial whose degree is explicitly given,  $P_{a,b}(T)$  is pure of weight  $(a+b)(n-1) + 1$ ,  $\delta_{a,b} = 0$  or  $1$  is explicitly given by Proposition 3.9,  $\alpha_{a,b}(k)$  is the coefficient of  $x^k z^b$  in the power series

$$\left\{ \frac{(1 - x^n) \cdots (1 - x^{a+n-1})}{(1 - x^2) \cdots (1 - x^a)} \right\} (1 + z)(1 + xz) \cdots (1 + x^{n-1}z),$$

where the quantity in the bracket is understood to be  $1 - x^n$  if  $a = 1$ , and  $1 - x$  if  $a = 0$ .

Let now  $s \in \mathbb{Z}_p$  be a  $p$ -adic integer and let  $r$  be a residue class modulo  $(p-1)$ . Choose a sequence of positive integers  $\{d_i\}_{i=1}^\infty$  in the residue class  $r$  modulo  $(p-1)$ , going to infinity as complex numbers but approaching to  $s$  as  $p$ -adic integers. For integers  $0 \leq b \leq n$ , we define

$$\mathcal{L}_{r,s,b}(\mathbb{A}^1, T) = \lim_{i \rightarrow \infty} L(\mathbb{A}^1, \mathcal{G}_{d_i-b,b}) \in 1 + \mathbb{Z}_p[[T]].$$

This limit exists as a formal  $p$ -adic power series. It depends only on  $r, s$  and  $b$ , not on the choice of the sequence  $\{d_i\}_{i=1}^\infty$ . It follows from the general result in [30] that  $\mathcal{L}_{r,s,b}(\mathbb{A}^1, T)$  is a  $p$ -adic meromorphic function in  $T$ . The formula

$$L(\mathbb{A}^1, \omega(\mathcal{F}_p)^r \otimes (\mathcal{F}_p \otimes \omega(\mathcal{F}_p)^{-1})^s) = \prod_{b=0}^n \mathcal{L}_{r,s,b}(\mathbb{A}^1, T)^{(-1)^{b-1}(b-1)}$$

shows that the unit root L-function on the left side is also  $p$ -adic meromorphic in  $T$ . Its study is reduced, to a large extent, to the study of the L-functions  $\mathcal{L}_{r,s,b}(\mathbb{A}^1, T)$  for all  $r, s$  and  $b$ .

Combining the above theorem together with the  $p$ -adic limiting argument in [30], we obtain the following more precise result. The proof is similar to the one given in [13] for the Kloosterman family. The key point is that the number of  $p$ -adic zeros of the polynomial  $P_{a,b}(T)$  in any fixed  $p$ -adic disc  $|T|_p < M$  ( $M$  finite) is uniformly bounded for all  $a$  and  $b$ . This fact holds only for those motive  $\mathcal{F}$  whose first Hodge number is 1, which is the case for Calabi-Yau hypersurfaces.

**Theorem 1.5.** *Assume that  $p$  does not divide  $n + 1$ . Let  $a$  and  $b$  be non-negative integers with  $0 \leq b \leq n$ . Then, for each  $s \in \mathbb{Z}_p$  and each*

residue class  $r \in \mathbb{Z}/(p-1)\mathbb{Z}$ , we have the factorization

$$\mathcal{L}_{r,s,b}(\mathbb{A}^1, T) = \mathcal{P}_{r,s,b}(T) \prod_{k=0}^{\infty} (1 - q^k T)^{\beta_b(k)},$$

where  $\mathcal{P}_{r,s,b}(T) \in 1 + T\mathbb{Z}_p[[T]]$  is a  $p$ -adic entire function and  $\beta_b(k)$  is the coefficient of  $x^k z^b$  in the power series

$$\frac{(1+z)(1+xz) \cdots (1+x^{n-1}z)}{(1-x^2)(1-x^3) \cdots (1-x^{n-1})}.$$

In particular,  $\mathcal{L}_{r,s,b}(\mathbb{A}^1, T)$  is a  $p$ -adic entire function with a zero at  $T = q^{-k}$  of multiplicity at least  $\beta_b(k)$  for each non-negative integer  $k$ .

It would be interesting to determine the slopes of the polynomials  $P_{a,b}(T)$  and the entire functions  $\mathcal{P}_{r,s,b}(T)$ . This seems to be quite difficult in general. The simplest case  $n = 2$  (the elliptic family case) has been studied extensively in connection to slopes of modular forms, over-convergent  $p$ -adic modular forms [27], the eigencurve [5] and the Gouvea-Mazur conjectures. The first step may be to get a good explicit lower bound for the  $p$ -adic Newton polygon of  $P_{a,b}(T)$  and  $\mathcal{P}_{r,s,b}(T)$ . Such a good lower bound is already quite non-trivial to obtain.

Taking partial derivative with respect to  $z$  in the generating function for  $\beta_b(k)$  and then setting  $z = -1$ , we deduce

$$\sum_{k=0}^{\infty} \left( \sum_{b=0}^n (-1)^{b-1} b \beta_b(k) \right) x^k = 1 - x.$$

This together with the previous theorem implies

**Corollary 1.6.** *Assume that  $p$  does not divide  $n + 1$ . Then, the unit root  $L$ -function is given by*

$$L(\mathbb{A}^1, \omega(\mathcal{F}_p)^r \otimes (\mathcal{F}_p \otimes \omega(\mathcal{F}_p)^{-1})^s) = \frac{1-T}{1-qT} \prod_{b=0}^n \mathcal{P}_{r,s,b}(T)^{(-1)^{b-1}(b-1)}.$$

It would be of great interest to understand the cancellation nature in the above alternating product of  $p$ -adic entire functions.

The paper is organized as follows. In Section 2, we determine both the local monodromy and the global monodromy of the sheaf  $\mathcal{F}$ . These results are then used in Section 3 to calculate the  $L$ -function of the sheaf  $\mathcal{G}_{a,b}$  and its local factors at bad points. In Section 4, we treat the degenerate case when  $p$  divides  $n + 1$ .

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by him in his forthcoming paper [23] on the Dwork family. The second author was partially supported by NSF. The first author was partially supported by MTM2004-07203-C02-01 and FEDER.

## 2. THE MONODROMY VIA FOURIER TRANSFORM.

Let  $k = \mathbb{F}_q$  be a finite field of characteristic  $p$ ,  $n \geq 2$  an integer,  $X \subset \mathbb{A}_k^{n+1}$  the hypersurface defined by  $x_1 \cdots x_{n+1} = 1$ , and  $\sigma : X \rightarrow \mathbb{A}_k^1$  the restriction of the sum map  $(x_1, \dots, x_{n+1}) \rightarrow x_1 + \dots + x_{n+1}$  to  $X$ . Fix a prime  $\ell \neq p$ . We want to study the local monodromy of the non-trivial part of the object  $K := R\sigma_! \bar{\mathbb{Q}}_\ell \in \mathcal{D}_c^b(\mathbb{A}_k^1, \bar{\mathbb{Q}}_\ell)$ , which parameterizes the cohomology of the family described in the introduction. The main results are summarized in the following theorem:

**Theorem 2.1.** *The cohomology sheaves  $\mathcal{H}^j(K) = R^j\sigma_! \bar{\mathbb{Q}}_\ell$  vanish for  $j < n - 1$  and  $j > 2n - 2$ . We have isomorphisms*

$$\mathcal{H}^j(K) \cong \bar{\mathbb{Q}}_\ell^{\binom{n}{j-n+2}}(n-1-j)$$

for  $n \leq j \leq 2n - 2$ , and an exact sequence

$$0 \rightarrow \bar{\mathbb{Q}}_\ell^n \rightarrow \mathcal{H}^{n-1}(K) \rightarrow \mathcal{F} \rightarrow 0$$

where  $\mathcal{F}$  is the extension by direct image of a geometrically irreducible smooth sheaf on the dense open set  $U = \mathbb{A}_k^1 - \{(n+1)\zeta : \zeta^{n+1} = 1\}$ , of rank  $n$  and punctually pure of weight  $n - 1$ . It is endowed with a non-degenerate pairing  $\Phi : \mathcal{F} \times \mathcal{F} \rightarrow \bar{\mathbb{Q}}_\ell(1 - n)$ , which is symmetric if  $n$  is odd and skew-symmetric if  $n$  is even. As a representation of the inertia group at infinity,  $\mathcal{F}$  is unipotent with a single Jordan block.

If  $p$  does not divide  $n + 1$ ,  $\mathcal{F}$  is everywhere tamely ramified. The inertia group at each of the  $n + 1$  singular points  $x = (n + 1)\zeta$  acts on  $\mathcal{F}_{\bar{\eta}}$  with invariant subspace of codimension 1. On the quotient  $\mathcal{F}_{\bar{\eta}}/\mathcal{F}_{\bar{\eta}}^{I_x}$ ,  $I_x$  acts trivially if  $n$  is even, and through its unique character of order 2 if  $n$  is odd.

If  $p$  divides  $n + 1$ , let  $n + 1 = p^a m$ , with  $m$  prime to  $p$ . Then  $\mathcal{F}$  is smooth on  $\mathbb{G}_m$ , and the inertia group at 0 acts with invariant subspace of dimension  $m - 1$ . The action of  $I_0$  on the quotient  $\mathcal{F}_{\bar{\eta}}/\mathcal{F}_{\bar{\eta}}^{I_0}$  is totally wild, with a single break  $1/(p^a - 1)$  with multiplicity  $m(p^a - 1) = n - m + 1$ . In particular, the Swan conductor at 0 is  $m$ .

The determinant of  $\mathcal{F}$  is the geometrically constant sheaf  $\bar{\mathbb{Q}}_\ell(-n(n-1)/2)$  if  $n$  is even or  $p$  divides  $n + 1$ , and the pulled back Kummer sheaf

$$\mathcal{L}_{\chi^{(\lambda^{n+1} - (n+1)^{n+1})}}(-n(n-1)/2)$$

if  $n$  is odd and  $(p, n + 1) = 1$ , where  $\chi$  is the unique character of order 2 of the inertia group  $I_0$ .



The geometric monodromy group of  $\mathcal{F}$  is given by

$$\left\{ \begin{array}{ll} Sp(n, \Phi) & \text{if } n \text{ is even} \\ O(n, \Phi) & \text{if } n \text{ is odd and } (p, n+1) = 1 \\ SO(n, \Phi) & \text{if } n \text{ is odd, } p|n+1 \\ & \text{and } (p, n) \neq (2, 5) \text{ or } (2, 7) \\ G_2 \text{ in its standard} & \\ \quad 7\text{-dimensional representation} & \text{if } p = 2, n = 7 \\ SL(2) \text{ in sym}^4 \text{ of its} & \\ \quad \text{standard representation} & \text{if } p = 2, n = 5 \end{array} \right.$$

We will deduce most of the properties of the object  $K$  from the properties of its Fourier transform  $L \in \mathcal{D}_c^b(\mathbb{A}_k^1, \bar{\mathbb{Q}}_\ell)$  with respect to a fixed non-trivial additive character  $\psi : k \rightarrow \mathbb{C}^* \xrightarrow{\sim} \bar{\mathbb{Q}}_\ell^*$ . The Fourier transform  $L$  is closely related to the Kloosterman sheaf. This connection of the Dwork family with Kloosterman sums was first discovered by Katz [18] (Section 5.5) who uses the properties of the family to get information on certain Kloosterman sums. We will use this connection the other way around and apply Katz's fundamental results for the Kloosterman sheaf.

Recall (cf. [22]) that the Fourier transform is defined by

$$FT_\psi(K) = R\pi_{2!}(\pi_1^*(K) \otimes \mu^* \mathcal{L}_\psi)[1]$$

where  $\pi_1, \pi_2 : \mathbb{A}_k^2 \rightarrow \mathbb{A}_k^1$  are the projections,  $\mu : \mathbb{A}_k^2 \rightarrow \mathbb{A}_k^1$  is the product map and  $\mathcal{L}_\psi$  is the Artin-Schreier sheaf on  $\mathbb{A}_k^1$  associated to the character  $\psi$ . It is an auto-equivalence of the triangulated category  $\mathcal{D}_c^b(\mathbb{A}_k^1, \bar{\mathbb{Q}}_\ell)$ , and has the following involution property:  $FT_{\bar{\psi}} FT_\psi(K) = K(-1)$ .

One of the main advantages of this equivalence is that, following Laumon (cf. [24]), the local properties of the object  $K$  can be read from those of its Fourier transform. This is the method that we will use to deduce most of the results about  $K$ .

Let us first determine what the Fourier transform of  $K$  is explicitly. Using proper base change on the cartesian diagram

$$\begin{array}{ccc} X & \xleftarrow{\tilde{\pi}_1} & X \times \mathbb{A}_k^1 \\ \sigma \downarrow & & \downarrow \tilde{\sigma} \\ \mathbb{A}_k^1 & \xleftarrow{\pi_1} & \mathbb{A}_k^2 \end{array}$$

we get

$$\pi_1^*(K) = \pi_1^*(R\sigma_! \bar{\mathbb{Q}}_\ell) = R\tilde{\sigma}_! \tilde{\pi}_1^* \bar{\mathbb{Q}}_\ell = R\tilde{\sigma}_! \bar{\mathbb{Q}}_\ell$$

By the projection formula, we have then

$$L = \mathbf{R}\pi_{2!}((\mathbf{R}\tilde{\sigma}_1\bar{\mathbb{Q}}_\ell) \otimes \mu^*\mathcal{L}_\psi)[1] = \mathbf{R}\pi_{2!}(\mathbf{R}\tilde{\sigma}_1(\tilde{\sigma}^*\mu^*\mathcal{L}_\psi))[1] = \mathbf{R}\tilde{\pi}_{2!}(\tilde{\mu}^*\mathcal{L}_\psi)[1]$$

where  $\tilde{\pi}_1$  and  $\tilde{\pi}_2$  are the projections of  $X \times \mathbb{A}_k^1$  onto its factors and  $\tilde{\mu} : X \times \mathbb{A}_k^1 \rightarrow \mathbb{A}_k^1$  is the map  $((x_1, \dots, x_{n+1}), t) \mapsto t(x_1 + \dots + x_{n+1})$ .

Extend the canonical map  $L \rightarrow j_*j^*L$  to a distinguished triangle

$$(1) \quad M \rightarrow L \rightarrow j_*j^*L \rightarrow .$$

in  $\mathcal{D}_c^b(\mathbb{A}_k^1, \bar{\mathbb{Q}}_\ell)$ , where  $j : \mathbb{A}_k^1 - \{0\} \hookrightarrow \mathbb{A}_k^1$  is the open immersion. The object  $M$  is punctual supported at 0, since  $L \rightarrow j_*j^*L$  is an isomorphism away from 0.

At 0, the object  $L$  is just  $\mathbf{R}\Gamma_c(X \otimes \bar{k}, \bar{\mathbb{Q}}_\ell)[1]$  by proper base change. Since  $X$  is just the product of  $n$  copies of  $\mathbb{G}_m$ , we have

$$L_0 = \bigotimes_{i=1}^n \mathbf{R}\Gamma_c(\mathbb{G}_{m, \bar{k}}, \bar{\mathbb{Q}}_\ell)[1]$$

From  $\mathbf{H}_c^1(\mathbb{G}_{m, \bar{k}}, \bar{\mathbb{Q}}_\ell) = \bar{\mathbb{Q}}_\ell$ ,  $\mathbf{H}_c^2(\mathbb{G}_{m, \bar{k}}, \bar{\mathbb{Q}}_\ell) = \bar{\mathbb{Q}}_\ell(-1)$  and  $\mathbf{H}_c^i(\mathbb{G}_{m, \bar{k}}, \bar{\mathbb{Q}}_\ell) = 0$  for  $i \neq 1, 2$ , we conclude

$$\mathcal{H}^{i-1}(L)_0 = \bar{\mathbb{Q}}_\ell^{\binom{n}{i-n}}(n-i)$$

for  $n \leq i \leq 2n$ , and 0 otherwise, so we get a quasi-isomorphism

$$L_0 \cong \bigoplus_{i=n}^{2n} \bar{\mathbb{Q}}_\ell^{\binom{n}{i-n}}(n-i)[1-i]$$

Away from 0, we have  $L = \mathbf{R}\tilde{\pi}_{2!}(\tilde{\mu}^*\mathcal{L}_\psi)[1]$ , where we now regard  $\tilde{\pi}_2$  as the projection  $X \times \mathbb{G}_m \rightarrow \mathbb{G}_m$ . Consider the automorphism  $\phi$  of  $\mathbb{A}_k^{n+1} \times \mathbb{G}_m$  given by  $\phi((x_1, \dots, x_{n+1}), t) = ((tx_1, \dots, tx_{n+1}), t)$ . The image of  $X \times \mathbb{G}_m$  under  $\phi$  is the variety  $Y$  defined by the equation  $x_1 \cdots x_{n+1} = t^{n+1}$ , and  $\tilde{\mu} = \tilde{\sigma} \circ \phi$ . Since  $\phi$  is an automorphism,  $\phi^* = \mathbf{R}\phi_* = \mathbf{R}\phi_!$ , and we get

$$\begin{aligned} j^*L &= \mathbf{R}\tilde{\pi}_{2!}(\tilde{\mu}^*\mathcal{L}_\psi)[1] = \mathbf{R}\tilde{\pi}_{2!}(\phi^*\tilde{\sigma}^*\mathcal{L}_\psi)[1] = \\ &= \mathbf{R}(\tilde{\pi}_2\phi)_!(\tilde{\sigma}^*\mathcal{L}_\psi)[1] = \mathbf{R}\tilde{\pi}_{2!}(\tilde{\sigma}^*\mathcal{L}_\psi)[1] \end{aligned}$$

The stalk of  $j^*L$  at a geometric point  $t \in \mathbb{G}_{m, \bar{k}}$  is then  $\mathbf{R}\Gamma_c(\{x_1 \cdots x_{n+1} = t^{n+1}\}, \mathcal{L}_{\psi(\sum x_i)})[1]$ . By [7], Théorème 7.4, we deduce that  $\mathcal{H}^i(j^*L) = 0$  for  $i \neq n-1$ , and  $\mathcal{H}^{n-1}(j^*L)$  is the pull-back by the  $(n+1)$ -th power map of the Kloosterman sheaf given in [7], Théorème 7.8 and, more generally, in [19], 4.1.1. Therefore we have a quasi-isomorphism

$$j^*L \cong [n+1]^*\mathbf{Kl}_{n+1}(\psi)[1-n]$$

Denote by  $\mathcal{L}$  the sheaf  $[n+1]^*\mathbf{Kl}_{n+1}(\psi)$  on  $\mathbb{G}_m$ . It is geometrically irreducible, because it is already irreducible as a representation of the

inertia group at 0: by [7], Théorème 7.8, the action of a topological generator is unipotent with a single Jordan block. In particular, the invariant subspace for the inertia action at 0 has dimension 1, so the stalk of  $j_*j^*L$  at 0 is quasi-isomorphic to  $\bar{\mathbb{Q}}_\ell[1-n]$ .

Taking stalks at 0 in the distinguished triangle (1) we get

$$M_0 \rightarrow \bigoplus_{i=n}^{2n} \bar{\mathbb{Q}}_\ell^{\binom{n}{i-n}}(n-i)[1-i] \rightarrow \bar{\mathbb{Q}}_\ell[1-n] \rightarrow .$$

and consequently a quasi-isomorphism

$$M_0 \simeq \bigoplus_{i=n+1}^{2n} \bar{\mathbb{Q}}_\ell^{\binom{n}{i-n}}(n-i)[1-i] = \bigoplus_{i=1}^n \bar{\mathbb{Q}}_\ell^{\binom{n}{i}}(-i)[1-n-i]$$

Then since  $M$  is punctual supported at 0, the distinguished triangle (1) reads

$$\bigoplus_{i=1}^n \bar{\mathbb{Q}}_\ell^{\binom{n}{i}}(-i)[1-n-i]_0 \rightarrow L \rightarrow j_*\mathcal{L}[1-n] \rightarrow .$$

Taking Fourier transform with respect to the complex conjugate character  $\bar{\psi}$  and using the facts that  $FT_{\bar{\psi}}FT_{\psi}(K) = K(-1)$  and that the Fourier transform of the punctual sheaf  $(\bar{\mathbb{Q}}_\ell)_0$  is the shifted constant sheaf  $\bar{\mathbb{Q}}_\ell[1]$ , we get the distinguished triangle

$$\bigoplus_{i=1}^n \bar{\mathbb{Q}}_\ell^{\binom{n}{i}}(-i)[2-n-i] \rightarrow K(-1) \rightarrow FT_{\bar{\psi}}(j_*\mathcal{L})[1-n] \rightarrow .$$

Since  $\mathcal{L}$  is a geometrically irreducible sheaf of rank  $\geq 2$ , its direct image  $j_*\mathcal{L}$  is a Fourier sheaf in the sense of [19], 8.2 (cf. [19], lemma 8.3.1). Then its Fourier transform is a sheaf of the same kind, by ([19], Theorem 8.2.5). Namely, it is the extension by direct image to  $\mathbb{A}^1$  of a geometrically irreducible sheaf on a dense open set  $U \subset \mathbb{A}^1$ , and we get a distinguished triangle

$$\bigoplus_{i=1}^n \bar{\mathbb{Q}}_\ell^{\binom{n}{i}}(1-i)[2-n-i] \rightarrow K \rightarrow \mathcal{F}[1-n] \rightarrow .$$

where  $\mathcal{F} = FT_{\bar{\psi}}(j_*\mathcal{L})(1)$ . Taking the associated long exact sequence of cohomology sheaves and using the fact that  $\mathcal{F}$  has no punctual sections, we get an exact sequence

$$0 \rightarrow \bar{\mathbb{Q}}_\ell^n \rightarrow \mathcal{H}^{n-1}(K) \rightarrow \mathcal{F} \rightarrow 0$$

and isomorphisms

$$\mathcal{H}^j(K) \xrightarrow{\simeq} \bar{\mathbb{Q}}_\ell^{\binom{j-n}{j-n+2}}(n-1-j) \text{ for } n \leq j \leq 2n-2$$

and

$$\mathcal{H}^j(K) = 0 \text{ for } j \notin \{n-1, \dots, 2n-2\}.$$

Thus the cohomology of our family has a “constant part”, which has dimension  $\binom{n}{j-n+2}$  and is pure of weight  $2(j-n+1)$  on degree  $j$  for every  $j = n-1, \dots, 2n-2$ , and a non-constant geometrically irreducible part on degree  $n-1$  given by the sheaf  $\mathcal{F}$ . If  $n+1$  is prime to  $p$ , this sheaf is the pull-back by the  $(n+1)$ -th power map of a hypergeometric sheaf, as defined by Katz in [20] (Section 8). Namely, using the same notation as in the reference, it is  $[n+1]^*\text{Hyp}_{(n+1)^{n+1}}(1, \psi, \text{all nontrivial characters } \chi \text{ of order dividing } n+1; n \text{ times the trivial character})$  (cf. [20], Theorem 9.3.2). We will not make use of this fact in what follows.

**Proposition 2.2.** *The sheaf  $\mathcal{F}$  is smooth of rank  $n$  and punctually pure of weight  $n-1$  on  $U = \mathbb{A}_{\bar{k}}^1 - \{(n+1)\zeta : \zeta^{n+1} = 1\}$ .*

**Proof.** If  $n+1$  is prime to  $p$ , by [12], lemma 1.4, the wild inertia group of  $\mathbb{A}_{\bar{k}}^1$  at infinity acts on  $\mathcal{L}$  as  $\bigoplus_{\zeta^{n+1}=1} \mathcal{L}_{\psi_{(n+1)\zeta}}$ , where  $\psi_{(n+1)\zeta}(t) = \psi((n+1)\zeta t)$ . By [20], Lemma 7.3.9,  $\mathcal{F}$  is smooth at  $t \in \mathbb{A}_{\bar{k}}^1$  if and only if all breaks of  $\mathcal{L} \otimes \mathcal{L}_{\bar{\psi}_t}$  at infinity are  $\geq 1$ . But, as a representation of  $P_\infty$ ,  $\mathcal{L} \otimes \mathcal{L}_{\bar{\psi}_t} = \bigoplus_{\zeta^{n+1}=1} \mathcal{L}_{\psi_{(n+1)\zeta-t}}$  has all its breaks equal to 1 unless  $t = (n+1)\zeta$  for some  $\zeta \in \mu_{n+1}(\bar{k})$ . This proves that  $\mathcal{F}$  is smooth on  $U$ . If  $p$  divides  $n+1$ , all breaks of  $\mathcal{L}$  at infinity are  $< 1$ , so  $\mathcal{F}$  is smooth on  $U = \mathbb{G}_{m, \bar{k}}$  by [19], 8.5.8.

Since  $\mathcal{L}$  is pure of weight  $n$ , so is its direct image  $j_*\mathcal{L}[0]$  as a derived category object. The Fourier transform preserves purity and shifts weights by 1, so  $\mathcal{F}(-1)[0]$  is pure of weight  $n+1$  as a derived category object. In particular, on the open set where  $\mathcal{F}$  is smooth, it is punctually pure of weight  $(n+1) - 2 = n-1$ . To compute the rank, we use the formula in [20], 7.3.9, which gives

$$\text{rank}(\mathcal{F}) = \text{drop}_0(\mathcal{L}) = (n+1) - 1 = n.$$

□

**Proposition 2.3.** *There is a non-degenerate pairing  $\Phi : \mathcal{F}_U \times \mathcal{F}_U \rightarrow \bar{\mathbb{Q}}_\ell(1-n)$  which is symmetric for  $n$  odd and skew-symmetric for  $n$  even.*

**Proof.** According to [19] 4.1.3, the dual of the sheaf  $\text{Kl}_{n+1}(\psi)$  on  $\mathbb{G}_{m, \bar{k}}$  is  $\text{Kl}_{n+1}(\bar{\psi})(n-1)$ . Therefore, the dual of the object  $j_*\mathcal{L}[0] \in \mathcal{D}_c^b(\mathbb{A}_{\bar{k}}^1, \bar{\mathbb{Q}}_\ell)$  is  $j_*\bar{\mathcal{L}}[0](n-1)$ , where  $\bar{\mathcal{L}} = [n+1]^*\text{Kl}_{n+1}(\bar{\psi})$ .

By [22], Théorème 2.1.5, the dual of the Fourier transform with respect to  $\psi$  of an object is the Fourier transform with respect to  $\bar{\psi}$  of the dual object. Therefore, the dual of  $FT_{\bar{\psi}}(j_*\mathcal{L}[0]) = \mathcal{F}[0]$  is  $FT_{\psi}(j_*\bar{\mathcal{L}}[0](n-1)) = \mathcal{F}[0](n-1)$ . In particular, we have a non-degenerate pairing on the open set  $U$  where  $\mathcal{F}$  is smooth:  $\mathcal{F}_U \times \mathcal{F}_U \rightarrow$

$\bar{\mathbb{Q}}_\ell(1-n)$ . Since  $\mathcal{F}_U$  is irreducible, the pairing is unique up to a scalar and either symmetric or skew-symmetric. The actual sign is given by the usual cup product sign, since  $\mathcal{F}$  is a subsheaf of  $R^{n-1}\sigma_!(\bar{\mathbb{Q}}_\ell)$ .  $\square$

**Proposition 2.4.** *The sheaf  $\mathcal{F}$  is tamely ramified at infinity. The tame inertia group at infinity  $I_\infty^{\text{tame}}$  acts unipotently on  $\mathcal{F}_{\bar{\eta}}$  with a single Jordan block.*

**Proof.** Since  $\mathcal{L}$  is tamely ramified at 0 and the inertia group acts unipotently with a single Jordan block, the same is true for  $\mathcal{F}$  at  $\infty$  by [20], Theorem 7.5.4.  $\square$

**Proposition 2.5.** *Suppose that  $n+1$  is prime to  $p$ . Then  $\mathcal{F}$  is everywhere tamely ramified, and for every  $(n+1)$ -th root of unity  $\zeta$  in  $\bar{k}$ , the action of the inertia group at  $(n+1)\zeta$  on  $\mathcal{F}_{\bar{\eta}}$  has invariant subspace of codimension 1.*

**Proof.** Let  $\zeta$  be a  $(n+1)$ -th root of unity in  $\bar{k}$ . Then  $\zeta : (x_1, \dots, x_{n+1}) \rightarrow (\zeta x_1, \dots, \zeta x_{n+1})$  is an automorphism of  $X$ . Therefore,  $K := R\sigma_!\bar{\mathbb{Q}}_\ell = R(\sigma \circ \zeta)_!\bar{\mathbb{Q}}_\ell = R(\tilde{\zeta} \circ \sigma)_!\bar{\mathbb{Q}}_\ell = [\tilde{\zeta}]_* R\sigma_!\bar{\mathbb{Q}}_\ell = [\tilde{\zeta}]_* K$  where  $[\tilde{\zeta}] : \mathbb{A}_k^1 \rightarrow \mathbb{A}_k^1$  is multiplication by  $\zeta$ . So the sheaf  $\mathcal{F}$  is invariant under multiplication by  $(n+1)$ -th roots of unity on  $\mathbb{A}_k^1$ . In particular, the local monodromies at  $(n+1)\zeta$  are isomorphic for all  $\zeta \in \mu_{n+1}(\bar{k})$ .

By the Euler-Poincaré formula,

$$\chi_c(\mathcal{F}) = \text{rank}(\mathcal{F}) - \sum_{t \in (n+1)\mu_{n+1}(\bar{k})} (\text{drop}_t \mathcal{F} + \text{swan}_t \mathcal{F})$$

since  $\mathcal{F}$  is tamely ramified at infinity and smooth on  $\mathbb{A}_k^1 - (n+1)\mu_{n+1}(\bar{k})$ . We can compute this Euler characteristic directly:

$$\chi_c(K) = \chi_c(R\sigma_!\bar{\mathbb{Q}}_\ell) = \chi_c(X, \bar{\mathbb{Q}}_\ell) = 0$$

since  $X$  is a product of copies of  $\mathbb{G}_m$ . Therefore

$$\begin{aligned} 0 = \chi_c(K) &= \sum_{j=n-1}^{2n-2} (-1)^j \chi_c(\mathcal{H}^j(K)) \\ &= (-1)^{n-1} \chi_c(\mathcal{F}) + (-1)^{n-1} n + \sum_{j=n}^{2n-2} (-1)^j \binom{n}{j-n+2} \\ &= (-1)^{n-1} \chi_c(\mathcal{F}) + \sum_{j=1}^n (-1)^{j+n} \binom{n}{j} = (-1)^{n-1} \chi_c(\mathcal{F}) - (-1)^n, \end{aligned}$$

so  $\chi_c(\mathcal{F}) = -1$ . We conclude that

$$\sum_{t \in (n+1)\mu_{n+1}(\bar{k})} (\text{drop}_t \mathcal{F} + \text{swan}_t \mathcal{F}) = n + 1$$

and therefore the only possibility is  $\text{drop}_t \mathcal{F} = 1$  and  $\text{swan}_t \mathcal{F} = 0$  for every  $t \in (n+1)\mu_{n+1}(\bar{k})$ . In particular,  $\mathcal{F}$  is everywhere tamely ramified.  $\square$

**Proposition 2.6.** *Suppose that  $n+1$  is prime to  $p$ , and let  $t \in (n+1)\mu_{n+1}(\bar{k})$ . If  $n$  is even, the inertia group  $I_t$  acts trivially on the one-dimensional space  $\mathcal{F}_{\bar{\eta}}/\mathcal{F}_{\bar{\eta}}^{I_t}$ . That is, the action of  $I_t$  on  $\mathcal{F}_{\bar{\eta}}$  is unipotent with a Jordan block of size 2 and all other blocks of size 1. If  $t \in \mathbb{F}_q$ , the action of a geometric Frobenius element at  $t$  on  $\mathcal{F}_{\bar{\eta}}^{I_t}$  has one of  $\pm q^{(n-2)/2}$  as an eigenvalue, and all other eigenvalues of absolute value  $q^{(n-1)/2}$ .*

*If  $n$  is odd,  $I_t$  acts on the one-dimensional space  $\mathcal{F}_{\bar{\eta}}/\mathcal{F}_{\bar{\eta}}^{I_t}$  via its unique character of order 2. In particular, the action of  $I_t$  on  $\mathcal{F}_{\bar{\eta}}$  is semisimple. If  $t \in \mathbb{F}_q$ , the action of a geometric Frobenius element at  $t$  on  $\mathcal{F}_{\bar{\eta}}^{I_t}$  has all eigenvalues of absolute value  $q^{(n-1)/2}$ .*

**Proof.** This can be proven using the Picard-Lefschetz formulas (cf. [8], exposé XV), since the fibres of  $\sigma : X \rightarrow \mathbb{A}^1$  have only isolated ordinary quadratic singularities. Alternatively, one may use the explicit description of the monodromy at infinity of the Kloosterman sheaf and Laumon's local Fourier transform theory.

According to [12], Theorem 1.1, the action of the inertia group at infinity on  $\text{Kl}_{n+1}(\psi)$  is given by  $[n+1]_* \mathcal{L}_{\psi_{n+1}}$  if  $n$  is even and  $[n+1]_* (\mathcal{L}_{\psi_{n+1}} \otimes \mathcal{L}_{\chi_2})$  if  $n$  is odd. Therefore, the action on  $[n+1]^* \text{Kl}_{n+1}(\psi)$  is given by  $\bigoplus_{\zeta^{n+1}=1} \mathcal{L}_{\psi_{(n+1)\zeta}}$  if  $n$  is even and  $\bigoplus_{\zeta^{n+1}=1} \mathcal{L}_{\psi_{(n+1)\zeta}} \otimes \mathcal{L}_{\chi_2}$  if  $n$  is odd (cf. [12], Lemma 1.4). We conclude by [20], 7.4.1 and 7.5.4.

In particular, the Frobenius eigenvalues of  $\mathcal{F}_{\bar{\eta}}^{I_t}$  all have weight  $n-1$  if  $n$  is odd by [19], 7.0.8. If  $n$  is even, there are  $n-2$  eigenvalues of weight  $n-1$  and one of weight  $n-2$ . Since the local  $L$ -function has integral coefficients, the non-real eigenvalues must appear in complex conjugate pairs, and therefore the one with weight  $n-2$  must be real, necessarily  $\pm q^{(n-2)/2}$ .  $\square$

**Proposition 2.7.** *Suppose that  $p$  divides  $n+1$ , and write  $n+1 = p^a m$  with  $(p, m) = 1$ . Then the inertia group at 0 acts with invariant subspace of dimension  $m-1$ , and its action on the quotient  $\mathcal{F}_{\bar{\eta}}/\mathcal{F}_{\bar{\eta}}^{I_0}$  is totally wild, with a single break  $1/(p^a-1)$  with multiplicity  $m(p^a-1) = n-m+1$ .*

**Proof.** In this case  $\mathcal{L} = j_*[n+1]^* \text{Kl}_{n+1}(\psi) = j_*[m]^*[p^a]^* \text{Kl}_{n+1}(\psi) = j_*[m]^* \text{Kl}_{n+1}(\psi')$ , where  $\psi'$  is the additive character given by  $\psi'(t) = \psi(t^{p^a})$ . We deduce by [19], 1.13.1 that  $\mathcal{L}$  is totally wild at  $\infty$  with a single break  $m/(n+1) < 1$  with multiplicity  $n+1$ . Therefore, by

[20] 7.5.4, we conclude that  $\mathcal{F}$  has break  $m/(n - m + 1)$  at 0 with multiplicity  $n - m + 1$ . In particular, the Swan conductor at 0 is  $m$ .

It remains to compute the tame part of the monodromy at 0. By the Euler-Poincaré formula,

$$-1 = \chi_c(\mathcal{F}) = \dim \mathcal{F}_{\bar{\eta}}^{I_0} - \text{swan}_0 \mathcal{F} = \dim \mathcal{F}_{\bar{\eta}}^{I_0} - m$$

so  $\dim \mathcal{F}_{\bar{\eta}}^{I_0} = m - 1$  which is precisely the codimension of the wild part. Therefore, the inertia group at 0 has dimension  $m - 1$  invariant subspace, and the action in  $\mathcal{F}_{\bar{\eta}}/\mathcal{F}_{\bar{\eta}}^{I_0}$  is totally wild, with a single break  $m/(n - m + 1) = 1/(p^a - 1)$  with multiplicity  $n - m + 1$ .  $\square$

**Proposition 2.8.** *The L-function of  $\mathcal{F}$  on  $\mathbb{A}_k^1$  is given by*

$$L(\mathbb{A}^1, \mathcal{F}, T) = 1 - T.$$

*The eigenvalues of a geometric Frobenius element  $F_\infty$  at infinity acting on  $\mathcal{F}$  are  $1, q, \dots, q^{n-1}$ .*

**Proof.** By Theorem 2.1 we have

$$\begin{aligned} L(\mathbb{A}^1, K, T) &= \prod_{j=n-1}^{2n-2} L(\mathbb{A}^1, \mathcal{H}^j(K), T)^{(-1)^j} = \\ &= \prod_{j=n-1}^{2n-2} (1 - q^{j+2-n}T)^{(-1)^{j+1} \binom{n}{j+2-n}} \cdot L(\mathbb{A}^1, \mathcal{F}, T)^{(-1)^{n-1}} = \\ &= \prod_{j=1}^n (1 - q^jT)^{(-1)^{j+n-1} \binom{n}{j}} \cdot L(\mathbb{A}^1, \mathcal{F}, T)^{(-1)^{n-1}} \end{aligned}$$

On the other hand, we have  $L(\mathbb{A}^1, K, T) = L(\mathbb{A}^1, R\sigma_! \bar{\mathbb{Q}}_\ell, T) = Z(X, T)$ . Since  $X$  is a product of  $n$  copies of the torus  $\mathbb{G}_m$ , we get

$$L(\mathbb{A}^1, K, T) = \prod_{j=0}^n (1 - q^jT)^{(-1)^{j+n-1} \binom{n}{j}}.$$

Comparing both expressions, we conclude that  $L(\mathbb{A}^1, \mathcal{F}, T) = 1 - T$ .

Let  $j : U \rightarrow \mathbb{P}^1$  be the inclusion. Since  $\mathcal{F}$  is irreducible and not geometrically constant,  $H^0(\mathbb{P}^1, j_* \mathcal{F}) = H^2(\mathbb{P}^1, j_* \mathcal{F}) = 0$ . On the other hand, the Euler-Poincaré formula gives  $\chi(\mathbb{P}^1, j_* \mathcal{F}) = n+1 - \sum_{\zeta^{n+1}=1} 1 = 0$  if  $n+1$  is prime to  $p$ , and  $\chi(\mathbb{P}^1, j_* \mathcal{F}) = 1 + \dim \mathcal{F}^{I_0} - \text{Sw}_0 \mathcal{F} = 1 + (m-1) - m = 0$  if  $p$  divides  $n+1$ , so in either case  $H^1(\mathbb{P}^1, j_* \mathcal{F}) = 0$  too. Therefore, the  $L$ -function of  $j_* \mathcal{F}$  on  $\mathbb{P}^1$  is trivial, so

$$L(\mathbb{A}^1, \mathcal{F}, T) = L(\mathbb{P}^1, j_* \mathcal{F}, T) \det(1 - TF_\infty | \mathcal{F}^{I_\infty}) = \det(1 - TF_\infty | \mathcal{F}^{I_\infty}).$$

In particular, the action of  $D_\infty/I_\infty$  on the one dimensional space  $\mathcal{F}^{I_\infty}$  is trivial, and the eigenvalues of a geometric Frobenius element acting on  $\mathcal{F}$  are  $1, q, \dots, q^{n-1}$  by [19], 7.0.7.  $\square$

**Proposition 2.9.** *If  $n$  is even or  $p$  divides  $n + 1$ , the determinant of  $\mathcal{F}$  is the geometrically constant sheaf  $\bar{\mathbb{Q}}_\ell(-n(n-1)/2)$ . If  $n$  is odd and  $(p, n + 1) = 1$ ,*

$$\det(\mathcal{F}) = \mathcal{L}_{\chi^{(t^{n+1} - (n+1)^{n+1})}}(-n(n-1)/2)$$

where  $\chi$  is the unique character of order 2 of the inertia group of  $\mathbb{A}^1$  at 0 and  $\mathcal{L}_{\chi^{(t^{n+1} - (n+1)^{n+1})}}$  is the pullback of the extension by zero to  $\mathbb{A}^1$  of the corresponding Kummer sheaf on  $\mathbb{G}_m$  under the map  $t \mapsto t^{n+1} - (n+1)^{n+1}$ .

**Proof.** If  $n$  is even, the Tate-twisted sheaf  $\mathcal{F}((n-1)/2)$  is symplectically self-dual, so its determinant is trivial. Since  $\det(\mathcal{F}((n-1)/2)) = (\det \mathcal{F})(n(n-1)/2)$ , we conclude that  $\det \mathcal{F} \cong \bar{\mathbb{Q}}_\ell(-n(n-1)/2)$ .

If  $p$  divides  $n + 1$ , let  $n + 1 = p^a m$  as in Proposition 2.7. If  $\zeta$  is a primitive  $m$ -th root of unity, exactly as in the proof of Proposition 2.5 we get an isomorphism  $\mathcal{F} \cong [t \rightarrow \zeta t]^* \mathcal{F}$ . In particular, there is a sheaf  $\mathcal{G}$  on  $\mathbb{G}_m$  such that  $\mathcal{F}|_{\mathbb{G}_m} = [m]^* \mathcal{G}$ , where  $[m] : \mathbb{G}_m \rightarrow \mathbb{G}_m$  is the  $m$ -th power map. By [19], 1.13.1 and Proposition 2.7, as a representation of the wild inertia group at 0 the sheaf  $\mathcal{G}$  has a single positive break  $1/m(p^a - 1) = 1/(n+1-m)$  with multiplicity  $n+1-m = m(p^a - 1) > 1$ , and Swan conductor 1. At infinity the inertia group acts quasi-unipotently with a single Jordan block, and after tensoring with a suitable Kummer sheaf we can assume that the action is unipotent. Then  $\det \mathcal{G}$  is smooth of rank 1 on  $\mathbb{G}_m$ , unramified at infinity and its break at 0 is  $\leq 1/(n+1-m) < 1$ . Since this break (which is the Swan conductor of  $\det \mathcal{G}$  at 0) is an integer, it has to be zero. Thus  $\det \mathcal{G}$  is tamely ramified at zero, and therefore geometrically trivial, and the same is true for  $\det \mathcal{F} = [m]^* \det \mathcal{G}$ .

So there is some  $\ell$ -adic unit  $\alpha$  such that  $\det \mathcal{F} \cong \alpha^{\deg}$ , where  $\alpha^{\deg}$  is the pullback to  $\pi_1(\mathbb{G}_{m,k})$  of the character of  $\pi_1(\mathbb{G}_{m,k})/\pi_1(\mathbb{G}_{m,\bar{k}}) \cong \text{Gal}(\bar{k}/k)$  that maps the canonical generator  $F$  to  $\alpha$ . To find the value of  $\alpha$  we need to compute the determinant of the action of an element of degree 1 of  $\pi_1(\mathbb{G}_{m,k})$  on  $\det \mathcal{F}$ . But from Proposition 2.8 we know that the action of the geometric Frobenius element at infinity (which has degree 1) on  $\mathcal{F}$  has eigenvalues  $1, q, \dots, q^{n-1}$ . Therefore,  $\alpha = q^{1+2+\dots+(n-1)} = q^{n(n-1)/2}$ , so  $\det \mathcal{F} \cong (q^{n(n-1)/2})^{\deg} = \bar{\mathbb{Q}}_\ell(-n(n-1)/2)$ .

If  $n$  is odd and  $(p, n + 1) = 1$ , from Propositions 2.4 and 2.6 we know that  $\det \mathcal{F}$  is smooth on  $U = \mathbb{A}_k^1 - \{(n+1)\zeta : \zeta^{n+1} = 1\}$ , unramified at infinity and tamely ramified at the  $n + 1$  singular points



$(n+1)\zeta$ , with the inertia groups acting via their character  $\chi$  of order two. Therefore,  $(\det \mathcal{F}) \otimes \check{\mathcal{L}}_{\chi(t^{n+1}-(n+1)^{n+1})}$  is everywhere unramified, and thus geometrically trivial. So there is some  $\ell$ -adic unit  $\alpha$  such that  $\det \mathcal{F} \cong \alpha^{\deg} \otimes \mathcal{L}_{\chi(t^{n+1}-(n+1)^{n+1})}$ . To find the exact value of  $\alpha$ , we again evaluate the determinant at  $t = \infty$  to be  $q^{n(n-1)/2}$  using Proposition 2.8. On the other hand, using that  $\mathcal{L}_{\chi(t^{n+1}-(n+1)^{n+1})} = \mathcal{L}_{\chi(t^{n+1})} \otimes \mathcal{L}_{\chi(1+\frac{(n+1)^{n+1}}{t^{n+1}})} = \mathcal{L}_{\chi(1+\frac{(n+1)^{n+1}}{t^{n+1}})}$  (since  $\chi$  has order 2 and  $n+1$  is even), we conclude that the Frobenius element at infinity acts trivially on  $\mathcal{L}_{\chi(t^{n+1}-(n+1)^{n+1})}$ , and therefore  $\alpha = q^{n(n-1)/2}$  and  $\det(\mathcal{F}) = \mathcal{L}_{\chi(t^{n+1}-(n+1)^{n+1})}(-n(n-1)/2)$ .  $\square$

**Corollary 2.10.** *Suppose that  $n$  is odd and  $(p, n+1) = 1$ , and let  $t \in \mathbb{F}_q$ . Then the action of a geometric Frobenius element  $F_t$  at  $t$  on  $\mathcal{F}$  has  $\chi(t^{n+1}-(n+1)^{n+1})q^{(n-1)/2}$  as an eigenvalue (where  $\chi: \mathbb{F}_q^* \rightarrow \mathbb{C}^*$  is the unique character of order 2) and the remaining eigenvalues appear in complex conjugate pairs.*

**Proof.** From the previous theorem we know that the product of the eigenvalues is  $\chi(t^{n+1}-(n+1)^{n+1})q^{n(n-1)/2}$ . They all have absolute value  $q^{(n-1)/2}$  and, given that  $\mathcal{F}((n-1)/2)$  is self-dual, they are permuted by the map  $z \mapsto q^{n-1}/z$ . So the non-real eigenvalues show up in complex conjugate pairs. There are an odd number of real eigenvalues, all of them necessarily equal to  $q^{(n-1)/2}$  or  $-q^{(n-1)/2}$ . Grouping them in pairs of identical eigenvalues, we are left with just one, whose sign must be  $\chi(t^{n+1}-(n+1)^{n+1})$  (since the product of the other ones is positive).  $\square$

**Proposition 2.11.** *The geometric monodromy group  $G$  of  $\mathcal{F}$  is given by*

$$\left\{ \begin{array}{ll} Sp(n, \Phi) & \text{if } n \text{ is even} \\ O(n, \Phi) & \text{if } n \text{ is odd and } (p, n+1) = 1 \\ SO(n, \Phi) & \text{if } n \text{ is odd, } p|n+1 \\ & \text{and } (p, n) \neq (2, 5) \text{ or } (2, 7) \\ G_2 \text{ in its standard} & \\ 7\text{-dimensional representation} & \text{if } p = 2, n = 7 \\ SL(2) \text{ in } \text{sym}^4 \text{ of its} & \\ \text{standard representation} & \text{if } p = 2, n = 5 \end{array} \right.$$

**Proof.** The connected component  $G_0$  of  $G$  containing the identity is semisimple by [6], 1.3.9. Since  $G$  contains a unipotent element with a single Jordan block, its Lie algebra  $\mathfrak{g}$  is simple and contains a nilpotent element with a single Jordan block and the representation  $\mathfrak{g} \rightarrow \text{End}(\mathcal{F}_{\bar{\eta}})$  is faithful and irreducible, by [19], 11.5.2.3. By 2.3, we have an a priori inclusion  $G \subset Sp(n, \Phi)$  for  $n$  even and  $G \subset O(n, \Phi)$  for  $n$  odd.

Suppose that  $n+1$  is prime to  $p$ . Then  $G$  contains pseudo-reflections (i.e. elements with invariant subspace of codimension 1). Since any element in  $G$  normalizes  $\mathfrak{g}$ , from [20], Theorem 1.5 we conclude that  $\mathfrak{g} = \mathfrak{sp}_n$  if  $n$  is even and  $\mathfrak{g} = \mathfrak{so}_n$  if  $n$  is odd. Consequently,  $G = Sp(n, \Phi)$  if  $n$  is even and  $G = SO(n, \Phi)$  or  $O(n, \Phi)$  if  $n$  is odd. But the local monodromies at the points  $t \in (n+1)\mu_{n+1}(\bar{k})$  contain elements of determinant  $-1$ , so  $G$  must be the full orthogonal group.

When  $p$  divides  $n+1$ , we will make use of the classification theorem in [19], 11.6. According to it, the possibilities for  $\mathfrak{g}$  are:  $\mathfrak{sl}_2$  in the  $(n-1)$ -th symmetric power of its standard representation,  $\mathfrak{sp}_n$  if  $n$  is even,  $\mathfrak{so}_n$  if  $n$  is odd and  $\mathfrak{g}_2$  in its standard 7-dimensional representation if  $n = 7$ .

Suppose that  $\mathfrak{g} = \mathfrak{sl}_2$ , and let  $n+1 = p^a m$  with  $m$  prime to  $p$ . As in the proof of Proposition 2.9 we find a smooth sheaf  $\mathcal{G}$  on  $\mathbb{G}_m$  such that  $\mathcal{F}|_{\mathbb{G}_m} = [m]^* \mathcal{G}$ . Since the geometric monodromy group of  $\mathcal{F}$  has finite index in that of  $\mathcal{G}$ , their Lie algebras are the same.

Let  $G'$  be the monodromy group of  $\mathcal{G}$ . The proof of [19], 11.5.2.4 shows that we have a faithful representation  $G' \hookrightarrow GL(2)$  if  $n$  is even and  $G' \hookrightarrow SO(3) \times \mu_n \subset GL(3)$  if  $n$  is odd. Let  $\mathcal{H}$  be the corresponding sheaf. As a representation of the wild inertia group  $P_0$  at 0, the breaks of  $\mathcal{G}$  are 0 and  $1/(n+1-m)$ , so the breaks of  $\mathcal{H}$  are at most  $1/(n+1-m)$ . In particular, the Swan conductor of  $\mathcal{H}$  as a representation of  $P_0$  is  $\leq 2/(n+1-m)$  if  $n$  is even ( $\leq 3/(n+1-m)$  if  $n$  is odd). If  $n+1-m > 3$  (or  $> 2$  if  $n$  is even), this automatically implies that  $\mathcal{H}$  is tame at zero as a representation of  $\pi_1(\mathbb{G}_{m, \bar{k}})$  (since the Swan conductor is an integer) and therefore it factors through the abelian tame fundamental group of  $\mathbb{G}_m$ . In particular, the monodromy group would be finite, which contradicts the assumption that  $\mathfrak{g} = \mathfrak{sl}_2$ . This rules out the possibility  $\mathfrak{g} = \mathfrak{sl}_2$  for all cases except  $(p, n) = (2, 3), (2, 5)$  or  $(3, 2)$ .

Therefore the classification theorem forces  $\mathfrak{g} = \mathfrak{sp}_n$  if  $n$  is even and  $\mathfrak{g} = \mathfrak{so}_n$  if  $n$  is odd as long as  $(p, n) \neq (2, 3), (2, 5), (2, 7)$  or  $(3, 2)$ . So in that case  $G = Sp(n, \Phi)$  if  $n$  is even, and  $G = SO(n, \Phi)$  if  $n$  is odd (since the determinant of  $\mathcal{F}$  is geometrically trivial by Proposition 2.9).

If  $(p, n) = (2, 3), (2, 7)$  or  $(3, 2)$ ,  $n+1$  is a power of  $p$ , so  $\mathcal{F}$  is totally wild at 0 with Swan conductor 1. By [19], Theorem 8.7.1, applied to the sheaf  $\iota^* \mathcal{F}$  (where  $\iota : \mathbb{G}_m \rightarrow \mathbb{G}_m$  is the inversion map),  $\iota^* \mathcal{F}$  is just a translation of a Kloosterman sheaf on  $\mathbb{G}_m$ , so it has the same geometric monodromy group. Using [19], Theorem 11.1, we conclude that  $G = Sp(n, \Phi)$  if  $(p, n) = (3, 2)$ ,  $G = SO(n, \Phi)$  if  $(p, n) = (2, 3)$  and  $G = G_2$  if  $(p, n) = (2, 7)$ .

For the remaining case  $p = 2$ ,  $n = 5$ , we have two possibilities,  $\mathfrak{g} = \mathfrak{so}_5$  or  $\mathfrak{g} = \mathfrak{sl}_2$  in the fourth symmetric power of its standard representation. In the first case,  $G$  would be  $SO(5)$ , since the determinant is trivial. We will rule out this possibility by computing the third moment of  $\mathcal{F}$  over  $\mathbb{F}_{2^{16}}$ . Suppose that  $G = SO(5)$ , and let  $V$  be the stalk of  $\mathcal{F}$  at the generic point of  $\mathbb{A}^1$ , viewed as a representation of  $SO(5)$ . The alternating square of  $\wedge^2 V$  of  $V$  is irreducible, and the symmetric square  $\text{sym}^2 V$  contains the trivial representation and another irreducible factor  $W$ . So  $V \otimes V$  decomposes as  $\wedge^2 V \oplus \mathbf{1} \oplus W$ . None of these irreducible factors is isomorphic to  $V$ , so  $V \otimes V \otimes V \cong \text{Hom}_G(V \otimes V, V)$  (since  $V$  is self-dual) does not contain the trivial representation. Therefore  $H_c^2(\mathbb{G}_{m, \bar{k}}, \mathcal{F}^{\otimes 3})$  vanishes, being the dual of  $(V \otimes V \otimes V)^G = 0$ . Since  $\mathcal{F}^{\otimes 3}$  does not have punctual sections, its  $H_c^0$  vanishes too, and then the trace formula gives

$$\left| \sum_{t \in k^*} \text{Tr}(F_t | \mathcal{F}_t)^3 \right| = |\text{Tr}(F | H_c^1(\mathbb{G}_{m, \bar{k}}, \mathcal{F}^{\otimes 3}))| \leq \dim H_c^1(\mathbb{G}_{m, \bar{k}}, \mathcal{F}^{\otimes 3}) q^{6 + \frac{1}{2}}$$

since  $\mathcal{F}^{\otimes 3}$  is pure of weight 12. Now  $\mathcal{F}^{\otimes 3}$  has rank 125, it is smooth on  $\mathbb{G}_m$ , tamely ramified at infinity and all its breaks at 0 are  $\leq 1$  (since the only breaks of  $\mathcal{F}$  at 0 are 0 and 1). Therefore its Swan conductor at 0 is at most 125, and then the Euler-Poincaré formula gives

$$\dim H_c^1(\mathbb{G}_{m, \bar{k}}, \mathcal{F}^{\otimes 3}) = -\chi(\mathbb{G}_{m, \bar{k}}, \mathcal{F}^{\otimes 3}) = \text{Sw}_0(\mathcal{F}^{\otimes 3}) \leq 125$$

so

$$\left| \sum_{t \in k^*} \text{Tr}(F_t | \mathcal{F}_t)^3 \right| \leq 125 \cdot q^{6 + \frac{1}{2}}.$$

Now using the explicit formula given in Proposition 4.1, we find for  $k = \mathbb{F}_{2^{16}}$  that

$$\sum_{t \in k^*} \text{Tr}(F_t | \mathcal{F}_t)^3 \simeq 5.48857 \cdot 10^{33} > 2.5353 \cdot 10^{33} \simeq 125 \cdot 2^{16(6 + \frac{1}{2})}$$

in contradiction with the inequality above. So  $\mathfrak{g} = \mathfrak{sl}_2$  in  $\text{sym}^4$  of its standard representation, and therefore  $G_0 = SL(2)$  in  $\text{sym}^4$  of its standard representation.  $G_0$  is normal in  $G$ , being its identity component. For every  $g \in G$ , conjugation by  $g$  gives an automorphism of  $G_0$ . But every automorphism of  $SL(2)$  is inner, so there is an element  $g_0 \in G_0$  such that  $gg_0^{-1}$  is in the centralizer of  $G_0$ . Now the centralizer of  $G_0$  in  $GL(5)$  is the set of scalar matrices (a matrix commuting with all matrices of the form

$$\text{sym}^4 \begin{pmatrix} 1 & a \\ 0 & 1 \end{pmatrix} \text{ and } \text{sym}^4 \begin{pmatrix} 1 & 0 \\ a & 1 \end{pmatrix}$$

must already be a scalar). But  $G \subset SO(5)$ , and the only scalar matrix in  $SO(5)$  is the identity. Therefore,  $g = g_0 \in G_0$ , and  $G = G_0 = SL(2)$  in  $\text{sym}^4$  of its standard representation.  $\square$

### 3. $L$ -FUNCTIONS OF SYMMETRIC AND ALTERNATING POWERS OF $\mathcal{F}$

Throughout this section we will assume that  $n + 1$  is prime to  $p$ . We will describe the  $L$ -function of the smooth sheaf  $\text{Sym}^a \mathcal{F} \otimes \wedge^b \mathcal{F}$  on the set  $U = \mathbb{A}_k^1 - \{(n + 1)\zeta : \zeta^{n+1} = 1\}$ . For simplicity, we will assume that  $k = \mathbb{F}_q$ , with  $(n + 1) | (q - 1)$ , which is always true after a finite extension of the base field.

**Proposition 3.1.** *The  $L$ -function of  $\mathcal{F}$  on  $U$  is given by*

$$L(U, \mathcal{F}, T) = (1 - T)P(T)^{n+1}$$

where  $P(T) \in 1 + T\mathbb{Z}[T]$  is a polynomial of degree  $n - 1$ . If  $n$  is odd, all reciprocal roots of  $P(T)$  have absolute value  $q^{(n-1)/2}$ . If  $n$  is even,  $P(T) = (1 \pm q^{(n-2)/2}T)P_1(T)$ , where all reciprocal roots of  $P_1(T)$  have absolute value  $q^{(n-1)/2}$ .

**Proof.** Since  $\mathcal{F}$  is smooth, geometrically irreducible and not geometrically constant on  $U$ ,  $L(U, \mathcal{F}, T) = \det(1 - F \cdot T | H_c^1(U \otimes \bar{k}, \mathcal{F}))$ . If  $j : U \rightarrow \mathbb{P}^1$  is the inclusion, the Euler-Poincaré formula gives  $\chi(\mathbb{P}_{\bar{k}}^1, j_* \mathcal{F}) = 1 + n - (n + 1) = 0$ . Therefore,  $H^i(\mathbb{P}_{\bar{k}}^1, j_* \mathcal{F}) = 0$  for all  $i$ , and we get an isomorphism

$$H_c^1(U \otimes \bar{k}, \mathcal{F}) \cong \left( \bigoplus_{\zeta^{n+1}=1} \mathcal{F}^{I_{(n+1)\zeta}} \right) \oplus \mathcal{F}^{I_\infty}$$

A similar argument gives

$$\mathcal{F}^{I_\infty} \cong H_c^1(\mathbb{A}_{\bar{k}}^1, \mathcal{F}).$$

By Proposition 2.8, we have then

$$L(U, \mathcal{F}, T) = (1 - T) \prod_{\zeta^{n+1}=1} \det(1 - F \cdot T | \mathcal{F}^{I_{(n+1)\zeta}})$$

But the isomorphism  $\mathcal{F} \cong [\zeta]^* \mathcal{F}$  implies that  $P(T) = \det(1 - F \cdot T | \mathcal{F}^{I_{(n+1)\zeta}})$  is independent of  $\zeta$ . The absolute values of the reciprocal roots of  $P$  are given by Proposition 2.6.  $\square$

We now turn to the study of the  $L$ -function of the sheaf  $\mathcal{G}_{a,b} := \text{Sym}^a \mathcal{F} \otimes \wedge^b \mathcal{F}$ , which is smooth of rank  $\binom{n+a-1}{a} \binom{n}{b}$  and pure of weight  $(a + b)(n - 1)$  on  $U$ . Let us find the bad factor of the  $L$ -function at infinity first. The local monodromy of  $\mathcal{G}_{a,b}$  at infinity is clearly unipotent, since that of  $\mathcal{F}$  is. By Proposition 3.1, the eigenvalues of the geometric Frobenius element at infinity acting on  $\mathcal{G}_{a,b}$  are  $q^{i_1 + \dots + i_a + j_1 + \dots + j_b}$  for

all possible choices of integers  $0 \leq i_1 \leq i_2 \leq \cdots \leq i_a \leq n-1$  and  $0 \leq j_1 < j_2 < \cdots < j_b \leq n-1$ . Let  $N_{n,a,b,k}$  be the number of such possible choices with  $i_1 + \cdots + i_a + j_1 + \cdots + j_b = k$ , that is,

$$N_{n,a,b,k} = \#\{(i_1, \dots, i_a, j_1, \dots, j_b) : 0 \leq i_1 \leq i_2 \leq \cdots \leq i_a \leq n-1, \\ 0 \leq j_1 < j_2 < \cdots < j_b \leq n-1, i_1 + \cdots + i_a + j_1 + \cdots + j_b = k\}$$

It is clear that  $N_{n,a,b,k} = N_{n,a,b,(a+b)(n-1)-k}$  (just change  $i_l \mapsto n-1-i_{a+1-l}$  and  $j_l \mapsto n-1-j_{b+1-l}$ ) and  $N_{n,a,b,k} = 0$  for  $k < b(b-1)/2$  and  $k > (a+b)(n-1) - b(b-1)/2$ .

**Proposition 3.2.** *The dimension of the invariant subspace  $\mathcal{G}_{a,b}^{I_\infty}$  is  $N_{n,a,b,c}$  where  $c = \lfloor \frac{(a+b)(n-1)}{2} \rfloor$  and  $N_{n,a,b,c}$  is the coefficient of  $x^c z^b$  in the expansion of the power series*

$$\frac{(1-x^n) \cdots (1-x^{a+n-1})}{(1-x) \cdots (1-x^a)} (1+z)(1+xz) \cdots (1+x^{n-1}z).$$

If  $(a+b)(n+1)$  is even, all Jordan blocks for the action of  $I_\infty$  on  $\mathcal{G}_{a,b}$  have odd size, and the number of blocks of size  $2k+1$  is  $N_{n,a,b,c-k} - N_{n,a,b,c-k-1}$  for all  $k \geq 0$ . If  $(a+b)(n+1)$  is odd, all Jordan blocks for the action of  $I_\infty$  on  $\mathcal{G}_{a,b}$  have even size, and the number of blocks of size  $2k+2$  is  $N_{n,a,b,c-k} - N_{n,a,b,c-k-1}$  for all  $k \geq 0$ .

**Proof.** This is just a translation of [6], 1.8.4 and [19], 7.0.7 to this particular situation, considering that  $\mathcal{G}_{a,b}$  is pure of weight  $(a+b)(n-1)$  and all Frobenius eigenvalues of  $\mathcal{G}_{a,b}$  at infinity are integral powers of  $q$  (that is, they have even weight). In fact, the multiplicity  $N_{n,a,b,0}$  of the minimum Frobenius eigenvalue  $q^0$  is equal to the number of Jordan blocks with length  $(a+b)(n-1) + 1$ . Removing these blocks, then the multiplicity  $N_{n,a,b,1} - N_{n,a,b,0}$  of the minimum remaining Frobenius eigenvalue  $q$  is equal to the number of blocks with length  $(a+b)(n-1) - 1$ . By induction, for  $0 < k \leq c$ , one deduces that  $N_{n,a,b,k} - N_{n,a,b,k-1}$  is equal to the number of blocks with length  $(a+b)(n-1) - 2k + 1$  and with minimum Frobenius eigenvalue  $q^k$ . The dimension of the invariant subspace  $\mathcal{G}_{a,b}^{I_\infty}$  is simply the total number of Jordan blocks:

$$\sum_{k=0}^c (N_{n,a,b,k} - N_{n,a,b,k-1}) = N_{n,a,b,c}.$$

□

**Corollary 3.3.** *The local  $L$ -function of  $j_* \mathcal{G}_{a,b}$  at infinity has degree  $N_{n,a,b,c}$  and is given by*

$$\det(1 - F_\infty \cdot T | \mathcal{G}_{a,b}^{I_\infty}) = \prod_{k=0}^c (1 - q^k T)^{\alpha_{a,b}(k)}$$

where  $\alpha_{a,b}(k) = N_{n,a,b,k} - N_{n,a,b,k-1}$ .

We can construct a generating function for  $\alpha(k)$  in the following way. Let  $C_{n,a,k} = \#\{(i_1, \dots, i_a) : 0 \leq i_1 \leq i_2 \leq \dots \leq i_a \leq n-1, i_1 + \dots + i_a = k\} = \#\{(h_0, \dots, h_{n-1}) : 0 \leq h_i, h_0 + \dots + h_{n-1} = a, h_1 + 2h_2 + \dots + (n-1)h_{n-1} = k\}$  (to check that both numbers agree, just let  $h_j$  be the number of  $l = 1, \dots, a$  such that  $i_l = j$ ). By [13], Theorem 3.1, we have

$$\sum_{k \geq 0} (C_{n,a,k} - C_{n,a,k-1})x^k = \left\{ \frac{(1-x^n) \cdots (1-x^{n+a-1})}{(1-x^2) \cdots (1-x^a)} \right\},$$

where the quantity in the bracket is understood to be  $1-x^n$  if  $a=1$ , and  $1-x$  if  $a=0$ . Let

$$B_{n,b,j} = \#\{(j_1, \dots, j_b) : 0 \leq j_1 < \dots < j_b \leq n-1, j_1 + \dots + j_b = j\}.$$

It is the coefficient of  $x^j z^b$  in the expansion of  $(1+z)(1+xz) \cdots (1+x^{n-1}z)$ . Then

$$N_{n,a,b,k} = \sum_{j=0}^k C_{n,a,k-j} B_{n,b,j},$$

and thus

$$\alpha_{a,b}(k) = N_{n,a,b,k} - N_{n,a,b,k-1} = \sum_{j=0}^{k-1} (C_{n,a,k-j} - C_{n,a,k-j-1}) B_{n,b,j} + B_{n,b,k}.$$

Therefore  $\alpha_{a,b}(k)$  is the coefficient of  $x^k z^b$  in the expansion of

$$\left\{ \frac{(1-x^n) \cdots (1-x^{a+n-1})}{(1-x^2) \cdots (1-x^a)} \right\} (1+z)(1+xz) \cdots (1+x^{n-1}z).$$

In particular, the number  $N_{n,a,b,c}$  is the coefficient of  $x^c z^b$  in the expansion of the power series

$$\frac{(1-x^n) \cdots (1-x^{a+n-1})}{(1-x) \cdots (1-x^a)} (1+z)(1+xz) \cdots (1+x^{n-1}z).$$

We now look for the bad factors of the  $L$ -function at the finite singular points  $t = (n+1)\zeta$  with  $\zeta^{n+1} = 1$ . Suppose that  $n$  is even. Then the local monodromy at  $t$  is unipotent, with a Jordan block of size 2 and all other blocks of size 1. The Frobenius eigenvalues on  $\mathcal{F}^{I_t}$  are  $\epsilon q^{(n-2)/2}$ , with  $\epsilon = 1$  or  $-1$ , and  $(n-2)/2$  pairs of conjugate complex numbers  $\alpha_1, \dots, \alpha_{(n-1)/2}, \bar{\alpha}_1, \dots, \bar{\alpha}_{(n-1)/2}$  of absolute value  $q^{(n-1)/2}$ . That is, as a representation of  $I_t$ ,  $\mathcal{F} \cong U_2 \oplus \mathbf{1}^{n-2}$ , where  $U_m$  denotes the unique (up to isomorphism) non-trivial unipotent tame representation

of  $I_t$  of dimension  $m$  with a single Jordan block. Therefore, we get isomorphisms

$$\mathrm{Sym}^a \mathcal{F} \cong \bigoplus_{i=0}^a \mathrm{Sym}^i U_2 \otimes \mathrm{Sym}^{a-i} \mathbf{1}^{n-2} = \bigoplus_{i=0}^a U_{i+1}^{\binom{n-3+a-i}{n-3}}$$

$$\wedge^b \mathcal{F} \cong \wedge^b \mathbf{1}^{n-2} \oplus (U_2 \otimes \wedge^{b-1} \mathbf{1}^{n-2}) \oplus \wedge^{b-2} \mathbf{1}^{n-2} \cong \mathbf{1}^{\binom{n-2}{b-2} + \binom{n-2}{b}} \oplus U_2^{\binom{n-2}{b-1}}.$$

**Lemma 3.4.** *Let  $V$  and  $W$  be vector spaces of dimensions  $n \geq 2$  and 2 respectively over an algebraically closed field  $k$  of characteristic 0, and let  $T : V \rightarrow V$  and  $U : W \rightarrow W$  be unipotent endomorphisms with a single Jordan block. Then  $T \otimes U : V \otimes W \rightarrow V \otimes W$  is unipotent with two Jordan blocks of sizes  $n + 1$  and  $n - 1$ .*

**Proof.** Let  $\{\mathbf{x}, \mathbf{y}\}$  be a basis for  $W$  such that  $U(\mathbf{x}) = \mathbf{x}$  and  $U(\mathbf{y}) = \mathbf{x} + \mathbf{y}$ . We claim that the invariant subspace of  $T \otimes U$  is the subspace of elements that can be written as  $\mathbf{v} \otimes \mathbf{x} + (\mathbf{v} - T(\mathbf{v})) \otimes \mathbf{y}$  for  $\mathbf{v} \in \mathrm{Ker}((T - I_V)^2)$ , which has dimension 2 by hypothesis:

$$\begin{aligned} (T \otimes U)(\mathbf{v} \otimes \mathbf{x} + (\mathbf{v} - T(\mathbf{v})) \otimes \mathbf{y}) &= T(\mathbf{v}) \otimes \mathbf{x} + T(\mathbf{v} - T(\mathbf{v})) \otimes (\mathbf{x} + \mathbf{y}) \\ &= T(\mathbf{v}) \otimes \mathbf{x} + (\mathbf{v} - T(\mathbf{v})) \otimes (\mathbf{x} + \mathbf{y}) = \mathbf{v} \otimes \mathbf{x} + (\mathbf{v} - T(\mathbf{v})) \otimes \mathbf{y}. \end{aligned}$$

Conversely, if  $(T \otimes U)(\mathbf{v} \otimes \mathbf{x} + \mathbf{w} \otimes \mathbf{y}) = \mathbf{v} \otimes \mathbf{x} + \mathbf{w} \otimes \mathbf{y}$ , we get  $T(\mathbf{w}) = \mathbf{w}$  and  $T(\mathbf{v}) + T(\mathbf{w}) = \mathbf{v}$ , so  $\mathbf{w} = T(\mathbf{w}) = \mathbf{v} - T(\mathbf{v})$  and  $(T - I_V)^2(\mathbf{v}) = 0$ . This shows that  $T \otimes U$  has precisely two Jordan blocks. From

$$T \otimes U - I \otimes I = (T - I) \otimes (U - I) + I \otimes (U - I) + (T - I) \otimes I$$

we get that  $(T \otimes U - I \otimes I)^{n+1}$  is a sum of terms  $(T - I)^\alpha \otimes (U - I)^\beta$  with  $\alpha + \beta \geq n + 1$  and therefore equal to 0, since  $(T - I)^n = (U - I)^2 = 0$ . So the Jordan blocks of  $T \otimes U$  have size  $\leq n + 1$ . Finally, if  $\mathbf{v} \in V$  is a vector such that  $\mathbf{w} := (T - I)^{n-1}(\mathbf{v}) \neq 0$  and  $\mathbf{x}, \mathbf{y} \in W$  are as above, the same expression shows that  $(T \otimes U - I \otimes I)^n(\mathbf{v} \otimes \mathbf{y}) = (n - 1)(T - I)^{n-1}(\mathbf{v}) \otimes (U - I)(\mathbf{y}) = (n - 1)\mathbf{w} \otimes \mathbf{x} \neq 0$ , so  $\mathbf{v} \otimes \mathbf{y}$  generates a Jordan block of size  $n + 1$ , and the other block must have size  $2n - (n + 1) = n - 1$ .  $\square$

**Corollary 3.5.** *Suppose that  $n$  is even. As a representation of  $I_t$ ,  $\mathcal{G}_{a,b} = \mathrm{Sym}^a \mathcal{F} \otimes \wedge^b \mathcal{F}$  is isomorphic to*

$$\bigoplus_{i=0}^a U_{i+1}^{\binom{n-3+a-i}{n-3} [\binom{n-2}{b-2} + \binom{n-2}{b}]} \oplus U_i^{\binom{n-3+a-i}{n-3} \binom{n-2}{b-1}} \oplus U_{i+2}^{\binom{n-3+a-i}{n-3} \binom{n-2}{b-1}} = \bigoplus_{i=1}^{a+2} U_i^{d(i)}$$

$$\text{where } d(i) = \left[ \binom{n-3+a-i}{n-3} + \binom{n-1+a-i}{n-3} \right] \binom{n-2}{b-1} + \binom{n-2+a-i}{n-3} \left[ \binom{n-2}{b-2} + \binom{n-2}{b} \right].$$

**Corollary 3.6.** *Suppose that  $n$  is even. The local  $L$ -function of  $j_*\mathcal{G}_{a,b}$  at  $t$ ,  $\det(1 - F_t \cdot T | \mathcal{G}_{a,b}^{I_t})$  has degree*

$$D_{n,a,b} := \sum_{i=1}^{a+2} d(i) = \left[ \binom{n-3+a}{n-2} + \binom{n-1+a}{n-2} \right] \binom{n-2}{b-1} + \binom{n-2+a}{n-2} \left[ \binom{n-2}{b-2} + \binom{n-2}{b} \right].$$

For every  $i = 1, \dots, a+2$ , it has  $d(i)$  roots which are pure of weight  $(a+b)(n-1) - (i-1)$ .

For  $n$  odd, the situation is much simpler. In that case, as a representation of  $I_t$ ,  $\mathcal{F} \cong \chi_2 \oplus \mathbf{1}^{n-1}$ , where  $\chi_2 : I_t \rightarrow \bar{\mathbb{Q}}_\ell^*$  is the unique character of order 2. Therefore, we get isomorphisms

$$\begin{aligned} \mathrm{Sym}^a \mathcal{F} &\cong \bigoplus_{i=0}^a \mathrm{Sym}^i \chi_2 \otimes \mathrm{Sym}^{a-i} \mathbf{1}^{n-1} \cong \bigoplus_{\substack{i=0 \\ \text{ieven}}}^a \mathbf{1}^{\binom{n-2+a-i}{n-2}} \oplus \bigoplus_{\substack{i=0 \\ \text{i odd}}}^a \chi_2^{\binom{n-2+a-i}{n-2}} \\ \wedge^b \mathcal{F} &\cong \wedge^b \mathbf{1}^{n-1} \oplus (\chi_2 \otimes \wedge^{b-1} \mathbf{1}^{n-1}) \cong \mathbf{1}^{\binom{n-1}{b}} \oplus \chi_2^{\binom{n-1}{b-1}}. \\ \mathrm{Sym}^a \mathcal{F} \otimes \wedge^b \mathcal{F} &\cong \mathbf{1}^{\alpha \binom{n-1}{b} + \beta \binom{n-1}{b-1}} \oplus \chi_2^{\alpha \binom{n-1}{b-1} + \beta \binom{n-1}{b}} \end{aligned}$$

where

$$\alpha = \sum_{\substack{i=0 \\ \text{ieven}}}^a \binom{n-2+a-i}{n-2}, \beta = \sum_{\substack{i=0 \\ \text{i odd}}}^a \binom{n-2+a-i}{n-2}$$

**Corollary 3.7.** *Suppose that  $n$  is odd. The local  $L$ -function of  $j_*\mathcal{G}_{a,b}$  at  $t$ ,  $\det(1 - F_t \cdot T | \mathcal{G}_{a,b}^{I_t})$  has degree*

$$D_{n,a,b} := \binom{n-1}{b} \sum_{\substack{i=0 \\ \text{ieven}}}^a \binom{n-2+a-i}{n-2} + \binom{n-1}{b-1} \sum_{\substack{i=0 \\ \text{i odd}}}^a \binom{n-2+a-i}{n-2}.$$

All its roots are pure of weight  $(a+b)(n-1)$ .

Consider the sheaf  $j_*\mathcal{G}_{a,b}$  on  $\mathbb{P}^1$ . The Tate-twisted sheaf  $\mathcal{G}_{a,b}((n-1)(a+b)/2)$  is self-dual, so Poincaré duality gives a perfect pairing of  $\mathrm{Gal}(\bar{k}/k)$ -modules

$$H^i(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b}) \times H^{2-i}(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b}) \rightarrow \bar{\mathbb{Q}}_\ell((a+b)(1-n) - 1)$$

for  $i = 0, 1, 2$ . Since  $\mathcal{G}_{a,b}$  is smooth on  $U$ , the zeroth cohomology group  $H^0(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b})$  corresponds to the maximal geometrically constant subsheaf of  $\mathcal{G}_{a,b}$ . Since  $\mathcal{G}_{a,b}$  is pure of weight  $(n-1)(a+b)$  and all Frobenius eigenvalues of  $j_*\mathcal{G}_{a,b}$  at infinity are integral powers of  $q$ , such a subsheaf must be a direct sum of copies of  $\bar{\mathbb{Q}}_\ell((1-n)(a+b)/2)$ . Incidentally, this shows that  $H^0(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b}) = 0$  if  $(n-1)(a+b)$  is odd. Therefore, we have:



**Proposition 3.8.** *The L-function of  $j_*\mathcal{G}_{a,b}$  on  $\mathbb{P}^1$  has the form*

$$L(\mathbb{P}^1, j_*\mathcal{G}_{a,b}) = \frac{P_{a,b}(T)}{(1 - q^{(a+b)(n-1)/2}T)^{\delta_{a,b}}(1 - q^{(a+b)(n-1)/2+1}T)^{\delta_{a,b}}}$$

where  $\delta_{a,b} = \dim H^0(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b})$ , and  $P_{a,b}(T)$  is a polynomial that satisfies the functional equation

$$P_{a,b}(T) = \pm T^r q^{((a+b)(n-1)+1)r/2} P_{a,b}(1/q^{(a+b)(n-1)+1}T)$$

where  $r = \deg(P_{a,b})$ .

**Proof.** We have just seen that  $H^0(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b}) = \bar{\mathbb{Q}}_\ell((1-n)(a+b)/2)^{\delta_{a,b}}$ , and Poincaré duality implies that  $H^2(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b}) = \bar{\mathbb{Q}}_\ell((1-n)(a+b)/2 - 1)^{\delta_{a,b}}$ . This gives the denominator.

The numerator is  $P_{a,b}(T) = (1 - \alpha_1 T) \cdots (1 - \alpha_r T)$ , where  $\alpha_1, \dots, \alpha_r$  are the Frobenius eigenvalues of  $H^1(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b})$ . By Poincaré duality, these eigenvalues are permuted by  $\alpha \mapsto q^{(a+b)(n-1)+1}/\alpha$ . In particular,  $(\prod \alpha_i)^2 = q^{((a+b)(n-1)+1)r}$ . We have

$$\begin{aligned} P_{a,b}(1/q^{(a+b)(n-1)+1}T) &= (1 - \frac{1}{\alpha_1 T}) \cdots (1 - \frac{1}{\alpha_r T}) \\ &= \frac{1}{\alpha_1 \cdots \alpha_r T^r} (\alpha_1 T - 1) \cdots (\alpha_r T - 1) = \frac{(-1)^r}{\pm T^r q^{((a+b)(n-1)+1)r/2}} P_{a,b}(T) \end{aligned}$$

and the functional equation follows.  $\square$

To find the dimension of  $H^0(\mathbb{P}_{\bar{k}}^1, j_*\mathcal{G}_{a,b})$  we will use the knowledge of the global monodromy of  $\mathcal{F}$ , as in [21]. Let  $V$  be the geometric generic fibre of  $\mathcal{F}$ , regarded as a representation of  $\pi_1(U \otimes \bar{k})$ . We know that the Zariski closure  $G$  of the image of  $\pi_1(U \otimes \bar{k})$  in  $\mathrm{GL}(V)$  is  $Sp(n)$  if  $n$  is even and  $O(n)$  if  $n$  is odd. The dimension we are looking for is the dimension of the invariant subspace  $\dim(\mathrm{Sym}^a(V) \otimes \wedge^b(V))^G = \dim \mathrm{Hom}_G(\mathrm{Sym}^a(V), \wedge^b(V))$  (since  $V$  is self-dual as a representation of  $G$ ).

Suppose  $n = 2m$  is even. The representations of  $G = Sp(n)$  are in one to one correspondence with the representations of the Lie algebra  $\mathfrak{g} = \mathfrak{sp}_n$ . If  $L_1, \dots, L_m$  are generators of the weight lattice for  $\mathfrak{g}$ , then  $\mathrm{Sym}^d V$  is the irreducible representation with maximal weight  $dL_1$ , and the kernel of the natural contraction map  $\wedge^d V \rightarrow \wedge^{d-2} V$  is the irreducible representation of maximal weight  $L_1 + \dots + L_d$  for  $1 \leq d \leq m$ . ([15], ch.17) Therefore we have

$$\wedge^b V \cong W(L_1 + \dots + L_b) \oplus W(L_1 + \dots + L_{b-2}) \oplus \dots \oplus V$$

if  $b \leq m$  is odd and

$$\wedge^b V \cong W(L_1 + \dots + L_b) \oplus W(L_1 + \dots + L_{b-2}) \oplus \dots \oplus \mathbf{1}$$

if  $b \leq m$  is even and  $\wedge^b V \cong \wedge^{n-b} V$  for  $m \leq b \leq n$ . So  $\text{Sym}^a V \otimes \wedge^b V$  contains exactly one copy of the trivial representation if  $a = 0$  and  $b \leq n$  is even or if  $a = 1$  and  $b \leq n$  is odd, and does not contain the trivial representation otherwise.

Suppose  $n = 2m + 1$  is odd. The representations of  $SO(n)$ , the connected component of  $G$  containing the identity, are in one-to-one correspondence with the representations of the Lie algebra  $\mathfrak{g} = \mathfrak{so}_n$  contained in the tensor algebra of the standard representation. Each of them gives rise to two different representations of  $O(n)$  (given one of them, the other one is obtained by tensoring with the determinant). If  $L_1, \dots, L_m$  are generators of the weight lattice for  $\mathfrak{g}$ , then  $\wedge^d V$  is the irreducible representation with maximal weight  $L_1 + \dots + L_d$  for  $d \leq m$ ,  $\wedge^d V \cong \wedge^{n-d} V$  for  $m+1 \leq d \leq n$ , and the kernel of the natural contraction map  $\text{Sym}^d V \rightarrow \text{Sym}^{d-2} V$  is the irreducible representation of maximal weight  $dL_1$  (cf. [15], ch.19). Therefore we have

$$\text{Sym}^a V \cong W(aL_1) \oplus W((a-2)L_1) \oplus \dots \oplus V$$

if  $a$  is odd and

$$\text{Sym}^a V \cong W(aL_1) \oplus W((a-2)L_1) \oplus \dots \oplus \mathbf{1}$$

if  $a$  is even. So  $\text{Sym}^a V \otimes \wedge^b V$  (as a representation of  $\mathfrak{g}$ ) contains exactly one copy of the trivial representation if  $a$  is even and  $b = 0$  or  $n$ , or if  $a$  is odd and  $b = 1$  or  $n-1$ , and does not contain the trivial representation otherwise.

For  $G$  itself, since the determinant becomes trivial only in even tensor powers of the standard representation, we get that  $\text{Sym}^a V \otimes \wedge^b V$  contains exactly one copy of the trivial representation and no copies of the determinant representation if  $a$  is even and  $b = 0$ , or if  $a$  is odd and  $b = 1$ , it contains exactly one copy of the determinant representation and no copies of the trivial representation if  $a$  is even and  $b = n$  or if  $a$  is odd and  $b = n-1$ , and it does not contain the trivial or the determinant representations otherwise. Therefore we get:

**Proposition 3.9.** *The dimension  $\delta_{a,b} = \dim H^0(\mathbb{P}_{\bar{k}}^1, j_* \mathcal{G}_{a,b})$  is*

$$\begin{array}{l} \text{if } n \text{ is even} \\ \text{if } n \text{ is odd} \end{array} \quad \begin{cases} 1 & \text{if } a = 0 \text{ and } b \leq n \text{ is even or } a = 1 \text{ and } b \leq n \text{ is odd} \\ 0 & \text{otherwise} \\ 1 & \text{if } a \text{ is even and } b = 0 \text{ or } a \text{ is odd and } b = 1 \\ 0 & \text{otherwise} \end{cases}$$

Putting everything together, we get the following expression for the  $L$ -function of  $\mathcal{G}_{a,b}$ :

**Theorem 3.10.** *The  $L$ -function of  $\mathcal{G}_{a,b}$  on  $U$  has total degree  $n \binom{n+a-1}{a} \binom{n}{b}$  and is given by*

$$L(U, \mathcal{G}_{a,b}) = \frac{P_{a,b}(T) Q_{a,b}(T)^{n+1} \prod_{k=0}^{\lfloor (a+b)(n-1)/2 \rfloor} (1 - q^k T)^{\alpha_{a,b}(k)}}{(1 - q^{(a+b)(n-1)/2} T)^{\delta_{a,b}} (1 - q^{(a+b)(n-1)/2+1} T)^{\delta_{a,b}}}$$

where  $\delta_{a,b} = 0$  or  $1$  is given by Proposition 3.9,  $\alpha_{a,b}(k) = N_{n,a,b,k} - N_{n,a,b,k-1}$ ,  $Q_{a,b}(T)$  is a polynomial whose degree  $D_{n,a,b}$  and the weights of its roots are given in Corollaries 3.6 and 3.7 and  $P_{a,b}(T)$  is a polynomial in  $1 + T\mathbb{Z}[T]$  of degree

$$n \binom{n+a-1}{a} \binom{n}{b} + 2\delta_{a,b} - N_{n,a,b,c} - (n+1)D_{n,a,b},$$

where  $c = \lfloor \frac{(a+b)(n-1)}{2} \rfloor$ . Furthermore,  $P_{a,b}(T)$  is pure of weight  $(a+b)(n-1) + 1$  and it satisfies the functional equation

$$P_{a,b}(T) = \pm T^r q^{((a+b)(n-1)+1)r/2} P_{a,b}(1/q^{(a+b)(n-1)+1} T).$$

**Proof.** The total degree of the  $L$ -function is the negative Euler characteristic  $-\chi(U, \mathcal{G}_{a,b})$ . Since  $\mathcal{G}_{a,b}$  is everywhere tamely ramified, this Euler characteristic is  $\chi(U) \text{rank}(\mathcal{G}_{a,b}) = -n \binom{n+a-1}{a} \binom{n}{b}$ . The stated formula is just the decomposition

$$L(U, \mathcal{G}_{a,b}) = L(\mathbb{P}^1, j_* \mathcal{G}_{a,b}) \det(1 - F_\infty \cdot T | \mathcal{G}_{a,b}^{I_\infty}) \prod_{t \in (n+1)\mu_{n+1}} \det(1 - F_t \cdot T | \mathcal{G}_{a,b}^{I_t}),$$

and the shape of each of the factors has already been determined.  $\square$

The fact that

$$L(\mathbb{A}^1, \mathcal{G}_{a,b}) = \frac{L(U, \mathcal{G}_{a,b})}{Q_{a,b}(T)^{n+1}}$$

together with the above theorem immediately implies Theorem 1.1.

**Corollary 3.11.** *The  $L$ -function of  $[\mathcal{F}]^d$  on  $\mathbb{A}^1$  is given by*

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = P_d(T) (1 - q^{\frac{d(n-1)}{2}} T) (1 - q^{\frac{d(n-1)}{2}+1} T) \prod_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1 - q^{dk} T}{1 - q^{dk+1} T}$$

if  $n$  and  $d$  are even,

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = P_d(T) \prod_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1 - q^{dk} T}{1 - q^{dk+1} T}$$

if  $n$  is even and  $d$  is odd,

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = P_d(T) (1 - q^{\frac{d(n-1)}{2}+1} T)^{-1} \prod_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1 - q^{dk} T}{1 - q^{dk+1} T}$$

if  $n$  is odd and  $d$  is even and

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = P_d(T) (1 - q^{\frac{d(n-1)}{2}} T) \prod_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1 - q^{dk} T}{1 - q^{dk+1} T}$$

if  $n$  and  $d$  are odd, where

$$P_d(T) = \prod_{b=0}^n P_{d-b,b}(T)^{(-1)^{b-1}(b-1)}.$$

Alternatively, the above four expressions can be unified into the following single expression

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = P_d(T) \frac{(1 - q^{\frac{d(n-1)}{2}} T)^{\frac{1+(-1)^{d+n}}{2}}}{(1 - q^{\frac{d(n-1)}{2}+1} T)^{\frac{-(-1)^n - (-1)^{n+d}}{2}}} \prod_{k=0}^{\lfloor \frac{n-2}{2} \rfloor} \frac{1 - q^{dk} T}{1 - q^{dk+1} T}.$$

**Proof.** From the  $L$ -function decomposition

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = \prod_{b=0}^n L(\mathbb{A}^1, \mathcal{G}_{d-b,b})^{(-1)^{b-1}(b-1)}$$

and Theorem 1.1 we get

$$L(\mathbb{A}^1, [\mathcal{F}]^d) = P_d(T) \frac{\prod_{k=0}^{\lfloor d(n-1)/2 \rfloor} (1 - q^k T)^{\sum_{b=0}^n (-1)^{b-1} b \alpha_{d-b,b}(k)}}{(1 - q^{d(n-1)/2} T)^{\delta_d} (1 - q^{d(n-1)/2+1} T)^{\delta_d}}$$

where  $\delta_d = \sum_{b=0}^n (-1)^{b-1} (b-1) \delta_{d-b,b}$ . Using Proposition 3.9, we find  $\delta_d = -d + (d-1) = -1$  if  $n$  and  $d$  are even,  $\delta_d = 1$  if  $n$  is odd and  $d$  is even and  $\delta_d = 0$  if  $d$  is odd. It remains to compute the numerator of the previous expression, which is just the local  $L$ -function at infinity of the virtual sheaf  $[\mathcal{F}]^d$ . Write  $[\mathcal{F}]^d = [\mathcal{H}_+] - [\mathcal{H}_-]$ , where  $\mathcal{H}_+ = \bigoplus_{b=0, b \text{ odd}}^n \mathcal{G}_{d-b,b}^b$  and  $\mathcal{H}_- = \bigoplus_{b=0, b \text{ even}}^n \mathcal{G}_{d-b,b}^b$  are “real” sheaves. We know that  $\mathcal{H}_+$  and  $\mathcal{H}_-$  are pure of weight  $n-1$ , the inertia group  $I_\infty$  acts unipotently on them and all their Frobenius eigenvalues at infinity are integral powers of  $q$ . If  $\mu(k)$  (resp.  $\nu(k)$ ) is the number of Frobenius eigenvalues of  $\mathcal{H}_+$  (resp. of  $\mathcal{H}_-$ ) at infinity which are equal to  $q^k$ , the local factor at infinity of the  $L$ -function of  $[\mathcal{F}]^d$  is given by  $\prod_{k=0}^{\lfloor d(n-1)/2 \rfloor} (1 - q^k T)^{(\mu(k) - \nu(k)) - (\mu(k-1) - \nu(k-1))}$ , again by [6], 1.8.4 and [19], 7.0.7.

On the other hand, for every  $r \geq 1$  the trace of the action of the  $dr$ -th power of the local Frobenius at infinity on  $[\mathcal{F}]^d$  is

$$\text{Trace}(F_\infty^{dr} | \mathcal{F}) = 1 + q^{dr} + \cdots + q^{dr(n-1)}.$$

But

$$\text{Trace}(F_\infty^{dr}|\mathcal{F}) = \text{Trace}(F_\infty^r|[\mathcal{F}]^d) = \sum_{k \geq 0} (\mu(k) - \nu(k))q^{kr}.$$

Since this holds for every  $r \geq 1$ , we conclude that  $\mu(k) - \nu(k) = 1$  if  $k = 0, d, \dots, (n-1)d$  and 0 otherwise. Therefore, the local factor at infinity of the  $L$ -function of  $[\mathcal{F}]^d$  is

$$\begin{aligned} & \prod_{k=0}^{[d(n-1)/2]} (1 - q^k T)^{(\mu(k) - \nu(k)) - (\mu(k-1) - \nu(k-1))} \\ &= (1 - q^{d(n-1)/2} T) \prod_{k=0}^{\frac{n-3}{2}} \frac{1 - q^{dk} T}{1 - q^{d(k+1)} T} \end{aligned}$$

if  $n$  is odd and

$$\begin{aligned} & \prod_{k=0}^{[d(n-1)/2]} (1 - q^k T)^{(\mu(k) - \nu(k)) - (\mu(k-1) - \nu(k-1))} \\ &= \prod_{k=0}^{\frac{n}{2}-1} \frac{1 - q^{dk} T}{1 - q^{d(k+1)} T} \end{aligned}$$

if  $n$  is even. This combined with the explicit description of  $\delta_d$  proves the result.  $\square$

We can now finish the proof of Theorem 1.1. By Theorem 2.1, we deduce

$$L(\mathbb{A}^1, [\mathcal{H}^{n-1}(K)]^d) = L(\mathbb{A}^1, [\mathcal{F}]^d) L(\mathbb{A}^1, \bar{\mathbb{Q}}_\ell^n) = L(\mathbb{A}^1, [\mathcal{F}]^d) (1 - qT)^{-n},$$

and for  $n \leq j \leq 2(n-1)$ ,

$$L(\mathbb{A}^1, [\mathcal{H}^j(K)]^d) = L(\mathbb{A}^1, \bar{\mathbb{Q}}_\ell(d(n-1-j))^{(j-\frac{n}{2})}) = (1 - q^{d(j-(n-1))+1} T)^{-\binom{n}{j-\frac{n}{2}}}.$$

Also, by Theorem 2.1 and the Grothendieck trace formula,

$$Z_d(\mathbb{A}^1, X_\lambda) = \prod_{j=n-1}^{2(n-1)} L(\mathbb{A}^1, [\mathcal{H}^j(K)]^d)^{(-1)^j}.$$

Substituting the above calculation, we obtain

$$Z_d(\mathbb{A}^1, X_\lambda)^{(-1)^{n-1}} = L(\mathbb{A}^1, [\mathcal{F}]^d) \prod_{i=0}^{n-1} (1 - q^{di+1} T)^{(-1)^{i+1} \binom{n}{i+1}}.$$

This together with Corollary 3.11 gives Theorem 1.1. The proof is complete.

## 4. ZETA FUNCTION IN TERMS OF GAUSS SUMS

In this section, we give an elementary formula for the number  $N_q(\lambda)$  of  $\mathbb{F}_q$ -rational points in the fibre  $X_\lambda$  in terms of Gauss sums for every  $\lambda \in \mathbb{F}_q$ . This type of elementary formulas for a general equation can be found in Koblitz [25]. We derive a more explicit formula in the special case of  $X_\lambda$  and in particular deduce an explicit formula for the zeta function of  $X_0$ . This allows us to determine the rank of the sheaf  $\mathcal{F}$  when  $p$  divides  $n+1$  and the local factor at 0 of the sheaf  $\mathcal{F}$ .

Let  $\omega : \mathbb{F}_q^\star \rightarrow \mathbb{C}^\star$  be a primitive character of order  $q-1$ . For every  $k \in \mathbb{Z}$ , define the Gauss sum  $G_q(k)$  by

$$G_q(k) = - \sum_{a \in \mathbb{F}_q^\star} \omega(a)^{-k} \zeta_p^{\text{Tr}_{\mathbb{F}_q/\mathbb{F}_p}(a)}$$

where  $\zeta_p = \exp(2\pi i/p)$ . It is clear that  $G_q(k) = 1$  if  $(q-1)|k$ , and  $|G_q(k)| = \sqrt{q}$  otherwise. We have the inversion formula

$$(2) \quad \zeta_p^{\text{Tr}(a)} = \sum_{k=0}^{q-2} \frac{G_q(k)}{1-q} \omega(a)^k$$

for every  $a \in \mathbb{F}_q^\star$ . We find that

$$N_q(\lambda) = \frac{1}{q} \sum_{x_0 \in \mathbb{F}_q} \sum_{x_1, \dots, x_n \in \mathbb{F}_q^\star} \zeta_p^{\text{Tr}(x_0 x_1 + \dots + x_0 x_n + \frac{x_0}{x_1 \dots x_n} - x_0 \lambda)} = \frac{(q-1)^n}{q} + \frac{1}{q} S_q(\lambda)$$

where

$$S_q(\lambda) = \sum_{x_0, x_1, \dots, x_n \in \mathbb{F}_q^\star} \zeta_p^{\text{Tr}(x_0 x_1 + \dots + x_0 x_n + \frac{x_0}{x_1 \dots x_n} - x_0 \lambda)}.$$

Using equation 2, we deduce for  $\lambda \neq 0$ :

$$\begin{aligned} S_q(\lambda) &= \sum_{x_0, x_1, \dots, x_n \in \mathbb{F}_q^\star} \zeta_p^{\text{Tr}(x_0 x_1)} \dots \zeta_p^{\text{Tr}(x_0 x_n)} \zeta_p^{\text{Tr}(x_0/x_1 \dots x_n)} \zeta_p^{\text{Tr}(-x_0 \lambda)} \\ &= \sum_{k_1, \dots, k_{n+2}=0}^{q-2} \frac{G_q(k_1) \dots G_q(k_{n+2})}{(1-q)^{n+2}} \sum_{y_i^{q-1}=1} (y_0 y_1)^{k_1} \dots (y_0 y_n)^{k_n} \left( \frac{y_0}{y_1 \dots y_n} \right)^{k_{n+1}} (y_0 \omega(-\lambda))^{k_{n+2}} \\ &= \sum_{k_1, \dots, k_{n+2}=0}^{q-2} \frac{G_q(k_1) \dots G_q(k_{n+2})}{(1-q)^{n+2}} \omega(-\lambda)^{k_{n+2}} \sum_{y_i^{q-1}=1} y_0^{k_1 + \dots + k_{n+2}} y_1^{k_1 - k_{n+1}} \dots y_n^{k_n - k_{n+1}} \\ &= (-1)^n \sum_{\substack{a, b=0 \\ (n+1)a+b \equiv 0 \pmod{q-1}}}^{q-2} \frac{G_q(a)^{n+1} G_q(b)}{q-1} \omega(-\lambda)^b \end{aligned}$$

$$= (-1)^n \left( \frac{1}{q-1} + \sum_{\substack{(n+1)a+b \equiv 0 \pmod{q-1} \\ (a,b) \neq (0,0)}} \frac{G_q(a)^{n+1} G_q(b)}{q-1} \omega(-\lambda)^b \right).$$

Thus, we obtain

**Proposition 4.1.** *If  $\lambda \neq 0$ , the number of  $\mathbb{F}_q$ -rational points in  $X_\lambda$  is given by*

$$N_q(\lambda) = \frac{(q-1)^n - (-1)^n}{q} + \frac{(-1)^n}{q-1} + \frac{(-1)^n}{q(q-1)} \sum_{\substack{(n+1)a+b \equiv 0 \pmod{q-1} \\ (a,b) \neq (0,0)}} G_q(a)^{n+1} G_q(b) \omega(-\lambda)^b.$$

We can rewrite this as

$$N_q(\lambda) = \frac{(q-1)^n - (-1)^n}{q} + \frac{(-1)^n}{q-1} + \frac{(-1)^n}{q(q-1)} \sum_{k=1}^{q-2} G_q(k)^{n+1} G_q(-(n+1)k) \omega(-\lambda)^{-(n+1)k}.$$

If  $\lambda = 0$ , then equation 2 gives

$$\begin{aligned} S_q(0) &= \sum_{x_0, x_1, \dots, x_n \in \mathbb{F}_q^*} \zeta_p^{\text{Tr}(x_0 x_1 + \dots + x_0 x_n + \frac{x_0}{x_1 \dots x_n})} \\ &= \sum_{x_0, x_1, \dots, x_n \in \mathbb{F}_q^*} \zeta_p^{\text{Tr}(x_0 x_1)} \dots \zeta_p^{\text{Tr}(x_0 x_n)} \zeta_p^{\text{Tr}(x_0/x_1 \dots x_n)} \\ &= \sum_{k_1, \dots, k_{n+1}=0}^{q-2} \frac{G_q(k_1) \dots G_q(k_{n+1})}{(1-q)^{n+1}} \sum_{y_i^{q-1}=1} (y_0 y_1)^{k_1} \dots (y_0 y_n)^{k_n} \left( \frac{y_0}{y_1 \dots y_n} \right)^{k_{n+1}} \\ &= \sum_{k_1, \dots, k_{n+1}=0}^{q-2} \frac{G_q(k_1) \dots G_q(k_{n+1})}{(1-q)^{n+1}} \sum_{y_i^{q-1}=1} y_0^{k_1 + \dots + k_{n+1}} y_1^{k_1 - k_{n+1}} \dots y_n^{k_n - k_{n+1}} \\ &= (-1)^{n+1} \sum_{\substack{k=0 \\ (n+1)k \equiv 0 \pmod{q-1}}}^{q-2} G_q(k)^{n+1} = (-1)^{n+1} \left( 1 + \sum_{\substack{k=1 \\ (n+1)k \equiv 0 \pmod{q-1}}}^{q-2} G_q(k)^{n+1} \right). \end{aligned}$$

And therefore

$$N_q(0) = \frac{(q-1)^n - (-1)^n}{q} + \frac{(-1)^{n+1}}{q} \sum_{\substack{k=1 \\ (n+1)k \equiv 0 \pmod{q-1}}}^{q-2} G_q(k)^{n+1}.$$

Writing  $(n+1) = p^a m$  with  $(p, m) = 1$ , this is

$$(3) \quad N_q(0) = \frac{(q-1)^n - (-1)^n}{q} + \frac{(-1)^{n+1}}{q} \sum_{\substack{k=1 \\ mk \equiv 0 \pmod{q-1}}}^{q-2} G_q(k)^{n+1}.$$

Let  $S_m = \{\frac{1}{m}, \frac{2}{m}, \dots, \frac{m-1}{m}\}$ . It is clear that multiplication by  $p$  induces an action on  $S_m$ , called  $p$ -action:

$$r \mapsto \{pr\}$$

where  $\{pr\}$  denotes the fractional part of  $pr$ . For a given  $r \in S_m$ , let  $d(r)$  denote the length of the  $p$ -orbit containing  $r$ , that is, the smallest positive integer  $d$  such that  $(p^d - 1)r \in \mathbb{Z}$ . Let  $S_{m,d}$  denote the set of  $p$ -orbits of length  $d$  in  $S_m$ .

Since  $G_{p^d}(k) = G_{p^d}(pk)$ , it is clear that if  $r_1$  and  $r_2$  are in the same  $p$ -orbit  $\sigma$  in  $S_{m,d}$ ,  $G_{p^d}(r_1(p^d - 1)) = G_{p^d}(r_2(p^d - 1))$ . Let us denote this common value by  $G_{p^d}(\sigma(p^d - 1))$ . Since the set of  $p$ -orbits of  $S_m$  is the union of  $S_{m,d}$  for all  $d \geq 1$ , we have

**Theorem 4.2.** *The zeta function of  $X_0$  over  $\mathbb{F}_p$  is given by*

$$Z(X_0, T)^{(-1)^n} = \prod_{i=0}^{n-1} (1 - p^i T)^{\binom{n}{i+1} (-1)^i} \prod_{d \geq 1} \prod_{\sigma \in S_{m,d}} \left( 1 - T^d \frac{G_{p^d}^{n+1}(\sigma(p^d - 1))}{p^d} \right).$$

**Proof.** By equation 3,

$$\log Z(X_0, T) = \sum_{k \geq 1} \frac{T^k}{k} \frac{(p^k - 1)^n - (-1)^n}{p^k} + \sum_{k \geq 1} \frac{T^k}{k} \frac{(-1)^{n+1}}{p^k} \sum_{\substack{h=1 \\ mh \equiv 0 \pmod{p^k - 1}}}^{p^k - 2} G_{p^k}(h)^{n+1}.$$

The second sum is

$$\begin{aligned} & \sum_{k \geq 1} \frac{T^k}{k} \frac{(-1)^{n+1}}{p^k} \sum_{\substack{r \in S_m \\ r(p^k - 1) \in \mathbb{Z}}} G_{p^k}(r(p^k - 1))^{n+1} \\ &= (-1)^{n+1} \sum_{d \geq 1} \sum_{\sigma \in S_{m,d}} \sum_{r \in \sigma} \left( \sum_{k \geq 1} \frac{T^{dk}}{dk} \frac{G_{p^{dk}}(r(p^{dk} - 1))^{n+1}}{p^{dk}} \right) \\ &= (-1)^{n+1} \sum_{d \geq 1} \sum_{\sigma \in S_{m,d}} \left( \sum_{k \geq 1} \frac{T^{dk}}{k} \frac{G_{p^{dk}}(\sigma(p^{dk} - 1))^{n+1}}{p^{dk}} \right). \end{aligned}$$

By the Hasse-Davenport relation, this sum becomes

$$= (-1)^{n+1} \sum_{d \geq 1} \sum_{\sigma \in S_{m,d}} \left( \sum_{k \geq 1} \frac{T^{dk}}{k} \frac{G_{p^d}(\sigma(p^d - 1))^{k(n+1)}}{p^{dk}} \right),$$

which gives the stated formula for the zeta function.  $\square$



**Corollary 4.3.** 1) The rank of the sheaf  $\mathcal{F}$  at 0 is  $m - 1$ .

2) The local  $L$ -function of the sheaf  $\mathcal{F}$  at 0 is given by

$$\prod_{d \geq 1} \prod_{\sigma \in S_{m,d}} \left( 1 - T^d \frac{G_{p^d}^{n+1}(\sigma(p^d - 1))}{p^d} \right).$$

**Proof.** From the given formula for the  $L$ -function, we see that the degree of the non-trivial part is given by  $|S_m| = m - 1$ .  $\square$

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