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Corrected 20 July 2012 to replace incorrect version of Fig. 2.

TLR13 Recognizes Bacterial 23*S* rRNA Devoid of Erythromycin Resistance–Forming Modification

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Host protection from infection relies on the recognition of pathogens by innate pattern recognition receptors such as Toll-like receptors (TLRs). Here we show that the orphan receptor TLR13 in mice recognizes a conserved 23*S* ribosomal RNA (rRNA) sequence that is the binding site of macrolide, lincosamide, and streptogramin group (MLS) antibiotics (including erythromycin) in bacteria. Notably, 23*S* rRNA from clinical isolates of erythromycin-resistant *S. aureus* and synthetic oligoribonucleotides carrying methylated adenosine or a guanosine mimicking a MLS resistance–causing modification failed to stimulate TLR13. Our results thus reveal both a natural TLR13 ligand and specific mechanisms of antibiotic resistance as potent bacterial immune evasion strategy, avoiding recognition via TLR13.

Whereas TLR2, TLR4 and TLR9 are major host sensors of Gram-negative bacteria and TLR2 is thought to be the central detector of Gram-positive bacteria, other pattern recognition receptors (PRRs) such as TLR7 contribute to bacteria sensing, too (*1*–*7*). The high sensitivity of mice lacking expression of these TLRs to Gram-positive bacteria, however, implies that other TLRs or members of other classes of pattern recognition receptors (PRRs) such as C-type lectins, RIG-I–like helicases (RLHs), or nucleotide binding domain– and leucine-rich repeat–containing proteins (NLRs) play a role in the detection of Gram-positive bacteria. We therefore compared the responsiveness of macrophages lacking the expression of molecules that signal downstream of these PRRs, including caspase recruitment domain (CARD) 9, receptor-interacting protein 2 (RIP2), apoptosis-associated speck-like protein containing a CARD (ASC), interleukin (IL)-1 receptor 1, IL-18, or MyD88, to heat inactivated *S. aureus* (hiSa) or *Streptococcus pneumoniae* (both Gram-positive) in the presence of a TLR2-blocking antibody (*2*, *8*–*10*). Cytokine production was found to strictly depend on MyD88 (fig. S1A), which suggested that TLRs rather than RLHs or NLRs are responsible for the detection of these bacteria. Moreover, analysis of ectopically expressed RLH function indicated a lack of RLH involvement in Gram-positive bacteria sensing (fig. S1B).

Next we asked whether endosomal TLRs (TLR3, -7, -8, -9, -11, and -13) are involved in cell activation. We inhibited endosomal acidification with bafilomycin and analyzed UNC93B1-mutant (*3D*) macrophages that lack endoplasmic reticulum–endosome TLR trafficking and are susceptible to *S. aureus* infection (*2*, *11*, *12*). Bafilomycin treatment abrogated recognition of Gram-positive bacteria in *Tlr2*$^{-/-}$ macrophages (Fig. 1A). Furthermore, 3D/*Tlr2/4*$^{-/-}$ and 3D/*Tlr2*$^{-/-}$ mice or corresponding macrophages (but not those generated from *3D* mice unless TLR2 was blocked), were unresponsive to Gram-positive bacterial challenge (Fig. 1, B and C, and fig. S1C). Unexpectedly, *Tlr23479*$^{-/-}$ macrophages (or mice) responded well to hiSa challenge unless the bacterial preparations were subjected to RNase A treatment, which did not impair TLR2-driven activation of wt controls, or endosomal TLR function was abrogated (Fig. 1, D-F). These data suggested that an endosomal RNA sensor besides TLR3 and TLR7 can act as cellular detector of hiSa.

Dendritic cell (DC) subsets express different sets of TLRs (*13*). We generated bone marrow-derived conventional (c) DC and plasmacytoid (p) DC in vitro. The responsiveness of these cells to hiSa was dependent on MyD88 and UNC93B1. Specifically, *Tlr23479*$^{-/-}$ CD8^{high} (expressing TLR11, -12, -13) and signal regulatory protein α (Sirp)^{high} cDCs (expressing TLR13 but lacking TLR11, -12) responded to hiSa, whereas *Tlr23479*$^{-/-}$ pDCs (expressing TLR12 but lacking TLR11, -13) failed to do so (Fig. 1G). Together, these findings implied that TLR13 acts as bacterial single-stranded (ss) RNA sensor, even though TLR13 has recently been linked with the recognition of vesicular stomatitis virus (*14*).

To identify the relevant RNA, we incubated hiSa with calf intestinal phosphatase, 5′-phosphate–specific phosphatase (to affect the integrity of 16*S* and 23*S* rRNA), or double-stranded (ds) RNA–specific RNase III or VI. These treatments did not alter the stimulatory activity of hiSa, in line with a recent report (fig. S2, A-C) (*15*). However, ssRNA-specific RNase A treatment abrogated the *Tlr23479*$^{-/-}$ cDC (and macrophage) stimulatory activity of hiSa as did nucleic acid-degrading benzonase (Fig. 1, D, E, and G; and fig. S2B, please note that Flt3L-expanded CD8^{+} cDCs do not produce IL-12p70 in response to TLR2 ligands that are contained in hiSa (*16*)). We then treated total RNA with 5′-phosphate–dependent exonuclease (to degrade specifically large rRNAs, namely 16*S* and 23*S* rRNA) and purified large rRNAs (fig. S2C) to narrow down the stimulatory activity. After transfection, large rRNA isolates of both *S. aureus* and *E. coli* triggered the activation of *Tlr23479*$^{-/-}$ macrophages and cDCs while 16*S*/23*S* rRNA digestion abrogated stimulatory activity (Fig. 2A). Accordingly, low molecular weight (lmw) portions from total RNA lacked stimulatory activity, whereas high molecular weight (hmw) portions of Gram-positive and Gram-negative bacterial RNA activated *Tlr23479*$^{-/-}$ cells (Fig. 2B and fig. S2, D and E). These findings suggested that a fraction of large bacterial rRNAs activates macrophages and cDCs in a MyD88-dependent manner. We assume that the increased RNA-driven activation of *Tlr23479*$^{-/-}$ macrophages in comparison to wt cells reflects a lack of TLRs compet-

ing for downstream signal transduction molecules.

To analyze if rRNA modifications induced in antibiotic resistant strains by antibiotic treatment (e.g., with erythromycin (*17*, *18*)) would modify the immunostimulatory capacity of rRNA we applied five clinical *S. aureus* isolates displaying various resistance phenotypes, including erythromycin resistance. Isolates grown in the presence of erythromycin largely lacked the capacity to activate *Tlr23479*$^{-/-}$ macrophages and induced lower amounts of serum cytokines early after infection (2 hours) of *Tlr23479*$^{-/-}$ mice (Fig. 2, C and D). In contrast, wt as well as *Tlr23479*$^{-/-}$ mice and corresponding macrophages responded largely normally toward the same isolate grown in the absence of erythromycin (Fig. 2, C and D, and fig. S2, F to H). The later (16 hours) increase and equalization of serum cytokine levels independent of erythromycin treatment (fig. S2H) suggested the loss of 23*S* rRNA methylation in the absence of erythromycin within the host. Together, these results demonstrate an erythromycin-driven camouflage of RNA from its receptor. Specifically, N^6 methylation of rRNA adenosine (A) 2085 in *S. aureus* (corresponding to *E. coli* A2058) by the erythromycin resistance methyltransferase (erm) B or ermC confers macrolide, lincosamide, and streptogramin group (MLS) antibiotic (that include erythromycin) resistance (*17*, *18*). Accordingly and also in line with inducibility of erm expression by erythromycin (*17*, *18*), 23*S* rRNA from *S. aureus* grown in erythromycin failed to stimulate *Tlr23479*$^{-/-}$ macrophages (Fig. 2E). In contrast, 23*S* rRNA from resistant *S. aureus* not grown in erythromycin and 23*S* rRNA from *E. coli* (including enterohemorrhagic *Escherichia coli*) activated *Tlr23479*$^{-/-}$ macrophages, while the respective 16*S* RNAs failed to do so. (Fig. 2E, and fig. S2, I and J). Moreover, overexpression of ermB and ermC (the latter being subcloned from cDNA of an erythromycin grown *S. aureus* isolate) in *E. coli* and *B. subtilis* strains conferred not only erythromycin resistance but also ablated 23*S* rRNA stimulatory activity (Fig. 2F and fig. S2K). These data indicated that resistance to MLS group antibiotics (including erythromycin) mediated by site-specific methylation (targeting A2085 in *S. aureus* and A2058 in *E. coli* 23*S* rRNA) rendered 23*S* rRNA non-stimulatory.

To address the immune stimulatory activity of 23*S* rRNA in more detail, we designed three oligoribonucleotides (ORNs) as analogs of *S. aureus* 23*S* rRNA segments, each of which carries an A in its center that becomes methylated constitutively or under growth restriction to modulate the docking of protein synthesis cofactors or antibiotics. The three ORNs named SaI, SaII, and SaIII represented *S. aureus* A1662 (*E. coli* A1616, methylation of which promotes fitness (*19*)), *S. aureus* A2530 (*E. coli* A2503, targeted by chloramphenicol, florfenicol, and clindamycin resistance RNA methyltransferase (*20*)), as well as *S. aureus* A2085 (*E. coli* A2058, modification of which costs fitness (*17*, *18*, *21*), respectively (table S1).

Only SaIII (which mirrors *S. aureus* A2085) activated *Tlr23479*$^{-/-}$ cells (Fig. 3A). pDCs recognized SaIII via TLR7, but this activity was lost with 3′-terminal deletion (fig. S3). ORNs resulting from deletions of 3′- and 5′-termini (SaIIId3, SaIIId5, and Sa23) equally activated *Tlr23479*$^{-/-}$ cDCs (Fig. 3B), whereas preincubation of *S. aureus* RNA or of ORN Sa23 with an antisense SaIII RNA strand (SaIIIas) abrogated the stimulatory activity (Fig. 3C). These results indicated single strand structure and singularity of the stimulatory activity within the bacterial transcriptome. Successive terminal deletions toward a 12-mer ORN (Sa12, table S1) led to sequences that were identical in *S. aureus* and *E. coli* 23*S* rRNAs. Length dependent reduction of stimulatory capacity could largely be compensated by terminal fill-ups (Sa12A19, Fig. 3D) (*22*). When Sa12 was N^6-methylated at A6 (corresponding to *S. aureus* A2085 and mimicking erm-methylated 23*S* rRNA) it lacked stimulatory capacity, whereas N^6-methylation at A7 merely caused a partial reduction (Fig. 3E). Consecutive single substitutions of Sa12 revealed "CGGAAAGACC" as the minimal stimulatory segment because ORNs with substitutions at position one or two of Sa12 (Sa12s1 and Sa12s2) were fully stimulatory whereas further substitutions resulted in drastic loss (Sa12s10 and Sa12s12) or abrogation of the stimulatory activity (Fig. 3F and table S1).

In contrast, Sa12 derivatives mimicking eukaryotic 28*S* rRNA or specific 23*S* rRNA mutations that render bacteria resistant to MLS antibiotics (*S. aureus* 23*S* rRNA A2085G, mimicked by ORN Sa12s6G or Sa12s6U) failed to stimulate bone marrow cells (Fig. 3F and table S1) (*18*, *23*). These findings suggest that molecular mechanisms rendering bacteria resistant to naturally occurring antibiotics also impede MyD88 dependent host recognition by an ill-defined endosomal TLR.

To characterize the responsible TLR, we focused on TLR13, because analysis of *Tlr8*$^{-/-}$ macrophages ruled out the involvement of TLR8. Specifically, wt and *Tlr8*$^{-/-}$ macrophages exhibited comparable response to hiSa upon blockade TLR7, TLR9 and TLR2. Moreover, responsiveness to 23*S* rRNA–derived SaIII was similar (fig. S4A). Notably, siRNA-driven suppression of TLR13 mRNA accumulation impaired the recognition of stimulatory ORNs such as SaIII by *Tlr23479*$^{-/-}$ macrophages (Fig. 4A). Although recognition of low doses of hiSa by *Tlr23479*$^{-/-}$ macrophages treated with siRNA for TLR13 was strongly impaired, high dose hiSa challenge activated not only control but also TLR13 siRNA-treated cells, presumably via unsuppressed TLR13 molecules (fig. S4B). In addition, knock-down of MAPK1 mRNA indicated involvement of MAPK1 in TLR13-driven signal transduction (Fig. 4A and fig. S4B). Furthermore, ectopic expression of TLR13 but not of CD14, TLR3, -7, -8, -9 or -12 conferred responsiveness of HEK293 cells toward hiSa or the ORNs SaIII, Sa23, Sa17, or Sa12 (Fig. 4, B-D, and fig. S4, C and D). Other ORNs such as RNA40 (TLR7 ligand) or CpG-containing oligodeoxynucleotides (ODNs, TLR9 ligands) were inactive (Fig. 4E).

Having identified the conserved 23*S* rRNA sequence "CGGAAAGACC" as ligand for TLR13, we set out to evaluate its importance in vivo. Therefore we compared the cytokine storm induced by systemic application of TLR13 activating ORNs with that of TLR9 activating CpG-ODNs. Application of a nuclease resistant phosphorothioate Sa19 variant (Sa19 PSO) in vivo triggered systemic pro-inflammatory cytokine release similar to that elicited by the PSO-CpG oligonucleotide 1668 (Fig. 4F and fig. S4, E and F). Consequently, systemic application of Sa19PSO to mice along with interferon-γ (IFN-γ) and D-galactosamine (D-GalN) sensitization induced a fatal septic shock like syndrome in mice with functional TLR13 (wt and *Tlr23479*$^{-/-}$) whereas the *3D/Tlr24*$^{-/-}$ mice which lack responsiveness to TLR13 were resistant (fig. S4G), concordant with the genotype-selective fatal pathology elicited by systemic challenge with hiSa (Fig. 1F). In contrast to the ORN Sa19, an ODN version of Sa19 (Sa19DNA, containing two CpG motifs), lacked TLR13 stimulatory activity, but activated TLR9 (fig. S4F). All together, these data indicated that TLR13 functions as important bacteria sensor by recognizing an ssRNA segment within the peptidyl transferase loop of bacterial 23*S* rRNA that binds antibiotics of the MLS group.

Our data unravel an unanticipated link between antibiotic resistance and evasion from TLR13 recognition, because 23*S* rRNA modifications generating resistance toward MLS antibiotics also camouflaged bacteria from TLR13 recognition. MLS antibiotic-producing bacteria such as *Saccharopolyspora erythraea* were possibly first to express erms (to resist their own antibiotics) (*17*). Erm expression plasmids might have been acquired from *S. erythraea* by staphylococci, pneumococci, and mycobacteria (which seem to accompany or even correlate with tuberculous property of the latter) (*17*, *24*). Even though macrolide resistance appears to be associated with fitness costs (*21*), the pathogenic recipients did gain invisibility to TLR13. We therefore speculate that widespread ancient antibiotic resistance (*25*) has subverted TLR13 driven antibacterial immune resistance. This may explain why TLR13 expression has been abandoned in certain mammalian species, including human. If so, we anticipate that in human the function of TLR13 has been replaced by

an RNA sensing PRR that is able to still recognize erythromycin resistance-forming RNA modifications.

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Supplementary Materials

www.sciencemag.org/cgi/content/full/science.1220363/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S4
Table S1
References (*26*–*32*)

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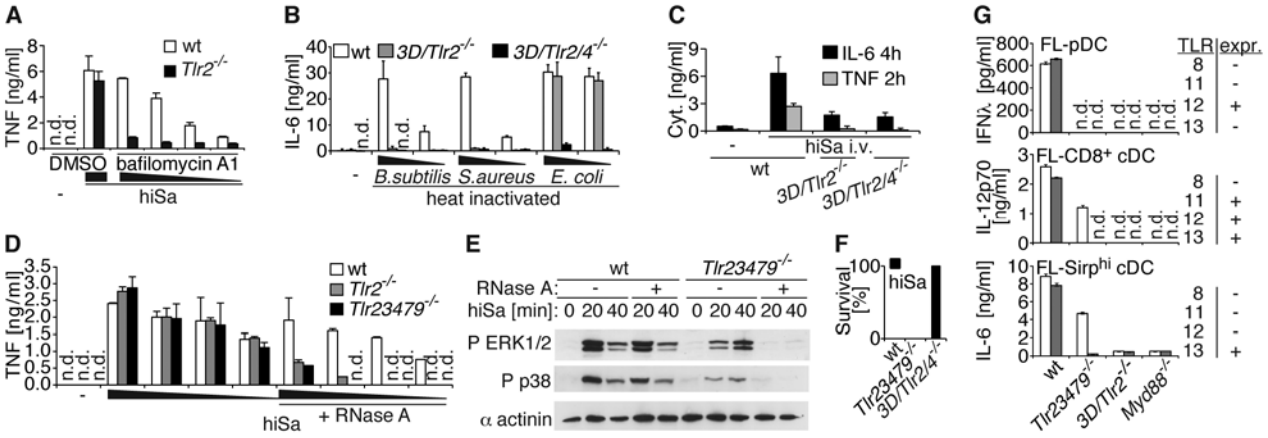

Fig. 1. Gram-positive bacteria and their RNA activate *Tlr23479*$^{-/-}$ macrophages and DCs via an unknown TLR. (**A**) Macrophages were preincubated for 30 min with dimethyl sulfoxide (DMSO) alone or 50 nM bafilomycin A1, challenged for 8 hours with 10^9 cfu/ml heat inactivated *S.aureus* (hiSa; DMSO) or 10^9, 10^8, 10^7, and 10^6 cfu/ml hiSa (bafilomycin A1; -, unchallenged). Supernatants were analyzed by ELISA. (**B**) Macrophages were challenged for 16 hours with 10^9 or 10^8 cfu/ml of bacterial suspensions whereas (**C**) corresponding mice were challenged i.v. with 10^9 cfu hiSa or PBS only (-) 2 and 4 hours upon which serum was drawn. Supernatants and serum samples were analyzed by ELISA (C, Cyt., cytokine; one out of three experiments with similar results and respectively n=3 mice per group is illustrated as mean ±SD). (**D** and **E**) Macrophages were challenged for 16 hours (D) or times indicated (E; P, phosphorylated) with untreated (-) or RNase A-treated (+) hiSa suspensions. (D) 10^9, 10^8, 10^7, and 10^6 or (E) 10^8 cfu/ml hiSa used for challenge upon which supernatants were analyzed by ELISA or lysates were analyzed by SDS PAGE and immuno blotting. (**F**) Mice were challenged by injection with hiSa (1.6×10^{11} cfu/kg body weight) and α-D-galactosamine (800 mg/kg body weight) i.p. 45 min upon injection of IFNγ (50 µg/kg body weight) i.v.. Survival was monitored and all deaths occurred within 16 hours of treatment (n=6 per wt and *3D/Tlr2/4*$^{-/-}$ groups, n=4 for *Tlr23479*$^{-/-}$ mice). (**G**) Flt3-ligand-derived DC subsets were challenged with untreated (white bars) or RNase A treated (grey bars) hiSa at 5×10^6 cfu/ml for 16 hours. Supernatants were analyzed for cytokine contents by bead array (n.d., not detected). The respective TLR expression (expr.) in DC subsets is indicated (-, no detectable expression; +, expression). (A-E and G) For each panel representative results from at least three experiments are shown and each illustrated data point (A-D and G) represents mean ±SD of duplicates.

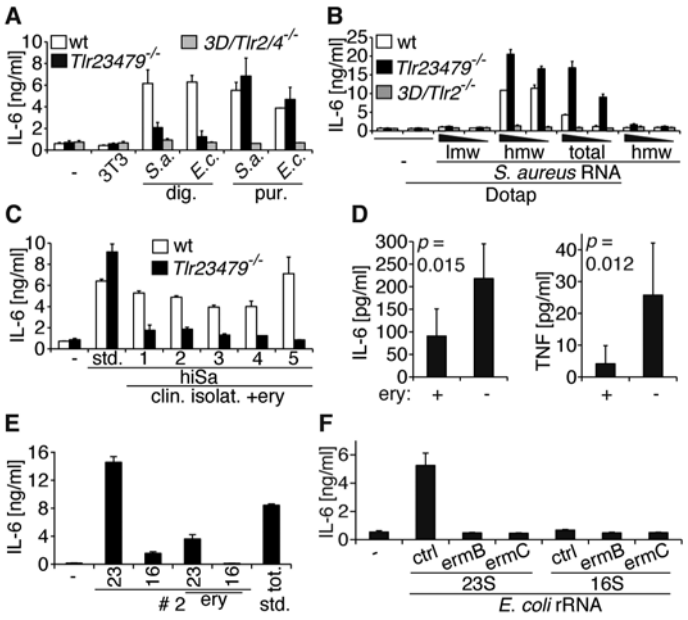

Fig. 2. Bacterial 23*S* rRNA is stimulatory unless it is methylated by erythromycin resistance methyltransferases (erms). (**A**) Bacterial RNA preparations resulting from incubation of total RNAs with 5′-phosphate–specific exo RNase targeting large rRNAs (dig.) or precipitation of both large rRNAs (pur.), as well as untreated mouse fibroblast cell line (3T3) RNA (control) were transfected into macrophages using Dotap. (**B**) Bacterial total RNAs were separated by anion-exchange chromatography into low molecular weight (lmw) and high molecular weight (hmw) fractions, which were used to challenge macrophages with or without Dotap transfection. (**C**) Macrophages were challenged with 10^9 cfu/ml erythtromycin sensitive (std.) hiSa or five erythromycin resistant clinical *S. aureus* isolates cultured in 10 mg/l erythromycin (clin. isolat. +ery). (A-C) Supernatants were analyzed 16 hours post stimulation using ELISA. (**D**) *Tlr23479*$^{-/-}$ mice were infected i.v. with 10^8 cfu erythromycin resistant *S. aureus* clinical isolate growing logarithmically in the presence (+) or absence (-) of erythromycin. Serum was drawn after 2 hours and analyzed for cytokines by cytometric bead array. Illustrated is the mean ±SD for n=6 mice per each group. (**E**) Total (tot.) RNA from erythromycin sensitive *S. aureus* (std.) and agarose gel-purified 16*S* (16) and 23*S* (23) rRNAs from clinical isolate 2 grown in the absence or presence of erythromycin (ery) were transfected into *Tlr23479*$^{-/-}$ macrophages using lyovec. (**F**) *E. coli* BL21 was transformed with empty vector control (ctrl) or erythromycin resistance methyltransferase (erm) B or ermC expression plasmids. After 16 hours culture l16*S* and 23*S* rRNA was isolated and transfected into *Tlr23479*$^{-/-}$ macrophages. (E and F) Supernatants were analyzed 16h post challenge using ELISA. (A-C, E, and F) Each panel illustrates a representative result of three independent experiments and means ±SD of duplicate samples. For D one statistically significant experiment has been performed ($p \leq 0.015$).

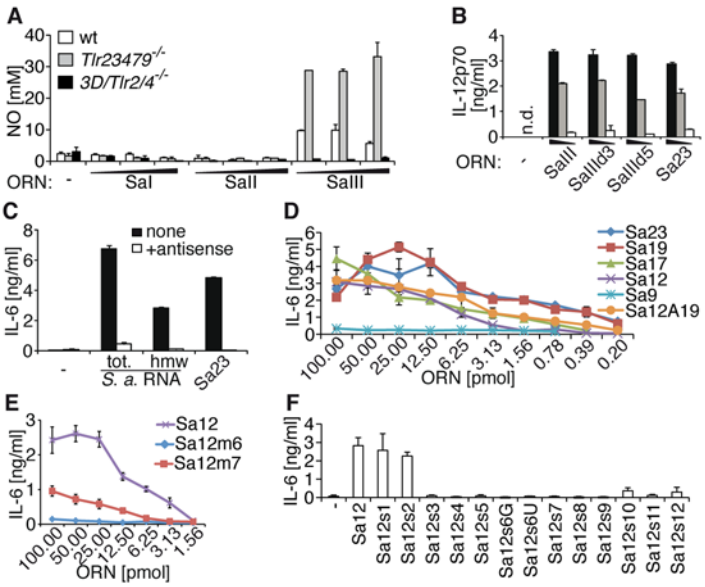

Fig. 3. Oligoribonucleotides (ORNs) covering the erythromycin resistance methyltransferase (erm) target site in 23*S* rRNA (region around A2085 in *S. aureus* / 2058 in *E. coli*) activate macrophages and cDCs. (**A**) Sequence motifs covering 3 separate methylation sites in *S. aureus* 23*S* rRNA were mirrored by ORNs (see table S1). Macrophages were challenged with 1, 10, and 100 pmol/well of the ORNs. (**B**) *Tlr23479*$^{-/-}$ FL-CD8^{+} cDCs were transfected with the ORNs indicated (amount/well [pmol]: black, 10; grey, 1; white, 0.1). (**C**) *Tlr23479*$^{-/-}$ Sirp^{high} cDCs were transfected with 100 ng/well of the *S. aureus* RNA preparations indicated or an ORN covering the SaIII core sequence (10 pmol/well), either in the absence (none) of or upon preincubation for 20 min with 100 pmol/well antisense RNA ORN (SaIIIas, +antisense). (**D** to **F**) Undifferentiated bone marrow cells were challenged with ORNs at doses per well indicated (D and E) or 100 pmol/well (F). (A to F) Cells were transfected (A, Dotap; B-F, lyovec) for 16 hours with the indicated RNAs and ORNs. In each experiment supernatants were assayed for nitrite (NO) content by Griess assay (A) or proinflammatory cytokine contents by bead assay (B and C) or ELISA (D-F). Each panel illustrates a representative result of three independent experiments and depicts means ±SD of duplicate samples (A-E) or the mean ±SD of at least three independent experiments (F).

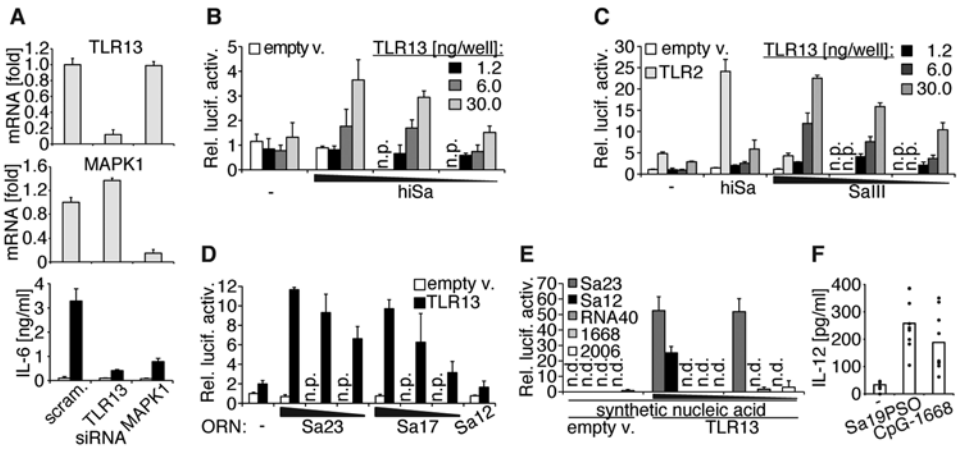

Fig. 4. TLR13 recognizes heat-inactivated *S. aureus* and ORNs mirroring bacterial 23*S* rRNA segments covering A2085/2058. (**A**) 5 × 10^5 *Tlr23479*$^{-/-}$ macrophages were transfected with 50 pmol mRNA specific siRNAs or scrambled control siRNA (scram.). After 48 hours cells were challenged for 16 hours with with 100 pmol/well ORN SaIII (black columns, lower diagram) or left untreated (white columns, lower diagram) and supernatants were analyzed by ELISA (lower diagram). Untreated cells were lysed to isolate mRNA and levels of corresponding mRNAs were determined by RT PCRs (two upper diagrams). (**B** to **E**) Human embryonic kidney (HEK) 293 line cells were transfected with control-, TLR2 or TLR13 expression and luciferase reporter plasmids. In general, cells were transfected with 15 ng empty vector (v.), 2 ng TLR2 (C), 15 ng TLR13 (D and E) or amounts of TLR13 expression plasmid indicated (B and C). 24 hours post transfection cells were challenged with 10^9, 10^8, and 10^7 cfu/ml of hiSa (B), 10^9 cfu/ml hiSa (C), 100, 10, and 1 pmol/well ORN (C and D), 100 pmol/well ORN only (D and E), or 100 and 10 pmol/well ORN (E). Either 10 μM of oligo-deoxynucleotides (ODN, 1668 and 2006) only, or 10 and 1 μM of ODN was applied. ORN RNA40 was transfected with the reagent Dotap (E). After incubation for 16 hours NF-κB driven relative luciferase activity was analyzed (rel. lucif. activ.; n.d., not detected; n.p., not performed; v., vector; -, no challenge). (A-E) Each panel illustrates a representative result of three experiments and depicts means ±SD of triplicate samples. (**F**) Wt mice were challenged by i. v. injection of 10 nmol of ORN or ODN (n=9 per group) in 200 μl PBS or PBS alone (-). Serum was drawn 6 hours later and analyzed for cytokine content by cytometric bead arrays (IL-12, IL-12p70). Combined data of three experiments in which 3 mice/group were applied are illustrated as mean of individual results.