Single-cell transcriptomic analysis of antiviral responses and viral antagonism in Chikungunya virus-infected synovial fibroblasts

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Abstract

In recent years, (re-)emerging arboviruses including Chikungunya virus (CHIKV) and Mayaro virus (MAYV) have caused growing concern due to expansion of insect vector ranges. No protective vaccine or specific antiviral strategies are currently available. Long-term morbidity after CHIKV infection includes debilitating chronic joint pain, which has associated health and economic impact. Here, we analyzed the early cell-intrinsic response to CHIKV and MAYV infection in primary human synovial fibroblasts. This interferon-competent cell type represents a potential source of polyarthralgia induced by CHIKV infection. Synovial fibroblasts from healthy and osteoarthritic donors were similarly permissive to CHIKV and MAYV infection *ex vivo*. Using RNA-seq, we defined a CHIKV infection-induced transcriptional profile with several hundred interferon-stimulated and arthralgia-mediating genes upregulated. Type I interferon was both secreted by infected fibroblasts and protective when administered exogenously. IL-6 secretion, which mediates chronic synovitis, however, was not boosted by infection. Single-cell RNA-seq and flow cytometric analyses uncovered an inverse correlation of activation of innate immunity and productive infection at the level of individual cells. In summary, primary human synovial fibroblasts serve as bona-fide *ex vivo* primary cell model of CHIKV infection and provide a valuable platform for studies of joint tissue-associated aspects of CHIKV immunopathogenesis.

Keywords: chikungunya, fibroblasts, innate immunity, single-cell RNA-seq, transcriptomics

Introduction

Chikungunya virus (CHIKV) and Mayaro virus (MAYV) are arthritogenic alphaviruses of the *Togaviridae* family, which are transmitted by *Aedes sp.* mosquitoes and circulate both in urban cycles between vectors and humans, and in sylvatic cycles [1-3]. Beyond the typically short acute phase associated with febrile illness and rashes, excruciating pain in multiple joints represents the most severe consequence of a CHIKV or MAYV infection in humans. The arthritis-like pain often manifests itself during the acute phase of the infection, but can persist in a subgroup of patients for months to years [4-6]. Symptoms cause a severe loss of quality of life and high economic costs, which is a burden especially for low-income countries [7]. The underlying pathophysiology of the chronic symptoms remains largely unclear, but appears to associate with circulating IL-6 [8] and IL-12 [9]. Furthermore, it may involve persisting viral RNA [9,10], although this scenario has been debated [11].

Multiple studies on alphaviruses in immortalized model cell lines and *in vivo* in immunodeficient mice have provided valuable information on key aspects of CHIKV and MAYV tropism and replication, including host factors for entry and replication [12,13], the impact of mutations in the viral glycoproteins on cell entry [14], and cellular restriction factors acting against CHIKV and other alphaviruses [15,16]. Additionally, studies investigating immune responses to infection have demonstrated that CHIKV nsP2 counteracts host immunity by blocking nuclear translocation of STAT1 [17,18] and inducing a host transcriptional shutdown [19,20]. However, the relevance of these and potentially additional immunity-subverting mechanisms in infected patients remains unclear. *In vivo* studies in mice, though recapitulating both innate and adaptive immune responses, require a type I interferon (IFN)-deficient background, neglecting the impact of type I IFN-mediated antiviral responses [21]. However, type I IFN induced in and acting on nonhematopoietic cells appears to be essential for the control and early clearance of CHIKV *in vivo* [22-24]. Therefore, these systems do not

fully recapitulate the cellular environment of human primary cells and tissues that are targeted by CHIKV and MAYV *in vivo*. Primary human cells have been used sporadically, but only few studies properly characterized their unique properties [25-27]. Here, we perform an in depth-characterization of primary human synovial fibroblasts as an *ex vivo* model of CHIKV and MAYV infection. Synovial fibroblasts have been described to be a key driver for rheumatoid arthritis by facilitating proinflammatory processes and stimulating the degradation of cartilage [28,29]. Here, we establish synovial fibroblasts as being fully susceptible and permissive to CHIKV and MAYV infection. Using bulk and single-cell approaches, we identified cell-intrinsic immune responses that were most pronounced in abortively infected bystander cells, suggestive of effective viral antagonism of innate immunity in productively infected cells.

Material and Methods [1372 Words]

Cells and Viruses

Human osteosarcoma U2OS cells (a kind gift from T. Stradal, Hanover), human HEK293T cells (a kind gift from J. Bohne, Hanover), human foreskin fibroblast HFF-1 cells (ATCC SCRC-1041), human HL116 cells (a kind gift from Sandra Pellegrini, Institut Pasteur, France [30]), and hamster BHK-21 cells (ATCC CCL-10) were grown in Dulbecco's modified Eagle's medium - high glucose (DMEM, Sigma-Aldrich D5671) supplemented with 10 % heat-inactivated fetal bovine serum (FBS, Sigma-Aldrich F7524), 2mM L-Glutamine (Gibco 25030081), and 100 units/ml penicillin-streptomycin (Gibco 11548876). HL116 cell received 1X HAT supplement (Gibco 21060017) in addition. Primary human fibroblasts were obtained from synovial biopsies from donors suffering from osteoarthritis (osteroarthrosis synovial fibroblasts, OASF) or a non-arthritic background (healthy donor synovial fibroblasts, HSF), purified, and cultured as described before [31]. The local ethic committee (Justus-Liebig-University Giessen) approved the cooperative study (ethical vote IDs 66-08 and 74-05). All patients gave written informed consent. Mycoplasma testing was routinely performed and negative in all primary human cell cultures. After 2-4 passages of initial cultivation, cells were expanded and used for experiments in high glucose DMEM supplemented with 20 % FBS, 2 mM L-Glutamine, 100 units/ml penicillin-streptomycin, 1 % non-essential amino acids (Gibco 11140050), and 1 % sodium pyruvate (Gibco 11360070). The CHIKV LR2006-OPY 5'GFP and MAYV TRVL4675 5'GFP infectious clones expressing EGFP under the control of a subgenomic promotor (hereafter referred to as CHIKV and MAYV) have been described previously [32,33]. Virus was produced by *in vitro*-transcription of and subsequent electroporation of RNA into BHK-21 cells. Virus-containing supernatant was collected, passaged once on BHK-21 cells and viral titers were determined by titration on HEK293T cells.

98 **Infection, Treatments, Transfections**

99 EGFP expression as surrogate for productive CHIKV or MAYV infection was quantified on a
100 BD FACSCalibur, FACSLyric or Accuri C6. For neutralization assays, virus-containing
101 supernatants were pre-incubated for one hour with anti-CHIKV E2 antibody C9 (Integral
102 Molecular C9, Lot INT MAB-003) at 1 µg/ml or with recombinant MXRA8-Fc (a kind gift
103 from M. Diamond) at 150 ng/ml. Recombinant IFN-α2a (Roferon L03AB04, Roche) and IFN-
104 λ1 (Peprotech 300-02L) was used where indicated. Transfections were performed using
105 Lipofectamine2000 (Thermo Fisher 11668019) for plasmid DNA (pcDNA6 empty vector) or
106 5'triphosphate dsRNA (InvivoGen tlrl-3prna).

107

108 **Bulk RNA-Seq Analysis**

109 RNA was extracted using the Promega Maxwell 16 with LEV simplyRNA Tissue Kits
110 (Promega AS1270). RNA quality was assessed using the Agilent Bioanalyzer and appropriate
111 samples were used for NGS library preparation with the NEBNext Ultra II Directional RNA kit
112 (NEB E7760) and sequenced with 50 bp paired-end reads and 30 mio reads per sample on the
113 Illumina HiSeq 2500. Data was analyzed with CLC Genomics Workbench 12 (QIAGEN) by
114 mapping the human reads onto the hg19 reference genome scaffold (GCA_000001405.28).
115 Unmapped reads not matching the human genome were subsequently mapped onto the CHIKV
116 genome LR2006_OPY (DQ443544.2). For HSF, infection and analysis were performed
117 similarly, but RNA was extracted with the Direct-Zol RNA MiniPrep Kit (Zymo Research
118 R2051), NGS libraries were prepared with the TruSeq stranded mRNA kit (Illumina 20020594)
119 and sequencing was performed on the Illumina NextSeq500 with 65 mio reads per sample.
120 Biological process enrichment was analyzed by Gene Ontology [34,35].

121

122 **Single-Cell RNA-Seq Analysis**

123 Infected cells were trypsinized, debris was removed by filtration, and the suspension was
124 adjusted to a final amount of ~16,000 cells per lane to achieve the recovery of 10,000 cells per
125 donor after partitioning into Gel-Beads in Emulsion (GEMs) according to the instructions for
126 Chromium Next GEM Single Cell 3' GEM, Library & Gel Bead Kit v3.1 provided by the
127 manufacturer (10X Genomics PN-1000121). Polyadenylated mRNAs were tagged with unique
128 16 bp 10X barcodes and the 10 bp Unique Molecular Identifiers (UMIs), reverse transcribed
129 and resulting cDNAs were bulk amplified. After enzymatic fragmentation and size selection,
130 resulting double-stranded cDNA amplicons optimized for library construction were subjected
131 to adaptor ligation and sample index PCRs needed for Illumina bridge amplification and
132 sequencing. Single-cell libraries were quantified using Qubit (Thermo Fisher) and quality-
133 controlled using the Bioanalyzer System (Agilent). Sequencing was performed on a HiSeq4000
134 device (Illumina) aiming for 175 mln reads per library (read1: 26 nucleotides, read2: 64
135 nucleotides). Data was analyzed using CellRanger v5.0 (10X Genomics) using human and
136 CHIKV genome scaffolds as described above, and the R packages Seurat v4.0 [36] and
137 DoRothEA v3.12 [37].

138

139 **Quantitative RT-PCR**

140 RNA was extracted using the Promega Maxwell 16 with the LEV simplyRNA tissue kit
141 (Promega AS1270), the Roche MagNAPure with the Cellular Total RNA Large Volume kit
142 (Roche 05467535001), or the DirectZol RNA Mini kit (Zymo R2051). cDNA was prepared
143 using dNTPs (Thermo Fisher R0181), random hexamers (Jena Bioscience PM-301) and M-
144 MuLV reverse transcriptase (NEB M0253). For quantitative RT-PCR, specific Taqman probes
145 and primers (Thermo Fisher 4331182) were used with TaqMan Universal PCR Master Mix
146 (Applied Biosystems 4305719) or LightCycler© 480 Probes Master (Roche 04887301001).

147 PCRs were performed on the Applied Biosystems ABI 7500 Fast or the Roche LightCycler 480
148 in technical triplicates.

149

150 **Flow Cytometry, Confocal and Live Cell Imaging**

151 For flow cytometric analysis of protein expression, OASF were fixed in 4 % PFA (Carl Roth
152 4235.2), permeabilized in 0.1 % Triton-X (Invitrogen HFH10) and immunostained with
153 antibodies against IFIT1 (Origene TA500948, clone OTI3G8), MX1/2 (Santa Cruz sc-47197),
154 and IFITM3 (Abgent AP1153a) in combination with Alexa Fluor-647 conjugated antibodies
155 against mouse- (Thermo Fisher A28181), rabbit- (Thermo Fisher A27040), or goat-IgG
156 (Thermo Fisher A-21447). Flow was performed on a BD FACSCalibur or FACSLyric and
157 analyzed with FlowJo v10. For immunofluorescence microscopy, OASF were seeded in 8-well
158 µ-slides (ibidi 80826), fixed and permeabilized as described above, stained with antibodies
159 against MXRA8 (biorbyt orb221523) with AlexaFluor647-conjugated secondary antibody
160 (Thermo Fisher A28181), and counterstained with DAPI (Invitrogen D1306). For fluorescence
161 microscopy and live cell imaging, cells were infected with CHIKV at an MOI of 10 and imaged
162 with the Zeiss LSM800 Airyscan Confocal Microscope. Images were analyzed and merged
163 using Zeiss ZEN Blue 3.0.

164

165 **Immunoblotting**

166 Cell lysates were separated on 10 % acrylamide gels by SDS-PAGE and protein transferred to
167 a 0.45 µm PVDF membrane (GE Healthcare 15259894) using the BioRad TransBlot Turbo
168 system. Expression was detected using primary antibodies detecting MXRA8 (biorbyt
169 orb221523), FHL1 (R&D Systems MAB5938), IFITM3 (Abgent AP1153a), MX2 (Santa Cruz
170 sc-47197), ISG15 (Santa Cruz sc-166755), and α-Tubulin (Cell Signaling Technology 2144S)

171 and appropriate secondary IRDye antibodies. CHIKV proteins were detected using anti-CHIKV
172 antiserum (IBT Bioservices Cat #01-0008 Lot #1703002). Fluorescence was detected and
173 quantified using the LI-COR Odyssey Fc system.

174

175 **Measurement of IL-6 and Bioactive IFN**

176 Anti-IL-6 ELISA (BioLegend 430504) was performed according to manufacturer's protocols.
177 Briefly, plates were coated with capture antibodies and incubated with diluted supernatant from
178 CHIKV- or mock-infected cell cultures . Detection antibody and substrate were added and the
179 OD measured with the Tecan Sunrise microplate reader. Concentrations were then calculated
180 the concentration according to a standard curve measured on the same plate. Bioactive type I
181 IFN was quantified by incubating supernatant from CHIKV-infected cells on HL116 cells
182 harboring a firefly luciferase gene under the control of an IFN-sensitive promotor. After six h,
183 cells were lysed, incubated with luciferase substrate solution (Promega E1500), and luciferase
184 activity was quantified with the BioTek Synergy HTX microplate reader.

185

186 **Data and Code Availability**

187 RNA-seq and single-cell RNA-seq datasets are available at the NCBI GEO database under the
188 accession number GSE152782 and GSE176361, respectively. All generated code is available at
189 https://github.com/GoffinetLab/CHIKV_scRNAseq-fibroblast.

190

191 **Data Presentation and Statistical Analysis**

192 If not stated otherwise, bars and symbols show the arithmetic mean of indicated amount of
193 repetitions. Error bars indicate S.D. from at least three or S.E.M. from the indicated amount of
194 individual experiments. Statistical analysis was performed using CLC Workbench for RNA-

seq and GraphPad Prism 8.3.0 for all other analysis. Unpaired t-tests were applied with assumed equal standard deviation when comparing results obtained in the same cell line and Mann-Whitney-U-tests when comparing between cell lines or between cell lines and primary cells. For treatment analysis, ratio paired t-tests were applied. For IC50 calculation, nonlinear fit curves with variable slopes were calculated. FDR correction was applied for RNA-seq analysis and Bonferroni correction for Gene Ontology analysis. *P* values <0.05 were considered significant (*), <0.01 very significant (**), <0.001 highly significant (***); < 0.0001 extremely significant, n.s. = not significant (≥0.05).

203 **Results**

204 **Osteoarthritic fibroblasts are susceptible and permissive to CHIKV and MAYV infection**

205 First, we examined the ability of primary human synovial fibroblasts to support the entire
206 CHIKV and MAYV replication cycle. Therefore, we infected synovial fibroblasts obtained
207 from osteoarthritic patients (OASF) and from patients with a non-arthritic background (HSF)
208 with CHIKV strain LR2006-OPY or MAYV strain TRVL7546 expressing EGFP under the
209 control of a second subgenomic promotor. 24 hours post-infection, the proportion of EGFP-
210 positive cells ranged between 4 and 24.5 % for CHIKV and between 8.5 and 39 % for MAYV
211 and did not differ between fibroblast types (Fig. 1A). At the same time point, supernatants of
212 both OASF and HSF displayed CHIKV titers of 1.6-8.8x10^5 infectious particles per ml and
213 MAVV titers of 0.12-2.75x10^5 infection particles per ml, with significantly higher titers
214 produced by OASF. At 48 hours post-infection, CHIKV titers produced by HSF did not further
215 increase, whereas the titers produced by OASF reached up to 1.5x10^7 infectious particles per
216 ml (Fig. 1B, left panel), suggesting slightly higher virus production and/or viral spread in OASF
217 as compared to HSF. MAYV titers did not significantly increase in OASF or HSF at 48 hours
218 post-infection (Fig. 1B, right panel).

219 Susceptibility of cells to CHIKV infection is enhanced by the attachment factor MXRA8
220 [12] and the cytosolic protein FHL-1 is essential for CHIKV genome replication [13]. We
221 confirmed expression of these two cellular cofactors in OASF and HSF by immunoblotting
222 and/or immunofluorescence (Fig. 1C). We assessed the functional relevance of the MXRA8
223 attachment factor using a soluble MXRA8-Fc fusion protein, which blocks the binding site on
224 the E1-E2 glycoprotein complex on the virus surface [12,38]. At a low MOI, MXRA8-Fc-
225 preincubated CHIKV was 50 % less infectious to synovial fibroblasts, and this inhibition was
226 abolished when saturating amounts of infectious virus particles were used (Fig. 1D), indicating
227 that endogenous MXRA8 contributes, at least partially, to CHIKV entry in OASF.

228 Subsequently, we investigated whether IL-1β-mediated activation of synovial
229 fibroblasts, a hallmark of rheumatoid arthritis [39-41], modulates their susceptibility to CHIKV
230 infection. Treatment with IL-1β, did not alter the percentage of EGFP-positive cells upon
231 CHIKV challenge (Fig. 1E), while readily inducing IL-6 secretion (Fig. 1F). Conversely,
232 CHIKV infection only very mildly, if at all, enhanced IL-1β-induced IL-6 secretion (Fig. 1F).
233 These data suggest that CHIKV infection of synovial fibroblasts neither induces nor modulates
234 IL-6 secretion, arguing against their activation.

235 To determine the importance of IFN-mediated antiviral immunity in this primary cell
236 system, we analyzed the secretion of type I IFN upon CHIKV infection, which reached higher
237 levels than after prestimulation with IFN-α (Fig. 1G). Additionally, we monitored the CHIKV
238 infection in the absence or presence of the JAK/STAT inhibitor Ruxolitinib. Using live-cell
239 imaging, we documented the increase in EGFP-positive cells between ten and 48 hours post-
240 infection, which progressed faster in Ruxolitinib-treated cultures, with an onset of cytopathic
241 effects observed after 24 hours in all infected cultures (Fig. 1H, Suppl. Mov. 1). Analysis of the
242 EGFP intensity in each frame over time confirmed the higher expression of EGFP in
243 Ruxolitinib-treated cultures (Fig. 1I, Suppl. Mov. 2). Overall, these experiments establish the
244 susceptibility and permissiveness of synovial fibroblasts to CHIKV and MAYV infection and
245 their expression of important cellular cofactors. Furthermore, we show an absence of
246 interconnection between IL1-β activation and susceptibility to CHIKV infection, and restriction
247 of infection through JAK/STAT-mediated innate immunity.

248

249 **CHIKV infection provokes a strong cell-intrinsic immune response in OASF**

250 Next, we performed RNA-seq analysis on OASF and HSF that had been infected with CHIKV
251 in the presence or absence of the glycoprotein E2-binding, neutralizing antibody C9 [42], and
252 on mock-infected cells. C9 pre-treatment resulted in potent inhibition of the infection by on

average 16-fold (Fig. 2A). Upon infection, expression of numerous IFN-stimulated genes (ISGs) was induced at the protein level in a C9 treatment-sensitive manner, including IFITM3, ISG15, and MX2. As expected, production of the viral E1-E2 and capsid proteins was detectable specifically in CHIKV-infected, but not in cells exposed to C9-pretreated virus (Fig. 2B). Global transcriptional profiling by RNA-seq revealed 992 (OASF) and 1221 (HSF) upregulated genes as well as 99 (OASF) and 353 (HSF) downregulated genes in CHIKV-infected cells 24 hours post-infection as compared to uninfected cells (Fig. 2C). Uninfected cells and cells exposed to C9-treated virus shared a similar profile (data not shown). A high similarity of the gene expression profile of uninfected OASF and HSF (R^2=0.9086) argues against a potential transcriptional predisposition that could have exerted a rheumatoid arthritis-related gene expression profile or a broad proinflammatory activation (Fig. S1A). Uninfected OASF and HSF differed in genes involved in organ development and cellular regulatory processes, and not inflammatory or antiviral processes (Fig. S1B). Additionally, the transcriptional profile in infected OASF and HSF was very similar (R^2=0.9085, Fig. S1C-D), with an equivalently strong upregulation of a set of prototypic inflammation and arthritis-related genes which we defined for further analysis (R^2=0.8202, Fig. 2D). Interestingly, the number of genes significantly up- and downregulated upon infection was 1.23-fold and 3.57-fold higher in HSF compared to OASF, respectively, but 55.4% of upregulated genes from both groups overlapped (Fig. 2E). Most of the prototypic antiviral and proinflammatory genes were highly upregulated in infected cells, demonstrating a broad and strong activation of antiviral immune responses in cells from four different donors with no statistically significant deviation in the magnitude of induction (Fig. 2F, left panel). Upregulation of *IFNB* and *IFNL1*, *IFNL2*, and *IFNL3* expression was statistically significant but low in magnitude, with almost no *IFNA* mRNA detectable. Expression of arthritis-associated genes, including genes encoding immune cell chemoattractants (*CXCL5, IL8, CD13, RANTES/CCL5*), matrix-metalloproteases (*MMP3,*

-*9, -14, ADAMTS5*) and genes commonly expressed by fibroblasts in rheumatoid arthritis (*FGF2, PDPN, NGF, FAP*), was not grossly altered in CHIKV-infected cells. Exceptions were a strong CHIKV-induced upregulation of *RANTES/CCL5* in both OASF and HSF and *IL8* in HSF (Fig. 2F, right panel). mRNAs for all IFN receptors were detectable and stable with exception of *IFNLR1*, whose expression was upregulated upon CHIKV infection (Fig. S1E). Established host factors for CHIKV as well as fibroblast marker genes and cellular housekeeping genes were not quantitatively altered in their expression. Virtual absence of expression of monocyte/macrophage lineage-specific genes excluded the possibility of a contamination of the fibroblast culture with macrophages, which occasionally has been reported in early passages of *ex vivo*-cultured synovial fibroblasts [31] (Fig. S1E). Conclusively, OASF and HSF share similar basal and CHIKV infection-induced transcriptional profiles. Overall, CHIKV-infected OASF sense and react to productive CHIKV infection with the extensive upregulation of antiviral and proinflammatory ISGs. IFN expression itself was low at 24 hours post-infection, not excluding the possibility that it peaked transiently at earlier time points.

High viral RNA levels in cells of infected cultures with an excess replication of the viral structural subgenome

We noticed very little inter-donor variation regarding the distribution of identified viral reads along the viral genome. The 5´ region of the genome, encoding the non-structural CHIKV proteins, was replicated to a lower extent than the 3´, 26S subgenomic promoter-driven, structural protein-encoding genomic region. Interestingly, this differential abundance of 5´and 3´ reads was also detected in cultures inoculated with C9-neutralized virus, suggesting infection in a small number of cells (Fig. 3A). Overall, the 26S subgenomic viral RNA was 5.3-fold more abundant than nonstructural subgenomes (Fig. 3B). 18-54 % and 17-44 % of the total reads in productively infected OASF and HSF, respectively, were attributed to the CHIKV genome (Fig.

303 3C, D). In summary, our analysis revealed efficient replication of the CHIKV genome in
304 infected fibroblasts with an excess of structural protein-encoding subgenomic RNA.

305

306 **Exogenous IFN administration provokes higher immune responses and leads to improved**
307 **protection from infection in primary fibroblasts than in commonly used cell lines**

308 CHIKV and MAYV infection rates in OASF did not increase after 24 hours post-infection (Fig.
309 4A), and we suspected this to be the result of the strong immune activation and subsequent IFN
310 signaling. The commonly used osteosarcoma cell line U2OS was more susceptible, while the
311 immortalized fibroblast cells line HFF-1 displayed reduced susceptibility to alphaviral infection
312 (Fig. 4A). OASF exhibited strong induction of *IFIT1* and *MX2* CHIKV infection, which
313 exceeded those mounted by U2OS and HFF-1 cells at both 24 and 48 hours post-infection by
314 15- to 150-fold. MAYV infection-provoked ISG responses in OASF were inferior to those
315 induced by CHIKV, despite similar percentages of infected cells (Fig. 4B). Contrasting the cell
316 system-specific magnitude of gene expression upon CHIKV infection, both OASF and cell lines
317 shared similar responsiveness to 5'-triphosphate dsRNA (5-ppp-RNA) transfection, which
318 exclusively stimulates the RNA sensor RIG-I [43], the main sensor of CHIKV RNA in infected
319 cells [44], and plasmid DNA transfection (Fig. S2A).

320 Next, we tested the cells´ ability to respond to exogenous type I and III IFNs, which
321 play a crucial role in limiting virus infection and protecting the host [45-47]. We stimulated
322 OASF individually with a range of IFN-α2 and -λ concentrations at 48 hours prior to infection.
323 At all investigated concentrations, even the lowest dose, of IFN-α induced a potent upregulation
324 of *IFIT1* and *MX2* (Fig. S2B), and almost completely inhibited CHIKV infection (Fig. 4C). In
325 contrast, IFN-λ induced lower ISG expression levels (Fig. S2B), and inhibited infection less
326 efficiently (Fig. 4C). Although less effective than in OASF, IFN-α restricted CHIKV infection
327 both in U2OS and HFF-1 cells, while IFN-λ pre-treatment was more potent in U2OS cells than

328 in OASF, and ineffective in HFF-1 cells (Fig. 4C). These antiviral activities were largely
329 consistent with the respective degree of ISG expression at the time point of infection (Fig. S2B).
330 IFN-α and -λ induced expression of *IFIT1* and *MX2* was higher in U2OS cells than in HFF-1.
331 We next investigated the sensitivity of CHIKV infection to IFN when applied four hours post-
332 infection. In this set-up, IFN-α still displayed a clear, though less potent antiviral activity when
333 compared to the pre-treatment setting (Fig. 4D). In contrast, treatment of both immortalized cell
334 lines with IFN-α post-infection was very ineffective (Fig. 4D).

335 Interestingly, in all three cells systems, a preceding CHIKV infection did not antagonize
336 IFN-mediated induction of ISGs, and led to expression levels of *IFIT1* and *MX2* exceeding
337 those induced by IFN-α alone (Fig. S2C). Overall, the data suggest a stronger sensitivity of
338 OASF to IFN-α-induced immunity compared to commonly used immortalized cell lines. Most
339 interestingly, and in striking contrast to the immortalized cell lines, OASF were unique in their
340 ability to transform a post-infection treatment of IFN-α into a relatively potent antiviral
341 program. Collectively, these data uncover crucial differences between primary synovial
342 fibroblasts and widely used immortalized cell lines regarding their cell-intrinsic innate response
343 to infection and their sensitivity to exogenous IFNs.

344

345 **Virus-inclusive single-cell sequencing reveals a switch from induction to repression of**
346 **immune responses depending on a threshold level of viral RNA in infected cells**

347 Finally, we asked how the cell-intrinsic defenses correlate with the amounts of viral RNA
348 within cells of a given infected culture by analyzing infected OASF for their expression of
349 antiviral proteins using flow cytometry. As expected, expression of IFIT1, IFITM3 and MX1/2
350 was enhanced in OASF upon IFN-α treatment (Fig. 5A). Interestingly, these proteins were
351 expressed at even higher levels in EGFP-negative cells of CHIKV-infected cultures, while the

352 productively infected, EGFP-positive cells displayed markedly reduced expression levels of
353 these factors (Fig. 5A).

354 Since absence of EGFP expression does not necessarily exclude the presence of viral,
355 potentially abortive RNA, we performed virus-inclusive single-cell RNA-seq to establish
356 potential correlations of the quantity of viral RNA and a specific cellular transcriptional profile.
357 To this end, we analyzed infected OASF infected at escalating MOIs. No EGFP-positive cells
358 were detectable at six hours post-infection by flow cytometry (Fig. 5B, left panel). In contrast,
359 24 hours post-infection, the reporter was expressed in an MOI-dependent fashion, ranging from
360 virtually 0% to 15% (Fig. 5B, left panel). *IFIT1* and *MX2* mRNA expression was largely
361 proportional to EGFP expression (Fig, 5B, right panel).

362 Single-cell (sc) RNA-seq of the very same cells showed very little inter-donor
363 variability, and we merged data from both donors throughout the rest of the analysis (Fig. 5C).
364 In order to identify potential correlations of viral RNA abundance and the cellular transcription
365 profile, we compared the expression of CHIKV RNA to expression of 203 IFN signaling genes
366 listed in the REACTOME database (identifier R-HSA-913531, Table 1). For each cell, the
367 expression of this collection of genes was summarized using Seurat's AddModuleScore
368 function. Briefly, this summarizes the expression of a select group of genes by normalizing the
369 aggregate expression to a randomly selected, non-overlapping subset of genes and scores each
370 cell based on its expression of genes in this module, creating a module score (IFN Module
371 Score, IMS). 24 hours post-infection, most identified CHIKV reads corresponded to the 3' end
372 of the genome, along with a minor number of reads mapping to the 3' end of *EGFP*, which is
373 expressed as a subgenomic RNA in infected cells (Fig. S3A). As expected for mock-infected
374 cells, CHIKV reads were undetectable, and IFN signaling genes were expressed at basal levels,
375 as calculated by the IMS. CHIKV RNA abundance per cell increased in an MOI-dependent
376 manner, however susceptibility to infection was unequally distributed over individual cells, and

377 a subset of cells displayed a higher susceptibility than others, as reflected by a high percentage
378 of reads attributed to the viral genome (Fig. S3B). Most interestingly, IFN signaling genes
379 appeared to be induced predominantly in cells displaying low CHIKV gene expression. *Vice*
380 *versa*, CHIKV RNA-positive cells maintained basal or reduced expression of IFN signaling
381 related genes (Fig. 5D). Of note, six hours post-infection, CHIKV expression was low and
382 antiviral responses as presented by the IMS was were largely absent at low MOIs, while
383 individual ISGs were induced at higher MOIs (Fig. S3C, D). As opposed to the induction of
384 IFN signaling genes, known CHIKV cofactors *MXRA8*, *FHL1*, and the fibroblast marker genes
385 *VIM* and *COL3A1* were broadly and stably expressed under all experimental conditions.
386 Surprisingly, *FURIN*, encoding the cellular protease considered important for viral polyprotein
387 cleavage, was detectable only in a minority of cells (Fig. S4).
388

389 **Correlating viral and cellular gene expression reveals a selective suppression of**
390 **transcription factor and ISG expression**

391 In order to quantify expression of IFN signaling genes according to viral RNA abundance, we
392 divided cells into three groups: cells without detectable viral RNA expression (bystander), cells
393 displaying low amounts of viral RNA (low) and cells displaying high levels of viral RNA (high)
394 (Fig. 6A). Mirroring our initial observations (Fig. 5), we detected a significantly lower IMS in
395 high cells when compared to low or bystander cells of the identical culture (Fig. S5A). Six
396 hours post-infection, differential expression of non-ISGs was very modest between bystander
397 and viral RNA-positive cells, while it was clearly more pronounced 24 hours post-infection
398 (Fig. S5B). In contrast, over 250 ISGs, including *ISG15*, *IFIT1*, *MX2*, *IFITM3*, *MX1*, and *IFI6*,
399 were upregulated in viral RNA-positive cells as compared to bystander cells at both investigated
400 time points. Individual comparisons of either low or high cells with bystander cells gave similar
401 overall observations. However, at both investigated time points, no further upregulation of ISGs

402 was detected in the high cells as compared to low cells, but rather a significant downregulation
403 of three ISGs at 24 hours post-infection and six ISGs at six hours post-infection. This suggests
404 either a loss of cellular transcription activity or a lowered stability of cellular RNA in cells
405 containing high loads of CHIKV RNA (Fig. S5B).

406 To improve resolution, we calculated the average CHIKV and EGFP RNA expression
407 and the average IMS in bins of 1000 cells for a total of 36 bins, sorted by their expression level
408 of CHIKV RNA. At both time points, while the first 7-10 bins represented cells expressing no
409 or virtually no CHIKV RNA, the following 18-21 bins represented cells displaying (according
410 to the cut-off defined in Fig. 6A) low, but gradually increasing levels of CHIKV RNA, and
411 largely undetectable EGFP RNA. We considered the latter cells to represent abortively infected
412 cells due to their lack of subgenomic transcripts. The last eight bins displayed cells with overall
413 high, starkly increasing levels of CHIKV RNA and with significant levels of EGFP mRNA.
414 We hypothesize that these cells represent productively infected cells. Strikingly, in abortively
415 infected cells, IMS values increased proportionally to the abundance of viral RNA per cell,
416 whereas in productively infected cells, an inverse proportionality was observed (Fig. 6B). This
417 dataset suggests that expression of IFN signaling genes is upregulated in cells harboring low-
418 to-intermediate levels of viral RNA, which, however, do not or have not yet progressed to a
419 productive infection. In contrast, cells that exceed a certain threshold of viral RNA show a
420 prevention or downregulation of the expression of IFN signaling genes. The analysis of
421 expression of selected genes confirmed this observation. Expression of individual ISGs,
422 including including *ISG15*, *IFI6*, *MX1*, *OASL*, *IFITs*, and *IFITMs,* and transcription factors,
423 including *STAT1* and *IRF7*, was low in mock-infected and bystander cells, and more
424 pronounced in a representative low cells (six hours post-infection: bin 27-29, 24 hours post-
425 infection: bin 26-28) than in high cells (bins 34-36) (Fig. 6C). To identify further putative
426 targets of viral antagonism, we correlated the expression of all 203 genes of the IMS to the viral

RNA expression in infected cells at 24 hours post-infection. We identified 13 genes displaying a significant positive correlation ($r > 0.3$) in the low CHIKV group, and a significant negative correlation ($r < -0.3$) in the high CHIKV group (*IFITM3, IFIT3, OAS1, XAF1, GBP1, EIF4A1, EIF2AK2, STAT1, GBP3, UBC, PSMB8, UBA52*). Strikingly, the only transcription factor present in both groups, *STAT1*, was also negatively correlated at six hours post-infection in the high viral RNA group. We additionally identified transcription factors *JAK1* and *IRF7* to switch from weak correlation in the low CHIKV group to a negative correlation in the high CHIKV group at 24 hours post-infection (Fig. 6D). We confirmed this finding using a transcription factor activity score analysis using the DoRotheEa database, which scores cells based on the activity of transcription factors inferred from the expression of the associated target genes in regulons, and found the regulon of *STAT1* to be strongly induced in bystander and low CHIKV groups at high MOIs, yet highly susceptible to viral antagonism in the high CHIKV group. This was also true for multiple other transcription factors – IRFs and STATs as well as NFκB and c-JUN - at higher MOIs, indicating a strong and sensitive induction that is counteracted in highly infected cells (Fig. 6E). Taken together, we demonstrate that the interaction between the virus and the host cell can be defined more precisely at single-cell resolution than by analyzing bulk data, and that the activation of innate immune responses can be well defined and correlated to the amount of viral RNA in the cell. Furthermore, viral antagonism may be masked by strong immune responses in cells infected at low levels, making it difficult to analyze using conventional RNA-seq.

447 **Discussion**

448 Considering the CHIKV-induced arthritis, it is likely that cells of the synovium are directly
449 implicated in the pathophysiology of CHIKV infection. Cells of the synovial tissue and synovial
450 fluid contain CHIKV RNA and protein upon CHIKV infection *in vivo* in humans [9],
451 experimentally infected macaques [48], and mice [49]. The main cell types composing the
452 synovium are macrophages and fibroblasts. The latter have been identified to be susceptible to
453 CHIKV infection *ex vivo* [12,50,51]. However, the corresponding basal innate immune state
454 of primary synovial fibroblasts and their ability to exert IFN-mediated antiviral restriction is
455 unknown. Here, we establish that the widely available OASF and less available HSF share
456 susceptibility and permissiveness to CHIKV infection, and describe their basal and infection-
457 induced transcriptional programs. These findings are in line with reports on overall
458 transcriptional similarity of the two cell types, except in some signaling pathways unrelated to
459 immunity [52]. CHIKV infection provoked a striking cellular response that involves
460 upregulation of multiple ISGs, many of them exerting antiviral activity. Although we did not
461 define the PAMP(s) that trigger responses in synovial macrophages, infection by alphaviruses
462 typically raises RIG-I-mediated responses through exposure of dsRNA intermediates and
463 provokes mitochondrial DNA leakage that is sensed via cGAS/STING [44,53,54]. Indeed,
464 experimental ligands of both sensors were highly reactive in OASF, as was IFN-α treatment.
465 Surprisingly, also IFN-λ pre-treatment translated into an antiviral state, indicating that synovial
466 fibroblasts may represent an exception to the notion of otherwise IFN-λ-nonresponsive
467 fibroblasts [55]. Finally, CHIKV infection of synovial fibroblasts was sensitive to IFN-α
468 applied after inoculation with virus. These findings appear to contrast with potent virus-
469 mediated antagonism of IFN in U2OS and HFF-1 cell lines, which has been suggested to
470 involve counteraction of nuclear translocation of STAT1 [17,18]. CHIKV was unable to
471 suppress ISG expression upon exogenous IFN treatment in any cell type, indicating that the

472 proposed antagonistic functions may not be strong enough to be detectable at the bulk level.
473 Also, unaltered levels of expression of housekeeping genes and genes encoding fibroblast
474 markers in primary synovial fibroblasts did not generate evidence for a general virus-mediated
475 host transcriptional shut-off that has been reported for several cell lines [19,20]. Overall,
476 synovial fibroblasts appear to respond differently to CHIKV infection as commonly used cell
477 lines. The underlying reason for this difference is unknown, but may involve a different
478 intracellular milieu that is hyper-responsive to CHIKV infection.

479 While our single-cell RNA-seq approach is dependent on 3' end capture and does not
480 allow for the discrimination between full-length and partial viral RNA, we found an excess of
481 subgenomic RNA in infected cells. We found a similar the ratio of subgenomic to genomic
482 RNA as measured in Sindbis virus infected cells [56]. The enhanced replication of the
483 subgenomic RNA, which is mediated by the four cleaved nonstructural proteins forming a
484 replication complex, ensures the rapid production of viral structural proteins and the formation
485 of new virions [57,58]. While packaging of subgenomic RNA into virions has been described
486 so far for one alphavirus, Aura virus [59], CHIKV holds a packaging signal in the nsP2 region
487 of its genome, selecting only for full genomic RNA to be packaged into virions [60]. Therefore,
488 we assume that the different abundance is based on de *novo* produced subgenomic RNA rather
489 than on incoming viral RNA.

490 Through correlating cellular gene expression with CHIKV RNA abundance in
491 individual infected cells, it appears that a certain threshold of viral RNA is required to initiate
492 viral RNA sensing and eventually trigger ISG expression. However, expression of most ISGs
493 is negatively regulated in the presence of a high viral RNA burden per cell. This is fully
494 consistent with the idea that productive infection involves the synthesis of viral antagonists that
495 hamper the induction and/or evade the function of ISGs, resulting in efficient virus propagation.
496 Along these lines, West Nile virus infection also results in lowered ISG expression levels in

497 cells harboring high viral RNA quantities [61]. *In vivo,* actively SARS-CoV-2 infected
498 monocytes of COVID-19 patients expressed lower levels of ISGs than non-infected bystander
499 [62]. Monocytes of Ebola-infected rhesus monkeys display similar dynamics, with an additional
500 downregulation of *STAT1* mRNA in infected cells [63]. On the contrary, cells that undergo
501 abortive infection, or alternatively haven´t yet reached sufficient levels of virus replication, fail
502 to mount a strong antiviral profile. HIV-1 infection of lymphoid resting T-cells, that provide a
503 sub-optimal environment for HIV-1 infection, has been reported to result in the accumulation
504 of abortive viral cDNA products that are sensed by IFI16 in an inflammasome/pyroptosis-
505 dependent manner [64]. HSV-1 infection results in antiviral signaling specifically in cells in
506 which replication is stalled and that display relatively low levels of viral gene expression [65].
507 Owing to genetic recombination and low fidelity of the alphaviral RNA-dependent polymerase,
508 defective alphaviral genomes (DVGs) and defective alphaviral particles arise during virus
509 replication, but are themselves replication-incompetent [66,67]. Of note, our virus-inclusive
510 sequencing approach does not have the power to distinguish between full-length viral genomes
511 and defective or otherwise dead-end genomes. It will be interesting to test the contribution of
512 the latter to triggering the strong cell-intrinsic innate recognition that we linked here to high
513 intracellular viral RNA quantities in general. Strikingly, we find indication that the expression
514 of some genes, such as proinflammatory transcription factors, may be actively targeted by
515 CHIKV.

516 Finally, the interplay of tissue-resident, synovial macrophages and fibroblasts likely
517 additionally modulates CHIKV infection and cellular responses. Macrophages have been found
518 to productively infect primary human macrophages [68] and to harbor persistent viral RNA in
519 a nonhuman primate infection model [48]. Furthermore, human synovial fibroblasts secrete
520 cytokines such as IL-6, IL1B, and RANTES stimulating monocyte migration upon CHIKV
521 infection, and drive them towards an osteoclast-like phenotype [69,70]. Interestingly, we find

522 a similar phenotype in infected fibroblasts with upregulation and/or secretion of IL-6 and
523 RANTES, but not matrix-metalloproteases (MMPs), as described before [69]. This suggests an
524 indirect role of synovial fibroblasts in the induction of arthralgia upon infection, however, a
525 paracrine stimulation of MMP expression by infiltrating immune cells can not be excluded in
526 this model. Bystander cells, defined here as cells from infected cultures without detectable viral
527 RNA, may be strongly impacted through paracrine signaling by infected cells [71].
528 Interestingly, at 24 hours post-infection we do not observe an extensive activation of bystander
529 cells in cultures infected with a low MOI, despite an established infection and a number of
530 *IFNB*-expressing cells. On the other hand, at six hours post-infection in cultures infected with
531 an MOI 10, a condition in which we expect that almost all cells have made contact with virus
532 particles, we observe a strong activation of the RNA-negative cells. This indicates that either a
533 rapid release of cytokines and interferons only in highly infected cultures, or an interferon-
534 independent sensing of viral PAMPs leads to abortive infection.

535 It is tempting to speculate that the synovial fibroblast-specific hyperreactivity is linked
536 to the long-term arthralgia observed *in vivo* in chronic CHIKV patients, and that
537 pharmacological interference with hyperinflammation represents a feasible intervention
538 approach towards the alleviation of long-term arthralgia. In rheumatoid arthritis, hyperactivated
539 synovial fibroblasts invade the joint matrix, destroying/disrupting the cartilage and causing
540 long-term inflammation [28,72]. This and the subsequent attraction of immune cells, including
541 monocyte-derived macrophages to the damaged sites, may represent important events in the
542 progression to long-term morbidity [73]. Indeed, data obtained in recent clinical studies
543 suggests that treatment of chikungunya-induced arthritis with the immunosuppressant
544 methotrexate may be a beneficial strategy [74,75]. The data presented here does not fully
545 support the hypothesis that infected synovial fibroblasts display a phenotype similar to
546 fibroblasts in rheumatoid arthritis, but key features such as the IL-1β-mediated IL-6 release, the

aggressive proinflammatory gene expression in productively infected cells, and the strong expression of important cofactors make them likely to contribute to viral replication and disease progression *in vivo*.

Author contributions

FP and CG conceptualized the study, designed experiments, and interpreted the data. FP and CG wrote the manuscript with input from all co-authors. FP performed all experiments. EN extracted the fibroblasts and performed the first culturing passages. DP, RJPB, and EW performed RNA-seq alignments and bioinformatic analysis. DP wrote major parts of the code used for single-cell RNA-seq analysis and performed the transcription factor analysis. CG, ML, and TP supervised the study and acquired funding. All authors critically discussed the findings and approved of the final version of the manuscript.

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Declaration of Interest

The authors declare they have no actual or potential competing financial interests.

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760

761

762 **Figure Legends [1150 Words]**

763 **Figure 1. Osteoarthritis fibroblasts are susceptible and permissive to CHIKV infection.**
764 (**A**) OASF or HSF were infected with 5'EGFP-CHIKV or -MAYV (MOI 10). 24 hours post-
765 infection, the percentage of EGFP-positive cells was quantified by flow cytometry (n = 3-12).
766 (**B**) Supernatants of CHIKV- and MAYV-infected OASF or HSF were collected at 24 and 48
767 hours post-infection, and titers were determined by analyzing EGFP expression at 24 hours
768 post-infection of HEK293T cells. For background controls (post-wash), samples were taken
769 after one hour of virus inoculation and subsequent washing (n = 3).
770 (**C**) Uninfected OASF and HSF were analyzed for MXRA8 and FHL1 expression by
771 immunoblotting (n = 4-6) and for MXRA8 expression by immunofluorescence. Scale bar = 50
772 μm (n = 3, representative images shown).
773 (**D**) OASF were infected with 5'EGFP-CHIKV at the indicated MOIs upon treatment of the
774 virus with MXRA8-Fc recombinant protein or mock treatment. At 24 hours post-infection, cells
775 were analyzed for EGFP expression (n = 4).
776 (**E**) OASF were stimulated with IL-1β at 10 ng/ml for 16 hours and subsequently infected with
777 CHIKV (MOI 10) in the presence of IL-1β. Mock-stimulated OASF were infected as a control.
778 At 24 and 48 hours post-infection, cells were analyzed for EGFP expression and (**F**) supernatant
779 was collected and analyzed for IL-6 secretion by ELISA (n = 3).
780 (**G**) OASF were infected with 5'EGFP-CHIKV or treated with 200 IU/ml IFN-α. 24 h later,
781 supernatants of the infected cells were incubated on HL116 reporter cells to quantify secreted
782 bioactive type I IFN (n = 4).
783 (**H**) OASF were infected with 5'EGFP-CHIKV (MOI 10) in the presence or absence of 1 or 10
784 μM Ruxolitinib or mock-infected. Infection was recorded by live-cell imaging and
785 representative images for untreated and 10 μM Ruxolitinib-treated cells are shown. Scale bar =
786 100 μm.

787 (**I**) Infected cells recorded by live-cell imaging in G were analyzed for EGFP intensity using
788 ImageJ (n = 3).
789

790 **Figure 2. Productive CHIKV infection provokes a strong cell-intrinsic immune response**
791 **in OASF and HSF.**
792 (**A**) OASF were infected with 5'EGFP-CHIKV at an MOI of 10 in the presence or absence of
793 the anti-E2 antibody C9 and the percentage of EGFP-positive cells was measured by flow
794 cytometry (OASF: squares, HSF: diamonds. The infected samples are marked with their
795 respective donor number).
796 (**B**) Selected proteins of cells infected in A were analyzed by immunoblotting.
797 (**C-F**) RNA from cells infected in A was extracted and subjected to RNA-seq (n = 4).
798 (**C**) Analysis of up- and downregulated genes in CHIKV-infected samples compared to mock.
799 Dotted lines indicate cutoff for <1.5 fold regulation and a p-value of >0.05.
800 (**D**) Visualization of the fold change induction of indicated genes in CHIKV-infected OASF
801 and HSF. Average fold change (log_2) values for infected OASF are plotted on the x-axis, with
802 corresponding values from infected HSF plotted on the y-axis. R^2 value and regression line for
803 the comparison are inset, dot sizes indicate significance.
804 (**E**) Overlap of significantly (FDR-p <0.05) up- and downregulated genes in infected OASF
805 and HSF. Numbers of genes up- or downregulated in either OASF or HSF only, or in both cell-
806 types, are indicated.
807 (**F**) Heatmaps of selected gene expression profiles related to innate immune responses (left) or
808 to secreted proinflammatory mediators and arthritis-connected genes (right) in uninfected or
809 CHIKV-infected cells.
810

811 **Figure 3. The CHIKV genome is replicated to a high degree with a strong bias towards**
812 **the structural subgenome in infected OASF.**

813 (**A**) NGS reads attributed to each individual position in the CHIKV genome plotted for cells
814 infected with CHIKV in the presence or absence of neutralizing antibody (nAb). SGP:
815 subgenomic promotor.
816 (**B**) Normalized amount of reads attributed to the structural and nonstructural part of the CHIKV
817 genome in CHIKV-infected OASF and HSF.
818 (**C**) Number of NGS reads attributed to the human or CHIKV reference genome in CHIKV or
819 neutralizing antibody-treated CHIKV infected OASF or (**D**) HSF.
820

821 **Figure 4. OASF react to CHIKV infection more strongly than commonly used cell lines**
822 **and can potently inhibit viral infection after IFN treatment.**

823 (**A**) OASF and HFF-1 cells were infected with 5'EGFP-CHIKV at an MOI of 10, U2OS cells
824 were infected at an MOI of 0.5. EGFP-positive cells were quantified at 24 and 48 hours post-
825 infection by flow cytometry (n = 3-6).
826 (**B**) Cells infected in (A) were analyzed for expression of *IFIT1* and *MX2* mRNA at 24 and 48
827 hours post-infection by quantitative RT-PCR (n = 3-6).
828 (**C**) Cells were treated with IFN-α or -λ for 48 h before infection with 5'EGFP-CHIKV (OASF
829 and HFF-1: MOI 10; U2OS: MOI 0.5) in the continuous presence of IFN. Inset numbers
830 indicate IC50 values for each timepoint.
831 (**D**) Cells were infected with 5'-EGFP CHIKV (OASF and HFF-1: MOI 10; U2OS: MOI 0.5)
832 and IFN-α was added four hours post-infection. 24 and 48 hours post-infection, EGFP-positive
833 cells were quantified by flow cytometry. Inset numbers indicate IC50 values for each timepoint.
834 UT: untreated, IU: international units (n = 3 for all experiments)

835

836 **Figure 5. Reduced induction of antiviral protein and gene expression in productively**
837 **infected cells.**

838 (**A**) OASF were infected with 5'EGFP-CHIKV (MOI 10) or treated with 100 IU/ml IFN-α and
839 immunostained for IFIT1, IFITM3, and MX1/2 24 hours post-infection. Numbers in the dot
840 plots indicate mean fluorescence intensities (MFI) of one representative experiment, and the
841 bar diagram shows quantification of three individual experiments.

842 (**B**) OASF were infected with 5'EGFP-CHIKV at indicated MOIs. Six and 24 hours post-
843 infection, EGFP-positive cells were quantified by flow cytometry (left panel), and cells were
844 analyzed for expression of *IFIT1* and *MX2* mRNA (right panel, n = 6).

845 (**C**) Using OASF infected with 5'EGFP-CHIKV, single-cell RNA-sequencing was conducted
846 and UMAP visualizations for sample overlapping after integration are shown.

847 (**D**) UMAP projections from infected OASF (24 hours post-infection) indicate the abundance
848 of CHIKV 3' end reads, EGFP 3' end reads, and IFN signaling gene expression as calculated
849 by IMS.

850

851 **Figure 6. Transcriptomic differences between uninfected, bystander, and lowly or highly**
852 **CHIKV infected OASF.**

853 (**A**) Visualization of the viral RNA content of infected OASF from Fig. 5 at six and 24 hours
854 post-infection. Line indicates the cutoff dividing cells displaying low and high content of viral
855 RNA. Bystander cells were defined as cells with no detectable viral RNA.

856 (**B**) Infected OASF were sorted into digital bins of 1000 cells displaying a gradual increase of
857 the amount of viral reads per cell. Viral reads and the IMS at six and 24 hours post-infection
858 are plotted. Colored bins indicate selected representative cells for low and high content of viral
859 RNA.

860 (**C**) Expression of selected genes within mock, bystander, representative low cell bins (bin 26-
861 29) and high cell bins (bin 34-36) defined in A and B at six and 24 hours post-infection. Arrows
862 indicate a statistically significant ($p<0.05$, fold change >1.5) up- or downregulation (depending
863 on the arrow direction) in low or high CHIKV bins versus bystander (inside the boxes) or in
864 high CHIKV bins versus low (next to the boxes).
865 (**D**) Correlation of CHIKV RNA expression with expression of IFN signaling genes in high and
866 low CHIKV RNA groups calculated by non-parametric Spearman's test. Transcription factors
867 are plotted in white, with selected genes in red.
868 (**E**) Activity of transcription factor regulons within groups defined in A at six and 24 hours
869 post-infection. Arrows indicate a significant up- or downregulation between bystander and low
870 or high CHIKV groups (inside the boxes) or between low and high CHIKV groups (next to the
871 boxes).
872
873 **Supplemental Figure 1. HSF and OASF share a similar basal and CHIKV infection-**
874 **induced transcriptome.**
875 (**A**) Visualization of global transcriptional differences between OASF and HSF under regular
876 culturing conditions. Average RPKM ($\log_{10}$) values for all detected transcripts from OASF are
877 plotted on the x-axis, with corresponding values from HSF plotted on the y-axis. R^2 value and
878 regression line for comparison are inset.
879 (**B**) Gene ontology analysis of differentially expressed genes in OASF compared to HSF.
880 (**C**) Visualization of global transcriptomic differences between CHIKV-infected OASF and
881 HSF as described in A.
882 (**D**) Gene ontology analysis of the top significantly upregulated pathways in OASF, HSF, and
883 shared by both in response to CHIKV infection.

884 **(E)** Heatmaps of selected gene expression profiles of IFN receptors, CHIKV host cofactors,
885 and celltype markers.

886

887 **Supplemental Figure 2. OASF, U2OS, and HFF-1 respond with a differently strong**
888 **upregulation of ISGs to IFN treatment and CHIKV infection despite similar**
889 **responsiveness to PAMPs.**

890 (**A**) Indicated cell cultures were transfected with 5'-triphosphate dsRNA (5-ppp-RNA, left) or
891 plasmid DNA (right) and analyzed for the expression of *IFIT1* (left) and *MX2* (right) mRNA at
892 24 and 48 hours post transfection (n = 3-4).
893 (**B**) OASF, U2OS, and HFF-1 cells were analyzed for the expression of *IFIT1* and *MX2* by
894 quantitative RT-PCR after 48 h treatment with the indicated amounts of IFN-α or –λ.
895 (**C**) OASF, U2OS, and HFF-1 cells were infected with 5'-EGFP CHIKV (MOI 10) and
896 indicated amounts of IFN-α were added four hours post-infection. At 24 and 48 hours post-
897 infection, OASF were analyzed for the expression of *IFIT1* and *MX2* mRNA by quantitative
898 RT-PCR (n = 3).

899

900 **Supplemental Figure 3. Cofactor expression in OASF and mild IFN signaling gene**
901 **expression in infected OASF.**
902 (**A**) NGS reads after 3' mRNA capture attributed to each individual position in the CHIKV
903 genome plotted for cells infected with CHIKV at six and 24 hours post-infection. SGP =
904 subgenomic promotor
905 (**B**) Infected OASF were sorted into 100 digital bins per infection condition (MOI) displaying
906 a gradual increase of the amount of viral reads per cell. Average proportion of reads per cell
907 attributed to CHIKV at six and 24 hours post infection are plotted.

908 (**C**) UMAP projections were generated for the six hours post infection time point. Shown is the
909 abundance of CHIKV 3' end reads and of IFN signaling genes according to IMS.
910 (**D**) Expression of IFN-stimulated genes in infected OASF at six and 24 hours post-infection.
911 UMAP visualization shows infected cells split by the MOI and mock-infected cells separately.

912

913 **Supplemental Figure 4. IFN-stimulated gene expression in infected OASF.**
914 Expression of alphavirus infection cofactors and fibroblast marker genes in infected OASF.
915 UMAP visualization shows infected cells split by the MOI and mock-infected cells separately.

916

917 **Supplemental Figure 5. IFN signaling gene expression and transcriptional changes**
918 **between infected subgroups of cells.**
919 (**A**) IMS in uninfected, bystander, CHIKV low and CHIKV high OASF at six and 24 hours
920 post-infection. Statistical significance between groups was tested using a non-parametric KS-
921 test.
922 (**B**) Analysis of significantly up- and downregulated genes between indicated cell subgroups at
923 six and 24 hours post-infection.

924

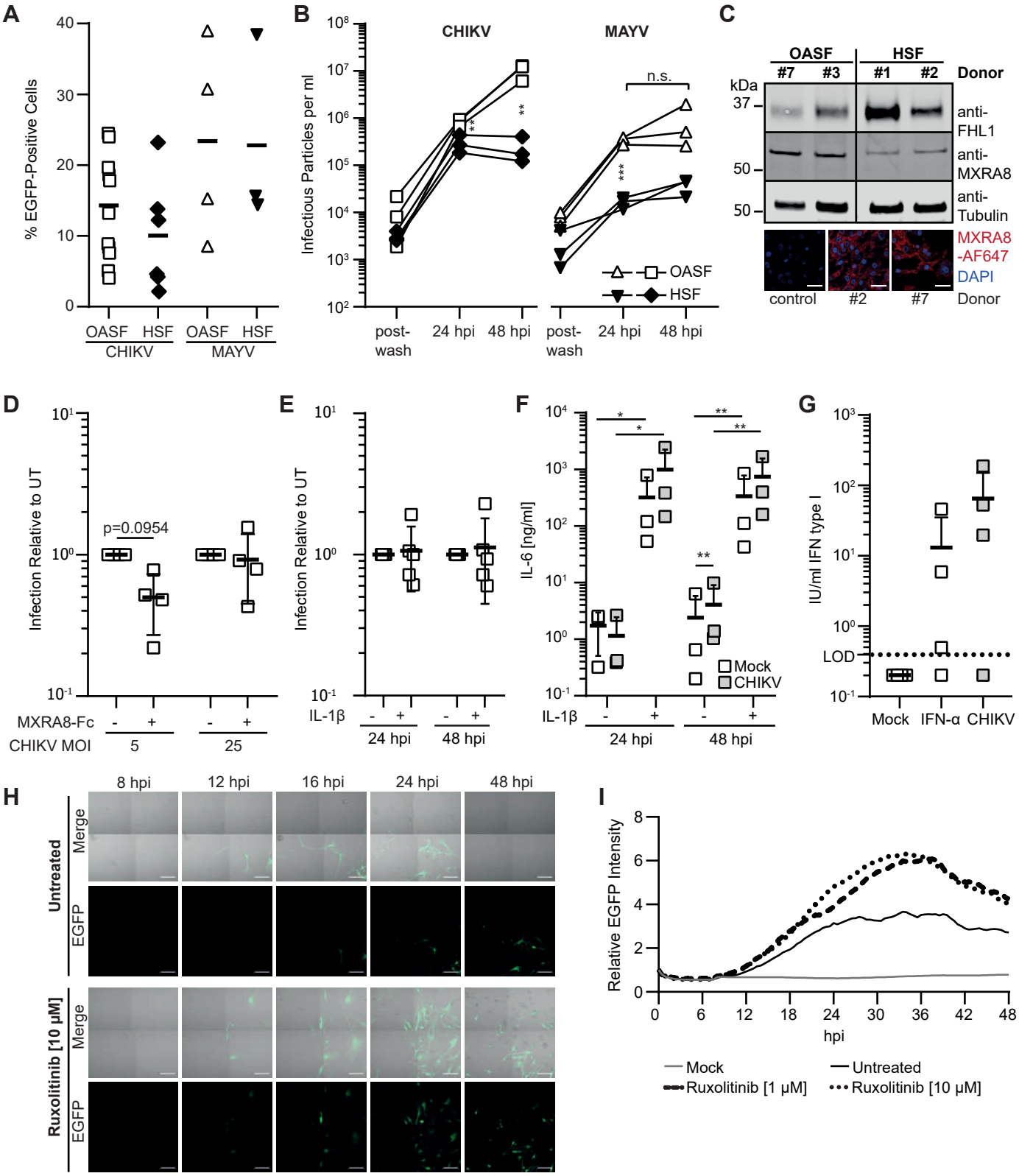
925 **Supplemental Movie 1. CHIKV spreads in OASF culture.**
926 OASF 5'-EGFP-CHIKV-infected OASF were monitored for EGFP expression by live-cell
927 imaging. Scale bar = 100 µm.

928

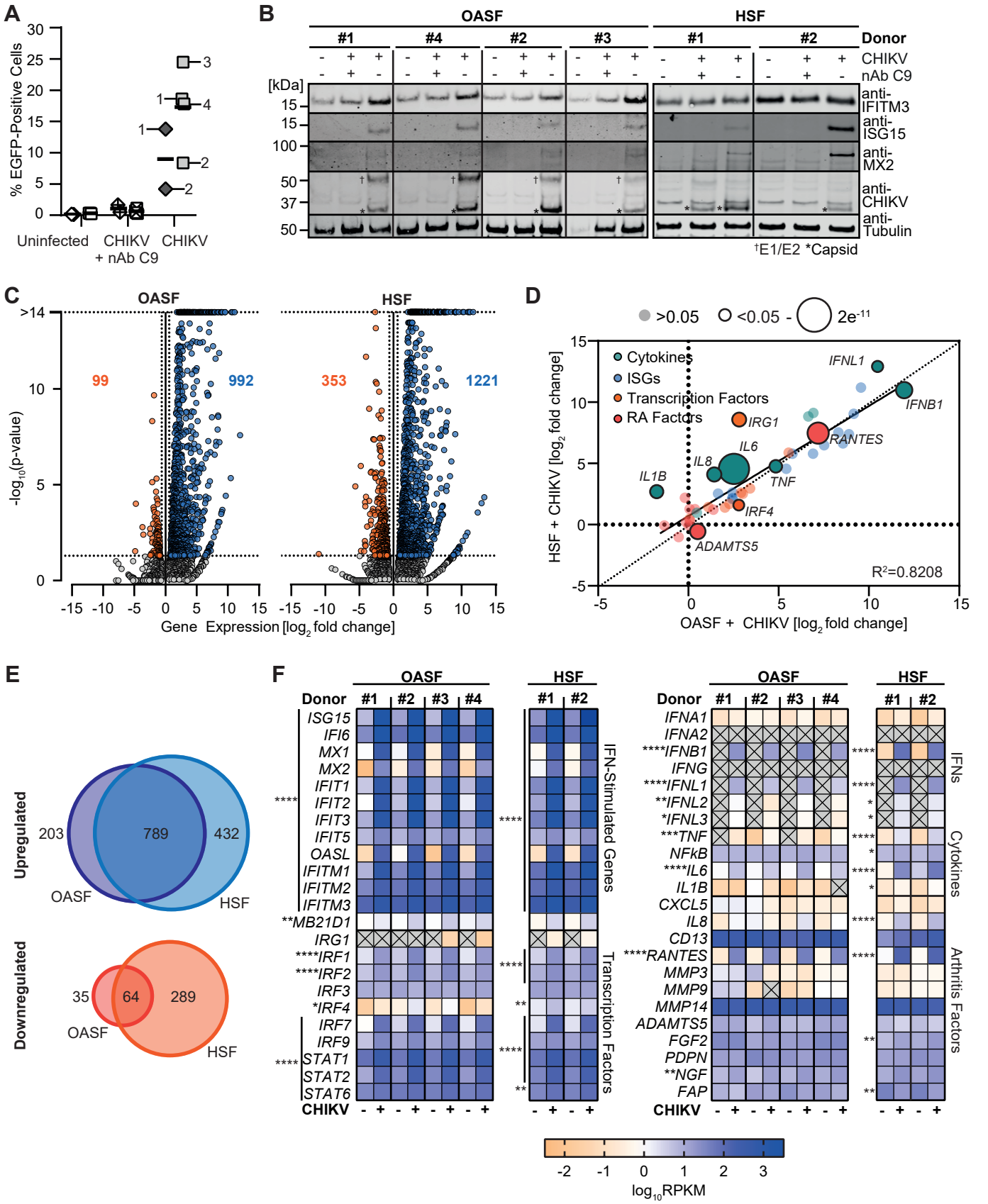
929 **Supplemental Movie 2. Ruxolitinib treatment boosts CHIKV spread.**

930 OASF were pretreated with 10 μM Ruxolitinib for 16 hours, infected with 5'-EGFP-CHIKV in
931 the presence of Ruxolitinib and monitored for EGFP expression by live-cell imaging. Scale bar
932 = 100 μm.

Pott *et al.*, Figure 1



Pott *et al.*, Figure 2



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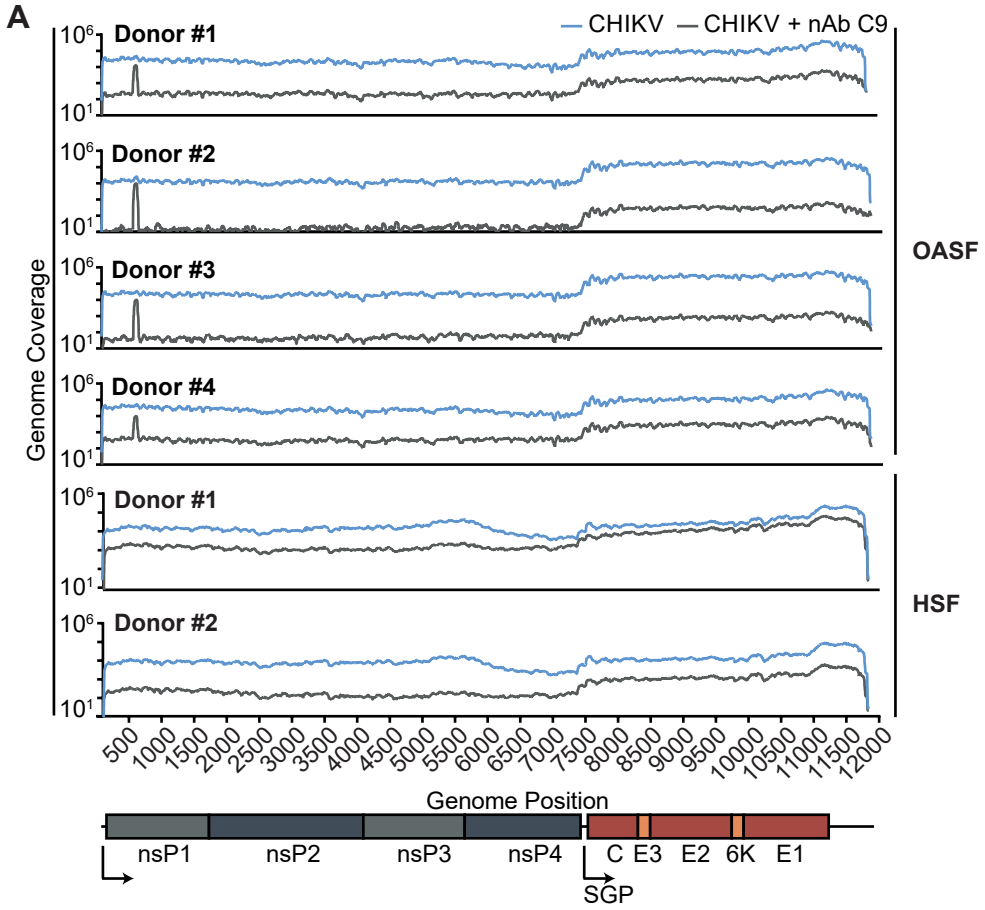

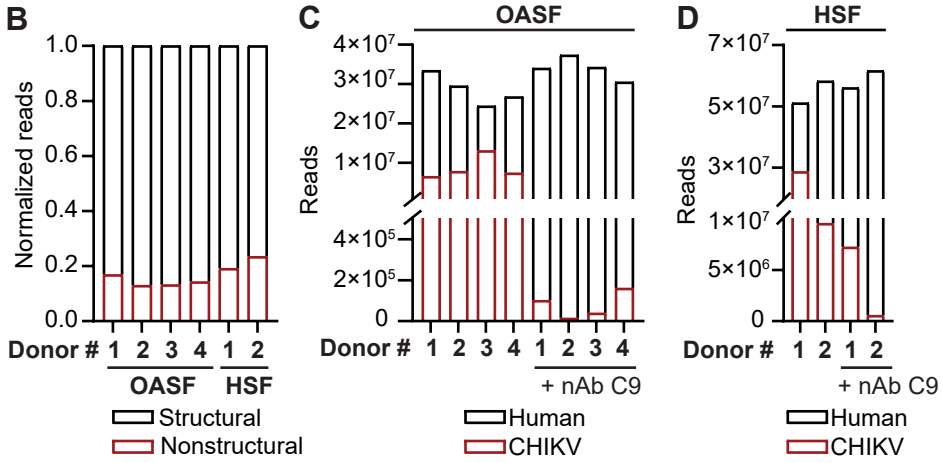

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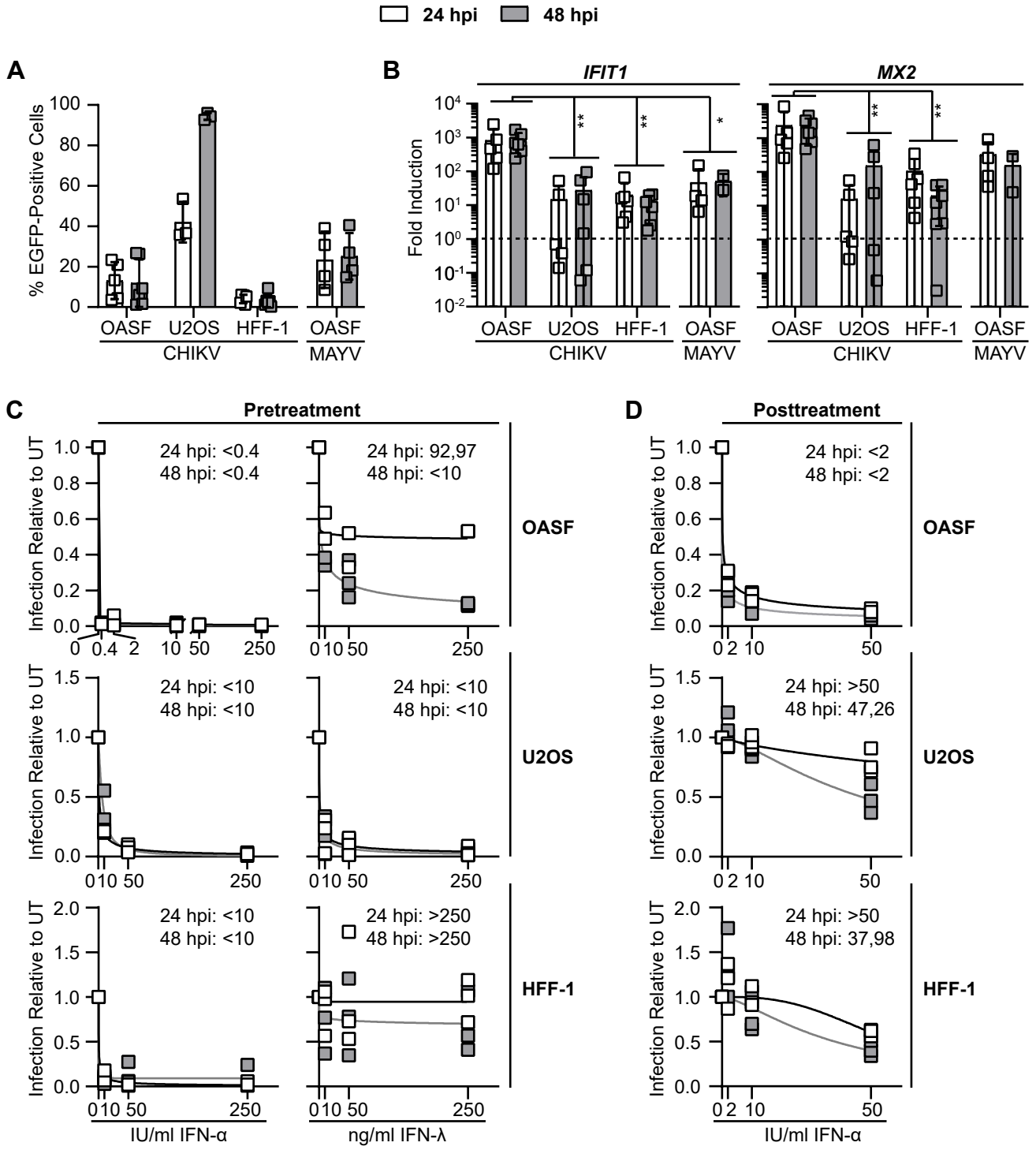
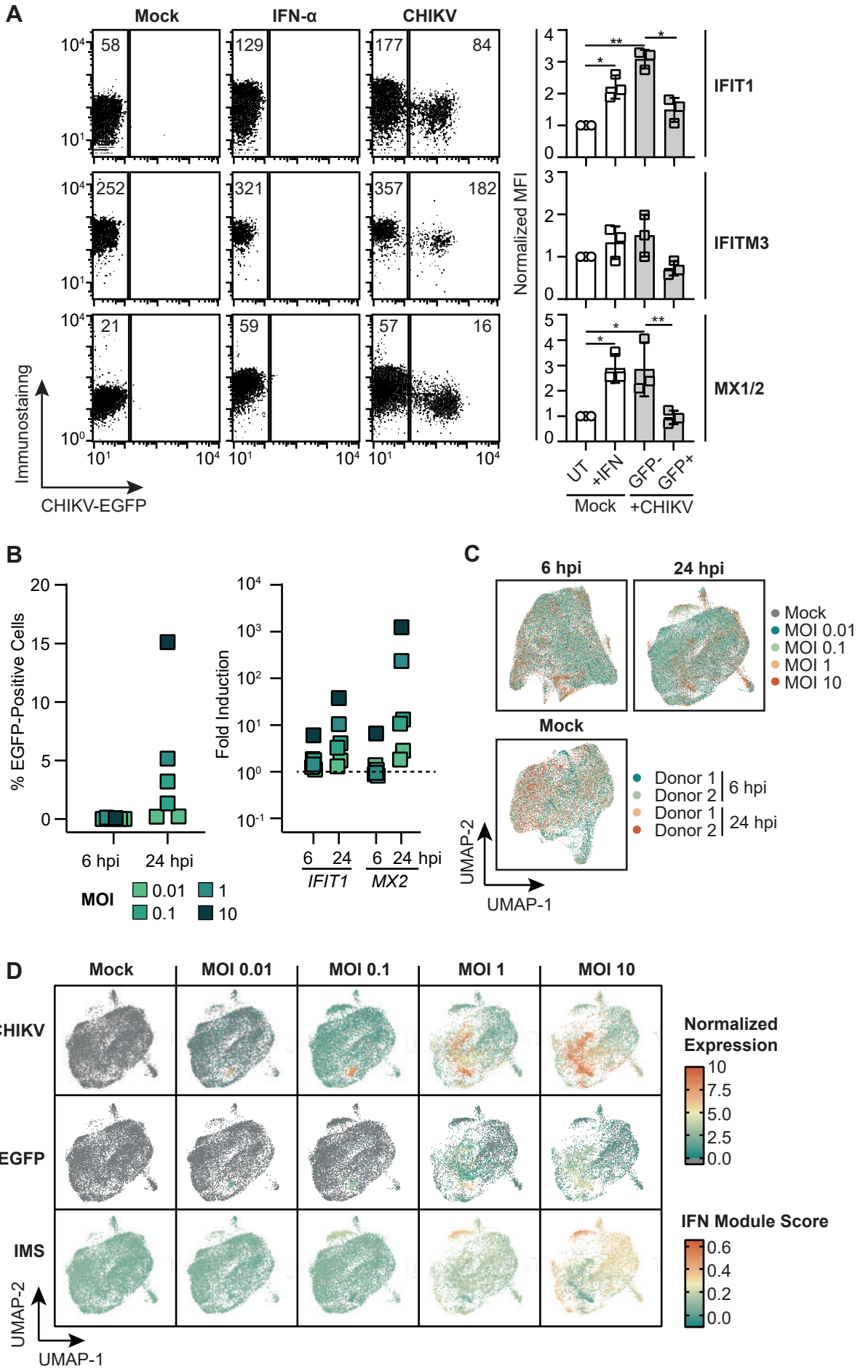


Pott et al, Figure 5



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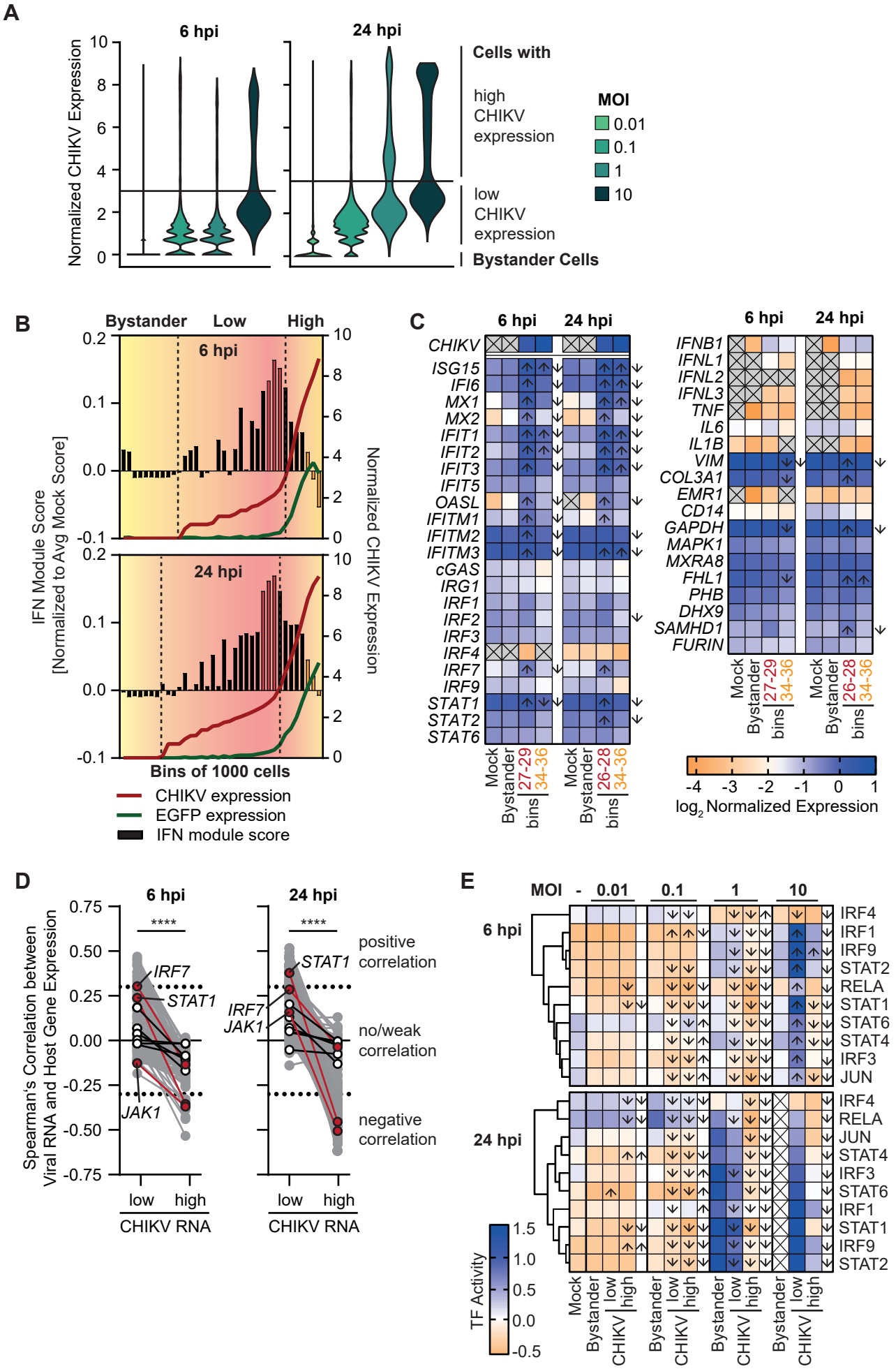
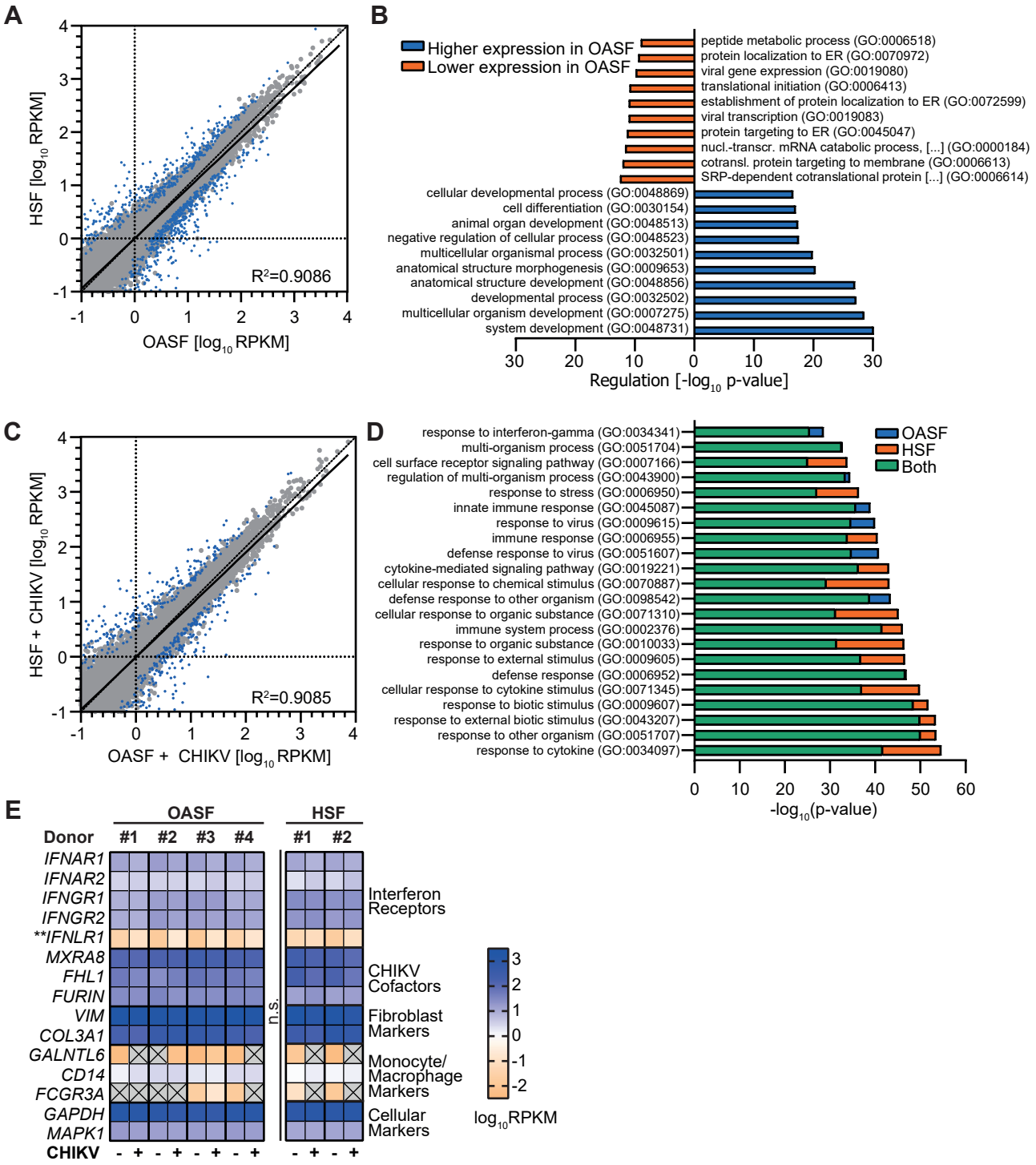


Pott *et al.*, Supplementary Figure 1



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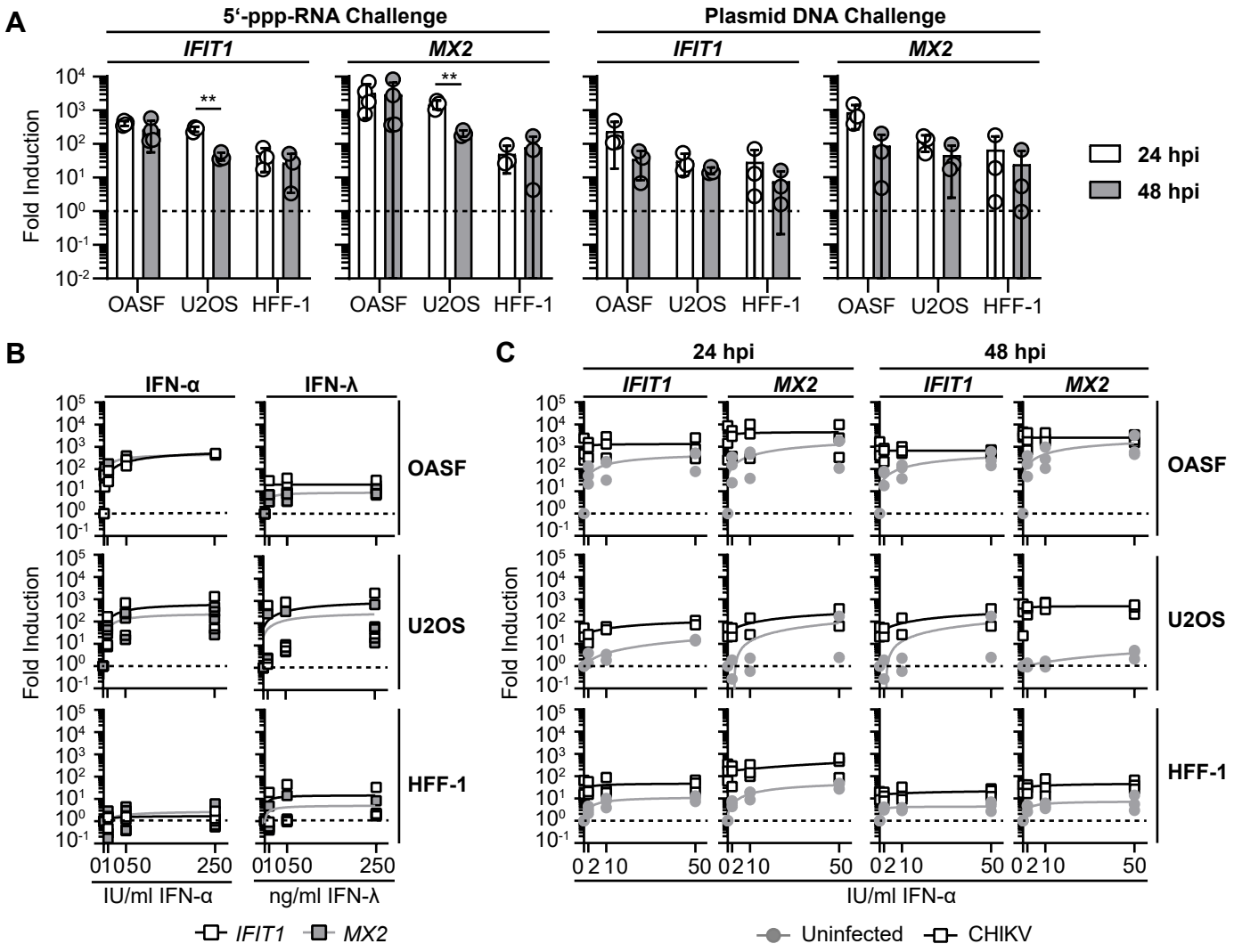

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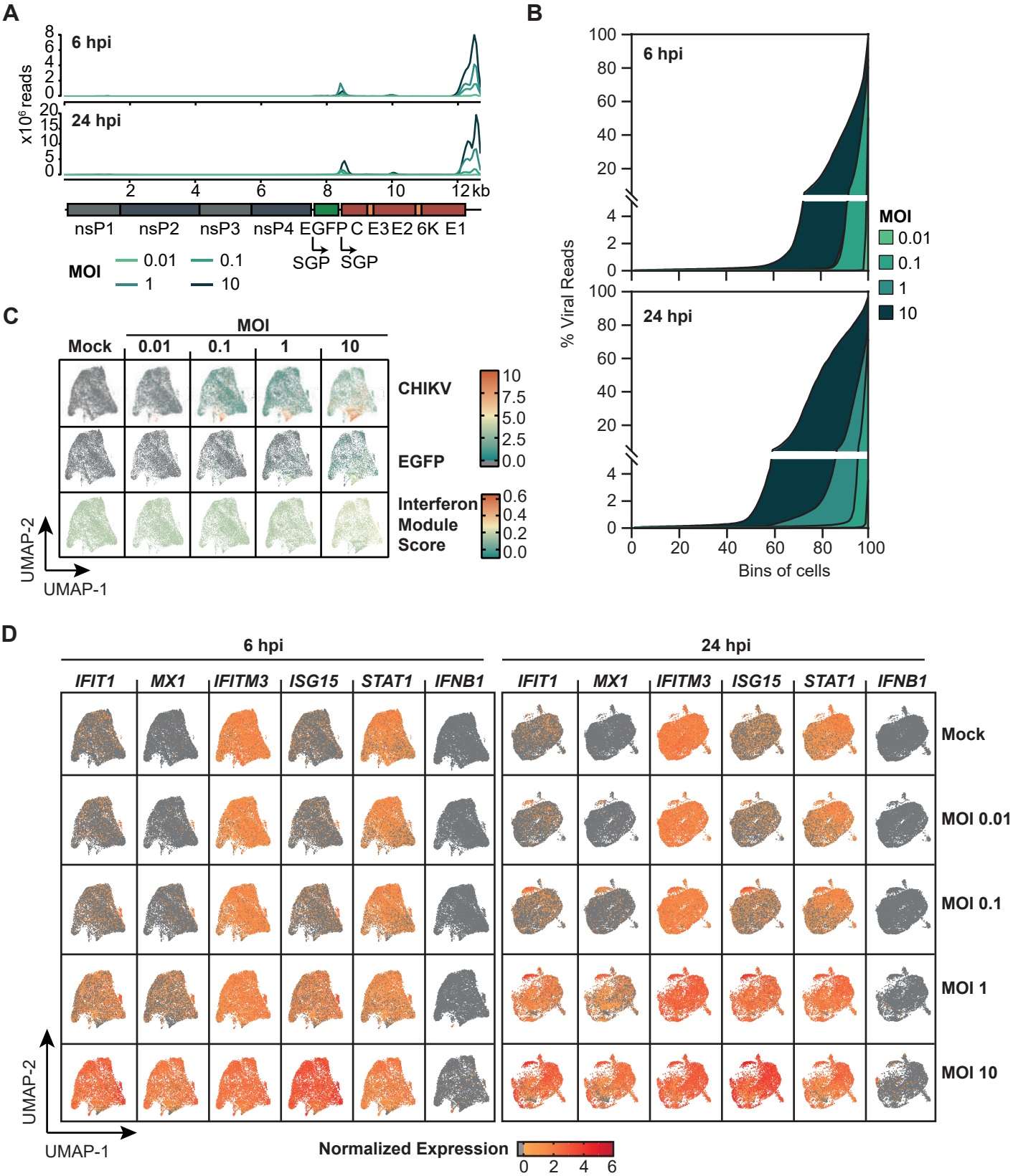

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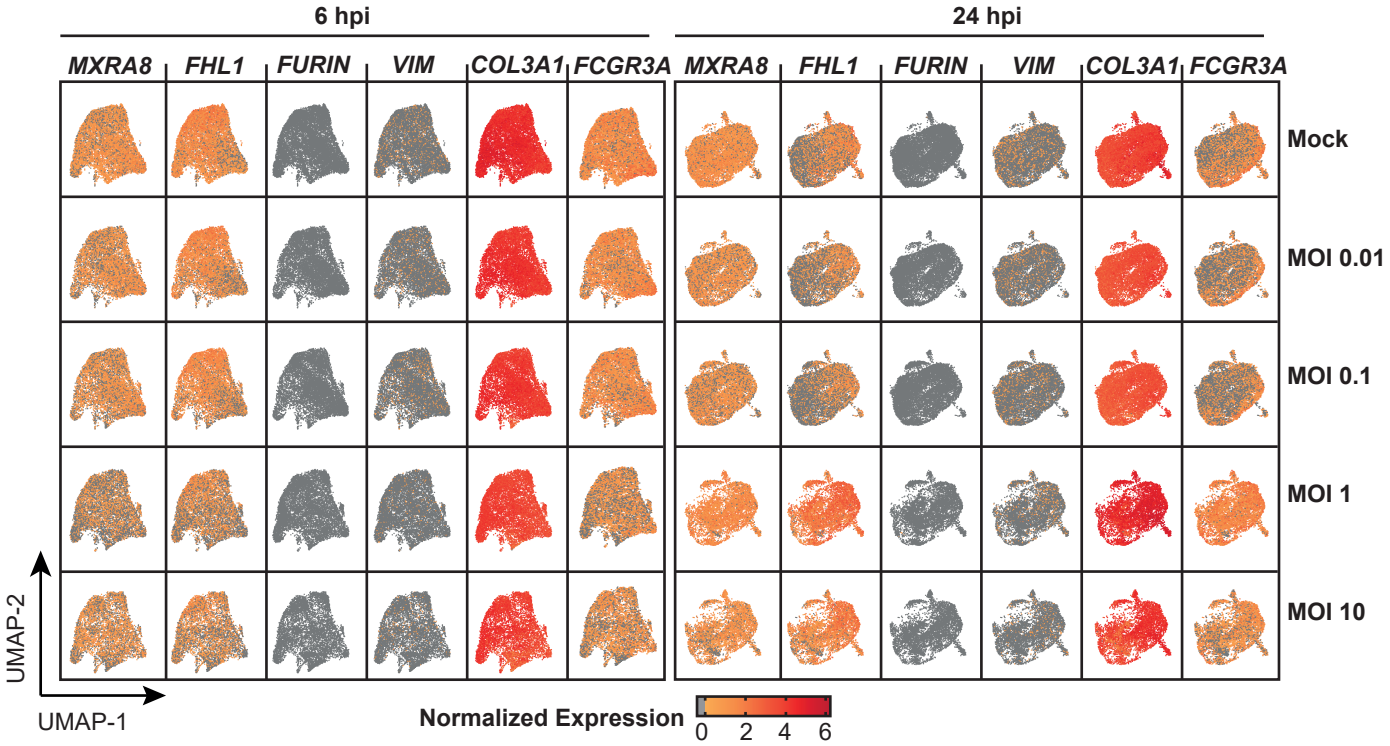

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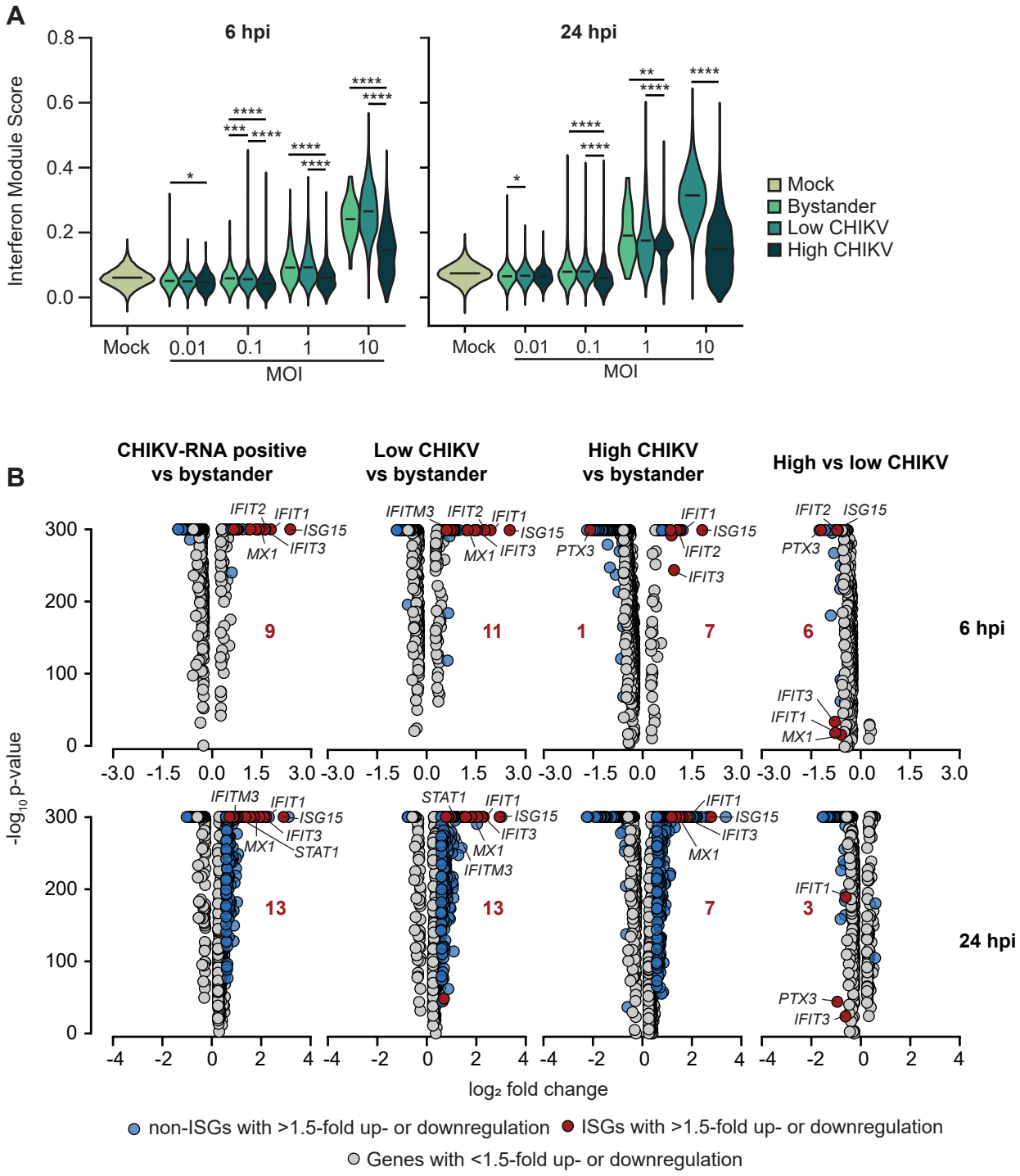

Pott et al., Table 1

AAAS	HLA-DRB3	ISG15	PLCG1	TRIM68
ABCE1	HLA-DRB4	ISG20	PML	TRIM8
ADAR	HLA-DRB5	JAK1	POM121	TYK2
ARIH1	HLA-E	JAK2	POM121C	UBA52
B2M	HLA-F	KPNA1	PPM1B	UBA7
BST2	HLA-G	KPNA2	PRKCD	UBB
CAMK2A	HLA-H	KPNA3	PSMB8	UBC
CAMK2B	ICAM1	KPNA4	PTAFR	UBE2E1
CAMK2D	IFI27	KPNA5	PTPN1	UBE2L6
CAMK2G	IFI30	KPNA7	PTPN11	UBE2N
CD44	IFI35	KPNB1	PTPN2	USP18
CIITA	IFI6	MAPK3	PTPN6	USP41
DDX58	IFIT1	MID1	RAE1	VCAM1
EGR1	IFIT2	MT2A	RANBP2	XAF1
EIF2AK2	IFIT3	MX1	RNASEL	
EIF4A1	IFITM1	MX2	RPS27A	
EIF4A2	IFITM2	NCAM1	RSAD2	
EIF4A3	IFITM3	NDC1	SAMHD1	
EIF4E	IFNA1	NEDD4	SEC13	
EIF4E2	IFNA10	NUP107	SEH1L	
EIF4E3	IFNA13	NUP133	SOCS1	
EIF4G1	IFNA14	NUP153	SOCS3	
EIF4G2	IFNA16	NUP155	SP100	
EIF4G3	IFNA17	NUP160	STAT1	
FCGR1A	IFNA2	NUP188	STAT2	
FCGR1B	IFNA21	NUP205	SUMO1	
FLNA	IFNA4	NUP210	TPR	
FLNB	IFNA5	NUP214	TRIM10	
GBP1	IFNA6	NUP35	TRIM14	
GBP2	IFNA7	NUP37	TRIM17	
GBP3	IFNA8	NUP42	TRIM2	
GBP4	IFNAR1	NUP43	TRIM21	
GBP5	IFNAR2	NUP50	TRIM22	
GBP6	IFNB1	NUP54	TRIM25	
GBP7	IFNG	NUP58	TRIM26	
HERC5	IFNGR1	NUP62	TRIM29	
HLA-A	IFNGR2	NUP85	TRIM3	
HLA-B	IP6K2	NUP88	TRIM31	
HLA-C	IRF1	NUP93	TRIM34	
HLA-DPA1	IRF2	NUP98	TRIM35	
HLA-DPB1	IRF3	OAS1	TRIM38	
HLA-DQA1	IRF4	OAS2	TRIM45	
HLA-DQA2	IRF5	OAS3	TRIM46	
HLA-DQB1	IRF6	OASL	TRIM48	
HLA-DQB2	IRF7	PDE12	TRIM5	
HLA-DRA	IRF8	PIAS1	TRIM6	
HLA-DRB1	IRF9	PIN1	TRIM62	