The testis protein ZNF165 is a SMAD3 cofactor that coordinates oncogenic TGFβ signaling in triple-negative breast cancer

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ABSTRACT

Cancer/testis (CT) antigens are proteins whose expression is normally restricted to germ cells yet aberrantly activated in tumors, where their functions remain relatively cryptic. Here we report that ZNF165, a CT antigen frequently expressed in triple-negative breast cancer (TNBC), associates with SMAD3 to modulate transforming growth factor β (TGFβ)-dependent transcription and promote growth and survival. In addition, we identify the KRAB zinc finger protein, ZNF446, and its associated tripartite motif protein, TRIM27, as obligate components of the ZNF165-SMAD3 complex that also support tumor cell viability. Importantly, we find that TRIM27 alone is necessary for ZNF165 transcriptional activity and is required for orthotopic tumor growth *in vivo*. Our findings indicate that aberrant expression of a testis-specific transcription factor is sufficient to co-opt somatic transcriptional machinery to drive a pro-tumorigenic gene expression program.

INTRODUCTION

Tumors frequently activate genes whose expression is normally restricted to the testes (Sahin et al. 2000; Atanackovic et al. 2007; Wang et al. 2016). Since the testes are immune-

31 privileged, the protein products encoded by these genes can evoke an immune response
32 when expressed in tumors (van der Bruggen et al. 1991; Sahin et al. 1995; Fijak and
33 Meinhardt 2006). Given this feature, these ~270 genes are collectively termed cancer/testis
34 (CT) genes and their encoded proteins are known as CT antigens (Simpson et al. 2005). CT
35 antigens have long been considered attractive targets for immunotherapy in a wide variety of
36 cancers (Whitehurst 2014; Thomas et al. 2018). In addition, recent work from multiple
37 groups has found that many CT antigens can support neoplastic behaviors in tumor cells
38 (Gibbs and Whitehurst 2018). Specifically, CT antigens have been implicated in supporting
39 mitotic progression, degradation of tumor suppressors, promoting DNA repair and thwarting
40 apoptosis (Whitehurst et al. 2010; Hosoya et al. 2011; Cappell et al. 2012; Maxfield et al.
41 2015; Pineda et al. 2015; Viphakone et al. 2015; Nichols et al. 2018; Gallegos et al. 2019).
42 Collectively, studies on CT antigen function over the last 15 years indicate that these
43 proteins are not merely innocuous by-products of aberrant tumor gene expression programs,
44 but rather integral agents of tumor growth and survival.
45 Using a large-scale, loss-of-function screening approach, our group previously identified
46 the CT antigen, ZNF165, as essential for triple-negative breast cancer (TNBC) survival
47 (Maxfield et al. 2015). Depletion of ZNF165 *in vitro* or *in vivo* reduces survival of TNBC cells.
48 Importantly, elevated ZNF165 mRNA expression correlates significantly with reduced
49 survival time in breast cancer, indicating that expression of this protein may confer an
50 aggressive tumorigenic phenotype (Maxfield et al. 2015).
51 ZNF165 is a C_2H_2 zinc finger transcription factor that contains an N-terminal SCAN
52 domain and six canonical Zn^{2+} fingers at its C-terminus. Consistent with its characterization
53 as a CT antigen, ZNF165 expression is restricted to human testes and is extremely low or
54 undetectable in normal breast tissues (Tirosvoutis et al. 1995; Maxfield et al. 2015).
55 Unfortunately, ZNF165 lacks conservation in mice, thereby precluding genetic studies that
56 could illuminate its normal function within the testes (Tirosvoutis et al. 1995). However,
57 investigation of its function in TNBC revealed that ZNF165 associates with chromatin to

58 regulate expression of its target genes, which includes approximately 25% of all TGFβ-
59 responsive genes in TNBC cells (Maxfield et al. 2015).
60 The cellular response to TGFβ is highly context selective, often resulting in dramatically
61 different phenotypes. For example, TGFβ is well known to facilitate growth inhibition in
62 breast epithelia and most other somatic tissues, primarily through transcriptional activation of
63 cyclin-dependent kinase inhibitors that result in cell cycle arrest (Hannon and Beach 1994;
64 Polyak et al. 1994; Morikawa et al. 2016). Conversely, TGFβ has also been shown to
65 stimulate the growth and differentiation of multiple cell types, including chondrocytes,
66 hematopoietic stem cells, and endothelial cells (Goumans et al. 2002; Li et al. 2005; Challen
67 et al. 2010). These contrasting responses to TGFβ are generally dictated by cell type-
68 specific transcription factors, which associate with TGFβ-responsive SMAD proteins and
69 recruit them to appropriate target genes for transcriptional regulation (Chen et al. 2002;
70 Gomis et al. 2006; Mullen et al. 2011; Massague 2012). In TNBC, TGFβ induces a
71 metastatic phenotype by promoting survival, chemoresistance, and the epithelial-to-
72 mesenchymal transition (Massague 2008; Bhola et al. 2013). These processes are generally
73 attributed to the activity of SMAD3, which binds directly to chromatin and whose expression
74 is elevated in late-stage breast tumors compared to other receptor-activated SMADs (Tian et
75 al. 2003; Padua et al. 2008; Petersen et al. 2010).
76 Here, we investigate the mechanisms by which ZNF165 modulates TGFβ-dependent
77 transcription in TNBC. We find that ZNF165 co-occupies a subset of SMAD3 genomic
78 binding sites and physically interacts with SMAD3 on chromatin, enhancing SMAD3
79 recruitment to specific loci. We also identify ZNF446 and TRIM27, two proteins never
80 implicated in TGFβ signaling or TNBC, as critical components of the ZNF165-SMAD3
81 transcriptional complex. Importantly, loss of function of this complex, through genetic
82 inhibition of TRIM27, attenuates growth of an orthotopic xenograft model of TNBC *in vivo*.
83 These findings establish that anomalous expression of ZNF165 promotes the assembly of a

84 neomorphic transcriptional complex that modulates the TGFβ-responsive transcriptional
85 landscape in TNBC.
86
87 **RESULTS**
88 **SMAD3 is enriched at ZNF165 binding sites in TNBC cells**
89 To comprehensively investigate whether ZNF165 interfaces with the TGFβ transcriptional
90 network, we first generated a SMAD3 genomic binding profile in WHIM12 cells, where
91 ZNF165 is essential for growth (Maxfield et al. 2015). WHIM12 cells were originally
92 developed from a patient-derived xenograft established from a triple-negative, highly chemo-
93 resistant tumor (Li et al. 2013). Moreover, these cells are classified within the claudin-low
94 molecular subtype of breast cancer, which exhibits activated TGFβ signaling (Prat et al.
95 2010; Asiedu et al. 2011; Sabatier et al. 2014). We found that SMAD3 binding is associated
96 with over >27,000 sites in WHIM12 cells, comparable to previous studies of SMAD3 binding
97 in TNBC cell lines (Tufegdzic Vidakovic et al. 2015). Intersecting SMAD3 and ZNF165-
98 associated genes revealed that >90% of ZNF165 target genes are also bound by SMAD3,
99 an overlap representing a statistically significant enrichment ($p = 5.50e-120$, hypergeometric
100 distribution) (Figure 1A). This is in agreement with our previous findings that ZNF165 targets
101 a significant fraction of the TGFβ-responsive transcriptome (Maxfield et al. 2015). Mapping
102 the distance between binding sites further revealed that 90% of shared targets were bound
103 by both transcription factors at a distance of less than 100 kb from one another (Figure 1B).
104 Furthermore, 36% of shared target genes had ZNF165 and SMAD3 binding sites within 1 kb,
105 a proximity at which both factors exhibited overlap on chromatin due to the broad enrichment
106 profile of SMAD3 as observed within our dataset (Figure 1B-E). We next established
107 ZNF165 and SMAD3 binding profiles in SUM159 cells, which are also classified within the
108 claudin-low molecular subtype and require ZNF165 for viability (Prat et al. 2010; Maxfield et
109 al. 2015). SMAD3 enrichment at the ZNF165 binding sites here closely resembled that of
110 WHIM12 cells (Figure 1C-E). Further analysis of SMAD3 binding in MDA-MB-231 cells

111 corroborated these findings (Figure 1-figure supplement 1A-C). Together these data
112 demonstrate that despite differences in the genetic backgrounds of TNBC tumor cells,
113 ZNF165 and SMAD3 exhibit significant co-occupancy on chromatin throughout the genome.
114 We next applied a motif discovery strategy to the 118 regions where both transcription
115 factors were bound within 1 kb of each other. More than 50% of these co-bound sites were
116 present in gene promoters (-1 kb or +100 bp from TSS) while SMAD3 binding sites were
117 relatively evenly distributed across genetic regions (Figure 1F). This analysis revealed that
118 GC-rich elements are significantly enriched at co-bound regions (n=118) compared to those
119 bound by ZNF165 alone (n=204) (Figure 1G and 1H). Such GC-rich SMAD binding elements
120 (SBEs) have recently been characterized as universal binding sites for receptor-activated
121 SMAD proteins, and SMAD3 can bind variants of these motifs with high affinity (Martin-
122 Malpartida et al. 2017). Thus, the GC-rich SMAD3 binding element may be an underlying
123 genomic feature of the ZNF165-occupied sites that facilitates co-occupancy. Collectively,
124 these data suggest that ZNF165 and SMAD3 may form cis-regulatory modules on chromatin
125 to direct TGFβ-mediated gene expression in TNBC. In support of this notion, gene set
126 enrichment analysis of ZNF165-responsive genes in WHIM12 cells revealed a significant
127 enrichment of genes involved in the epithelial-to-mesenchymal transition (EMT), a SMAD3-
128 dependent process that promotes metastasis in response to TGFβ signaling (Figure 1-figure
129 supplement 1D) (Tian et al. 2003; Xu et al. 2009; Petersen et al. 2010). Consistent with this,
130 elevated ZNF165 expression in patients with breast cancer is associated with a greater
131 metastatic potential (Hazard Ratio (HR) = 1.4; p = 0.004) (Figure 1-figure supplement 1E).
132
133 **ZNF165 and SMAD3 cooperate to modulate TGFβ-responsive gene expression**
134 Given the enrichment of SMAD3 and ZNF165 at shared sites and their general proximity to
135 one another on chromatin, we next asked whether these transcription factors cooperate to
136 regulate expression of co-bound genes. We leveraged a previously generated gene
137 expression data set of TGFβ responsiveness in WHIM12 cells (Maxfield et al. 2015). Here,

138 we assembled a set of 65 TGFβ-responsive genes that are co-bound by SMAD3 and
139 ZNF165 (Figure 2-figure supplement 1A). We then compared the impacts of ZNF165 and
140 SMAD3 depletion on a subset of these genes. This analysis revealed a significant correlation
141 (r = 0.52) between expression fold-changes in response to depletion of either transcription
142 factor (Figure 2A). In particular, ZNF165 and SMAD3 were required to either activate or
143 repress expression of the majority of shared target genes (quadrant I and III, Figure 2A). We
144 also observed opposing effects of SMAD3 and ZNF165 on a smaller subset of genes,
145 suggesting that in some cases, the activities of these two proteins may oppose one another
146 (quadrant II and quadrant IV, Figure 2A).
147 The observed expression changes in Figure 2A suggest two modes of regulation for
148 ZNF165-SMAD3 targets. First, ZNF165 collaborates with SMAD3 to activate or oppose
149 TGFβ-mediated gene expression changes (quadrant I and III, Figure 2A). Alternatively,
150 ZNF165 can antagonize SMAD3-mediated activation or repression of shared target genes in
151 response to TGFβ (quadrant II and IV, Figure 2A). The majority of genes fell into the former
152 category, with *SMURF2* and *RRAD* being the two most responsive and were thus selected
153 as archetypes for follow-up analysis. Importantly, we found that RRAD and SMURF2 protein
154 accumulation corresponded to mRNA alterations upon ZNF165 or SMAD3 depletion (Figure
155 2B and 2C).
156 Given the observed collaborative function of ZNF165 and SMAD3 on target gene
157 expression, we next asked whether their association with chromatin was cooperative.
158 ZNF165 knockdown resulted in a ~50% reduction of SMAD3 enrichment at the ZNF165
159 binding sites proximal to both *SMURF2* and *RRAD* (Figure 2D). Importantly, SMAD3 binding
160 at the promoter of LBH, a site not co-bound by ZNF165, was unaffected by ZNF165
161 depletion. SMAD3 commonly recruits the histone acetyltransferase, p300, to activate gene
162 expression of its targets (Feng et al. 1998; Janknecht et al. 1998). Consistent with this, we
163 observed a reduction of H3K27ac at the ZNF165-SMAD3 binding site proximal to *RRAD* in
164 response to ZNF165 knockdown (Figure 2E). Conversely, an increase in H3K27ac was

165 detected upon ZNF165 overexpression (Figure 2F). These findings suggest that ZNF165 is
166 essential for recruitment of SMAD3 to shared target gene promoters and transcriptional
167 activation. We reasoned that this activity could promote expression of genes required for
168 tumorigenic phenotypes. Indeed, a report from 2001 indicated that RRAD is sufficient to
169 promote proliferation of breast tumor cells *in vitro* and *in vivo* (Tseng et al. 2001). Based on
170 this observation, we investigated breast cancer gene expression data sets for clinical
171 correlates with RRAD expression. In the mesenchymal subtype of TNBC, which is enriched
172 for active TGFβ signaling and an EMT gene expression signature, RRAD expression
173 correlated with reduced overall survival (HR = 2.31; p = 0.04) and greater metastatic
174 potential (HR = 3.18; p = 0.05) (Figure 2-figure supplement 1B) (Lehmann et al. 2011).
175 Conversely, in luminal tumors, which are traditionally ER^+ and exhibit tumor-suppressive
176 TGFβ signaling, RRAD expression correlated with improved overall survival (HR = 0.63; p =
177 0.01) and no correlation was observed with distant metastasis free survival (HR = 1.12; p =
178 0.55) (Figure 2-figure supplement 1C) (Perou et al. 2000; Sato et al. 2014). Moreover,
179 DepMap analysis revealed that RRAD perturbation generally leads to a reduction in 2D
180 growth of TNBC cell lines, and we found that RRAD was essential for growth of SUM159
181 cells in soft agar (Figure 2-figure supplement 1D and 1E). However, we observed an
182 enhanced growth phenotype in ER^+ MCF7 cells, supporting the notion that TGFβ mediates
183 tumor-suppressive phenotypes in more differentiated breast cancer cells and pro-
184 tumorigenic effects in less differentiated cell types (Figure 2-figure supplement 1F) (Tian et
185 al. 2003; Massague 2008). Collectively, these data suggest that ZNF165 is capable of
186 directing SMAD3 recruitment to TGFβ-responsive target genes, whose altered expression
187 can support malignant behaviors in the context of TNBC.
188
189 **ZNF165 physically associates with SMAD3 in a TGFβ-dependent manner**
190 As ZNF165 appears to facilitate SMAD3 recruitment to chromatin, we asked whether these
191 proteins physically associate. Interaction studies using co-expression/co-

192 immunoprecipitation indicated an association between ZNF165 and SMAD3 (Figure 3A). In
193 addition, we found that ZNF165 interacts with the active, phosphorylated form of SMAD3 on
194 chromatin in SUM159 cells stably expressing ZNF165-V5 (Figure 3B). Activation of SMAD3
195 and its resulting nuclear translocation is dependent on the phosphorylation of its C-terminus
196 by TGFβRI in response to TGFβ (Massague 2012). Thus, we employed the serine/threonine
197 kinase inhibitor SB-431542, which selectively inhibits TGFβRI and downstream
198 phosphorylation of SMAD3, to assess whether the ZNF165-SMAD3 interaction is dependent
199 on pathway activation (Figure 3C) (Inman et al. 2002; Massague 2012). Proximity ligation
200 assays (PLAs) in SUM159 cells treated with TGFβ revealed an endogenous association
201 between ZNF165 and SMAD3, which was significantly diminished by pre-treatment with SB-
202 431542 (Figure 3D). Furthermore, we found that endogenous ZNF165 and SMAD4 also
203 interact in a TGFβ-dependent manner (Figure 3E). Taken together, these results indicate
204 that in response to TGFβ, ZNF165 physically associates with phosphorylated SMAD3.
205
206 **ZNF446 is an obligate component of the ZNF165-SMAD3 transcriptional complex**
207 We reasoned that ZNF165 and SMAD3 likely function within a multi-protein transcriptional
208 complex to mediate gene expression changes in response to TGFβ. Therefore, we searched
209 for additional ZNF165 interactors using proteomics data generated from a systematic yeast
210 two-hybrid (Y2H) screening approach (Rolland et al. 2014). This search returned 48 putative
211 ZNF165 interacting partners, 17 of which are likely transcriptional regulators based on the
212 presence of known gene regulatory domains (Supplementary File 2). To triage these
213 candidates, we focused on those containing a SCAN (SRE-ZBP, Ctfin51, AW-1 and Number
214 18) domain, which is well-documented to mediate specific interactions among SCAN-zinc
215 finger proteins (ZFPs) and the only domain within ZNF165 aside from its zinc finger array
216 (Figure 4A) (Edelstein and Collins 2005). We identified five putative interactors with SCAN
217 domains and examined the consequences of their depletion on *SMURF2* expression. Of the
218 proteins tested, ZNF446 and SCAND1 phenocopied the changes in gene expression

219 observed for ZNF165 and SMAD3 in two TNBC cell lines (Figure 4B). Examination of their
220 tumor expression patterns revealed that ZNF446 is upregulated in breast tumors, an
221 increase that trends with reduced survival in the triple-negative enriched basal-like subtype
222 of breast cancer (HR = 1.89; p = 0.059) (Figure 4-figure supplement 1A and 1B) (Perou et al.
223 2000; Sorlie et al. 2001). Moreover, we found that depletion of ZNF446 significantly reduced
224 anchorage-independent growth of TNBC cells (Figure 4-figure supplement 1C). Co-
225 expression/co-immunoprecipitation assays confirmed that ZNF165 and ZNF446 interact and
226 that deletion of the ZNF165 SCAN domain abrogates this association (Figure 4C). In
227 addition, an endogenous interaction between ZNF165 and ZNF446 was detectable in TNBC
228 tumor cell nuclear extracts, confirming these proteins interact in the relevant subcellular
229 compartment (Figure 4D). We then employed the SMAD3/4 PLA assay described above and
230 found that ZNF446 interacts with both SMAD3 and SMAD4 in a TGFβ-dependent fashion,
231 similar to ZNF165 (Figure 4E and 4F).
232 To determine if ZNF446 also associates with ZNF165-SMAD3 target genes, we
233 performed ChIP-seq for ZNF446-V5 stably expressed in WHIM12 and SUM159 cells. This
234 led to the identification of 5,039 and 7,926 binding sites in WHIM12 and SUM159 cells,
235 respectively. In both cell lines, ZNF446 was enriched at the ZNF165 binding sites (Figure 5A
236 and 5B; Figure 5-figure supplement 1A). Intersecting the ZNF446 and ZNF165 genomic
237 binding profiles further revealed a highly statistically significant overlap in both settings (p =
238 <0.0001) (Figure 5C and 5D). Approximately half of all ZNF446 binding sites in WHIM12
239 cells were also co-occupied by SMAD3 (Figure 5E and 5F; Figure 5-figure supplement 1B).
240 These co-bound sites were largely enriched for promoter regions compared to the total
241 binding sites for either factor (Figure 5-figure supplement 1C). Of further significance,
242 differential motif enrichment analysis revealed the presence of a short GC-rich element at
243 ZNF446-SMAD3 bound sites, closely resembling the motif we identified at ZNF165-SMAD3
244 bound sites and identical to the recently reported SMAD consensus binding motif (Figure 5G
245 and 5H; Figure 1G) (Martin-Malpartida et al. 2017).

246 With respect to target genes, we found that over half of those shared by ZNF165 and
247 SMAD3 (251/446) are also targeted by ZNF446 (Figure 5I). The impact of ZNF446 depletion
248 on expression these genes significantly correlated with both ZNF165 (r = 0.49) and SMAD3
249 (r = 0.86) (Figure 5J). Collectively, these findings implicate ZNF446 as a member of the
250 ZNF165-SMAD3 complex that can influence TGFβ-dependent transcription in TNBC.
251
252 **TRIM27 is essential for ZNF165 transcriptional activity and tumor growth *in vivo***
253 ZNF446 contains a KRAB (Krüppel-associated box) domain, which is well documented to
254 interact with the RBCC (RING, B-box, coiled-coil) domain of proteins within the tripartite
255 motif (TRIM) family that in turn function as co-repressors or, as recently demonstrated, co-
256 activators (Friedman et al. 1996; Schultz et al. 2001; Schultz et al. 2002; Chen et al. 2019).
257 Y2H-based proteomics confirmed such an interaction of TRIM27, which contains the classic
258 RBCC domain, with ZNF446 (Figure 6A; Supplementary File 2). Originally identified as an
259 oncogenic fusion with the RET tyrosine kinase, TRIM27 has been ascribed roles in
260 numerous cellular processes that include transcriptional repression, proliferation, meiosis,
261 innate immunity, and endosomal trafficking (Takahashi et al. 1985; Shimono et al. 2000;
262 Shimono et al. 2003; Zha et al. 2006; Hao et al. 2013; Zaman et al. 2013; Zheng et al. 2015;
263 Ma et al. 2016). However, its function as a transcriptional regulator in TNBC has not been
264 characterized. Co-expression/co-immunoprecipitation experiments revealed that both
265 ZNF446 and ZNF165 interact with TRIM27 and that all three proteins immunoprecipitate as
266 a complex (Figure 6B). We subsequently confirmed a nuclear interaction between ZNF165-
267 V5 and endogenous TRIM27 by proximity ligation in SUM159 cells and found that TRIM27
268 depletion also phenocopied changes in ZNF165-SMAD3 target gene expression (r = 0.81)
269 (Figure 6C and 6D). Notably, TRIM27 appears to be bi-functional, either positively or
270 negatively regulating expression of the ZNF165-SMAD3 targets (Figure 6D). Indicative of a
271 co-activator function, we found that TRIM27 is required for the transcriptional activation of
272 *RRAD* following ZNF165 or ZNF446 overexpression (Figure 6E; Figure 6-figure supplement

273 1A). Similar to ZNF165 and ZNF446, proximity ligation assays revealed endogenous,
274 nuclear interactions between TRIM27 and both SMAD3 and SMAD4, which were reduced by
275 TGFβ pathway inhibition (Figure 6F and 6G).

276 TRIM27 expression is elevated in several cancers including colon, lung, endometrial and
277 ovarian, and often correlates with poor prognosis (Tsukamoto et al. 2009; Horio et al. 2012;
278 Iwakoshi et al. 2012; Zoumpoulidou et al. 2012; Ma et al. 2016; Zhang et al. 2018). Using
279 TCGA data, we found that TRIM27 expression is significantly elevated in TNBC compared to
280 normal breast tissue (Figure 6-figure supplement 1B). Moreover, we stained a small cohort
281 of normal and TNBC tissues for TRIM27 and observed a striking difference in its subcellular
282 localization. TRIM27 appeared to be predominantly cytoplasmic in normal breast epithelia
283 and more nuclear in TNBC tissues, suggesting that its transcriptional activity might associate
284 with the transformed state (Figure 6-figure supplement 1C). This finding is in agreement with
285 previous reports and the Human Tissue Atlas, where TRIM27 is mostly cytoplasmic in
286 normal breast and nuclear in testis and a subset of breast cancer tissues (Tezel et al. 1999;
287 Tezel et al. 2009; Uhlen et al. 2015).

288 Given that TRIM27 was critical for ZNF165-dependent gene regulation, we next asked
289 whether TRIM27 was essential for malignant behaviors. While depletion of TRIM27 does not
290 seem to strongly affect TNBC tumor cell growth in 2D, we observed a significant defect in
291 anchorage-independent growth using soft agar assays (Figure 6-figure supplement 1D and
292 1E). We next perturbed TRIM27 as a means to inhibit the activity of the ZNF165
293 transcriptional complex and assess its impact on TNBC tumor growth and survival at the
294 orthotopic site in mice. Following stable depletion of TRIM27, SUM159 cells were injected
295 into the mammary fat pad of immunocompromised mice (Figure 6-figure supplement 1F and
296 1G). In this setting, we observed a significant decrease in both tumor growth rate and size,
297 suggesting that TRIM27 is essential for TNBC tumor growth *in vivo* and that inhibition of the
298 ZNF165 transcriptional complex may be a promising avenue of therapeutic intervention
299 (Figure 6H and 6I). Together, these results suggest that TRIM27 is a previously

300 unrecognized regulatory component of TGFβ signaling in TNBC and functions to modulate
301 TGFβ-dependent transcription in cooperation with ZNF165, ZNF446, and SMAD3.
302
303 **DISCUSSION**
304 Striking similarities between tumors and developing germ cells have been noted for over a
305 century (Simpson et al. 2005). As a result, it has been speculated that a fundamental
306 attribute of cancer is the usurpation of developmental signaling programs. Tumors frequently
307 activate expression of gametogenic genes, which encode a group of proteins termed
308 cancer/testis antigens (CT antigens) (Chen et al. 1997; Simpson et al. 2005). While these
309 proteins have long been considered optimal targets for immunotherapy, their function, if any,
310 in tumor cells has not been well-established.
311 In recent years, an increasing number of studies have begun to indicate that CT antigens
312 are not merely innocuous by-products of aberrant gene expression programs, but instead
313 can be essential to the progression of cancer. The list of tumor cell mechanisms regulated
314 by these proteins includes mitosis, protein turnover, mitigating DNA damage, and disrupting
315 normal transcriptional programs (Gibbs and Whitehurst 2018). This variety of biological
316 processes is attributable to the high degree of diversity in the functions of proteins classified
317 as CT antigens, and speaks to the ability of tumor cells to engage aberrant gene expression
318 programs in order to support their growth and survival. In support of this, our study of the
319 testis protein ZNF165 has revealed a previously unrecognized mechanism by which TGFβ
320 signaling is co-opted to promote malignancy in late-stage breast tumors.
321 Our findings expose a high degree of flexibility in tumor cell transcriptional networks. We
322 reason that this feature could be the result of the modular domains present in many
323 transcriptional regulators, particularly zinc finger proteins (ZFPs), which make up the largest
324 family of transcription factors in the human genome (Lambert et al. 2018). The vast majority
325 of these proteins contain KRAB, BTB/POZ, or SCAN domains, that mediate interactions with
326 transcriptional partners (Bellefroid et al. 1991; Bardwell and Treisman 1994; Albagli et al.

327 1995; Williams et al. 1995). The SCAN domain in particular regulates the assembly and thus
328 function of specific transcriptional complexes (Edelstein and Collins 2005). SCAN domains
329 are not promiscuous, but demonstrate selectivity for co-association, the basis of which is not
330 clear. Nevertheless, ectopic introduction of a SCAN domain-containing protein, such as
331 ZNF165, may drive assembly of a neomorphic transcriptional complex, ZNF165-ZNF446-
332 SMAD3-TRIM27, that is otherwise not present in somatic cells (Figure 7). This finding
333 highlights the importance of silencing lineage-specific transcription factors, as their
334 anomalous expression may be sufficient to disrupt transcriptional networks that regulate
335 tissue homeostasis.

336 The study of CT antigen function generally, and ZNF165 in particular, has the capacity to
337 reveal new principles underlying tumor cell regulatory networks. Specifically, our data
338 indicate that both ZNF446 and TRIM27 are complicit in the activation of oncogenic TGFβ
339 signaling in TNBC. While ZNF446 has been reported to act as a transcriptional repressor for
340 SRF and AP-1 via its KRAB domain, a physiological function for ZNF446 in either normal or
341 malignant contexts has not been reported (Liu et al. 2005). Our findings suggest that in
342 addition to functioning as a chromatin-bound cofactor for ZNF165 and SMAD3, ZNF446 may
343 recruit TRIM27 to modulate TGFβ-induced transcription. Furthermore, despite reports
344 describing only repressive capabilities of TRIM27, we find that TRIM27 can either activate or
345 repress expression of genes targeted by the ZNF165-ZNF446-SMAD3 complex (Shimono et
346 al. 2000; Shimono et al. 2003). This finding dovetails with a recent report demonstrating that
347 TRIM28 serves as a co-activator for ZFP30-mediated adipogenesis, and together these
348 studies begin to establish that tripartite motif proteins may be bi-functional with respect to
349 transcriptional repression or activation (Chen et al. 2019). TRIM27 is also a well
350 characterized E3 ligase and has been reported to modify numerous protein substrates via
351 ubiquitination and SUMOylation (Chu and Yang 2011; Zurek et al. 2012; Lee et al. 2013).
352 Future studies to address whether the catalytic activity of TRIM27 is required for ZNF165-

353 dependent transcriptional regulation are therefore crucial, as small molecule inhibitors of
354 TRIM27 could selectively disrupt pro-tumorigenic TGFβ signaling in TNBC.
355 An additional, unexpected finding is that *RRAD*, whose transcription is highly regulated by
356 the ZNF165 transcriptional complex, is a TGFβ target gene that can exert opposing
357 behaviors depending on context. TGFβ signaling is well known to drive pro-tumorigenic
358 phenotypes in less differentiated breast tumor cell types, such as TNBC, while facilitating
359 tumor suppression in more differentiated cell types (Tian et al. 2003; Massague 2008). Our
360 study indicates that RRAD contributes to such context-specific phenotypes conferred by
361 TGFβ signaling, which may help to explain extensive data that report opposing impacts of
362 RRAD expression in a variety of cancer types (Suzuki et al. 2007; Lee et al. 2010; Mo et al.
363 2012; Yeom et al. 2012). With respect to function, RRAD is a small GTPase reported to
364 negatively regulate L-type calcium channels in the heart, where its deficiency can promote
365 cardiac hypertrophy (Chang et al. 2007; Manning et al. 2013; Meza et al. 2013). In cancer,
366 RRAD has been implicated in numerous processes, including the regulation of glycolysis,
367 proliferation, NF-κB signaling, and apoptosis (Lee et al. 2010; Yeom et al. 2012; Hsiao et al.
368 2014; Zhang et al. 2014; Liu et al. 2015; Shang et al. 2016). Although the exact function of
369 RRAD in TNBC will need to be elucidated in future studies, the vast array of phenotypes
370 associated with this protein undoubtedly reflect the context within which it functions.
371 Ultimately, further investigation could indicate that RRAD itself is a tractable intervention
372 point in TNBC.
373
374 **MATERIAL AND METHODS**
375 **Cell lines and transfections**
376 Cell lines were obtained from American Type Culture Collection (ATCC) except for: WHIM12
377 (Matthew Ellis, Baylor College of Medicine), SUM159 (Asterand), and SUM159T-Luceiferase
378 (Gray Pearson, Georgetown University). All cell lines were cultured in the provider's
379 recommended medium. For siRNA transfections, cells were trypsinized and seeded in Opti-

380 MEM™ containing Lipofectamine RNAiMAX (Thermo Fisher Scientific, Waltham, MA) and
381 pooled siRNAs at a final concentration of 50 nM. cDNA transfections in HEK293T cells were
382 performed using the calcium phosphate method as previously described (Maxfield et al.
383 2015).
384
385 **Antibodies and reagents**
386 The following antibodies were used for immunoblotting: HA (3F10; 1:1000; Roche, Basel,
387 Switzerland), c-Myc (sc-789; 1:1000; Santa Cruz Biotechnology; Dallas, TX), V5 (13202;
388 1:1000; Cell Signaling Technology, Danvers, MA), SMAD3 (ab28379; 1:1000; Abcam,
389 Cambridge, United Kingdom), phospho-SMAD3 (9520, 1:1000; Cell Signaling Technology),
390 SMURF2 (sc-393848; 1:500; Santa Cruz Biotechnology), RRAD (PA537885; 1:1000;
391 Thermo Fisher Scientific), ZNF165 (2B8; 1:1000; Novus Biologicals, Centennial, CO),
392 ZNF165 (HPA007247, 1:1000; Atlas Antibodies, Bromma, Sweden), Tubulin (2128; 1:1000;
393 Cell Signaling Technology), ZNF446 (16218-1-AP; 1:1000; Proteintech, Rosemont, IL),
394 TRIM27 (15099; 1:1000; Cell Signaling Technology). The following antibodies were used for
395 proximity ligation assays: V5 (R960-25; 1:500; Thermo Fisher Scientific), SMAD3 (ab28379;
396 1:200; Abcam), SMAD3 (sc-101154, 1:200; Santa Cruz Biotechnology), SMAD4 (sc-7966;
397 1:200, Santa Cruz Biotechnology), ZNF165 (HPA007247, 1:200; Atlas Antibodies), ZNF446
398 (16218-1-AP; 1:200; Proteintech), TRIM27 (12205-1-AP; 1:200, Proteintech). ChIP-qPCR
399 experiments were performed with 1.5 µg SMAD3 (ab28379; Abcam), 5 µg phospho-SMAD3
400 (9520; Cell Signaling Technology), 2 µg H3K27ac (ab4729; Abcam), or the appropriate
401 amount of normal rabbit IgG (2729; Cell Signaling Technology). ChIP-seq in WHIM12 and
402 SUM159 cells was performed with 10 µg SMAD3 (ab28379; Abcam) or 5 µg V5 (ab9116;
403 Abcam). Immunoprecipitations used for interaction studies were performed with HA (3F10;
404 Roche), V5 (R960-25; Thermo Fisher Scientific), and ZNF165 (HPA007247, 1:200; Atlas
405 Antibodies). IHC was performed using TRIM27 (12205-1-AP; Proteintech) at 1:200.

406 Transforming growth factor-β1 was purchased from Cell Signaling Technology (8915) and
407 SB-431542 was purchased from Tocris Bioscience (Bristol, United Kingdom) (1614). siRNAs
408 targeting ZNF165, SMAD3, ZNF446, TRIM27, SCAND1, ZNF24, ZNF263, or ZKSCAN8, and
409 non-targeting control #2 were obtained from Dharmacon (Lafayette, CO) (siGENOME
410 siRNA). siRNAs targeting RRAD (SASI_Hs01_00221658, SASI_Hs01_00221655,
411 SASI_Hs01_00221652, SASI_Hs01_00221653) and shRNAs targeting TRIM27 (SHCLNG-
412 NM_006510; TRCN0000280319 and TRCN0000011021) or a non-targeting control were
413 purchased from Sigma (St. Louis, MO).
414
415 **Expression plasmids**
416 ZNF165 and ZNF446 cDNA was purchased in pDONR223 vectors from the DNASU Plasmid
417 Repository (Tempe, AZ) and cloned into pLX302-V5 or pLX304-V5 lentiviral vectors,
418 respectively, using the Gateway™ Cloning system (Thermo Fisher Scientific). psPAX2 and
419 pMD2.G were gifts from Didier Trono (Addgene plasmids #12260 and #12259). SMAD3,
420 SMAD4, and TRIM27 cDNA was obtained in pENTR221 vectors from the UT Southwestern
421 (UTSW) McDermott Center for Human Genetics and subcloned into pCMV-HA or pCMV-
422 myc (Clontech, Mountain View, CA) between SalI and NotI restriction sites. pCMV6-ZNF165-
423 myc was obtained from Origene (Rockville, MD) (RC205600). The SCAN domain of pCMV6-
424 ZNF165-myc was deleted using overlap extension PCR and verified by sequencing and
425 western blot (primers listed in Supplementary File 1).
426
427 **Generation of stable cell lines**
428 Stable cell lines were generated through lentiviral-mediated transduction. HEK293T cells
429 were co-transfected with the target gene vectors (pLX302 or pLX304) and lentiviral
430 packaging plasmids (psPAX2 and pMD2.G). Virus conditioned media was collected 48h post
431 transfection and used to infect target cells in the presence of polybrene. Selection with
432 appropriate antibiotics was performed for 3 days following infection to generate stable

433 populations. ZNF165-V5 or ZNF446-V5 expression was confirmed by RT-qPCR, western
434 blotting, and immunofluorescence.
435
436 **Western blotting and gene expression analysis**
437 Western blotting was done as previously described (Maxfield et al. 2015). RNA was isolated
438 using the GenElute™ Mammalian Total RNA Miniprep Kit (Sigma), and 500 ng RNA was
439 reverse transcribed using the High Capacity cDNA Reverse Transcription Kit (Thermo Fisher
440 Scientific) according to manufacturer's instructions. Taqman Real-Time PCR (Thermo Fisher
441 Scientific) gene expression assays were run in technical duplicate to quantify expression on
442 an Applied Biosystems QuantStudio™ 5 Real-Time PCR System. Relative expression
443 values were calculated using the $2^{-\Delta\Delta CT}$ method and the data were normalized to RPL27
444 values. Catalog numbers for Taqman probes can be found in Supplementary File 1.
445
446 **Chromatin immunoprecipitation (ChIP) and sequencing (ChIP-seq)**
447 Cells were grown to ~90% confluency and crosslinked with 1% formaldehyde for 15 minutes
448 at 37°C. Crosslinking was then quenched with 0.125 M glycine for 5 minutes at 4°C. Cells
449 were washed twice with cold PBS and lysed in hypotonic buffer (5 mM PIPES pH 8, 85 mM
450 KCl, 0.5% NP-40, 1 mM DTT). All buffers were supplemented with Complete Protease
451 Inhibitor Cocktail (Sigma). Nuclei were pelleted at 2,000 rpm for 5 minutes and resuspended
452 in lysis buffer containing 50 mM Tris pH 7.9, 1% SDS, 10 mM EDTA, and 1 mM DTT.
453 Chromatin was sheared into 200-400 bp fragments using a Bioruptor sonicator (Diagenode),
454 clarified by centrifugation at max speed for 10 minutes, and diluted (1:10) in buffer containing
455 20 mM Tris pH 7.9, 0.5% Triton X-100, 150 mM NaCl, 2 mM EDTA, and 1 mM DTT. Lysates
456 were pre-cleared with Protein A/G agarose beads (Thermo Fisher Scientific) for 1 hour and,
457 following removal of input material, incubated with appropriate antibodies overnight at 4°C.
458 Protein A/G agarose beads blocked with BSA were then added to lysates for 2 hours,
459 followed by one low salt wash (20 mM Tris pH 7.9, 125 mM NaCl, 0.05% SDS, 1% Triton X-

460 100, 2 mM EDTA), one high salt wash (20 mM Tris pH 7.9, 500 mM NaCl, 0.05% SDS, 1%
461 Triton X-100, 2 mM EDTA), a more stringent wash (10 mM Tris pH 7.9, 250 mM LiCl, 1%
462 NP-40, 1% sodium deoxycholate, 1 mM EDTA), and a final wash in TE buffer (10 mM Tris
463 pH 7.9, 1 mM EDTA). For western blotting of immunoprecipitated proteins, beads were
464 boiled in 2X Laemmli sample buffer (containing 4% β-mercaptoethanol) for 5-10 minutes.
465 Otherwise, chromatin was eluted from beads with 100 mM NaHCO3 and 1% SDS, and de-
466 crosslinking was carried out overnight at 65°C. RNA and protein were digested with RNase
467 A (3 µg/mL) and Proteinase K (50 µg/mL), respectively. DNA was purified using
468 phenol/chloroform/isoamyl alcohol (25:24:1) and precipitated overnight with isopropyl alcohol
469 at -20°C.
470 Libraries of ChIP DNA were prepared using the KAPA Hyper Prep Kit (KAPA Biosystems,
471 Cape Town, South Africa) according to the manufacturer's instructions. Samples were
472 multiplexed with Illumina adapters (NEB, Ipswich, MA) and 75 bp single end reads (~50M
473 per sample) were generated on an Illumina NextSeq 500 (UTSW McDermott Center Next
474 Generation Sequencing Core). Raw reads were aligned to the human genome assembly
475 (hg19) using Bowtie2 (ver 2.3.2) with the "sensitive" parameters enabled, and the mapped
476 read files were sorted and indexed with SAMtools (ver 1.6). BigWig files for visualization on
477 the IGV genome browser (Robinson et al. 2011) were generated using DeepTools (ver
478 2.3.5). ChIP-seq was performed using biological duplicates for each sample. WHIM12
479 ZNF165-V5 ChIP-seq data was previously generated and is available under GEO accession
480 GSE65937. All other ChIP-seq datasets have been deposited under GEO accession
481 GSE130364.
482
483 **ChIP-seq peak calling and annotation**
484 Peaks were called using the HOMER (ver 4.9) findPeaks module with size and minimum
485 distance parameters set to 150 bp and 370 bp, respectively. Target genes for ZNF165,
486 SMAD3, and ZNF446 were defined for each transcription factor using GREAT version 3.0.0

487 (great.stanford.edu) with default parameters. The HOMER mergePeaks module was used to
488 identify overlapping peaks with a size parameter of 1000 bp. Tag density plots were
489 generated using the HOMER annotatePeaks module with size and bin size parameters set
490 to 5000 and 5 bp, respectively. The same module with the genomeOntology parameter
491 enabled was used to annotate the genomic regions associated with each factor. For
492 heatmap generation, the HOMER annotatePeaks module was used to create matrix files,
493 which were clustered with Cluster 3.0 and visualized with Java TreeView (ver 1.1.6r4). To
494 identify motifs enriched at co-bound sites, motif discovery was performed with MEME (ver
495 5.1.1) in "differential enrichment" mode. Motif density plots were generated using the
496 HOMER annotatePeaks module with size and bin size parameters set to 5000 and 5 bp,
497 respectively.
498
499 **ChIP-qPCR**
500 ChIP was performed as described above, and qPCR was carried out using SYBR green
501 reagents in technical duplicates (Thermo Fisher Scientific) on an ABI QuantStudio™ 5 Real-
502 Time PCR System. Three ten-fold dilutions were used to generate standard curves and the
503 amount of ChIP DNA relative to corresponding input values (percent input) was calculated.
504 SMAD3 enrichment was determined relative to IgG percent input values within the same
505 treatment or condition. Primer sequences are listed in Supplementary File 1.
506
507 **Proximity ligation assays**
508 Proximity ligation assays (PLAs) were performed using Duolink® reagents (Sigma)
509 according to manufacturer's instructions. Briefly, cells attached to glass coverslips were fixed
510 with 3.7% formaldehyde for 15 minutes and then permeabilized with 0.5% Triton X-100 for
511 15 minutes. Blocking was performed for 1 hour at 37°C, and cells were incubated with
512 appropriate antibodies overnight at 4°C. After washing, coverslips were incubated with PLUS
513 (rabbit) and MINUS (mouse) secondary probes for 1 hour at 37°C. Ligation was performed

514 for 30 minutes at 37°C, followed by rolling circle amplification for 100 minutes at 37°C.
515 Coverslips were washed, mounted to glass slides in medium containing DAPI, and kept at
516 4°C. Cells were imaged using a Keyence BZ-X710 fluorescence microscope at 100x
517 magnification and 5-10 regions of interest were captured on each coverslip. PLA signals
518 were quantified using ImageJ by counting the average number of foci per nucleus in any
519 given image.
520
521 **Immunoprecipitation**
522 For co-expression/co-immunoprecipitation studies, cells were lysed for 30 minutes on ice in
523 non-denaturing lysis buffer (NDLB) containing 50 mM HEPES pH 7.4, 150 mM NaCl, 1%
524 Triton X-100, 0.5% sodium deoxycholate, 25 mM β-glycerophosphate, 1 mM EDTA, 1 mM
525 EGTA, 1 mM Na3VO4, 1 μg mL^{-1} pepstatin, 2 μg mL^{-1} leupeptin, 2 μg mL^{-1} aprotinin, and 10
526 μM bestatin. Lysates were clarified at 12,000g for 10 minutes and pre-cleared with Protein
527 A/G agarose beads for 1 hour at 4°C. 5% of the lysates were set aside as input material and
528 the remainder was immunoprecipitated with appropriate antibodies for 0.5-4 hours at 4°C.
529 Protein A/G agarose beads blocked with 0.5% BSA were added in the final 30 minutes of
530 immunoprecipitation. Beads were then washed three times in NDLB and once in NDLB
531 containing 500 mM NaCl. For endogenous immunoprecipitation of ZNF165, ~$2x10^8$ cells
532 were collected and lysed in a hypotonic buffer (5 mM PIPES pH 8, 85 mM KCl, 0.5% NP-40)
533 supplemented with Complete Protease Inhibitor Cocktail (Sigma) for 20 minutes. Nuclei were
534 pelleted at 2,000 rpm for 5 minutes and resuspended in RIPA buffer (50 mM HEPES pH 7.4,
535 150 mM NaCl, 1% Triton X-100, 0.5% sodium deoxycholate, 0.5% SDS, 25 mM β-
536 glycerophosphate, 1 mM EDTA, 1 mM EGTA, 1 mM Na3VO4) supplemented with Complete
537 Protease Inhibitor Cocktail. Nuclear lysis was facilitated by gentle agitation at 4°C with
538 intermittent sonication (5-10 pulses at 5 seconds each). Lysates were clarified at 16,000g for
539 10 minutes, concentrated to a volume of 1-2 mL, and pre-cleared with Protein A/G agarose
540 beads for 1 hour at 4°C. 5% of the lysates were set aside as input material and the

541 remainder was subjected to immunoprecipitation overnight at 4°C. The next day, Protein A/G
542 agarose beads blocked with BSA were added to lysates for 2 hours, followed by four washes
543 in a buffer containing 50 mM HEPES pH 7.4, 150 mM NaCl, 1% Triton X-100, 25 mM β-
544 glycerophosphate, 1 mM EDTA, 1 mM EGTA, 1 mM Na3VO4, and Complete Protease
545 Inhibitor Cocktail. Immunoprecipitated proteins were eluted in 2X Laemmli sample buffer
546 (containing 4% β-mercaptoethanol) by boiling for 5-10 minutes.
547
548 **Soft agar assays**
549 4 X 10^3 SUM159 or MCF7 cells were trypsinized, counted, and resuspended in 0.366%
550 Bacto agar in complete medium and seeded on a layer of solidified 0.5% Bacto agar in 6-
551 well plates 48 hours post-transfection. After solidification, another layer of complete medium
552 containing 2X FBS was added. Cells were grown for 14 days (fed every 3 days) and then
553 stained with 0.05% crystal violet in phosphate-buffered saline (PBS) overnight. Images were
554 taken using a LEICA MZ75 stereomicroscope at a magnification of 6.3X and colony number
555 was quantified using ImageJ software.
556
557 **Tumor expression and patient survival analysis**
558 Normal/tumor expression data for ZNF446 and TRIM27 was generated by the TCGA
559 Research Network (https://www.cancer.gov/tcga) and visualized with Oncomine and
560 UALCAN, respectively (Rhodes et al. 2004; Chandrashekar et al. 2017). Survival analysis
561 was performed using Kaplan Meier plotter (Gyorffy et al. 2010). Hazard ratios and p-values
562 were calculated using the logrank test.
563
564 **Human breast tissue immunohistochemistry (IHC)**
565 Normal breast and TNBC tissues were obtained with informed consent from the UTSW
566 Tissue Management Shared Resource (TMSR) in compliance with the UTSW Internal
567 Review Board committee. TRIM27 IHC was optimized and performed by the TMSR

568 according to internal protocols using the Dako Autostainer Link 48 system. Quantification of
569 nuclear TRIM27 signal was performed using IHC Profiler (ImageJ) according to the
570 developer's guidelines (Varghese et al. 2014).
571
572 **Orthotopic xenografts**
573 SUM159T-Luciferase cells ($5x10^5$) stably expressing TRIM27 shRNAs or a non-targeting
574 hairpin were injected in the mammary fat pad of 10-week old female NOD.Cg-*Prkdc*^{scid}
575 *Il2rg*^{tm1Wjl}/SzJ (NSG) mice obtained from the Jackson Laboratory as previously described
576 (Westcott et al. 2015). Ten mice were injected per group. Tumors were measured weekly
577 using a digital caliper and volume (V) was calculated using the following formula: V =
578 (Length x Width x Width)/2. Starting four weeks post injection, tumors were measured
579 weekly with bioluminescent imaging (BLI). At six weeks post injection, mice were sacrificed
580 after obtaining final BLI measurements. These studies were conducted in accordance with a
581 UT Southwestern Institutional Animal Care and Use Committee (IACUC) approved protocol.
582
583 **Statistical analysis**
584 Graphpad Prism (Graphpad Software) was used to perform statistical analyses. Data were
585 assessed by one or two-tailed, unpaired t-tests or Mann-Whitney, or hypergeometric
586 distribution. P-values less than 0.05 were considered significant. Biological replicates were
587 considered to be experiments performed on distinct samples, while technical replicates were
588 considered identical samples run in parallel.
589
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599

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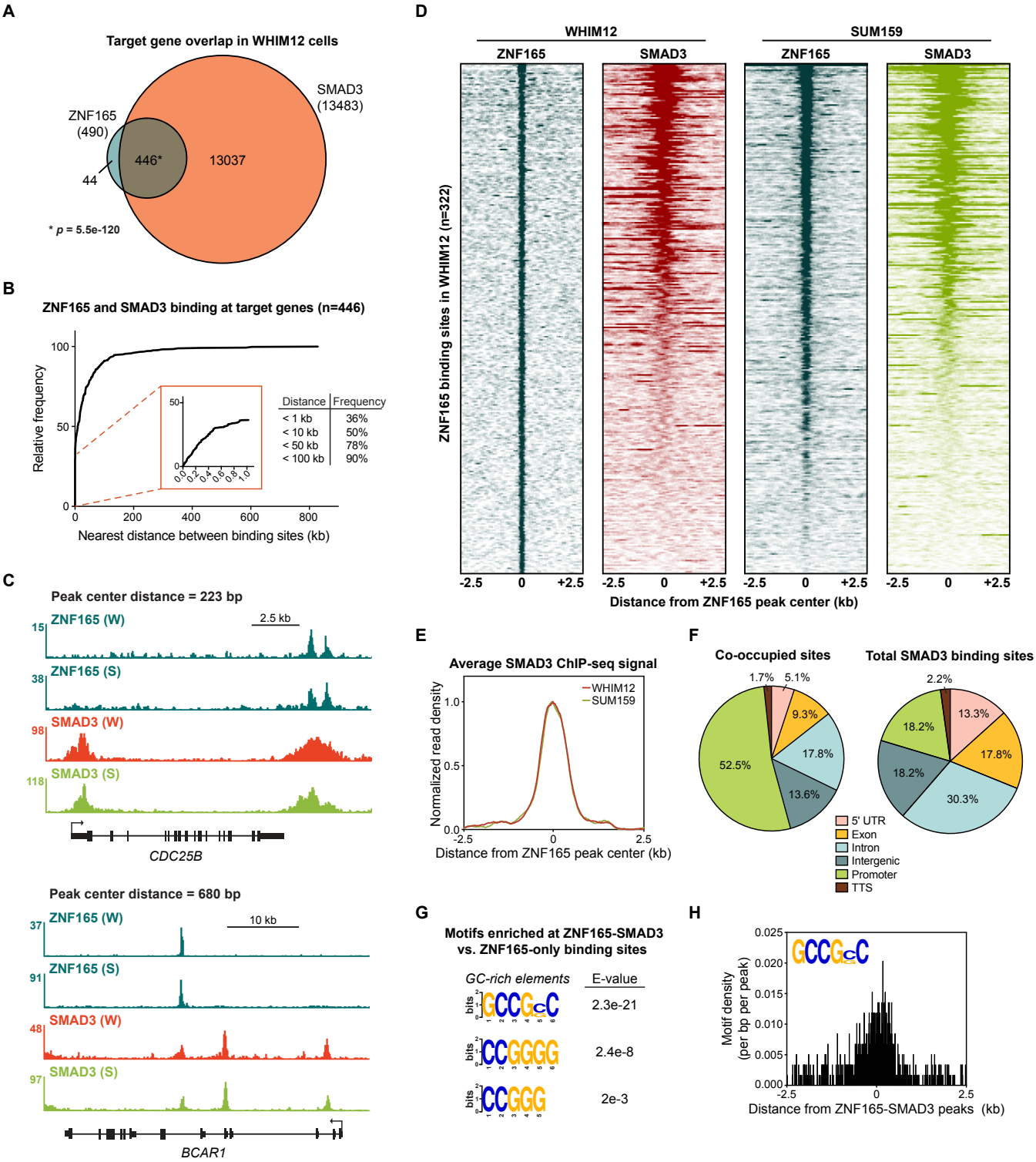


Figure 1. SMAD3 is enriched at ZNF165 binding sites in TNBC cells. (A) Venn diagram displaying the overlap between ZNF165 and SMAD3 target genes in WHIM12 cells as identified by GREAT (ver 3.0.0). Significance was determined using the hypergeometric distribution. (B) Cumulative frequency distribution of the nearest distance between ZNF165 and SMAD3 binding sites associated with each shared target gene. Distance was calculated using the peak coordinates of each factor nearest to one another. (C) Browser tracks of ChIP-seq data showing peaks for ZNF165 and SMAD3 near the *CDC25B* and *BCAR1* loci with overlapping distances of 223 and 680 bp, respectively. (W) WHIM12, (S) SUM159. (D) Heatmaps of ChIP-seq data for ZNF165 and SMAD3 in the indicated TNBC cell lines. All peaks within each heatmap are centered ± 2.5 kb from the ZNF165 peaks identified in WHIM12 cells (n=322). (E) Normalized read density (per bp per peak) for SMAD3 plotted ± 2.5 kb from the ZNF165-SMAD3 co-bound peaks identified in WHIM12 cells (n=118). (F) Pie charts displaying the distribution of genomic features bound by ZNF165-SMAD3 or only SMAD3 in WHIM12 cells. (G) Motifs enriched at ZNF165-SMAD3 co-bound sites within WHIM12 cells. The 204 ZNF165 binding sites not occupied by SMAD3 were used as a control set of sequences to identify differentially enriched motifs at the shared sites (n=118). (H) Motif density (per bp per peak) for the GCCG(G|C)C motif plotted ± 2.5 kb from the centers of ZNF165-SMAD3 co-bound peaks in WHIM12 cells.

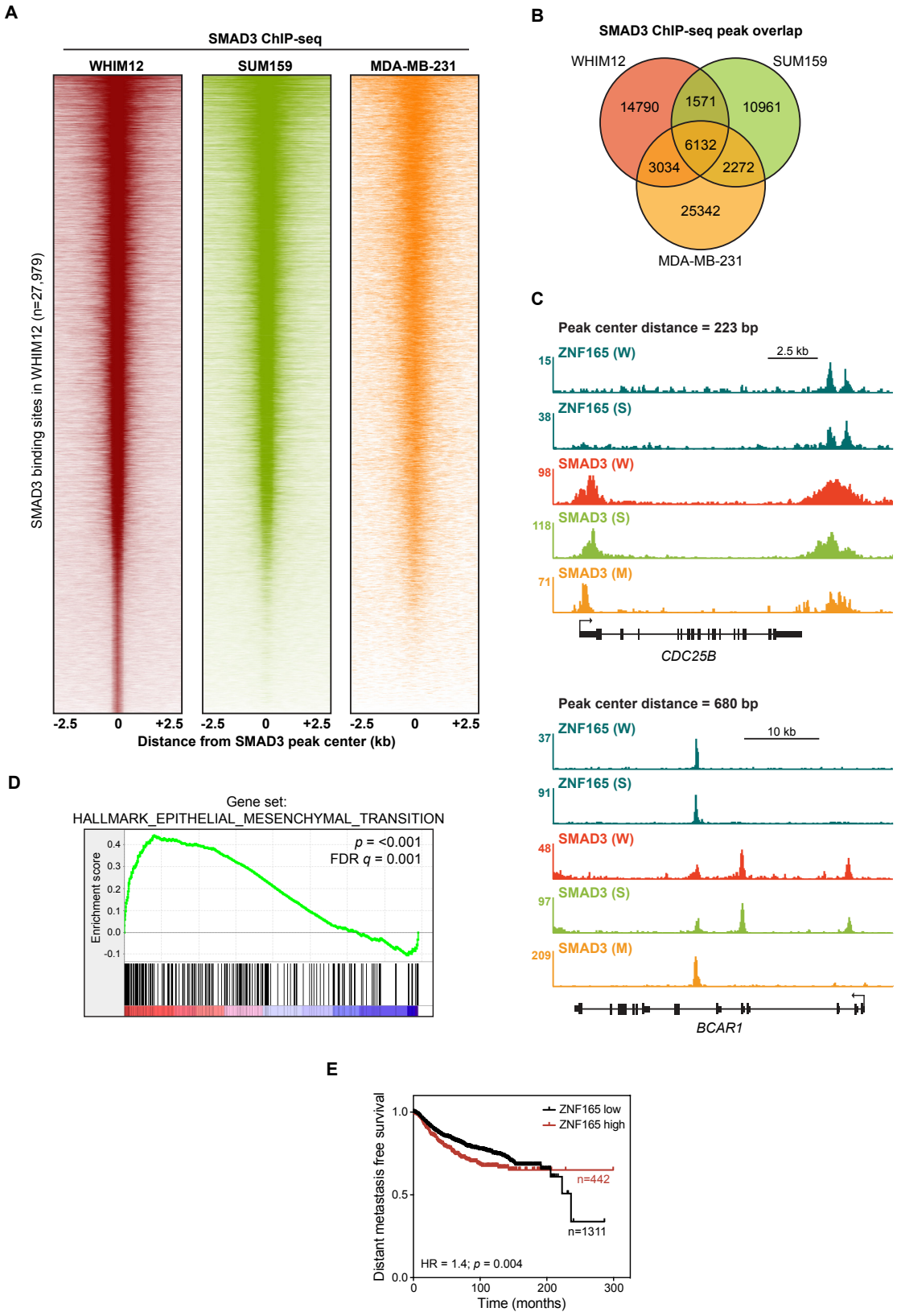


Figure 1-figure supplement 1. SMAD3 is enriched at ZNF165 binding sites in TNBC cells. (A) Heatmaps of SMAD3 ChIP-seq data in WHIM12, SUM159, and MDA-MB-231 cells. All peaks within each heatmap are centered ± 2.5 kb from the SMAD3 peaks identified in WHIM12 cells (n=27,979). Data for MDA-MB-231 cells were obtained from EGAS00001001570 (Tufegdzic Vidakovic et al. 2015). (B) Venn diagram displaying the overlap between SMAD3 peaks identified in each cell line. (C) Browser tracks of ChIP-seq data showing peaks for ZNF165 and SMAD3 near the *CDC25B* and *BCAR1* loci with overlapping distances of 223 and 680 bp, respectively. (W) WHIM12, (S) SUM159, (M) MDA-MB-231. (D) Gene set enrichment analysis (GSEA) of ZNF165-responsive genes in WHIM12 cells. Transcriptome data for ZNF165 knockdown was obtained from GSE63984 (Maxfield et al. 2015). (E) Kaplan-Meier plot displaying distant metastasis free survival in breast cancer patients with high or low ZNF165 expression. P-value and hazard ratio (HR) were calculated using the logrank test.

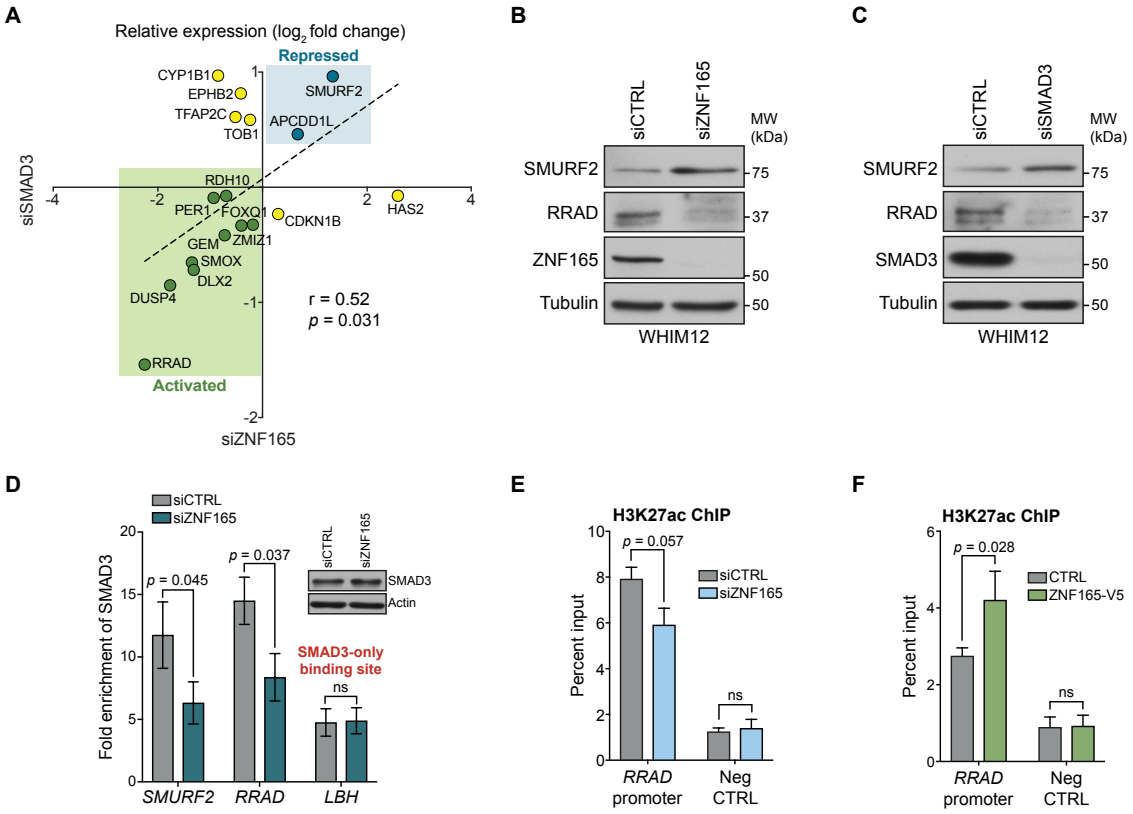
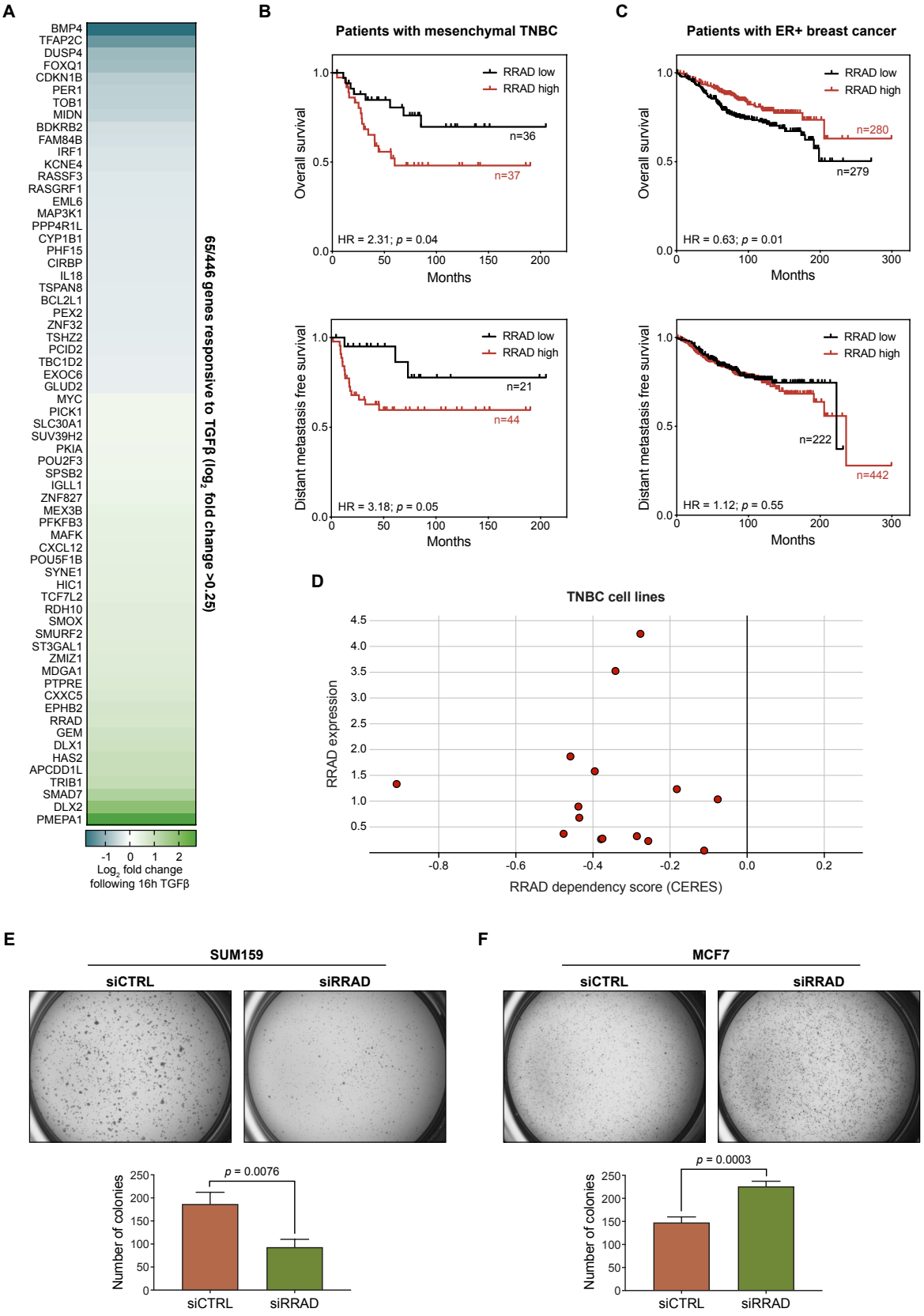


Figure 2. ZNF165 and SMAD3 cooperate to modulate TGFβ-responsive gene expression. (A) WHIM12 cells were transfected with siRNA for 48h, and qPCR was used to quantify relative expression ($\log_2$ fold change) of ZNF165-SMAD3 target genes upon depletion of ZNF165 (x-axis) or SMAD3 (y-axis). The Pearson correlation coefficient is indicated by r. Data are representative of four independent experiments. (B) WHIM12 cells were transfected with siRNA for 72h. Whole cell lysates were collected and immunoblotted for the indicated proteins. Data are representative of two independent experiments. (C) As in (B) except cells were transfected with siRNA targeting SMAD3. (D) SUM159 cells were transfected with siRNA for 32h and subjected to SMAD3 ChIP followed by qPCR using primers targeting the indicated binding sites. Fold enrichment was determined by dividing the percent input values for SMAD3 by those for IgG. Error bars represent mean ± SEM. P-values were calculated using an unpaired, two-tailed Student's t-test. Data are representative of four independent experiments. (E) SUM159 cells were transfected with siRNA for 32h and subjected to H3K27ac ChIP followed by qPCR using primers targeted to the RRAD promoter or a negative control region. Error bars represent mean + SEM. P-value was calculated using an unpaired, two-tailed Mann-Whitney test. Data are representative of four independent experiments. (F) SUM159 cells stably expressing ZNF165-V5 or control cDNA were subjected to H3K27ac ChIP followed by qPCR using primers targeted to the RRAD promoter or a negative control region. Error bars represent mean + SEM. P-value was calculated using an unpaired, two-tailed Mann-Whitney test. Data are representative of four independent experiments.

Figure 2-figure supplement 1. ZNF165 and SMAD3 activate *RRAD* to drive neoplastic behaviors in TNBC. (A) Heatmap plotting the $\log_2$ fold-change in expression of 65/446 shared ZNF165-SMAD3 target genes (cutoff > 0.25) following TGFβ exposure in WHIM12 cells. Expression data were obtained from GSE63986 (Maxfield et al. 2015). (B) Kaplan-Meier plots displaying overall survival and distant metastasis free survival (DMFS) for patients with the mesenchymal subtype of TNBC and high or low RRAD expression. P-values and hazard ratios (HRs) were calculated using the logrank test. (C) As in (B) except for patients with ER^+ breast cancer. (D) TNBC cell line dependency scores calculated from CRISPR-mediated perturbation (as determined by CERES) plotted against RRAD expression (log2(TPM+1)) (Barretina et al. 2012; Meyers et al. 2017). Negative dependency scores represent a decrease in viability. Data were obtained from the Cancer Dependency Map (depmap.org). (E) Soft agar growth assays for SUM159 cells transfected with indicated siRNAs. Error bars represent mean + SEM. P-value was calculated using an unpaired, two-tailed Student's t-test. Data are representative of three independent experiments. (F) As in (E) except using MCF7 cells.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FOXQ1
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MIDN
BDKRB2
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RASSF3
RASGRF1
EML6
MAP3K1
PPP4R1L
CYP1B1
PHF15
CIRBP
IL18
TSPAN8
BCL2L1
PEX2
ZNF32
TSHZ2
PCID2
TBC1D2
EXOC6
GLUD2
MYC
PICK1
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SPSB2
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ZNF827
MEX3B
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MAFK
CXCL12
POU5F1B
SYNE1
HIC1
TCF7L2
RDH10
SMOX
SMURF2
ST3GAL1
ZMIZ1
MDGA1
PTPRE
CXXC5
EPHB2
RRAD
GEM
DLX1
HAS2
APCDD1L
TRIB1
SMAD7
DLX2
PMEPA1
65/446 genes responsive to TGFβ (log2 fold change >0.25)
-1 0 1 2
Log2 fold change following 16h TGFβ
B
Patients with mesenchymal TNBC
RRAD low
RRAD high
n=36
n=37
HR = 2.31; p = 0.04
Overall survival
Months
n=21
n=44
HR = 3.18; p = 0.05
Distant metastasis free survival
C
Patients with ER+ breast cancer
n=280
n=279
HR = 0.63; p = 0.01
n=222
n=442
HR = 1.12; p = 0.55
D
TNBC cell lines
RRAD expression
RRAD dependency score (CERES)
E
SUM159
siCTRL
siRRAD
p = 0.0076
Number of colonies
F
MCF7
p = 0.0003

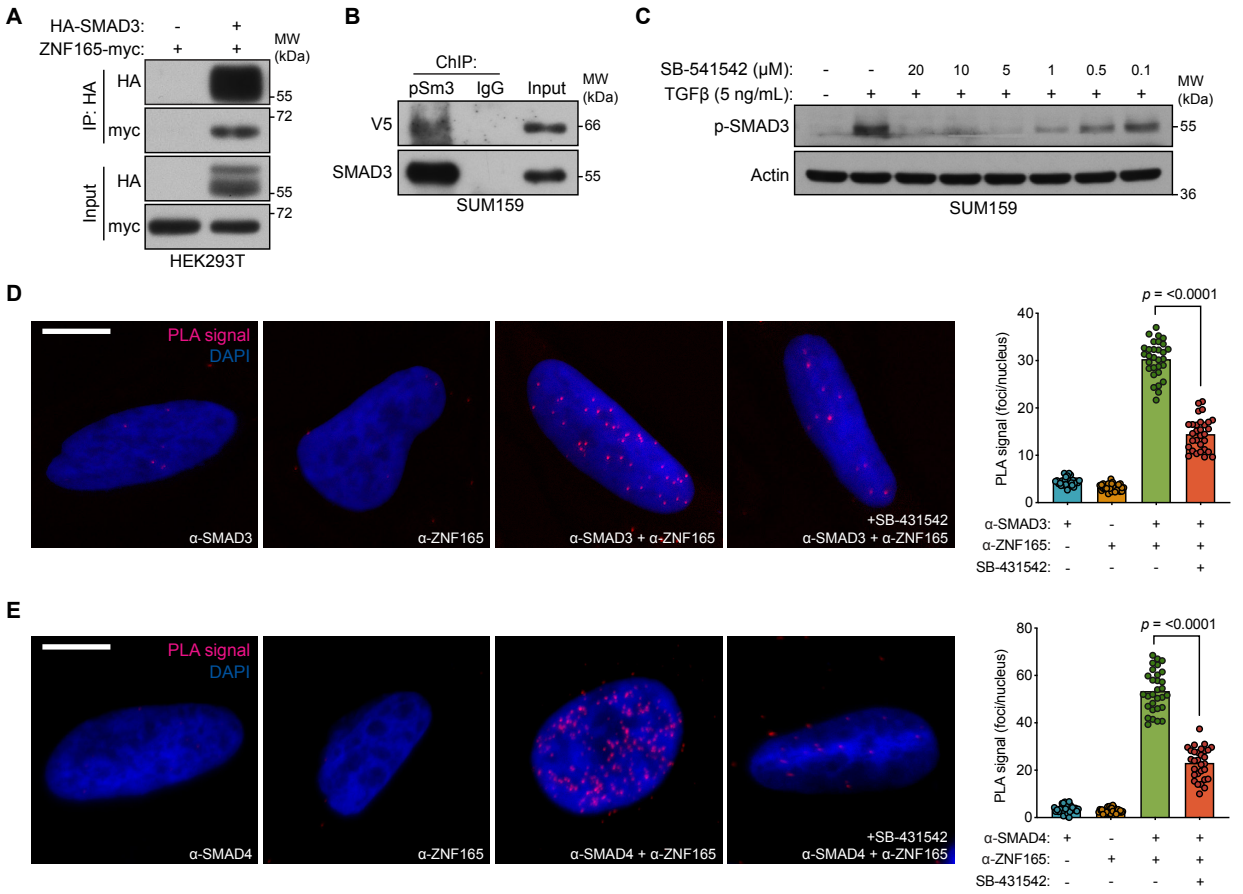


Figure 3. ZNF165 physically associates with SMAD3 in a TGFβ-dependent manner. (A) Forty-eight hours after transfection with HA-SMAD3 and/or ZNF165-myc cDNA, HEK293T cells were subjected to immunoprecipitation with HA antibody. Immunoblotting was performed with indicated antibodies. Data are representative of two independent experiments. (B) ChIP was performed in SUM159 cells with antibodies against phosphorylated SMAD3 (Ser423/425) or IgG, and the precipitated material was immunoblotted with indicated antibodies. Data are representative of two independent experiments. (C) SUM159 cells were pre-treated with SB-431542 at the indicated concentrations for 15 minutes, followed by stimulation with 5 ng mL^{-1} TGFβ for 30 minutes. Immunoblotting was performed with indicated antibodies. Data are representative of two independent experiments. (D) Proximity ligation assays (PLAs) performed using antibodies against endogenous ZNF165 and SMAD3 in SUM159 cells, where either antibody alone was used as a negative control. Cells were pre-treated with 20 μM SB-431542 or DMSO for 15 minutes, followed by stimulation with 5 ng mL^{-1} TGFβ for 30 minutes. Scale bars, 10 μm. The mean PLA signal (number of foci per nucleus) is quantified (right), where each data point represents the mean signal calculated within one image. P-value was calculated using an unpaired, two-tailed Student's t-test. Ten images were used per condition and data are representative of three independent assays. (E) As in (D) except antibodies against endogenous ZNF165 and SMAD4 were used.

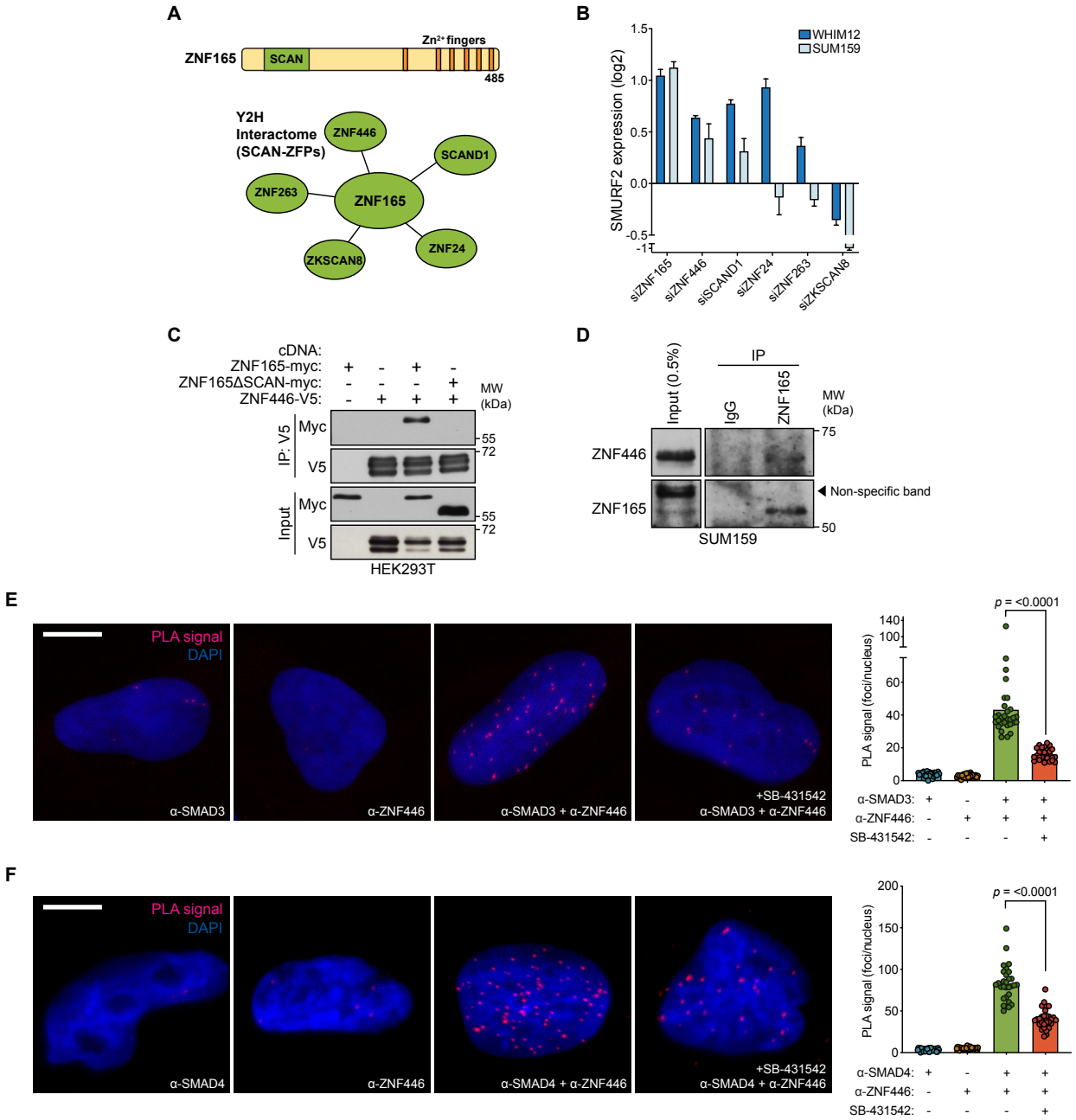


Figure 4. ZNF446 is an obligate component of the ZNF165-SMAD3 transcriptional complex. (A) ZNF165 interactors that contain a SCAN domain as identified from a systematic yeast two-hybrid screening approach (interactome.dfci.harvard.edu). A domain map of ZNF165 is shown above for reference. (B) Forty-eight hours after transfection with indicated siRNAs, RNA was extracted from WHIM12 or SUM159 cells and qPCR was used to determine the relative expression of SMURF2. Log_2 fold-change values normalized to control knockdown samples are displayed. Error bars represent mean + SEM. P-values were calculated for each sample using a one-tailed Mann-Whitney test. Data are representative of three independent experiments. (C) Forty-eight hours after transfection with indicated cDNA, HEK293T lysates were subjected to immunoprecipitation with V5 antibody. Immunoblotting was performed with indicated antibodies. Data are representative of three independent experiments. (D) SUM159 nuclear lysates were immunoprecipated with antibodies against endogenous ZNF165 or IgG. Immunoblotting was performed with indicated antibodies. (E) Proximity ligation assays (PLAs) performed using antibodies against endogenous ZNF446 and SMAD3 in SUM159 cells, where either antibody alone was used as a negative control. Cells were pre-treated with 20 μM SB-431542 or DMSO for 15 minutes, followed by stimulation with 5 ng mL^{-1} TGFβ for 30 minutes. Scale bars, 10 μm. The mean PLA signal (number of foci per nucleus) is quantified (right), where each data point represents the mean signal calculated within one image. P-value was calculated using an unpaired, two-tailed Student's t-test. Ten images were used per condition and data are representative of three independent assays. (F) As in (E) except antibodies against endogenous ZNF446 and SMAD4 were used.

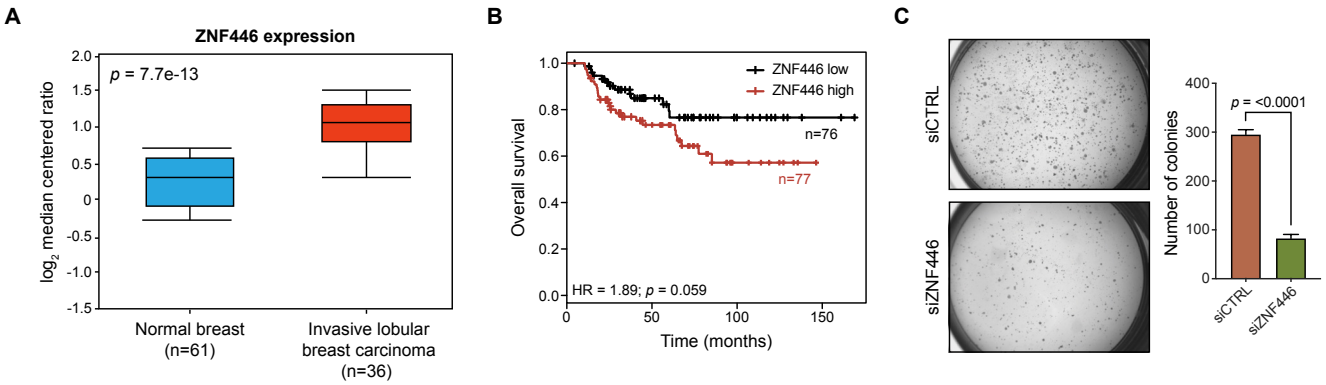
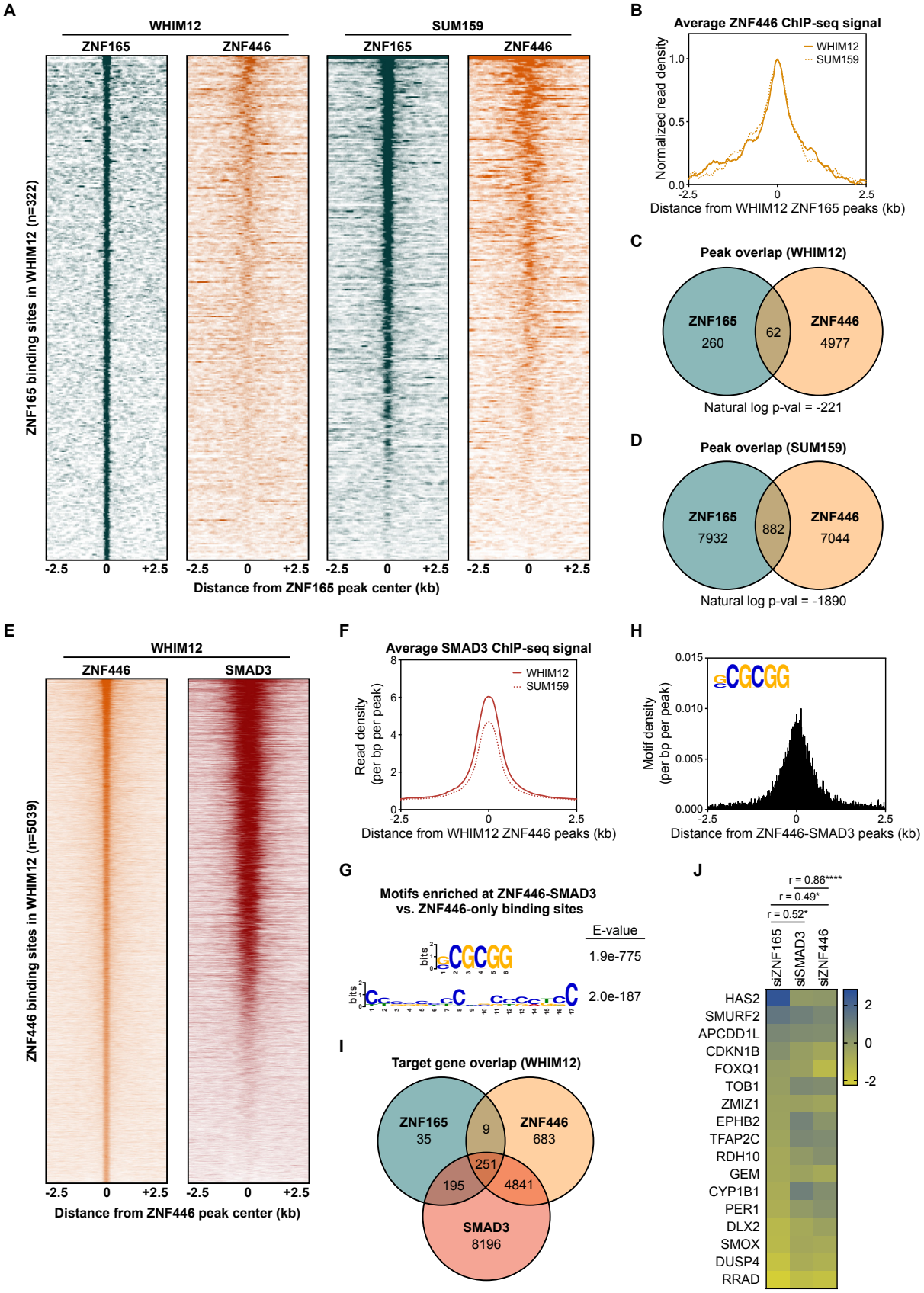


Figure 4-figure supplement 1. ZNF446 expression is elevated in breast cancer and associated with poor prognosis. (A) Box-plot showing ZNF446 expression values (log_2 median centered ratio) from normal breast and invasive lobular breast carcinoma. Data were obtained from TCGA and p-value was calculated using an unpaired, two-tailed Student's t-test. (B) Kaplan-Meier plot displaying overall survival of patients with the basal-like subtype of breast cancer and either low or high ZNF446 expression. P-value and hazard ratio (HR) were calculated using the logrank test. (C) Soft agar growth assays for SUM159 cells transfected with indicated siRNAs. Error bars represent mean + SEM. P-value was calculated using an unpaired, two-tailed Student's t-test. Data are representative of three independent experiments.

Figure 5. ZNF446 co-occupies a subset of both ZNF165 and SMAD3 binding sites in TNBC cells. (A) Heatmaps of ChIP-seq data for ZNF165 and ZNF446 in the indicated TNBC cell lines. All peaks within each heatmap are centered ± 2.5 kb from the WHIM12 ZNF165 peaks (n=322). (B) Normalized read density (per bp per peak) for ZNF446 plotted ± 2.5 kb from the ZNF165 peaks identified in WHIM12 cells (n=322). (C) Peak overlap between ZNF165 and ZNF446 in WHIM12 cells. P-value was calculated using the hypergeometric distribution. (D) As in (C) except using peaks identified for ZNF165 and ZNF446 in SUM159 cells. (E) Heatmaps of ChIP-seq data for ZNF446 and SMAD3 in WHIM12 cells. All peaks within each heatmap are centered ± 2.5 kb from the ZNF446 peaks (n=5,039). (F) Read density (per bp per peak) for SMAD3 plotted ± 2.5 kb from the ZNF446 peaks identified in WHIM12 cells (n=5,039). (G) Motifs enriched at ZNF446-SMAD3 co-bound sites within WHIM12 cells. The ZNF446 binding sites not occupied by SMAD3 (n=2,587) were used as a control set of sequences to identify differentially enriched motifs at the shared sites (n=2,376). (H) Motif density (per bp per peak) for the (G|C)CGCGG motif plotted ± 2.5 kb from the centers of ZNF446-SMAD3 co-bound peaks in WHIM12 cells. (I) Venn diagram displaying the overlap between ZNF165, SMAD3, and ZNF446 target genes from WHIM12 cells as identified by GREAT (ver 3.0.0). (J) Heatmap displaying log_2 fold-changes of ZNF165-SMAD3 targets in response to depletion of ZNF446, as well as either ZNF165 or SMAD3. The Pearson correlation coefficient is indicated by r. Significance is indicated by asterisks, where * = p < 0.05 and **** = p < 0.0001. Data are representative of four independent experiments.


A
WHIM12
SUM159
ZNF165
ZNF446
ZNF165
ZNF446
ZNF165 binding sites in WHIM12 (n=322)
-2.5
0
+2.5
Distance from ZNF165 peak center (kb)
B
Average ZNF446 ChIP-seq signal
WHIM12
SUM159
Normalized read density
Distance from WHIM12 ZNF165 peaks (kb)
C
Peak overlap (WHIM12)
ZNF165
260
62
ZNF446
4977
Natural log p-val = -221
D
Peak overlap (SUM159)
ZNF165
7932
882
ZNF446
7044
Natural log p-val = -1890
E
WHIM12
ZNF446
SMAD3
ZNF446 binding sites in WHIM12 (n=5039)
Distance from ZNF446 peak center (kb)
F
Average SMAD3 ChIP-seq signal
WHIM12
SUM159
Read density
(per bp per peak)
Distance from WHIM12 ZNF446 peaks (kb)
G
Motifs enriched at ZNF446-SMAD3
vs. ZNF446-only binding sites
E-value
1.9e-775
2.0e-187
H
Motif density
(per bp per peak)
Distance from ZNF446-SMAD3 peaks (kb)
I
Target gene overlap (WHIM12)
ZNF165
35
9
ZNF446
683
251
195
4841
SMAD3
8196
J
r = 0.86****
r = 0.49*
r = 0.52*
siZNF165
siSMAD3
siZNF446
HAS2
SMURF2
APCDD1L
CDKN1B
FOXQ1
TOB1
ZMIZ1
EPHB2
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CYP1B1
PER1
DLX2
SMOX
DUSP4
RRAD

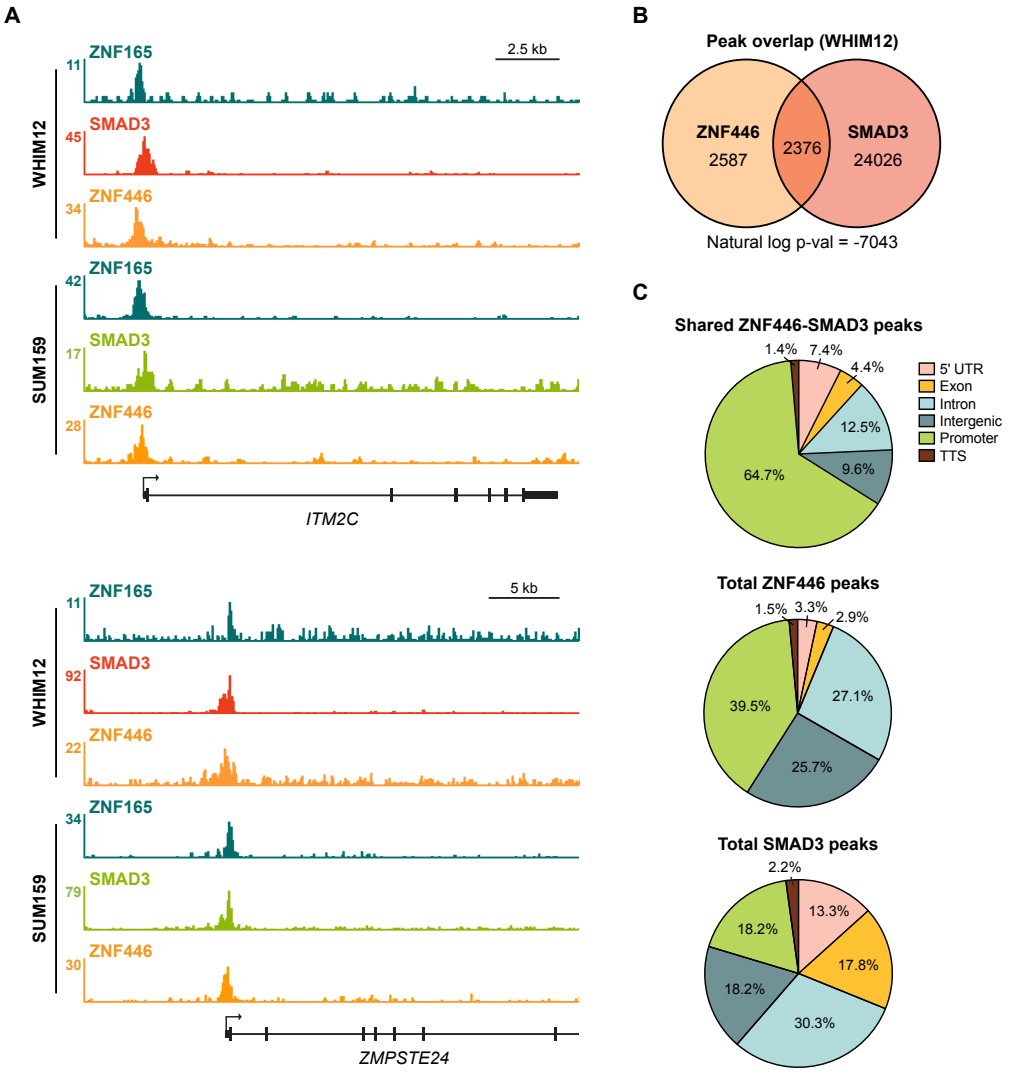
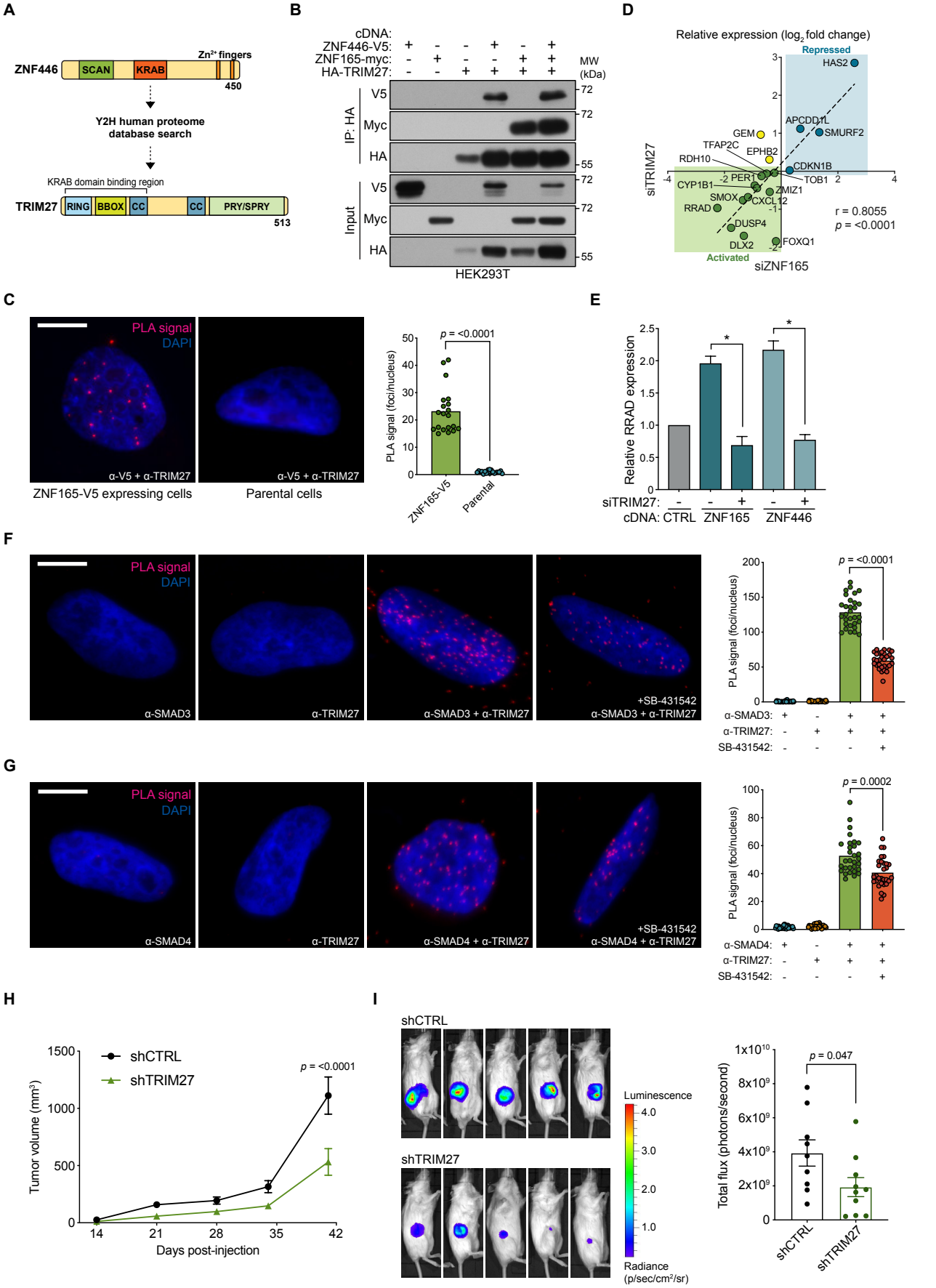


Figure 5-figure supplement 1. ZNF446 co-occupies a subset of both ZNF165 and SMAD3 binding sites in TNBC cells. (A) Browser tracks of ChIP-seq data showing peaks for ZNF165, SMAD3, and ZNF446 near the *ITM2C* and *ZMPSTE24* loci in WHIM12 or SUM159 cells. (B) Peak overlap between ZNF446 and SMAD3 in WHIM12 cells. P-value was calculated using the hypergeometric distribution. (C) Pie charts displaying the distribution of genomic features bound by ZNF446-SMAD3 or either transcription factor alone in WHIM12 cells.

Figure 6. TRIM27 is essential for ZNF165 transcriptional activity and tumor growth *in vivo*. (A) Cartoon maps showing the domains of ZNF446 and TRIM27. The KRAB-binding domain of TRIM27 is highlighted for reference. (B) Forty-eight hours after transfection with indicated cDNA, HEK293T lysates were subjected to immunoprecipitation with HA antibody. Immunoblotting was performed using indicated antibodies. Data are representative of three independent experiments. (C) Proximity ligation assays (PLAs) performed using V5 and TRIM27 antibodies in SUM159 cells stably expressing ZNF165-V5. Parental SUM159 cells were used as a negative control with the V5/TRIM27 antibody combination. Cells were stimulated with 5 ng mL^{-1} TGFβ for 30 minutes. Scale bar, 10 μm. The mean PLA signal (number of foci per nucleus) is quantified (right), where each data point represents the mean signal calculated within one image. P-values were calculated using an unpaired, two-tailed Student's t-test. Five images were used per condition and data are representative of four independent assays. (D) WHIM12 cells were transfected with siRNA for 48h and qPCR was used to quantify relative expression (log_2 fold change) of shared ZNF165-SMAD3 target genes upon depletion of ZNF165 (x-axis) or TRIM27 (y-axis). The Pearson correlation coefficient is indicated by r. Data are representative of three independent experiments. (E) SUM159 cells stably expressing indicated cDNA were transfected with siRNA targeting TRIM27 for 48h. Relative RRAD expression was measured using qPCR and the data were normalized to the CTRL sample (grey). Error bars represent mean + SEM. P-values were calculated using an unpaired, two-tailed Mann-Whitney test. Significance is indicated by asterisks, where * = $p < 0.05$. Data are representative of four independent experiments. (F) PLAs performed using antibodies against endogenous TRIM27 and SMAD3 in SUM159 cells, where either antibody alone was used as a negative control. Cells were pre-treated with 20 μM SB-431542 or DMSO for 15 minutes, followed by stimulation with 5 ng mL^{-1} TGFβ for 30 minutes. Scale bar, 10 μm. The mean PLA signal (number of foci per nucleus) is quantified (right), where each data point represents the mean signal calculated within one image. P-value was calculated using an unpaired, two-tailed Student's t-test. Ten images were used per condition and data are representative of three independent assays. (G) As in (F) except antibodies against endogenous TRIM27 and SMAD4 were used. (H) Tumor volumes from mice orthotopically injected with SUM159T-Luciferase cells stably expressing shRNAs against TRIM27 (n=10) or a non-targeting control (n=9). P-value was calculated using an unpaired, two-tailed Student's t-test. (I) Representative images of bioluminescence (BLI) measurements taken for mice from each group. BLI data was quantified (right) and the p-value was calculated using an unpaired, two-tailed Student's t-test.


A
ZNF446
SCAN
KRAB
Zn2+ fingers
450
Y2H human proteome database search
KRAB domain binding region
TRIM27
RING
BBOX
CC
CC
PRY/SPRY
513
B
cDNA:
ZNF446-V5:
ZNF165-myc:
HA-TRIM27:
MW (kDa)
IP: HA
Input
V5
Myc
HA
72
55
HEK293T
D
Relative expression (log2 fold change)
Repressed
Activated
HAS2
APCDD1L
SMURF2
GEM
TFAP2C
EPHB2
RDH10
CDKN1B
TOB1
PER1
CYP1B1
ZMIZ1
SMOX
CXCL12
RRAD
DUSP4
DLX2
FOXQ1
siTRIM27
siZNF165
r = 0.8055
p = <0.0001
C
PLA signal
DAPI
α-V5 + α-TRIM27
ZNF165-V5 expressing cells
Parental cells
p = <0.0001
PLA signal (foci/nucleus)
ZNF165-V5
Parental
E
Relative RRAD expression
siTRIM27:
cDNA: CTRL ZNF165 ZNF446
F
α-SMAD3
α-TRIM27
α-SMAD3 + α-TRIM27
+SB-431542
α-SMAD3 + α-TRIM27
p = <0.0001
PLA signal (foci/nucleus)
α-SMAD3:
α-TRIM27:
SB-431542:
G
α-SMAD4
α-TRIM27
α-SMAD4 + α-TRIM27
+SB-431542
α-SMAD4 + α-TRIM27
p = 0.0002
PLA signal (foci/nucleus)
α-SMAD4:
α-TRIM27:
SB-431542:
H
shCTRL
shTRIM27
p = <0.0001
Tumor volume (mm3)
Days post-injection
I
shCTRL
shTRIM27
Luminescence
Radiance (p/sec/cm2/sr)
p = 0.047
Total flux (photons/second)
shCTRL
shTRIM27

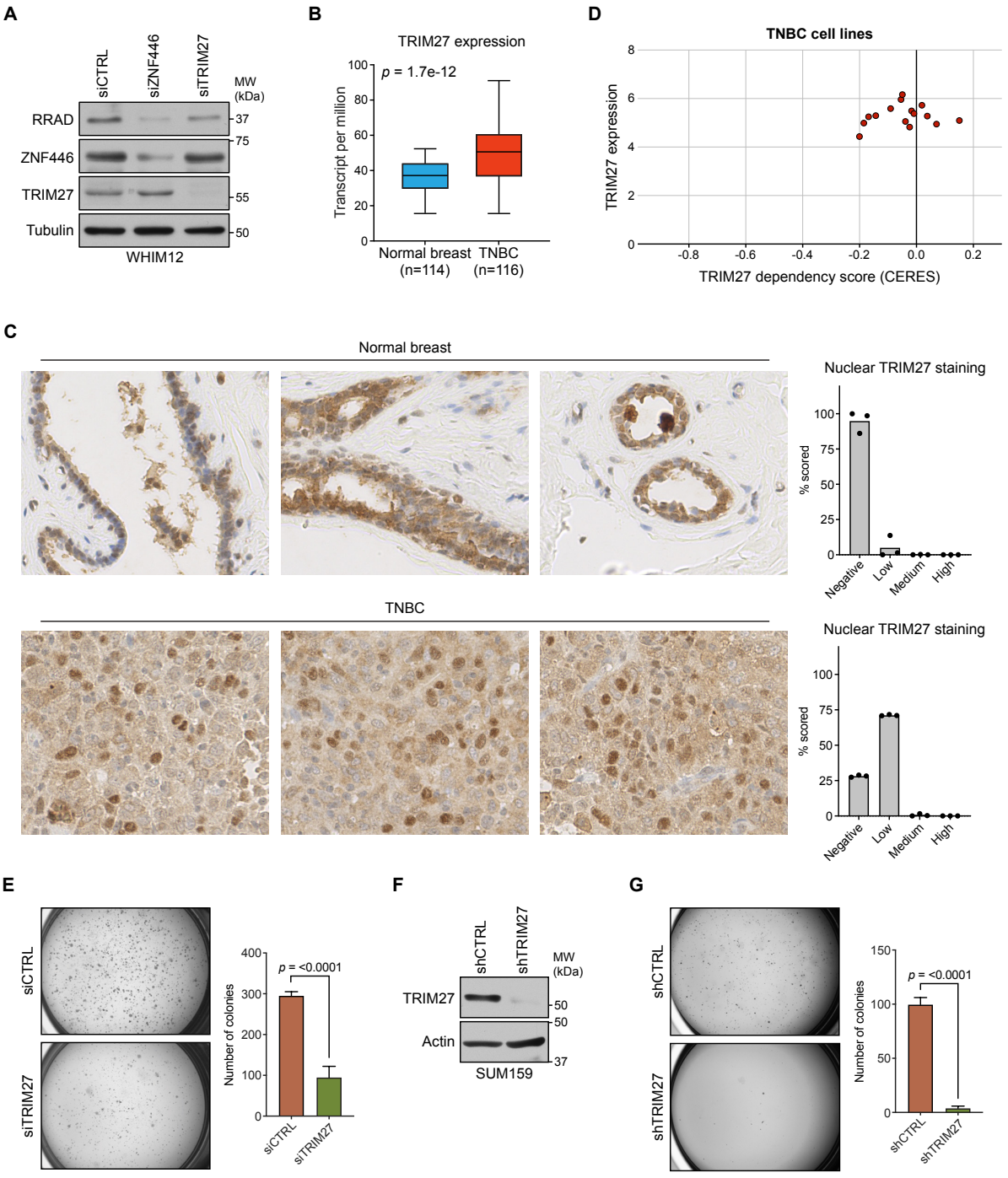


Figure 6-figure supplement 1. Analysis of TRIM27 expression and contribution to neoplastic behaviors in TNBC. (A) WHIM12 cells were transfected with indicated siRNA for 72h. Whole cell lysates were collected and immunoblotted for the indicated proteins. Data are representative of two independent experiments. (B) Box-plot showing TRIM27 expression values (transcript per million) from normal breast and TNBC. Data were obtained from TCGA and the p-value was calculated using an unpaired, two-tailed Student's t-test. (C) Immunohistochemistry (IHC) staining for TRIM27 in patient-derived normal breast and TNBC tissues. Nuclear staining was scored (right) using IHC Profiler (Varghese et al. 2014). (D) TNBC cell line dependency scores calculated from CRISPR-mediated perturbation (as determined by CERES) plotted against TRIM27 expression (log2(TPM+1)) (Barretina et al. 2012; Meyers et al. 2017). Negative or positive dependency scores represent a decrease or increase in viability, respectively. Data were obtained from the Cancer Dependency Map (depmap.org). (E) Soft agar growth assays for SUM159 cells transfected with indicated siRNAs. Error bars represent mean + SEM. P-value was calculated using an unpaired, two-tailed Student's t-test. Data are representative of three independent experiments. (F) SUM159T-Luciferase cells were transduced with indicated shRNAs. After 72h, whole cell lysates were collected and immunoblotted for the indicated proteins. Data are representative of two independent experiments. (G) Soft agar growth assays for SUM159T-Luciferase cells transduced with indicated shRNAs. Error bars represent mean + SEM. P-value was calculated using an unpaired, two-tailed Student's t-test. Data are representative of three independent experiments.

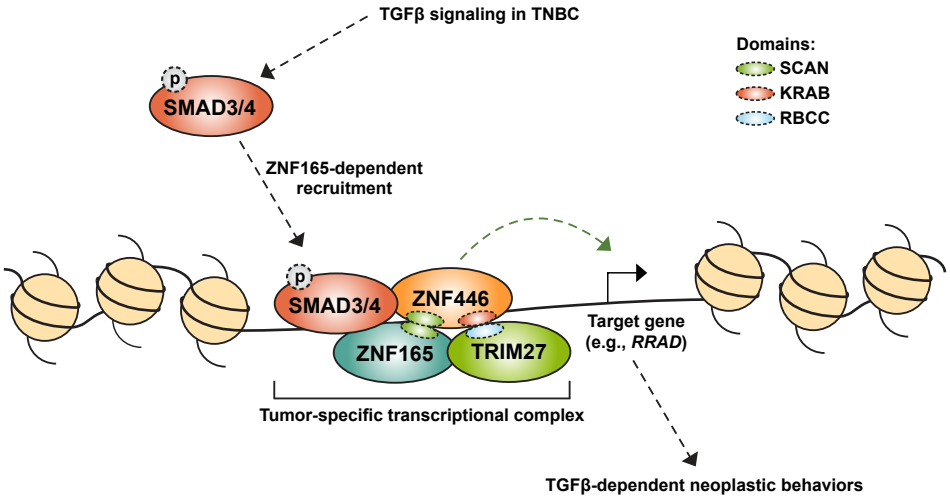


Figure 7. Model for assembly of a neomorphic ZNF165 transcriptional complex in TNBC. Aberrant expression of testis-specific ZNF165 in TNBC co-opts somatic transcriptional machinery to modulate TGFβ-dependent transcription. The ZNF165 SCAN domain recruits ZNF446, and together these factors associate with SMAD3 at shared binding sites throughout the genome and alter gene expression to promote neoplastic behaviors. Via its KRAB domain, ZNF446 recruits the co-activator/co-repressor TRIM27, which is essential for ZNF165 transcriptional activity and tumor growth *in vivo*. Given the testis/tumor-restricted expression of ZNF165, disruption of this complex holds potential as a therapeutic strategy to specifically inhibit pro-tumorigenic TGFβ signaling in TNBC.