Expression of nano-engineered RNA organelles in bacteria

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Abstract

Designing synthetic biomolecular condensates, or membrane-less organelles, offers insights on the functions of their natural counterparts, and is equally valuable for cellular and metabolic engineering. Choosing *E. coli* for its biotechnological relevance, we deploy RNA nanotechnology to design and express non-natural membrane-less organelles in vivo. The designer condensates assemble co-transcriptionally from branched RNA motifs interacting *via* base-pairing. Exploiting binding selectivity we express orthogonal, non-mixing condensates, and by embedding a protein-binding aptamer we achieve selective protein recruitment. Condensates can be made to dissolve and re-assemble upon thermal

cycling, thereby reversibly releasing and re-capturing protein clients. The synthetic organelles are expressed robustly across the cell population and remain stable despite enzymatic RNA processing. Compared with existing solutions based on peptide building blocks or repetitive RNA sequences, these nanostructured RNA motifs enable algorithmic control over interactions, affinity for clients, and condensate microstructure, opening new directions in synthetic biology and biotechnology.

Keywords: RNA Nanotechnology, Biomolecular Condensates, Membrane-less Organelles, Synthetic Biology, *E. coli*

Introduction

Membraneless organelles (MLOs), emerging from condensation of proteins and nucleic acids, are found in most living cells, where they orchestrate biochemical reactions by sequestering and co-localising enzymes, substrates, and metabolites, and by maintaining homeostasis [1–6]. Historically thought not to contain intracellular compartments, prokaryotes are now recognised to leverage membraneless organelles, such as BR-bodies, carboxysomes, polyP granules, ParB condensates, and RNA polymerase clusters, to modulate processes including division, polarisation, nucleoid replication, transcription, and protein homeostasis [5–8].

Engineering non-natural, *designer* MLOs both in vitro and in vivo is key to unravelling the biophysics and functions of natural condensates [9–11], and equally valuable as a tool to program metabolism and cellular functions in synthetic biology and biomanufacturing [12, 13]. To this end, establishing robust strategies to engineer biomolecular condensation in widely adopted prokaryotic chassis is particularly urgent.

Synthetic MLOs have been constructed from peptides and proteins, demonstrating remarkable functionalities [14–28]. Condensate-forming proteins, however, often assemble through non-specific interactions between Intrinsically Disordered Regions (IDRs), commonly combining electrostatic, $\pi - \pi$ and hydrophobic interactions between amino acid residues [29, 30]. The complexity of these interactions makes them difficult to prescribe by design [31–33], with modelling often requiring advanced numerical simulations [34–36].

Alternative to proteins, naturally occurring RNA repeats can be deployed for MLO assembly [37–39], but their simple structure limits the scope for more advanced engineering.

Different from proteins, however, nucleic acids benefit from highly predictable base-pairing interactions, which have led to the emergence of robust, algorithmic strategies to design nanostructures and materials [40–44]. DNA nanotechnology has been successfully deployed to construct synthetic condensates with precisely controlled size and microstructure [45–50], and displaying advanced functions ranging from reversible assembly and disassembly [51–53], to large-scale morphological re-structuring [54–60], capture and release of functional payloads [51, 61, 62], and spatial organization of biocatalytic pathways [63–66]. Despite this versatility, the use of synthetic DNA building

blocks is limited to in vitro applications, as DNA nanostructures cannot be expressed by living cells [67].

To overcome this roadblock, here we deploy RNA nanostructures, which retain much of the programmability of DNA constructs [68–71], but can be synthesized in vivo [72]. We engineer *E. coli* to express branched RNA motifs that assemble into synthetic MLOs when featuring complementary base-pairing domains, while remaining largely soluble when designed to be non-interacting. Base-pairing selectivity enables the expression of orthogonal nanostructures, producing non-mixing, co-existing MLOs, while embedding aptamers facilitates specific protein capture. MLOs can be made to assemble and disassemble upon thermal cycling, reversibly releasing and re-capturing payloads in the process. Our results demonstrate the potential of co-transcriptional RNA nanotechnology for engineering non-natural MLOs, combining a robust and programmatic design paradigm with genetic encodability.

Results and discussion

Design and expression of condensate-forming RNA motifs in *E. coli*

The condensate-forming motifs consist of branched RNA *nanostars* (NS), with four double stranded (ds) 'arms' emanating from a central junction (Fig. 1A) [69]. Each nanostar arm terminates with a 9-nucleotide (nt) kissing loop (KL), consisting of a 6 nt recognition domain asymmetrically flanked by adenines (Fig. 1A). NS designs A and B feature palindromic, self-complementary domains in the KLs, producing affinity between same-type NSs and leading to condensation [69]. A and B KLs are mutually orthogonal resulting in negligible cross-binding [69]. NS designs $\bar{\text{A}}$ and $\bar{\text{B}}$ are identical to A and B, respectively, but have KL sequences scrambled to eliminate self-complementarity and prevent condensation [69]. Fluorescent Light-Up Aptamers (FLAPs) are embedded in one of the NS arms to facilitate detection and visualisation. Designs A and $\bar{\text{A}}$ include a 'Pepper aptamer' binding the HBC620 dye [73] (Fig. 1A(i) and Supplementary Fig. 1), while B and $\bar{\text{B}}$ feature a 'Broccoli aptamer' [74] binding the TBI dye (Fig. 1A(ii) and Supplementary Fig. 1) [75]. All NS sequences are reported in Table S1.

For all NS designs, correct expression, condensate formation (or lack thereof) and interaction orthogonality were confirmed with in vitro transcription experiments (Extended Data Fig. 1 and Supplementary Figs. 2, 3, 4, 5, 6, Methods).

NS sequences, followed by transcription termination domains [76, 77], were then cloned in plasmids for expression in the *E. coli* BL21(DE3) strain with the IPTG-inducible T7 transcription system, as outlined in the Methods. Plasmid maps and sequences are reported in Supplementary Figs. 7, 8 and Supplementary Table 2. *E. coli* were grown from a single colony in supplemented M9 medium to mid-log phase (OD 0.7) before inducing NS expression. Cells were characterized by confocal microscopy one hour post-induction (Methods).

We first tested *E. coli* expressing individual NSs: A, B, $\bar{\text{A}}$ or $\bar{\text{B}}$. For both "sticky" motifs, A and B, visual inspection confirms MLO formation (Fig. 1B(i)-C(i) and Supplementary Figs. 9, 10). Condensates appear to be overwhelmingly located at the

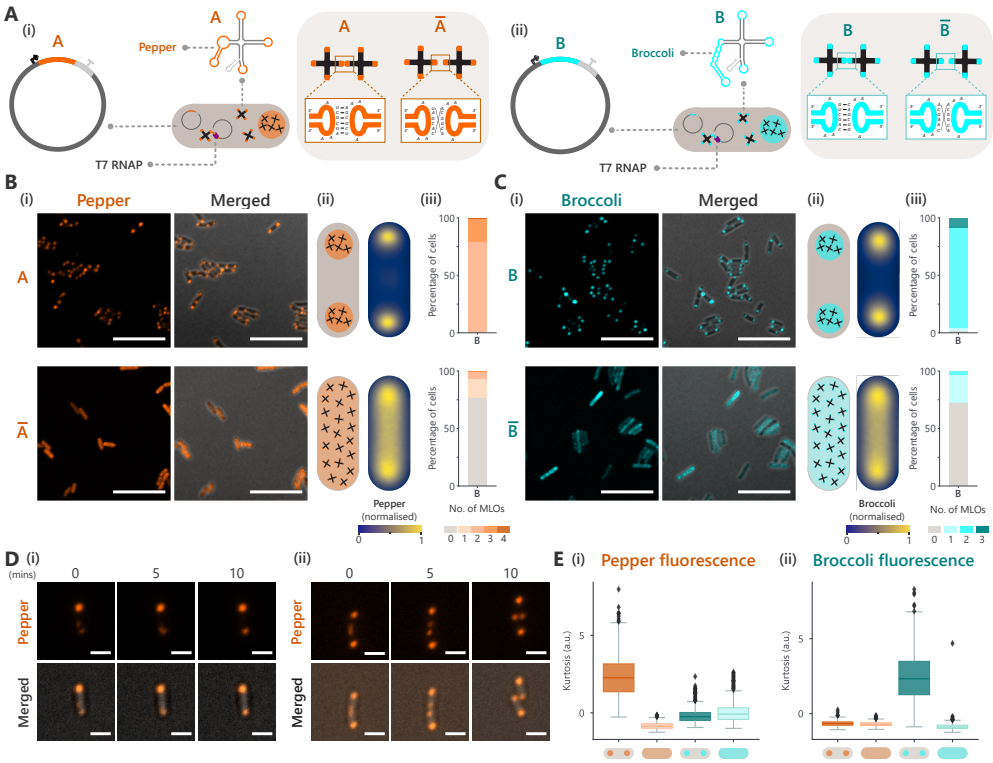

Fig. 1: **Expression of nanostructured RNA MLOs in *E. coli*.** (**A**) Schematic of nanostar (NS) expression and membrane-less organelle (MLO) formation in *E. coli*. (i) NS A contains four self-complementary kissing loops (KLs), driving condensation. NS Ā has non-complementary KLs with scrambled sequences, preventing assembly. Both A and Ā contain a Pepper aptamer, which binds to HBC620 activating its fluorescence.[73] (ii) NS B contains four self-complementary KLs, with a different sequence from that in A. B̄ has non-complementary loops and does not form MLOs. Both B and B̄ include a Broccoli aptamer [74], which binds TBI and activates its fluorescence [75]. Each NS sequence is cloned into a plasmid for expression with T7 RNA polymerase (T7 RNAP) upon transformation into *E. coli*. A terminator sequence (gray loop) is included. (**B**) Expression of A (top) and Ā (bottom) in *E. coli*. (i) Confocal micrographs. Left: Pepper fluorescence. Right: Merged Pepper fluorescence with bright-field. Scale bars, 10 µm. (ii) Schematic representation (left) and population-averaged maps (right) of Pepper fluorescence distribution in *E. coli* (Methods). (iii) Percentage of *E. coli* containing 0, 1, 2, 3 or 4 MLOs per cell. (**C**) Data as for panel **B**, but for the expression of B (top) and B̄ (bottom) NSs in *E. coli*. (**D**) Time-lapse confocal micrographs of *E. coli* expressing A MLOs. Top: Pepper fluorescence. Bottom: Merged Pepper and bright-field fluorescence. Time is shown relative to the first frame (0 min). (i) MLOs fusion events within cells. Scale bars, 2 µm. (ii) Cell division in the presence of MLOs. Scale bars, 2 µm. (**E**) Box plots of the values of kurtosis extracted from the pixel-value distribution of fluorescence intensity in single cells. Analysis is performed on (i) Pepper and (ii) Broccoli fluorescence for *E. coli* expressing A, Ā, B and B̄ NSs (from left to right). Outcomes of statistical test are provided in Tables 4 and 5. In **B**, **C** and **E**, data were obtained from 3 separate cultures, each starting from a single colony.

poles of the cell, a common pattern in protein MLOs [8]. This observation is confirmed by averaging the fluorescence distributions of individual cells across the populations, producing the 2D maps in Fig. 1B(ii)-C(ii). Pole localisation may result from steric hindrance by the nucleoid located in the central section of the cell [78], but has also been hypothesized to be a consequence of condensation in anisotropic confinement [8]. Pole accumulation consistently emerges from the distribution of MLOs positions (Extended Data Fig. 2), with a sparse third cluster seen in the central section of the cell.

Dataset	Pepper channel (NSs A or $\bar{A}$)											Broccoli channel (NSs B or $\bar{B}$)										n
No. of MLOs	**0**		**1**		**2**		**3**		**4**		**Mean**	**0**		**1**		**2**		**3**		**Mean**	
A	1	0%	3	1%	379	78%	98	20%	4	1%	2.21	485	100%	-		-		-		0.00		485
$\bar{A}$	315	76%	68	16%	28	7%	2	0%	-		0.31	413	100%	-		-		-		0.00		413
B	482	100%	-		-		-		-		0.00	7	1%	12	2%	423	88%	40	8%	2.03		482
$\bar{B}$	505	100%	-		-		-		-		0.00	366	72%	124	25%	15	3%	-		0.30		505
AB	3	1%	327	81%	72	18%	-		-		1.17	33	8%	277	69%	92	23%	-		1.15		402
A$\bar{B}$	1	0%	128	31%	283	69%	1	0%	-		1.69	301	73%	109	26%	3	1%	-		0.28		413
$\bar{A}$B	257	92%	23	8%	-		-		-		0.08	9	3%	193	69%	78	28%	-		1.25		280
$\bar{A}\bar{B}$	380	95%	21	5%	-		-		-		0.05	394	98%	7	2%	-		-		0.02		401

Table 1: **Statistical snapshot of the number and percentage of cells expressing a given number of MLOs of each type**. "Dataset" indicates experiment types with *E. coli* expressing one or a combination of NSs, as indicated. "Mean" indicates the mean number of MLOs per cell in each dataset. n is the number of cells analysed for each dataset. For each dataset, data are collated from 3 separate cultures, each starting from a single colony.

Inspection of the time evolution of individual cells reveals instances in which small condensates form in the central section, before merging with one of the polar MLOs, suggesting a pathway for condensate accretion alternative to single-monomer addition (Fig. 1D(i) and Extended Data Fig. 3A), as previously observed for repeat-RNA MLOs [38]. These coalescence events hint at a liquid like-state of the MLOs. To support this hypothesis, we performed Fluorescence Recovery After Photobleaching (FRAP) experiments, which reveal partial recovery (Extended Data Fig. 3B-C). It should however be noted that recovery rates may be enhanced by the exchange of FLAP dyes [69].

Image analysis confirms that most cells, 78% for A and 88% for B, contain two MLOs, while some feature three (20% for A and 8% for B, Fig. 1B(iii)-C(iii)). Rarely, cells have a single MLO, and a negligible fraction is condensate-free. Detailed statistics on condensate numbers are reported in Table 1.

Time lapses suggest that a third MLO may appear near the equator of cells with two polar condensates as they approach division, when the central section is free from the nucleoid (Fig. 1D(ii) and Extended Data Fig. 4). Consistent with this picture, for both A and B designs, we find a significant correlation between the length of the cells and the number of hosted MLOs (Supplementary Fig. 11). In some instances, the central condensates then appear to split between the two daughter cells, which emerge with two polar condensates of asymmetric intensity (Fig. 1D(ii) and Extended Data Fig. 4(i)). In other cases, the newly formed MLO partitions entirely in one of the daughter cell, leaving the other with a single condensate (Extended Data Fig. 4(ii)). Evidence of division confirms the viability of the MLO-expressing cells.

Expressing NS designs with scrambled KLs, $\bar{A}$ and $\bar{B}$, largely results in uniformly distributed fluorescence (Figs. 1B(i)-(ii), 1C(i)-(ii) and Supplementary Figs. 12, 13), with a small fraction of the cells (23% for $\bar{A}$ and 28% for $\bar{B}$, Fig. 1B(iii)-C(iii)) displaying regions of increased signal. These clusters likely arise from non-sequence-specific interaction between NSs or with other cellular RNA or proteins [79, 80]. Average fluorescence maps (Fig. 1B(ii)-C(ii)) and location analysis (Extended Data Fig. 2) show that, like specific MLOs, non-specific NS clusters are preferentially located at the cell poles.

Owing to imaging noise and cell-to-cell variation, it is sometimes challenging to distinguish slight non-uniformities in the fluorescent signal from NS condensates, which may lead to false-positive MLO detections for $\bar{A}$ and $\bar{B}$ (Methods). To discriminate more reliably, we analyse the frequency distribution of pixel values within single cells

and extract values for the kurtosis (Methods). A positive kurtosis reflects highly localised fluorescence, characteristic of MLO formation, whereas a negative kurtosis reflects a more uniform fluorescence distribution (Extended Data Fig. 5). Consistently, we observe positive kurtosis for NS A and B, and negative values for $\bar{A}$ and $\bar{B}$ (Fig. 1E, and Supplementary Tables 4, 5). Alternative to the kurtosis, fluorescence-distribution skewness also discriminates well between MLO-forming and scrambled NS designs (Extended Data Figs. 5, 6).

Optical density measurements performed in bulk cultures reveal an expected decrease in growth rate upon induction, which is marginally more prominent in *E. coli* expressing MLO-forming NSs compared to those producing non-sticky designs (Extended Data Fig. 7A(i) and Supplementary Figs. 14, 15A). Simultaneous detection of NS fluorescence shows the anticipated signal growth upon induction, with stronger emission observed for A and B NSs compared to $\bar{A}$ and $\bar{B}$ (Extended Data Fig. 7A(ii) and Supplementary Fig. 15B). Uninduced controls do not show significant induction leakage.

Given the limited half life of mRNA in *E. coli* [81], it is expected that nanostars may also be progressively degraded. We thus investigated stability and processing of the expressed A and B NSs with nanopore RNA sequencing and Polyacrylamide Gel Electrophoresis (PAGE) (Extended Data Figs. 8, 9). We find that both constructs are cleaved at specific sites, located on two of the arms of NS A and on one arm of NS B. For both nanostructures, fragments corresponding to all sections of the designed transcript are detected, implying that the observed fragmentation is likely the result of endonucleases acting on folded constructs, rather than abortive transcription. In this scenario, cleavage of one of the dsRNA arms would reduce NS valency without impacting the folded construct downstream of the restriction site. This picture is consistent with the evidence of robust MLO formation: while a fraction of NS population may have reduced valency, a sufficient proportion of the constructs must retain three or four KLs to support phase separation.

Despite occurring at two distinct sites, enzymatic degradation is less pronounced for NS A compared to NS B (Extended Data Figs. 8B, 9B). Denaturing PAGE (Extended Data Figs. 8C, 9C) shows substantial quantities of the full, uncleaved transcript for NS A, which are not detected for NS B. Native PAGE shows the full-length construct as the dominant species for NS A, indicating that most cleavage events detected by sequencing may only nick the dsRNA arms, rather than fully detaching them, allowing the construct to retain the designed secondary structure (Extended Data Figs. 8D). For NS B, a moderate amount of the complete, folded construct is present (Extended Data Fig. 9D), likely featuring a nicked but not fully cleaved arm. The most abundant species, however, has lower molecular weight and likely corresponds to the NS lacking one KL and having, therefore, reduced valency (Extended Data Fig. 9D). This observation highlights the advantage of using tetravalent rather than trivalent NS designs: given that a minimum valency of three is required to sustain phase separation [69], the built-in redundancy of tetravalent constructs makes them intrinsically more resilient. We finally note that both NSs feature an additional cleaving site in the terminator loop, which is thus likely to be detached in many transcripts (Extended Data Figs. 8A-B, 9A-B).

Expression of orthogonal membrane-less organelles in *E. coli*

KL orthogonality between A and B designs should enable co-expression of non-mixing MLOs. We test this hypothesis by designing plasmids containing two distinct NS sequences (Fig. 3A and Supplementary Fig. 8). Different T7 terminator sequences [77] are used for the two NS to minimize the potential for non-specific affinity between the constructs induced by the terminator loops.

When co-expressing A and B, confocal microscopy confirms the formation of non-mixing MLOs (Fig. 3B(i), Extended Data Fig. 10, and Supplementary Fig. 16). Similar to single-NS systems, condensates are preferentially located towards the poles, as evident from both average fluorescence maps (Fig. 3B(ii)) and the locations of individual MLOs (Fig. 3C). There is, however, a clear asymmetry between the exact positioning of A and B condensates: the former are nearly always in contact with a pole, while the latter may occupy more central locations. Inspection of individual micrographs confirms that B condensates tend to accumulate around polar A MLOs (Extended Data Fig. 10). We ascribe this behaviour to the tendency of A NSs to form larger condensates (Supplementary Fig. 17), which may appear faster than B MLOs and grow to occupy the entire polar region, pushing smaller B condensates more towards the central segment of the cell. Slower condensation kinetics for the B design may be linked to its greater susceptibility to degradation and consequent reduced valency.

Most cells express one MLO of each kind, with a smaller percentage containing two A and/or two B MLOs (Fig. 3B(iii) and Table 1). The overall number of MLOs in cells co-expressing A and B (averaging 2.3) is similar to that of cells expressing only A (2.2) or only B (2.0), indicating that co-expression does not significantly alter condensate formation.

Cells co-expressing one sticky NS and one non-sticky NS, A + $\bar{\text{B}}$ or $\bar{\text{A}}$ + B, behave as expected, with MLOs of the intended NS species (A or B) coexisting with a largely diffuse phase of the soluble NSs ($\bar{\text{B}}$ or $\bar{\text{A}}$, Fig. 3B(i) and Supplementary Figs. 18, 19). The fluorescent signal distribution (Fig. 3B(ii)) and condensate locations (Extended Data Fig. 2) of A and B MLOs are similar to those observed for cells that do not simultaneously express $\bar{\text{B}}$ or $\bar{\text{A}}$ (Fig. 1B(ii)-C(ii) and Extended Data Fig. 2), indicating that soluble NSs do not interfere with the condensation of sticky motifs. Condensate numbers are, however, lower, with a greater proportion of cells expressing a single A or B MLO (Fig. 3B(iii)), arguably due to a lower overall expression of the MLO-forming motif due to the simultaneous production of the soluble NSs.

The fluorescence distribution of $\bar{\text{B}}$, when co-expressed with A, is largely uniform, with a small fraction of the cells (27%) displaying regions of increased $\bar{\text{B}}$ signal at the poles (Fig. 3B(ii)-(iii) and Table 1), similar to that observed in cells expressing $\bar{\text{B}}$ only (28%). The fluorescence distribution of $\bar{\text{A}}$, when co-expressed with B, is almost completely uniform, with only 8% of cells displaying regions of increased $\bar{\text{A}}$ signal (Fig. 3B(ii) and Table 1), compared to 25% for *E. coli* expressing only $\bar{\text{A}}$. Cells co-expressing the two soluble NSs, $\bar{\text{A}}$ and $\bar{\text{B}}$, display near-uniform fluorescence distribution (Fig. 3B(ii) and Supplementary Fig. 20), with non-specific $\bar{\text{A}}$ and $\bar{\text{B}}$ clusters detected only in 5% and 2% of the cells, respectively (Fig. 3B(iii) and Table 1).

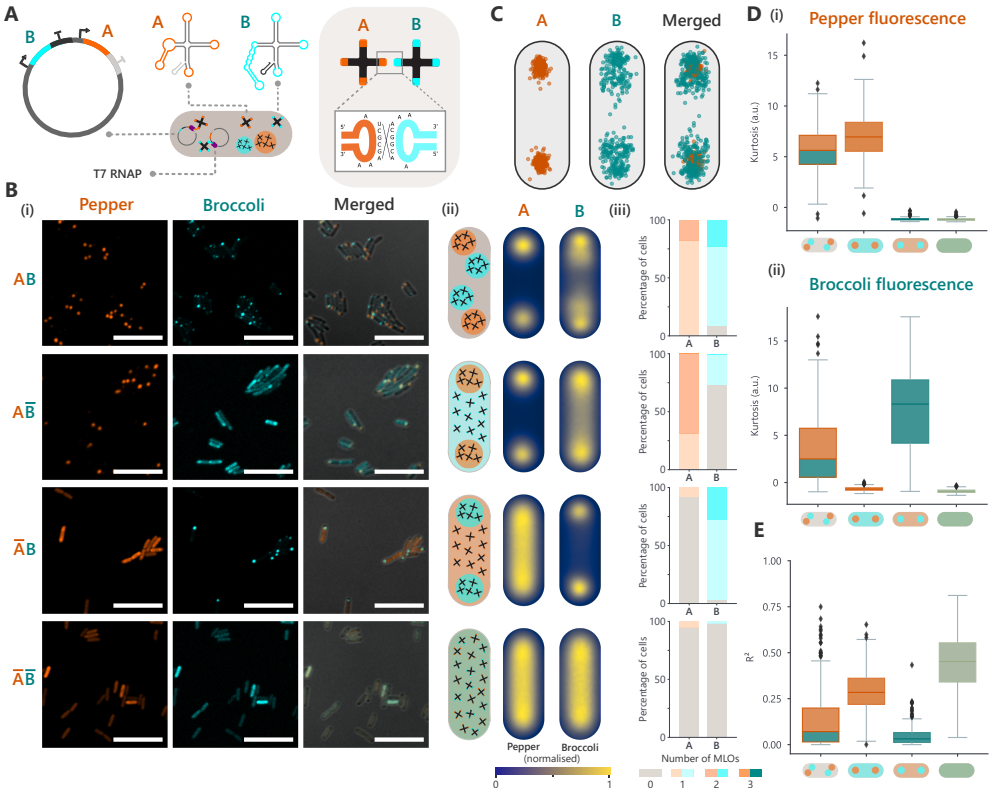

Fig. 2: **Co-expression of orthogonal, non-mixing RNA MLOs in *E. coli*.** (**A**) Schematic of the co-expression of A and B NSs in *E. coli*. A and B motifs have different kissing loop sequences and cannot interact by base-pairing, therefore forming separate MLOs in *E. coli*. Both NS sequences are cloned into a single plasmid for T7 RNA polymerase transcription, each controlled by its own promoter and a distinct terminator [77]. (**B**) Co-expression of NS pairs in *E. coli*. Top to bottom: A+B, A+$\bar{\text{B}}$, $\bar{\text{A}}$+B and $\bar{\text{A}}$+$\bar{\text{B}}$ NSs. (i) Confocal micrographs. Left: Pepper fluorescence (NSs A and $\bar{\text{A}}$). Middle: Broccoli fluorescence (NSs B and $\bar{\text{B}}$). Right: Merged Pepper fluorescence, Broccoli fluorescence, and bright-field. Scale bars: 10µm. (ii) Schematic representation (left) and population-averaged maps of Pepper fluorescence distribution (middle), and Broccoli fluorescence distribution (right) in *E. coli* (Methods). (iii) Percentage of *E. coli* containing 0, 1, 2 or 3 A or B MLOs per cell. (**C**) Scatter plot of the locations of MLOs in *E. coli* co-expressing both A and B NSs. Each symbol represents the position of a detected MLO (Methods). (**D**) Box plots of the values of kurtosis extracted from the pixel-value distribution of fluorescence intensity in single cells. Analysis is performed on (i) Pepper and (ii) Broccoli fluorescence for cells expressing A+B, $\bar{\text{A}}$+B, A+$\bar{\text{B}}$ and $\bar{\text{A}}$+$\bar{\text{B}}$ NSs (left to right). Outcomes of statistical tests are provided in Supplementary Tables 6 and 7. (**E**) Box plots of the correlation coefficient (R^2) values computed between Broccoli and Pepper fluorescent signals. Outcomes of statistical tests are provided in Supplementary Table 3. In **D**-**E**, each data point refers to an individual *E. coli*. In **B**-**E**, data are obtained from 3 separate cultures, each starting from a single colony.

The lesser tendency of $\bar{\text{A}}$ and $\bar{\text{B}}$ to form non-specific clusters is consistent with a reduced NS concentration caused by the simultaneous expression of two constructs. The greater abundance of non-specific clusters seen when non-sticky NS are co-expressed with sticky motifs, particularly for A+$\bar{\text{B}}$ expression, may be due to MLO-templated clustering of the otherwise soluble NSs. The soluble NSs may indeed weakly partition within, or coat the specifically-assembled MLO, or the condensates may serve as heterogeneous nucleation sites for non-specific aggregation. Either process may be facilitated by weak affinity between the soluble and sticky NSs due to

base pairing, misfolding, enzymatic degradation, or the action of native RNA-binding proteins. In addition, fluorescence bleed-through from the Pepper (NS A) to the Broccoli (NS $\bar{\mathrm{B}}$) channels, observed in vitro (Extended Data Fig. 1), may contribute to the appearance of $\bar{\mathrm{B}}$ clusters, despite optimizing imaging settings (Methods and Supplementary Fig. 21).

As done for single-NS systems, we use the kurtosis of pixel-intensity distributions to assess the tendency of individual NS components to condense. In line with observations made on Fig. 3B, for all combinations tested, cell populations expressing A or B NSs have positive kurtosis in the relevant fluorescent channels, while those expressing $\bar{\mathrm{A}}$ or $\bar{\mathrm{B}}$ have negative kurtosis (Fig. 3D and Supplementary Tables 6, 7). Skewness analysis can similarly distinguish between cells expressing condensate-forming and non-sticky NSs (Extended Data Fig. 6).

To further assess the relative distribution of co-expressed NS components, we study the cross-correlation between Pepper (NS A) and Broccoli (NS B) fluorescence signals (Supplementary Fig. 22A), extracting distributions of the coefficient of determination, R^2, across *E. coli* populations (Fig. 3E and Supplementary Table 3). In cells expressing A and B, the low R^2 confirms that MLOs are orthogonal and non-overlapping. When expressing $\bar{\mathrm{A}}$ and $\bar{\mathrm{B}}$, R^2 is highest, as both NSs are evenly distributed throughout the cell. In *E. coli* producing A and $\bar{\mathrm{B}}$, a low R^2 follows from the localised Pepper (NS A) signal in a diffused Broccoli (NS B) background. The higher R^2 value found for cells expressing A+$\bar{\mathrm{B}}$ supports the hypothesis that $\bar{\mathrm{B}}$ may non-specifically partition within MLOs, or the occurrence of fluorescence bleed-through. Note that weak co-localisation of the Broccoli and Pepper signals is also apparent when A and $\bar{\mathrm{B}}$ are co-expressed in vitro (Extended Data Fig. 1B).

Bulk growth curves collected for *E. coli* expressing two NS species are similar to those recorded for single-NS expression (Extended Data Fig. 7B(i) and Supplementary Fig. 23A). Samples show no significant differences in the trend and magnitude of the fluorescent traces recorded simultaneously (Extended Data Fig. 7B(ii) and Supplementary Fig. 23B). We also observe that some cells still contain MLOs after a week at room temperature, indicating long-term stability of the condensates despite enzymatic degradation of individual NSs (Supplementary Fig. 24).

Selective protein recruitment in RNA membrane-less organelles

Owing to their modularity and controlled structure, the RNA motifs can be straightforwardly modified to feature additional functional motifs, including aptamers enabling the capture of molecular clients. As proof-of-concept, we embedded the GFP-binding AP3 aptamer [82] in one of the arms of NS A, opposite to the arm hosting the Pepper FLAP (Fig. 4A). Note that $\mathrm{A}_{\mathrm{AP3}}$ remains tetravalent, as the kissing loop is inserted between two stem loops of the aptamer.

Confocal micrographs and image analysis confirm that $\mathrm{A}_{\mathrm{AP3}}$ expression in *E. coli* produces MLOs with similar spatial distribution and numbers as those measured for NS A (Fig. 3B(i)-(iii), Table 2, and Supplementary Fig. 25). Co-expression of GFP results in a clear co-localisation of the protein with the $\mathrm{A}_{\mathrm{AP3}}$ signal (Fig. 4B(i)-(ii) and Supplementary Fig. 26). Cells expressing $\mathrm{A}_{\mathrm{AP3}}$ alone and those co-expressing $\mathrm{A}_{\mathrm{AP3}}$

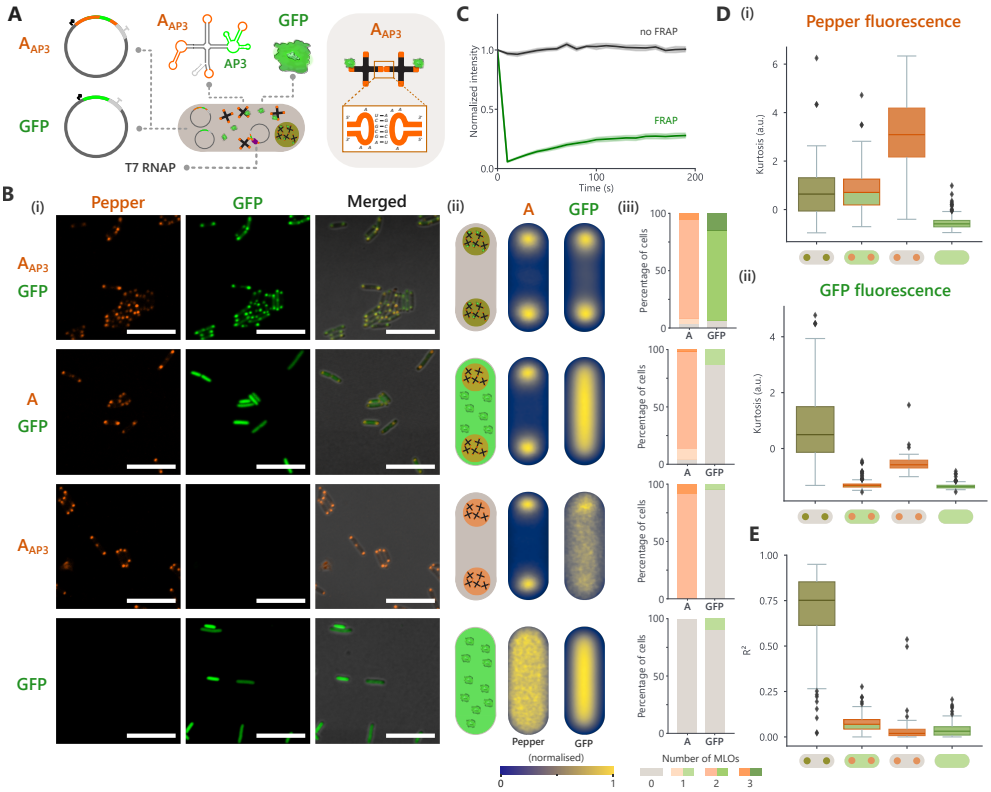

Fig. 3: **Proteins can be selectively captured in RNA MLOs expressed in *E. coli*.** (**A**) Schematic of GFP co-expression with NS A_{AP3}, carrying the GFP-binding AP3 aptamer [82], in *E. coli*. (**B**) Co-expression of NSs and GFP in *E. coli*. Top to bottom: A_{AP3} + GFP, A + GFP, A_{AP3} only, and GFP only. (i) Confocal micrographs. Left: Pepper (NS) fluorescence. Middle: GFP fluorescence. Right: Merged Pepper fluorescence, GFP fluorescence, and bright-field. Scale bars, 10 µm. (ii) Schematic representation (left) and population-averaged maps of Pepper fluorescence distribution (middle), and GFP fluorescence distribution (right). (iii) Percentage of *E. coli* containing 0, 1, 2 or 3 MLOs per cell. (**C**) Fluorescence Recovery After Photobleaching (FRAP) curves of GFP captured in A_{AP3} MLOs. For each MLO, fluorescence intensity prior to photobleaching is normalized to 1. The green solid line is the mean intensity of photobleached samples ($n = 25$ condensates), while the black solid line is the mean intensity of non-photobleached samples ($n = 15$ condensates). Shaded areas indicate the standard error of the mean. (**D**) Box plots of the values of kurtosis extracted from the pixel-value distribution of fluorescence intensity in single cells. Analysis is performed on (i) Pepper and (ii) GFP fluorescence for cells expressing A_{AP3} + GFP, A + GFP, A_{AP3} only, and GFP only. Outcomes of statistical tests are provided in Supplementary Tables 8, 9. (**E**) Box plots of the coefficient of determination (R^2) values computed between Pepper and GFP fluorescent signals. Outcomes of statistical tests are provided in Table 3. In **D**-**E**, each data point refers to an individual *E. coli*. In **B**-**E**, data are obtained from 3 separate cultures, each starting from a single colony.

and GFP both contained an average of 2.0 condensates per cell (Table 2), indicating that GFP expression does not noticeably affect A_{AP3} condensate formation.

In contrast, GFP remains evenly distributed when co-expressed with NS A lacking the GFP-binding aptamer, confirming the specificity of the recruitment mechanism (Fig. 3B(i)-(ii) and Supplementary Fig. 27). Expressing GFP in the absence of NSs confirms the lack of spontaneous protein aggregation and the formation of inclusion bodies (Fig. 3B(i)-(ii) and Supplementary Fig. 28)[83]. The small number of GFP clusters detected by our segmentation algorithm in the absence of A_{AP3} NSs come

Dataset	Pepper channel (NSs A or A_{AP3})									GFP channel									n
No. of MLOs	0		1		2		3		Mean	0		1		2		3		Mean	
A_{AP3}+GFP	5	3%	7	5%	125	86%	8	6%	1.94	9	6%	-		114	79%	22	15%	2.03	145
A+GFP	9	4%	18	9%	174	85%	4	2%	1.84	177	86%	28	14%	-		-		0.14	205
A_{AP3}	-		-		75	91%	7	9%	2.09	78	95%	4	5%	-		-		0.05	82
GFP	189	100%	-		-		-		0.00	170	90%	19	10%	-		-		0.10	189

Table 2: **Statistical snapshot of the number and percentage of cells expressing a given number of MLOs for protein capture experiments**. "Dataset" indicates experiment types with *E. coli* expressing NSs and/or GFP as indicated. "Mean" indicates the mean number of MLOs per cell in each dataset. n is the number of cells analysed for each dataset. For each dataset, data are collated from 3 separate cultures, each starting from a single colony.

from segmentation artefacts linked to the 3D shape of the cell [84], which results in brighter central sections that may be occasionally misclassified as MLOs.

Partial recovery of the GFP signal in FRAP experiments demonstrates that the recruited protein can exchange with cytosolic GFP (Fig. 4C).

Analysis of the kurtosis of the pixel-fluorescence distribution in Fig. 4D show the expected trends: positive kurtosis is measured in the Pepper (NS) channel for all MLO-forming NS designs, and in the GFP channel only when the protein-binding A_{AP3} is expressed (Supplementary Tables 8, 9). Consistent trends are observed when analysing skewness (Extended Data Fig. 6). Finally, image correlation analysis shows a strong fluorescence co-localisation between GFP and A_{AP3} MLOs but not between GFP and A MLOs (Fig. 4E, Supplementary Fig. 22, and Supplementary Table 3).

Temperature-dependent dissolution and re-assembly of MLOs

Since the NSs self-assemble through base-pairing interactions, we anticipated that the MLOs would dissolve at sufficiently high temperature, as observed in vitro [69].

Consistent with this expectation, heating *E. coli* containing A-MLOs led to their dissolution at 61 °C. This process was reversible, with A-MLOs reassembling with similar polar distribution as the cells were cooled (Fig. 4A(i)-(ii) and Supplementary Fig. 29). Sampling the skewness of the pixel-intensity distribution across the bacteria population provides information of the condensate melting process (Fig. 4A(iii)). At the starting temperature, the skewness is high across the population, reflecting the presence of MLOs. As temperature is increased, the distribution becomes bimodal, with a second population of cells displaying low skewness following MLO dissolution. The intra-population variability in the onset of melting may be due to cell-to-cell variation in NS expression and therefore concentration. At sufficiently high temperature most cells display low skewness. By fitting the skewness distributions, we can extract a temperature-dependent fraction of cells hosting MLOs, which shows a small hysteresis between heating and cooling ramps, likely caused by slow assembly kinetics or delays in thermal equilibration in the samples (Fig. 4A(iv) and Supplementary Fig. 30).

B-MLOs showed a reversible disassembly behaviour similar to the A design, but with a lower melting temperature: condensates begin to melt at 49 °C and fully dissolve by 58 °C (Fig. 4B(i)-(iv) and Supplementary Figs. 30, 31).

The difference in melting temperature between the two constructs is unlikely to result from different KL affinity, having observed that NSs with KL A disassemble at slightly lower temperature compared to those with KL B in vitro [69]. Instead, it

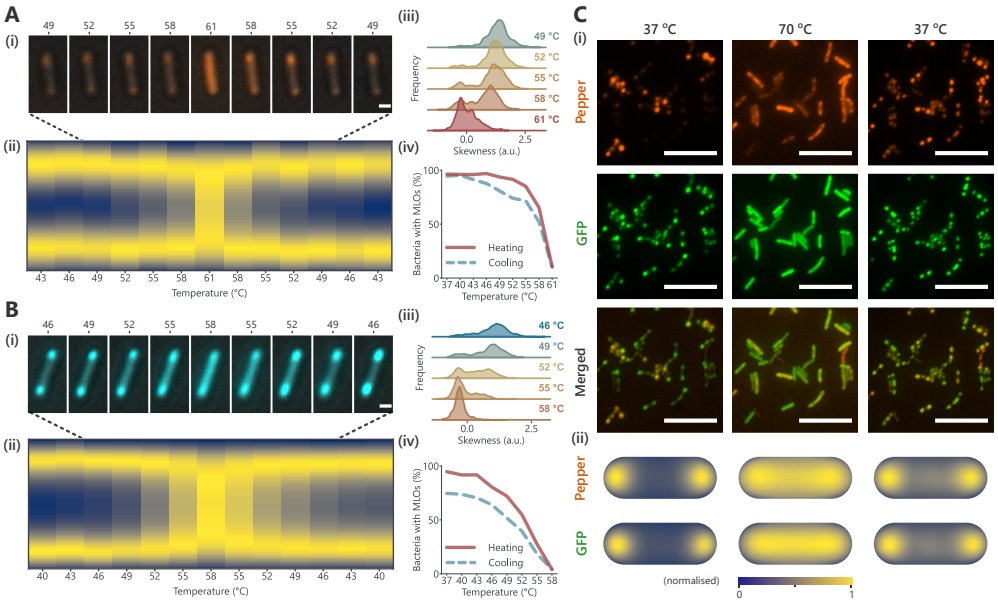

Fig. 4: **Synthetic RNA MLOs reversibly disassemble and reassemble in *E. coli* upon temperature cycling.** (**A**) Reversible disassembly and reassembly of A MLOs. (i) Merged epifluorescence and bright-field micrographs showing disassembly and reassembly of A MLOs in a single cell. Scale bars, 1 µm. (ii) Population-averaged maps of Pepper (NS) fluorescence as a function of temperature upon heating and subsequent cooling. (iii) Cell-population distribution of the values of skewness computed for the fluorescence-intensity distributions of Pepper signal in individual *E. coli* on heating and cooling. (iv) Percentage of single cells containing MLOs as extracted from the skewness distributions (Methods). (**B**) Reversible disassembly and reassembly of B MLOs. Data are presented as in panel **A**, using Broccoli fluorescence to image NSs. (**C**) Disassembly and reassembly of A_{AP3} MLOs with captured GFP. (i) Confocal micrographs of samples at 37 °C (left), after heating to 70 °C (middle), and after cooling back to 37 °C (right). Top: Pepper (NS) fluorescence; middle: GFP fluorescence; bottom: merged Pepper fluorescence, GFP fluorescence, and bright-field. Scale bars, 10 µm. (ii) Population-averaged maps of Pepper (top) and GFP (bottom) fluorescence at the temperatures shown in (i). In **A**–**C**, fluorescence maps and quantitative analyses are based on *E. coli* from 3 independent cultures, each starting from a single colony.

may result from the greater degree of enzymatic degradation experienced by NS B (Extended Data Figs. 8, 9). A reduction in NS valency is also consistent with the broader melting transition seen in NS B compared to the A design.

Different from A NSs, a small fraction ($\sim$ 20%) of cells expressing B MLOs do not re-assemble condensates when cooled, possibly due to nanostructure misfolding or failure to re-fold upon cooling.

We then demonstrate temperature-triggered release of captured proteins by heating MLOs that had sequestered GFP. When cells expressing the A_{AP3} NSs and GFP were briefly heated to 70 °C for 2 minutes, the GFP and nanostar fluorescent signal dispersed throughout the cell. Upon cooling, the MLOs reassembled at the poles, with GFP relocalising accordingly (Fig. 4C(i)-(ii) and Supplementary Figs. 32, 33).

We further note that melting temperatures measured in vivo are substantially higher than those we observe in vitro, where the MLOs melted around 40 °C (Supplementary Fig. 34) [69]. The intracellular environment likely promotes NS-NS affinity, potentially as a result of molecular crowding [85].

Importantly, the cells remained viable and were able to grow and divide after heating and cooling (Supplementary Fig. 35).

Conclusion

We demonstrate the expression of RNA nanostructures, capable of forming non-natural membrane-less organelles in live *E. coli*. Sequence selectivity enables the production of non-mixing and addressable organelle types with distinct composition, while embedding aptamers facilitates protein uptake. The genetically encoded synthetic organelles are liquid-like and exhibit upper critical solution temperature behaviour, enabling reversible disassembly and reassembly upon heating and subsequent cooling. The system provides valuable insights on the biophysics of biomolecular condensation in prokaryotes, as we show by probing organelle number, spatial distribution, fluidity and response upon division. Compared to platforms reliant on engineered proteins and peptides, or simpler RNA repeats, the nano-structured motifs offer advantages in terms of rational and modular design. The observation that the RNA nanostars retain programmability and functionality within the complex intracellular environment is noteworthy, particularly for expression in *E. coli* that despite its biotechnological relevance, poses substantial challenges due to rapid RNA degradation. By overcoming this hurdle, our contribution paves the way to deploying nano-structured RNA condensates to metabolic engineering and biomanufacturing, leveraging the possibility of sequestering arbitrary proteins or nucleic acids within the condensates. One may indeed aim to optimize biocatalytic pathways by (co)localising enzymes and/or substrates, enhance expression yields by sequestering toxic products or intermediates, or improve separation and purification pipelines. The platform could further be adapted to other specialized prokaryotic expression strains, including *Bacillus subtilis*, *Pseudomonas putida* and *Lactococcus lactis*. We expect that, taken together, these characteristics of robustness, modularity, structural programmability and interaction selectivity, will establish nano-structured RNA condensates as a prominent tool for next-generation cellular engineering.

Supplementary information. Supplementary figures, supplementary tables, and gene sequences are available in the supplementary information.

Acknowledgements. L.D.M., L.M., and C.F. acknowledge support from the European Research Council (ERC) under the Horizon 2020 research and innovation programme (ERC-STG No 851667 - NANOCELL). L.D.M. acknowledges support from a Royal Society University Research Fellowship (UF160152, URF\R\221009). L.D.M., B.N. and M.T. acknowledge support from the UK Biotechnology and Biological Sciences Research Council (BBSRC) through a Japan Interdisciplinary Partnership Award Plus (BB/X012557/1) and from JST ASPIRE (JPMJAP24B4). M.T. acknowledges support from MEXT/JSPS KAKENHI (Nos. JP24H00070 and JP25H01361). R.R.S. acknowledges funding from the Biotechnology and Biological Sciences Research Council through a BBSRC Discovery Fellowship (BB/X010228/1). M.D. acknowledges support for a studentship awarded by Ernest Oppenheimer Fund (School of Physical Sciences, University of Cambridge). A.K. acknowledges the University of Cambridge Harding Distinguished Postgraduate Scholars Programme and the UK

Engineering and Physical Sciences Research Council (EPSRC, 2928387). G.F. acknowledges funding from the Department of Chemistry at Imperial College London. S.P.N. acknowledges support from EPSRC (EP/S023518/1). The team thank Yuval Elani, Elisa Franco and Hirohide Saito for useful discussions and the support staff of the Department of Chemical Engineering and Biotechnology, University of Cambridge, especially Danita Pearson, for their dedicated assistance.

Competing interests. B.N., C.F, M.D., A.K. and L.D.M., through the University of Cambridge, have filed a patent application in the UK Intellectual Property Office, which includes disclosure of inventions described in this manuscript, provisional application serial number 2510955.4, filed on 7 July 2025. The other authors declare no conflict of interest.

Data availability. All data underpinning this manuscript are available from the corresponding author during peer-review. Upon acceptance in a peer-reviewed journal, data will be made available on a freely accessible permanent repository.

Code availability. The data analysis code used in this publication is available at https://github.com/adamkni/Condensate_Segmentation.

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Methods

Chemicals and reagents

All reagents were obtained from Merck unless otherwise specified. *E. coli* Bl21(DE3) and XL10-Gold cells were obtained from Agilent. DH5α cells were purchased from Thermo Fisher Scientific. TBI was purchased from Torcis Bioscience. HBC620 was purchased from MedChem Express. DFHBI-1T was purchased from Cayman Chemical. Recombinant GFP was purchased from Caltag Medsystems. Pico-Surf fluorinated oil was purchased from Sphere Fluidics. CellBrite Fix 640 membrane dye was purchased from biotium. The T7-FlashScribe™ Transcription Kit was purchased from Cellscript. The RNeasy Mini kit and Bacteria Protect Reagent were obtained from Qiagen. GeneRuler 100 bp DNA Ladder and RiboRuler Low Range RNA Ladder were obtained from Thermo Fisher Scientific. LB-agar plates, glycerol, ultra-pure water, and SOC media were obtained from the technical support team of the Department of Chemical Engineering and Biotechnology, University of Cambridge. Linear DNA strands were obtained from Integrated DNA Technologies (IDT) as gBlocks. Geneframes were obtained from Thermo Fisher Scientific. Glass capillaries were purchased from VitroCom. Nunc MicroWell 96-Well Optical-Bottom Plates with Polymer Base (Cell culture, black, Surface Treatment: Cell Culture, Bottom: Flat) were obtained from Thermo Fisher Scientific. The pET plasmid (53137) was obtained from Addgene. The NEBuilder HiFi kit and the Monarch miniprep kit were obtained from New England Biolabs (NEB).

Expression and characterization of RNA nanostars in vitro

In vitro transcription reactions were prepared at room temperature using the T7-FlashScribe™ Transcription Kit and 40 nM of the relevant linear DNA template with T7 terminator or 5 nM of the relevant plasmid (for samples used in PAGE analysis). The final reaction mixture contained 9 mM of each ribonucleotide triphosphate, 0.05 units per µL RNase inhibitor, and 10 mM dithiothreitol. In addition, the reaction contained 50 µM of the Broccoli aptamer-binding dye DFHBI-1T, and 0.5 µM of the Pepper aptamer-binding dye HBC620. Mixtures were loaded into borosilicate glass capillaries with rectangular cross section (0.2 mm $\times$ 2 mm, VitroCom) and capped with paraffin oil. Capillaries were then immediately placed at 37 °C and incubated for 4 hours, until imaging. Epifluorescence micrographs were obtained using a Nikon Eclipse Ti2-E inverted microscope equipped with a Hamamatsu ORCA-Flash4.0 V3 sCMOS camera, a tuneable light source (Lumencor SPECTRA X LED engine), and a Plan Apo λ 20 $\times$ 0.75 N.A. dry objective. The HBC620 dye was excited using a 590 nm LED source with an LED-DA/FI/TR/Cy5-B filter, 10 ms excitation time, and fluorescence was recorded through an FF01-624/40 emission filter. DFHBI-1T was excited using a 470 nm LED source with an LED-DA/FI/TR/Cy5-B filter, 500 ms excitation time, and fluorescence was recorded through an EM510 emission filter. For the in vitro transcription of NS A_{AP3}, the reaction was prepared as described above with the addition of 750 nM recombinant GFP. The transcription mixture was then encapsulated within water-in-oil droplets by mixing 22 µL of the solution with 90 µL

of 2% w/w Pico-surf fluorinated oil and vortexing at 2,500 rpm for 30 s. The top layer, containing the emulsion droplets, was extracted, loaded into capillaries, and incubated at 37 °C for 8 h before being imaged on the Nikon Eclipse Ti2-E inverted microscope. The settings described above were used for imaging the Pepper channel (NS A_{AP3}), while GFP fluorescence was imaged using the 470 nm LED source with an LED-DA/FI/TR/Cy5-B filter and 2 ms excitation time. To induce thermal disassembly of the in vitro A_{AP3}+GFP samples, the loaded capillaries were heated using a Peltier microscope stage (Temikra Ltd.) to 20 °C, 37 °C and 40 °C, and subsequently cooled to 20 °C.

Plasmid construction

Nanostar design

RNA NSs A, $\bar{A}$, B, and $\bar{B}$ were adapted from Ref. [69]. Each construct consists of a four-way junction with 25 bp double-stranded RNA arms. One arm in each design contains a FLAP, Pepper for A and $\bar{A}$ [73], and Broccoli for B and $\bar{B}$ [75]. Each arm in NS A ends with a KL with sequence 5'-AUCGCCAAA-3', while arms in NS B terminate with KL 5'-AGUCGACAA-3'. The KL sequences were designed in Ref. [69] to ensure similar binding strength while retaining mutual orthogonality and self-complementarity. NSs $\bar{A}$ and $\bar{B}$ have KL nucleotide sequences scrambled to eliminate self-complementarity. NS A_{AP3} additionally features the GFP-binding AP3 aptamer in one of the arms, opposite to the one hosting the Pepper aptamer [82]. NS arms that include fluorescent or GFP-binding aptamers retain KLs, ensuring that the constructs remain tetravalent. All NS designs were verified with Nupack [86] and Kinefold [87]. Sequences of all NS designs are reported in Supplementary Table 1.

Plasmid design and construction

To construct plasmids expressing single NSs (A, $\bar{A}$, B, $\bar{B}$, A_{AP3}), the natural T7 terminator sequence [88] was appended to the 3' end of the NS sequences. The NS+terminator sequences were cloned into a pET plasmid with ampicillin resistance gene (Addgene #53137), using NEBuilder HiFi kit, following the manufacturer's instructions. To construct plasmids expressing two NSs (A+B, A+$\bar{B}$, $\bar{A}$+B, or $\bar{A}$+$\bar{B}$), the natural T7 terminator was appended to the 3' end of NSs A and $\bar{A}$, while a T7 terminator variant [77] was used for NSs B, and $\bar{B}$. Different terminators were used to reduce chances of non-specific interactions between the two constructs induced by the terminators. As for single NSs, the resulting sequences were cloned into the pET plasmid (Addgene #53137) using the NEBuilder HiFi kit. A 44 bp linker separates the two NS sequences on the plasmid. All plasmid maps are provided in Supplementary Figs. 7, 8. The GFP expressing plasmid was constructed by cloning the eGFP sequence from pEGFP-N1 (Takara) into the pACYCDuet-1 backbone (Novagen), from which LacI had been removed. Both DNA fragments were obtained as linear sequences and assembled using the NEBuilder HiFi kit. The plasmids containing ampicillin resistance genes were propagated with XL-10 Gold cells, while plasmids containing chloramphenicol resistance genes were propagated in DH5α cells. Plasmids were extracted

from the cloning strains using the Monarch miniprep kit. The sequences of all of the constructed plasmids were verified by whole-plasmid sequencing (Full Circle Labs).

RNA nanostars expression in *E. coli*

Throughout all experiments, antibiotics matching the relevant resistance genes were used, namely ampicillin (50 µg mL^{-1}), and chloramphenicol (34 µg mL^{-1}).

Transformation of BL21(DE3) strains

To transform BL21(DE3) bacteria with plasmids containing the ampicillin resistance gene, 10 ng of the target plasmid were mixed with 10 µL of BL21(DE3) competent cells, and incubated on ice for 15 min. The samples were plated on LB-agar containing carbenicillin and incubated at 37 °C for 16 h. To transform BL21(DE3) bacteria with plasmids containing chloramphenicol resistance gene, or for co-transformation with plasmids containing different antibiotic resistance genes, 10 ng of each plasmid were added to 10 µL of BL21(DE3) competent cells and incubated on ice for 30 min. The samples were placed in a 42 °C water bath for 30 s, followed by 2 min incubation on ice, and addition of 250 µL Super Optimal broth with Catabolite repression (SOC) medium. The samples were placed in a shaking incubator (Multitron Standard, Infors HT, 37 °C, 225 rpm) for 1 h, before plating on LB-agar with matching antibiotics, and incubating at 37 °C for 16 h. LB-agar plates with transformed cells were stored at 4 °C for up to two weeks before RNA expression experiments.

RNA and protein expression in *E. coli*

A single colony was transferred to 5 mL M9 minimal medium, supplemented with 0.4% glycerol, 0.2% casamino acids, 2 mM $MgCl_2$, 100 µL $CaCl_2$ (hereby referred to as M9 medium with supplements), and matching antibiotics. The culture was grown for 4 h (225 rpm, 37 °C) in a shaking incubator, to reach an OD_{600} around 0.6-0.8, measured by spectrophotometer (SmartSpec Plus, Bio-Rad). IPTG (0.4 mM), TBI (10 µM), HBC620 (5 µM) were added to 2 mL of the sample, and the samples were further incubated for 1 h (225 rpm, 37 °C) in a shaking incubator. TBI dye was used instead of DFHBI-1T for imaging in cells due to its improved photostability in vivo, which makes it better suited for cellular imaging applications [75]. 10 µL of the sample were diluted with 10 µL of the M9 medium with supplements, including the same concentrations of dyes, inducer, and antibiotics. The samples were stained with 0.2 µL of CellBrite Fix 640 membrane dye (1000 ×) at 25 °C for 10 minutes, before transferring to agarose pads for imaging.

Extraction of RNA from *E. coli*

Bacteria samples were prepared as described previously. RNA was extracted from bacteria using Qiagen RNeasy Mini kit with Bacteria Protect Reagent, following the manufacturer's instructions. In the cell lysis step, the cells were sonicated for three cycles at maximum speed for 30 s, with 1 min rest between the cycles (Soniprep 150, MSE supplies LLC).

Preparation of agarose pads for imaging

For *E. coli* imaging on agarose pads, we prepared 2% molten low gelling temperature agarose in M9 media with supplements and added IPTG (0.4 mM), TBI (10 µM), HBC620 (5 µM), and matching antibiotics. The molten agarose solution was kept at 50 °C, and 100 µL were added to a smaller gene frame (10 mm × 10 mm) adhered to a microscope slide (Clear ground 0.8-1.0 mm, Fisher Scientific). The molten agarose was sandwiched between two glass slides and left at 25 °C for 10 min to solidify. The solidified agarose was transferred to larger gene frames (17 mm × 28 mm) adhered to a glass slide. 2 µL of the prepared cells were added to each agarose pad, and after 5 minutes at 25 °C, a coverslip (24 mm × 60 mm, No.1, Epredia) was adhered to the other side of the gene frame.

Confocal imaging of *E. coli*

The prepared agarose pads were imaged with a Zeiss LSM 800 confocal microscope, using a Plan-Apochromat 63× 1.4 N.A. Oil DIC M27 objective. The fluorescent signal from the Pepper aptamer was acquired using a 561 nm laser set to 1.0% intensity and a Master Gain of 500 V, with an emission window of 580 to 650 nm. The fluorescent signal from the Broccoli aptamer and GFP was acquired using a 488 nm laser set at 2.0% intensity for A+$\bar{\text{B}}$ and 1.0% for all other samples and a Master Gain of 500 V, with an emission window of 470 to 580 nm for all samples other than for A+$\bar{\text{B}}$, which had a restricted emission window of 470 to 530 nm. The settings for samples A+$\bar{\text{B}}$ were optimized to minimize bleed-through of the Pepper fluorescence in the Broccoli channel. While this fluorescence is weak and generally not noticeable in other samples, it becomes noticeable here because A is concentrated at MLOs, and $\bar{\text{B}}$ is mostly evenly distributed (Supplementary Fig. 21). The image frame size was set to 1192 pixels × 1192 pixels with 16 bit depth. Line-averaging was enabled and set to 4×. The scan mode along the x direction was selected to be bidirectional. The scanning rate was set to produce a scanning time of 1.77 µs per pixel.

FRAP of *E. coli*

The 561 nm laser was set at 100% intensity for photobleaching A MLOs, while the 488 nm laser was set at 100% intensity for photobleaching B MLOs and GFP-containing MLOs. A total of 25 A MLOs, 12 B MLOs, and 25 GFP-containing MLOs were chosen for photobleaching, with the entire condensate bleached in each case. A total of 15 A MLOs, 8 B MLOs, 15 GFP-containing MLOs were chosen as non-photobleached controls. Fluorescence recovery was monitored at 10 s intervals. Condensate intensity was quantified as the mean intensity of the 10 brightest pixels within the MLO.

Epifluorescence imaging of *E. coli*

Time-lapse images of *E. coli*

Time-lapse images of cells expressing NS A were acquired with a Ti2 Eclipse Epifluorescent microscope (Nikon), equipped with an sCMOS camera (Hamamatsu ORCA-Flash4.0 V3), a tuneable light source (Lumencor SPECTRA X LED engine),

and CFI Plan Apo λD 60× 1.42 N.A. oil immersion objective. The Pepper aptamer was excited using a 555 nm LED with an LED-DA/FI/TR/Cy5-B filter, and fluorescence was collected through an FF01-624/40 emission filter with a 500 ms exposure time. Images were taken every 5 min. Samples were incubated at 37 °C using a heating stage (Temikra Ltd.).

Temperature-dependent dissolution and re-assembly of MLOs

To study the melting and reforming of MLOs in bacteria, bacteria with NS A or NS B were prepared for imaging as described previously, except that 2% agarose low EEO was used for the agarose pads. *E. coli* samples on agarose pads were attached to a Peltier microscope stage (Temikra Ltd.) equipped with sapphire microscope window to ensure optical transparency and good thermal conduction (UQGOptics), and imaged with a Ti2 Eclipse Epifluorescent microscope (Nikon), equipped with an sCMOS camera (Hamamatsu ORCA-Flash4.0 V3), a tuneable light source (Lumencor SPECTRA X LED engine), and a CFI Plan Apo λD 60× 1.42 N.A. oil immersion objective. The Pepper aptamer was excited using a 555 nm LED with an LED-DA/FI/TR/Cy5-B filter, and fluorescence was collected through an FF01-624/40 emission filter with a 500 ms exposure time. The Broccoli aptamer was excited using a 470 nm LED with an LED-DA/FI/TR/Cy5-B filter, and fluorescence was collected through an EM510 emission filter with a 2 s exposure time. The samples were heated from 37 °C to either 58 °C or 60 °C with increments of 3 °C every 2 min. Samples were then cooled from their maximum temperature to 37 °C with increments of 3 °C every 2 min. For bacteria co-expressed with NS A_{AP3} and GFP, cells were imaged using the same Pepper aptamer settings as for Nanostar A, while the GFP signal was captured on the 470 nm LED with an LED-DA/FI/TR/Cy5-B filter, and fluorescence was collected through an EM510 emission filter with a 50 ms exposure time. Cells were heated to 37 °C, 60 °C, 70 °C and cooled to 37 °C, with 2 min incubation periods between each temperature.

Analysis of *E. coli* micrographs

Images and metadata were extracted from .czi (Zeiss) or .nd2 (Nikon) files using pylibCZIrw and Nd2Reader, respectively. Images were rescaled to a float range of [0,1] using skimage [89]. The brightfield image underwent flat-field correction and non-local means denoising. Initial binary masks of the cells were generated using a calculated threshold and adjusted manually if needed. Small holes were filled, and objects with an area smaller than half of a typical *E. coli* cell (2 µm × 0.5 µm) were removed. Since the algorithm struggled to segment individual bacteria within microcolonies, bacteria inside these regions were filtered out based on object proximity. Objects on image borders were discarded. The remaining objects were filtered based on eccentricity (higher than 0.85), aspect ratio (between 2.5 and 4.5), area (smaller than 7.07 μm^2), and width of *E. coli* (smaller than 1.5 µm) [90–93]. The final segmented set was further filtered manually via an interactive GUI. For R^2 calculation, pixel intensities from one fluorescent channel were compared against those from another, yielding the coefficient of determination (R^2). To compute kurtosis and skewness for each bacterium, pixel intensities in segmented single cells were normalized so that the top 5

% of pixels had a value of 1. These pixels were then removed, and kurtosis and skewness of the pixel-intensity distribution were calculated using Scipy [94]. To determine the number of MLOs per bacterium, each segmented bacterium was rotated so that its long axis aligned horizontally. To minimize interpolation loss, pixels were subdivided into 16 smaller pixels before rotation. Intensities were then averaged vertically to obtain a linear profile, from which peaks were detected using Scipy. The sensitivity of peak detection was manually adjusted based on noise levels. For heatmaps of fluorescence intensity, horizontally aligned bacteria were scaled to a standardized size of 48 pixels $\times$ 130 pixels, and pixel intensities were averaged across aligned positions. To determine locations of MLOs, the condensates were segmented using adaptive thresholding (cv2) [95]. MLO positions and sizes were validated by comparing them to peaks detected at similar locations within the cell to prevent misclassification. The MLO position was recorded as the highest-intensity pixel within the mask. All analyses were performed using Python 3.10, and visualisations were generated with Matplotlib [96] and Seaborn [97].

Analysis of the temperature-dependent dissolution and reassembly of MLOs

Micrographs were analyzed fully automatically to obtain segmented bacteria. Heatmap progression across different temperatures was determined by extracting the maximum intensity along the long axis of standard heatmaps, computed as discussed above. The skewness of the intensity distribution of the pixel intensity within single cells was used to monitor the progression of dissolution and reassembly. To estimate the proportion of cells with and without MLOs, the distribution of skewness values across the cell population at a given temperature was fitted using a mixture of two Gaussians (using skimage), with one Gaussian fitting the sub-population of cells with high skewness (featuring condensates) and the second fitting the sub-population of cells with low skewness (lacking condensates) [89]. For each cell, the probability of belonging to either sub-population was calculated. If the probability of belonging to the MLO-forming distribution exceeded 0.5, the cell was classified as MLO-forming.

Growth and RNA production curves in bulk cultures

To characterize growth and RNA production in bulk cell samples, *E. coli* from single colonies were grown in M9 media with supplements for 4 h as described previously. *E. coli* samples were then diluted to OD_{600}= 0.05. 100 µL of the diluted solutions were loaded in a Nunc MicroWell 96-Well Optical-Bottom well plate, together with TBI (10 µM), HBC620 (5 µM), and matching antibiotics. The samples were cultured at 37 °C in a plate reader (Tecan M2000). Every 7 minutes, the plate was shaken (orbital) for 5 s with 3.5 mm amplitude, followed by absorbance and fluorescence measurements. For absorbance, wavelength was set to 600 nm and bandwidth was set to 9 nm. For detecting Broccoli fluorescence we set excitation wavelength to 470 nm, excitation bandwidth to 9 nm, emission wavelength to 520 nm and emission bandwidth to 20 nm. For Pepper fluorescence, we set excitation wavelength to 570 nm, excitation bandwidth to 9 nm, emission wavelength to 620 nm and emission bandwidth to 20 nm. When the

OD_{600} reached 0.7, we added 0.4 mM IPTG to the samples requiring induction, before continuing the experiment with unchanged settings.

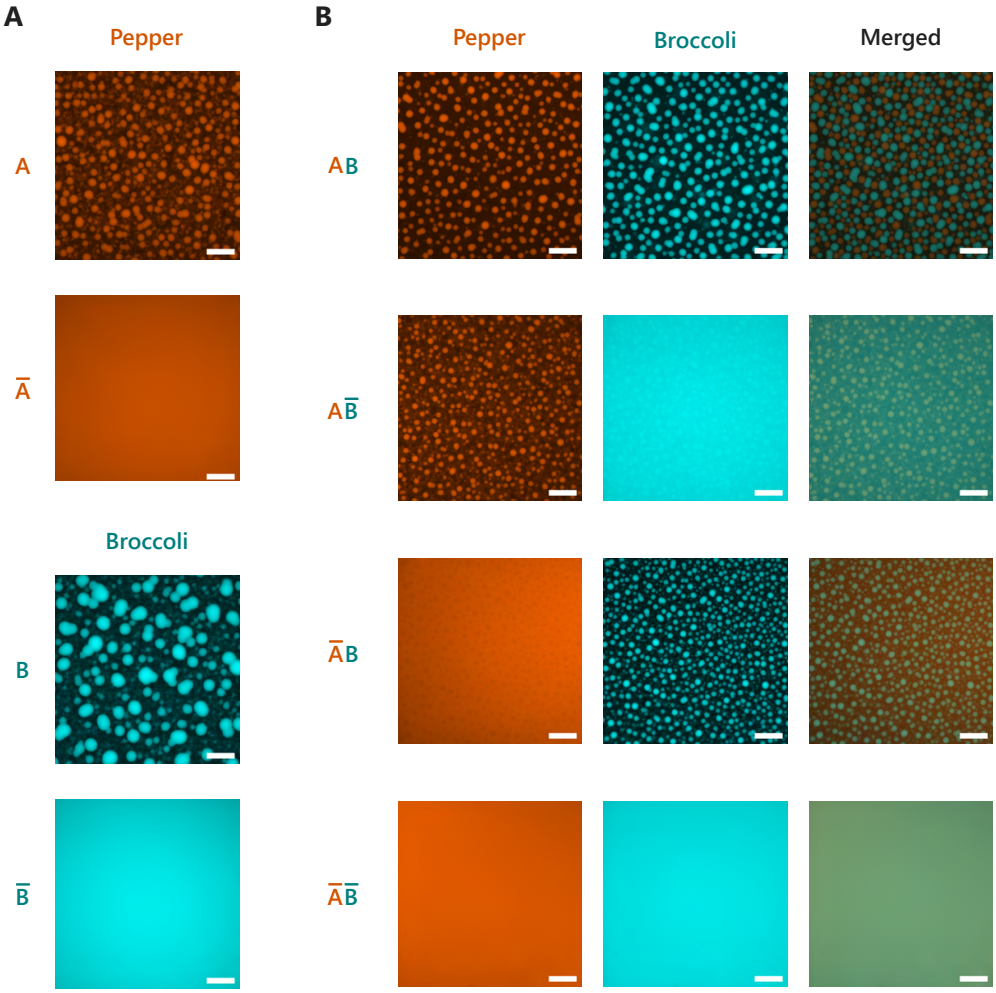
RNA sequencing of *E. coli*

E. coli expressing A or B nanostars were induced for 1 h as described previously. Cells were pelleted and shipped to Full Circle Labs for RNA extraction, poly(A) tailing, and nanopore sequencing. To identify start and end positions of RNA raw reads [98], the reads were aligned to the expected RNA sequence with Needleman-Wunsch algorithm [99], and reads with alignment scores corresponding to ≥ 7 matched nucleotides were retained for further analysis. Due to known imprecision in basecalling near the 5' ends of direct nanopore RNA reads [100], fragment start positions were defined as the first aligned nucleotide in a stretch of at least 3 consecutive matches between the read and the expected sequence.

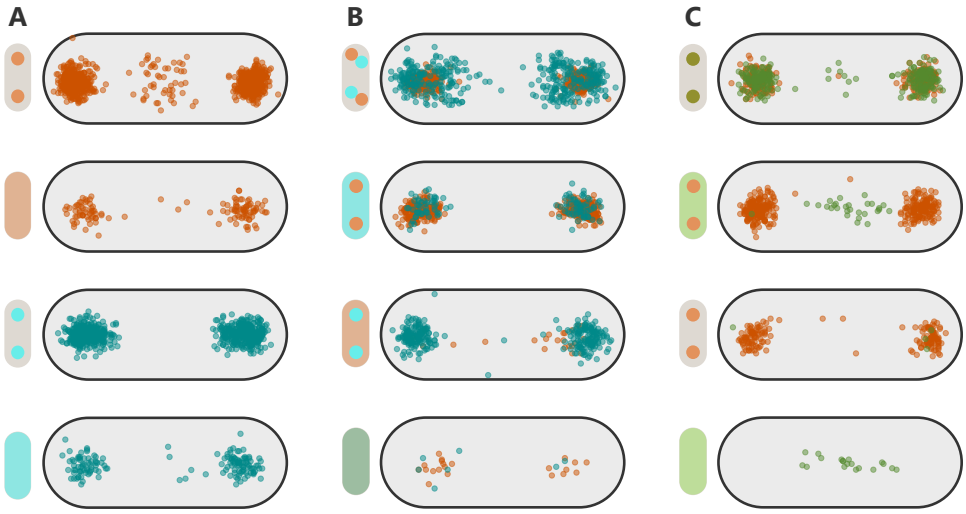
Polyacrylamide gel electrophoresis

The gels were prepared with a 19:1 w/v acrylamide:bis-acrylamide solution in Tris-Borate-EDTA (TBE) buffer. Acrylamide fractions (w/w) of 6 % and 8 % were used for native and denaturing gels, respectively. The denaturing gel contained 7 M urea. For both native and denaturing PAGE, samples transcribed in vitro were diluted 1:10 before loading in the respective lanes. For *E. coli* RNA extracts, 500 ng of RNA were used. Samples were heated to 70 °C for 10 min before loading. For native gels, one lane contained the GeneRuler 100 bp DNA Ladder, while a RiboRuler Low Range RNA Ladder was used for denaturing gels. For both native and denaturing gels, sample stacking was performed by running the gel at 40 V for 20 min immediately after loading. The native gels were then run 150 V for 60 min, while the denaturing gels were run at 270 V for 60 min. All gels were run in TBE. Gels were stained after electrophoresis with 1 × SYBR Gold nucleic acid gel stain and imaged using a Syngene G:BOX Chemi XRQ gel documentation system. Lane intensities were quantified using ImageJ [101]. The full, un-cropped gel images are shown in Supplementary Fig. 36.

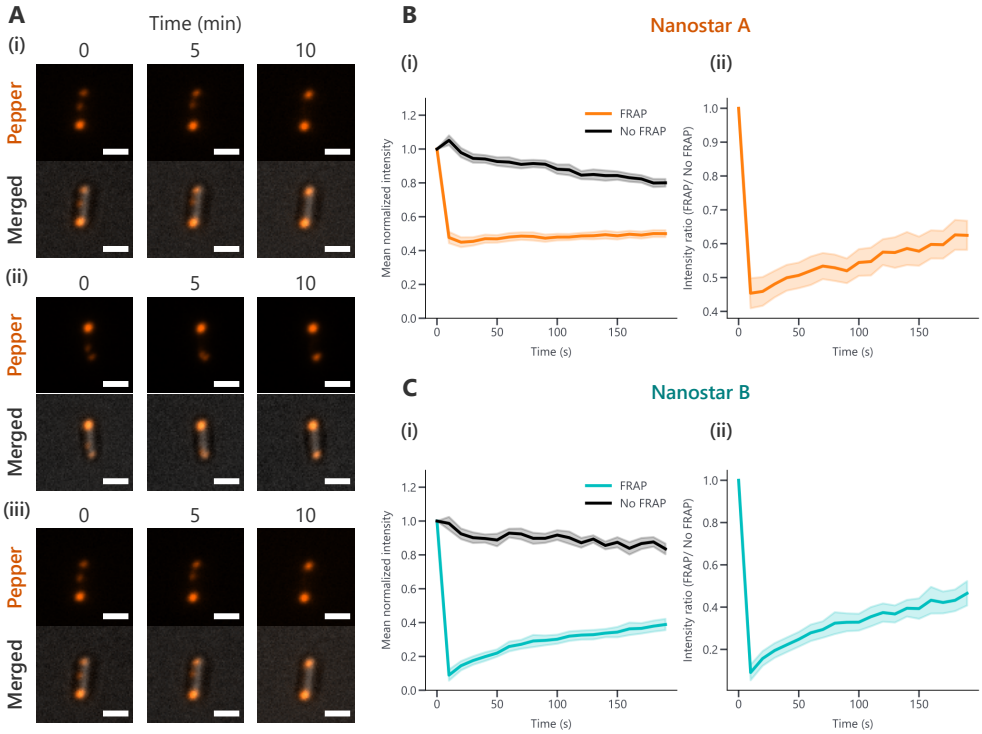
Extended data figures



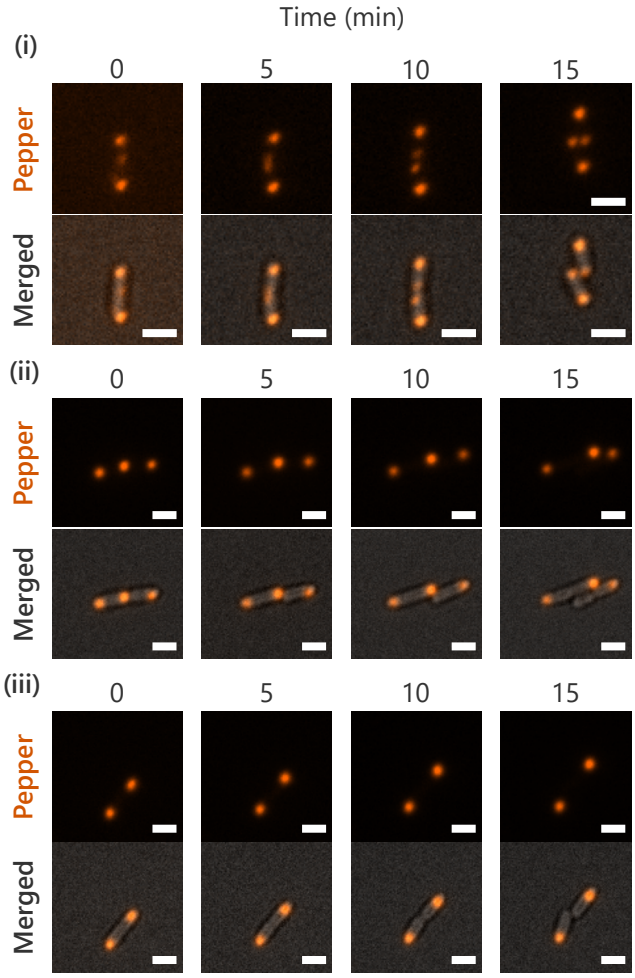
Extended Data Figure 1: **Epifluorescence micrographs of in vitro expression of single NSs and co-expression of two NSs.** (**A**) Epifluorescence images of samples expressing single NSs, from top to bottom: A, Ā, B, B̄. (**B**) Epifluorescence images of samples co-expressing two NSs, from top to bottom: A+B, A +B̄, Ā+B, Ā+B̄. Images are shown in the Pepper fluorescent channel (NS A, left), in the Broccoli fluorescent channel (NS B, centre) and merging both channels (right). All samples were expressed from linear DNA templates with terminators (Methods) and imaged 4 hours after initiating the reactions. Scale bars, 100 µm.



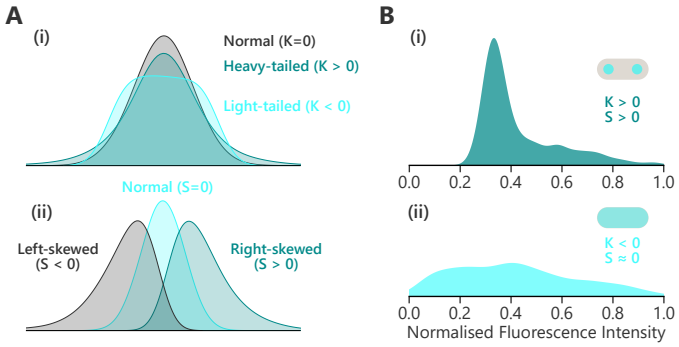
Extended Data Figure 2: **Locations of MLOs within bacteria.** (**A**) Data for cells expressing a single NS, from top to bottom: A, $\bar{A}$, B, $\bar{B}$. NSs A and B display MLOs tightly localised at the poles. In NS A, some MLOs were also found near the centre of the cell. In contrast, NSs $\bar{A}$ and $\bar{B}$ showed few clusters at the poles. (**B**) Data for cells expressing two NSs, from top to bottom: A+B (also shown in Fig. 2), A +$\bar{B}$, $\bar{A}$+B, $\bar{A}$+$\bar{B}$. In cells expressing A+B, A-MLOs are always found at the poles, while B NSs are sometimes closer to the centre of the cell. In cells expressing A+$\bar{B}$ and B+$\bar{A}$ both specific MLOs and non-specific clusters are located at the poles. (**C**) Data relative to GFP capture experiments. From top to bottom, cells express: A_{AP3} + GFP, A + GFP, A_{AP3} only, and GFP only. When A_{AP3} and GFP are expressed, we observe polar co-localisation of proteins and NSs. Expressing either NS A (in the presence of GFP) or A_{AP3} (in the absence of GFP) produces polar MLOs. No significant fluorescent localisation is observed if only GFP is expressed. Colour-coding is as follows. Orange: NS A (left and middle) and NS A_{AP3} (right); Cyan: NS B; Green: GFP. MLO locations were determined using segmentation and, as a result, not all MLOs identified by peak-picking were successfully located (Methods).



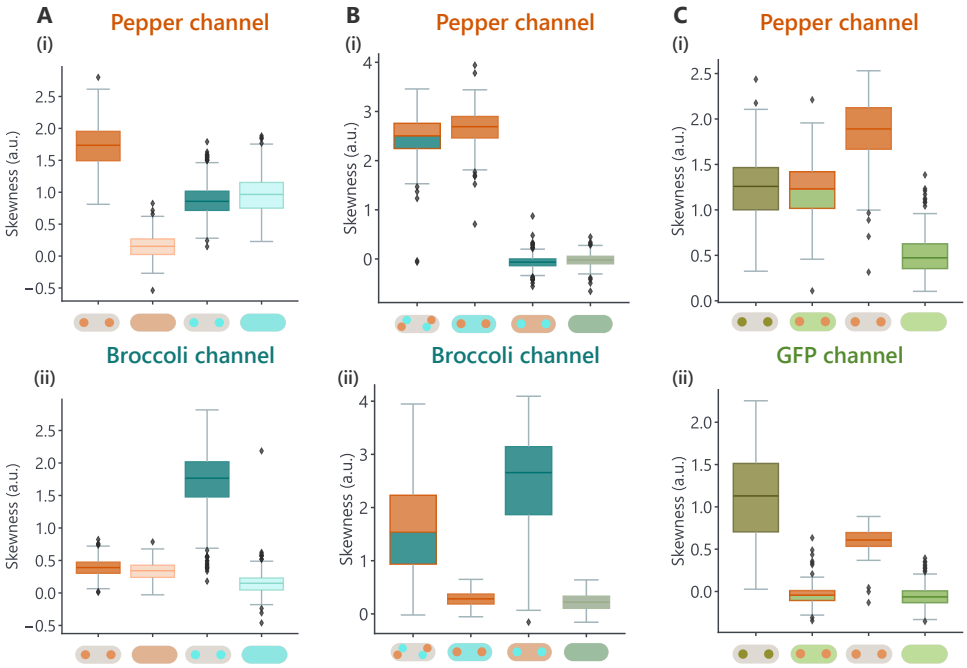
Extended Data Figure 3: **Fluidity of MLOs in *E. coli*.** (**A**) Timelapse micrographs of three fusion events (i-iii) involving A MLOs. For each sequence, the top row shows confocal images and the bottom row shows merged confocal and bright-field images. Scale bars, 2 µm. (**B**) Fluorescence recovery after photobleaching (FRAP) for A MLOs. (i) FRAP curves collected for A MLOs. For each condensate, fluorescence intensity prior to photobleaching was normalized to 1. MLOs were obtained from three separate cultures, each starting from an individual single colony. The orange solid line (FRAP) is the mean normalized intensity of photobleached condensates ($n = 25$ MLOs), while the black solid line (No FRAP) is the mean normalized intensity of non-photobleached condensates ($n = 15$ MLOs). The decreasing trend in the intensity of non-photobleached condensates is caused by a degree of photobleaching occurring during imaging in the recovery phase. Shaded areas indicate the standard error of the mean. (ii) Ratio of the mean normalized intensity of photobleached A MLOs to the mean normalized intensity of non-photobleached A MLOs, correcting for photobleaching occurring in the recovery phase. The shaded area represents the standard error of the mean of the intensity ratios. (**C**) Data as in panel **B**, but for FRAP of B MLOs. (i) The cyan solid line (FRAP) is the mean normalized intensity of photobleached condensates ($n = 12$ MLOs), while the black solid line (No FRAP) is the mean normalized intensity of non-photobleached condensates ($n = 8$ MLOs).



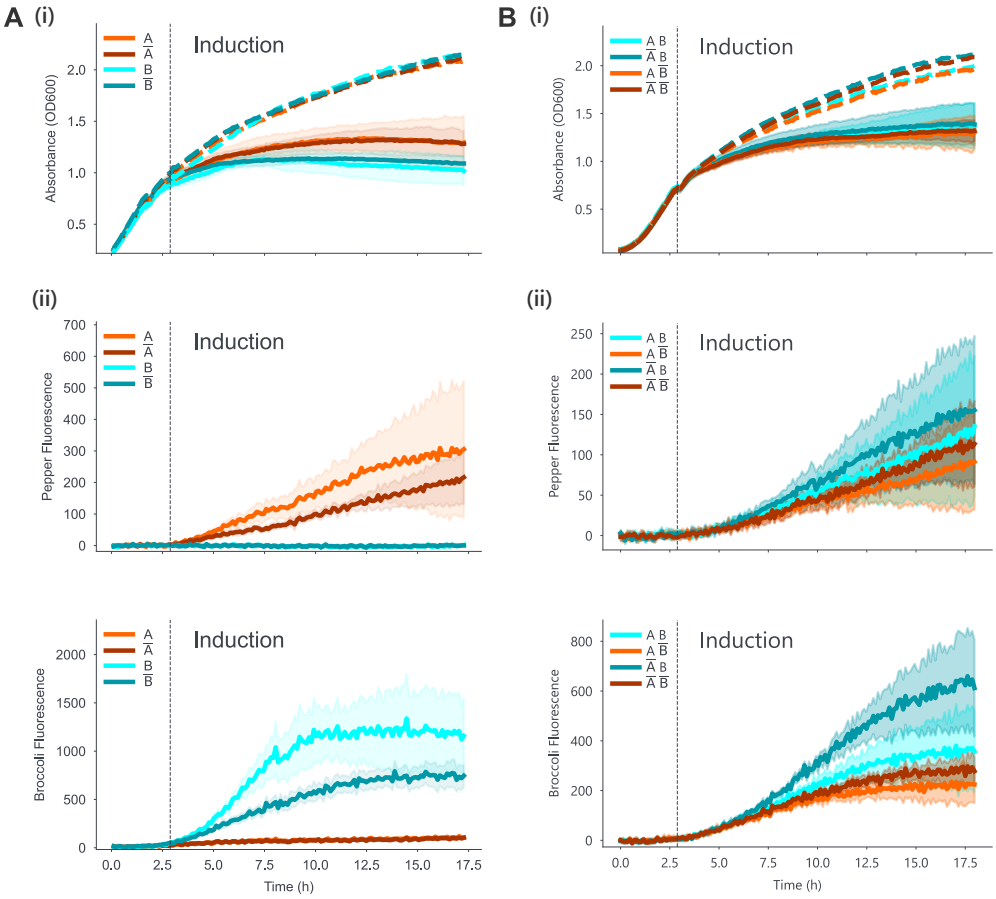
Extended Data Figure 4: Timelapse micrographs of three division events in cells expressing A MLOs. For each sequence, the top row shows confocal images and the bottom row shows merged confocal and bright-field images. The three examples show the different behaviours observed upon division. A typical cell featuring two polar MLOs may grow a third condensate in the central section as it approaches division (i-ii). The central condensate can then be split between the two daughter cells, resulting in both having two polar condensates (i). Alternatively, the central condensate may be fully encased in one of the daughter cell, leaving the other with a single MLO. In other cases, a cell may divide without forming a central condensate, leaving both daughter cells with a single MLO. Scale bars, 2 µm.



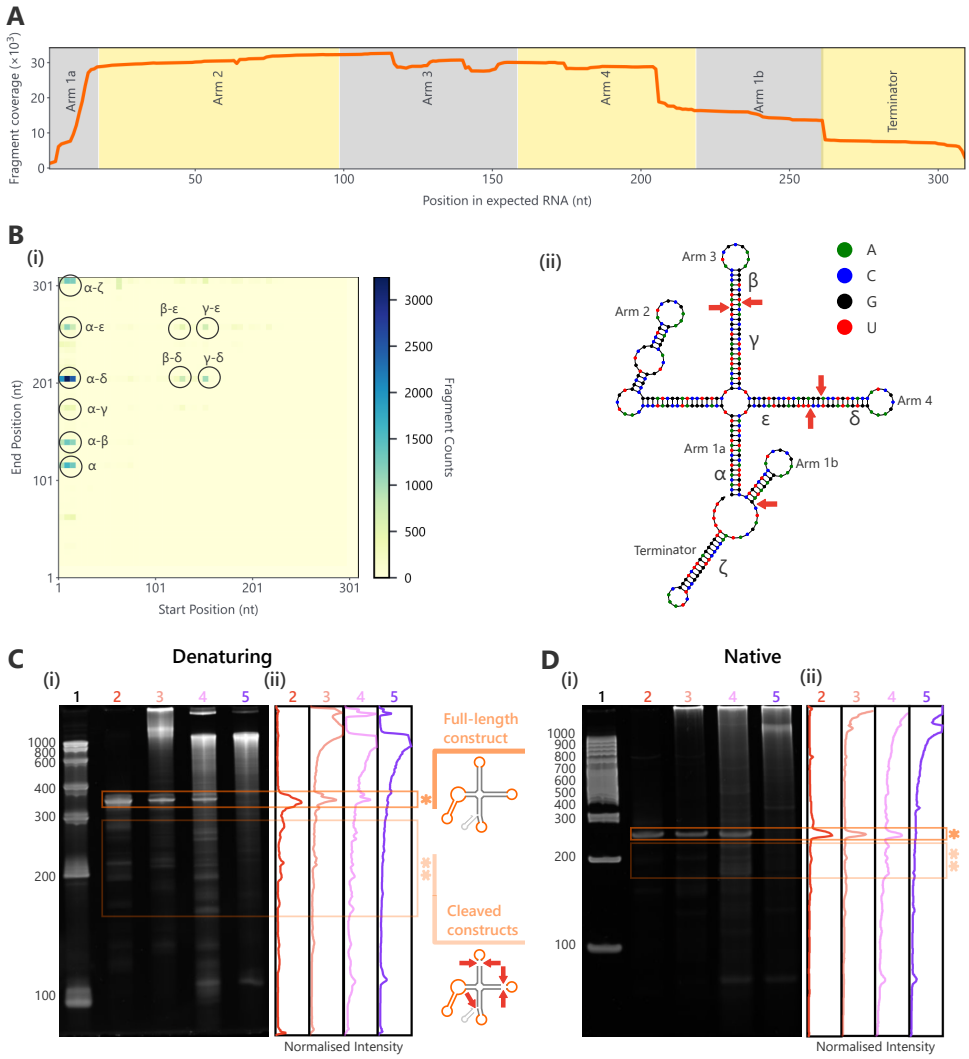
Extended Data Figure 5: **Interpretation of kurtosis and skewness of the pixel-fluorescence distributions of single cells, used to assess MLO formation.** (**A**)(i) Examples of neutral, positive, and negative kurtosis (K). Positive kurtosis indicates a heavy-tailed distribution, while negative kurtosis indicates a light-tailed one. (ii) Examples of neutral, positive, and negative skewness (S). Positive skewness reflects a right-skewed distribution, whereas negative skewness reflects a left-skewed one. (**B**) Examples of pixel-fluorescence distributions for MLO-forming (i) and non-MLO-forming cells (ii). To obtain the distributions used for calculating kurtosis and skewness, fluorescence intensities are normalized such that 5% of the data points have a value of 1; these points are then excluded from the distribution. In MLO-forming cells (i), the distribution shows a sharp peak corresponding to background fluorescence and a long right-skewed tail originating from the brighter MLOs, resulting in positive kurtosis and skewness. In contrast, non-MLO-forming cells (ii) exhibit a more uniform fluorescence distribution across the cell, leading to near-zero skewness and negative kurtosis, which reflect the absence of distinct intensity peaks or heavy tails.



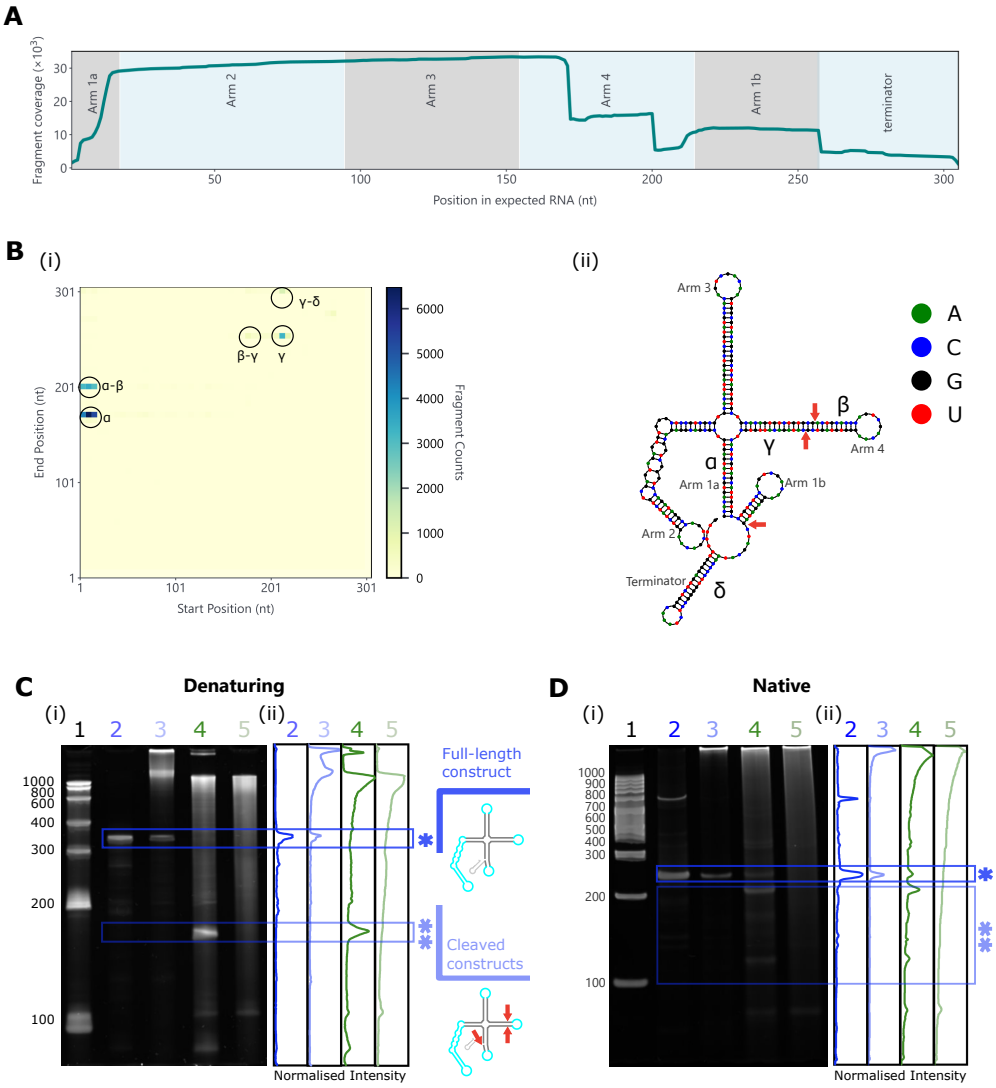
Extended Data Figure 6: **Comparing pixel-intensity-distribution skewness for NS-expressing *E. coli*.** (**A**) Cells expressing single NSs, from left to right: A, $\bar{A}$, B, and $\bar{B}$. In the Pepper channel (i), NS A exhibits high skewness compared to NS $\bar{A}$. Similarly, in the Broccoli channel (ii), NS B shows higher skewness than NS $\bar{B}$. Cells that do not express NSs fluorescent in the respective channel display skewness values around 0.5. (**B**) Cells expressing two NSs, from left to right: A+B, A+$\bar{B}$, $\bar{A}$+B, and $\bar{A}$+$\bar{B}$. Cells expressing NS A show high skewness in the Pepper channel (i) relative to those expressing NS $\bar{A}$. Likewise, cells expressing NS B exhibit high skewness compared to those expressing NS $\bar{B}$ in the Broccoli channel (ii). (**C**) Experiments designed to demonstrate GFP capture. From left to right, cells express A_{AP3} + GFP, A + GFP, A_{AP3} only, and GFP only. Cells expressing NSs A or A_{AP3} display high skewness in the Pepper channel (i) compared to those not expressing either NS. Cells that capture GFP into MLOs exhibit high skewness in the GFP channel (ii) compared to cells where GFP remains evenly distributed throughout the cytoplasm. Cells lacking GFP entirely show intermediate skewness values around 0.6.



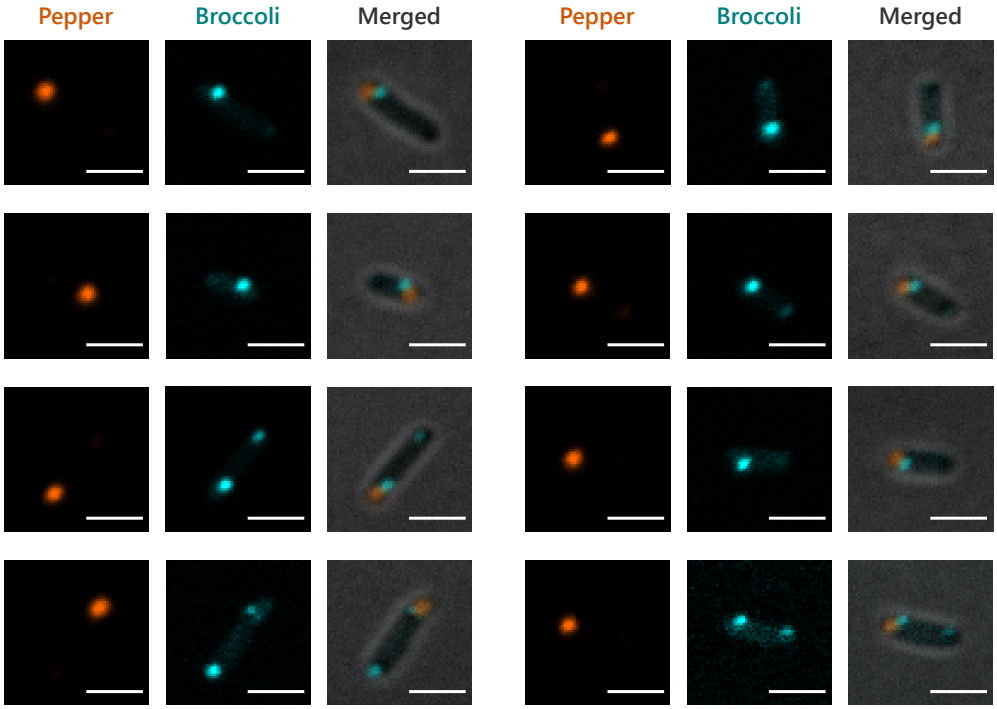
Extended Data Figure 7: Growth and fluorescence curves of bulk *E. coli* cultures expressing single NSs or co-expressing two NSs. (**A**) Single NSs. (i) Optical Density (OD) curves for samples with (solid line) and without IPTG induction (dashed line, Supplementary Fig. 15). (ii) Fluorescence curves collected in the Pepper (NSs A and $\bar{A}$) and Broccoli (NSs B and $\bar{B}$) channels for induced samples. (**B**) Data as panel **A**, but for growth and fluorescence curves of cultures expressing two NSs (Supplementary Fig. 23). For each condition, measurements were performed for three biological replicates from separate single colonies, with three technical replicates studied per biological replicate. Solid lines represent the mean values across all replicates, while the shaded regions indicate the standard deviation across all replicates.



Extended Data Figure 8: Sequencing and PAGE analysis of NS A. (**A**-**B**) Nanopore sequencing of NS A as extracted from *E. coli*. (**A**) Coverage plot showing the number of aligned RNA fragments overlapping the expected NS A transcript. Coloured sections indicate the structural elements of the NS, with Arm 2 including the FLAP. The coverage profile confirms that the entire NS is transcribed, and highlights cleavage at specific sites ascribed to the post-transcriptional action of endonucleases. Fewer counts are obtained for the smaller fragments, which may be a result of bias in library preparation for sequencing [102, 103]. (**B**) (i) Binned scatter plot displaying the frequency of sequencing reads starting and ending at specified positions of the expected NS A sequence. High frequency locations mark RNA fragments, which are circled and labelled. (ii) NUPACK [86] schematic of the NS structure highlighting the fragments labelled in (i) and the preferential cutting sites (red arrows). The full-length transcript (without the terminator sequence: α-ε; with the terminator sequence: α-ζ) can be found. (**C**)(i) Denaturing PAGE of NS A samples. Lane legend: 1, RiboRuler Low Range RNA Ladder with marked band sizes (nt); 2, NS A transcribed in vitro from a linear DNA template; 3, NS A transcribed in vitro from a plasmid; 4, total RNA extract from *E. coli* induced to express NS A; 5, total RNA extract from uninduced *E. coli*. (ii) Lane intensity profiles. * marks the full-length construct, ** cleaved constructs. The full-length transcript is detected in lanes 2-4, with lane 4 (induced *E. coli*) also showing truncated products, consistent with sequencing. (**D**) Native PAGE of NS A samples, with lanes as in **C** except for using the GeneRuler 100 bp DNA Ladder in Lane 1. The full-size construct is detected in lanes 2-4, and constitutes the dominant species. High molecular weight material in lane 3 likely results from non-terminated transcripts, given the lower efficiency of termination in vitro [77], while those in lanes 4 and 5 are ascribed to mRNA.



Extended Data Figure 9: **Sequencing and PAGE analysis of NS B.** (**A-B**) Nanopore sequencing of NS B as extracted from *E. coli*. (**A**) Coverage plot showing the number of aligned RNA fragments overlapping the expected NS B transcript. Coloured sections indicate the structural elements of the NS, with Arm 2 including the FLAP. The coverage profile confirms that the entire NS is transcribed, and highlights cleavage at specific sites ascribed to the post-transcriptional action of endonucleases. Fewer counts are obtained for the smaller fragments, which may be a result of bias in library preparation for sequencing [102, 103]. (**B**) (i) Binned scatter plot displaying the frequency of sequencing reads starting and ending at specified positions of the expected NS A sequence. High frequency locations mark RNA fragments, which are circled and labelled. (ii) NUPACK [86] schematic of the NS structure highlighting the fragments labelled in (i) and the preferential cutting sites (red arrows). The full-length transcript were not detected. (**C**)(i) Denaturing PAGE of NS B samples. Lane legend: 1, RiboRuler Low Range RNA Ladder with marked band sizes (nt); 2, NS B transcribed in vitro from a linear DNA template; 3, NS B transcribed in vitro from a plasmid; 4, total RNA extract from *E. coli* induced to express NS B; 5, total RNA extract from uninduced *E. coli*. (ii) Lane intensity profiles of the gels. * marks the full-length construct, ** cleaved constructs. The full-length transcript is detected in vitro (lanes 2 and 3) but not in induced *E. coli* (lane 4), consistent with sequencing. (**D**) Native PAGE of NS B samples, with lanes as in **C** except for using the GeneRuler 100 bp DNA Ladder in Lane 1. The full-size construct is detected in lane 4 in moderate quantities, likely nicked and stabilised by base pairing. The shorter dominant construct may lack the KL in Arm 4. High molecular weight material in lane 3 likely results from non-terminated transcripts, given the lower efficiency of termination in vitro [77], while those in lanes 4 and 5 are ascribed to mRNA.



Extended Data Figure 10: **Zoomed in micrographs of cells co-expressing NSs A and B.** Zoomed in confocal micrographs recorded in the Pepper channel (NS A, left), the Broccoli channel (NS B, centre) and merging both fluorescence channels with bright-field images (right) of *E. coli* co-expressing NS A and NS B, 1 h after IPTG induction. Scale bars, 2 µm.