Review
Who Regulates Whom? An Overview of RNA Granules and Viral Infections

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Abstract: After viral infection, host cells respond by mounting an anti-viral stress response in order to create a hostile atmosphere for viral replication, leading to the shut-off of mRNA translation (protein synthesis) and the assembly of RNA granules. Two of these RNA granules have been well characterized in yeast and mammalian cells, stress granules (SGs), which are translationally silent sites of RNA triage and processing bodies (PBs), which are involved in mRNA degradation. This review discusses the role of these RNA granules in the evasion of anti-viral stress responses through virus-induced remodeling of cellular ribonucleoproteins (RNPs).

Keywords: RNA granules; stress granules; P-bodies; anti-viral host immune response; translation control

1. Introduction

The control of the translation and turnover of mRNAs plays fundamental roles in the regulation of gene expression. Eukaryotic cells have developed different mechanisms to control these processes in order to respond to environmental stress, such as heat shock, UV irradiation, hypoxia, endoplasmic reticulum (ER) stress and viral infection. Among those mechanisms is the assembly of non-membrane-delimited bodies, called RNA granules, that contain RNA-binding proteins (RBPs) and translationally silenced mRNAs [1,2].

The classification of RNA granules is based on a number of factors, including their subcellular localization (nuclear, cytoplasmic, axonal, etc.), the presence of specific markers, the cell type where they are assembled (germ cells, neurons), response to stimuli (stress, viral infection), dynamic behavior and proposed functions (sites of mRNA storage/decay, stress response, etc.) [3]. The nucleus contains the nucleolus, nuclear speckles, nuclear stress bodies, the transcription factory, Cajal bodies, the Gemini of Cajal bodies, the histone locus body, paraspeckles and PML bodies, all of which have specific regulatory functions (reviewed in [4,5]). The cytoplasm harbors the polar and germinal granules, stress granules (SGs), processing bodies (P-bodies or PBs) and neuronal granules [6,7]. Many RNA viruses have evolved mechanisms to modulate the assembly of different RNA granules. In this review, we will summarize the regulation of SGs and PBs by different virus families.

2. RNA Granules: Stress Granules (SBs) and Processing Bodies (PBs)

SGs and PBs are associated with mRNA storage and decay, respectively [8]. Importantly, increasing evidence suggests that abnormal SG formation may promote several neurodegenerative
disorders, including amyotrophic lateral sclerosis (ALS), frontotemporal lobar degeneration (FTLD) and spinal muscular atrophy (SMA) [9]. The formation of SGs in response to chemotherapeutic treatments has also been associated with cancer cell survival [3]. SGs are specifically induced upon cellular stress [10], triggering global translational silencing typically through the phosphorylation of the translation initiation factor eIF2α. Four eIF2α kinases sense environmental stress: HRI (heme-regulated eIF2α kinase) is activated in heme deprivation and oxidative stress [11]; PKR, (Protein Kinase RNA-dependent) is a double-stranded RNA (dsRNA)-dependent protein kinase activated by viral infection [12]; PERK/PEK (PKR-like ER kinase) is activated during hypoxia and in response to misfolded proteins in the ER [13]; and GCN2 (general control non-derepressible-2) is activated during amino acid deprivation and UV irradiation [14]. The assembly of SGs can also occur independently of eIF2α phosphorylation, upon treatment with hippuristanol or pateamine A, drugs that inhibit the helicase activity of eIF4A [15,16]; oligomycin, FCCP or 2-deoxy-D-glucose, metabolic inhibitors that deplete cellular adenosine triphosphate [17]; hydrogen peroxide, a known inducer of reactive oxygen species [18]; as well as overexpression of the SG markers TIA1/TIAR [19] or G3BP-1 [20]. Recently, Kedersha and colleagues reported that SG assembly is finely regulated by the binding of G3BPs to Caprin1 or USP10 [21]. By contrast, PBs are constitutively present and respond to stimuli that affect mRNA translation and decay [7]. Three proteins are known to play a critical role in PB assembly, Edc3, Pat1 and Lsm4 [22,23], due to their Q/N-rich domains that have the potential to form aggregates [24]. PBs can release mRNA to allow their translation [25–27]. Additionally, emetine and cycloheximide, drugs that stabilize polysomes, dissolve both SGs and PBs, whereas puromycin, a drug that disrupts polysomes, promotes their assembly [27].

2.1. SG Components

SGs are composed of target mRNAs bound to translation initiation factors (eIF4G, eIF3, PABPC1, eIF2α-P, eIF5A) to allow the rapid restoration of translation once the stress is gone [19,28]. Many other proteins are involved in SG formation, such as mRNA binding proteins that provide translational control or mRNA stability (TIA-1, TIAR, HuR/ELAVL1, FXR1, Pum1) [6,29–31], proteins related to mRNA metabolism (G3BP1, G3BP2, p54/rck/DDX6, PMR1, SMN, Staufen1, DHX36, Caprin1, ZBP1, HDAC6, ADAR) [20,32–36] and signaling proteins (mTOR, RACK1, TRAF2) [37]. Moreover, interferon-stimulated gene (ISG) products, such as, PKR, ADAR1, RNA-sensing RIG-I-like receptors (RIG-I, MDA5, LGP2), RNase L and OAS, have been shown to colocalize with SGs following viral infections [38,39].

2.2. PB Components

PBs contain components of the mRNA decapping machinery (Dcp1/2, Lsm1-7, Edc3proteins) [40,41], scaffolding proteins (Ge-1/Hedls) [41], deadenylation factors (Ccr1, Caf1, Not1) [42], nonsense-mediated decay (NMD) proteins (SMG5-6-7, UPF1) [40,43] and translation control factors (CPEB, eIF4E-T) [32,44]. Most recently, Patel and colleagues showed that GW-bodies, which also are ribonucleoproteins (RNP)s involved in mRNA decay, are distinct from P-bodies. GW-bodies are unique in that they contain GW182, a large scaffolding protein containing an N-terminal domain composed of GW/GW motifs. The N-terminal GW/GW motif-bearing domain has been shown to bind to AGO2, while the C-terminus interacts with the CCR4-NOT deadenylation complex [45]. Moreover, GW-bodies have a different spatial-temporal regulation because they play a major functional role in miRNA-mediated gene silencing rather than degradation [45]. As a result of virus infection, ISGs can also be found in PBs [46]. Given that SGs and PBs are highly dynamic, many proteins have been described as being part of both RNA granules (APOBEC3G, Ago2, BRF1, DDX3, FAST, TTP, etc.) [29,47–49], suggesting that mRNAs can move between both mRNPs, thus regulating RNA homeostasis. A comprehensive list of SG, PB and SG/PB components is provided in Table 1.
Table 1. Components of stress granules (SGs) and processing bodies (PBs).

| SG Component       | Reference | SG Component | Reference |
|--------------------|-----------|--------------|-----------|
| ADAR               | [38,50]   | Mx67         | [51]      |
| AKAP350            | [52]      | MLN51        | [53]      |
| ANG                | [54]      | MS1          | [35]      |
| ATXN2/pbp1         | [56,57]   | mTOR         | [37,38]   |
| CALR               | [59]      | OFGOD1       | [60]      |
| Caprin1            | [61]      | P97/NAT1     | [62]      |
| CCAR1              | [52]      | PABP1        | [30]      |
| CIRP               | [63]      | PHB2         | [64]      |
| CUGBP1             | [65]      | PKP1/3       | [66]      |
| DDX1               | [67]      | PKR          | [38,50]   |
| DDX3/Ded1          | [51]      | PMR1         | [33]      |
| DHC1               | [68]      | PRTB         | [69]      |
| DIP5C1             | [70]      | PUM1         | [71]      |
| elf2B              | [72]      | PUM2         | [73]      |
| elf2x              | [74]      | RACK1        | [75]      |
| elf3               | [17]      | RRM42        | [76]      |
| elf4A1             | [17]      | RHAU/DHX36   | [36]      |
| elf4G              | [17]      | RIG-1        | [38,50]   |
| elf5A              | [77]      | RNU1         | [54]      |
| FAK                | [78]      | Rps20        | [79]      |
| FBP/KSRP           | [80]      | RSK-2        | [81]      |
| FUS                | [82]      | Sam68        | [83]      |
| FXR1/FXMR          | [31]      | SERBP1       | [84]      |
| FXR2P              | [31]      | SGNP         | [85]      |
| G3BP1              | [20]      | SMN          | [34]      |
| G3BP2              | [86]      | Staufen1     | [35]      |
| Grb7               | [78]      | TP43         | [87]      |
| HDAC6              | [88]      | TDRD3        | [84]      |
| hnRNP A1           | [89]      | TEF3         | [90]      |
| hnRNP K            | [76]      | TEFB         | [90]      |
| Hsp27              | [91]      | TRAF2        | [92]      |
| HuD                | [93]      | USP10        | [21,94]   |
| HuR                | [95]      | Vinexin      | [96]      |
| IFIH1/MDA-5        | [38,50]   | ZBP-1        | [97]      |
| IP5K               | [98]      |              |           |
| KHC/KLC            | [68]      |              |           |
| LINE1 ORF1p        | [99]      |              |           |
| MBNL1              | [67]      |              |           |

| PB Component       | Reference | PB Component | Reference |
|--------------------|-----------|--------------|-----------|
| Ccr4               | [100]     | Htt          | [101]     |
| Dcp1/Dcp2          | [100]     | LSM1         | [40]      |
| Ebs1               | [102]     | Pan2/3       | [103]     |
| Edc1-2             | [104]     | Pat1/Pat1L   | [100]     |
| Edc3               | [105]     | Pop2/Caf1    | [106]     |
| elf4E-T            | [107]     | PRMT1        | [108]     |
| Ge-1/Hedls         | [41]      | TNRC6B       | [109]     |
| GW182              | [110]     | UBF1         | [42]      |
| hMex3A             | [111]     | UBF2         | [42]      |
| hnRNP A3           | [112]     | UBF3         | [42]      |

| SG and PB Component| Reference | SG and PB Component | Reference |
|--------------------|-----------|---------------------|-----------|
| Ago1               | [48]      | NXF7                | [112]     |
| Ago2               | [113]     | PABP/Pab1          | [30,114]  |
| APOBEC3G           | [47,115]  | PCBP2               | [116]     |
| BRF1               | [117]     | RNP55/5cd6         | [118]     |
| CPEB               | [32]      | RCK/Dhh1/DDX6      | [32]      |
| Dcp2/Decpa         | [32]      | Roquin              | [119]     |
| elf4E              | [17]      | Smag1              | [120,121] |
| FAST               | [117]     | TIA1/TIAR          | [30,91,122] |
| hMex3B             | [123]     | TTP/BRF1           | [117]     |
| hnRNP Q            | [124]     | Xrn1                | [117]     |
| IPO8               | [125]     | YB-1                | [126]     |
| JNK                | [127]     |                     |           |
| Lin28              | [128]     |                     |           |
3. Viral Infection and Stress Granules

Several viruses modulate the assembly of SGs to promote viral replication and suppress the cellular stress response. The discussion below was performed upon the interaction between virus families and SGs (Table 2).

3.1. Double-Stranded DNA (dsDNA) Viruses

Members of the family Herpesviridae and Poxviridae are enveloped double-stranded DNA (dsDNA) viruses. Herpes simplex virus type 1 (HSV-1) shuts off host protein synthesis by impairing the activation of eIF2 kinases through the virion host shutoff (vhs) protein [129], Us11 [130], ICP34.5 [131] and glycoprotein B (gB) [132]. During HSV-1 infection, the SG components TIA-1, TIAR and TTP are upregulated, but do not form SG, however, infection with vhs-defective HSV-1 triggers SG assembly [133,134], relying on PKR activity in the absence of vhs [135]. Recently, Finnen and colleagues have shown that infection with HSV type 2 (HSV-2) impairs arsenite-mediated SG assembly, while the SG induced by treatment with pateamine A are not affected [136]. The blockage in arsenite-induced SG assembly is dependent on vhs, as cells infected with a vhs defective HSV-2 mutant form SGs late during infection [137]. Human cytomegalovirus (HCMV) infection suppresses the assembly of SGs in cells treated with the ER stressor thapsigargin [138], while simultaneously inducing an unfolded protein response (UPR) and activating PERK, but limiting eIF2α phosphorylation to maintain viral RNA translation [139].

Vaccinia virus (VV), a member of Poxviridae family, replicates within the cytoplasm in large foci called DNA factories that co-opt SG proteins, such as G3BP1, Caprin1, eIF4E, PABP and eIF4G [140,141]. VV appears to utilize SG components for different purposes. The G3BP1/Caprin1 complex aids VV transcription [140]; viral translation initiation is dependent on eIF4E/eIF4G/PABP; and the viral protein I3 associates with eIF4G to recruit viral ssDNA [142], suggesting that SG components may link VV transcription and translation [141]. TIA-1 is not sequestered in DNA factories [143]; however, infection with a VV mutant lacking E3L, which activates PKR, induces aggregates that contain TIA-1, eIF3b, G3BP1 and USP10, called antiviral granules (AVGs), given that they restrict viral replication [94].

3.2. Double-Stranded RNA (dsRNA) Viruses

The family Reoviridae is composed of non-enveloped virions with a 9–12 dsRNA segment genome. The prototypical member of the family, rotavirus, causes the shut off of host protein synthesis [144], and despite inducing eIF2α phosphorylation, SG assembly is not induced, likely due to the translocation of PABP from the cytoplasm to the nucleus [144]. The persistent phosphorylation of eIF2α during rotavirus infection is PKR-dependent as a consequence of the high amount of viral dsRNA in the cytoplasm [145]. By contrast, mammalian orthoreovirus (MRV) induces SG assembly during the early stages of infection, at a step between viral uncoating and viral mRNA transcription, and requires phosphorylation of eIF2α, which is important to promote virus replication [146]. However, despite high levels of phosphorylated eIF2α, SGs are disrupted at later times during MRV infection [147]. Recently, Carroll and colleagues showed that the nonstructural protein µNS is recruited to SGs, but its expression alone was not able to modulate assembly, suggesting a relationship between viral factories and SGs [148].

3.3. Positive-Sense Single Strand RNA ((+)ssRNA) Viruses

All members of the Picornaviridae family are composed of non-enveloped particles. Evidence indicates that poliovirus (PV) proteinase 2A induces assembly of SGs early post-infection (between 2 and 4 h) [16,149], which are dispersed later in the infection through the cleavage of G3BP1 by the PV 3C proteinase (3Cpro) [150]. Interestingly, at a later time post-infection, aggregates containing viral RNA and TIA-1, but excluding the bona fide SG components eIF4G and PABP, are observed, suggesting that TIA-1 aggregation is unlinked from SG formation [151,152]. Encephalomyocarditis virus (EMCV) and...
Coxsackievirus B3 (CVB3) also disrupt SGs by cleavage of G3BP1 through a mechanism similar to that used by PV [50,153]. By contrast, Theiler murine encephalomyelitis virus (TMEV) and mengovirus, a strain of EMCV, inhibit SG assembly through the expression of the leader (L) protein, maintaining the G3BP-1 intact [154,155]. A mutant mengovirus, in which the Zn-finger domain of L is disrupted, induces G3BP1 aggregation in a PKR-dependent manner [155], suggesting that a G3BP1-Caprin1-PKR complex could induce innate immune activation during mengovirus infection [156].

In 2005, McInerney and colleagues showed that Semliki Forest virus (SFV), a member of the Togaviridae family composed of enveloped virions, is able to induce eIF2α phosphorylation promoting SG assembly at early stages of infection [157]. However, at late times post-infection, concomitant to an increase in vRNA levels, SFV is no longer able to promote SG assembly [157]. It was determined that the SFV-induced SG disassembly is caused by the C-terminal domain of the viral nonstructural protein 3 (nsP3), which forms a complex with G3BP1, sequestering it into the vRNA replication complex [158]. Chikungunya virus (CHIKV) nsP3 also sequesters G3BP1 and forms specific virus-induced cytoplasmic foci that lack the SG marker eIF3 and are resistant to cycloheximide treatment [159]. Later, Scholte and colleagues demonstrated that G3BP2, a close relative of G3BP1 containing a similar domain architecture, which is recruited into SGs [160], colocalized with CHIKV nsP2/3 [161]. G3BP2-containing complexes differs from the replication and transcription complexes (RTCs), suggesting a role of G3BP's in the early step of the CHIKV replication cycle [161]. Rubella virus (RUBV) induces G3BP1 aggregates that colocalize with viral ssRNA and non-structural viral protein P150, suggesting a potential post-replicative role in encapsidation [162]. Finally, the infection with Sindbis virus (SINV), another alphavirus, induces the assembly of G3BP1 aggregates, which interact with nsP2, nsP3 [163,164] and nsP4 [165]. In addition, it has been shown that SINV-derived vectors induce the assembly of bona fide SGs, containing TIA-1, elf4E and elf4G in a PKR-dependent manner [166].

The Flaviviridae family are composed of enveloped virions and West Nile virus (WNV) was the first virus reported to block SG assembly. Li and colleagues showed that the 3′ stem loop in the viral genome is able to capture TIA-1 and TIAR [167]. In addition, Emara and colleagues expanded these observations to dengue virus DENV-infected cells, where TIA-1/TIAR are found in RTCs [168]. However, the chimeric WNV W956IC, which produces high levels of early viral RNA, activates PKR and subsequently induces the SG assembly [169]. In another report, Xia and colleagues showed that DENV-infected A549 cells were able to induce G3BP1 aggregates independently of TIA-1 [170]. In addition, a proteomic analysis found that G3BP1, G3BP2, Caprin1 and USP10 interact with DENV RNA [171], and it was reported that G3BP1, G3BP2 and Caprin1 regulate the translation of ISG mRNAs, thus protecting DENV replication from IFN-mediated antiviral effects [172]. Consistent with these findings, TIA-1 and TIAR were also recruited to sites of tick-borne encephalitis virus (TBEV) replication. Indeed, elf2α becomes phosphorylated, and SGs containing G3BP1, elf3 and elf4B are induced in TBEV-infected cells [173]. On the other hand, the Japanese encephalitis virus (JEV) core protein was shown to sequester G3BP1 and USP10 through an interaction with Caprin1, resulting in the suppression of SG formation [174]. There is also evidence showing that infection with bovine viral diarrhea virus (BVDV), a Flaviviridae pestivirus, impairs the arsenite-mediated SG assembly, despite the fact that BVDV N-terminal protease (Npro) is able to interact with several RNA granules components, such as YB-1, IGFBP2, DDX3, ILF2 and RHA (DXH9) [175]. Contrasting the aforementioned flavivirus, HCV modulates the SG assembly by controlling the phosphorylation of elf2α. Ariumi and colleagues reported evidence indicating that HCV infection downregulates components of SGs (G3BP1, ATX2, PABP1) to lipid droplets (LDs), while Garaigorta and colleagues reported that HCV induces the assembly of bona fide SGs in a PKR-dependent manner. This report also demonstrated that TIA-1, TIAR and G3BP1 play a pivotal role in several steps of the HCV life cycle [176]. In addition, Ruggieri and colleagues observed rapid cycles of SG assembly and disassembly during the HCV infection depending on the elf2α phosphorylation state [177]. They reported that while SG assembly is regulated by dsRNA promoting phosphorylation of elf2α mediated by PKR, SG disassembly is regulated by a rapid elf2α dephosphorylation through both protein phosphatase 1 (PP1) and its regulatory subunit, growth arrest
and DNA-damage-inducible 34 (GADD34) [177]. Recently, another component of SGs, DDX3, has been reported to bind the HCV 3' UTR and IKKα, leading to its activation to induce LD biogenesis [178]. However, late in infection, DDX3 and G3BP1 localize with the HCV core protein around LDs in order to initiate viral particle assembly [179,180]. These observations could explain the oscillation of SG assembly/disassembly detected in HCV-infected cells [177] and how SG formation is necessary for HCV RNA replication, assembly and egress [176,181,182].

The infection with Cricket paralysis virus (CrPV), a member of Dicistroviridae family, prevents the aggregation of Rox8 and Rin, Drosophila SG marker homologs of TIA-1 and G3BP-1, respectively, even in the presence of various stressors, such as arsenite, pateamine A or heat shock [183]. Although the CrPV 3C proteinase is sequestered in SGs, cleavage of the Rox8 or Rin is not detected in CrPV-infected cells [183].

The family Coronavirusidae is composed of membrane-enveloped virions and one of the most significant features of coronaviruses is the expression of downstream genes via transcription of multiple 3' nested subgenomic mRNAs [184]. It has been shown that both mouse hepatitis coronavirus (MHV) and transmissible gastroenteritis virus (TGEV) induce TIA-1/TIAR aggregates with a concomitant increase in eIF2α phosphorylation levels [185,186]. MHV promotes SG assembly at early times post-infection [185], while TGEV induces SG assembly at later times post-infection [186]. During TGEV infection, the polypyrimidine tract-binding protein (PTB) is redistributed to the cytoplasm, associated with both TGEV gRNA and subgenomic mRNA (sgmRNA) and confined to TIA-1/TIAR aggregates [186].

Finally, Caliciviridae family is composed of non-enveloped virions and recently, Humoud and colleagues showed that the feline calicivirus (FCV) infection triggers eIF2α phosphorylation without inducing SG assembly [187]. This report demonstrated that the FCV viral 3C-like proteinase NS6 inhibit SG assembly by cleaving G3BP1 [187]. On the other hand, the murine norovirus 1 (MNV1) infection triggers eIF4E phosphorylation to control the translational machinery of the host cell [188], but does not impair SG assembly [187].

3.4. Negative-Sense Single Strand RNA (−ssRNA) Viruses

The family Orthomyxoviridae is composed of enveloped virions with a segmented, negative ssRNA genome [184]. Influenza A virus (IAV) suppresses the assembly of SG during viral infection by expressing the non-structural protein NS1, which inhibits PKR activity [189]. The ability of IAV to interfere with SG assembly is reverted with the expression of an NS1-mutant virus unable to bind dsRNA [189] or by expressing an NS1-deficient IAV, which promote SG assembly containing retinoic acid inducible gene I (RIG-I)-like receptors (RLRs), such as RIG-I, MDA5 and LGP2, or ISGs, such as PKR, RnaseL and OAS [39]. The NS1-mediated inhibition of SG assembly is dependent on the interaction with the RNA-associated protein 55 (RAP55) [190]. Besides NS1, the nucleoprotein (NP) and polymerase acidic protein X (PA-X) also contribute to block the SG assembly independent of eIF2α phosphorylation [191]. In addition, given that DDX3 has been implicated in the sensing of viral RNA to modulate IFN production and SG assembly (reviewed in [180]), Thulasi Raman and colleagues showed that DDX3 interacts with NP and colocalizes in SGs upon infection with an IAV mutant lacking NS1, suggesting a novel antiviral function for DDX3 [192].

Junin virus (JUNV) is a virus belonging to Arenaviridae, a family of enveloped virions with a bi-segmented negative-sense single strand RNA (−ssRNA) genome, that prevents SG assembly by impairing the phosphorylation of eIF2α [193], while the expression of JUNV nucleoprotein (N) and/or the glycoprotein precursor (GPC) are enough to inhibit SG assembly [193]. In addition, arenavirus RTCs contain ribosomal proteins L10a and S6 and translation initiation factors eIF4G and eIF4A and G3BP1 [194], suggesting a role of the SG component in the viral replication cycle.

Vesicular stomatitis virus (VSV), a virus in the family Rhabdoviridae, induces the phosphorylation of eIF2α and promotes the assembly of SG-like particles that contain TIA-1, TIAR, PCBP2, viral replication
proteins and RNA, but not the eukaryotic initiation factor 3 (eIF3), nor eIF4A [195], suggesting that the SG-like structures may play a role in the VSV infection cycle.

Members of Paramyxoviridae family are composed of enveloped virions. Respiratory syncytial virus (RSV) induces SG assembly mediated by PKR, and its formation enhanced RSV replication [196, 197]. Given that RSV infection forms cytoplasmic inclusion bodies (IBs) to mediate viral replication, Lindquist and colleagues observed that HuR, another SG component, localized to IBs [196] as well as MDA5 and MAVS proteins, suggesting a role in the suppression of IFN production [198]. Moreover, it was recently reported that RSV sequesters phosphorylated p38 (p38 P) and O-linked N-acetylglucosamine (OGN) transferase (OGT) into viral IBs, inhibiting the MAPK-activated protein kinase 2 (MK2) pathway and suppressing the assembly of SGs, respectively [199]. Measles virus (MeV) has the capacity to affect the innate and adaptive immune response through the accessory viral proteins V and C [200]. Interestingly, while infection with a protein C-deficient MeV efficiently induces SG assembly mediated by PKR, wild-type MeV does not [38]. However, wild-type MeV induces the assembly of SGs in ADAR1-knockdown cells, suggesting a role between the viral C protein and ADAR1 in modulating the assembly of SGs [38]. Sendai virus (SeV) infection slightly induces SG assembly, while short transcripts generated from the 3’-ends of antigenome RNA, SeV trailer RNA, interact with TIAR to prevent the assembly of SG [201]. In addition, recent data showed that SeV viral C protein also play a role in impairing SG assembly and IFN production [202]. This study revealed that SeV C-deficient recombinant 4C(-) infection forms SG-like structures containing RIG-I and unusual viral RNA species, suggesting that these structures could be reminiscent of anti-viral stress granules (avSGs) (reviewed in [180]).

Bunyaviridae are a large family composed of enveloped virions with a tri-segmented (-)ssRNA genome [184]. The peculiarity of Bunyaviruses is that they require a capped oligonucleotide, which is scavenged from host mRNAs, to initiate its own mRNA synthesis, a process called “cap-snatching” [184]. These mechanisms take place in PBs, where the viral N protein binds to cap structures of cellular mRNAs, and the endonuclease domain of the RNA-dependent RNA polymerase (RdRp) cleaves cap-downstream sequences in a range of 10–18 ribonucleotides [203,204]. This capped-RNA fragment is used as a primer for mRNA synthesis by the viral RdRp. Interestingly, one report with Sin Nombre virus (SNV), a member of the hantaviruses genera, showed that the cellular mRNAs target of cap-snatching are mRNAs with a premature stop codon (PTC), which have been addressed to PBs for degradation through the non-sense mediated decay pathway (NMD) [205]. Another report with the Rift Valley fever virus (RVFV) from the Phlebovirus genera showed attenuation of the Akt/mTOR signaling pathway, which in turn increases the activity of 4EBP1/2 proteins leading to the arrest of cap-dependent translation [206]. Although SG formation would be expected upon inhibition of translation, this report demonstrated that SGs are instead disassembled during RVFV infection. It is noteworthy that during attenuation of Akt/mTOR 5’ TOP-containing mRNAs (including those coding for translation initiation factors), these are selectively targeted to SGs. Notably, the authors observed that 5’-end sequences from TOP mRNAs are included in RVFV’s mRNAs captured by the cap-snatching mechanism in PBs. Those data suggest that RVFV temporally induces SGs to nucleate important mRNAs and in turn promote mRNAs cargo from SGs to PBs where, finally, RVFV uses these cellular mRNAs for cap-snatching. Indeed, decay of the core of translation machinery would not represent a problem for bunyaviruses, since it has been described that SNV N protein is capable of replacing the entire eIF4F complex (eIF4E, eIF4A and eIF4G) and binding the 40S ribosomal subunit, thus recruiting the translation machinery to its own mRNAs [207,208]. Moreover, it is widely accepted that Bunyaviruses do not have a poly(A) tail at the 3’-end of their mRNAs. Indeed, there is evidence showing that Bunyamwera virus (BUNV) and Andes virus (ANDV) have a 3’ UTR, which replaces the poly(A) tail function, and interestingly, the translations of those mRNAs are poly(A) binding protein (PABP)-independent [209,210]. These findings show that bunyaviruses use complex mechanisms of transcription/translation that are potentially interconnected with cytoplasmic RNA granules.
On the other hand, Bunyaviral proteins, like other viral proteins, have evolved mechanisms to inactivate PKR and inhibit the IFN response. Similarly to the non-structural protein NS1 from IAV [211] or NS4A from Dengue virus [212], studies with Orthobunyaviruses, Hantaviruses and Phleboviruses have shown that the non-structural protein from the S segment (NSs) acts as an inhibitor of the IFN response [213–216], as well as glycoprotein Gn and the capsid N protein from Hantaviruses [217–219]. For example, the capsid N protein from Andes Hantavirus (ANDV) is an inhibitor of PKR dimerization, impairing its activation; however, the translation shut-off is not observed in Hantavirus-infected cells. [220]. In contrast, RVFV infection promotes a shut-off of global translation, where NSs protein mediate PKR degradation by the proteasome [221,222]. Undoubtedly, the field of cytoplasmic RNA granules related to the transcription and translation of bunyaviruses already began to show interesting findings, which will help to answer some ancient questions linked to the molecular mechanisms of its replication cycle, as it has been thought that transcription and translation are coupled like in prokaryotic systems [223,224]. However, the SG formation has not been addressed to date.

Recently, Nelson and colleagues showed that the infection with Ebola virus (EBOV), member of Filoviridae family composed of enveloped virions, does not trigger eIF2α phosphorylation or SG formation. However, SG components are sequestered within viral inclusions where they colocalize with viral mRNA [225]. In addition, viral protein VP35 not only prevents SG formation by blocking PKR activation, but also disrupts SG formation independently of eIF2α [225].

3.5. Single Strand RNA Retroviruses (ssRNA-RTs)

Retroviruses are enveloped, positive ssRNA viruses, which synthesize complementary DNA (cDNA) by reverse transcription that is integrated into the host chromosomal DNA [184]. The oncoretrovirus, human T-cell leukemia virus (HTLV-1), causes a blockade of SG assembly mediated by the viral regulatory protein, Tax. Legros and colleagues observed that Tax interacts with histone deacetylase 6 (HDAC6), a critical component of SG, to block SG assembly [226]. Tax also interacts with USP10, inhibiting SG assembly and enhancing the production of reactive oxygen species [227]. On the other hand, human immunodeficiency virus type 1 (HIV-1) significantly impairs SG assembly in favor of the assembly of Staufen1-containing HIV-1-dependent ribonucleoproteins [228]. Indeed, we showed that HIV-1 Gag blocks SG assembly irrespective of eIF2α phosphorylation [229]. In addition, we reported that the interaction between the N-terminal domain (NTD) of the capsid domain of Gag (p24) and host eukaryotic elongation factor 2 (eEF2) are critical for the SG blockade, while that eEF2 depletion not only lifted the SG blockade, but also resulted in impaired virus production and infectivity [229]. Interestingly, we also reported that HIV-1 Gag mediates the disassembly of preexisting SGs via an interaction with G3BP1 [229], and more recently, it was shown that G3BP1 binds HIV-1 unspliced mRNA (gRNA) in the cytoplasm of macrophages to inhibit viral replication [230]. At the same time, we reported that the HIV-1 unspliced mRNA (gRNA) promotes the assembly of a pre-translation initiation intermediate with DDX3, another SG component, and a subset of translation initiation factors, such as eIF4G1 and PABPC1, suggesting that these intermediates may serve to concentrate the gRNA and eIFs in order to enhance the efficiency of polysome association [231]. It is noteworthy that the mechanism associated with SGs-blockage by HIV-1 Gag was dependent on the kind of stressor. As such, sodium selenite (Se) causes 4EBP1-mediated mRNA translational arrest and the subsequent assembly of non-canonical type II SGs [232]. Recently, Cinti and colleagues showed that in HIV-1-expressing cells under Se treatment, Gag interacts with eLF4E, reducing hypophosphorylated 4EBP1 associated with the 5’ cap in order to promote the disassembly of SGs [233]. In contrast to HIV-1, the replication of human immunodeficiency virus type 2 (HIV-2) induces the spontaneous assembly of SG [231]. As such, the HIV-2 gRNA recruits TIAR to form a novel viral mRNP, where the switch between translation to packaging could occur [231].
Table 2. Virus families that modulate SGs.

| Genome | Virus Family | Virus | SG Induction | SG Blockade | Mechanism | Reference |
|--------|--------------|-------|--------------|-------------|-----------|-----------|
| I      | dsDNA        | Herpesviridae | Herpes simplex virus type 1 (HSV-1) | No | Yes | (-)RNA stem loop captures TIA-1/TIAR to favor replication | [133] |
|        |              |       | Herpes simplex virus type 2 (HSV-2) | Yes | Yes | Inhibits SG assembly dependent of eIF2α-P | [136] |
|        |              |       | Cytomegalovirus (HCMV) | No | Yes | Induces SG independent of eIF2α-P | [136] |
|        |              | Poxviridae | Vaccinia virus (VV) | Yes | Yes | Replication factories (RF) sequester G3BP1, Caprin1 | [140] |
|        |              |       | RF sequester eIF4G, eIF4E, PABP |   |     | VV lacking of E3L induces antiviral granules (AVGs) | [94] |
| III    | dsRNA        | Reoviridae | Rotavirus | No | Yes | NSP2, VP2 and NSP5 translocate PABP to the nucleus | [144] |
|        |              |       | Mammalian orthoreovirus (MRV) | Yes | Yes | Induces eIF2α-P | [234] |
|        |              |       | uNS is recruited to SGs |   |     | | [147,148] |
Table 2. Cont.

| Genome | Virus Family | Virus                        | SG Induction | SG Blockade | Mechanism                                                                 | Reference |
|--------|--------------|------------------------------|--------------|-------------|---------------------------------------------------------------------------|-----------|
| IV (+)ssRNA | Picornaviridae | Poliovirus (PV)             | Yes          | Yes         | Early PV-infection induces SG assembly                                     | [16]      |
|         |              |                              |              |             | viral C3 protease cleaves G3BP1                                            | [190]     |
|         |              | Encephalomyocarditis virus (EMCV) | No          | Yes         | Cleavage of G3BP1                                                          | [50]      |
|         |              |                              |              |             | PV-infection induces TIA-1 aggregates                                       | [151]     |
|         |              | Coxackievirus B3 (CVB3)     | No           | Yes         | Cleavage of G3BP1                                                          | [153]     |
|         |              | Theiler’s murine encephalomyelitis virus (TMEV) | No          | Yes         | Leader protein (L) inhibits SG assembly                                    | [154]     |
|         |              | Mengovirus, a strain of EMCV | No           | Yes         | Leader protein (L) inhibits SG assembly                                    | [155,156] |
|         | Togaviridae  | Semliki Forest virus (SFV)   | Yes          | Yes         | Induces eIF2α-P                                                            | [157]     |
|         |              |                              |              |             | nsP3 protein captures G3BP1                                                | [158]     |
|         |              | Chikungunya virus (CHIKV)    | No           | Yes         | nsp3 protein recruits G3BP1 to replication foci                            | [159]     |
|         |              |                              |              |             | G3BP2 colocalize with nsP3/nsP2                                             | [161]     |
|         |              | Rubella virus (RUBV)        | Yes          | No          | Accumulation of G3BP                                                        | [162]     |
|         |              | Sindbis virus (SINV)        | Yes          | Yes         | Nsp4 interacts with G3BP1                                                  | [163]     |
|         |              | West Nile Virus (WNV)       | No           | Yes         | 3′-end viral genome captures TIA-1/TIAR                                    | [167]     |
|         |              | Dengue virus (DENV)         | No           | Yes         | 3′-end viral genome captures TIA-1/TIAR                                    | [168]     |
|         |              |                              |              |             | 3′ UTR interacts with G3BP1, G3BP2, Caprin1 and USP1                       | [171]     |
|         |              | Tick-borne encephalitis virus (TBEV) | Yes | No         | Induces eIF2α-P                                                            | [173]     |
|         |              | Japanese encephalitis virus (JEV) | No         | Yes         | Core protein interacts with Caprin1                                       | [174]     |
|         |              | Beovine viral diarrhea virus (BVDV) | No         | Yes         | Impairs the Ars-mediated SG assembly                                       | [175]     |
|         |              | Hepatitis C virus (HCV)     | Yes          | Yes         | G3BP1, ataxin-2 and PABP localized to lipid droplets                       | [181]     |
|         |              |                              |              |             | Induces PKR                                                                | [176]     |
|         |              |                              |              |             | SG disassembly mediated by GADD34                                          | [177]     |
|         |              |                              |              |             | DDX3 binds 3′ UTR                                                           | [178]     |
|         |              |                              |              |             | DDX3 and G3BP1 localize with HCV core protein                              | [179]     |
|         |              | Cricket paralysis virus (CrPV) | No         | Yes         | 3Cpro sequesters to SG                                                     | [183]     |
|         | Dicistroviridae | Mouse hepatitis coronavirus (MHV) | Yes     | No          | Induces eIF2α-P                                                            | [185]     |
|         |              | Transmissible gastroenteritis virus (TGEV) | Yes | No         | PTB localizes to SG and correlates with replication increase              | [186]     |
|         |              | Murine Norovirus 1 (MNV1)   | nd           | No          | eIF4E phosphorylation                                                       | [188]     |
|         |              |                              |              |             |                                                                                           |
|         | Caliciviridae | Feline Calicivirus (FCV)     | No           | Yes         | Cleavage of G3BP1 by FCV NS6                                               | [187]     |
Table 2. Cont.

| Genome | Virus Family | Virus | SG Induction | SG Blockade | Mechanism | Reference |
|--------|--------------|-------|--------------|-------------|-----------|-----------|
| V (-)ssRNA | Orthomyxoviridae | Influenza A virus (FLUA) | No | Yes | NS1 inhibits PKR and eIF2α-P | [189,190] |
| | | | | | NP and PA-X block SGs | [191] |
| | | | | | DDX3 colocalize with NP | [192] |
| | Arenaviridae | Junin virus (JUNV) | No | Yes | N and GPC proteins impairs SG assembly | [193,194] |
| | Rhabdoviridae | Vesicular stomatitis virus (VSV) | Yes | No | Induces SG-like structures recruiting TIA-1, TIAR y PCBP2 | [195] |
| | Paramyxoviridae | Respiratory syncytial virus (RSV) | Yes | Yes | Induces PKR | [196,197] |
| | | | | | 5’ trailer region induces eIF3-aggregates | [235] |
| | | | | | RSV sequesters p38-P and OGN | [199] |
| | | Measles virus (MeV) | Yes | nd | Induces PKR | [38] |
| | | | | | viral C protein and ADAR1 modulate SGs | [38] |
| | | Sendai virus (SV) | Yes | Yes | Trailer RNA captures TIAR from SGs | [201] |
| | | | | | Forms antiviral stress granules (avSG) | [202] |
| Bunyaviridae | Rift Valley fever virus (RVFV) | Yes | Yes | attenuate Akt/mTOR signaling | [206] |
| | | Andes hantavirus (ANDV) | nd | Yes | N protein inhibits PKR activation | [220] |
| Filoviridae | Ebola virus | No | Yes | VP35 prevents SG formation by blocking PKR activation | [225] |
| VI ssRNA-RT | Retroviridae | Human T-cell leukemia virus (HTLV-1) | No | Yes | Tax protein interacts with HDAC6 | [226] |
| | | | | | Tax protein interacts with USP10 | [227] |
| | | Human immunodeficiency virus type 1 (HIV-1) | No | Yes | Staufen 1 and Gag block SG assembly | [228] |
| | | | | | EEF2 interacts with Gag to blocks SG assembly | [229] |
| | | | | | G3BP1 interacts with Gag to disassembly SG-preformed | [229] |
| | | | | | gRNA promote pre-translation initiation complex | [236] |
| | | | | | Gag interacts with eIF4E to promote disassembly of SGs | [233] |

nd = not determined; dsDNA = double-stranded DNA; dsRNA = double-stranded RNA; UPR = unfolded protein response; (+)ssRNA = positive-sense single strand RNA; (-)ssRNA = negative-sense single strand RNA; ssRNA-RT = single strand RNA retroviruses
4. Viral Infections and Processing Bodies

Several viruses are known to disrupt P-bodies. Here, we will summarize the most up-to-date information known about the relationships between viruses and PBs (Table 3).

4.1. dsDNA Viruses

Adenovirus regulates its gene expression over the time of infection, triggering an accumulation of viral late mRNA in the cytoplasm [184]. To prevent viral mRNA degradation, the early protein E4 11k binds Rck/p54/DDX6, relocalizing it with PB components such as Lsm-1, Ge-1, Ago2 and Xrn1, to aggresomes, sites where these proteins are inactivated [237]. In contrast, within the human papilloma virus (HPV), the oncoprotein E6 commands the re-colocalization of PKR in PBs, suggesting an antiviral effect for these granules [46]. Finally, during HCMV infection, PB components, such as Dcp1a, Edc4, Rck/p54/DDX6 and Raf55, increased in a translation-independent manner requiring cellular, but not viral RNA synthesis [238].

4.2. dsRNA Viruses

A recent report showed that rotavirus infection triggers a significant time-dependent decline of PB components XRN1, DCP1, Pan3, but not GW182 [239]. Pan3, but not XRN1 and DCP1, undergoes accelerated turn over in response to rotavirus infection, while XRN1 and DCP1 were translocated to the nucleus [239], as well as PABP [144].

4.3. (+)ssRNA Viruses

In the case of flaviviruses, WNV and DENV infections reveal a reduction in PB formation [168]. Indeed, WNV sequesters several components of PBs, such as Lsm1, GW182, Xrn1, DDX3 and Rck/p54/DDX6, in viral replication factories to promote viral replication [240]. Furthermore, it has been shown that Rck/p54/DDX6 binds a stem-loop present in the DENV 3’ UTR, inhibiting PB formation [171]. Interestingly, flaviviruses (including yellow fever virus (YFV) and DENV) generate a subgenomic flavivirus RNA (sfRNA), as a product of gRNA degradation by Xrn1 at pseudoknot 3 [241]. The sfRNA and Xrn1 colocalized in PBs and were essential for viral cytopathogenicity [242]. In addition, Moon and colleagues showed that inhibition of XRN1 by sfRNA-interaction results in accumulation of uncapped cellular mRNA [243]. Likewise, HCV infection relocalized PB components to viral factories close to lipid droplets, such as RCK/p54/DDX6, Lsm1, Xrn1, PatL1, Ago2 and DDX3 [181,182]. The depletion of these components has a detrimental role over HCV replication [181,182,244], while RCK/p54/DDX6, Lsm1 and PatL1 play a central role in HCV translation and replication [245,246]. However, the disruption of PB mediated by depletion of Rap55 does not affect HCV replication [247]. Together, these data strongly suggest that HCV co-opts several PB components to ensure viral replication, but if PBs are formed, they do not have an inhibitory effect during viral infection.

On the other hand, infection with picornaviruses, such as PV and CVB3, entirely disrupts PB formation through the virally-induced cleavage of Dcp1a mediated by viral protease 3C, as well as the degradation of Xrn1 and Pan3 mediated by the proteasome [248]. It has been recently shown that expression of PV-protease 2A also blocks PB formation more efficiently than protease 3C [149]; however, the mechanism remains unclear. Furthermore, CrPV infection only disrupts GW182/Dcp1 aggregates, but not Ago1/Ago2, suggesting that these PBs components could have a differential role in viral infection [183]. Moreover, the U-rich region close to the 3’-end of SINV mRNAs interacts with HuR, generating a dramatic translocation of the host protein out of the nucleus, stabilizing viral transcripts during infection and subsequently preventing the assembly of PBs [249].

4.4. (-)ssRNA Viruses

The negative-strand RNA viruses are known to use cap-snatching mechanism, to initiate its own mRNA synthesis. However, for IAV, this process occurs in the nucleus, while that for Bunyavirus
occurs in PBs. Mir and colleagues showed that hantavirus nucleocapsid protein (N) avoids the 5' cap degradation of cellular mRNAs, protecting them from Dcp1a/Dcp2-mediated decapping. In addition, the interaction of N protein with 5'-Cap, instead of eIF4E/eIF4F, allows the Hantavirus transcripts to escape from PB and recruit ribosomes [207]. In the case of IAV, the interaction of RAP55 with NS1 impairs PB formation, but also prevents the capture of NP in the PBs [190].

4.5. ssRNA-RT Viruses

Lastly, the protein APOBEC3 (apolipoprotein B mRNA editing enzyme catalytic polypeptide-like 3) provides anti-HIV-1 activity while being a PB component that interacts with Ago2, Dcp1a, Dcp2 and DDX6 [47,115]. However, the viral infectivity factor Vif protein induces APOBEC3 degradation, preventing its incorporation into virions [47], affecting its subcellular localization, degradation rates and antiviral properties [250]. Several groups have reported that depletion of PB components or RISC components (including DDX6, LSM-1, GW182, XRN1, DGCR8, Dicer and Drosha) increases the viral production and that gRNA and Gag protein localize to PBs [251–253]. Nevertheless, gRNA localization in PBs has not been detected by others [228,254], and the depletion of Ago2 or DDX6 resulted in the inhibition of HIV-1 replication [255,256]. Likewise, Abrahamyan and colleagues reported a dramatic decrease in the abundance of PBs around gRNA-foci in HIV-1-expressing cells, even in cells treated with sodium arsenite [228], suggesting a relocalization of PB during the HIV-1 infection. Given that the events of HIV-1 capsid assembly have not been associated with PBs, Reed and colleagues demonstrated that assembly intermediates (AIs), containing HIV-1 Gag, GagPol and Vif [257], are formed by the recruitment of DDX6 and ATP-binding cassette protein E1, ABCE1 [256]. On the other hand, the overexpression of Mov10, a putative RNA helicase that associates with APOBEC in RISC complexes and that was found in PBs, can inhibit viral replication and reduce Gag expression [258,259]. In addition, it was reported that the recruitment of Mov10 and APOBEC3G into virions is independent of localization on their PBs [260]. However, given the discrepancy between these reports, more work is needed to elucidate the role of PBs and their components during the HIV-1 replicative cycle.
Table 3. Virus families that modulate PBs.

| Genome | Virus Family | Virus | Genome Pathway | PB Induction | PB Blockade | Mechanism | Reference |
|--------|--------------|-------|----------------|--------------|-------------|-----------|-----------|
| I      | dsDNA        | Adenoviridae | Adenovirus | No | Yes | Decreased PB by redistribution of E4 11K | [237] |
|        | Papillomaviridae | Human papilloma virus (HPV) | Yes * | No | Re-colocalization of PKR in PBs | [46] |
|        | Herpesviridae  | Cytomegalovirus (HCMV) | Yes | No | Increased of Dcp1a, EDC4, Rck/p54/DDX6 and Rap55 protein levels | [238] |
| III    | dsRNA        | Reoviridae  | Rotavirus     | No | Yes | Decrease of XRN1, DCP1 and Pan3, but not GW182 protein levels | [239] |
| IV     | (+)ssRNA     | Flaviviridae | West Nile virus (WNV) | No | Yes | Captures of Lsm1, GW182, DDX6, DDX3 and Xrn1 to viral replication factories (RF) | [168,240] |
|        |              | Dengue virus (DENV) | No | Yes | Captures of Lsm1, GW182, DDX6, DDX3 and Xrn1 to viral replication factories (RF) | [168,240] |
|        |              | Yellow fever virus (YFV) | Yes * | No | sfRNA stalls Xrn1 and co-localizes at PB | [241] |
|        |              | Kunjin virus (KUNV), Australian strain of DENV | Yes * | No | sfRNA stalls Xrn1 and co-localizes at PB | [242] |
|        |              | Hepatitis C virus (HCV) | Yes * | Yes | DDX6, Lsm1, Xrn1, PATL1 and Ago2 localize to lipid droplets | [181] |
|        |              | Picornaviridae | Poliovirus (PV) | No | Yes | Cleavage of Xrn1, Dcp1a and Pan3 | [248] |
|        |              | Coxackievirus B3 (CVB3) | No | Yes | Cleavage of Xrn1, Dcp1a and Pan3 | [248] |
|        |              | Dicistroviridae | Cricket paralysis virus (CrPV) | Yes | Yes | Disrupts only GW182/DCP1 aggregate, but not Ago1/Ago2 | [183] |
| V      | (-)ssRNA     | Togaviridae | Sindbis virus (SINV) | No | Yes | HuR-translocation out of the nucleus | [249] |
|        |              | Orthomyxoviridae | Influenza virus A (IAV) | No | Yes | Interaction of RAP55 and NSP1 | [190] |
|        |              | Bunyaviridae | Hanta virus | Yes * | No | Cap snatching occurs in PBs | [204] |
| VI     | ssRNA-RT     | Retroviridae | Human immunodeficiency virus type 1 (HIV-1) | nd | Yes | HIV-1 mRNA interacts with DDX6, Ago 2 and APOB3G and displaces from the PB | [253] |
|        |              |              |              |              |              | Relocalization of PB during the HIV-1 infection | [228] |
|        |              |              |              |              |              | Assembly intermediates (AIs) recruits DDX6 and ABCE1 | [256] |
|        |              |              |              |              |              | Overexpression of MOV10 inhibits HIV-1 replication | [258] |

*maintains PB endogenously; nd = not determined; dsDNA = double-stranded DNA; dsRNA = double-stranded RNA; UPR = unfolded protein response; (+)ssRNA = positive-sense single strand RNA; (-)ssRNA = negative-sense single strand RNA; ssRNA-RT = single strand RNA retroviruses.
5. Conclusions

Although significant advances have been made to understand how viruses modulate the assembly/disassembly of RNA granules, there are still outstanding questions that need to be addressed. For example, could these mechanisms be targets of new antiviral drugs? What are the molecular mechanisms and/or signaling pathways that transport mRNAs from one RNA granule to another? Do post-translational modifications that serve as signals to modulate the formation of RNA granules exist? To answer these questions, several reports have helped us to comprehend the molecular biology of RNA granules [261–270], however, further work is necessary to determine the viral mechanisms that modulate the RNA granules. In addition, emerging evidence has related RNA granules with innate antiviral immunity as part of the integrated stress response. Finally, understanding how viruses counter anti-viral stress responses lays the groundwork for new strategies to bolster host cell immune defenses against invading pathogens.

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References
1. Kedersha, N.; Anderson, P. Regulation of translation by stress granules and processing bodies. Prog. Mol. Biol. Transl. Sci. 2009, 90, 155–185. [PubMed]
2. Buchan, J.R.; Parker, R. Eukaryotic stress granules: The ins and outs of translation. Mol. Cell 2009, 36, 932–941. [CrossRef] [PubMed]
3. Anderson, P.; Kedersha, N.; Ivanov, P. Stress granules, P-bodies and cancer. Biochim. Biophys. Acta 2015, 1849, 861–870. [CrossRef] [PubMed]
4. Morimoto, M.; Boerkoel, C.F. The role of nuclear bodies in gene expression and disease. Biology (Basel) 2013, 2, 976–1033. [CrossRef] [PubMed]
5. Dundr, M.; Misteli, T. Biogenesis of nuclear bodies. Cold Spring Harb. Perspect. Biol. 2010, 2, a000711. [CrossRef] [PubMed]
6. Anderson, P.; Kedersha, N. RNA granules. J. Cell Biol. 2006, 172, 803–808. [CrossRef] [PubMed]
7. Thomas, M.G.; Loschi, M.; Desbats, M.A.; Boccaccio, G.L. RNA granules: The good, the bad and the ugly. Cell. Signal. 2011, 23, 324–334. [CrossRef] [PubMed]
8. Anderson, P.; Kedersha, N. Stress granules. Curr. Biol. 2009, 19, 397–398. [CrossRef] [PubMed]
9. Buchan, J.R. mRNP granules: Assembly, function, and connections with disease. RNA Biol. 2014, 11, 1019–1030. [CrossRef] [PubMed]
10. Valiente-Echeverría, F.; Melnychuk, L.; Moulard, A.J. Viral modulation of stress granules. Virus Res. 2012, 169, 430–437. [CrossRef] [PubMed]
11. Han, A.P.; Yu, C.; Lu, L.; Fujiwara, Y.; Browne, C.; Chin, G.; Fleming, M.; Leboulch, P.; Orkin, S.H.; Chen, J.J. Heme-regulated eIF2alpha kinase (HRI) is required for translational regulation and survival of erythroid precursors in iron deficiency. EMBO J. 2001, 20, 6909–6918. [CrossRef] [PubMed]
12. Williams, B.R. Signal integration via PKR. Sci. STKE Signal Transduct. Knowl. Environ. 2001, 2001, re2. [CrossRef] [PubMed]
13. Harding, H.P.; Zhang, Y.; Bertolotti, A.; Zeng, H.; Ron, D. Perk is essential for translational regulation and cell survival during the unfolded protein response. Mol. Cell 2000, 5, 897–904. [CrossRef]
14. Jiang, H.Y.; Wek, R.C. GCN2 phosphorylation of eIF2alpha activates NF-kappaB in response to UV irradiation. Biochemistry 2005, 385, 371–380.
15. Dang, Y.; Kedersha, N.; Low, W.K.; Romo, D.; Gorospe, M.; Kaufman, R.; Anderson, P.; Liu, J.O. Eukaryotic initiation factor 2alpha-independent pathway of stress granule induction by the natural product pateamine A. J. Biol. Chem. 2006, 281, 32870–32878. [CrossRef] [PubMed]
16. Mazroui, R.; Sukarieh, R.; Bordeleau, M.E.; Kaufman, R.J.; Northcote, P.; Tanaka, J.; Gallouzi, I.; Pelletier, J. Inhibition of ribosome recruitment induces stress granule formation independently of eukaryotic initiation factor 1 alpha phosphorylation. *Mol. Biol. Cell* 2006, 17, 4212–4219. [CrossRef] [PubMed]

17. Kedersha, N.; Chen, S.; Gilks, N.; Li, W.; Miller, I.J.; Stahl, J.; Anderson, P. Evidence that ternary complex (eIF2-GTP- tRNA(Ile)-Met)-deficient preinitiation complexes are core constituents of mammalian stress granules. *Mol. Biol. Cell* 2002, 13, 195–210. [CrossRef] [PubMed]

18. Emara, M.M.; Fujimura, K.; Sciaranghella, D.; Ivanova, V.; Ivanov, P.; Anderson, P. Hydrogen peroxide induces stress granule formation independent of eIF2alpha phosphorylation. *Boilchem. Biophys. Res. Commun.* 2012, 423, 763–769. [CrossRef] [PubMed]

19. Kedersha, N.L.; Gupta, M.; Li, W.; Miller, I.; Anderson, P. RNA-binding proteins TIA-1 and TIAR link the phosphorylation of eIF-2alpha to the assembly of mammalian stress granules. *J. Cell Biol.* 1999, 147, 1431–1441. [CrossRef] [PubMed]

20. Tourriere, H.; Chebli, K.; Zekri, L.; Courselaud, B.; Blanchard, J.M.; Bertrand, E.; Tazi, J. The RasGAP-associated endoribonuclease G3BP assembles stress granules. *J. Cell Biol.* 2003, 160, 823–831. [CrossRef] [PubMed]

21. Kedersha, N.; Panas, M.D.; Achorn, C.A.; Lyons, S.; Tisdale, S.; Hickman, T.; Thomas, M.; Lieberman, J.; McInerney, G.M.; Ivanov, P.; et al. G3BP-Caprin1-USP10 complexes mediate stress granule condensation and associate with 40S subunits. *J. Cell Biol.* 2016, 212, 845–860. [CrossRef] [PubMed]

22. Decker, C.J.; Teixeira, D.; Parker, R. Edc3p and a glutamine/asparagine-rich domain of Lsm4p function in processing body assembly in *Saccharomyces cerevisiae*. *J. Cell Biol.* 2006, 179, 437–449. [CrossRef] [PubMed]

23. Pilkington, G.R.; Parker, R. Pat1 contains distinct functional domains that promote P-body assembly and activation of decapping. *Mol. Cell. Biol.* 2008, 28, 1298–1312. [CrossRef] [PubMed]

24. Reijns, M.A.; Alexander, R.D.; Spiller, M.P.; Beggs, J.D. A role for Q/N-rich aggregation-prone regions in translation. *Cell. Mol. Life Sci.* 2004, 61, 2658–2669. [CrossRef] [PubMed]

25. Brengues, M.; Teixeira, D.; Parker, R. Movement of eukaryotic mRNAs between polysomes and cytoplasmic processing bodies. *Science* 2005, 310, 486–489. [CrossRef] [PubMed]

26. Bhattacharyya, S.N.; Habermacher, R.; Martine, U.; Closs, E.I.; Filipowicz, W. Relief of microRNA-mediated translational repression in human cells subjected to stress. *Cell* 2006, 125, 1111–1124. [CrossRef] [PubMed]

27. Brengues, M.; Teixeira, D.; Parker, R. Movement of eukaryotic mRNAs between polysomes and cytoplasmic processing bodies. *Science* 2005, 310, 486–489. [CrossRef] [PubMed]

28. Chalupníková, K.; Lattmann, S.; Selak, N.; Iwamoto, F.; Fujiki, Y.; Nagamine, Y. Recruitment of the RNA helicase RHAU to stress granules via a unique RNA-binding domain. *J. Biol. Chem.* 2008, 283, 35186–35198. [CrossRef] [PubMed]
37. Wippich, F.; Bodenmiller, B.; Trajkovska, M.G.; Wanka, S.; Aebersold, R.; Pelkmans, L. Dual specificity kinase DYRK3 couples stress granule condensation/dissolution to mTORC1 signaling. *Cell* 2013, 152, 791–805. [CrossRef] [PubMed]

38. Okonski, K.M.; Samuel, C.E. Stress granule formation induced by measles virus is protein kinase PKR dependent and impaired by RNA adenosine deaminase ADAR1. *J. Virol.* 2013, 87, 756–766. [CrossRef] [PubMed]

39. Onomoto, K.; Jogi, M.; Yoo, J.S.; Narita, R.; Morimoto, S.; Takemura, A.; Sambhara, S.; Kawaguchi, A.; Osari, S.; Nagata, K.; et al. Critical role of an antiviral stress granule containing RIG-I and PKR in viral detection and innate immunity. *PLoS ONE* 2012, 7, e43031. [CrossRef]

40. Ingelfinger, D.; Arndt-Jovin, D.J.; Lührmann, R.; Achsel, T. The human LSm1–7 proteins colocalize with the mRNA-degrading enzymes Dcp1/2 and Xml in distinct cytoplasmic foci. *RNA (New York, NY)* 2002, 8, 1489–1501.

41. Yu, J.H.; Yang, W.-H.; Gulick, T.; Bloch, K.D.; Bloch, D.B. Ge-1 is a central component of the mammalian cytoplasmic mRNA processing body. *RNA (New York, NY)* 2005, 11, 1795–1802. [CrossRef] [PubMed]

42. Sheth, U.; Parker, R. Targeting of aberrant mRNAs to cytoplasmic processing bodies. *Cell* 2006, 125, 1095–1109. [CrossRef] [PubMed]

43. Durand, S.; Cougot, N.; Mahuteau-Betzer, F.; Nguyen, C.H.; Grierson, D.S.; Bertrand, E.; Tazi, J.; Lejeune, F. Inhibition of nonsense-mediated mRNA decay (NMD) by a new chemical molecule reveals the dynamic of NMD factors in P-bodies. *J. Cell Biol.* 2007, 178, 1145–1160. [CrossRef] [PubMed]

44. Andrei, M.A.; Ingelfinger, D.; Heintzmann, R.; Rivera-Pomar, R.; Lührmann, R. A role for eIF4E and eIF4E-transporter in targeting mRNPs to mammalian processing bodies. *RNA (New York, NY)* 2005, 11, 717–727. [CrossRef] [PubMed]

45. Patel, P.H.; Barbee, S.A.; Blankenship, J.T. GW-Bodies and P-bodies constitute two separate pools of sequestered Non-translating RNAs. *PloS ONE* 2016, 11, e0150291. [CrossRef] [PubMed]

46. Hebner, C.M.; Wilson, R.; Rader, J.; Bidder, M.; Laimins, L.A. Human papillomaviruses target the double-stranded RNA protein kinase pathway. *J. Gen. Virol.* 2006, 87, 3183–3193. [CrossRef] [PubMed]

47. Gallois-Montbrun, S.; Kramer, B.; Swanson, C.M.; Byers, H.; Lynham, S.; Ward, M.; Malim, M.H. Antiviral protein APOBEC3G localizes to ribonucleoprotein complexes found in P bodies and stress granules. *J. Virol.* 2007, 81, 2165–2178. [CrossRef] [PubMed]

48. Sen, G.L.; Blau, H.M. Argonaute 2/RISC resides in sites of mammalian mRNA decay known as cytoplasmic bodies. *Nat. Cell Biol.* 2005, 7, 633–636. [CrossRef] [PubMed]

49. Chen, D.; Wilkinson, C.R.M.; Watt, S.; Penkett, C.J.; Toone, W.M.; Jones, N.; Bähler, J. Multiple pathways differentially regulate global oxidative stress responses in fission yeast. *Mol. Biol. Cell* 2008, 19, 308–317. [CrossRef] [PubMed]

50. Ng, C.S.; Jogi, M.; Yoo, J.S.; Onomoto, K.; Koike, S.; Iwasaki, T.; Yoneyama, M.; Kato, H.; Fujita, T. Encephalomyocarditis virus disrupts stress granules, the critical platform for triggering antiviral innate immune responses. *J. Virol.* 2013, 87, 9511–9522. [CrossRef] [PubMed]

51. Lai, M.C.; Lee, Y.H.; Tarn, W.Y. The DEAD-box RNA helicase DDX3 associates with export messenger ribonucleoproteins as well as tip-associated protein and participates in translational control. *Mol. Biol. Cell* 2008, 19, 3847–3858. [CrossRef] [PubMed]

52. Kolobova, E.; Efimov, A.; Kaverina, I.; Rishi, A.K.; Schrader, J.W.; Ham, A.J.; Larocca, M.C.; Goldenring, J.R. Microtubule-dependent association of AKAP350A and CCAR1 with RNA stress granules. *Exp. Cell Res. 2009, 315, 542–555. [CrossRef] [PubMed]

53. Baguet, A.; Degot, S.; Cougot, N.; Bertrand, E.; Chenard, M.P.; Wendling, C.; Kessler, P.; Le Hir, H.; Rio, M.C.; Tomasetto, C. The exon-junction-complex-component metastatic lymph node 51 functions in stress-granule assembly. *J. Cell Sci.* 2007, 120, 2774–2784. [CrossRef] [PubMed]

54. Pizzo, E.; Sarcinelli, C.; Sheng, J.; Fusco, S.; Formigini, F.; Netti, P.; Yu, W.; D’Alessio, G.; Hu, G.-F. Ribonuclease/angiogenin inhibitor 1 regulates stress-induced subcellular localization of angiogenin to control growth and survival. *J. Cell Sci.* 2013, 126, 4308–4319. [CrossRef] [PubMed]

55. Kawahara, H.; Imai, T.; Imataka, H.; Tsujimoto, M.; Matsumoto, K.; Okano, H. Neural RNA-binding protein Musash1 inhibits translation initiation by competing with eIF4G for PABP. *J. Cell Biol.* 2008, 181, 639–653. [CrossRef] [PubMed]
56. Nonhoff, U.; Ralser, M.; Welzel, F.; Picconi, I.; Balzereit, D.; Yaspo, M.L.; Lehrach, H.; Krobitsch, S. Ataxin-2 interacts with the DEAD/H-box RNA helicase DDX6 and interferes with P-bodies and stress granules. *Mol. Biol. Cell* 2007, 18, 1385–1396. [CrossRef] [PubMed]

57. Swisher, K.D.; Parker, R. Localization to, and effects of Pbp1, Pbp4, Lsm12, Dhh1, and Pab1 on stress granules in Saccharomyces cerevisiae. *PLoS ONE* 2010, 5, e10006. [CrossRef] [PubMed]

58. Takahara, T.; Maeda, T. Transient sequestration of TORC1 into stress granules during heat stress. *Mol. Cell* 2012, 47, 242–252. [CrossRef] [PubMed]

59. Decca, M.B.; Carpio, M.A.; Bosc, C.; Galiano, M.R.; Job, D.; Andrieux, A.; Hallak, M.E. Post-translational arginylation of calreticulin: A new isospecies of calreticulin component of stress granules. *J. Biol. Chem.* 2007, 282, 8237–8245. [CrossRef] [PubMed]

60. Węchner, K.A.; Schutz, S.; Sarnow, P. OGFOD1, a novel modulator of eukaryotic translation initiation factor 2alpha phosphorylation and the cellular response to stress. *Mol. Cell. Biol.* 2010, 30, 2006–2016. [CrossRef] [PubMed]

61. Solomon, S.; Xu, Y.; Wang, B.; David, M.D.; Schubert, P.; Kennedy, D.; Schrader, J.W. Distinct structural features of caprin-1 mediate its interaction with G3BP-1 and its induction of phosphorylation of eukaryotic translation initiation factor 2alpha, entry to cytoplasmic stress granules, and selective interaction with a subset of mRNAs. *Mol. Cell. Biol.* 2007, 27, 2324–2342. [CrossRef] [PubMed]

62. Nousch, M.; Reed, V.; Bryson-Richardson, R.J.; Currie, P.D.; Preiss, T. The eIF4G-homolog p97 can activate translation independent of caspase cleavage. *RNA* 2007, 13, 374–384. [CrossRef] [PubMed]

63. De Leeuw, F.; Zhang, T.; Wauquier, C.; Huez, G.; Kruys, V.; Gueydan, C. The cold-inducible RNA-binding protein migrates from the nucleus to cytoplasmic stress granules by a methylation-dependent mechanism and acts as a translational repressor. *Exp. Cell Res.* 2007, 313, 4130–4144. [CrossRef] [PubMed]

64. Ohn, T.; Kedersha, N.; Hickman, T.; Tisdale, S.; Anderson, P. A functional RNAi screen links O-GlcNAc modification of ribosomal proteins to stress granule and processing body assembly. *Nat. Cell Biol.* 2008, 10, 1224–1231. [CrossRef] [PubMed]

65. Fujimura, K.; Kano, F.; Murata, M. Dual localization of the RNA binding protein CUGBP-1 to stress granule and perinucleolar compartment. *Exp. Cell Res.* 2008, 314, 543–553. [CrossRef] [PubMed]

66. Hofmann, I.; Casella, M.; Schnolzer, M.; Schlechter, T.; Spring, H.; Franke, W.W. Identification of the junctional plaque protein plakophilin 3 in cytoplasmic particles containing RNA-binding proteins and the recruitment of plakophilins 1 and 3 to stress granules. *Mol. Biol. Cell* 2006, 17, 1388–1398. [CrossRef] [PubMed]

67. Onishi, H.; Kino, Y.; Morita, T.; Futai, E.; Sasagawa, N.; Ishiura, S. MBNL1 associates with YB-1 in cytoplasmic stress granules. *J. Neurosci. Res.* 2008, 86, 1994–2002. [CrossRef] [PubMed]

68. Loschi, M.; Leishman, C.C.; Berardone, N.; Boccaccio, G.L. Dynein and kinesin regulator of caprine translation initiation factor 2alpha phosphorylation and the cellular response to stress. *Mol. Cell. Biol.* 2012, 47, 242–252. [CrossRef] [PubMed]

69. Kim, J.E.; Ryu, I.; Kim, W.J.; Song, O.K.; Ryu, J.; Kwon, M.Y.; Kim, J.H.; Jang, S.K. Proline-rich transcript in brain protein induces stress granule formation. *Mol. Cell. Biol.* 2008, 28, 803–813. [CrossRef] [PubMed]

70. Ogawa, F.; Kasai, M.; Akiyama, T. A functional link between Disrupted-In-Schizophrenia 1 and the eukaryotic translation initiation factor 2alpha phosphorylation and the cellular response to stress. *Mol. Cell. Biol.* 2007, 27, 2324–2342. [CrossRef] [PubMed]

71. Vessey, J.P.; Vaccani, A.; Xie, Y.; Dahm, R.; Karra, D.; Kiebler, M.A.; Macchi, P. Dendritic localization of the translational repressor Pumilio 2 and its contribution to dendritic stress granules. *J. Neurosci. Off. J. Soc. Neurosci.* 2006, 26, 6496–6508. [CrossRef] [PubMed]

72. Zurla, C.; Lifland, A.W.; Santangelo, P.I. Characterizing mRNA interactions with RNA granules during translation initiation inhibition. *PLoS ONE* 2011, 6, e19727. [CrossRef] [PubMed]
76. Fukuda, T.; Naiki, T.; Saito, M.; Irie, K. hnRNP K interacts with RNA binding motif protein 42 and functions in the maintenance of cellular ATP level during stress conditions. *Genes Cells Devot. Mol. Cell. Mech.* 2009, 14, 113–128. [CrossRef] [PubMed]
77. Li, C.H.; Ohn, T.; Ivanov, P.; Tisdale, S.; Anderson, P. eIF5A promotes translation elongation, polysome disassembly and stress granule assembly. *PLoS ONE* 2010, 5, e9492. [CrossRef] [PubMed]
78. Tsai, N.P.; Ho, P.C.; Wei, L.N. Regulation of stress granule dynamics by Grb7 and FAK signalling pathway. *EMBO J.* 2008, 27, 715–726. [CrossRef] [PubMed]
79. Hua, Y.; Zhou, J. Rpp20 interacts with SMN and is re-distributed into SMN granules in response to stress. *Biotechnol. Biophys. Res. Commun.* 2004, 314, 268–276. [CrossRef]
80. Rothe, F.; Gueydan, C.; Bellefroid, E.; Huez, G.; Kruys, V. Identification of FUSE-binding proteins as interacting partners of TIA proteins. *Proc. Natl. Acad. Sci. USA* 2006, 103, 574–578. [CrossRef] [PubMed]
81. Henao-Mejia, J.; He, J.J. Sam68 relocalization into stress granules in response to oxidative stress through complexing with TIA-1. *Exp. Cell Res.* 2009, 315, 3381–3395. [CrossRef] [PubMed]
82. Kwon, S.; Zhang, Y.; Matthias, P. The multifunctional FUS, EWS and TAF15 proto-oncoproteins show cell type-specific expression patterns involving in the maintenance of cellular ATP level during stress conditions. *Genes Cells Devot. Mol. Cell. Mech.* 2009, 14, 113–128. [CrossRef] [PubMed]
83. Goulet, I.; Boisvenue, S.; Mokas, S.; Mazroui, R.; Cote, J. TDRD3, a novel Tudor domain-containing protein, involved in the stress response. *Mol. Cell. Biol.* 2007, 27, 5383–5398. [CrossRef] [PubMed]
84. Simpson-Holley, M.; Kedersha, N.; Dower, K.; Rubins, K.H.; Anderson, P.; Hensley, L.E.; Connor, J.H. Stress granule formation following cellular stress. *PLoS ONE* 2010, 5, e35820. [CrossRef] [PubMed]
85. Gallouzi, I.E.; Brennan, C.M.; Stenberg, M.G.; Swanson, M.S.; Eversole, A.; Maizels, N.; Steitz, J.A. HuR binding to cytoplasmic mRNA is perturbed by heat shock. *Proc. Natl. Acad. Sci. USA* 2000, 97, 3073–3078. [CrossRef] [PubMed]
86. Chang, Y.W.; Huang, Y.S. Arsenite-activated JNK signaling enhances CPEB4-Vinexin interaction to Facilitate stress granule assembly and cell survival. *PLoS ONE* 2014, 9, e107961. [CrossRef] [PubMed]
87. Rothenburg, S.; Deigendesch, N.; Dittmar, K.; Koch-Nolte, F.; Haag, F.; Lowenhaupt, K.; Rich, A. A PKR-like eukaryotic initiation factor 2alpha kinase from zebrafish contains Z-DNA binding domains instead of dsRNA binding domains. *Proc. Natl. Acad. Sci. USA* 2005, 102, 1602–1607. [CrossRef] [PubMed]
98. Brehm, M.A.; Schenk, T.M.; Zhou, X.; Fanick, W.; Lin, H.; Windhorst, S.; Narayanswamy, M.M.; Kobras, M.; Shears, S.B.; Mayr, G.W. Intracellular localization of human Ins(1,3,4,5,6)P5 2-kinase. *Biochimie.* 2007, 89, 335–345.

99. Goodier, J.L.; Zhang, L.; Vetter, M.R.; Kazazian, H.H., Jr. LINE-1 ORF1 protein localizes in stress granules with other RNA-binding proteins, including components of RNA interference RNA-induced silencing complex. *Mol. Cell. Biol.* 2007, 27, 6469–6483. [CrossRef] [PubMed]

100. Sheth, U.; Parker, R. Decapping and decay of messenger RNA occur in cytoplasmic processing bodies. *Science* 2003, 300, 805–808. [CrossRef] [PubMed]

101. Savas, J.N.; Rakovsky, A.; Ottosen, S.; Baillat, D.; Then, F.; Krainc, D.; Shiekhattar, R.; Markey, S.P.; Tanese, N. Huntington’s protein contributes to RNA-mediated gene silencing through association with Argonaute and P bodies. *Proc. Natl. Acad. Sci. USA* 2008, 105, 10820–10825. [CrossRef] [PubMed]

102. Luke, B.; Azzalin, C.M.; Hug, N.; Deplazes, A.; Peter, M.; Lingner, J. Saccharomyces cerevisiae Ebs1p is a putative ortholog of human Smg7 and promotes nonsense-mediated mRNA decay. *Nucleic Acids Res.* 2007, 35, 7688–7697. [CrossRef] [PubMed]

103. Zheng, D.; Ezzeddine, N.; Chen, C.Y.; Zhu, W.; He, X.; Shyu, A.B. Deadenylation is prerequisite for P-body formation and mRNA decay in mammalian cells. *J. Cell Biol.* 2008, 182, 89–101. [CrossRef] [PubMed]

104. Lippincott-Schwartz, J.; Patterson, G.H. Development and use of fluorescent protein markers in living cells. *Science* 2003, 300, 87–91. [CrossRef] [PubMed]

105. Kshirsagar, M.; Parker, R. Identification of Edc3p as an enhancer of mRNA decapping in Saccharomyces cerevisiae. *Genes Dev.* 2004, 18, 729–739. [CrossRef] [PubMed]

106. Teixeira, D.; Parker, R. Analysis of P-body assembly in *Saccharomyces cerevisiae*. *Mol. Biol. Cell* 2007, 18, 2274–2287. [CrossRef] [PubMed]

107. Ferraiuolo, M.A.; Basak, S.; Dostie, J.; Murray, E.L.; Schoenberg, D.R.; Sonenberg, N. A role for the elf4E-binding protein 4E-T in P-body formation and mRNA decay. *J. Cell Biol.* 2005, 170, 913–924. [CrossRef] [PubMed]

108. Matsumoto, K.; Nakayama, H.; Yoshimura, M.; Masuda, A.; Dohmae, N.; Matsumoto, S.; Tsujimoto, M. PRMT1 is required for RAP55 to localize to processing bodies. *RNA Biol.* 2012, 9, 610–623. [CrossRef] [PubMed]

109. Meister, G.; Landthaler, M.; Peters, L.; Chen, P.Y.; Urlaub, H.; Luhrmann, R.; Tuschl, T. Identification of novel argonaute-associated proteins. *Curr. Biol. CB* 2005, 15, 2149–2155. [CrossRef] [PubMed]

110. Baillat, D.; Shiekhattar, R. Functional dissection of the human TNRC6 (GW182-related) family of proteins. *Mol. Cell. Biol.* 2009, 29, 4144–4155. [CrossRef] [PubMed]

111. Buchet-Poyau, K.; Courchet, J.; Le Hir, H.; Seraphin, B.; Scoazec, J.Y.; Duret, L.; Domon-Dell, C.; Freund, J.N.; Billaud, M. Identification and characterization of human Mex-3 proteins, a novel family of evolutionarily conserved RNA-binding proteins differentially localized to processing bodies. *Nucleic Acids Res.* 2007, 35, 1289–1300. [CrossRef] [PubMed]

112. Katahira, J.; Miki, T.; Takano, K.; Maruhashi, M.; Uchikawa, M.; Tachibana, T.; Yoneda, Y. Nuclear RNA export factor 7 is localized in processing bodies and neuronal RNA granules through interactions with shuttling hnRNPs. *Nucleic Acids Res.* 2008, 36, 616–628. [CrossRef] [PubMed]

113. Leung, A.K.; Calabrese, J.M.; Sharp, P.A. Quantitative analysis of Argonaute protein reveals microRNA-dependent localization to stress granules. *Proc. Natl. Acad. Sci. USA* 2006, 103, 18125–18130. [CrossRef] [PubMed]

114. Hoyle, N.P.; Castelli, L.M.; Campbell, S.G.; Holmes, L.E.; Ashe, M.P. Stress-dependent relocation of translationally primed mRNPs to cytoplasmic granules that are kinetically and spatially distinct from P-bodies. *J. Cell Biol.* 2007, 179, 65–74. [CrossRef] [PubMed]

115. Kozak, S.L.; Marin, M.; Rose, K.M.; Bystrom, C.; Kabat, D. The anti-HIV-1 editing enzyme APOBEC3G binds HIV-1 RNA and messenger RNAs that shuttle between polysomes and stress granules. *J. Biol. Chem.* 2006, 281, 29105–29119. [CrossRef] [PubMed]

116. Fujimura, K.; Kano, F.; Murata, M. Identification of PCBP2, a facilitator of IRES-mediated translation, as a novel constituent of stress granules and processing bodies. *Rna* 2008, 14, 425–431. [CrossRef] [PubMed]

117. Kedersha, N.; Stockell, G.; Ayodele, M.; Yacono, P.; Lykke-Andersen, J.; Fitzler, M.J.; Scheuner, D.; Kaufman, R.J.; Golan, D.E.; Anderson, P. Stress granules and processing bodies are dynamically linked sites of mRNP remodeling. *J. Cell Biol.* 2005, 169, 871–884. [CrossRef] [PubMed]
118. Yang, W.-H.; Yu, J.H.; Gulick, T.; Bloch, K.D.; Bloch, D.B. RNA-associated protein 55 (RAP55) localizes to mRNA processing bodies and stress granules. *RNA (New York, NY)* **2006**, 12, 547–554. [CrossRef] [PubMed]

119. Athanasopoulos, V.; Barker, A.; Yu, D.; Tan, A.H.; Srivastava, M.; Contreras, N.; Wang, J.; Lam, K.P.; Brown, S.H.; Goodnow, C.C.; et al. The ROQUIN family of proteins localizes to stress granules via the ROQ domain and binds target mRNAs. *FEBS J.* **2010**, 277, 2109–2127. [CrossRef] [PubMed]

120. Eulalio, A.; Behm-Ansmant, I.; Izaurralde, E. P bodies: At the crossroads of post-transcriptional pathways. *Nat. Rev. Mol. Cell Biol.* **2007**, 8, 9–22. [CrossRef] [PubMed]

121. Baez, M.V.; Boccaccio, G.L. Mammalian smaug is a translational repressor that forms cytoplasmic foci similar to stress granules. *J. Biol. Chem.* **2005**, 280, 43131–43140. [CrossRef] [PubMed]

122. Buchan, J.R.; Muhlrad, D.; Parker, R. P bodies promote stress granule assembly in *Saccharomyces cerevisiae*. *J. Cell Biol.* **2008**, 183, 441–455. [CrossRef] [PubMed]

123. Courchet, J.; Buchet-Poyau, K.; Potemski, A.; Bres, A.; Jariel-Encontre, I.; Billaud, M. Interaction with TIA-1/TIAR and both synthesis and cytoplasmic accumulation of tristetraprolin, two cellular proteins that bind and destabilize AU-rich RNAs. *J. Virol.* **2007**, 81, 3271–3276. [CrossRef] [PubMed]

124. Balzer, E.; Moss, E.G. Localization of the developmental timing regulator Lin28 to mRNP complexes, P-bodies and stress granules. *RNA Biol.* **2007**, 4, 16–25. [CrossRef] [PubMed]

125. Wasserman, T.; Katsenelson, K.; Daniliuc, S.; Hasin, T.; Choder, M.; Aronheim, A. A Novel c-Jun N-terminal Kinase (JNK)-binding Protein WDR62 Is Recruited to Stress Granules and Mediates a Nonclassical JNK Activation. *Mol. Biol. Cell* **2010**, 21, 117–130. [CrossRef] [PubMed]

126. Sciotino, M.T.; Parisi, T.; Siracusano, G.; Mastino, A.; Taddeo, B.; Roizman, B. The virion host shutoff RNase plays a key role in blocking the activation of protein kinase R in cells infected with herpes simplex virus 1. *J. Virol.* **2013**, 87, 3271–3276. [CrossRef] [PubMed]

127. Cassady, K.A.; Gross, M. The herpes simplex virus type 1 U(S)11 protein interacts with protein kinase R and stress granule formation. *J. Virol.* **2010**, 85, 5363–5373. [CrossRef] [PubMed]

128. Eulalio, A.; Behm-Ansmant, I.; Smiley, J.R. The herpes simplex virus 1 vhs protein enhances translation of viral true late mRNAs and virus production in a cell type-dependent manner. *J. Virol.* **2007**, 81, 3377–3390. [CrossRef] [PubMed]

129. Sciortino, M.T.; Parisi, T.; Siracusano, G.; Mastino, A.; Taddeo, B.; Roizman, B. The virion host shutoff RNase 135. Dauber, B.; Poon, D.; Dos Santos, T.; Duguay, B.A.; Mehta, N.; Saffran, H.A.; Smiley, J.R. The herpes simplex virus virion host shutoff protein enhances translation of viral true late mRNAs independently of suppressing protein kinase R and stress granule formation. *J. Virol.* **2016**, 90, 6049–6057. [CrossRef] [PubMed]

130. He, B.; Gross, M.; Roizman, B. The gamma(1)34.5 protein of herpes simplex virus 1 complexes with protein phosphatase 1alpha to dephosphorylate the alpha subunit of the eukaryotic translation initiation factor 2 and preclude the shutoff of protein synthesis by double-stranded RNA-activated protein kinase. *Proc. Natl. Acad. Sci. USA* **1997**, 94, 843–848. [PubMed]

131. He, B.; Gross, M.; Roizman, B. The gamma(1)34.5 protein of herpes simplex virus 1 complexes with protein phosphatase 1alpha to dephosphorylate the alpha subunit of the eukaryotic translation initiation factor 2 and preclude the shutoff of protein synthesis by double-stranded RNA-activated protein kinase. *Proc. Natl. Acad. Sci. USA* **1997**, 94, 843–848. [PubMed]

132. Muller, M.; Arias, C.; Mohr, I. Maintenance of endoplasmic reticulum (ER) homeostasis in herpes simplex virus type 1-infected cells through the association of a viral glycoprotein with PERK, a cellular ER stress sensor. *J. Virol.* **2007**, 81, 3377–3390. [CrossRef] [PubMed]

133. Esclatine, A.; Taddeo, B.; Roizman, B. Herpes simplex virus 1 induces cytoplasmic accumulation of TIA-1/TIAR and both synthesis and cytoplasmic accumulation of tristetraprolin, two cellular proteins that bind and destabilize AU-rich RNAs. *J. Virol.* **2004**, 78, 8582–8592. [CrossRef] [PubMed]

134. Dauber, B.; Pelletier, J.; Smiley, J.R. The herpes simplex virus 1 vhs protein enhances translation of viral true late mRNAs and virus production in a cell type-dependent manner. *J. Virol.* **2011**, 85, 5363–5373. [CrossRef] [PubMed]

135. Dauber, B.; Poon, D.; Dos Santos, T.; Duguay, B.A.; Mehta, N.; Saffran, H.A.; Smiley, J.R. The herpes simplex virus virion host shutoff protein enhances translation of viral true late mRNAs independently of suppressing protein kinase R and stress granule formation. *J. Virol.* **2016**, 90, 6049–6057. [CrossRef] [PubMed]

136. Finnen, R.L.; Pangka, K.R.; Banfield, B.W. Herpes simplex virus 2 infection impacts stress granule accumulation. *J. Virol.* **2012**, 86, 8119–8130. [CrossRef] [PubMed]
137. Finnen, R.L.; Hay, T.J.; Dauber, B.; Smiley, J.R.; Banfield, B.W. The herpes simplex virus 2 virion-associated ribonuclease vhs interferes with stress granule formation. *J. Virol.* 2014, 88, 12727–12739. [CrossRef] [PubMed]

138. Isler, J.A.; Skale, A.H.; Alwine, J.C. Human cytomegalovirus infection activates and regulates the unfolded protein response. *J. Virol.* 2005, 79, 6890–6899. [CrossRef] [PubMed]

139. Qin, Q.; Carroll, K.; Hastings, C.; Miller, C.L. Mammalian orthoreovirus escape from host translational shutoff correlates with stress granule disruption and is independent of eIF2alpha phosphorylation and PKR. *J. Virol.* 2011, 85, 8798–8810. [CrossRef] [PubMed]

140. Qin, Q.; Carroll, K.; Hastings, C.; Miller, C.L. Mammalian orthoreovirus escape from host translational shutoff correlates with stress granule disruption and is independent of eIF2alpha phosphorylation and PKR. *J. Virol.* 2011, 85, 8798–8810. [CrossRef] [PubMed]

141. Qin, Q.; Carroll, K.; Hastings, C.; Miller, C.L. Mammalian orthoreovirus escape from host translational shutoff correlates with stress granule disruption and is independent of eIF2alpha phosphorylation and PKR. *J. Virol.* 2011, 85, 8798–8810. [CrossRef] [PubMed]

142. Zaborowska, I.; Kellner, K.; Henry, M.; Meleady, P.; Walsh, D. Recruitment of host translation initiation factor eIF4G by the Vaccinia Virus ssDNA-binding protein I3. *Virology* 2012, 425, 11–22. [CrossRef] [PubMed]

143. Walsh, D.; Arias, C.; Perez, C.; Halladin, D.; Escandón, M.; Ueda, T.; Watanabe-Fukunaga, R.; Fukunaga, R.; Mohr, I. Eukaryotic translation initiation factor 4F architectural alterations accompany translation initiation factor redistribution in poxvirus-infected cells. *Mol. Cell. Biol.* 2008, 28, 2648–2658. [CrossRef] [PubMed]

144. Montero, H.; Rojas, M.; Arias, C.F.; Lopez, S. Rotavirus infection induces the phosphorylation of eIF2alpha but prevents the formation of stress granules. *J. Virol.* 2008, 82, 1496–1504. [CrossRef] [PubMed]

145. Rojas, M.; Arias, C.F.; Lopez, S. Protein kinase R is responsible for the phosphorylation of eIF2alpha in rotavirus infection. *J. Virol.* 2010, 84, 10457–10466. [CrossRef] [PubMed]

146. Qin, Q.; Hastings, C.; Miller, C.L. Mammalian orthoreovirus particles induce and are recruited into stress granules at early times postinfection. *J. Virol.* 2009, 83, 11090–11101. [CrossRef] [PubMed]

147. Qin, Q.; Carroll, K.; Hastings, C.; Miller, C.L. Mammalian orthoreovirus escape from host translational shutoff correlates with stress granule disruption and is independent of eIF2alpha phosphorylation and PKR. *J. Virol.* 2011, 85, 8798–8810. [CrossRef] [PubMed]

148. Qin, Q.; Carroll, K.; Hastings, C.; Miller, C.L. Mammalian orthoreovirus escape from host translational shutoff correlates with stress granule disruption and is independent of eIF2alpha phosphorylation and PKR. *J. Virol.* 2011, 85, 8798–8810. [CrossRef] [PubMed]

149. Dougherty, J.D.; Tsai, W.C.; Lloyd, R.E. Multiple poliovirus proteins repress cytoplasmic RNA granules. *Viruses* 2015, 7, 6127–6140. [CrossRef] [PubMed]

150. White, J.P.; Cardenas, A.M.; Marissen, W.E.; Lloyd, R.E. Inhibition of cytoplasmic mRNA stress granule formation by a viral proteinase. *Cell Host Microbe* 2007, 2, 295–305. [CrossRef] [PubMed]

151. Pirotrowska, J.; Hanssen, S.J.; Park, N.; Jamka, K.; Sarnow, P.; Gustin, K.E. Stable formation of compositionally unique stress granules in virus-infected cells. *J. Virol.* 2010, 84, 3654–3665. [CrossRef] [PubMed]

152. White, J.P.; Cardenas, A.M.; Marissen, W.E.; Lloyd, R.E. Inhibition of cytoplasmic mRNA stress granule formation by a viral proteinase. *Cell Host Microbe* 2007, 2, 295–305. [CrossRef] [PubMed]

153. Fung, G.; Ng, C.S.; Zhang, J.; Shi, J.; Wong, J.; Pesik, P.; Han, L.; Chu, F.; Jagdeo, J.; Jan, E.; et al. Production of a dominant-negative fragment due to G3BP1 cleavage contributes to the disruption of mitochondria-associated protective stress granules during CVB3 infection. *PLoS ONE* 2013, 8, e79546. [CrossRef] [PubMed]

154. Borghese, F.; Michiels, T. The leader protein of cardioviruses inhibits stress granule assembly. *PLoS Pathog.* 2005, 1, e28. [CrossRef] [PubMed]

155. Langereis, M.A.; Feng, Q.; van Kuppeveld, F.J. MDA5 localizes to stress granules, but this localization is not required for the induction of type I interferon. *J. Virol.* 2013, 87, 6314–6325. [CrossRef] [PubMed]

156. Reineke, L.C.; Kedersha, N.; Langereis, M.A.; van Kuppeveld, F.J.; Lloyd, R.E. Stress granules regulate double-stranded RNA-dependent protein kinase activation through a complex containing G3BP1 and Caprin1. *mBio* 2015, 6, e02486. [CrossRef] [PubMed]

157. Mcinerney, G.; Kedersha, N.; Kaufman, R.J.; Anderson, P.; Liljestrom, P. Importance of eIF2a Phosphorylation and Stress Granule Assembly in Alphavirus Translation Regulation. *Mol. Biol. Cell* 2005, 16, 3753–3763. [CrossRef] [PubMed]
158. Panas, M.D.; Varjak, M.; Lulla, A.; Eng, K.E.; Merits, A.; Karlsson Hedestam, G.B.; Mclnerney, G.M. Sequestration of G3BP coupled with efficient translation inhibits stress granules in Semliki Forest virus infection. *Mol. Biol. Cell* **2012**, *23*, 4701–4712. [CrossRef] [PubMed]

159. Fros, J.J.; Domeradzka, N.E.; Baggen, J.; Geertsema, C.; Flipse, J.; Vlak, J.M.; Pijlman, G.P. Chikungunya virus nsP3 blocks stress granule assembly by recruitment of G3BP into cytoplasmic foci. *J. Virol.* **2012**, *86*, 10873–10879. [CrossRef] [PubMed]

160. Matsuki, H.; Takahashi, M.; Higuchi, M.; Makokha, G.N.; Oie, M.; Fujii, M. Both G3BP1 and G3BP2 contribute to stress granule formation. *Genes Cells Devot. Mol. Cell. Mech.* **2013**, *18*, 135–146. [CrossRef] [PubMed]

161. Scholte, F.E.; Tas, A.; Albulescu, I.C.; Zusinaite, E.; Merits, A.; Snijder, E.J.; van Hemert, M.J. Stress granule formation in Sindbis virus-infected cells interferes with stress granule formation. *J. Virol.* **2010**, *84*, 6720–6732. [CrossRef] [PubMed]

162. Matthews, J.D.; Frey, T.K. Analysis of subcellular G3BP redistribution during rubella virus infection. *J. Gen. Virol.* **2012**, *93*, 267–274. [CrossRef] [PubMed]

163. Gorchakov, R.; Garmashova, N.; Frolova, E.; Frolov, I. Different types of nsP3-containing protein complexes in Sindbis virus-infected cells. *J. Virol.* **2008**, *82*, 10088–10101. [CrossRef] [PubMed]

164. Frolova, E.; Gorchakov, R.; Garmashova, N.; Atasheva, S.; Vergara, L.A.; Frolov, I. Formation of nsP3-specific protein complexes during Sindbis virus replication. *J. Virol.* **2006**, *80*, 4122–4134. [CrossRef] [PubMed]

165. Cristea, I.M.; Rozjabek, H.; Molloy, K.R.; Karki, S.; White, L.L.; Rice, C.M.; Rout, M.P.; Chait, B.T.; MacDonald, M.R. Host factors associated with the Sindbis virus RNA-dependent RNA polymerase: Role for G3BP1 and G3BP2 in virus replication. *J. Virol.* **2010**, *84*, 11043–11056. [CrossRef] [PubMed]

166. Venticinque, L.; Meruelo, D. Sindbis viral vector induced apoptosis requires translational inhibition and signaling through Mcl-1 and Bak. *Mol. Cancer* **2010**, *9*, 37. [CrossRef] [PubMed]

167. Li, W.; Li, Y.; Kedersha, N.; Anderson, P.; Emara, M.; Swiderek, K.M.; Moreno, G.T.; Emara, M.M.; Brinton, M.A. Cell proteins TIA-1 and TIAR interact with the 3′ stem-loop of the West Nile virus complementary minus-strand RNA and facilitate virus replication. *J. Virol.* **2002**, *76*, 11989–12000. [CrossRef] [PubMed]

168. Emara, M.M.; Brinton, M.A. Interaction of TIA-1/TIAR with West Nile and dengue virus products in infected cells interferes with stress granule formation and processing body assembly. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 9041–9046. [CrossRef] [PubMed]

169. Courtney, S.C.; Scherbik, S.V.; Stockman, B.M.; Brinton, M.A. West nile virus infections suppress early viral RNA synthesis and avoid inducing the cell stress granule response. *J. Virol.* **2012**, *86*, 3647–3657. [CrossRef] [PubMed]

170. Xia, J.; Chen, X.; Xu, F.; Wang, Y.; Shi, Y.; Li, Y.; He, J.; Zhang, P. Dengue virus infection induces formation of G3BP1 granules in human lung epithelial cells. *Arch. Virol.* **2015**, *160*, 2991–2999. [CrossRef] [PubMed]

171. Ward, A.M.; Bidet, K.; Yinglin, A.; Ler, S.G.; Hogue, K.; Blackstock, W.; Gunaratne, J.; Garcia-Blanco, M.A. Quantitative mass spectrometry of DENV-2 RNA-interacting proteins reveals that the DEAD-box RNA helicase DDx6 binds the DB1 and DB2 3′ UTR structures. *RNA Biol.* **2011**, *8*, 1173–1186. [CrossRef] [PubMed]

172. Bidet, K.; Dadlani, D.; Garcia-Blanco, M.A. G3BP1, G3BP2 and CAPRIN1 are required for translation of stress granule components G3BP1 and G3BP2 play a proviral role early in chikungunya virus replication. *J. Virol.* **2015**, *89*, 4457–4469. [CrossRef] [PubMed]

173. Albornoz, A.; Carletti, T.; Corazza, G.; Marcello, A. The stress granule component TIA-1 binds tick-borne encephalitis virus RNA and is recruited to perinuclear sites of viral replication to inhibit viral translation. *J. Virol.* **2014**, *88*, 6611–6622. [CrossRef] [PubMed]

174. Katoh, H.; Okamoto, T.; Fukuhara, T.; Kambara, H.; Morita, E.; Mori, Y.; Kamitani, W.; Matsuura, Y. Japanese encephalitis virus core protein inhibits stress granule formation through an interaction with Caprin-1 and facilitates viral propagation. *J. Virol.* **2013**, *87*, 489–502. [CrossRef] [PubMed]

175. Jefferson, M.; Donasiyivanov, A.; Pollen, S.; Dalmary, T.; Saalbach, G.; Powell, P.P. Host factors that interact with the pestivirus N-terminal protease, Npro, are components of the ribonucleoprotein complex. *J. Virol.* **2014**, *88*, 10340–10353. [CrossRef] [PubMed]

176. Garaigorta, U.; Heim, M.H.; Boyd, B.; Wieland, S.; Chisari, F.V. Hepatitis C virus (HCV) induces formation of stress granules whose proteins regulate HCV RNA replication and virus assembly and egress. *J. Virol.* **2012**, *86*, 11043–11056. [CrossRef] [PubMed]
177. Ruggieri, A.; Dazert, E.; Metz, P.; Hofmann, S.; Bergeest, J.P.; Mazur, J.; Bankhead, P.; Hiet, M.S.; Kallis, S.; Alvisi, G.; et al. Dynamic oscillation of translation and stress granule formation mark the cellular response to virus infection. Cell Host Microbe 2012, 12, 71–85. [CrossRef] [PubMed]

178. Li, Q.; Pene, V.; Krishnamurthy, S.; Cha, H.; Liang, T.J. Hepatitis C virus infection activates an innate pathway involving IKK-alpha in lipogenesis and viral assembly. Nat. Med. 2013, 19, 722–729. [CrossRef] [PubMed]

179. Li, Q.; Pene, V.; Sundar, S.; Hsu, C.S.; Liang, T.J. Dynamic interaction of stress granule, DDG3X and IKK-alpha mediates multiple functions in hepatitis C virus infection. J. Virol. 2015, 89, 5462–5477. [CrossRef] [PubMed]

180. Valiente-Echeverría, F.; Hermoso, M.A.; Soto-Rífo, R. RNA helicase DDX3: At the crossroad of viral replication and antiviral immunity. Rev. Med. Virol. 2015, 25, 286–299. [CrossRef] [PubMed]

181. Ariumi, Y.; Kuroki, M.; Kushima, Y.; Osugi, K.; Hijikata, M.; Maki, M.; Ikeda, M.; Kato, N. Hepatitis C virus hijacks P-body and stress granule components around lipid droplets. J. Virol. 2011, 85, 6882–6892. [CrossRef] [PubMed]

182. Pager, C.T.; Schutz, S.; Abraham, T.M.; Luo, G.; Sarnow, P. Modulation of hepatitis C virus RNA abundance and virus release by dispersion of processing bodies and enrichment of stress granules. Virology 2013, 435, 472–484. [CrossRef] [PubMed]

183. Khong, A.; Jan, E. Modulation of stress granules and P bodies during dicistrovirus infection. J. Virol. 2011, 85, 1439–1451. [CrossRef] [PubMed]

184. Fields, B.N.; Knipe, D.M.; Howley, P.M. Fields Virology, 6th ed.; Wolters Kluwer Health/Lippincott Williams & Wilkins: Philadelphia, PA, USA, 2013.

185. Raaben, M.; Groot Koerkamp, M.J.; Rottier, P.J.; de Haan, C.A. Mouse hepatitis coronavirus replication induces host translational shutoff and mRNA decay with concomitant formation of stress granules and processing bodies. Cell. Microbiol. 2007, 9, 2218–2229. [CrossRef] [PubMed]

186. Sola, I.; Galan, C.; Mateos-Gomez, P.A.; Palacio, L.; Zuniga, S.; Cruz, J.L.; Almazan, F.; Enjuanes, L. The polypyrimidine tract-binding protein affects coronavirus RNA accumulation levels and relocalizes viral RNAs to novel cytoplasmic domains different from replication-transcription sites. J. Virol. 2011, 85, 5136–5149. [CrossRef] [PubMed]

187. Humoud, M.N.; Doyle, N.; Royall, E.; Willcocks, M.M.; Sorgeloos, F.; van Kuppeveld, F.; Roberts, L.O.; Goodfellow, I.G.; Langereis, M.A.; Locker, N. Feline Calicivirus infection disrupts the assembly of cytoplasmic stress granules and induces G3BP1 cleavage. J. Virol. 2016. [CrossRef] [PubMed]

188. Royall, E.; Doyle, N.; Abdul-Wahab, A.; Emmott, E.; Morley, S.J.; Goodfellow, I.; Roberts, L.O.; Locker, N. Murine Norovirus 1 (MNV1) replication induces translational control of the host by regulating eIF4E activity during infection. J. Biol. Chem. 2015. [CrossRef] [PubMed]

189. Khapersky, D.A.; Hatchette, T.F.; McCormick, C. Influenza A virus inhibits cytoplasmic stress granule formation. FASEB J. Off. Publ. Fed. Am. Soc. Exp. Biol. 2012, 26, 1629–1639. [CrossRef] [PubMed]

190. Mok, B.W.-Y.; Song, W.; Wang, P.; Tai, H.; Chen, Y.; Zheng, M.; Wen, X.; Lau, S.-Y.; Wu, W.L.; Matsumoto, K.; et al. The NS1 protein of influenza A virus interacts with cellular processing bodies and stress granules through RNA-associated protein 55 (RAP55) during virus infection. J. Virol. 2012, 86, 12695–12707. [CrossRef] [PubMed]

191. Khapersky, D.A.; Emara, M.M.; Johnston, B.P.; Anderson, P.; Hatchette, T.F.; McCormick, C. Influenza virus host shutoff disables antiviral stress-induced translation arrest. PLoS Pathog. 2014, 10, e1004217. [CrossRef] [PubMed]

192. Thulasi Raman, S.N.; Liu, G.; Pyo, H.M.; Cui, Y.C.; Xu, F.; Ayalew, L.E.; Tikoo, S.K.; Zhou, Y. DDX3 interacts with influenza A NS1 and NP proteins and exerts antiviral function through regulation of stress granule formation. J. Virol. 2016, 90, 3661–3675. [CrossRef] [PubMed]

193. Linero, F.N.; Thomas, M.G.; Boccaccio, G.L.; Scolaro, L.A. Junin virus infection impairs stress-granule formation in Vero cells treated with arsenite via inhibition of eIF2alpha phosphorylation. J. Gen. Virol. 2011, 92, 2889–2899. [CrossRef] [PubMed]

194. Baird, N.L.; York, J.; Nunberg, J.H. Arenavirus infection induces discrete cytosolic structures for RNA replication. J. Virol. 2012, 86, 11301–11310. [CrossRef] [PubMed]

195. Dinh, P.X.; Beura, L.K.; Das, P.B.; Panda, D.; Das, A.; Pattnaik, A.K. Induction of stress granule-like structures in vesicular stomatitis virus-infected cells. J. Virol. 2013, 87, 372–383. [CrossRef] [PubMed]
196. Lindquist, M.E.; Lifland, A.W.; Utley, T.J.; Santangelo, P.J.; Crowe, J.E., Jr. Respiratory syncytial virus induces host RNA stress granules to facilitate viral replication. *J. Virol.* 2010, 84, 12274–12284. [CrossRef] [PubMed]

197. Lindquist, M.E.; Mainou, B.A.; Dermody, T.S.; Crowe, J.E., Jr. Activation of protein kinase R is required for induction of stress granules by respiratory syncytial virus but dispensable for viral replication. *Virology* 2011, 413, 103–110. [CrossRef] [PubMed]

198. Lifland, A.W.; Jung, J.; Alonas, E.; Zurla, C.; Crowe, J.E., Jr.; Santangelo, P.J. Human respiratory syncytial virus nucleoprotein and inclusion bodies antagonize the innate immune response mediated by MDA5 and MAVS. *J. Virol.* 2012, 86, 8245–8258. [CrossRef] [PubMed]

199. Fricke, J.; Koo, L.Y.; Brown, C.R.; Collins, P.L. p38 and OGT sequestration into viral inclusion bodies in cells infected with human respiratory syncytial virus suppresses MK2 activities and stress granule assembly. *J. Virol.* 2013, 87, 1333–1347. [CrossRef] [PubMed]

200. Randall, R.E.; Goodbourn, S. Interferons and viruses: An interplay between induction, signalling, antiviral responses and virus countermeasures. *J. Gen. Virol.* 2008, 89, 1–47. [CrossRef] [PubMed]

201. Iseni, F.; Garcin, D.; Nishio, M.; Kedersha, N.; Anderson, P.; Kolakofsky, D. Sendai virus trailer RNA binds TIAR, a cellular protein involved in virus-induced apoptosis. *EMBO J.* 2002, 21, 5141–5150. [CrossRef] [PubMed]

202. Yoshida, A.; Kawabata, R.; Honda, T.; Tomonaga, K.; Sakaguchi, T.; Irie, T. IFN-beta-inducing, unusual viral RNA species produced by paramyxovirus infection accumulated into distinct cytoplasmic structures in an RNA-type-dependent manner. *Front. Microbiol.* 2015, 6, 804. [CrossRef] [PubMed]

203. Garcin, D.; Lezzi, M.; Dobbs, M.; Elliott, R.M.; Schmaljohn, C.; Kang, C.Y.; Kolakofsky, D. The 5' ends of Hantaan virus (Bunyaviridae) RNAs suggest a prime-and-realign mechanism for the initiation of RNA synthesis. *J. Virol.* 1995, 69, 5754–5762. [PubMed]

204. Mir, M.A.; Duran, W.A.; Hjelle, B.L.; Ye, C.; Panganiban, A.T. Storage of cellular 5' mRNA caps in P bodies for viral cap-snatching. *Proc. Natl. Acad. Sci. USA* 2008, 105, 19294–19299. [CrossRef] [PubMed]

205. Ganaie, S.S.; Haque, A.; Panganiban, A.T. Ribosomal protein S19-binding protein NSs counteracts interferon regulatory factor 3-mediated induction of early cell death. *J. Virol.* 2013, 87, 1527–1536. [CrossRef] [PubMed]
215. Weber, F.; Bridgen, A.; Fazakerley, J.K.; Streitenfeld, H.; Kessler, N.; Randall, R.E.; Elliott, R.M. Bunyamwera bunyavirus nonstructural protein NSs counteracts the induction of alpha/beta interferon. *J. Virol.* 2002, 76, 7949–7955. [CrossRef] [PubMed]

216. Billecocq, A.; Spiegel, M.; Vialat, P.; Kohl, A.; Weber, F.; Bouloy, M.; Haller, O. NSs protein of Rift Valley fever virus blocks interferon production by inhibiting host gene transcription. *J. Virol.* 2004, 78, 9798–9806. [CrossRef] [PubMed]

217. Alff, P.J.; Gavrilovskaya, I.N.; Gorbunova, E.; Endriss, K.; Chong, Y.; Geimonen, E.; Sen, N.; Reich, N.C.; Mackow, E.R. The pathogenic NY-1 hantavirus G1 cytoplasmic tail inhibits RIG-I- and TBK-1-directed interferon responses. *J. Virol.* 2006, 80, 9676–9686. [CrossRef] [PubMed]

218. Cimica, V.; Dalrymple, N.A.; Roth, E.; Nasonov, A.; Mackow, E.R. An innate immunity-regulating virulence determinant is uniquely encoded by the Andes virus nucleocapsid protein. *mBio* 2014, 5. [CrossRef] [PubMed]

219. Matthys, V.S.; Cimica, V.; Dalrymple, N.A.; Glennon, N.B.; Bianco, C.; Mackow, E.R. Hantavirus GnT elements mediate TRAF3 binding and inhibit RIG-I/TBK1-directed beta interferon transcription by blocking IRF3 phosphorylation. *J. Virol.* 2014, 88, 2246–2259. [CrossRef] [PubMed]

220. Wang, Z.; Mir, M.A. Andes virus nucleocapsid protein interrupts protein kinase R dimerization to counteract host interference in viral protein synthesis. *J. Virol.* 2015, 89, 1628–1639. [CrossRef] [PubMed]

221. Habjan, M.; Pichlmair, A.; Elliott, R.M.; Overby, A.K.; Glatter, T.; Gstaiger, M.; Superti-Furga, G.; Unger, H.; Weber, F. NSs protein of rift valley fever virus induces the specific degradation of the double-stranded RNA-dependent protein kinase. *J. Virol.* 2009, 83, 4365–4375. [CrossRef] [PubMed]

222. Vialat, P.; Bouloy, M. Germiston virus transcriptase requires active 40S ribosomal subunits and utilizes capped cellular RNAs. *J. Virol.* 1992, 66, 685–693. [PubMed]

223. Barr, J.N. Bunyavirus mRNA synthesis is coupled to translation to prevent premature transcription termination. *RNA* 2007, 13, 731–736. [CrossRef] [PubMed]

224. Habjan, M.; Pichlmair, A.; Elliott, R.M.; Overby, A.K.; Glatter, T.; Gstaiger, M.; Superti-Furga, G.; Unger, H.; Weber, F. NSs protein of rift valley fever virus induces the specific degradation of the double-stranded RNA-dependent protein kinase. *J. Virol.* 2009, 83, 4365–4375. [CrossRef] [PubMed]

225. Nelson, E.V.; Schmidt, K.M.; Deflube, L.R.; Doganay, S.; Peters, C.J.; Olejnik, J.; Hume, A.J.; Ryabchikova, E.; Fujimura, K.; Sasaki, A. Selenite targets eIF4E-binding protein-1 to inhibit translation. *PLoS Pathog.* 2009, 5, e1000287. [CrossRef] [PubMed]

226. Legros, S.; Boxus, M.; Gatot, J.S.; Van Lint, C.; Kruys, V.; Kettmann, R.; Twizere, J.C.; Dequiedt, F. The HTLV-1 Tax protein inhibits formation of stress granules by interacting with histone deacetylase 6. *Oncogene* 2011, 30, 4050–4062. [CrossRef] [PubMed]

227. Alff, P.J.; Gavrilovskaya, I.N.; Gorbunova, E.; Endriss, K.; Chong, Y.; Geimonen, E.; Sen, N.; Reich, N.C.; Mackow, E.R. The pathogenic NY-1 hantavirus G1 cytoplasmic tail inhibits RIG-I- and TBK-1-directed interferon responses. *J. Virol.* 2006, 80, 9676–9686. [CrossRef] [PubMed]

228. Vialat, P.; Bouloy, M. Germiston virus transcriptase requires active 40S ribosomal subunits and utilizes capped cellular RNAs. *J. Virol.* 1992, 66, 685–693. [PubMed]

229. Takahashi, M.; Higuchi, M.; Makokha, G.N.; Matsuki, H.; Yoshita, M.; Tanaka, Y.; Fujii, M. HTLV-1 Tax oncprotein stimulates ROS production and apoptosis in T cells by interacting with USP10. *Blood* 2013, 122, 715–725. [CrossRef] [PubMed]

230. Abrahamyan, L.G.; Chatel-Chaix, L.; Ajamian, L.; Milev, M.P.; Monette, A.; Clement, J.F.; Song, R.; Lehmann, M; DesGroseillers, L.; Laughrea, M.; et al. Novel Staufen1 ribonucleoproteins prevent formation of stress granules but favour encapsidation of HIV-1 genomic RNA. *J. Cell Sci.* 2010, 123, 369–383. [CrossRef] [PubMed]

231. Vialat, P.; Bouloy, M. Germiston virus transcriptase requires active 40S ribosomal subunits and utilizes capped cellular RNAs. *J. Virol.* 1992, 66, 685–693. [PubMed]

232. Takahashi, M.; Higuchi, M.; Makokha, G.N.; Matsuki, H.; Yoshita, M.; Tanaka, Y.; Fujii, M. HTLV-1 Tax oncprotein stimulates ROS production and apoptosis in T cells by interacting with USP10. *Blood* 2013, 122, 715–725. [CrossRef] [PubMed]

233. Abrahamyan, L.G.; Chatel-Chaix, L.; Ajamian, L.; Milev, M.P.; Monette, A.; Clement, J.F.; Song, R.; Lehmann, M; DesGroseillers, L.; Laughrea, M.; et al. Novel Staufen1 ribonucleoproteins prevent formation of stress granules but favour encapsidation of HIV-1 genomic RNA. *J. Cell Sci.* 2010, 123, 369–383. [CrossRef] [PubMed]

234. Valiente-Echeverria, F.; Melnychuk, L.; Vyboh, K.; Ajamian, L.; Gallouzi, I.E.; Bernard, N.; Mouland, A.J. eEF2 and Ras-GAP SH3 domain-binding protein (G3BP1) modulate stress granule assembly during HIV-1 infection. *Nat. Commun.* 2014, 5, 4819. [CrossRef] [PubMed]

235. Abrahayman, L.G.; Chatel-Chaix, L.; Ajamian, L.; Milev, M.P.; Monette, A.; Clement, J.F.; Song, R.; Lehmann, M; DesGroseillers, L.; Laughrea, M.; et al. Novel Staufen1 ribonucleoproteins prevent formation of stress granules but favour encapsidation of HIV-1 genomic RNA. *J. Cell Sci.* 2010, 123, 369–383. [CrossRef] [PubMed]

236. Takahashi, M.; Higuchi, M.; Makokha, G.N.; Matsuki, H.; Yoshita, M.; Tanaka, Y.; Fujii, M. HTLV-1 Tax oncprotein stimulates ROS production and apoptosis in T cells by interacting with USP10. *Blood* 2013, 122, 715–725. [CrossRef] [PubMed]

237. Abrahamyan, L.G.; Chatel-Chaix, L.; Ajamian, L.; Milev, M.P.; Monette, A.; Clement, J.F.; Song, R.; Lehmann, M; DesGroseillers, L.; Laughrea, M.; et al. Novel Staufen1 ribonucleoproteins prevent formation of stress granules but favour encapsidation of HIV-1 genomic RNA. *J. Cell Sci.* 2010, 123, 369–383. [CrossRef] [PubMed]

238. Valiente-Echeverria, F.; Melnychuk, L.; Vyboh, K.; Ajamian, L.; Gallouzi, I.E.; Bernard, N.; Mouland, A.J. eEF2 and Ras-GAP SH3 domain-binding protein (G3BP1) modulate stress granule assembly during HIV-1 infection. *Nat. Commun.* 2014, 5, 4819. [CrossRef] [PubMed]

239. Coberos Jimenez, V.; Martinez, F.O.; Boonman, T.; van Dort, K.A.; van de Klundert, M.A.; Gordon, S.; Geijtenbeek, T.B.; Kootstra, N.A. G3BP1 restricts HIV-1 replication in macrophages and T-cells by sequestering viral RNA. *Virology* 2015, 486, 94–104. [CrossRef] [PubMed]

240. Soto-Rífo, R.; Valiente-Echeverria, F.; Rubilar, P.S.; García-de-Gracia, F.; Ricci, E.P.; Limousin, T.; Decimo, D.; Mouland, A.J.; Ohlmann, T. HIV-2 genomic RNA accumulates in stress granules in the absence of active translation. *Nucleic Acids Res.* 2014, 42, 12861–12875. [CrossRef] [PubMed]

241. Fujimura, K.; Sasaki, A.T.; Anderson, P. Selenite targets eIF4E-binding protein-1 to inhibit translation initiation and induce the assembly of non-canonical stress granules. *Nucleic Acids Res.* 2012, 40, 8099–8110. [CrossRef] [PubMed]
Viruses 2016, 8, 180

233. Cinti, A.; Le Sage, V.; Ghanem, M.; Mouland, A.J. HIV-1 gag blocks selenite-induced stress granule assembly by altering the mRNA cap-binding complex. mBio 2016, 7. [CrossRef] [PubMed]

234. Smith, J.A.; Schmechel, S.C.; Raghavan, A.; Abelson, M.; Reilly, C.; Katze, M.G.; Kaufman, R.J.; Bohjanen, P.R.; Schiff, L.A. Reovirus induces and benefits from an integrated cellular stress response. J. Virol. 2006, 80, 2019–2033. [CrossRef] [PubMed]

235. Hanley, L.L.; McGivern, D.R.; Teng, M.N.; Djang, R.; Collins, P.L.; Fears, R. Roles of the respiratory syncytial virus trailer region: Effects of mutations on genome production and stress granule formation. Virology 2010, 406, 241–252. [CrossRef] [PubMed]

236. Soto-Rifo, R.; Rubilar, P.S.; Ohlimann, T. The DEAD-box helicase DDX3 substitutes for the cap-binding protein eIF4E to promote compartmentalized translation initiation of the HIV-1 genomic RNA. Nucleic Acids Res. 2013, 41, 6286–6299. [CrossRef] [PubMed]

237. Greer, A.E.; Hearing, P.; Ketner, G. The adenovirus E4 11k protein binds and relocates the cytoplasmic P-body component Ddx6 to aggresomes. Virology 2011, 417, 161–168. [CrossRef] [PubMed]

238. Seto, E.; Inoue, T.; Nakatani, Y.; Yamada, M.; Isomura, H. Processing bodies accumulate in human cytomegalovirus-infected cells and do not affect viral replication at high multiplicity of infection. Virology 2014, 458–459, 151–161. [CrossRef] [PubMed]

239. Bhounick, R.; Mukherjee, A.; Patra, U.; Chawla-Sarkar, M. Rotavirus disrupts cytoplasmic P bodies during infection. Virus Res. 2015, 210, 344–354. [CrossRef] [PubMed]

240. Chahar, H.S.; Chen, S.; Manjunath, N. P-body components LSM1, GW182, DDX3, DDX6 and XRN1 are recruited to WNV replication sites and positively regulate viral replication. Virology 2013, 436, 1–7. [CrossRef] [PubMed]

241. Silva, P.A.; Pereira, C.F.; Dalebout, T.J.; Spaan, W.J.; Bredenbeek, P.J. An RNA pseudoknot is required for production of yellow fever virus subgenomic RNA by the host nuclease XRN1. J. Virol. 2010, 84, 11395–11406. [CrossRef] [PubMed]

242. Pijlman, G.P.; Funk, A.; Kondratieva, N.; van der Aa, L.; Liu, W.J.; Palmenberg, A.C.; Shi, P.Y.; Hall, R.A.; et al. A highly structured, nuclease-resistant, noncoding RNA produced by flaviviruses is required for pathogenicity. Cell Host Microbe 2008, 4, 579–591. [CrossRef] [PubMed]

243. Moon, S.L.; Anderson, J.R.; Kumagai, Y.; Wilusz, C.J.; Akira, S.; Khromykh, A.A.; Wilusz, J. A noncoding RNA produced by arthropod-borne flaviviruses inhibits the cellular exoribonuclease XRN1 and alters host mRNA stability. RNA 2012, 18, 2029–2040. [CrossRef] [PubMed]

244. Ariumi, Y.; Kuroki, M.; Abe, K.; Dansako, H.; Ikeda, M.; Wakita, T.; Kato, N. DDX3 DEAD-box RNA helicase is required for hepatitis C virus RNA replication. J. Virol. 2007, 81, 13922–13926. [CrossRef] [PubMed]

245. Scheller, N.; Mina, L.B.; Galão, R.P.; Chari, A.; Giménez-Barcons, M.; Noueiry, A.; Fischer, U.; Meyerhans, A.; Díez, J. Translation and replication of hepatitis C virus genomic RNA depends on ancient cellular proteins that control mRNA fates. Proc. Natl. Acad. Sci. USA 2009, 106, 13517–13522. [CrossRef] [PubMed]

246. Jangra, R.K.; Yi, M.; Lemon, S.M. DDX6 (Rck/p54) is required for efficient hepatitis C virus replication but not for internal ribosome entry site-directed translation. J. Virol. 2010, 84, 6810–6824. [CrossRef] [PubMed]

247. Perez-Vilaro, G.; Scheller, N.; Saludes, V.; Díez, J. Hepatitis C virus infection alters P-body composition but is independent of P-body granules. J. Virol. 2012, 86, 8740–8749. [CrossRef] [PubMed]

248. Dougherty, J.D.; White, J.P.; Lloyd, R.E. Poliovirus-mediated disruption of cytoplasmic processing bodies. J. Virol. 2011, 85, 64–75. [CrossRef] [PubMed]

249. Sokoloski, K.J.; Dickson, A.M.; Chaskey, E.L.; Carneau, N.L.; Wilusz, C.J.; Wilusz, J. Sindbis virus usurps the cellular HuR protein to stabilize its transcripts and promote productive infections in mammalian and mosquito cells. Cell Host Microbe 2010, 8, 196–207. [CrossRef] [PubMed]

250. Marin, M.; Gelem, S.; Rose, K.M.; Kozak, S.L.; Kabat, D. Human immunodeficiency virus type 1 Vif functionally interacts with diverse APOBEC3 cytidine deaminases and moves with them between cytoplasmic sites of mRNA metabolism. J. Virol. 2008, 82, 987–998. [CrossRef] [PubMed]

251. Chable-Bessia, C.; Meziane, O.; Latreille, D.; Triboulet, R.; Zamborlini, A.; Wagschal, A.; Jacquet, J.M.; Reynolds, J.; Levy, Y.; Saib, A.; et al. Suppression of HIV-1 replication by microRNA effectors. RetroVirology 2009, 6, 26. [CrossRef] [PubMed]

252. Martin, K.L.; Johnson, M.; D’Aquila, R.T. APOBEC3G complexes decrease human immunodeficiency virus type 1 production. J. Virol. 2011, 85, 9314–9326. [CrossRef] [PubMed]
253. Nathans, R.; Chu, C.Y.; Serquina, A.K.; Lu, C.C.; Cao, H.; Rana, T.M. Cellular microRNA and P bodies modulate host-HIV-1 interactions. *Mol. Cell* 2009, 34, 696–709. [CrossRef] [PubMed]

254. Phalora, P.K.; Sherer, N.M.; Steven, M.; Swanson, C.M.; Malim, M.H.; Phalora, P.K.; Sherer, N.M.; Wolinsky, S.M.; Swanson, C.M.; Malim, M.H. HIV-1 replication and APOBEC3 antiviral activity are not. *J. Virol.* 2012, 86, 11712. [CrossRef] [PubMed]

255. Bouktier, M.; Saumet, A.; Peter, M.; Courgnaud, V.; Schmidt, U.; Cazevieille, C.; Bertrand, E.; Lecellier, C.H. Retroviral GAG proteins recruit AGO2 on viral RNAs without affecting RNA accumulation and translation. *Nucleic Acids Res.* 2012, 40, 775–786. [CrossRef] [PubMed]

256. Reed, J.C.; Molter, B.; Geary, C.D.; McNevin, J.; McElrath, J.; Giri, S.; Klein, K.C.; Lingappa, J.R. HIV-1 Gag co-opts a cellular complex containing DDX6, a helicase that facilitates capsid assembly. *J. Cell Biol.* 2012, 198, 439–456. [CrossRef] [PubMed]

257. Bouttier, M.; Saumet, A.; Peter, M.; Courgnaud, V.; Schmidt, U.; Cazevieille, C.; Bertrand, E.; Lecellier, C.H. Retroviral GAG proteins recruit AGO2 on viral RNAs without affecting RNA accumulation and translation. *Nucleic Acids Res.* 2012, 40, 775–786. [CrossRef] [PubMed]

258. Reed, J.C.; Molter, B.; Geary, C.D.; McNevin, J.; McElrath, J.; Giri, S.; Klein, K.C.; Lingappa, J.R. HIV-1 Gag co-opts a cellular complex containing DDX6, a helicase that facilitates capsid assembly. *J. Cell Biol.* 2012, 198, 439–456. [CrossRef] [PubMed]

259. Lingappa, J.R.; Hill, R.L.; Wong, M.L.; Hegde, R.S. A multistep, ATP-dependent pathway for assembly of human immunodeficiency virus capsids in a cell-free system. *J. Cell Biol.* 1997, 136, 567–581. [CrossRef] [PubMed]

260. Reed, J.C.; Molter, B.; Geary, C.D.; McNevin, J.; McElrath, J.; Giri, S.; Klein, K.C.; Lingappa, J.R. HIV-1 Gag co-opts a cellular complex containing DDX6, a helicase that facilitates capsid assembly. *J. Cell Biol.* 2012, 198, 439–456. [CrossRef] [PubMed]

261. Panas, M.D.; Kedersha, N.; McInerney, G.M. Methods for the characterization of stress granules in virus infected cells. *Methods* 2015, 90, 57–64. [CrossRef] [PubMed]

262. Lin, Y.; Protter, D.S.; Rosen, M.K.; Parker, R. Formation and maturation of phase-separated liquid droplets by RNA-binding proteins. *Mol. Cell*. 2015. [CrossRef] [PubMed]

263. Lin, Y.; Protter, D.S.; Rosen, M.K.; Parker, R. Formation and maturation of phase-separated liquid droplets by RNA-binding proteins. *Mol. Cell* 2015. [CrossRef] [PubMed]

264. Kroschwald, S.; Maharana, S.; Mateju, D.; Malinovska, L.; Nuske, E.; Poser, I.; Richter, D.; Alberti, S. Promiscuous interactions and protein disaggregases determine the material state of stress-inducible RNP granules. *Elife* 2015, 4. [CrossRef] [PubMed]

265. Hilliker, A. Analysis of RNA helicases in P-bodies and stress granules. *Methods Enzymol.* 2012, 511, 323–346. [PubMed]

266. Kedersha, N.; Anderson, P. Mammalian stress granules and processing bodies. *Methods Enzymol.* 2007, 431, 61–81. [PubMed]

267. Kedersha, N.; Tisdale, S.; Hickman, T.; Anderson, P. Real-time and quantitative imaging of mammalian stress granules and processing bodies. *Methods Enzymol.* 2008, 448, 521–552. [CrossRef] [PubMed]

268. Lin, R.-J. RNA-Protein Complexes and Interactions; Springer: New York, NY, USA, 2016; Volume 1421.

269. Lin, Y.; Protter, D.S.; Rosen, M.K.; Parker, R. Formation and maturation of phase-separated liquid droplets by RNA-binding proteins. *Mol. Cell* 2015. [CrossRef] [PubMed]

270. Jain, S.; Wheeler, J.R.; Walters, R.W.; Agrawal, A.; Barsic, A.; Parker, R. ATPase-modulated stress granules contain a diverse proteome and substructure. *Cell* 2016, 164, 487–498. [CrossRef] [PubMed]

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