Unlocking the Drive

Exploiting Tesla Model 3

CODE BLUE
@TOKYO

SYNACKTIV

Who are we

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SYNACKTIV

- Offensive security
- 150 Experts
- Pentest, Reverse Engineering, Development, Incident Response

Reverse Engineering team

- 45 reversers
- Low level research, reverse Engineering, vulnerability research, exploit development, etc.

Pwn2own

& previous work

Competition organized by ZDI

Took place in Vancouver (April 2023)
New Pwn2Own Automotive in Tokyo (Jan. 2024)

Pwn2Own 2022

Infotainment preauth RCE (Wifi)
& sandbox escape & 2 kernel bugs

Pwn2own 2023

Timeline

GTW
Vulnerabilities & exploit
Dec 2022

Bluetooth
Vulnerability research
Mid Jan 2023

Bluetooth
Vulnerabilities
Mid Feb 2023

Bluetooth
Finalize exploit
6 mar 2023

Exploit
A useless service
8 mar 2023

LPE
Start LPE research
13 mar 2023

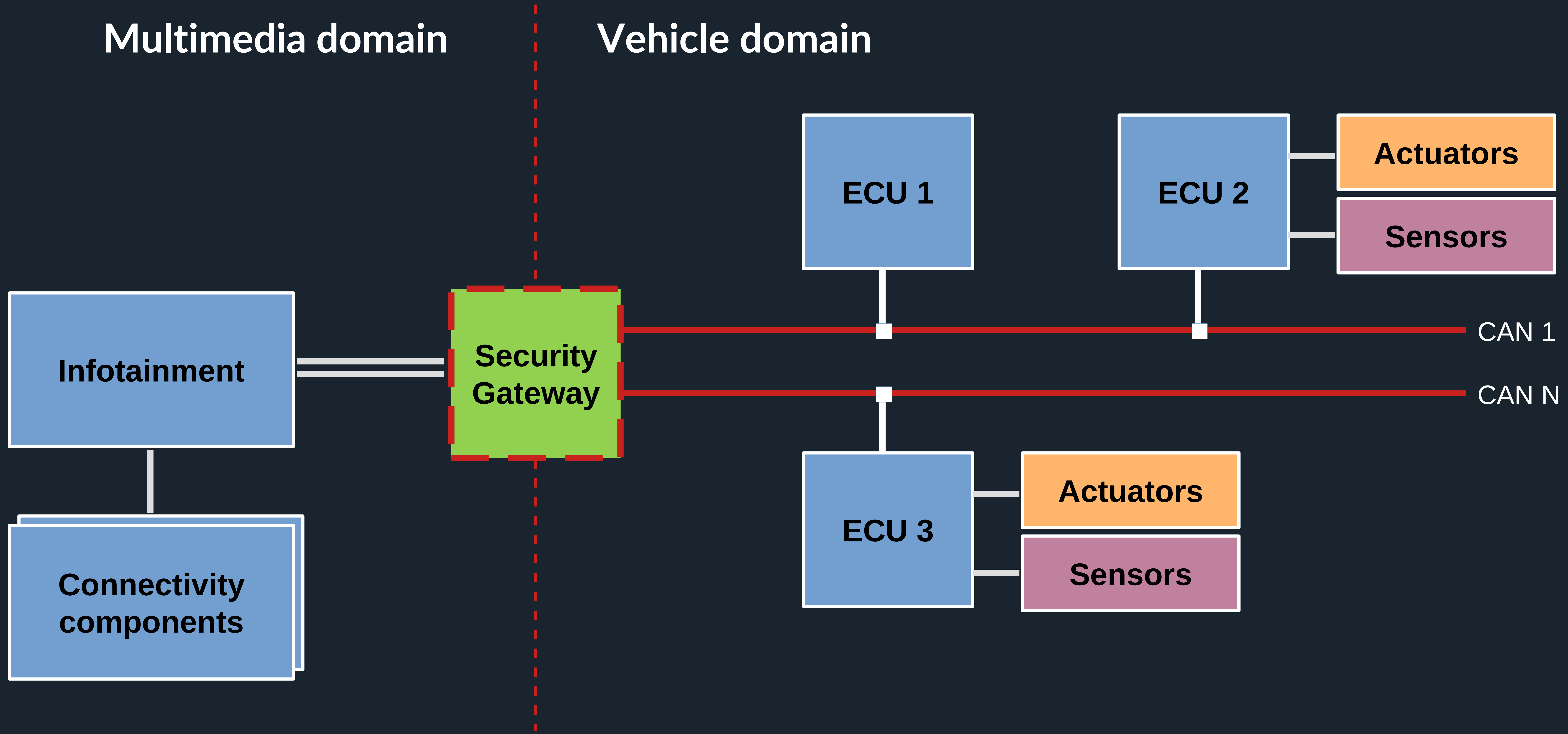
PC died
on the plane
Buy a new one
20 mar 2023

Exploit
Stabilisation & chaining
20-23 mar 2023

P2O
Event
22-23 mar 2023

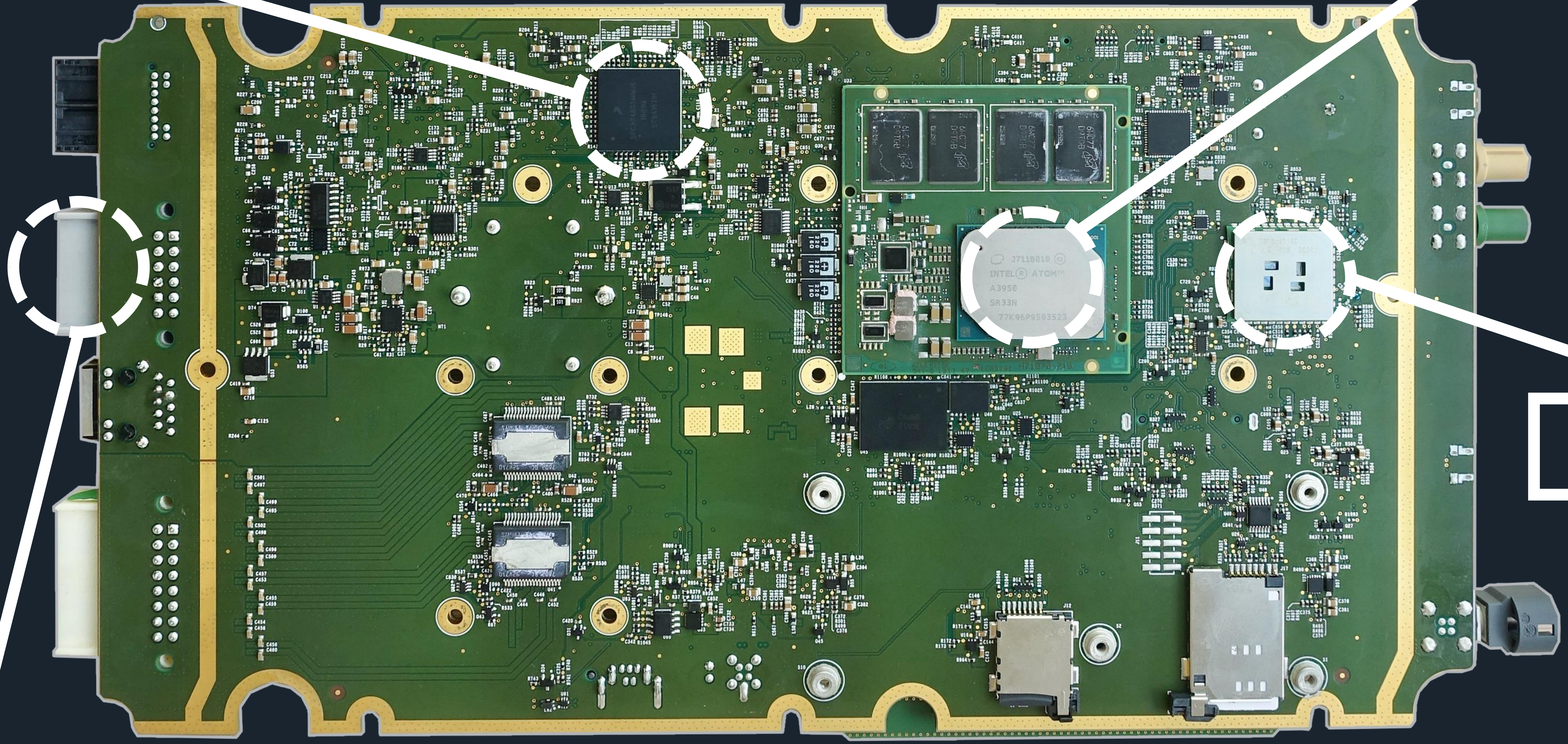
Car architecture

Multimedia and vehicule domains separared by a gateway



Model 3 – Infotainment

Hardware



Hardware setup

Lab

- Multiple Infotainment ECU
  - Some from Ebay
  - 2 provided by Tesla

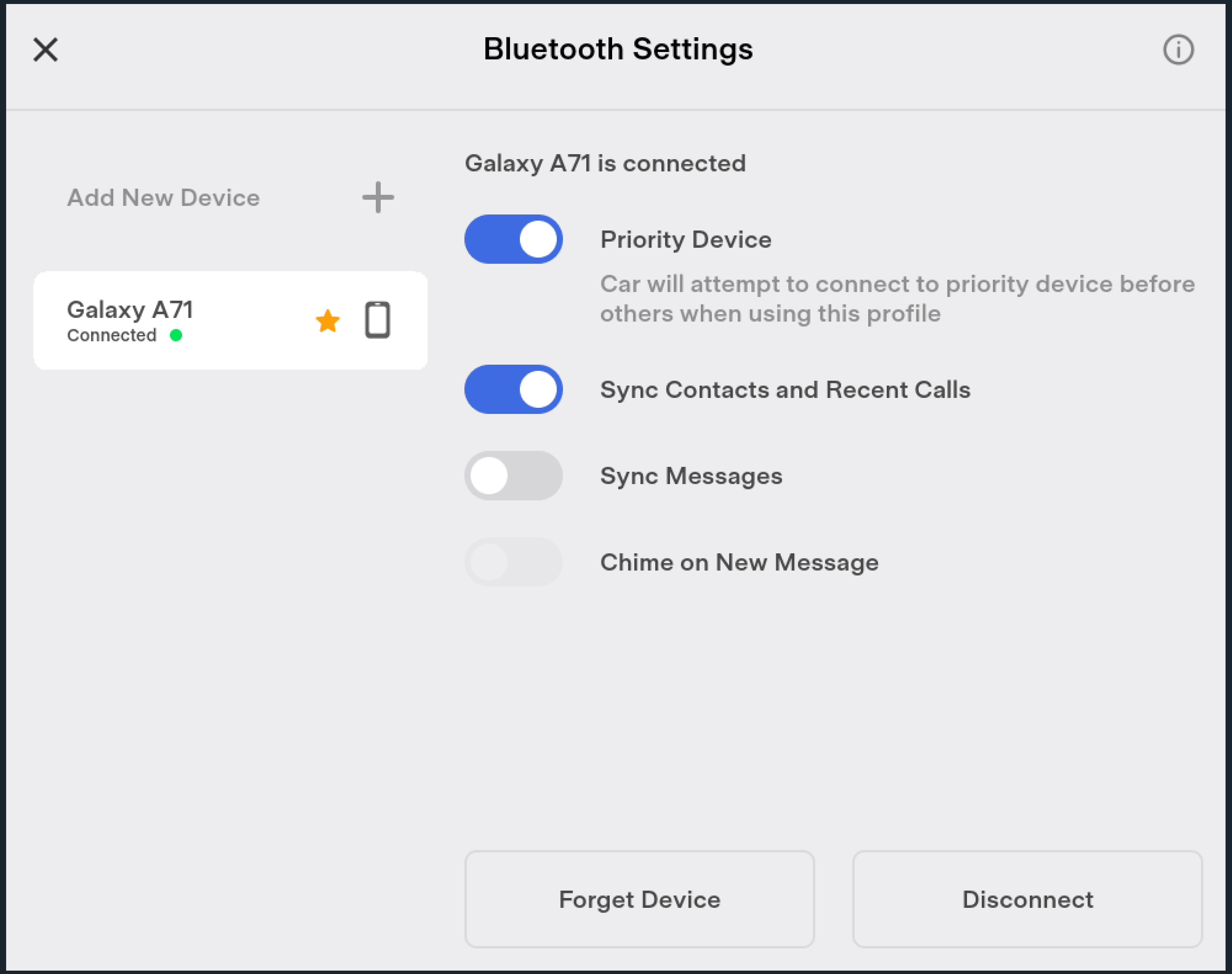
- After pwn2own 2022, Tesla gave us SSH keys to access our units

Exploit chain

Chaining three exploits for a remote-to-CAN fullchain

Bluetooth features

Why does the car need Bluetooth ?



Message and contact synchro.

Display received messages on the infotainment screen

Voice call

Display received SMS on the infotainment screen

Play music

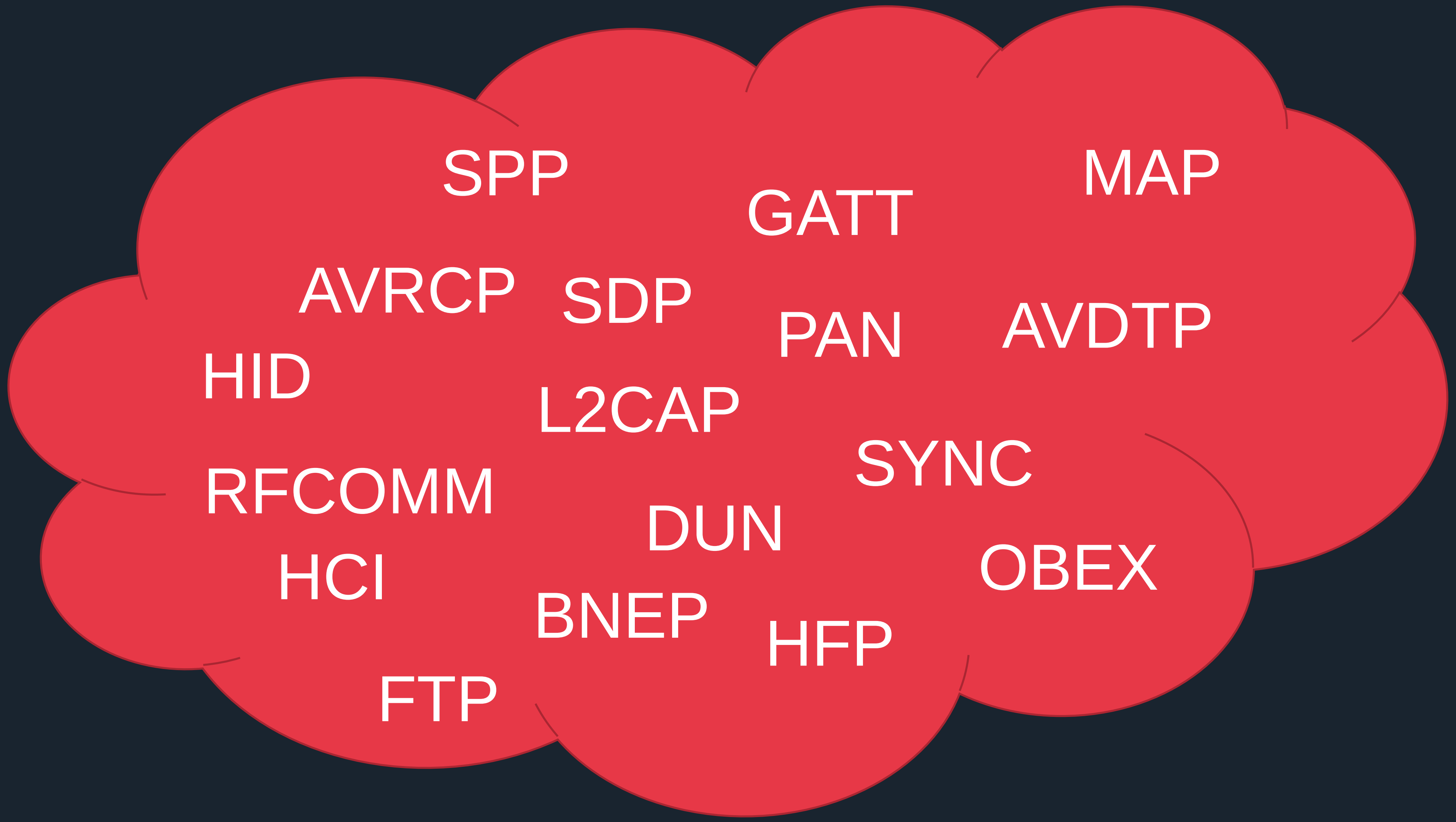
Play music from a phone using Bluetooth standards (supported by smartphones)

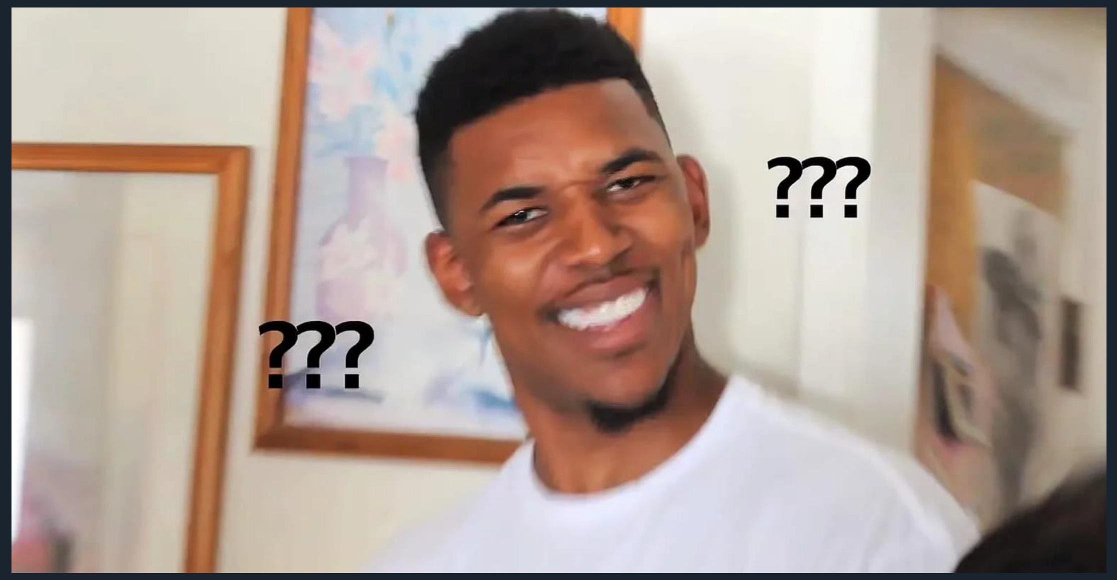
Spotify

Play music from a phone using Spotify

Bluetooth classic

A huge attack surface



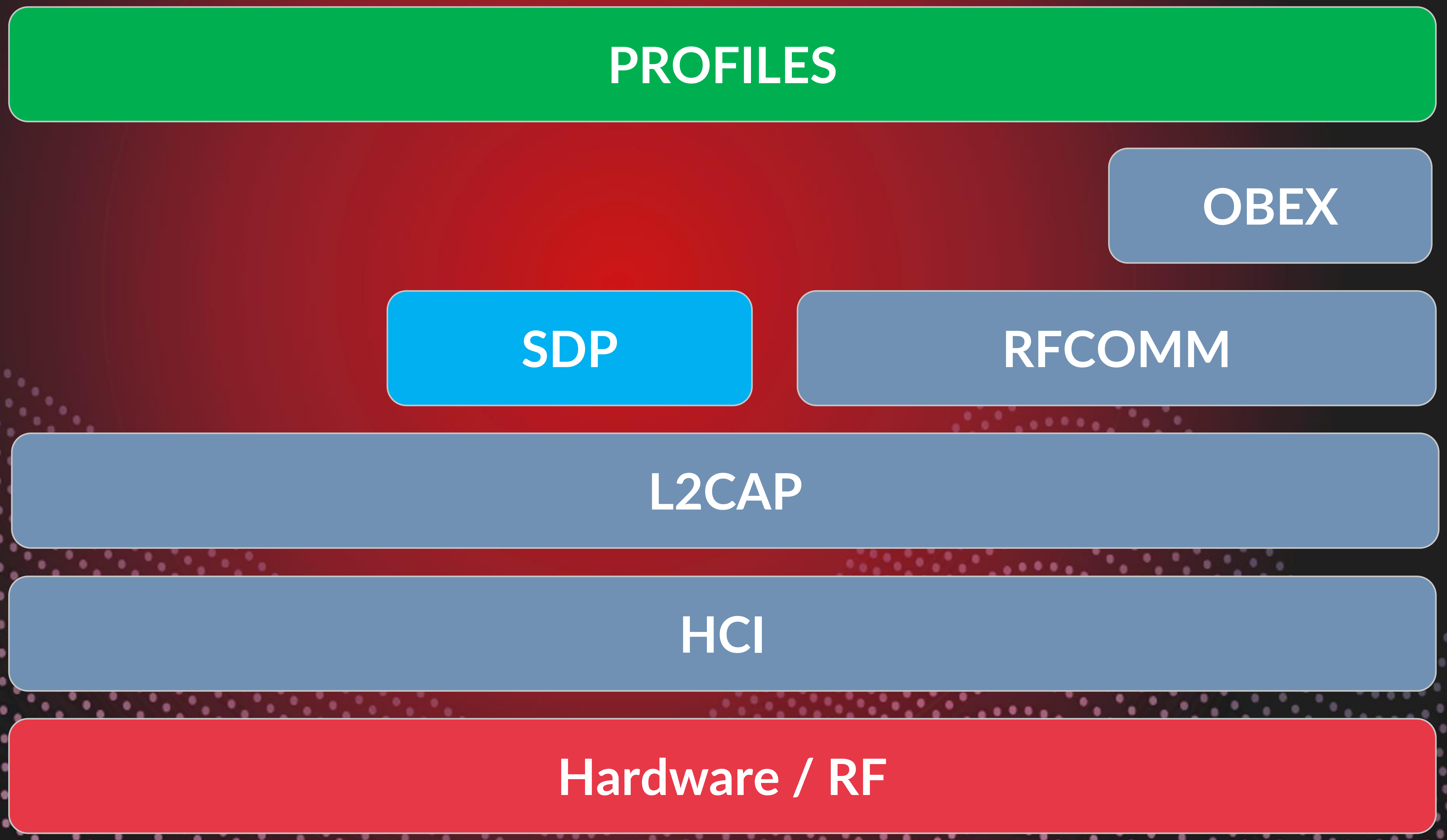


All these acronyms are real Bluetooth protocols / profiles

And there are **much** more…

Bluetooth classic

Attack surface on Tesla car



Profiles for Audio Playback

Service Discovery (SDP)

Retrieves the service list provided by the peer

Advanced Audio Distribution Profile (A2DP)

Protocol for audio streaming

Audio/Video Remote Control Profile (AVRCP)

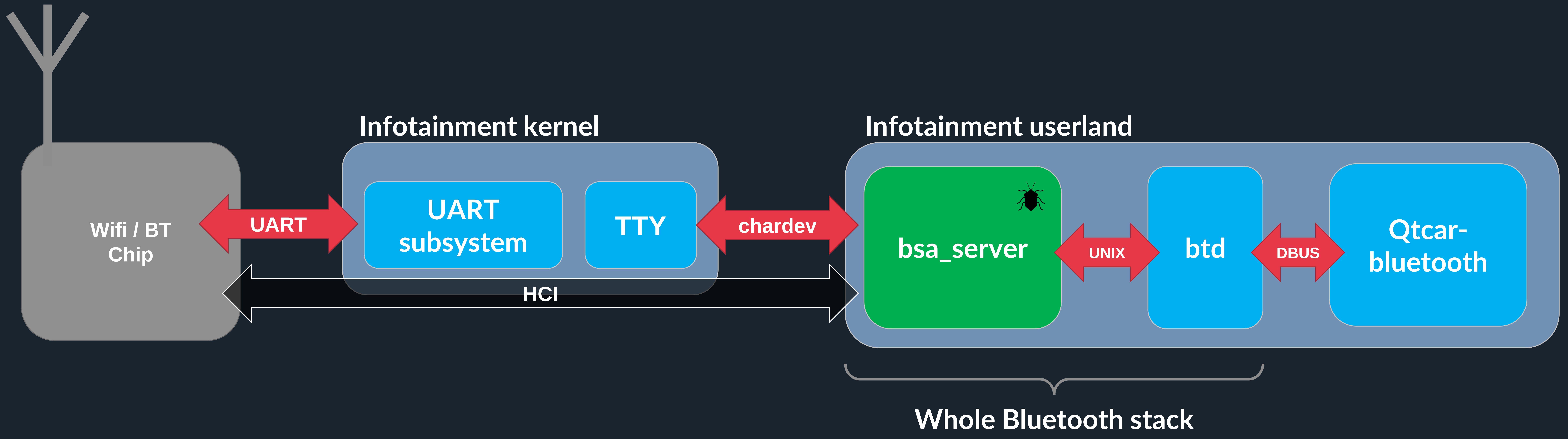
Audio controls (play/stop, playlist management, …)

Basic Imaging (BIP)

Allows to transfer the Cover Art image

Bluetooth stack

Implementation in the infotainment



bsa-server

Custom Bluetooth stack

Big attack surface

A lot of bluetooth features are managed by this program

High probability of vulnerability

Closed source vendor code written in C

Custom allocator

Bad hardening

Binary compiled without PIE

Debug symbols

Similar binary with debug symbols found on Github

Natural target for an attacker

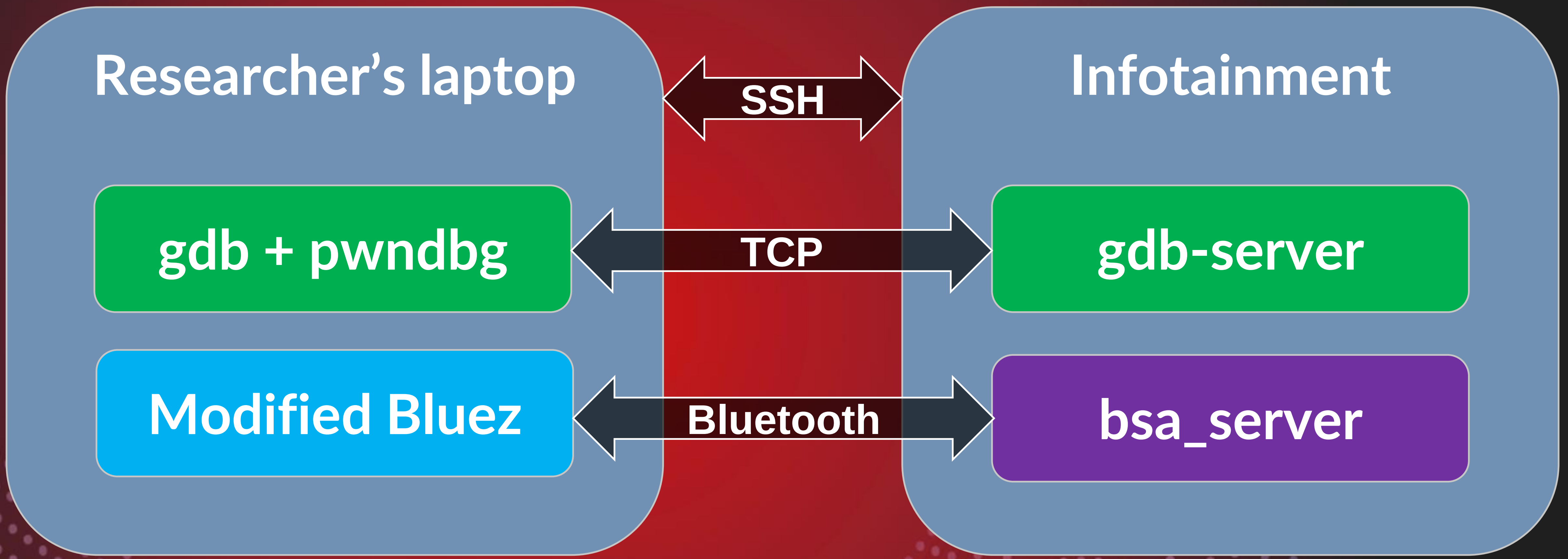
Looks like an exception in this heavily hardened system

Sandboxes

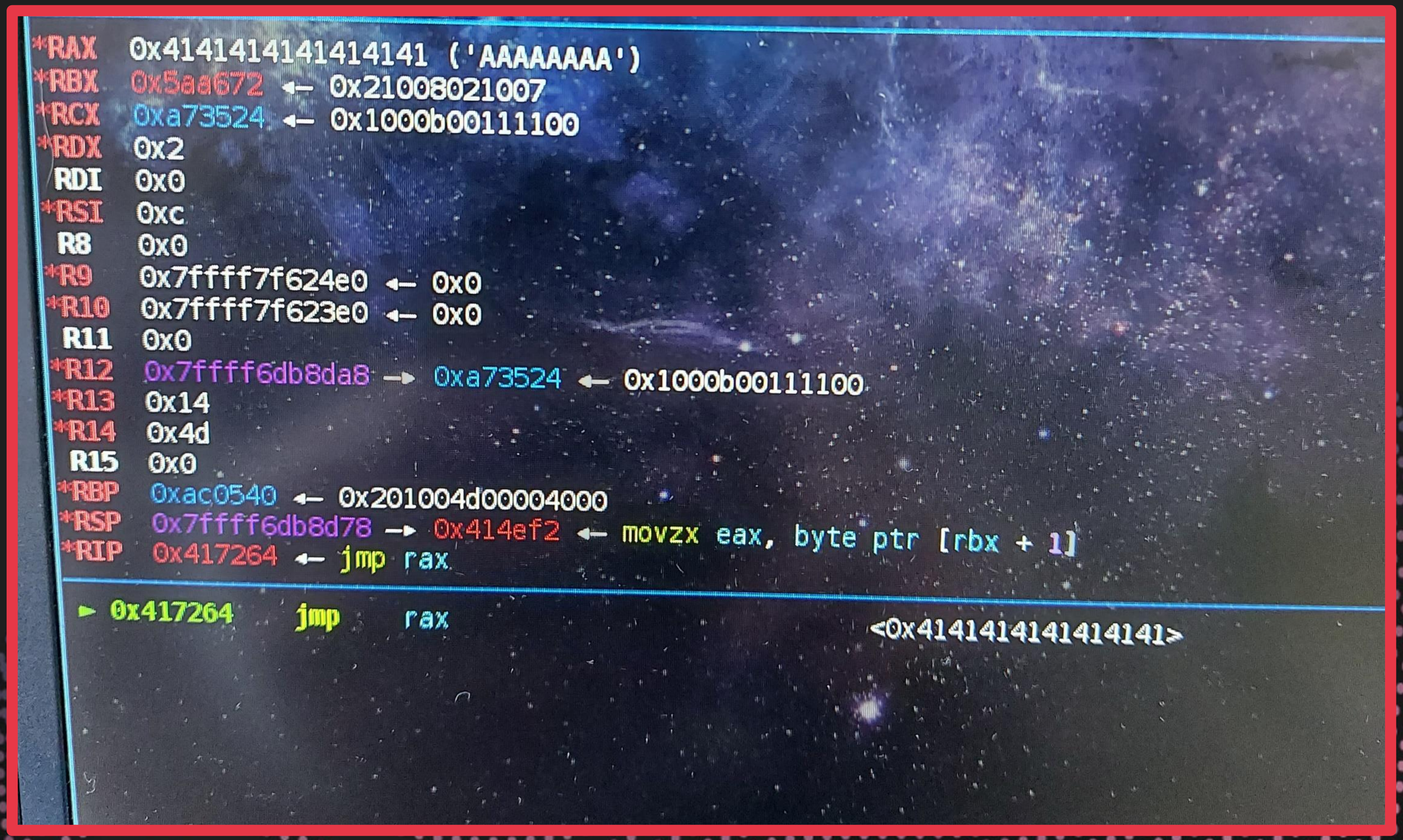
The process is still well sandboxed

Vulnerability research

Usual Workflow for Vulnerability research



Remote GDB on physical ECU



Static analysis

- Reverse engineering with Ghidra / IDA
- Help of debug symbols from another binary

Dynamic instrumentation

- Attacker device is a laptop with a standard bluetooth chip
- Bluez recompiled to add our exploit code
- Tesla Infotainment with SSH access and gdb

BIP

Reaching the BIP surface

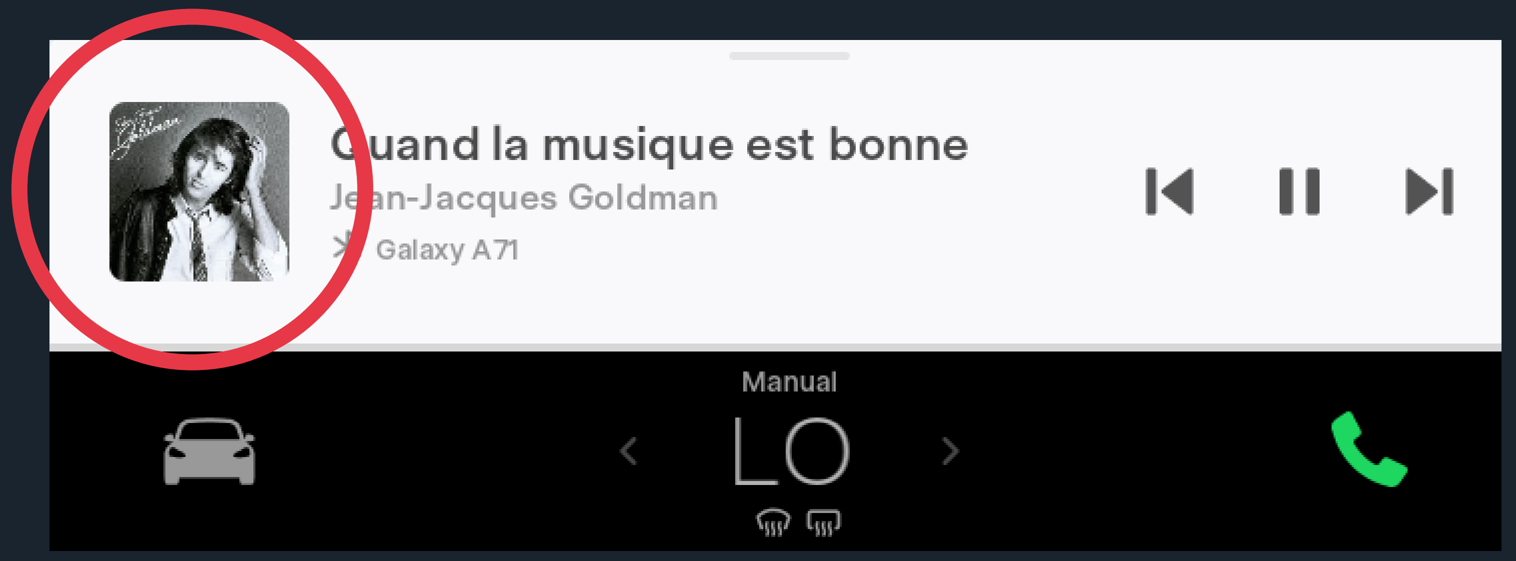
1. **Playback is configured by the phone (AVRC)**
2. **The car queries available Cover Art pictures** using OBEX protocol
3. **The phone send available images description** using OBEX protocol
4. **The car downloads and displays one image**

OBEX GET x-bt/img-img

<image-descriptor version='1.0'>…</image-descriptor>

OBEX Response

<?xml version='1.0' encoding='utf-8' standalone='yes' ?>
<image-properties>
…
</image-properties>



Vulnerability in BIP

OOB Write

Heap buffer overflow in the BIP protocol implementation

- In the BIP parsing function (bip_xp_parse)
- Parsing result is stored in an allocation of 0x2800 bytes containing an array of images metadata
- Adding an « attachment » fills 0x100 bytes, 38 are enough to overflow (limit is 256, due to a bug)
- Allows writing controlled bytes after the end of an allocation (custom allocator)

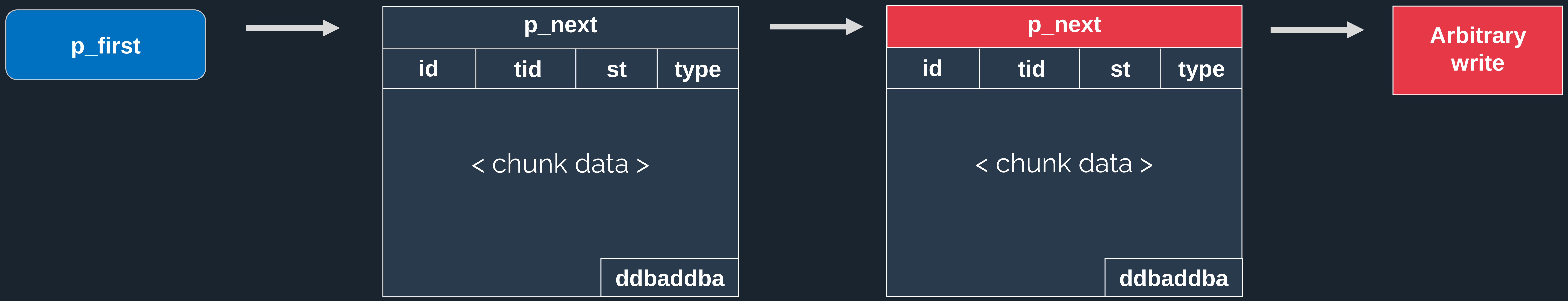
```
<?xml version='1.0' encoding='utf-8' standalone='yes' ?>
<image-properties>
<attachment />
<attachment />
<attachment />
...
<attachment name="AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA" />
</image-properties>
```

Heap exploitation

Bsa-server custom heap

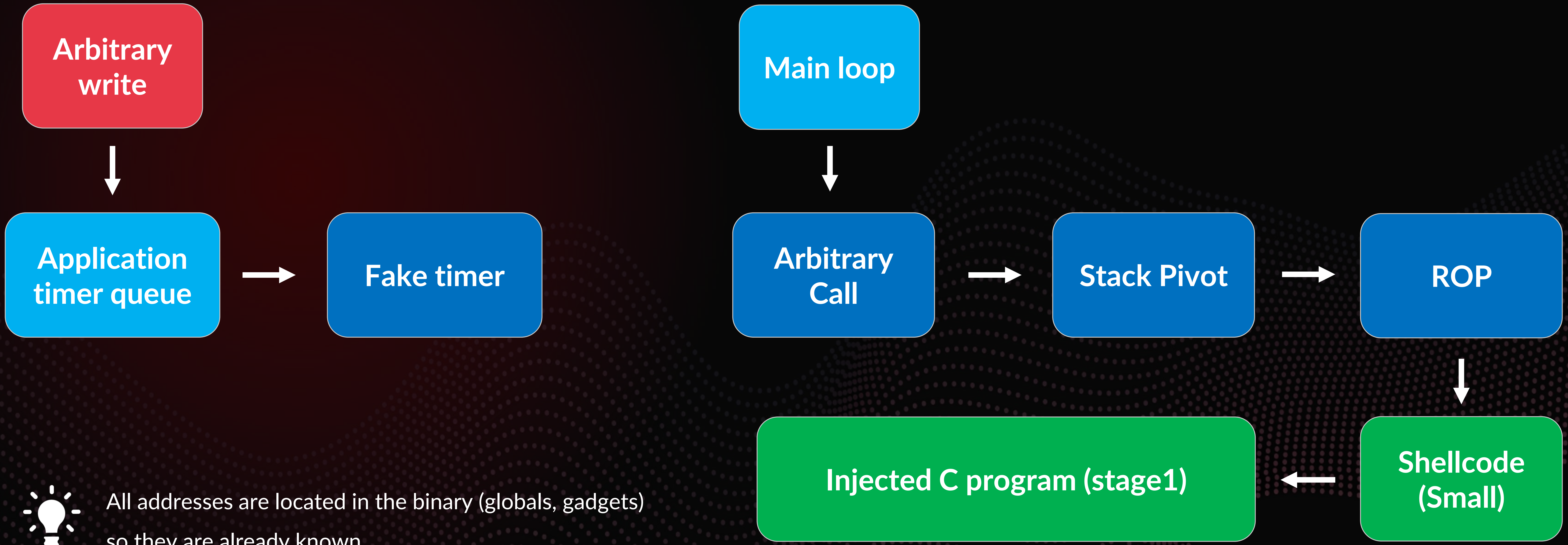
Custom heap management from a code base called GKI

- Allocations located in arrays in the data section (no PIE = no ASLR)
- Very few corruption checks compared to the glibc



Code execution

Taking over a timer, again…



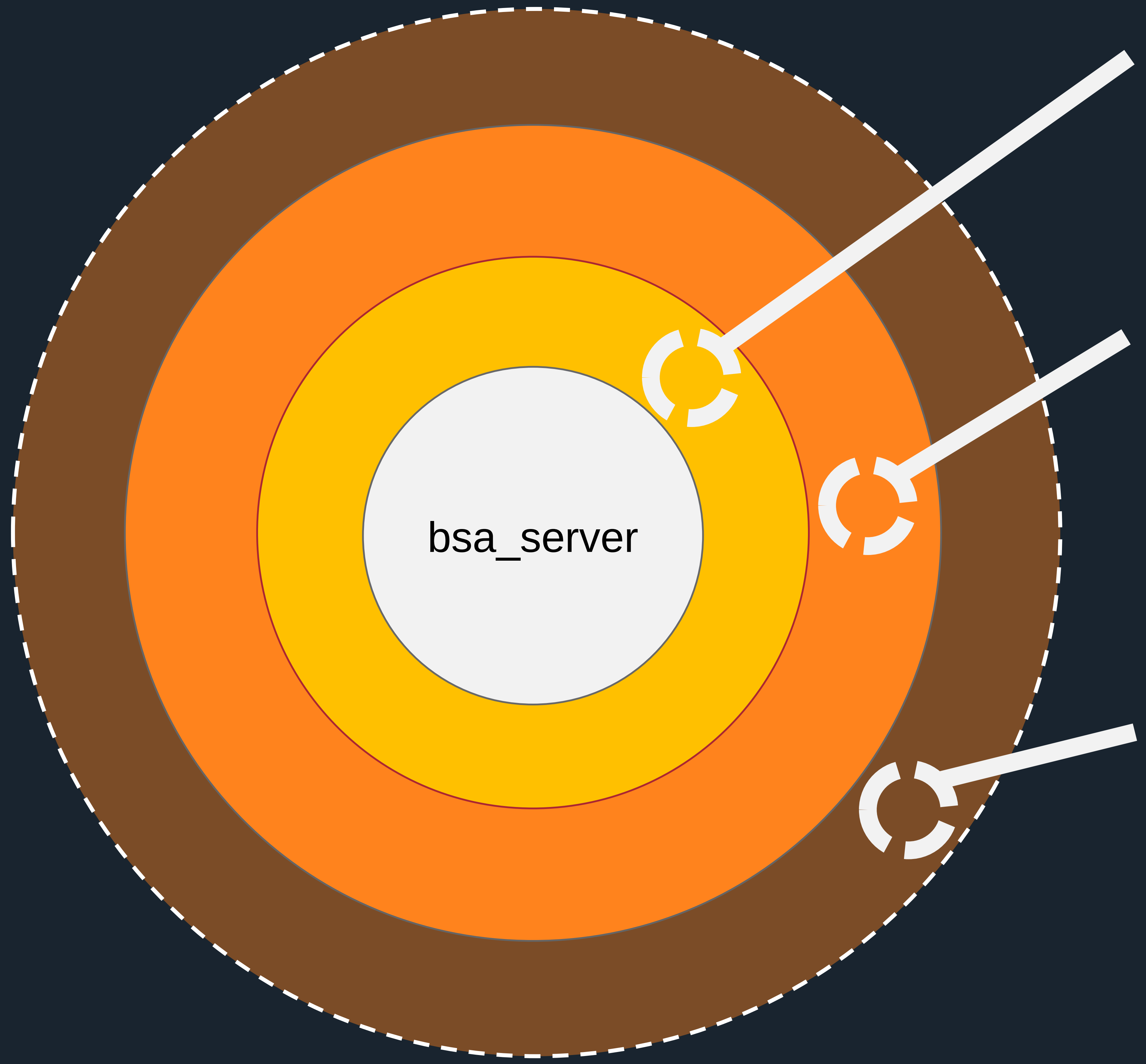
All addresses are located in the binary (globals, gadgets) so they are already known

The end ?

What can we do with this code execution ?

- Dedicated UID
- No useful capability
- No network
- All sandboxes activated

- But two legitimate APIs
  - TTY communication
  - One UNIX socket to communicate with btd
  - ➢ Limited attack surface



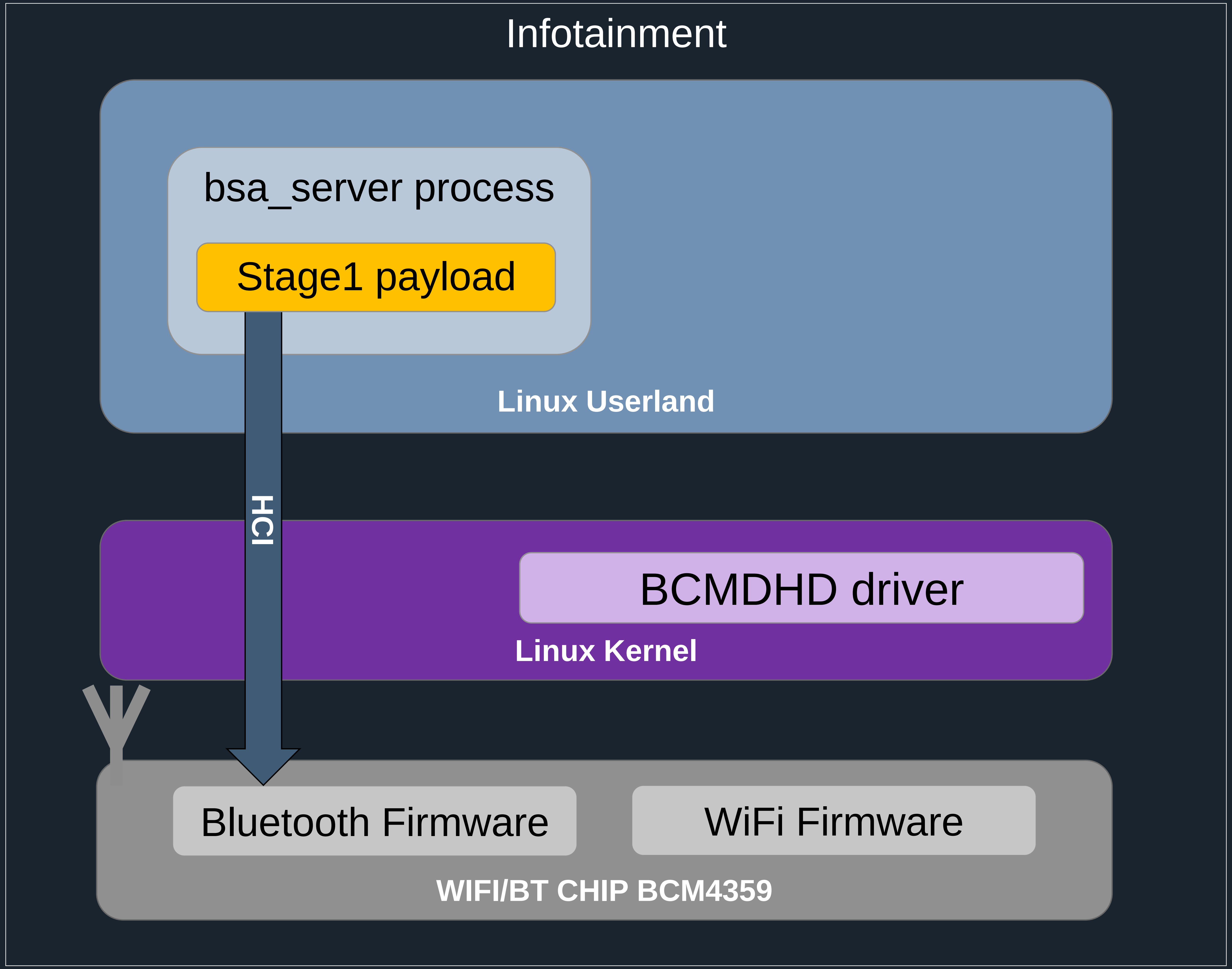
Kafel
- Syscalls filtering

AppArmor
- Whitelist for file access
- Cannot execute anything

Minijail
- Dedicated chroot
- Empty network stack

LPE

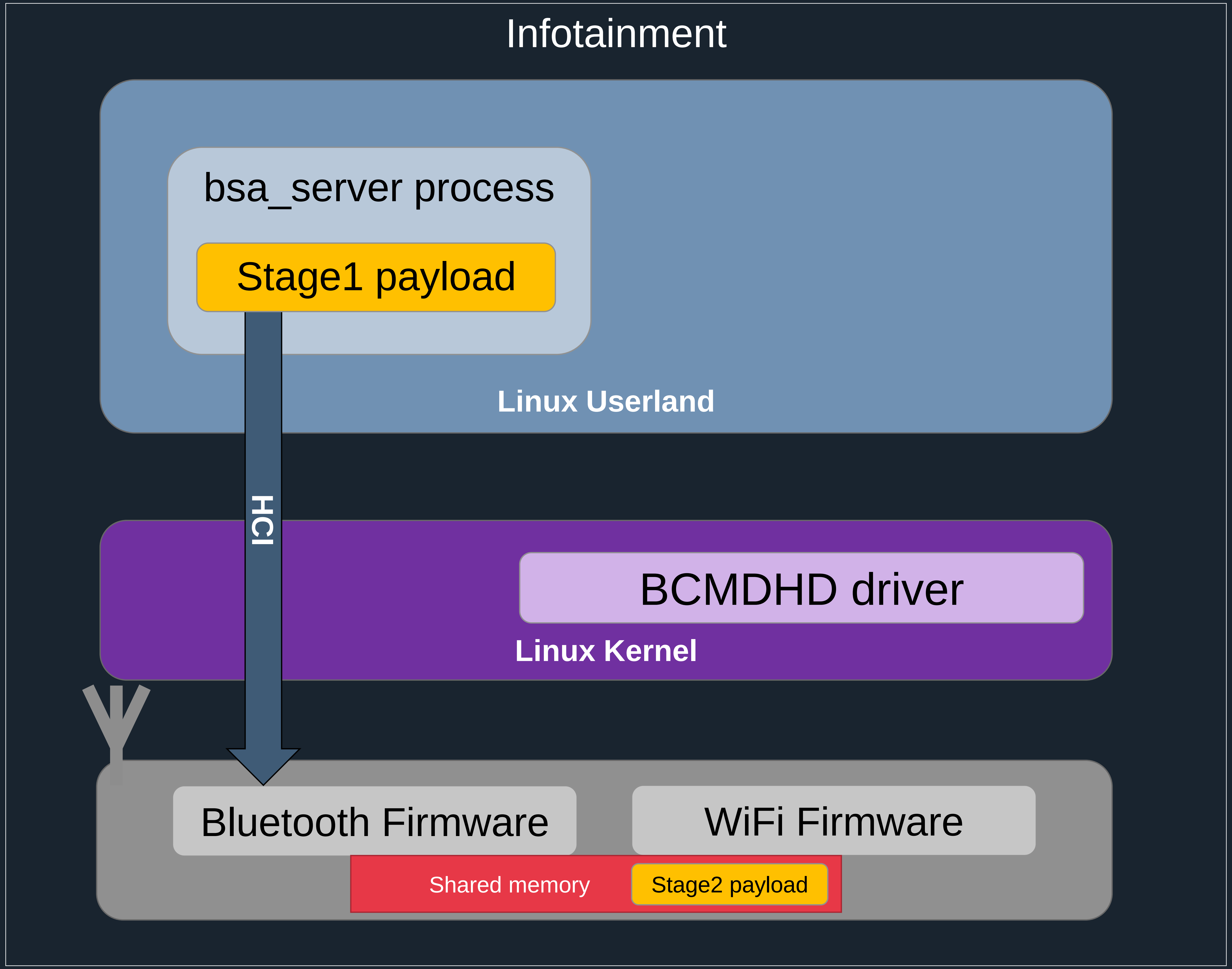
Arbitrary write inside the chipset firmware



- bsa_server communicates with Bluetooth chipset through HCI protocol
- Vendor specific commands are used to initialize the chipset (i.e. load Bluetooth firmware patches)
- At least HCI_BRCM_WRITE_RAM and HCI_BRCM_SUPER_PEEK_POKE commands allow arbitrary writting to the internal chipset memory
- So stage1 injected in bsa_server can write inside the chipset memory

LPE

Gaining code execution inside the WiFi chipset



- Bluetooth firmware and WiFi firmware share some memory regions
- WiFi firmware RAM code is mapped at address 0x500000 in the Bluetooth part
- HCI_BRCM_WRITE_RAM HCI command allows writing to the WiFi firmware RAM code
- WiFi firmware runs on an ARM core
- So stage1 injected in bsa_server can patch WiFi firmware to inject custom code
- WiFi Firmware Idle task is patched to jump on the injected code: stage2

LPE

Code execution inside the WiFi chipset

```
void hcibt_write_payload(struct hcibt* bt)
{
    uint32_t i;
    uint32_t *payload = (uint32_t *)&bin_payload_bin[0];
    for(i=0; i<(bin_payload_bin_len/4)+1; i++) {
        write_u32(bt, 0x01DE42C + 0x500000 + i*4, payload[i]);
    }
}
void hcibt_jump_payload(struct hcibt* bt)
{
    write_u32(bt, 0x189780 + 0x500000, 0xfe54f054); // idle thread, bl payload
}
```

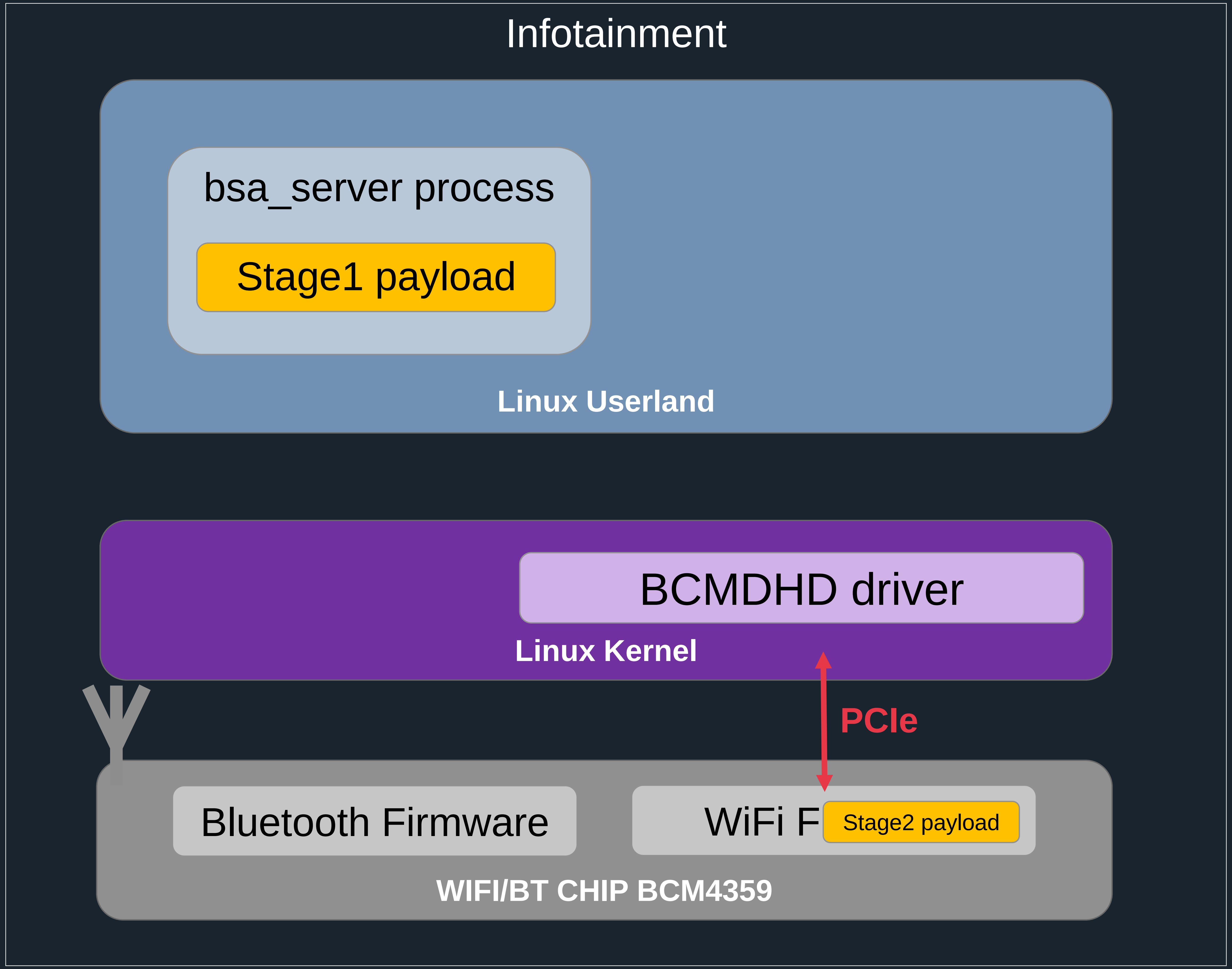
Stage1 WiFi code injector

```
ROM:0018977C
ROM:0018977C                idle_thread                            ; CODE XREF: idle_thread_entry+4↓j
ROM:0018977C 10 B5                          PUSH    {R4,LR}
ROM:0018977E 04 46                          MOV     R4, R0
ROM:00189780
ROM:00189780                loc_189780                             ; CODE XREF: idle_thread+E↓j
ROM:00189780 54 F0 54 FE                    BL      injected_code ; Keypatch modified this from:
ROM:00189780                                                       ;   BL threadx_idle_enter
ROM:00189784 20 46                          MOV     R0, R4
ROM:00189786 99 F6 FF F8                    BL      0x22988 ; hnd_poll
ROM:0018978A F9 E7                          B       loc_189780
ROM:0018978A                ; End of function idle_thread
```

Patched WiFi Firmware idle_thread to jump in stage2

LPE

Attack surface from the chipset



- WiFi part of the chipset uses PCIe to communicate with the main processor
  - DMA
  - Mailbox
- WiFi is managed by the BCMDHD Linux driver
- Stage2 in the WiFi firmware is well placed to attack the Linux driver

LPE

Bcmdhd to chipset memory structures

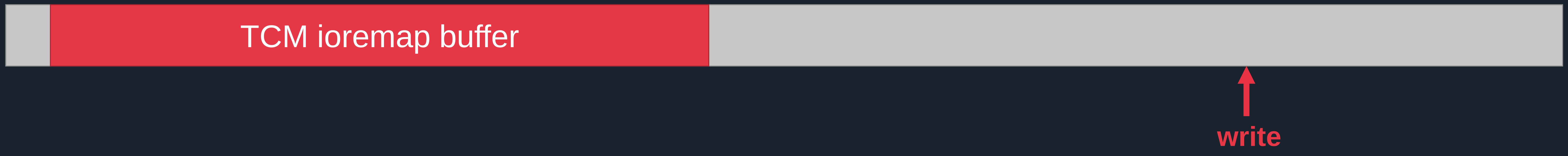
```
typedef struct ring_info {
    uint32      ringmem_ptr; /* ring mem location in dongle memory */

    /* Following arrays are indexed using h2dring_idx and d2hring_idx, and not
     * by a ringid.
     */

    /* 32bit ptr to arrays of WR or RD indices for all rings in dongle memory */
    uint32      h2d_w_idx_ptr; /* Array of all H2D ring's WR indices */
    uint32      h2d_r_idx_ptr; /* Array of all H2D ring's RD indices */
    uint32      d2h_w_idx_ptr; /* Array of all D2H ring's WR indices */
    uint32      d2h_r_idx_ptr; /* Array of all D2H ring's RD indices */

    /* PCIE_DMA_INDEX feature: Dongle uses mem2mem DMA to sync arrays in host.
     * Host may directly fetch WR and RD indices from these host-side arrays.
     *
     * 64bit ptr to arrays of WR or RD indices for all rings in host memory.
     */
    sh_addr_t   h2d_w_idx_hostaddr; /* Array of all H2D ring's WR indices */
    sh_addr_t   h2d_r_idx_hostaddr; /* Array of all H2D ring's RD indices */
    sh_addr_t   d2h_w_idx_hostaddr; /* Array of all D2H ring's WR indices */
    sh_addr_t   d2h_r_idx_hostaddr; /* Array of all D2H ring's RD indices */

    uint16      max_sub_queues; /* maximum number of H2D rings: common + flow */
    uint16      rsvd;
} ring_info_t;
```

- Some structures are shared between chipset and driver, like pciedev_shared_t / ring_info_t
- These structures are reloaded from the chipset memory while handling a mailbox interrupt
  - In normal operation: during chipset startup, and chipset software crash
- Stage2 can generate the mailbox interrupt to fill the structure ring_info_t

LPE

Out-of-bound write in bcmdhd

- d2h_r_idx_ptr is used as an offset to write inside a ioremap region (TCM)
- The offset is not checked to be in the TCM region!
- Ioremap places addresses in the vmalloc region
- Stage2 can write out of bound after the ioremap TCM region by setting d2h_r_idx_ptr to a value bigger than the TCM size
- Need to find something to write on!



LPE

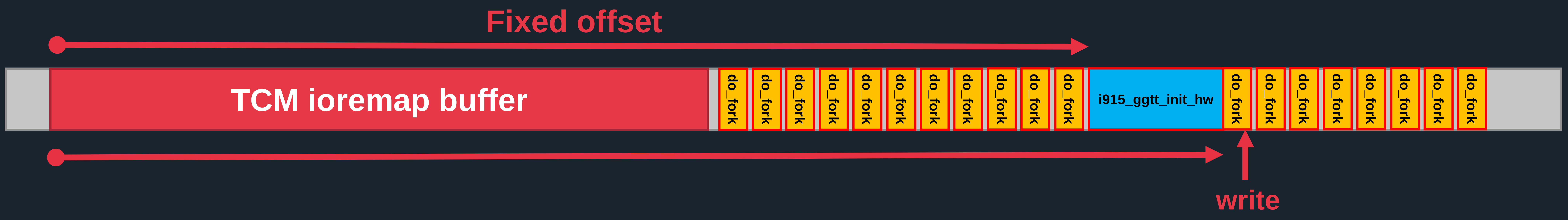
Out-of-bound write exploitation

- Process Kernel Stacks are good candidates

  - Are in vmalloc region (allocated in _do_fork function)
  - Can be sprayed from Stage1 by forking process multiple times
  - Process children can be blocked in a syscall to stay in Kernel (i.e. clock_nanosleep)
  - Write to Process Kernel Stacks is a powerful primitive => **direct ROP** after unblocking syscall

- Thanks to a big buffer allocated by the GPU driver, the offset (from TCM) of a process kernel stack is fixed

- Stage2 (payload in WiFi firmware) can patch a process kernel stack of a child of Stage1 (payload in bsa_server) blocked in clock_nanosleep



KASLR bypass

& hardened kernel configuration ☹

Random kernel base address
But not a lot of possibilities…

0xffffffff81000000
0xffffffff82000000
0xffffffff83000000
…
0xffffffffbf000000

Reading a nice blogpost on side-channels at the same time…

EntryBleed: Breaking KASLR under KPTI with Prefetch (CVE-2022-4543)

https://www.willsroot.io/2022/12/entrybleed.html

Similar side-channel issue
Prefetch times differ

ffffffffb0900000 179
ffffffffb0a00000 138
ffffffffb0b00000 136
ffffffffb0c00000 44
…
ffffffffb1300000 179

LPE

ROP chain

End of a kernel process stack

```
0xffffc90024007f50 | 75 00 a0 81 ff ff ff ff 44 44 44 44 44 44 44 44 |
0xffffc90024007f60 | 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 |
0xffffc90024007f70 | 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 44 |
0xffffc90024007f80 | 44 44 44 44 44 44 44 44 42 02 00 00 00 00 00 00 |
0xffffc90024007f90 | 00 00 00 00 00 00 00 00 44 44 44 44 44 44 44 44 |
0xffffc90024007fa0 | 44 44 44 44 44 44 44 44 da ff ff ff ff ff ff ff |
0xffffc90024007fb0 | b1 d2 23 92 c0 55 00 00 c0 ed 63 db ff 7f 00 00 |
0xffffc90024007fc0 | 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 |
0xffffc90024007fd0 | e6 00 00 00 00 00 00 00 b1 d2 23 92 c0 55 00 00 |
0xffffc90024007fe0 | 33 00 00 00 00 00 00 00 42 02 00 00 00 00 00 00 |
0xffffc90024007ff0 | 80 ec 63 db ff 7f 00 00 2b 00 00 00 00 00 00 00 |
```

Last return address

Some controllable saved task registers (used to restore register values)

Strategy

Pivot

1. Replace Return address by a RET gadget address (**that is executed when the clock_nanosleep syscall ends**)
2. Use saved register as a first ROP chain

Ropchain 1 (in saved registers)

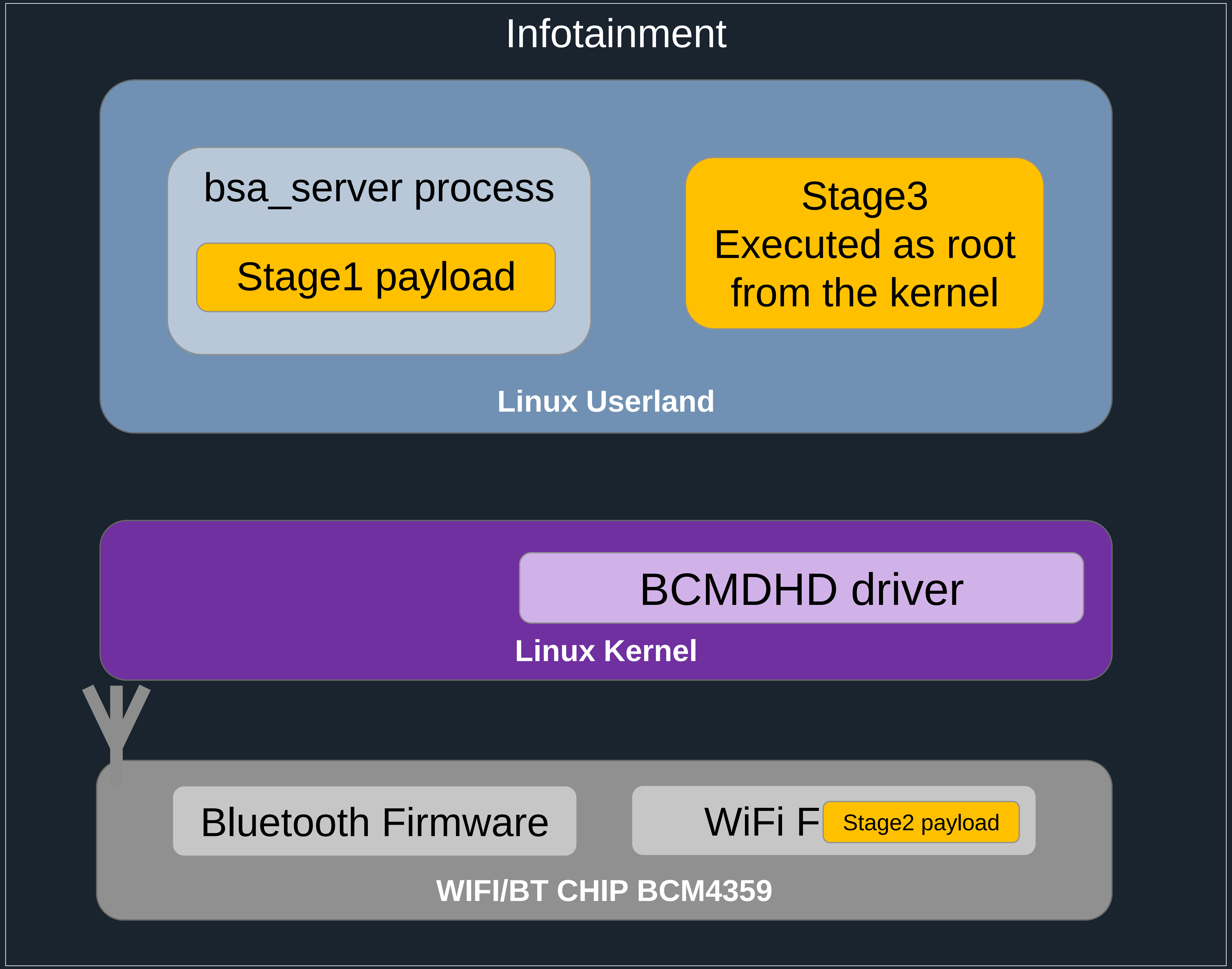
1. Jump in **copy_from_user** to fill the Kernel process stack with a second ROP chain

Ropchain 2

1. Jump in **copy_from_user** to override **poweroff_cmd** string in the kernel memory with the command we want to start
2. Call **poweroff_work_func** to start the command as root with User Mode Helper Linux subsystem
3. Call **do_exit** to end the task properly

LPE

root code execution



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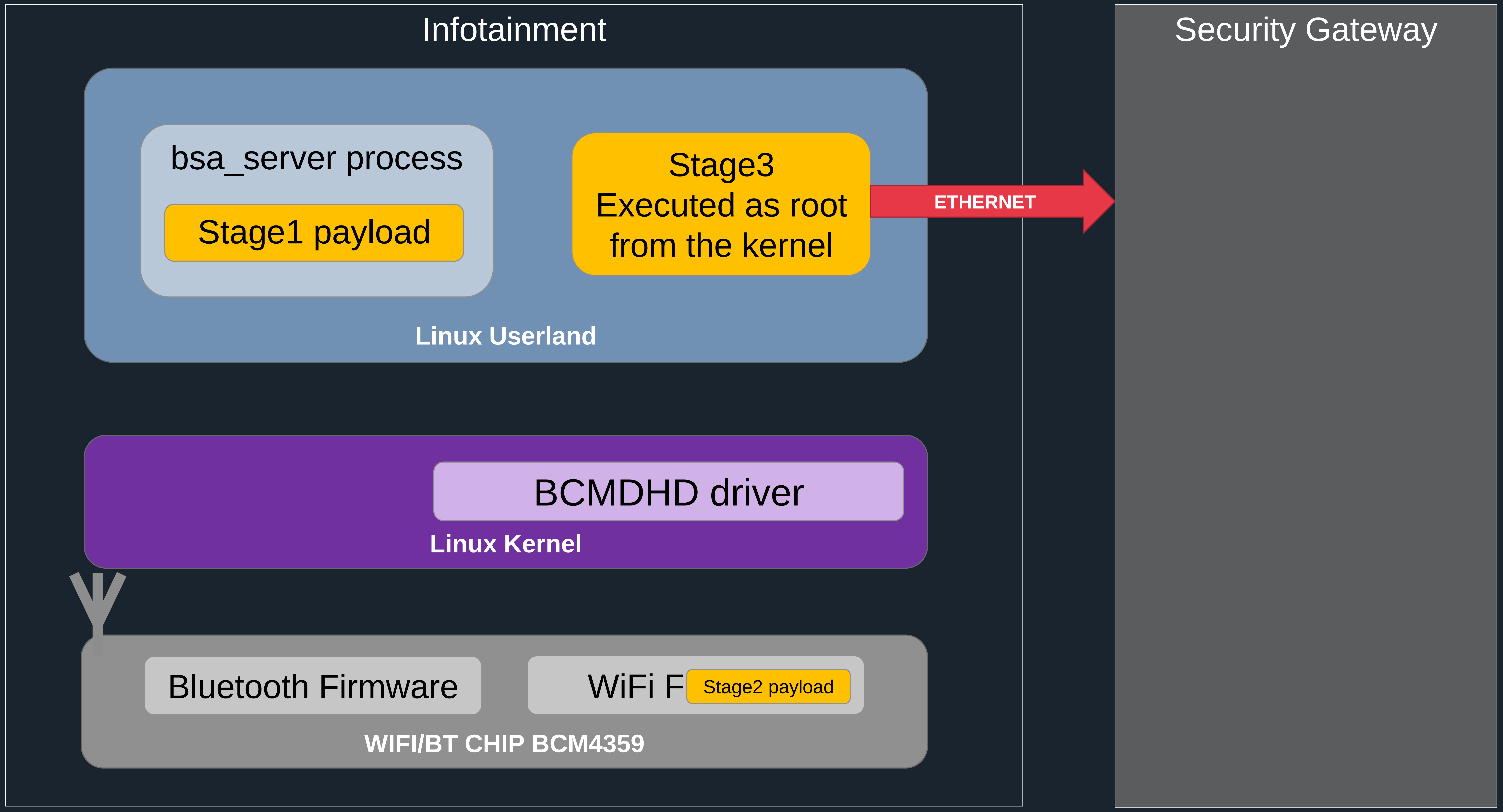
LPE

root code execution



GTW

Security Gateway architecture

SYSTEM

Same PCB as Infotainment

—

SoC NXP MCP5748G

—

FreeRTOS PPC-VLE

—

No hardware based secure-boot

—

Uses its own internal flash for software

NETWORKS

Ethernet

—

CAN buses (Chassis/Party/Vehicle)

Features

Filter CAN messages

—

Save log files

—

Update mode
Update other ECUs and itself

—

Provide sensitive information to other ECU
(VIN/Serial/...)

—

Config Ethernet switch

GTW

Security Gateway software & attack surface

- 3 main software parts
  - Bootloader
    - Selects between the two following modes and do software secure boot
  - Update mode
    - Fetches updates on the infotainment through TFTP
    - Checks them and updates ECUs through CAN
  - Main App mode
    - Handles CAN over UDP messages and filters them
    - Provides access to some sensitive values (VIN, autopilot subscriptions etc..)
    - Acts as a log server

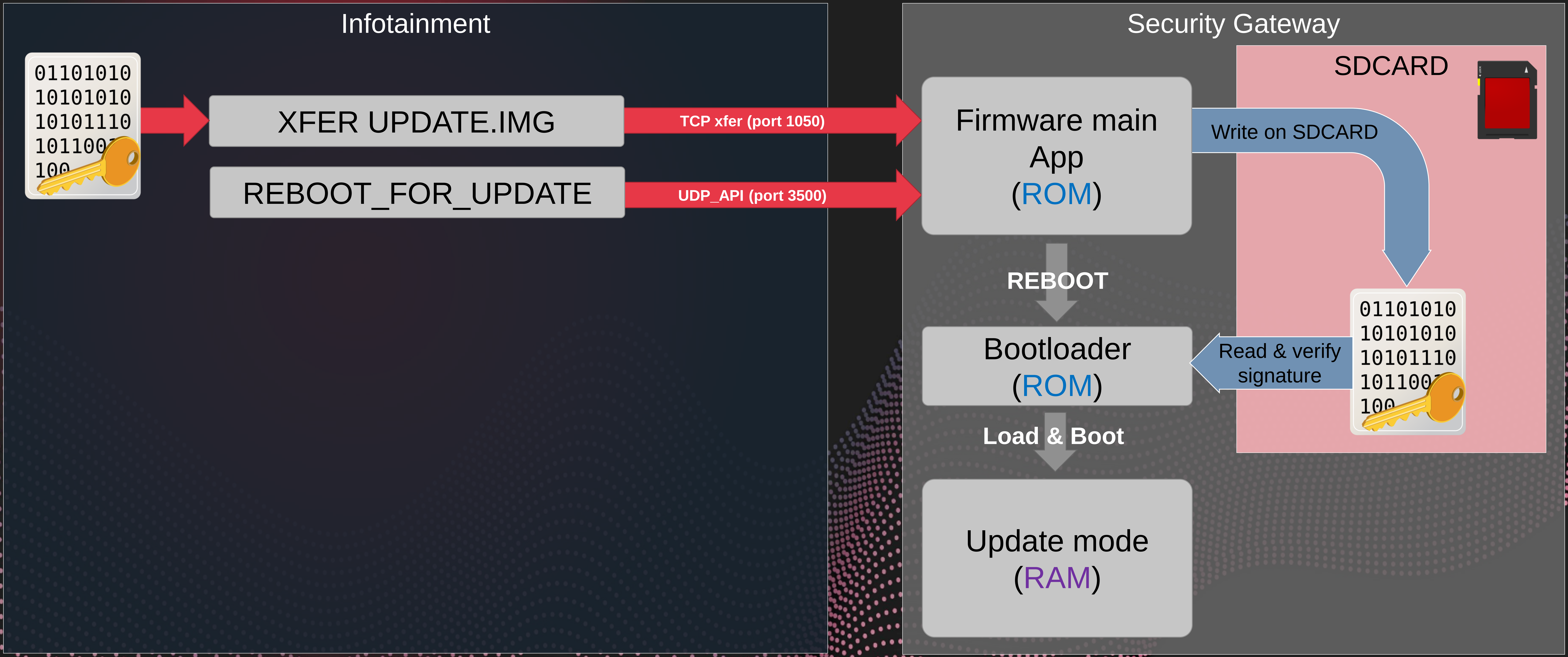
GTW

Security Gateway exploit

- GTW uses fixed addresses (no ASLR, code is in the internal flash)
- Seems to be greatly audited, and safely developed
- Logic TOCTOU bug inside the update mode => 100% stable

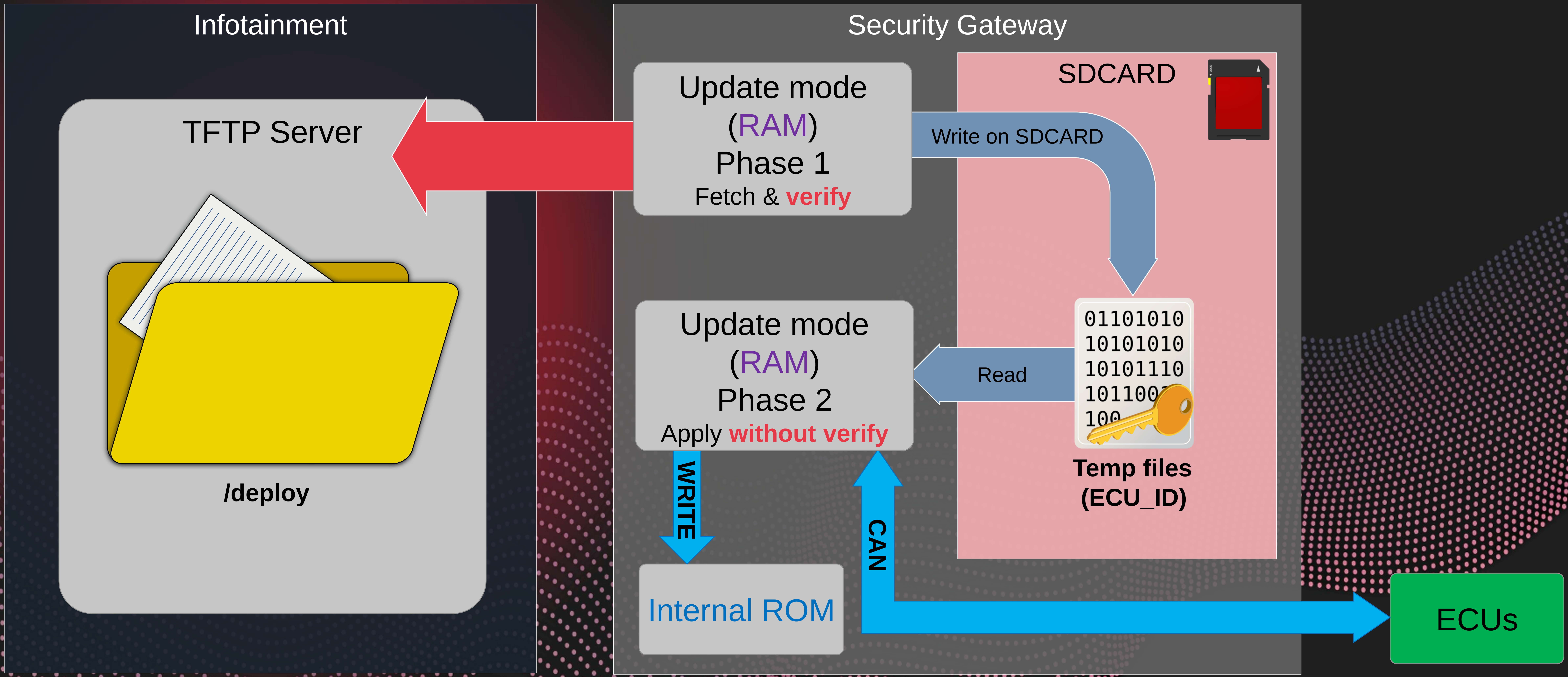
GTW

Booting the update mode



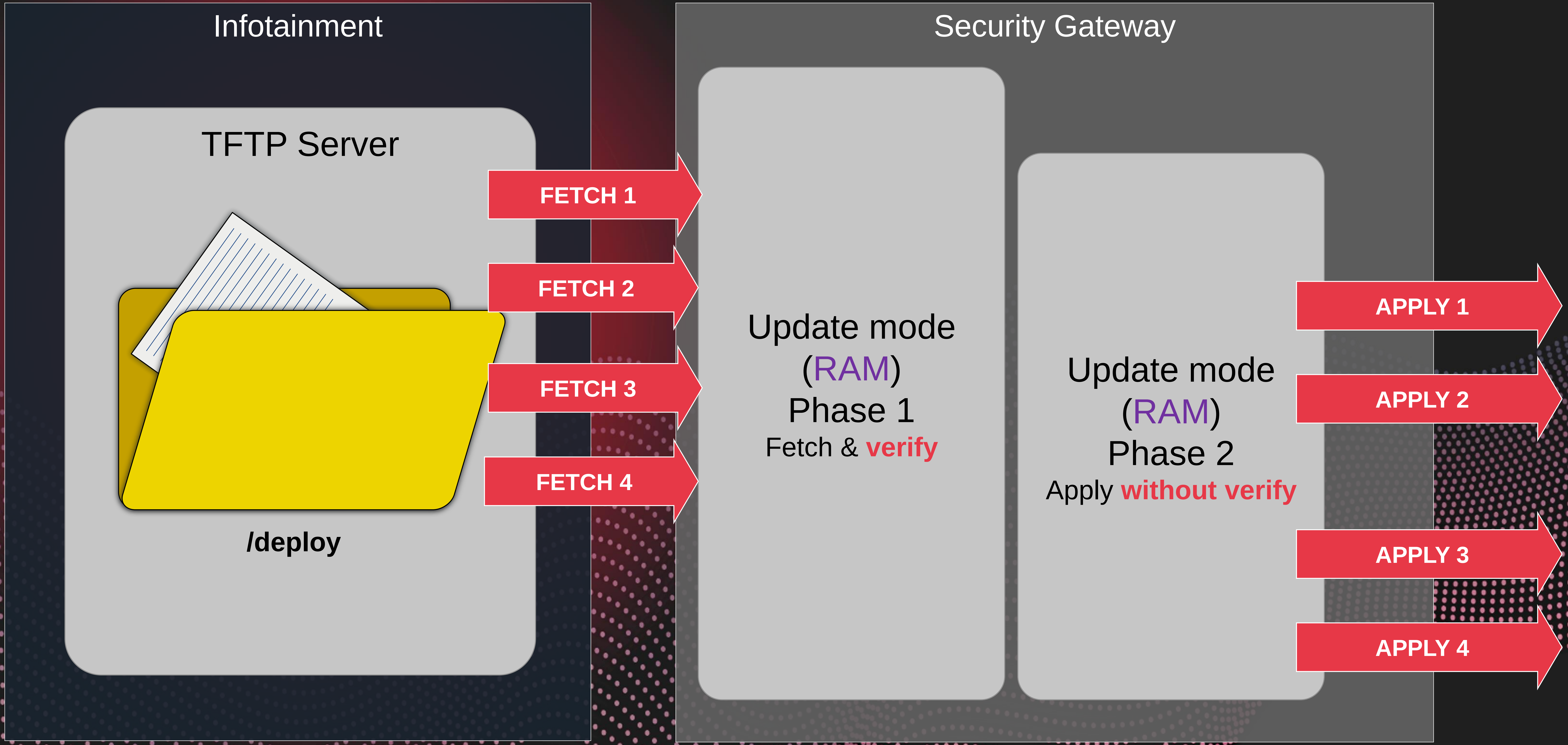
GTW

Update mode interactions



GTW

Update mode two phase mode



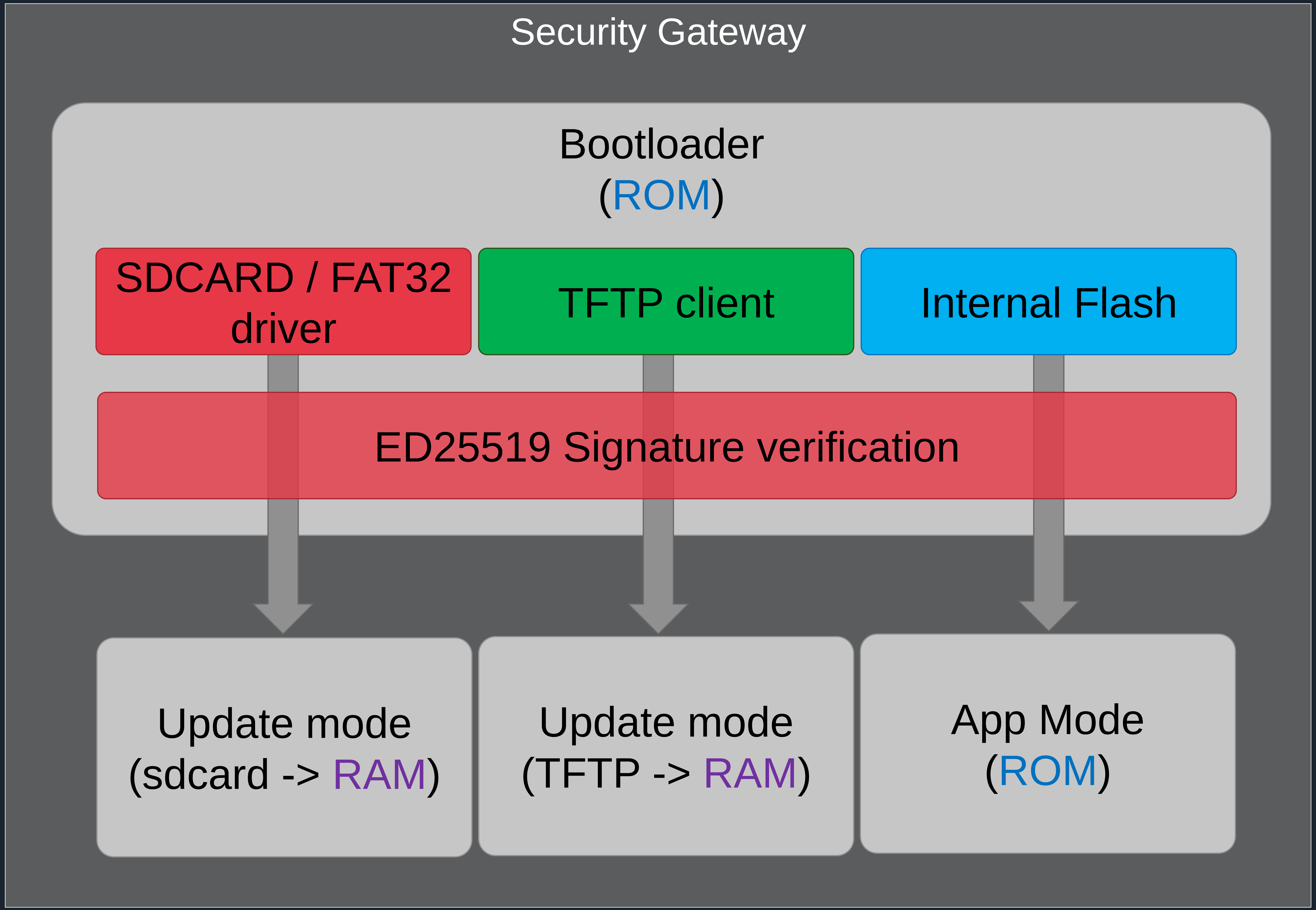
GTW

BUG

- Update mode can be forced to fetch two times the same ECU update
- The first time if the file has a good signature the update is scheduled to be applied, and the file is saved on the SDCARD
- The second fetch overrides the file on the SDCARD, if the signature is invalid the first one is still scheduled, and the bad temporary file is not removed
- When applying updates, the signature is not re-checked, so the the badly signed file is applied
- This bypasses the signature check, and allows an attacker to apply arbitrary updates, and can be used to gain code execution on the security gateway

GTW

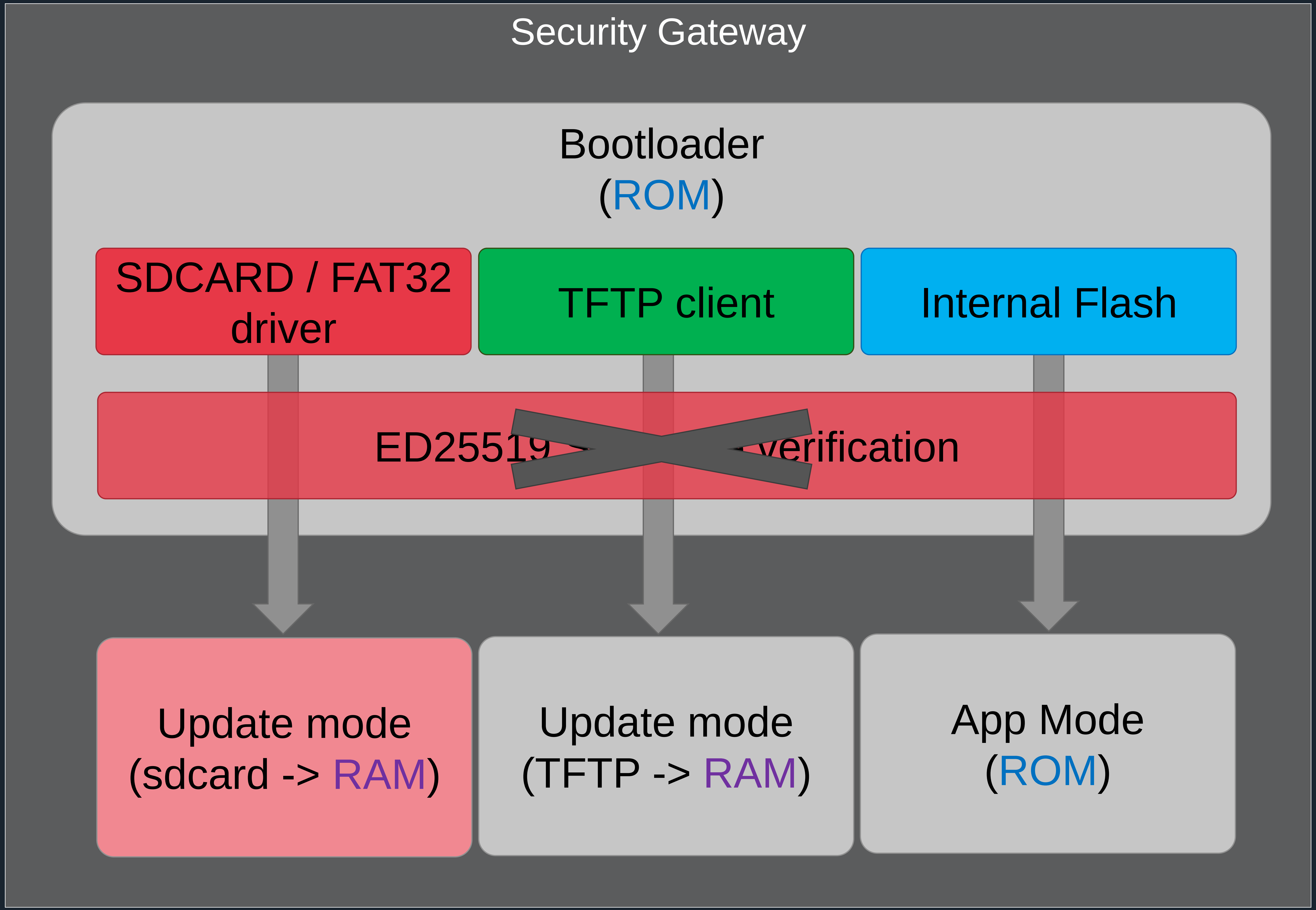
Secure boot



- Bootloader verifies next stages
- Hardware (NXP chip) doesn't provide secure boot, bootloader in the internal flash is never verified
- Gateway update mode allows to update its own firmware, including the bootloader
- Signature bypass in update mode => code exec in bootloader

GTW

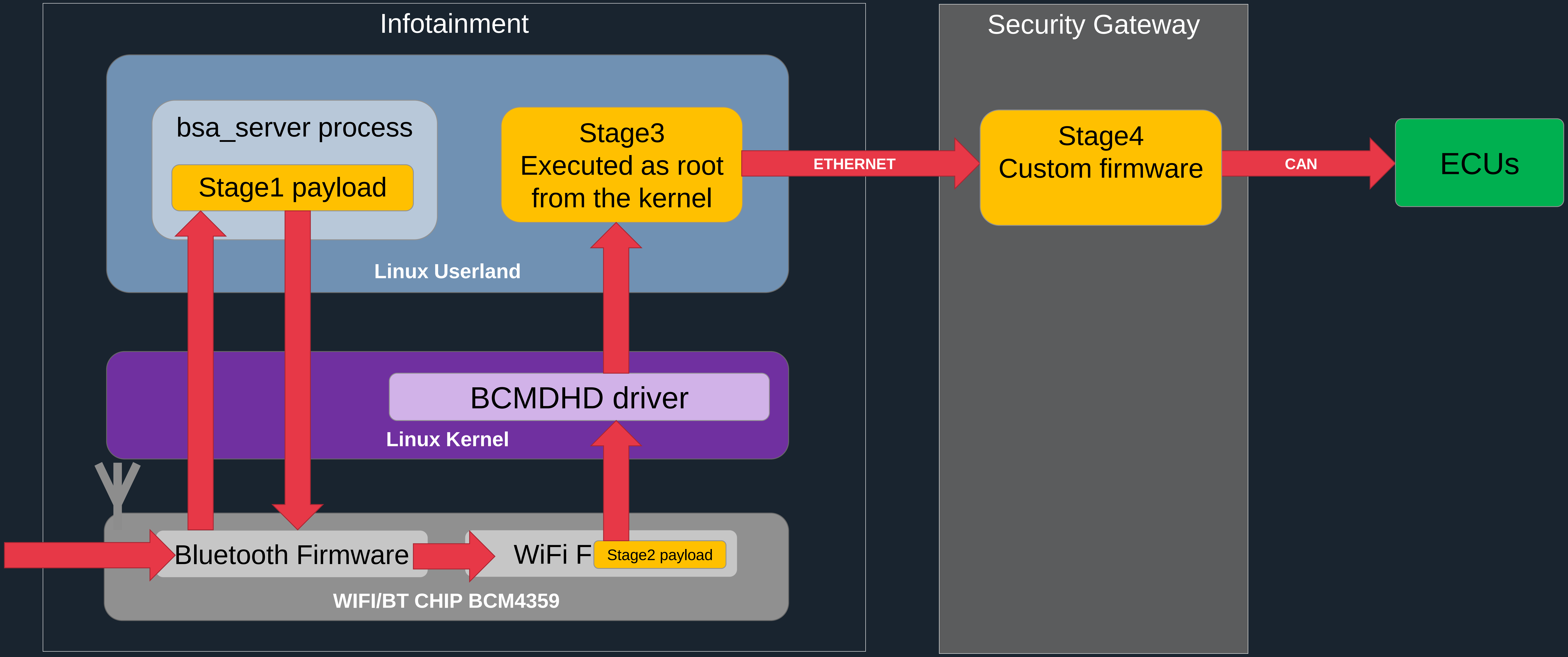
Secure boot



- Bootloader patch
- Remove ED25519 signature check
- Use Update mode boot mechanism to boot on a controlled firmware
- Controlled firmware has unrestricted access to the CAN vehicle & chassis buses

Access to CAN busses

From remote to CAN



Fixes

Tesla Response

- bsa_server is now a PIE binary and the vulnerability has been patched
- Bcmdhd vulnerability is patched
- Security GTW
  - Now moves files with a specific name when signature is correct
  - Manifest is now signed
  - If a signature check fails, the file is deleted for the SDcard

TheZDIBugs @TheZDIBugs · 18 juil.
[ZDI-23-973|CVE-2023-32157] (Pwn2Own) **Tesla** Model 3 bsa_server BIP Heap-based Buffer Overflow Arbitrary Code Execution Vulnerability (CVSS 4.6; Credit: David BERARD (@_p0ly_) and Vincent DEHORS (@vdehors) from Synacktiv (@Synacktiv))

zerodayinitiative.com
ZDI-23-973
(Pwn2Own) Tesla Model 3 bsa_server BIP Heap-based Buffer Overflow Arbitrary Code Execution ...

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TheZDIBugs @TheZDIBugs · 18 juil.
[ZDI-23-972|CVE-2023-32156] (Pwn2Own) **Tesla** Model 3 Gateway Firmware Signature Validation Bypass Vulnerability (CVSS 9.0; Credit: David BERARD (@_p0ly_) and Vincent DEHORS (@vdehors) from Synacktiv (@Synacktiv))

zerodayinitiative.com
ZDI-23-972
(Pwn2Own) Tesla Model 3 Gateway Firmware Signature Validation Bypass Vulnerability

9 · 23 · 4 313

TheZDIBugs @TheZDIBugs · 18 juil.
[ZDI-23-971|CVE-2023-32155] (Pwn2Own) **Tesla** Model 3 bcmdhd Out-Of-Bounds Write Local Privilege Escalation Vulnerability (CVSS 7.8; Credit: David BERARD (@_p0ly_) and Vincent DEHORS (@vdehors) from Synacktiv (@Synacktiv))

zerodayinitiative.com
ZDI-23-971
(Pwn2Own) Tesla Model 3 bcmdhd Out-Of-Bounds Write Local Privilege Escalation Vulnerability

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Pwn2Own 2023

Synacktiv was Master Of Pwn for the second time with many entries (Windows/macOS/Ubuntu/VirtualBox/Tesla)

First Tier 2 entry ever (could have been a Tier 1 but we had chosen to split RCE+LPE and Gateway entries)

Conclusion

- **Not so long of a work**
  - Strong knowledge of the Tesla cars architecture (Pwn2Own 2022)
  - Hardware and debug facilities
  - Not well hardened binary
- **Great support from Tesla**
  - Tesla provided us an ECU that can receive updates
  - ZDI and Tesla gave us updates
  - Version freeze 1 month before the event
  - **Thanks to them**
- **Was fun**
- **We won a car for our future research ☺**

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