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Efficient and fast container execution using image snapshotters

Max Fatouros, Derek Feichtinger, **Clemens Lange (PSI)**
Jakob Blomer, Amal Thundiyil, Valentin Völkl (CERN)
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Motivation

In its standard configuration,

docker run <image name> <command>

downloads the entire container image from the registry and unpacks it on disk before executing the actual command in the started container

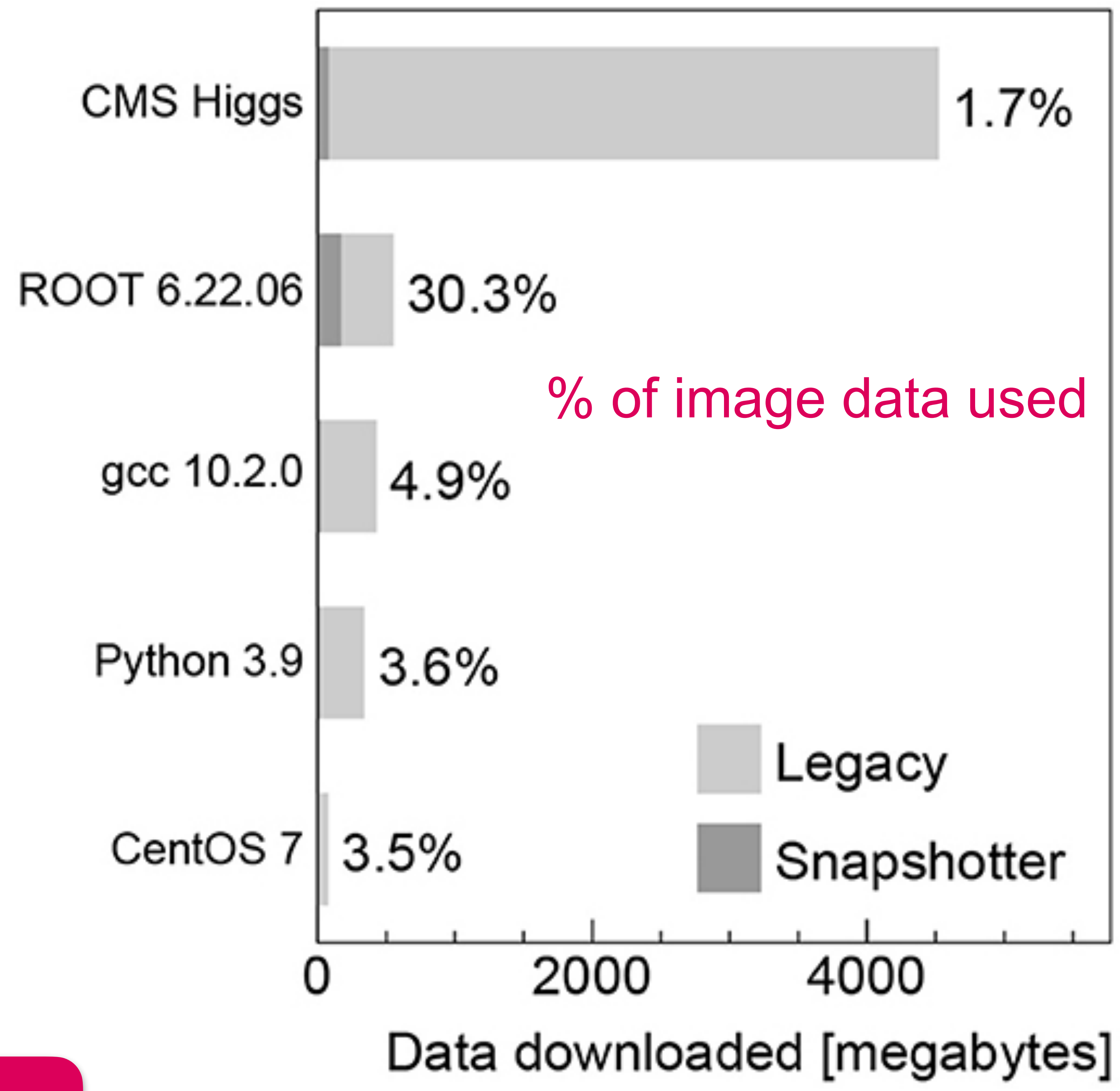
A typical container image used for physics analysis (important e.g. for analysis reusability) has a **size of ~gigabytes**

Executing containerised workloads on batch systems can therefore lead to **hundreds of parallel downloads** of several gigabytes of data

However, only a fraction of the container image is actually needed

→ download only what is actually needed

[Frontiers in Big Data Vol. 4 (2021) 673163]

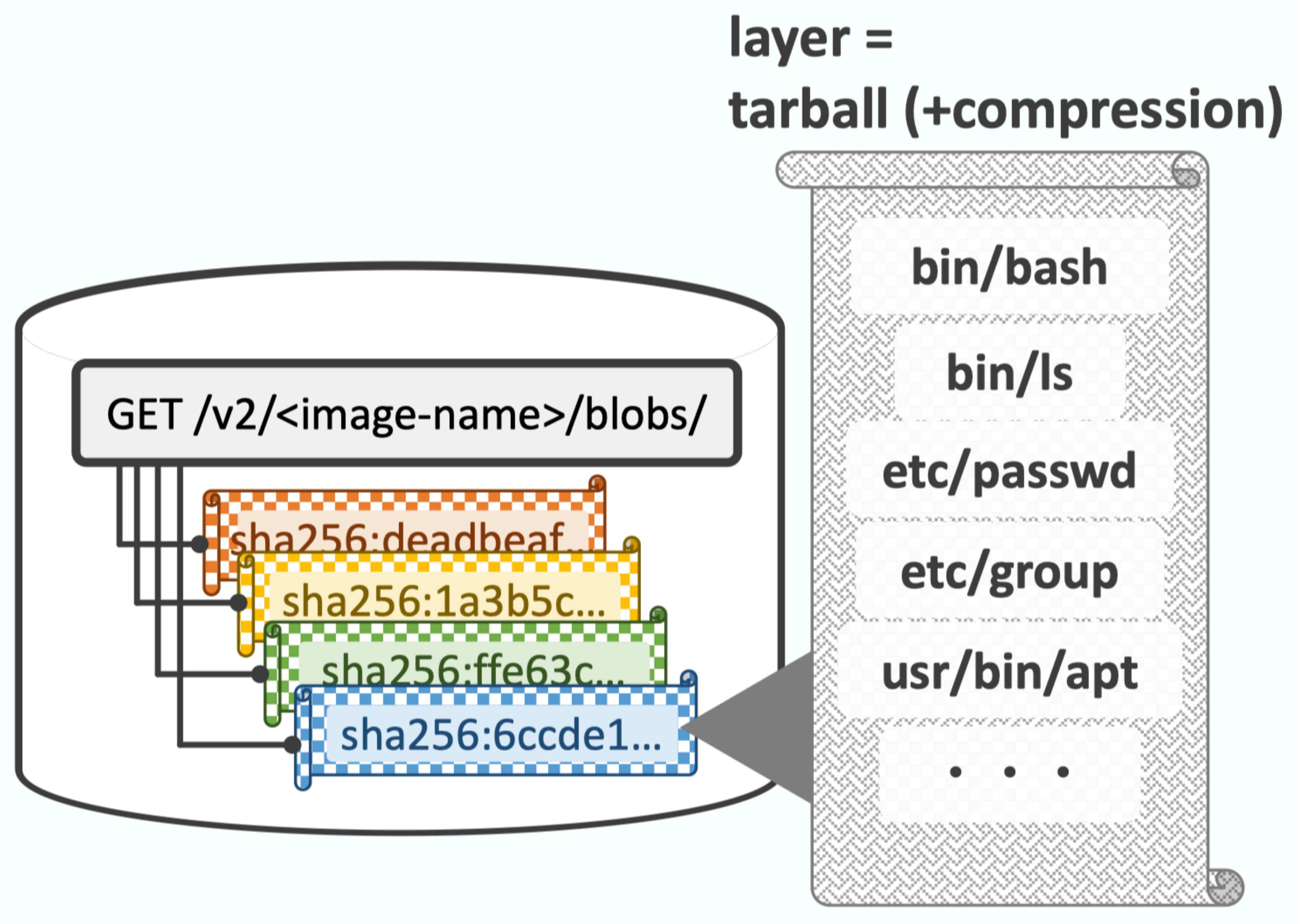


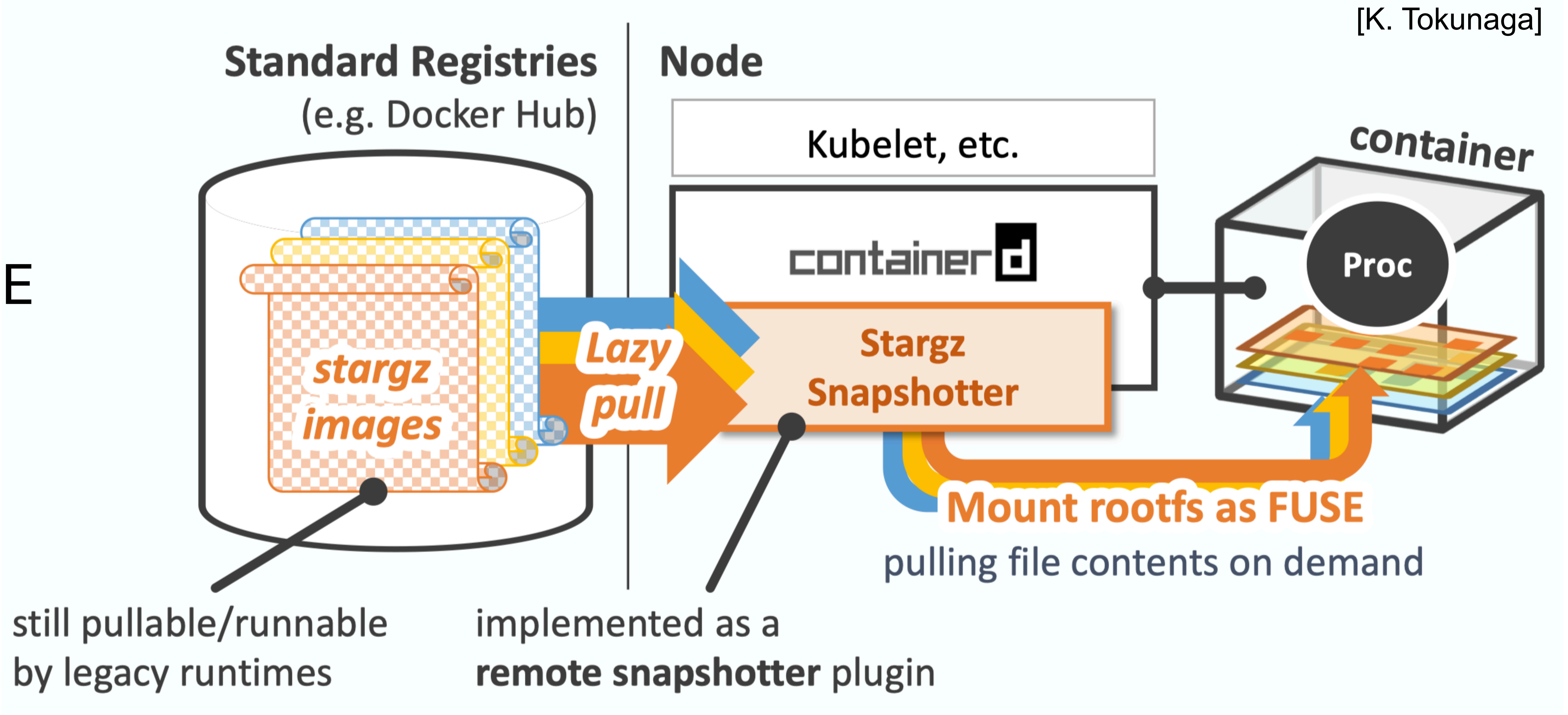
Lazy-pulling of container images

Lazy-pulling = pull/download only **what is needed**
when it is needed

Container reminder:

- A container is a set of tar-balls plus a manifest (list)
- Downloading and extracting the layers builds the container file system





[K. Tokunaga]

pulling file contents on demand

still pullable/runnable by legacy runtimes

implemented as a **remote snapshotter** plugin

Lazy pulling mounts (rootfs snapshots as FUSE and downloads) accessed file contents on-demand

- Can **start container** almost **immediately**
- Can be slower during execution

Implementations of lazy pulling

Solutions are implemented as so-called image snapshotters for use with containerd

Evaluated tools:

- Stargz snapshotter: use images in **searchable tar.gz format**
- SOCI snapshotter: add **separate index artifact** to image (hosted in registry)
- CVMFS snapshotter: use **unpacked images on CVMFS**
- Overlayfs snapshotter: the default/legacy, **non-lazy-loading** snapshotter

All snapshotters will **fall back to legacy pulling** if image not available in required format

CVMFS Snapshotter can additionally do this at **layer level**:

- Enables use of **"protected" layers** based on public base images
- Mind: this is something Singularity/Apptainer cannot do

Side note: "lazy pulling" with Apptainer achieved through unpacked images on CVMFS

Benchmarking approach

Use typical particle physics tasks and container images, e.g.:

- ROOT
- Python

Using nerdctl to run workloads with the various snapshotters:

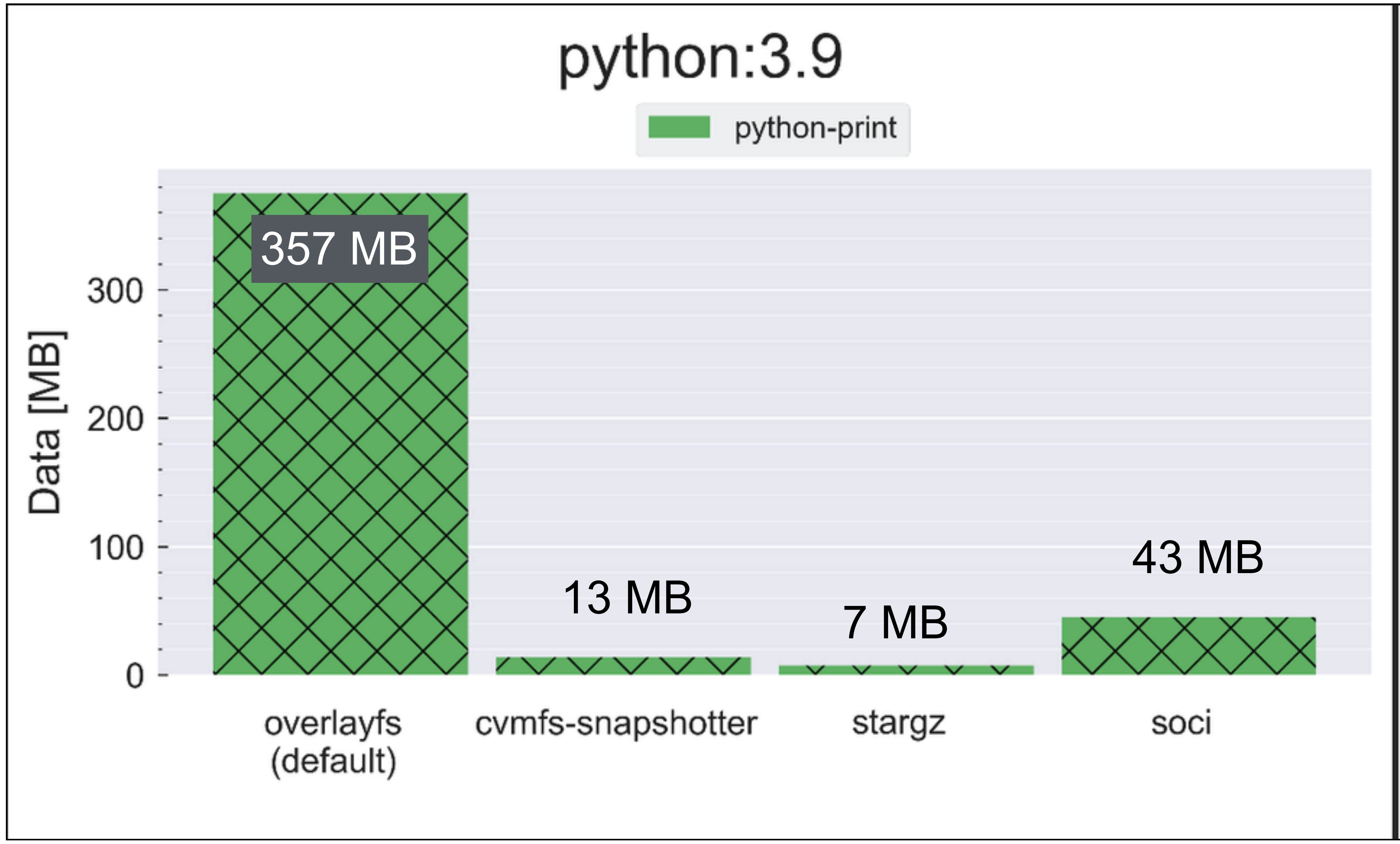
- Parse execution log files to extract timestamps
- Monitor traffic using network monitoring tools
- Repeat process several times, clear cache in between runs

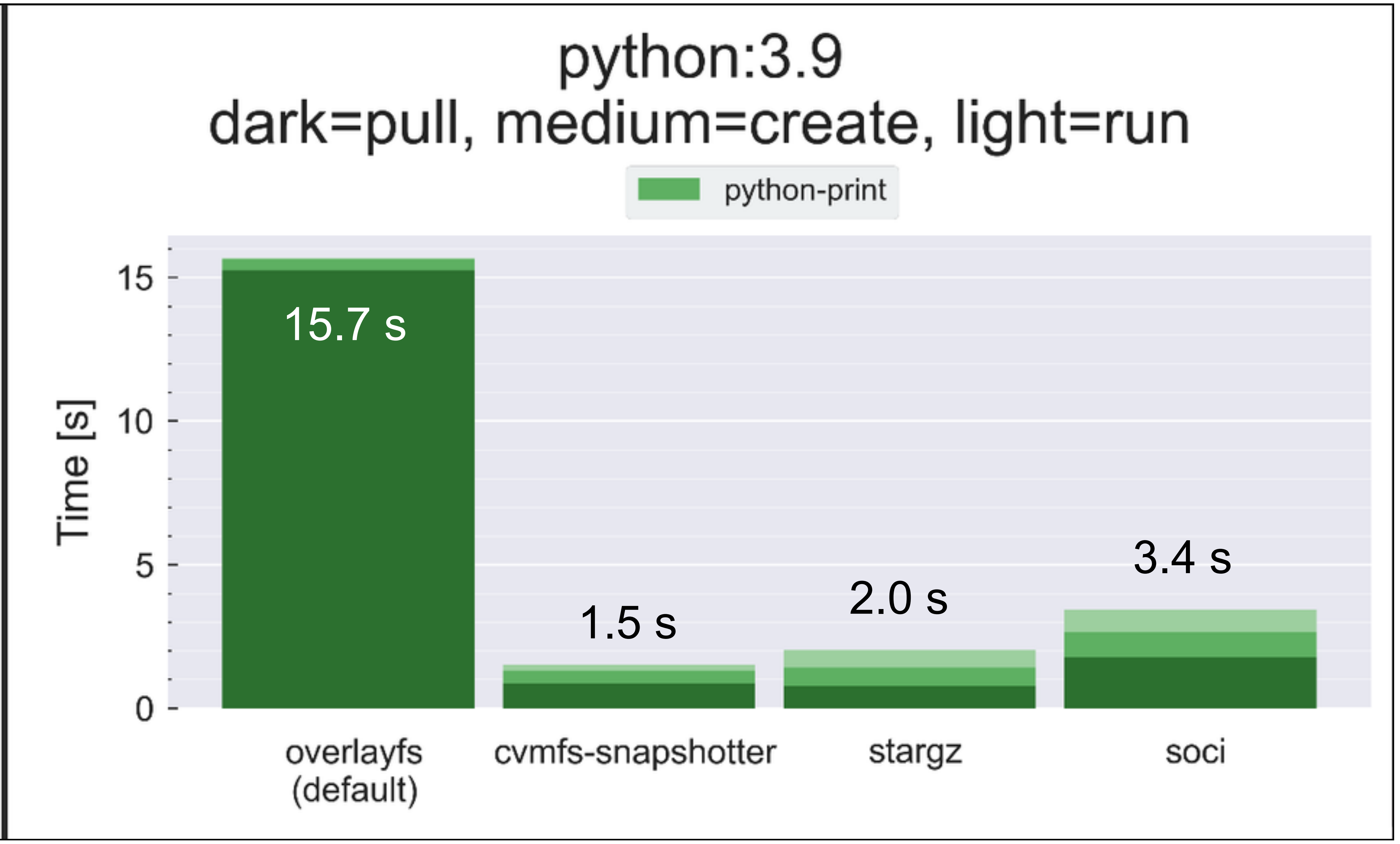
Also compare to “legacy” approach pulling entire image before execution

Using local PC in connection with both a local (same machine) registry, and Harbor registry (in the same network).

Using squid proxy for CVMFS caching (with images pre-cached)

Results: python image: print() — remote registry/cache

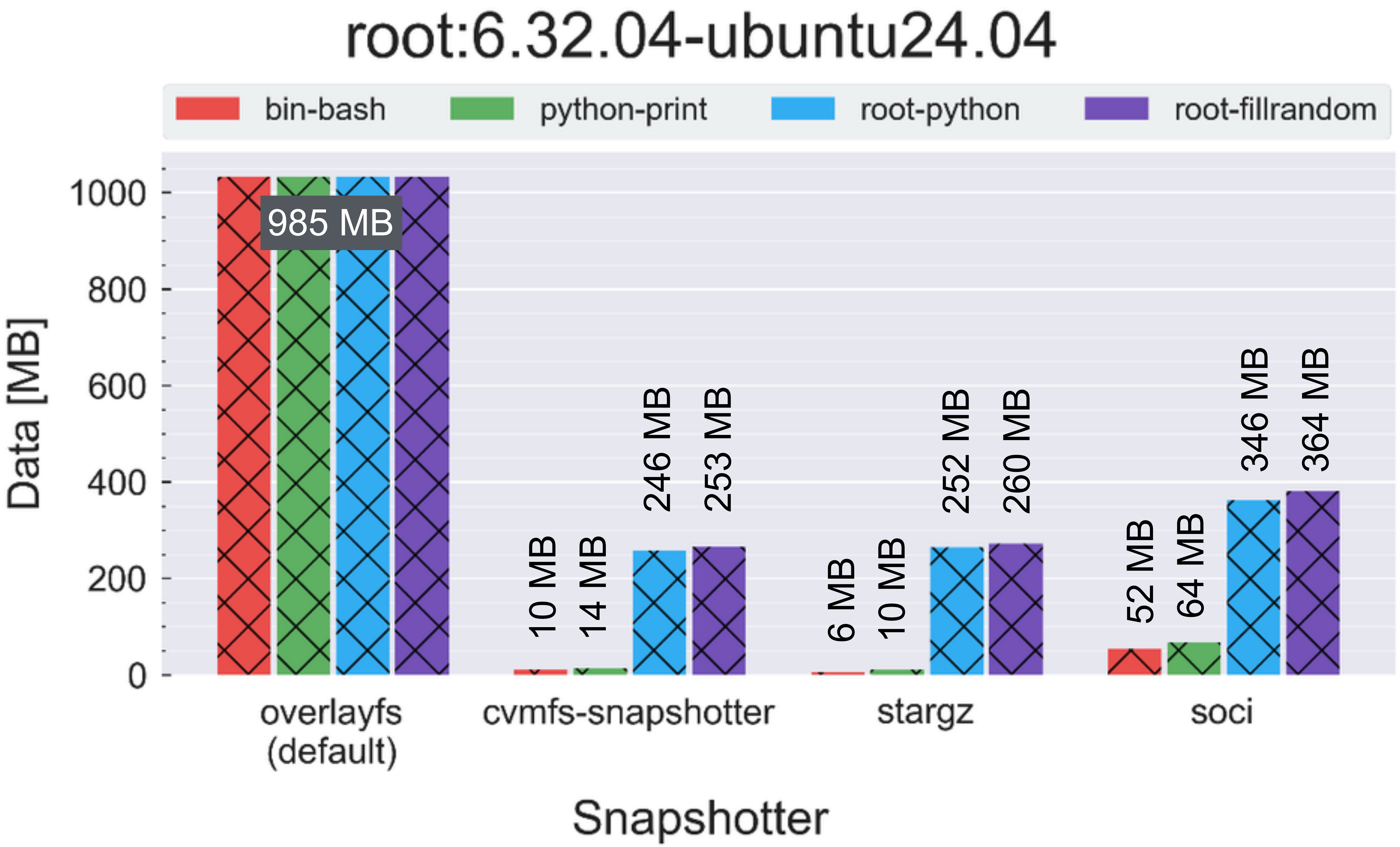




Observations:

- Time to start image drastically reduced for all lazy snapshotters
- Only a few megabytes downloaded
- SOCI loads more data because of layer minimum 10MB size requirement (configurable)
- Using a local registry is slightly faster (→ backup)

Results: ROOT image (1)



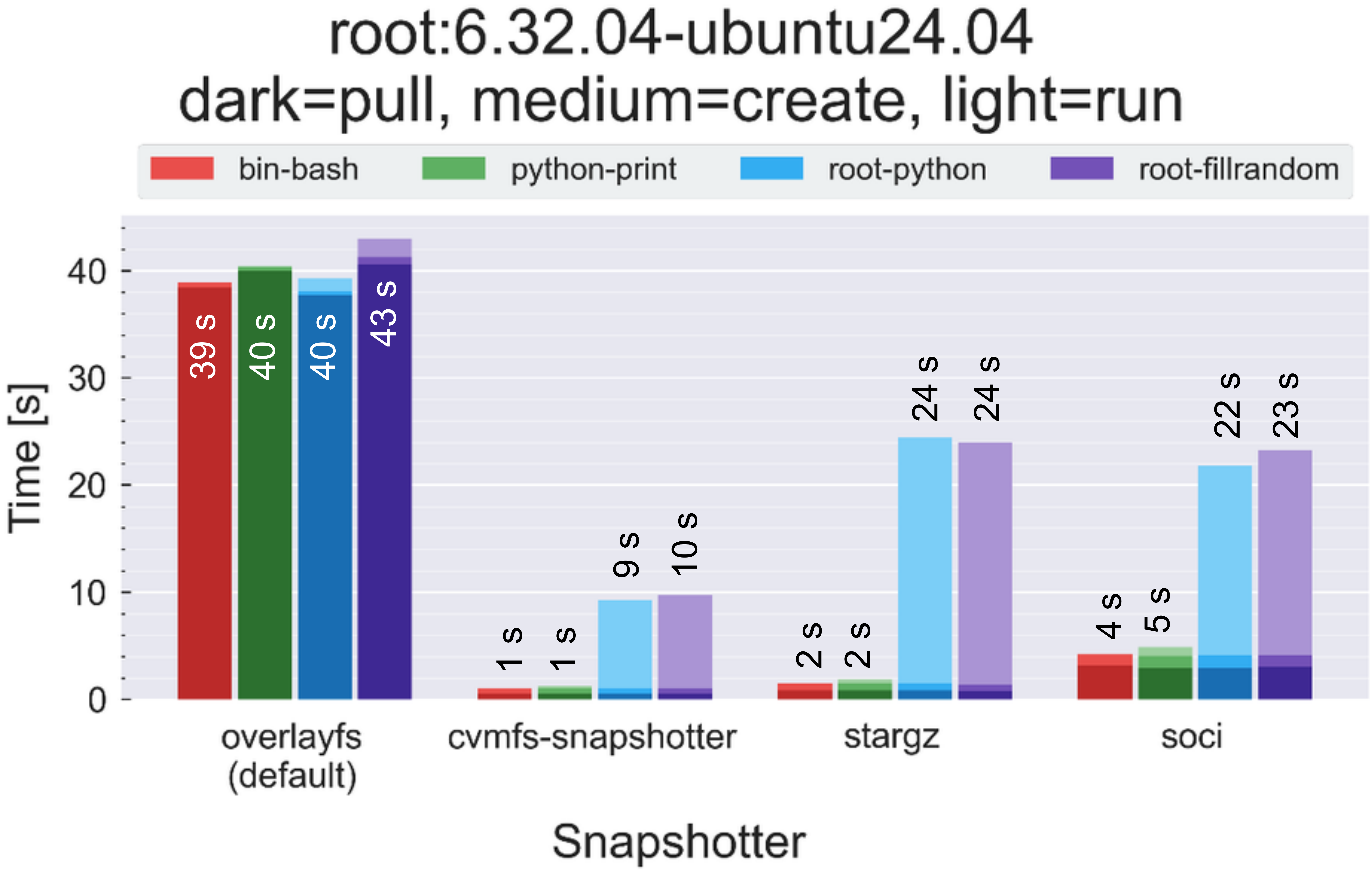
Investigate performance with workloads of increasing complexity:

- 🟥 */bin/bash*
- 🟩 *print()* in python
- 🟦 *import ROOT* in python
- 🟪 *fillrandom.py* using pyROOT

Observations:

- Comparable performance
- *import ROOT* loads a lot of data

Results: ROOT image (2)



Investigate performance with workloads of increasing complexity:

🟥 */bin/bash*

🟩 *print()* in python

🟦 *import ROOT* in python

🟪 *fillrandom.py* using pyROOT

Observations:

- CVMFS snapshotter faster than other two lazy snapshotters
- For complex workloads, pull time small compared to execution time (but mind significant data savings!)

Usability today

rootless docker available since RHEL 8 and kernel 4.18/5.11 — still requires (cluster) admin action

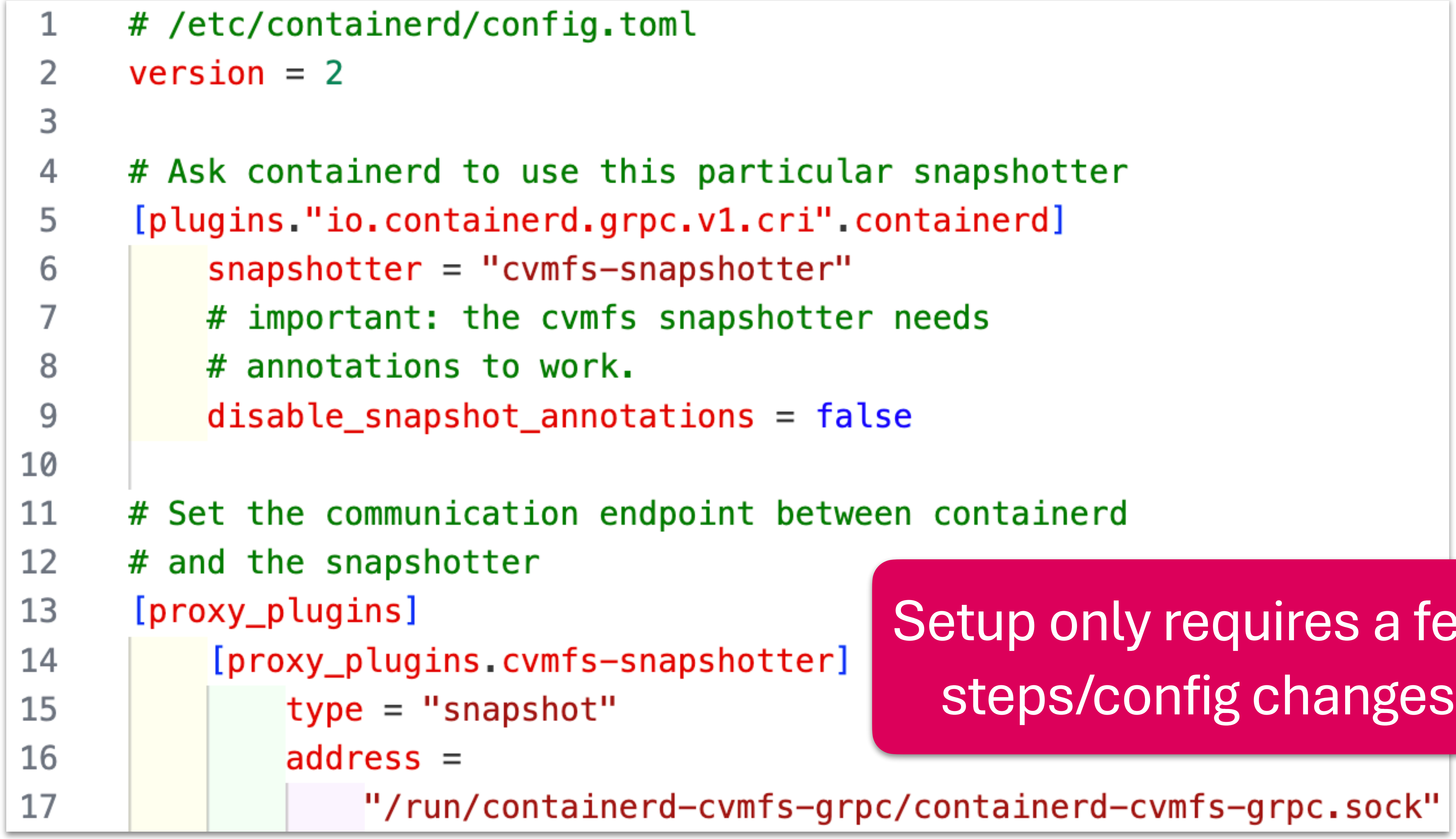
Use of Stargz snapshotter **requires images to be converted** (programatically) to a specific format → adoption might be slow/difficult

SOCI snapshotter only requires small addition to existing image—however, only certain registries support **additional artifacts** (Harbor ✅, GitLab ❌)

CVMFS snapshotter **requires images to be “unpacked”** → **delay** between building them and having them available (and they need to be added to the unpacker “sync” list)

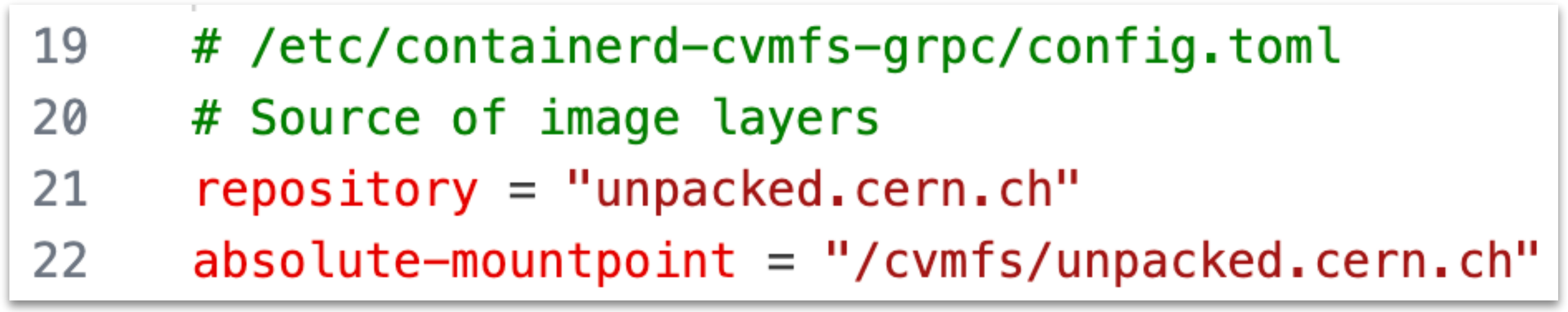
Example configurations for docker and kubernetes

containerd configs for CVMFS snapshotter:



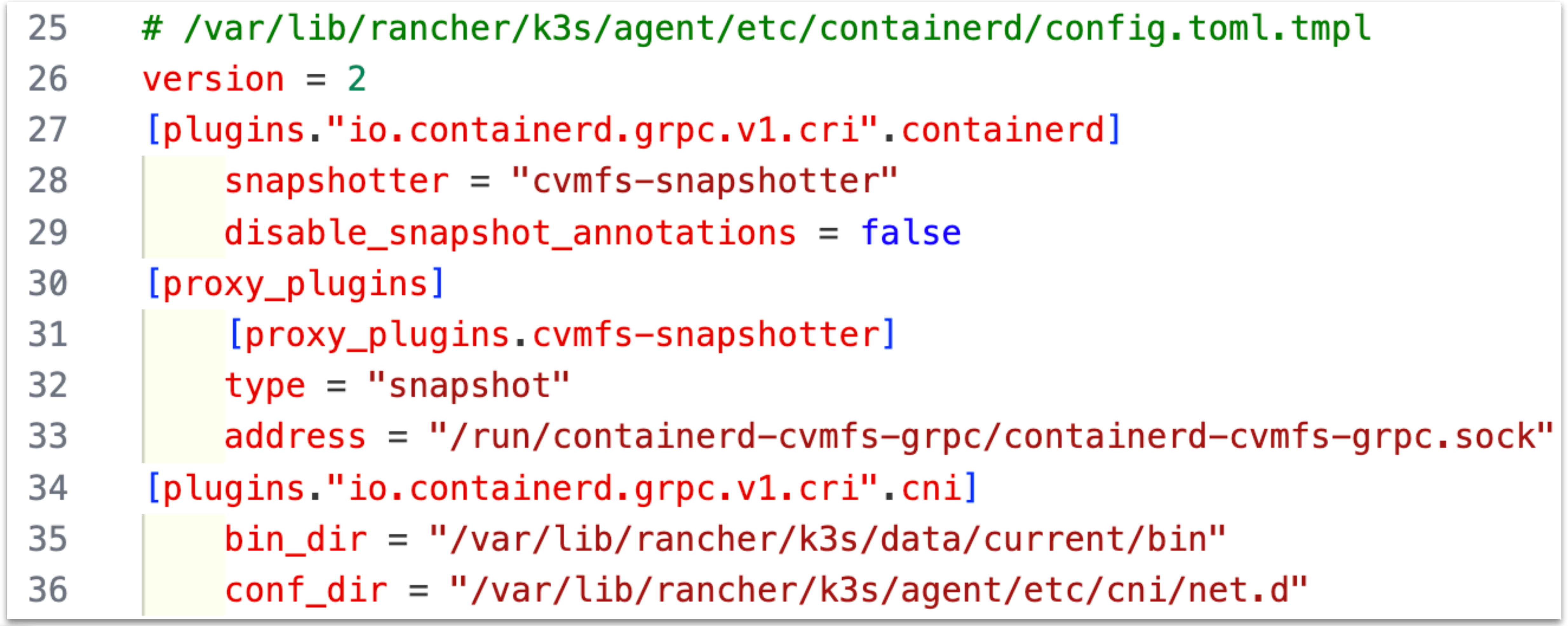
```
# /etc/containerd/config.toml
version = 2

# Ask containerd to use this particular snapshotter
[plugins."io.containerd.grpc.v1.cri".containerd]
    snapshotter = "cvmfs-snapshotter"
    # important: the cvmfs snapshotter needs
    # annotations to work.
    disable_snapshot_annotations = false

# Set the communication endpoint between containerd
# and the snapshotter
[proxy_plugins]
    [proxy_plugins.cvmfs-snapshotter]
        type = "snapshot"
        address =
            "/run/containerd-cvmfs-grpc/containerd-cvmfs-grpc.sock"
```

Setup only requires a few steps/config changes

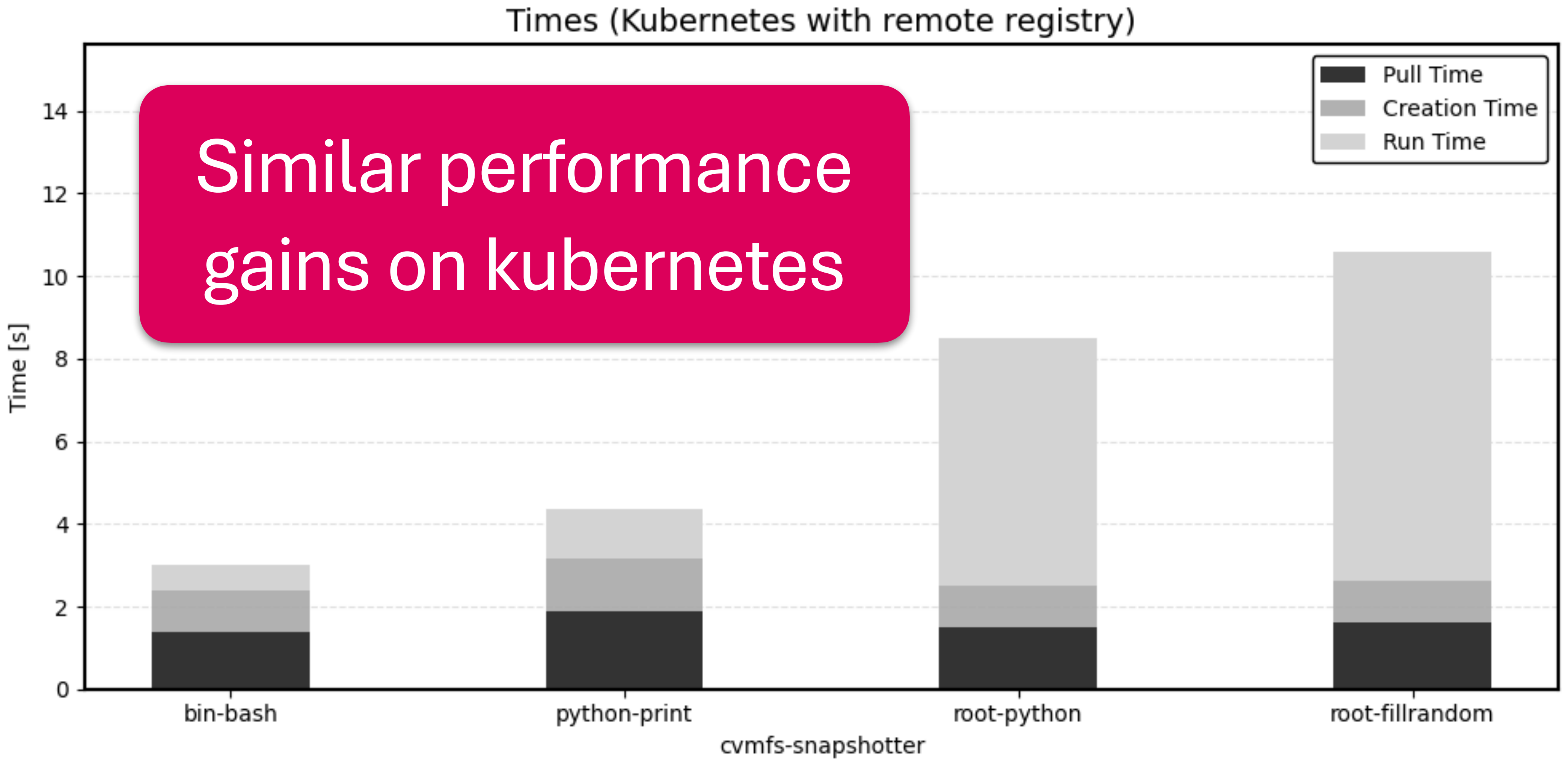


```
# /etc/containerd-cvmfs-grpc/config.toml
# Source of image layers
repository = "unpacked.cern.ch"
absolute-mountpoint = "/cvmfs/unpacked.cern.ch"
```

kubernetes (k3s) CVMFS snapshotter config:



```
# /var/lib/rancher/k3s/agent/etc/containerd/config.toml.tmpl
version = 2
[plugins."io.containerd.grpc.v1.cri".containerd]
    snapshotter = "cvmfs-snapshotter"
    disable_snapshot_annotations = false
[proxy_plugins]
    [proxy_plugins.cvmfs-snapshotter]
    type = "snapshot"
    address = "/run/containerd-cvmfs-grpc/containerd-cvmfs-grpc.sock"
[plugins."io.containerd.grpc.v1.cri".cni]
    bin_dir = "/var/lib/rancher/k3s/data/current/bin"
    conf_dir = "/var/lib/rancher/k3s/agent/etc/cni/net.d"
```



Similar performance gains on kubernetes

Conclusions

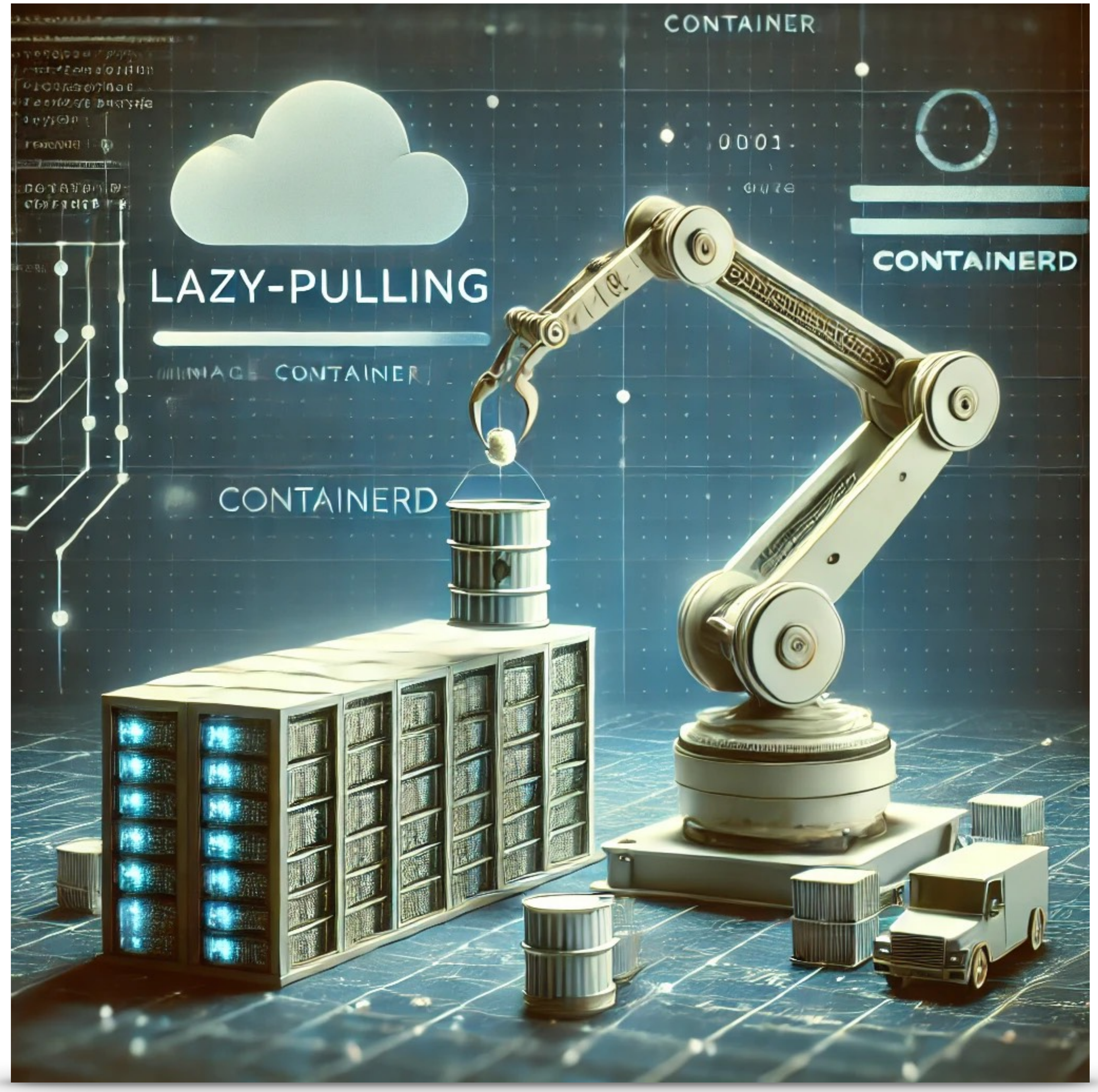
Container image snapshotters open up new possibilities for image distribution and access

- Large bandwidth/data savings observed (here > 65%)
- Time saving depends on workload/image details

Overall, evaluated snapshotters all have advantages and disadvantages in usability/requirements

Performance similar

- CVMFS snapshotter seems to be a bit faster than the other two snapshotters evaluated



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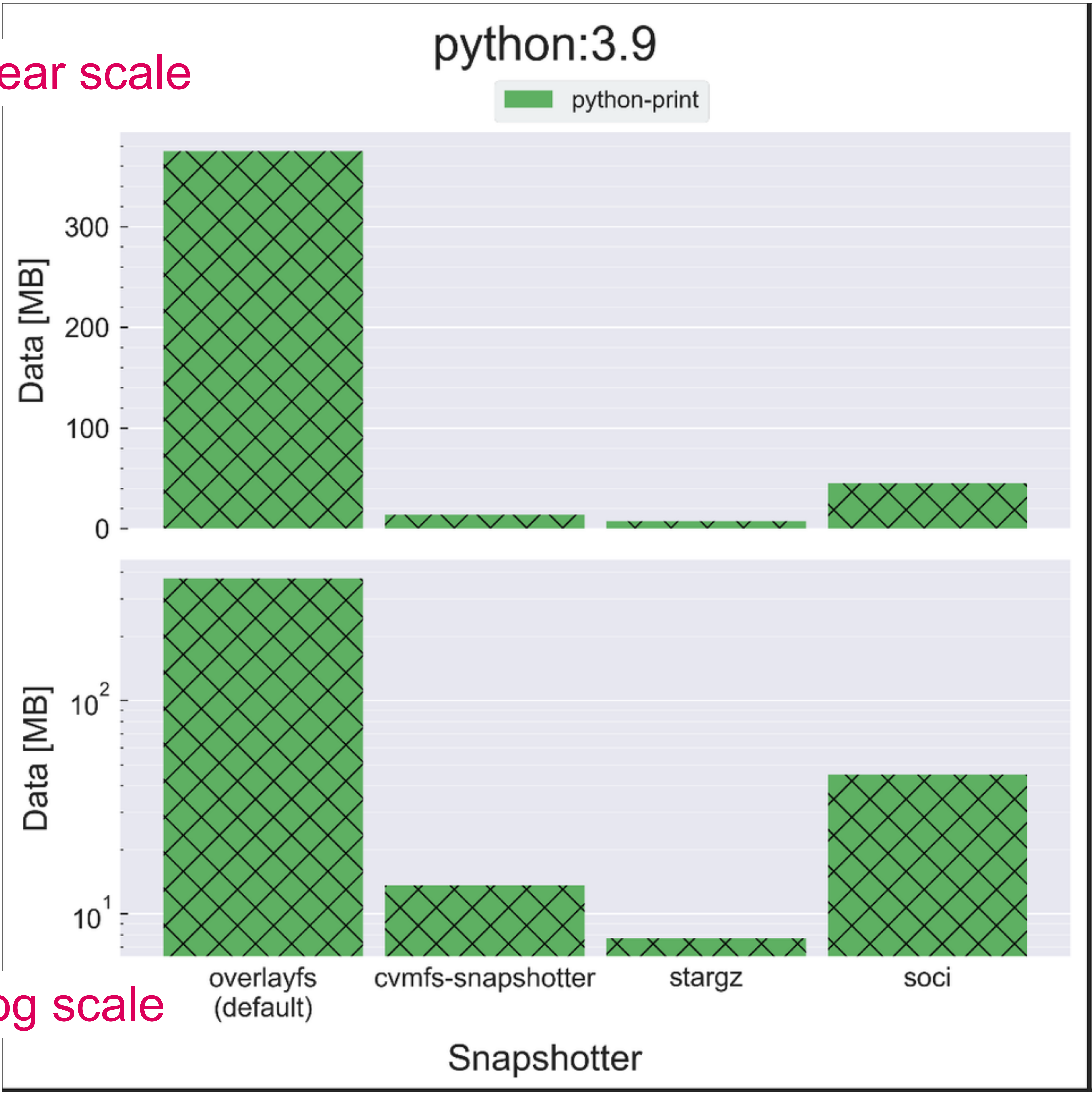
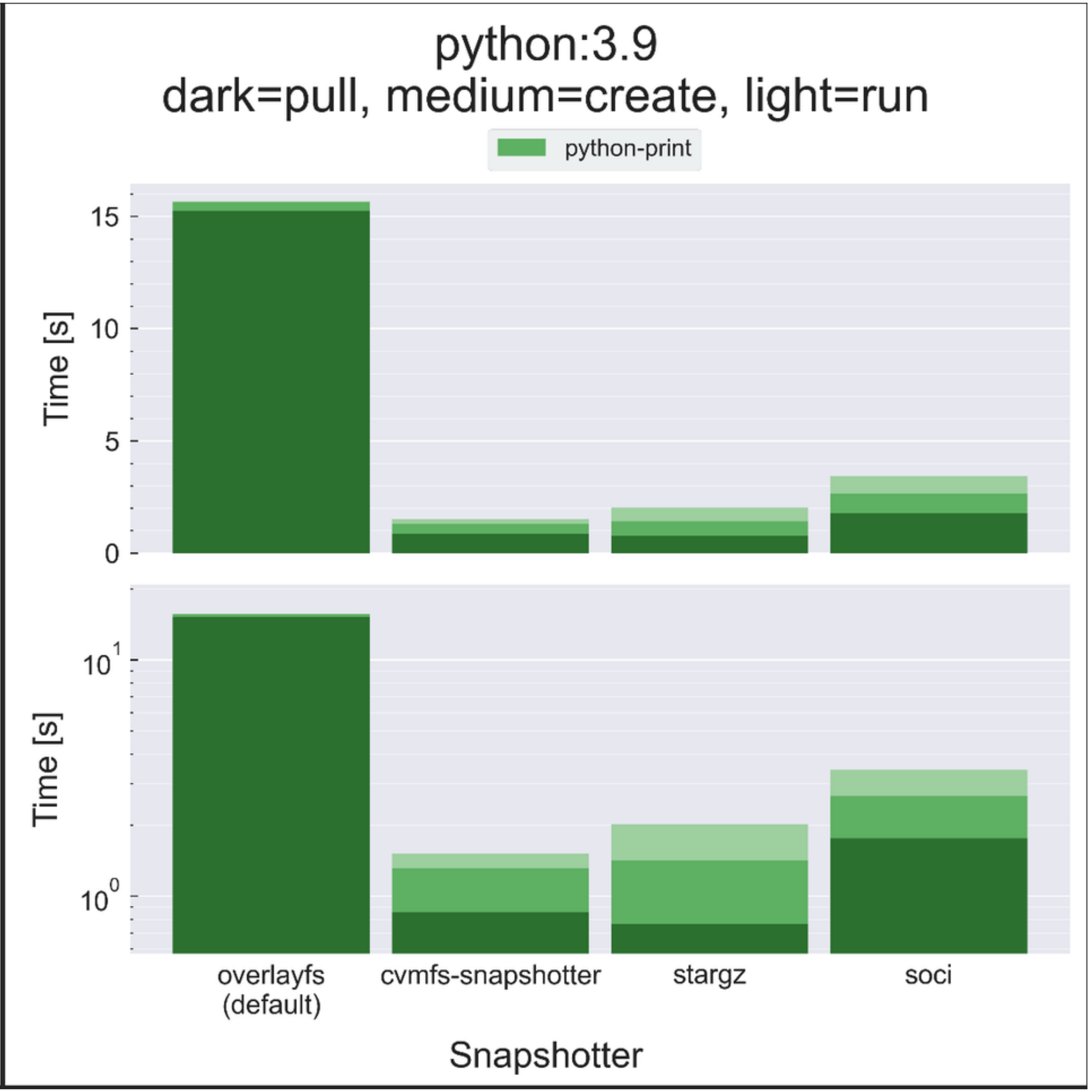
Results: python image: print() — remote registry/cache

linear scale

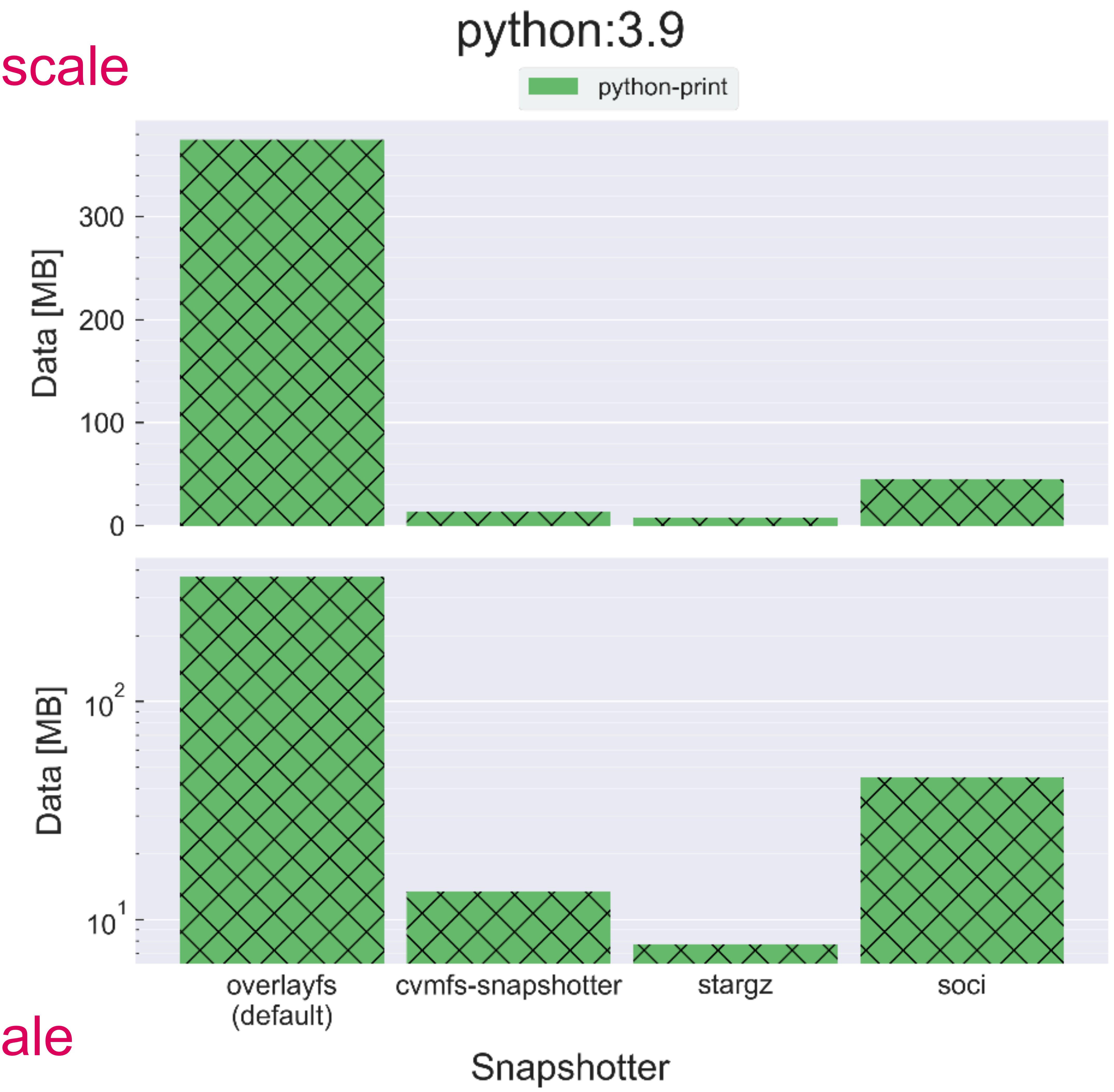


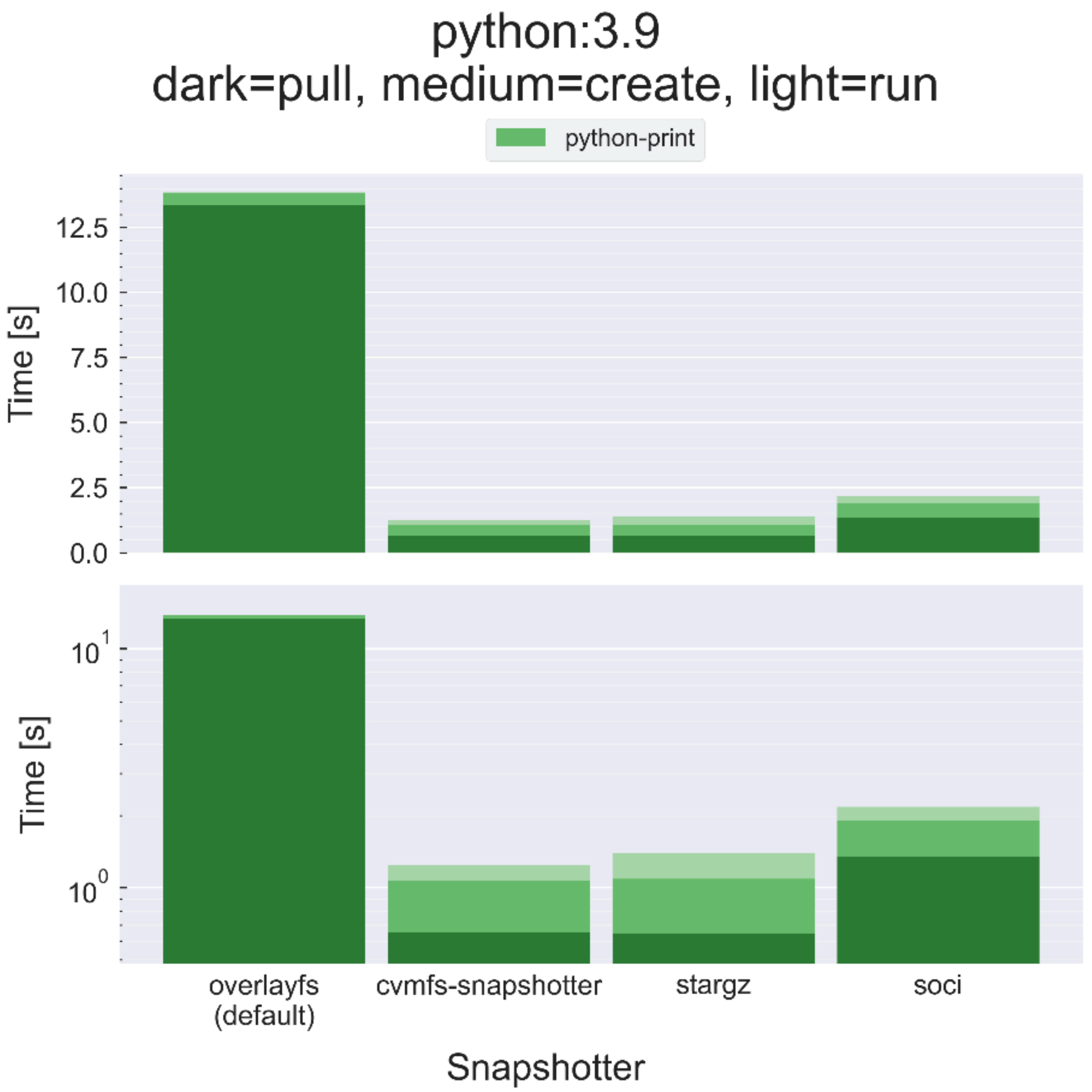
log scale



Results: python image: print() — local registry/cache

linear scale

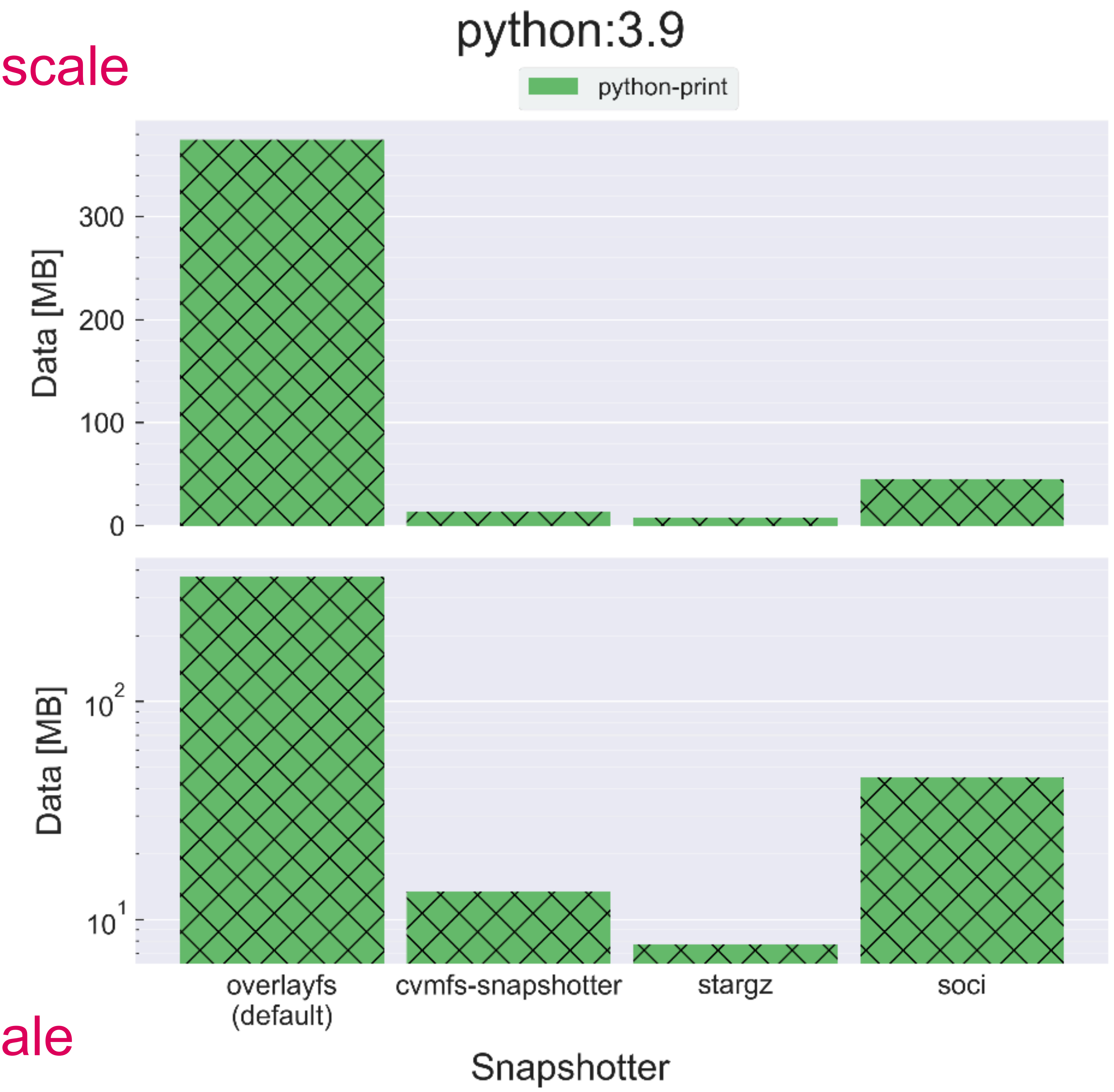




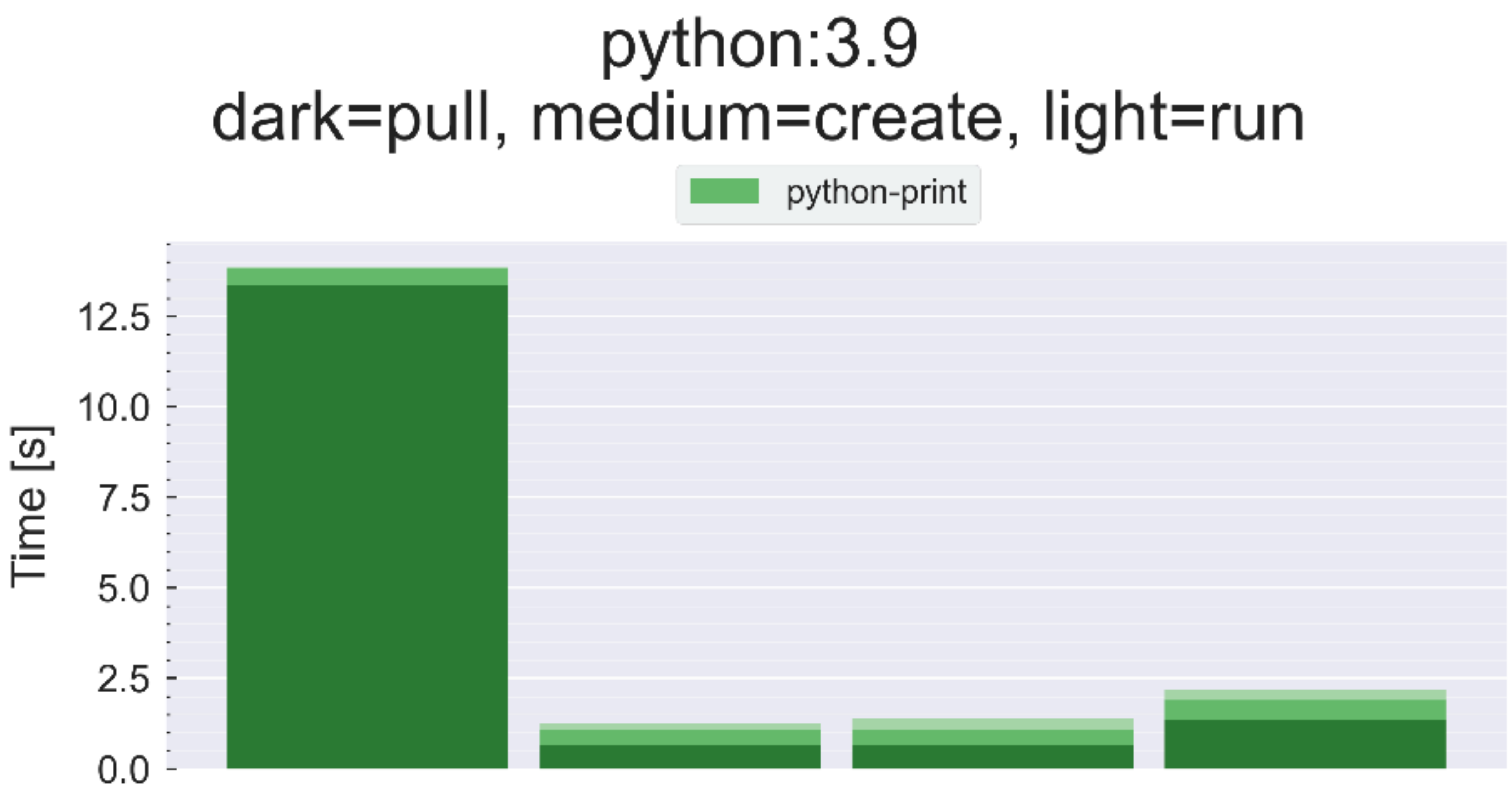
log scale

Results: python image: print() — local registry/cache

linear scale



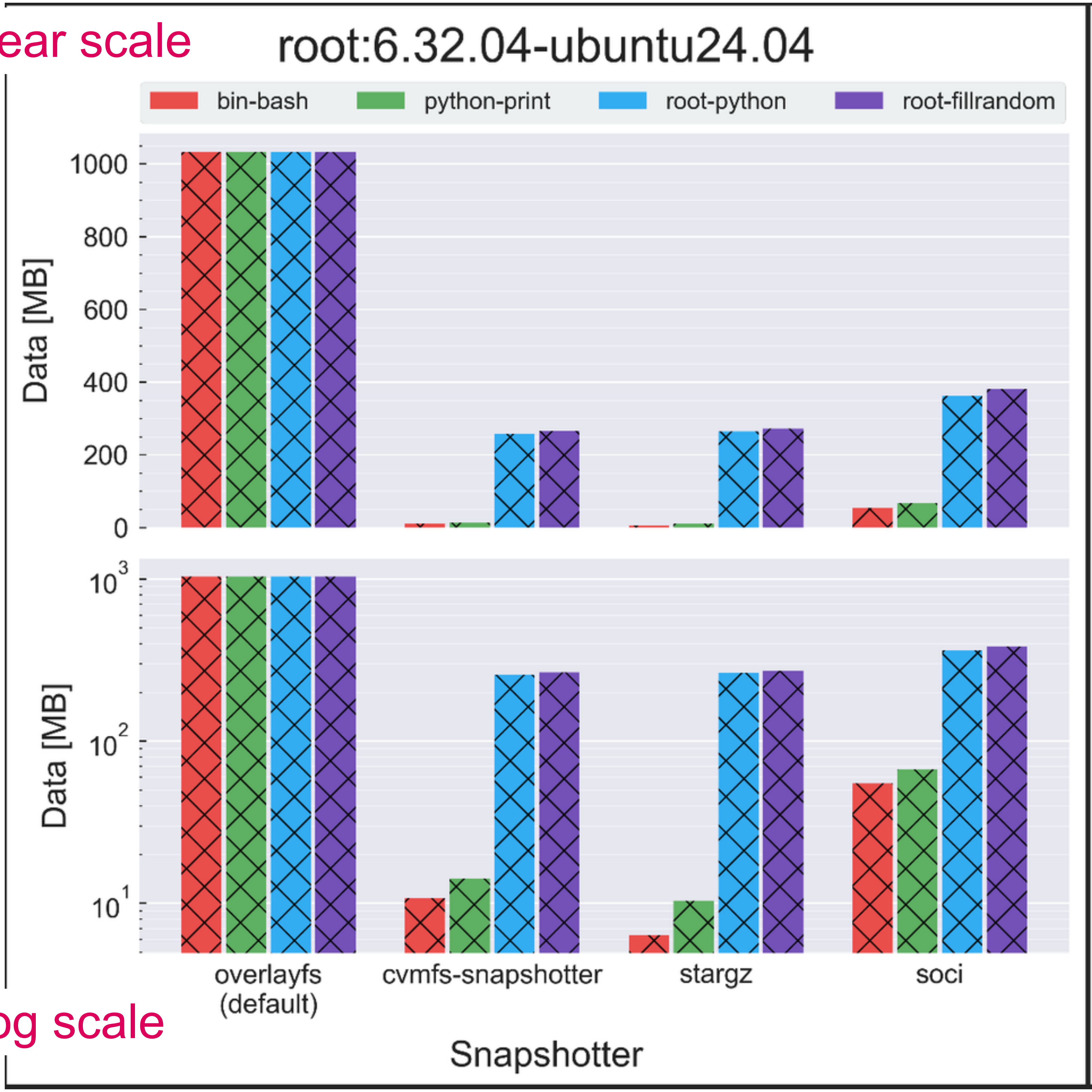
log scale



Observations:

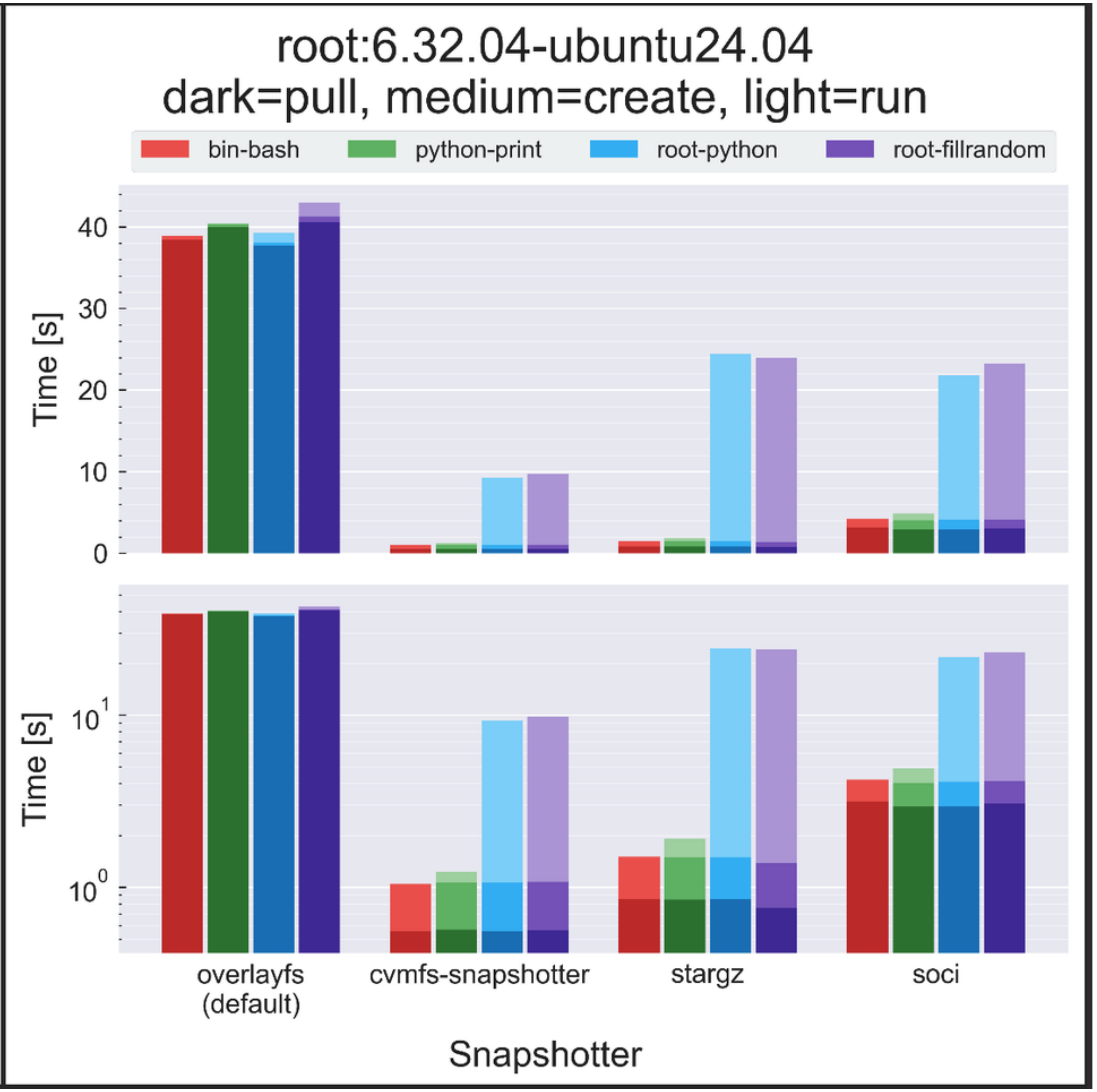
- Very similar behaviour w.r.t. remote registry/ cache
- Slightly faster due to reduced network overhead

Results: ROOT image



linear scale

log scale


root:6.32.04-ubuntu24.04
dark=pull, medium=create, light=run
bin-bash
python-print
root-python
root-fillrandom
Time [s]
10^1
10^0
overlayfs
(default)
cvmfs-snapshotter
stargz
soci
Snapshotter