Kubernetes at Belle II: Orchestrating the Computing Infrastructure for Particle Physics

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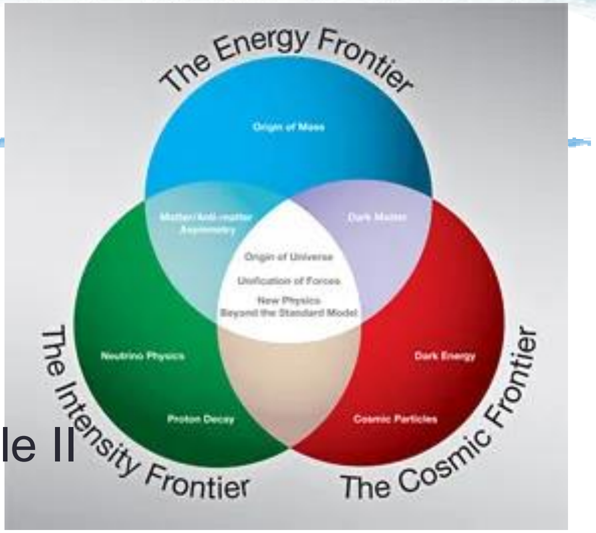
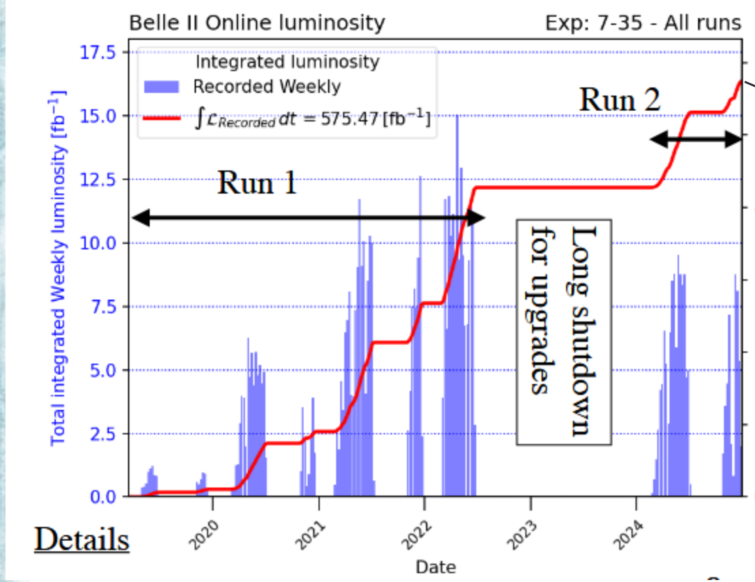
Belle II experiment

- HEP experiment for the intensity frontier
  - Ongoing rich physics program (not only B, but Tau, dark matter…)
  - Aiming at 50/ab corresponding to ~x50 of Belle ~60PB

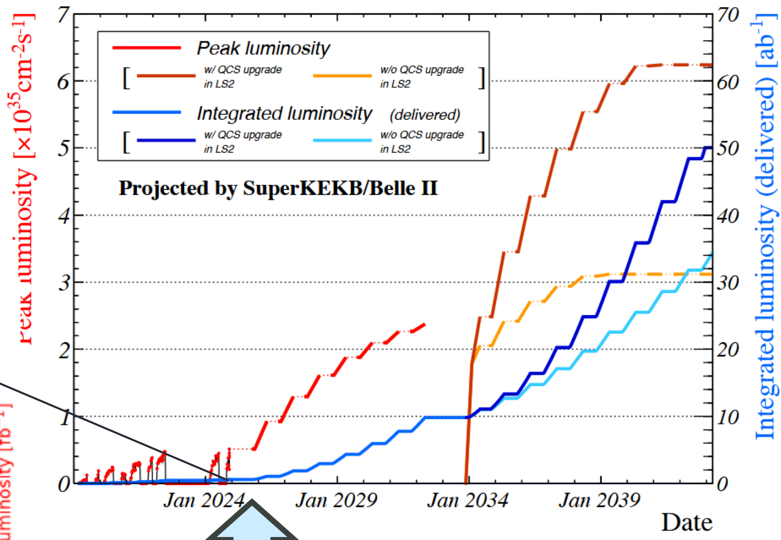


Belle II

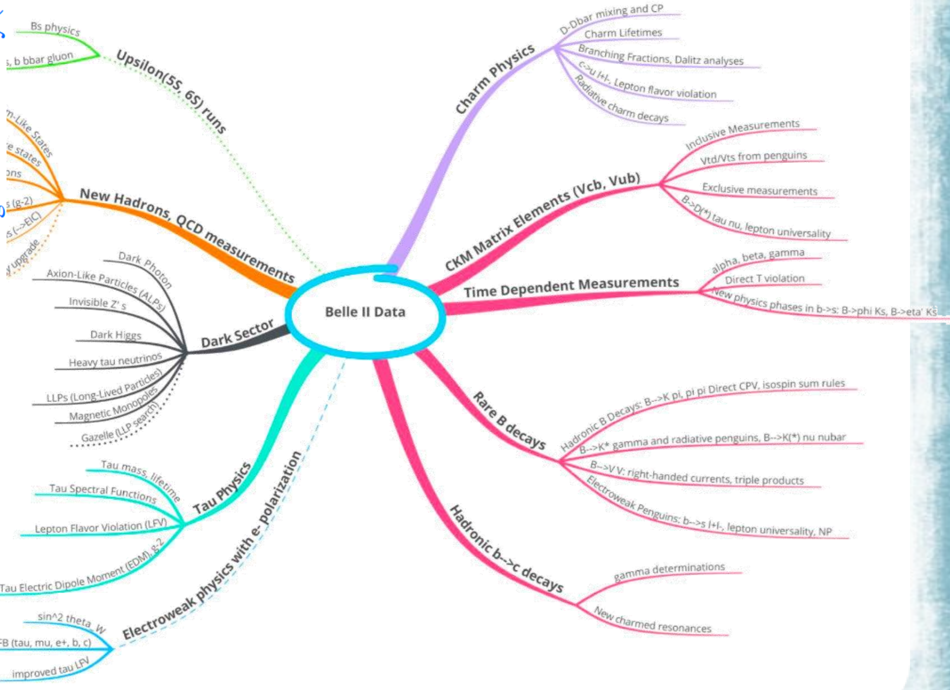
- First data: 2019
- Finished long shut down in 2024
- Start 2025 data taking soon



Details

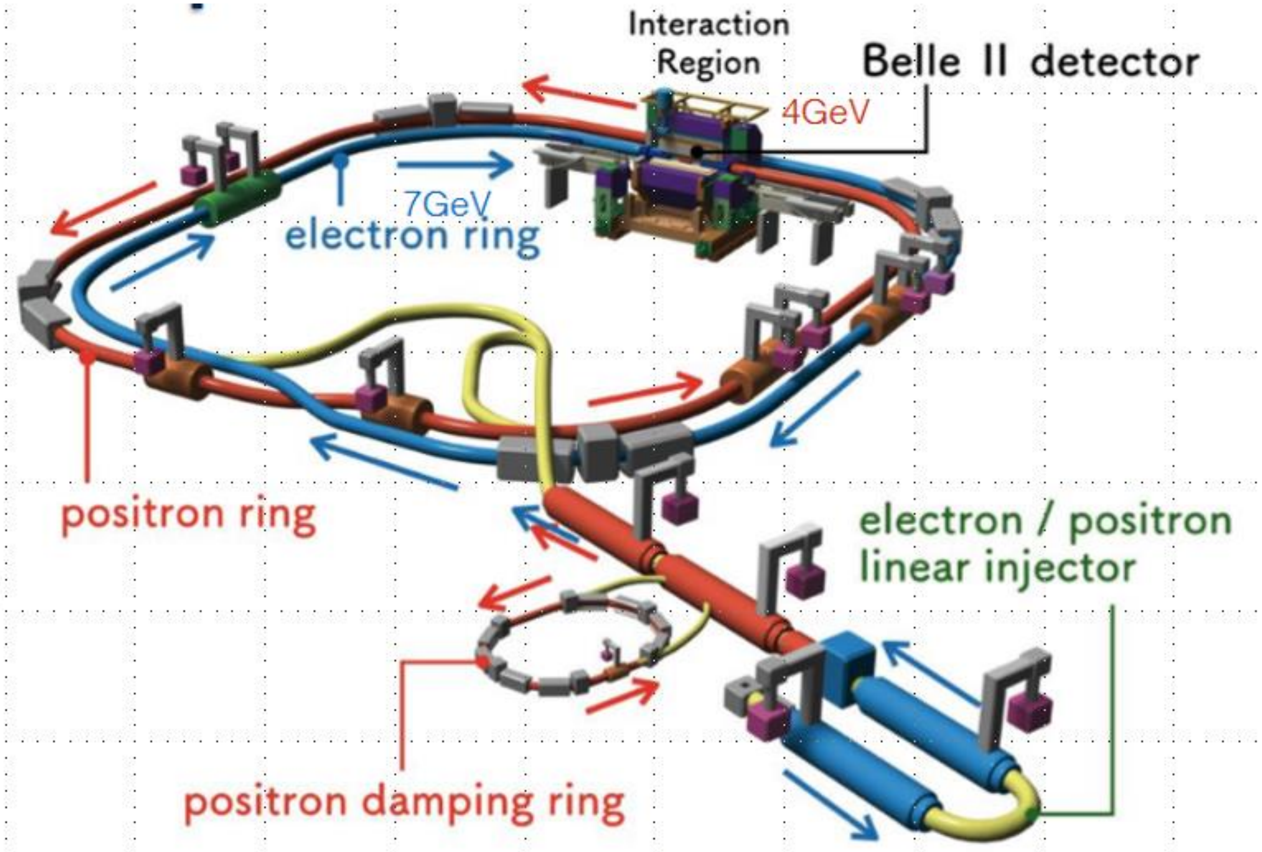


We're here

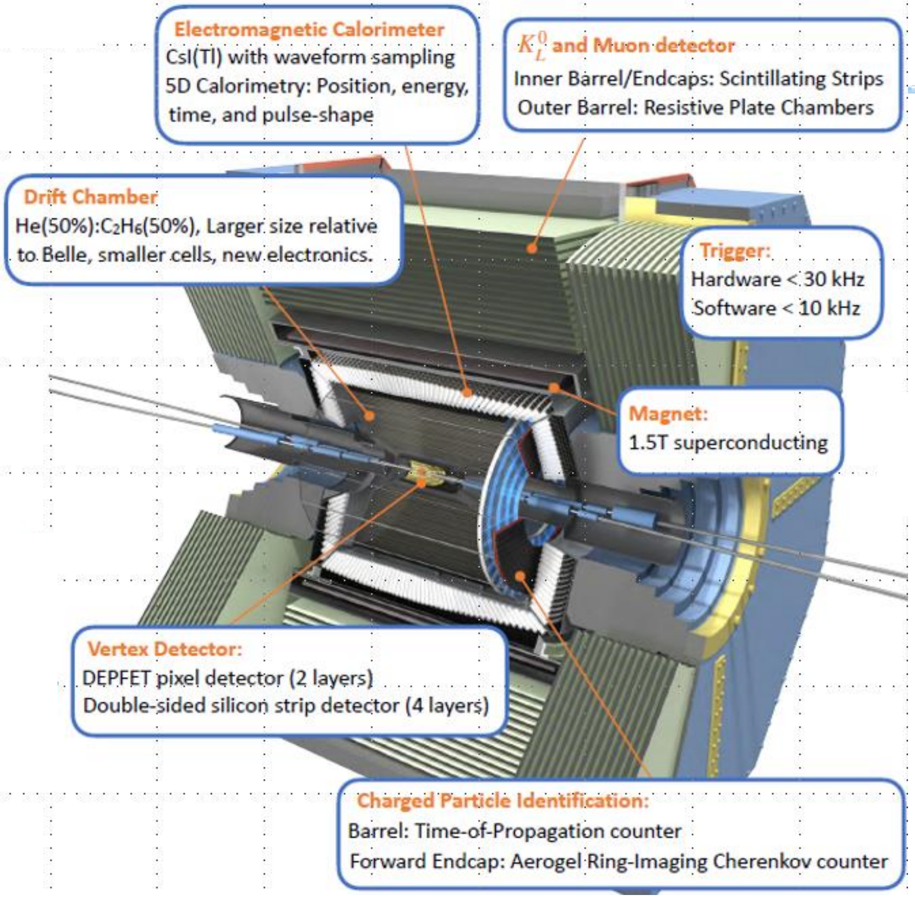


Belle II Data
Upsilon(5S, 6S) runs
Bs physics
, b bbar gluon
New Hadrons, QCD measurements
-Like States
e states
ons
s (g-2)
s (-->EIC)
upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
A_FB (tau, mu, e+, b, c)
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances

SuperKEKB + Belle II



PTEP 2013, 03A011 (2013)



Electromagnetic Calorimeter
CsI(Tl) with waveform sampling
5D Calorimetry: Position, energy, time, and pulse-shape

K_L^0 and Muon detector
Inner Barrel/Endcaps: Scintillating Strips
Outer Barrel: Resistive Plate Chambers

Drift Chamber
He(50%):C_2H_6(50%), Larger size relative to Belle, smaller cells, new electronics.

Trigger:
Hardware < 30 kHz
Software < 10 kHz

Magnet:
1.5T superconducting

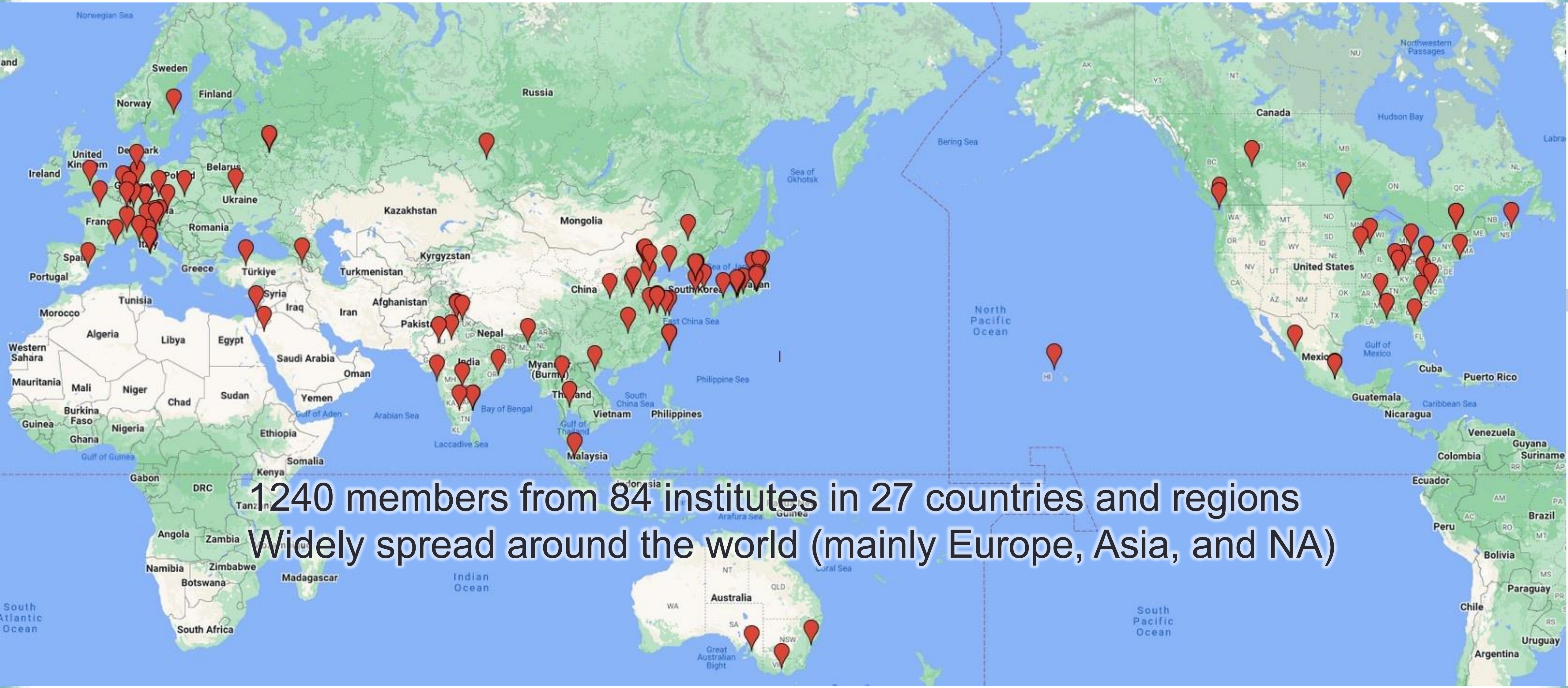
Vertex Detector:
DEPFET pixel detector (2 layers)
Double-sided silicon strip detector (4 layers)

Charged Particle Identification:
Barrel: Time-of-Propagation counter
Forward Endcap: Aerogel Ring-Imaging Cherenkov counter

Asymmetric e^+e^- collider at KEK (e^+:4GeV, e^-: 7GeV)
Instant luminosity record of $5.1\text{x}10^{34}$cm-2s^{-1} (x2.4 of KEKB)

- Composed of 7 major subdetectors
- Hermetic detector
- Good particle ID
- Excellent tracking efficiency and improved vertex resolution

Belle II collaboration

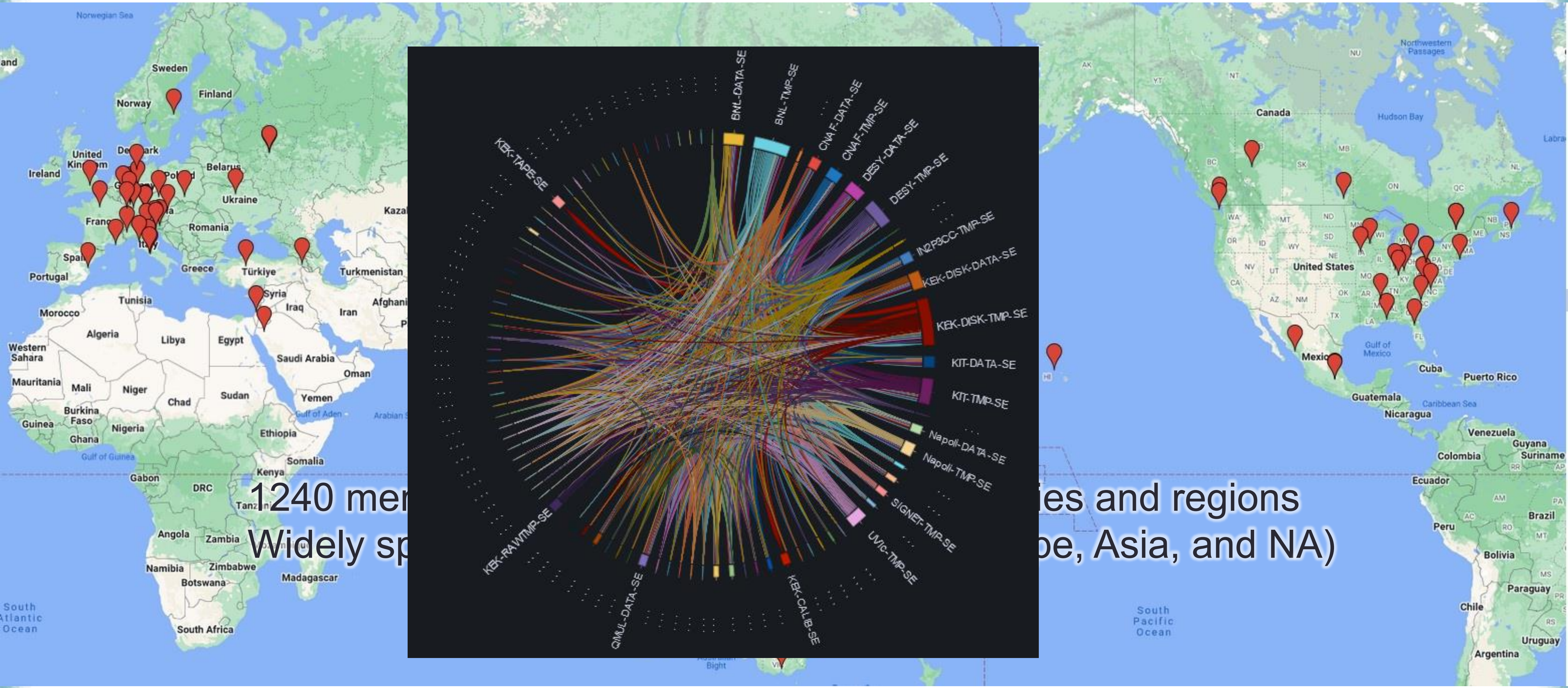


1240 members from 84 institutes in 27 countries and regions

Widely spread around the world (mainly Europe, Asia, and NA)

Belle II collaboration

High-speed network mesh is a key!

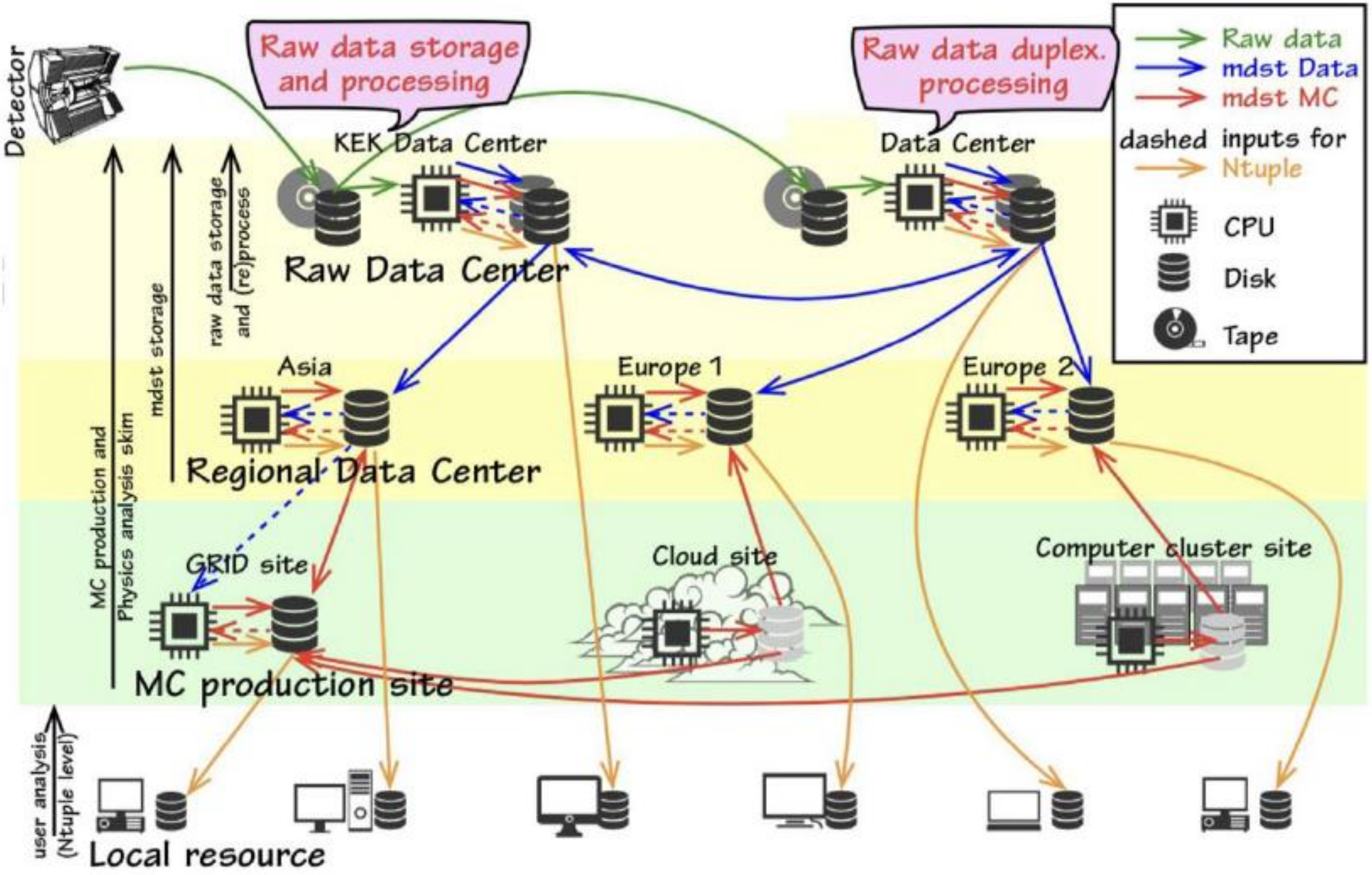


1240 mer ies and regions

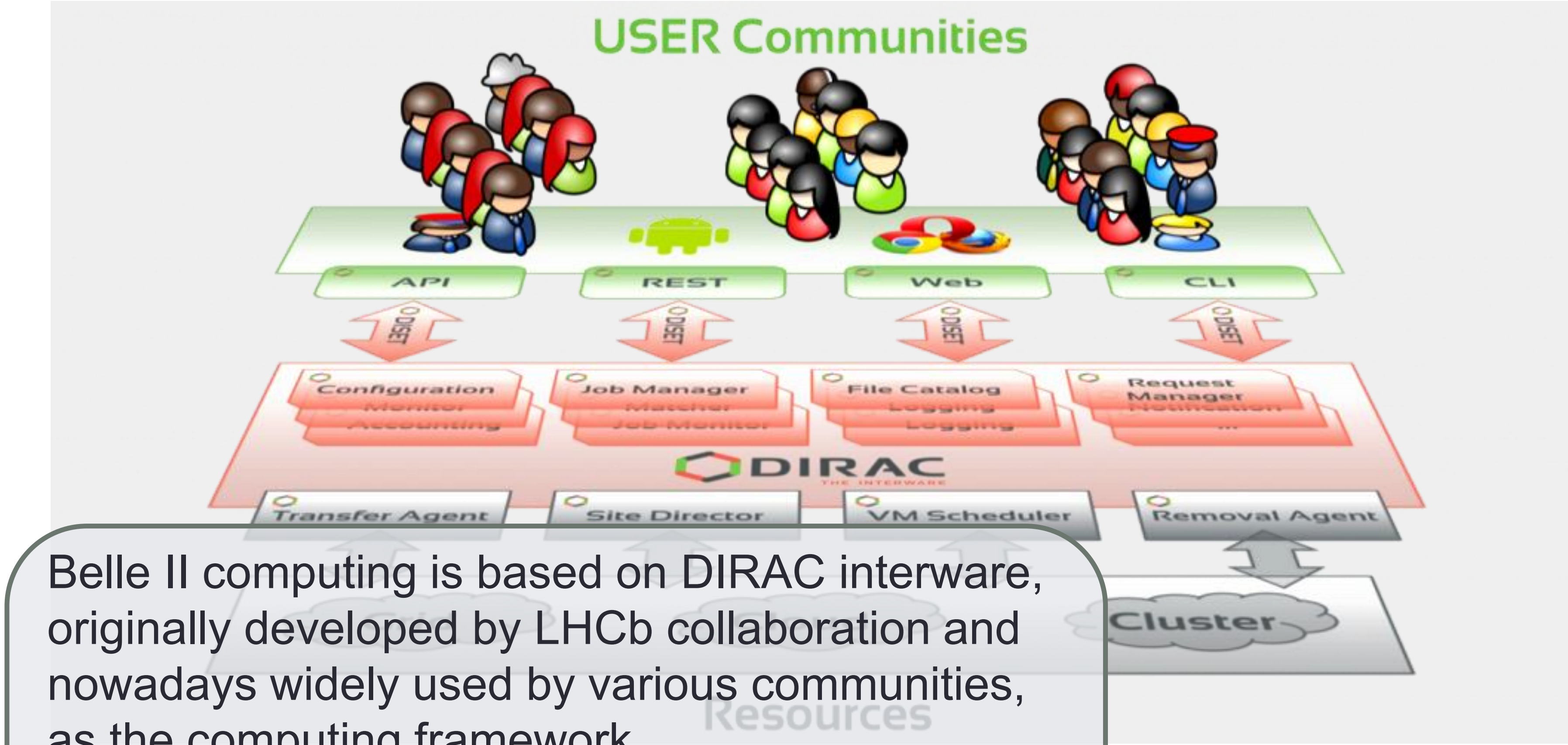
Widely sp pe, Asia, and NA)

Belle II computing model

- Data is transferred from the offline servers to the KEK data center.
- Raw data centers around the world keep a second copy of the full raw data set.
- Raw data is processed, skimmed and distributed over Raw Data Centers and Regional Data Centers.
- MC production is performed at all sites.
- Analyzers access data and MC sending jobs to the grid and downloading the output to local resources.



DIRAC



Belle II computing is based on DIRAC interware, originally developed by LHCb collaboration and nowadays widely used by various communities, as the computing framework

→single interface to handle various resources
→modular design: community can easily extend the functionality

Similar framework used in other communities

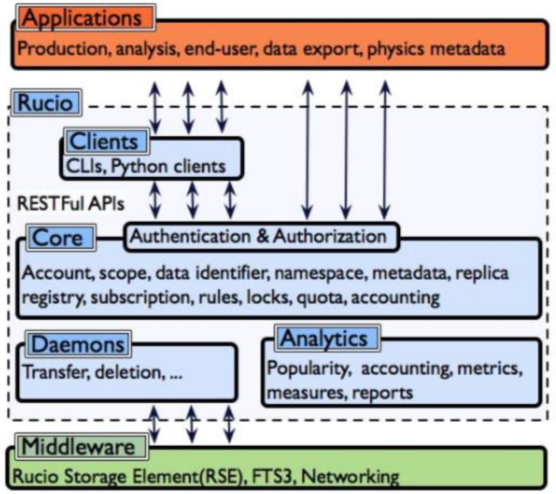
PanDA: ATLAS
JAliEn: ALICE
....

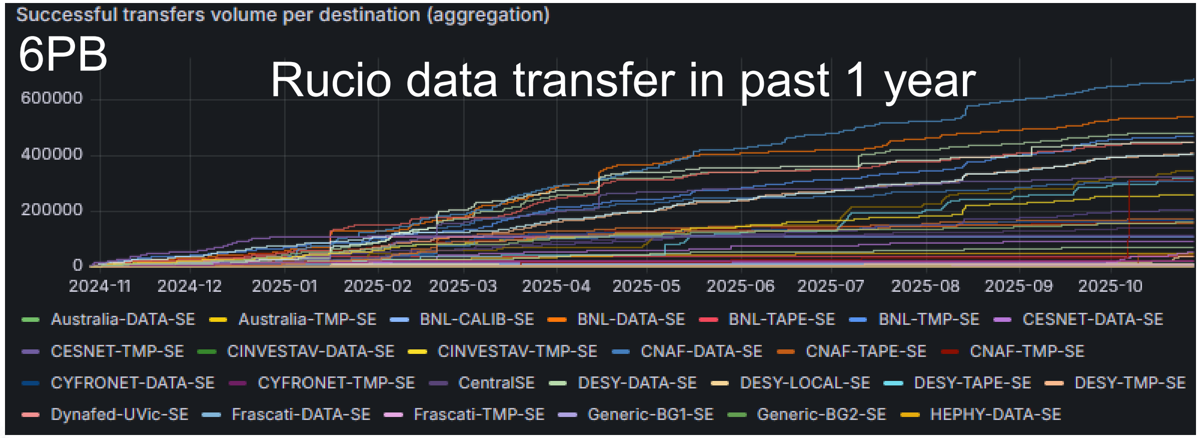
In Belle II, two different DIRAC systems are utilized
- BelleRawDIRAC for “Core Computing”
- BelleDIRAC for Distributed Computing

Rucio

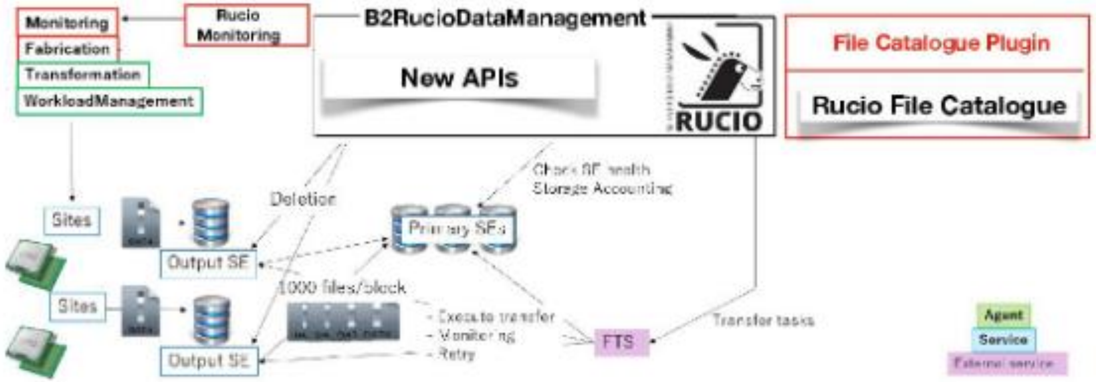
- Rucio is a highly-scalable policy-driven data management system
  - Originally built for ATLAS experiment and adopted by Belle II since 2021

  - In Belle II, Rucio is used for several purposes
    - As Distributed Data Management System
      - Transfers between site using policies engines (rules and subscriptions)
      - Monitoring and transfers, deletions, SE occupancy
    - As File Catalog
      - Provide coherent access to file replicas via LFN (logical file name)
    - As Metadata Catalog
      - We have long used AMGA to store "data of data"
      - Now in final phase to migrate to Rucio

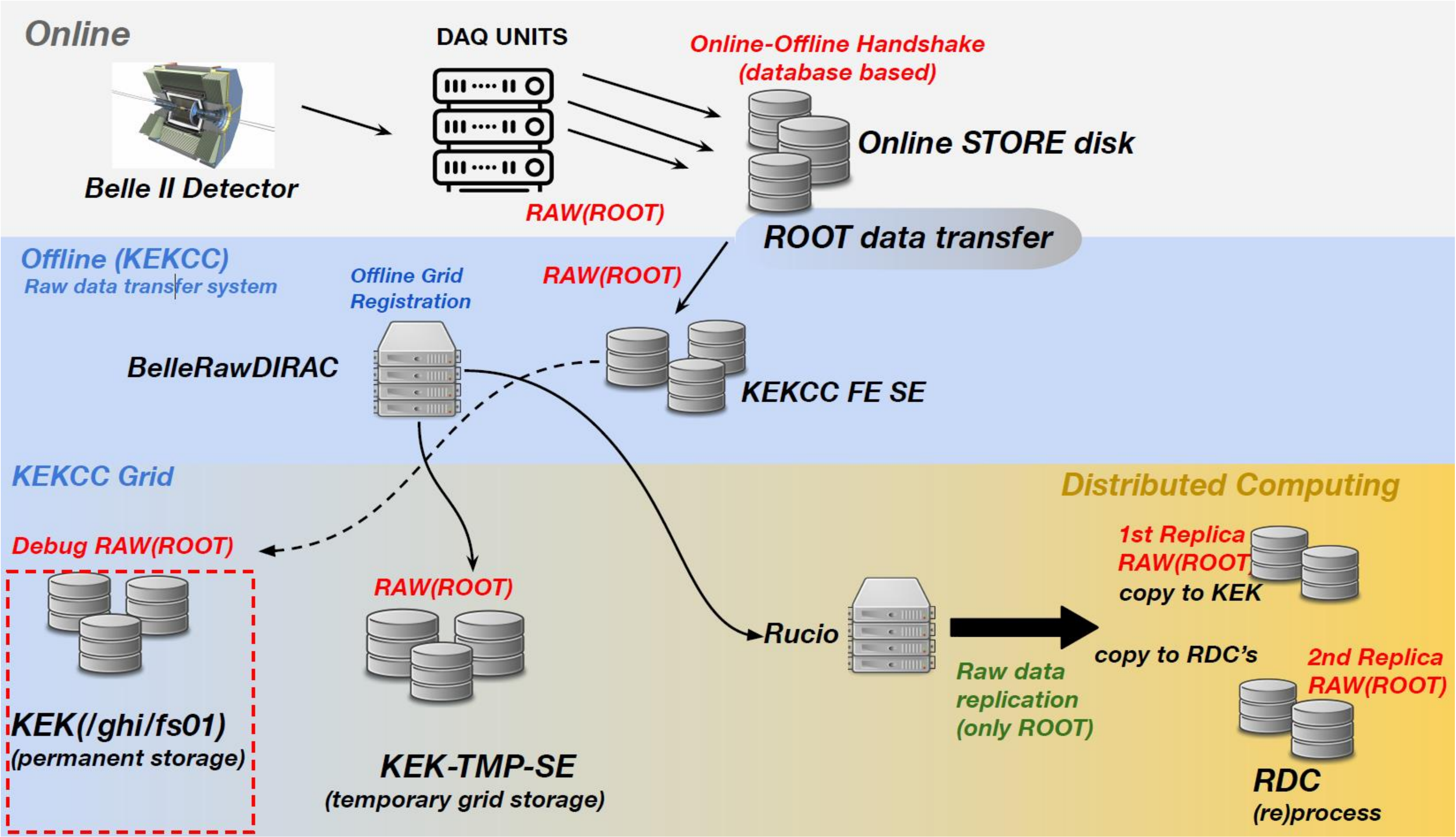

Applications
Production, analysis, end-user, data export, physics metadata
Rucio
Clients
CLIs, Python clients
RESTFul APIs
Core
Authentication & Authorization
Account, scope, data identifier, namespace, metadata, replica registry, subscription, rules, locks, quota, accounting
Daemons
Transfer, deletion, ...
Analytics
Popularity, accounting, metrics, measures, reports
Middleware
Rucio Storage Element(RSE), FTS3, Networking



Rucio data transfer in past 1 year

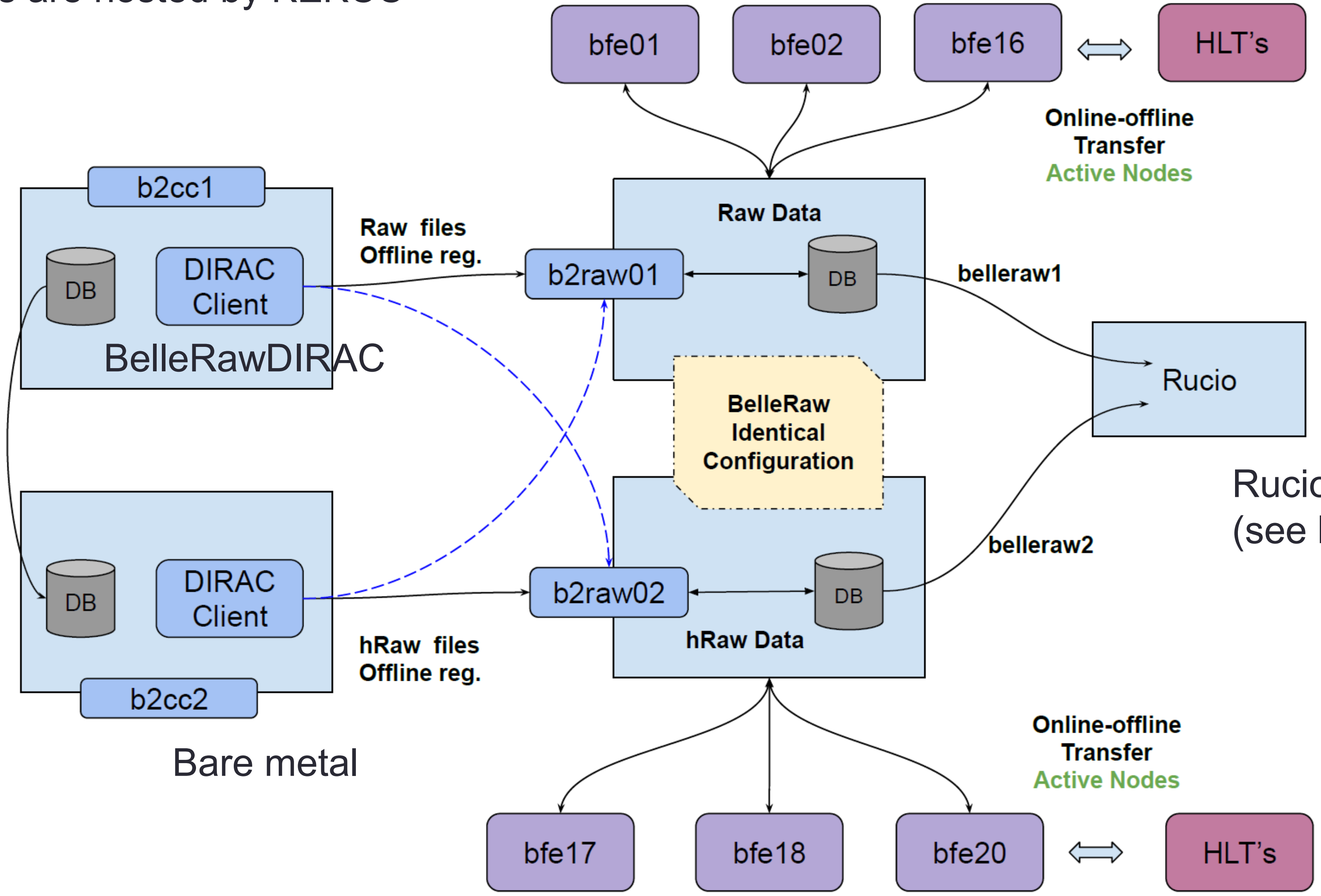


Raw data transfer in Belle II



Belle II “core computing” system

Most servers are hosted by KEKCC



Rucio is hosted by BNL
(see later slide)

Bare metal

Kubernetes for core computing

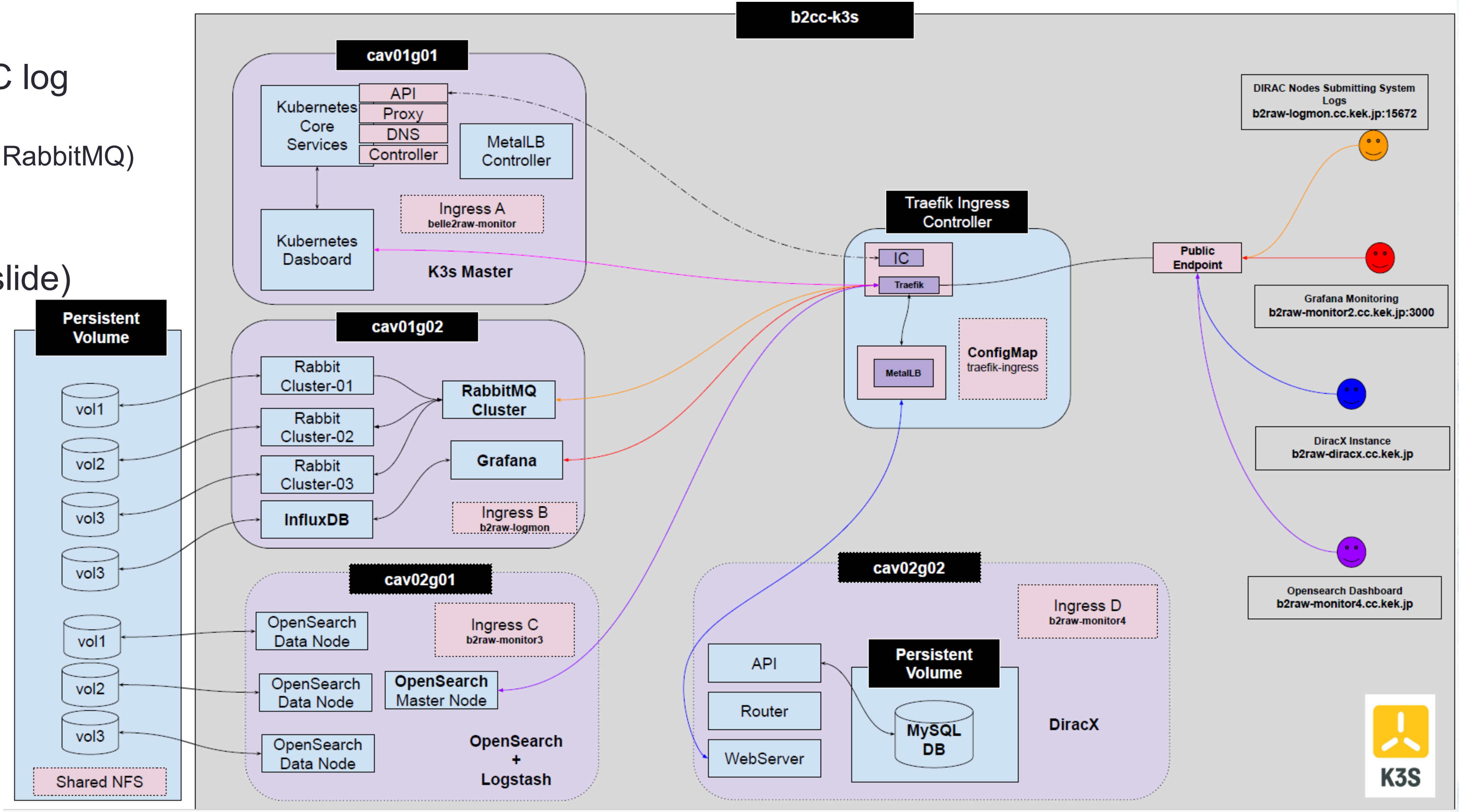
We started to use Kubernetes (K3s) to host some core computing functionalities

- Centralized DIRAC log
- Centralized syslog
(OpenSearch, LogStash, RabbitMQ)
- Grafana

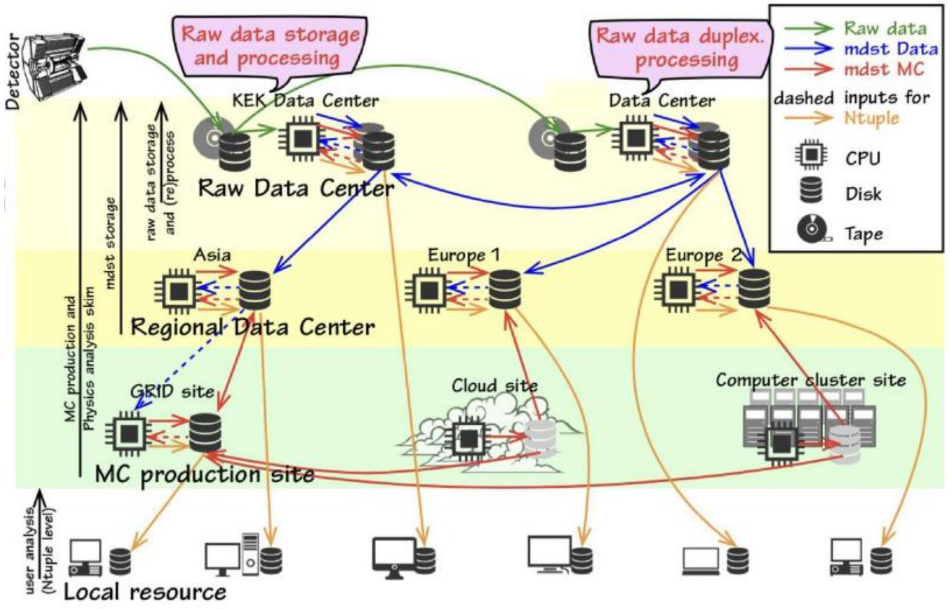
- DiracX (see later slide)

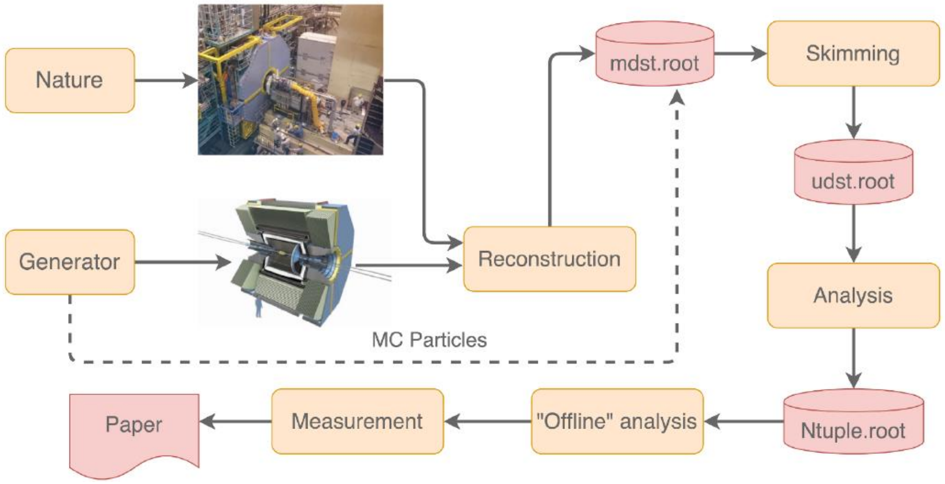
Infra for evaluation

4 VMs in 2 nodes
for now
(see later slide)



Distributed computing in Belle II



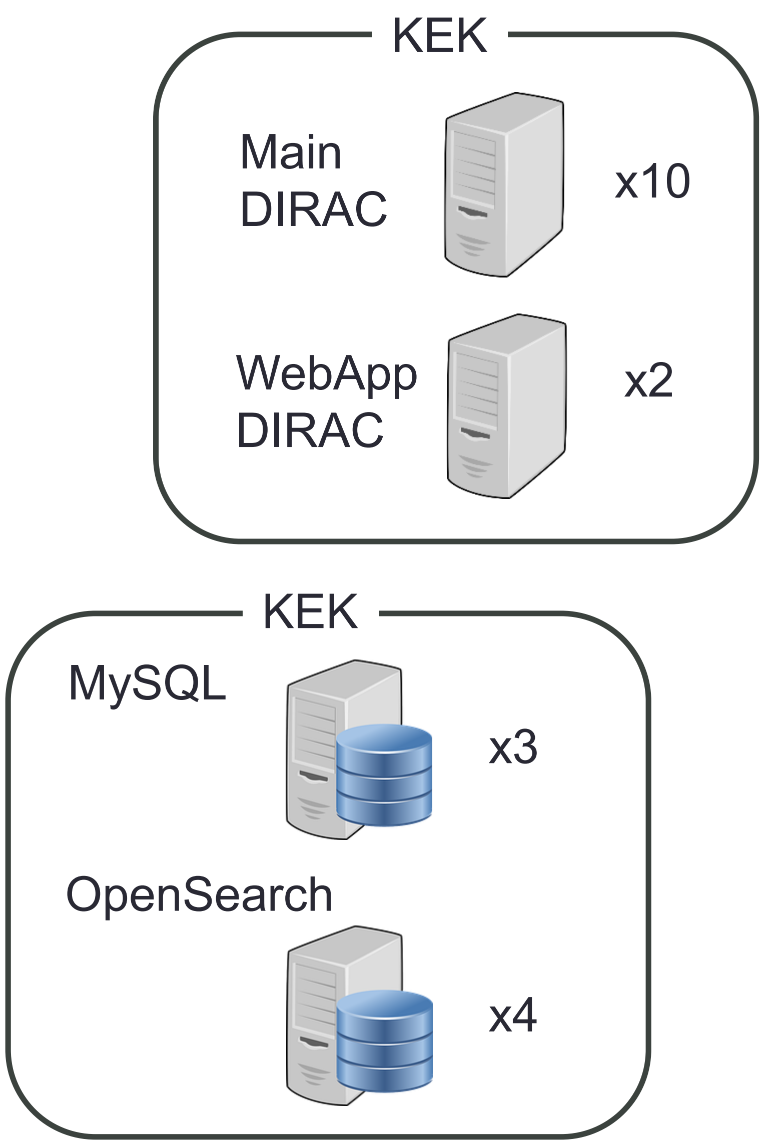


After Raw data is transferred to Raw data centers, apply various processing and filtering ("Skimming") toward final analysis result

Raw data (or MCProduction)	
mDST	Reconstructed event info
uDST	mDST+ particle list (high level objects)
nTuple	Analysis results (only values)

Typically the last step is done by individual (or group) while the others are processed by mass production system centrally

Belle II distributed computing system



KEK

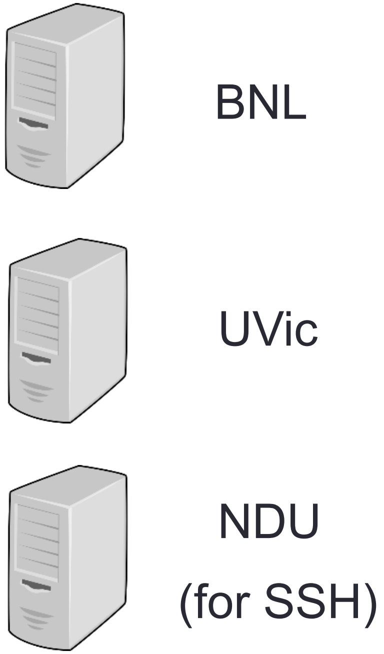
Main DIRAC x10

WebApp DIRAC x2

KEK

MySQL x3

OpenSearch x4



BNL

UVic

NDU (for SSH)

KEK DIRAC servers are on VM
MySQL and OS run on physical machine
No Kubernetes yet

DIRAC servers are maintained by Belle II
KEKCC maintains other essential computing resources hosted by KEK
BNL hosts FTS, Rucio, and relevant services

BNL
- Rucio
- FTS

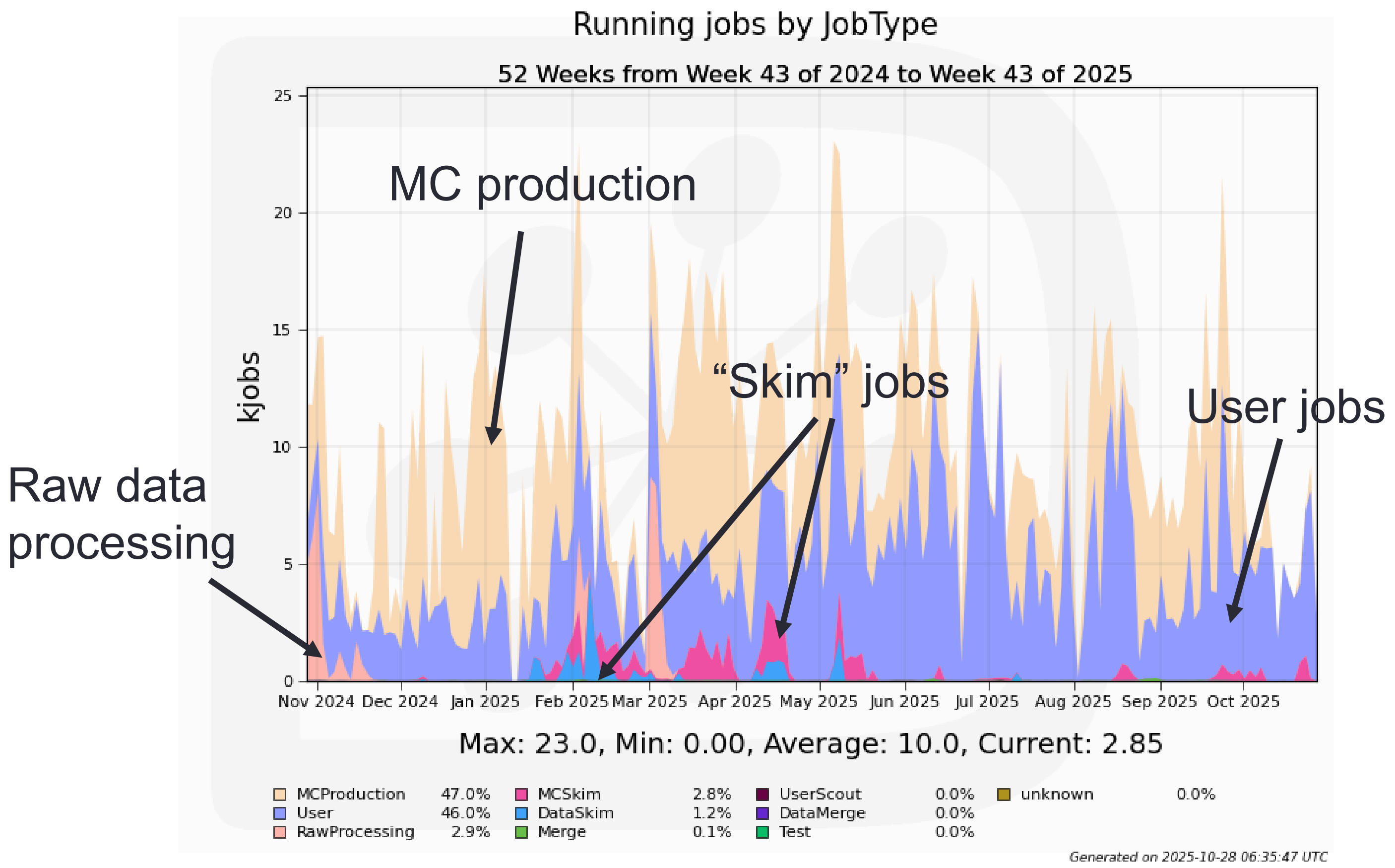
KEKCC
- VOMS
- IAM
- FTS
- AMGA
- CVMFS

Monitoring
- Grafana+VictoriaMetrics at KEK
- Grafana+InfluxDB+Elasticsearch at BNL

Belle II grid job status

- Intermittent peaks are seen but generally consistent
- Comparable CPU usage by MCProduction and User analysis

Operation with DIRAC is successful, but…



MC production

“Skim” jobs

User jobs

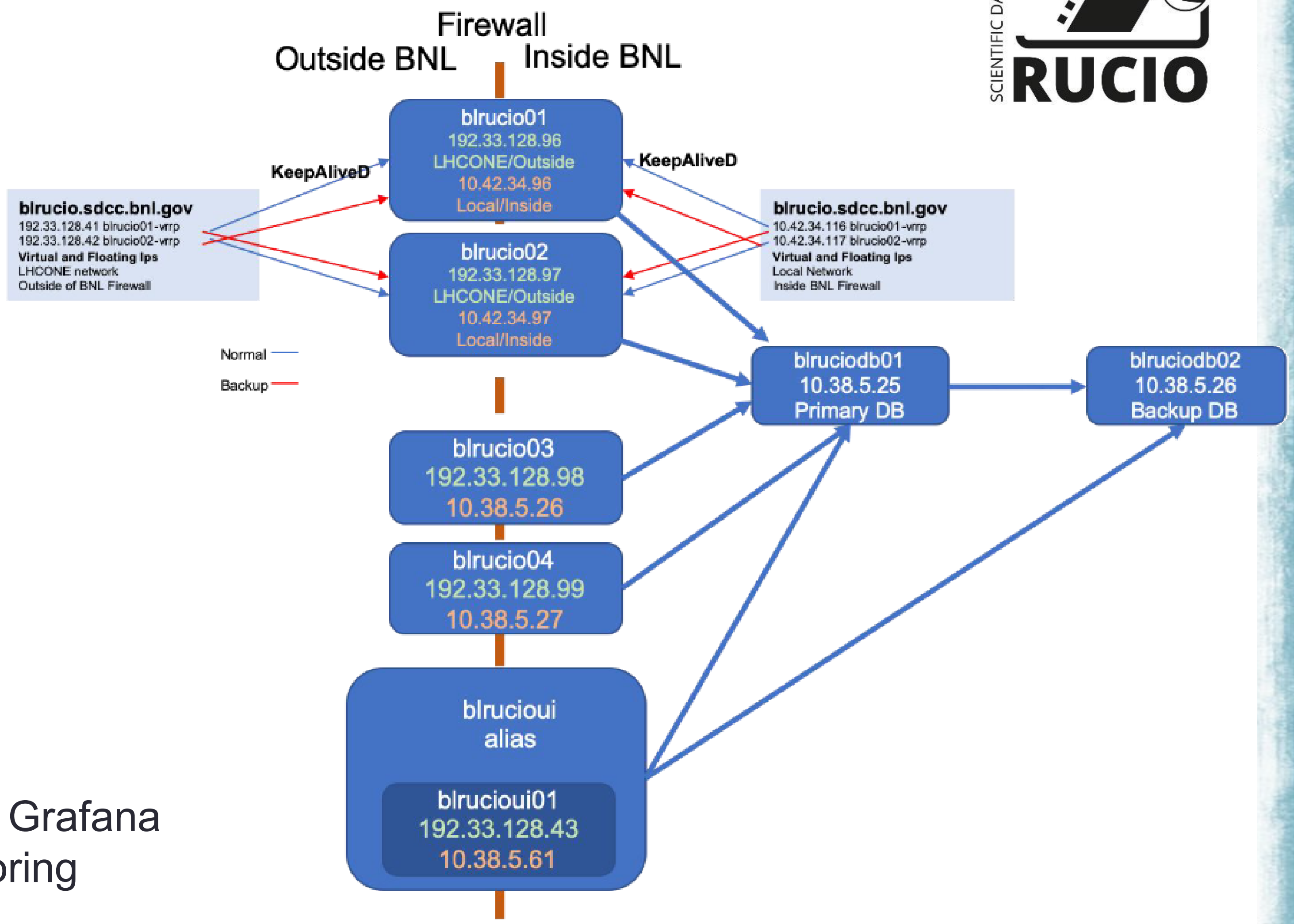
Raw data processing

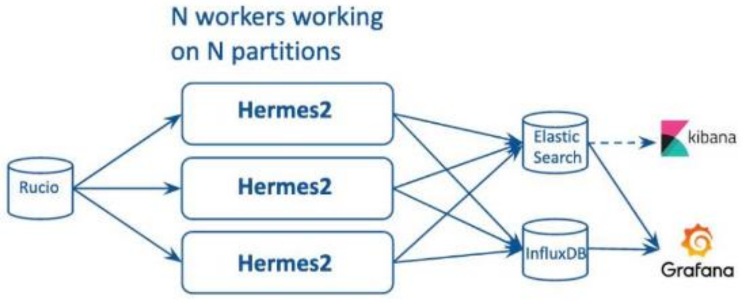
Belle II Rucio

- Belle II Rucio is hosted by BNL

- Initially on RHEV, then moved to OpenShift in this year
  - 4 servers, 2 DB and 1 UI

- In BNL OpenShift, conditions DB (e.g. calibration constant) is also deployed



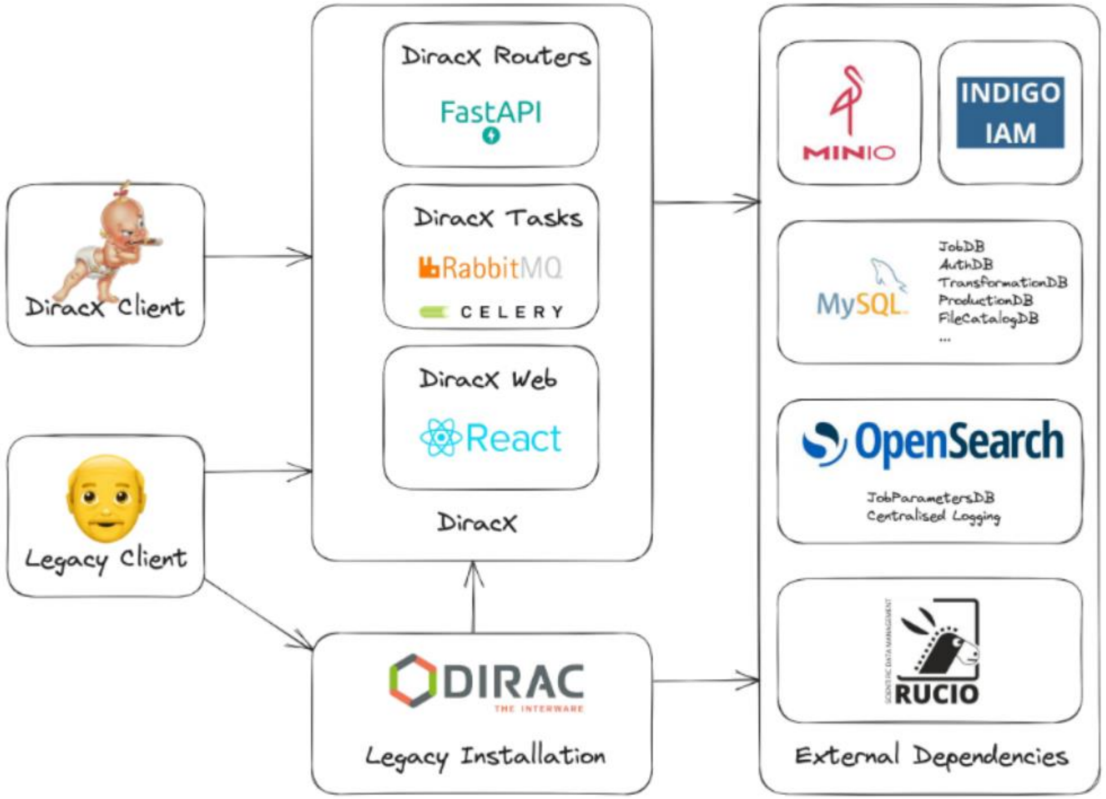


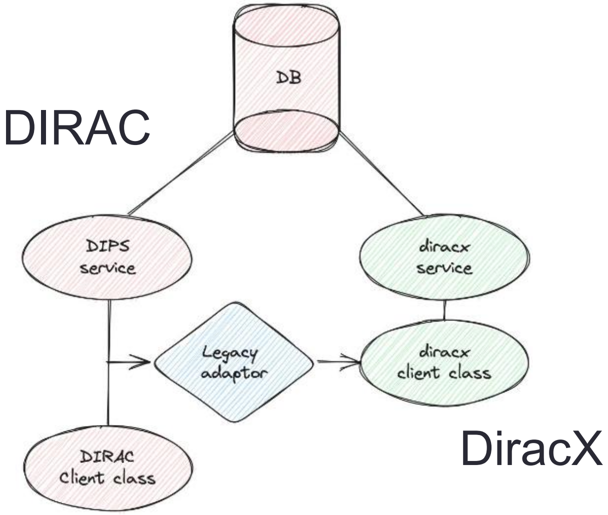
Belle II monitoring stack

Providing Grafana for monitoring

DiracX: The neXt DIRAC incarnation

- Current DIRAC has been developed more than 20 years
  - Many outdated technologies and house made tools/protocols
- DiracX
  - Completely different design
  - Standards based
  - A cloud native app
  - Providing transparent migration for users



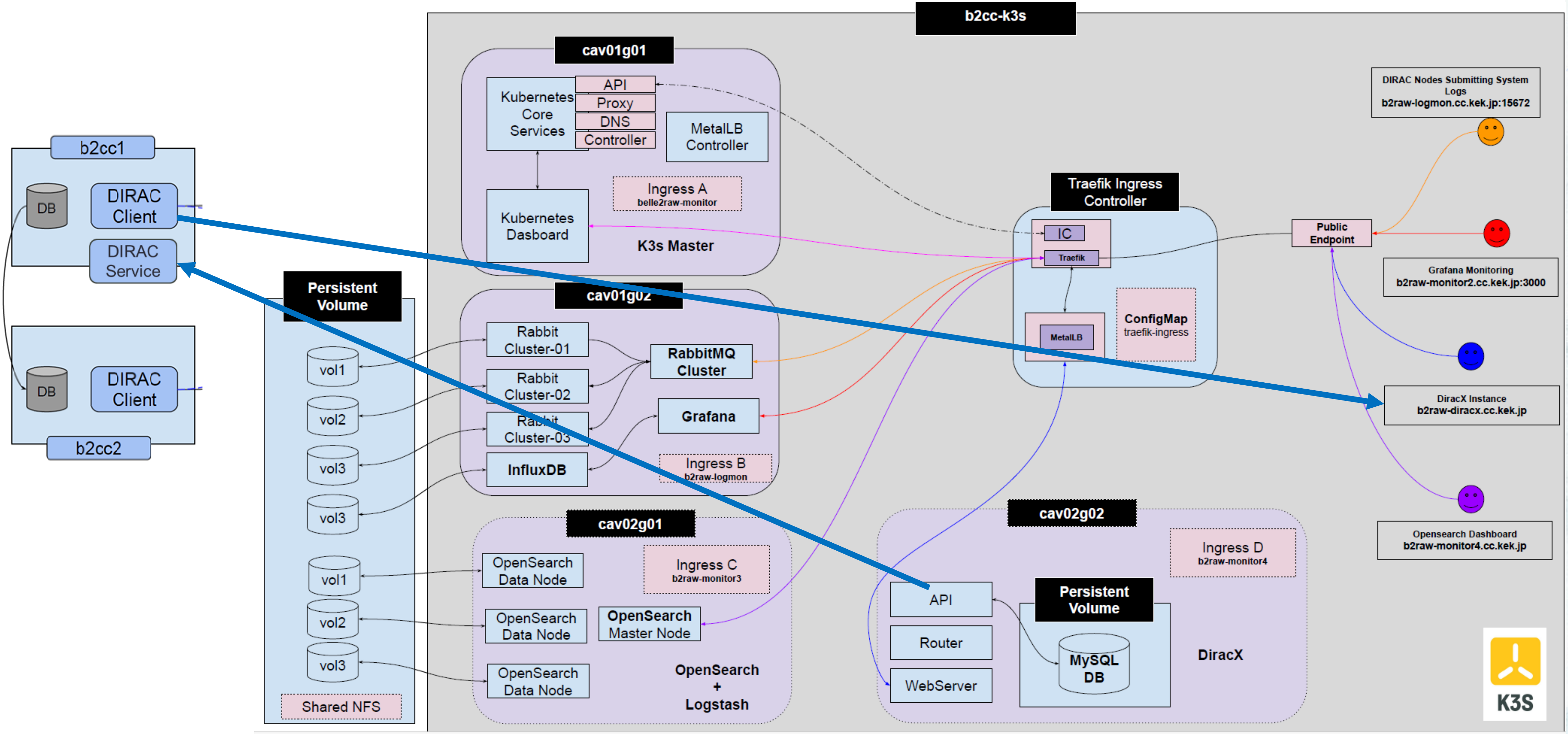


Current status

- LHCb already deployed DiracX in production (v0.1.0) with DIRAC v9 in this year
- Belle II core computing (BelleRawDIRAC) also deployed DIRAC v9 (bare metal) with DiracX on test K3s
- Belle II distributed computing (BelleDIRAC) is still running DIRAC v8 and no DiracX
- We plan to deploy “production K3s”

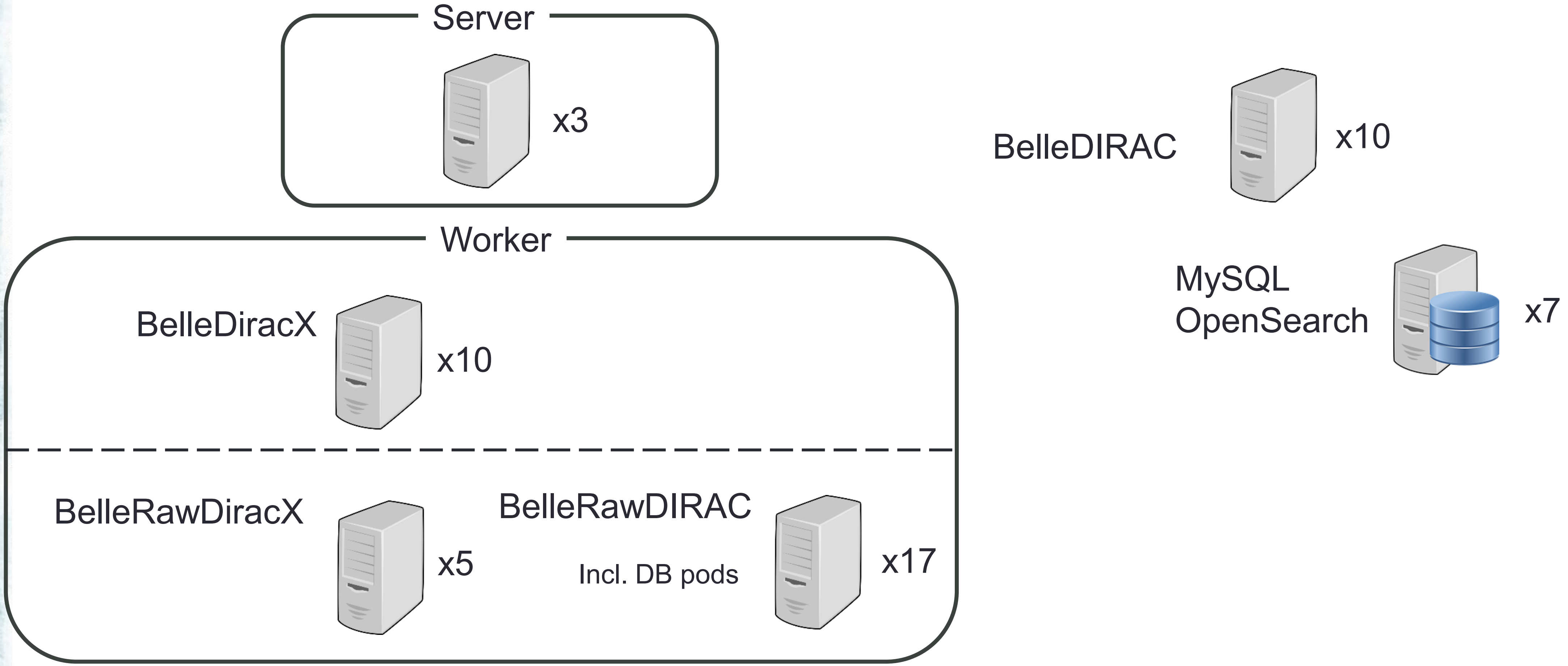
DiracX on test K3s

BelleRawDIRAC and BelleRawDiracX can access each other



Production K3s: plan

- We share K3s infrastructure between BelleDIRAC and BelleRawDIRAC



Server

x3

Worker

BelleDiracX x10

BelleRawDiracX x5

BelleRawDIRAC

Incl. DB pods

x17

BelleDIRAC x10

MySQL
OpenSearch

x7

BelleDiracX and BelleRawDiracX are deployed in different namespace

Some issues for production K3s

- Since we don’t have much experience for Kubernetes, we have spent time to decide some technology choices
- Although we are finalizing our production K3s design, still we are not confident if our design is correct
- We would appreciate it if you could give us any advices

- Our issues
  - Load balancer

  - Stateless operation (→persistent storage)

K3s: load balancer

- Choice of load balancer depends on each environment
  - In our case, load balancer is a part of experiment-specific infrastructure
- We initially prefer MetalLB (or Kube-VIP) L2 mode
  - Require no additional hardware and special network configuration

- MetalLB (no HA on control plane)
  - Configuration is rather simple
- Kube-VIP (allow HA on control plane)
  - Configuration is complicated
  - Newer project: potential bug, less documentation…
- Mixed (Kube-VIP for Server and MetalLB for Worker)
  - Should be careful with misconfiguration

Concern in L2 mode: Is our Worker tolerable with massive data access?

Now under evaluation

Once we discussed BGP mode solution…
Is this difficult option?

K3s: issues against stateless operation

- Some different approaches by BelleDiracX and BelleRawDiracX

- BelleDiracX
  - Run DB outside of K3s cluster
  - Need to access external storage (“sandbox”) (see next slide)

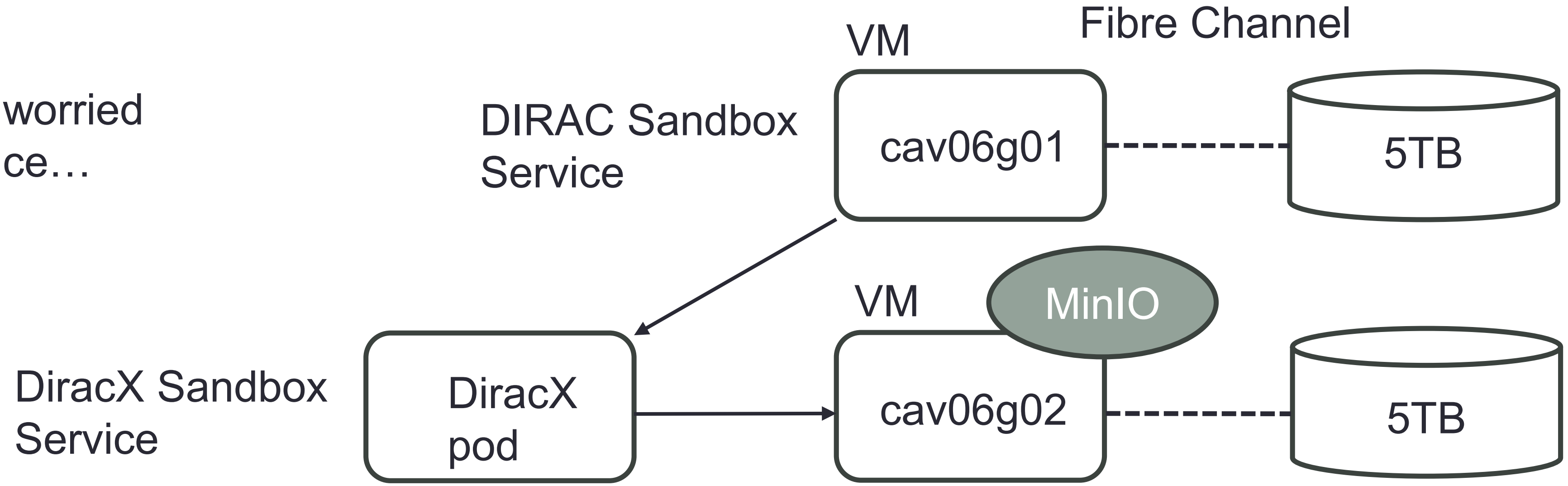
- BelleRawDiracX
  - Run DB inside K3s with persistent volume (volume is shared among Worker by NFS)
  - Need to access GPFS

Is LongHorn good option? (for non-expert operation)

K3s: sandbox

- Yet another persistent volume for BelleDIRAC
- Store input and output files of payload job and pilot
- Allocated volume size: 5TB
- Plan to operate MinIO (on VM, not in K3s)

Recently I’m getting worried
if MinIO is good choice…



Plan, perspective

- Deploy production K3s in coming months

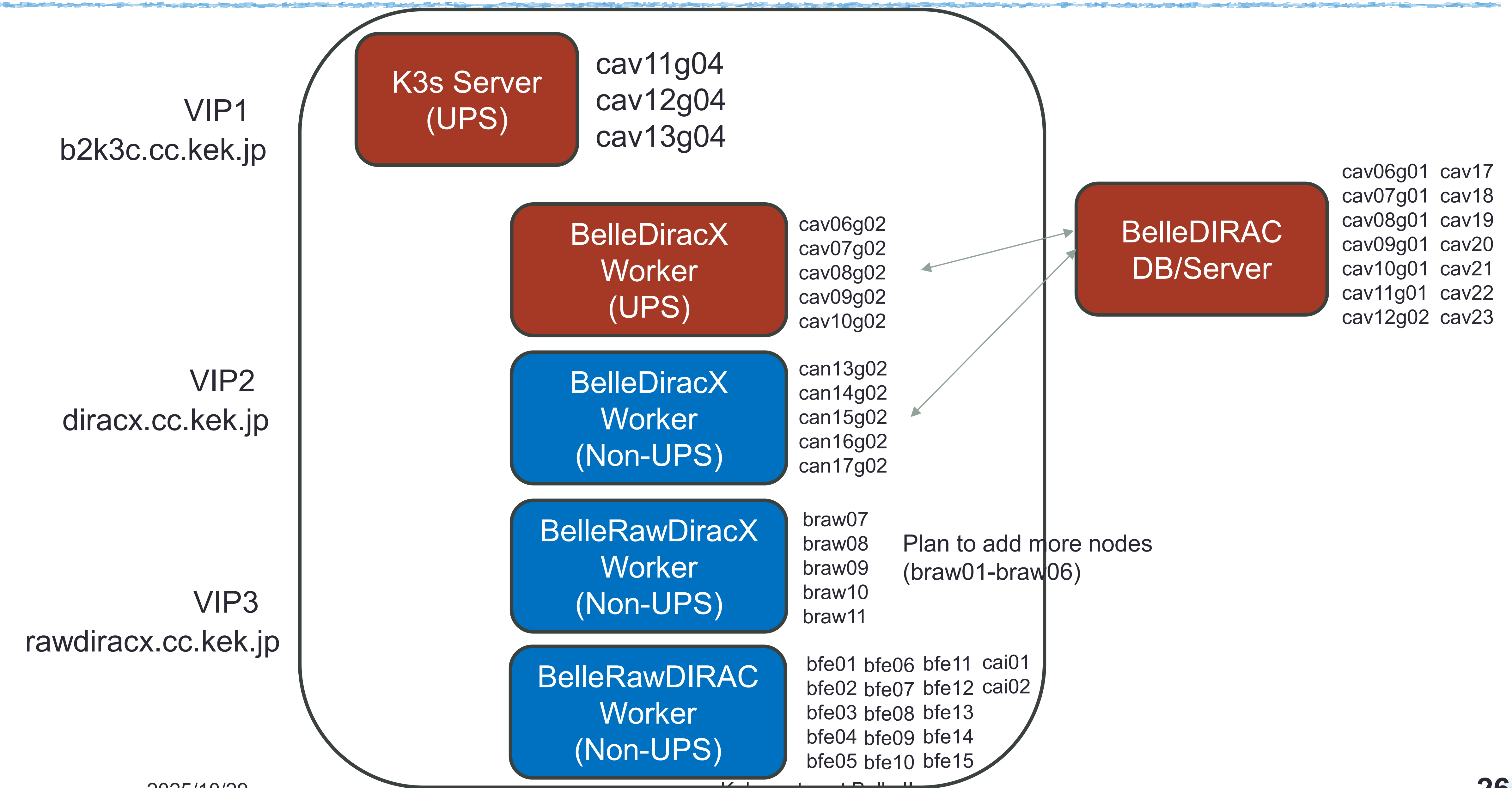
- BelleRawDIRAC (core computing)
  - Move DIRAC v9 and BelleRawDiracX to production K3s

- BelleDIRAC (distributed computing)
  - Deploy BelleDiracX (isolated) in production K3s
  - Deploy DIRAC v9 for BelleDIRAC (outside of K3s) and BelleDiracX on production K3s

- DIRAC functionalities are being replaced by DiracX
  - Ultimately, everything in DIRAC will be transferred to DiracX on Kubernetes

backup

Planned VMs to use



VIP1
b2k3c.cc.kek.jp

K3s Server
(UPS)

cav11g04
cav12g04
cav13g04

BelleDiracX
Worker
(UPS)

cav06g02
cav07g02
cav08g02
cav09g02
cav10g02

BelleDIRAC
DB/Server

cav06g01	cav17
cav07g01	cav18
cav08g01	cav19
cav09g01	cav20
cav10g01	cav21
cav11g01	cav22
cav12g02	cav23

VIP2
diracx.cc.kek.jp

BelleDiracX
Worker
(Non-UPS)

can13g02
can14g02
can15g02
can16g02
can17g02

VIP3
rawdiracx.cc.kek.jp

BelleRawDiracX
Worker
(Non-UPS)

braw07
braw08
braw09
braw10
braw11

Plan to add more nodes
(braw01-braw06)

BelleRawDIRAC
Worker
(Non-UPS)

bfe01	bfe06	bfe11	cai01
bfe02	bfe07	bfe12	cai02
bfe03	bfe08	bfe13	
bfe04	bfe09	bfe14	
bfe05	bfe10	bfe15	