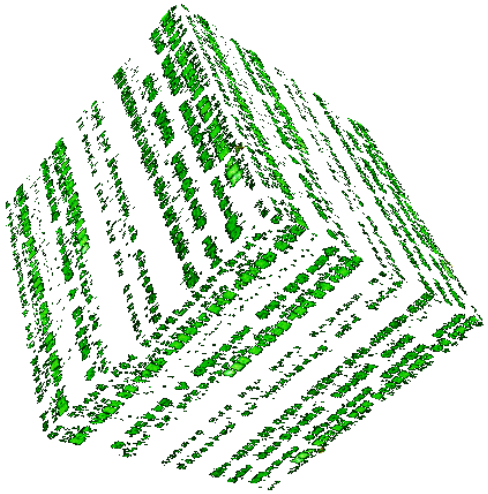


Array Databases

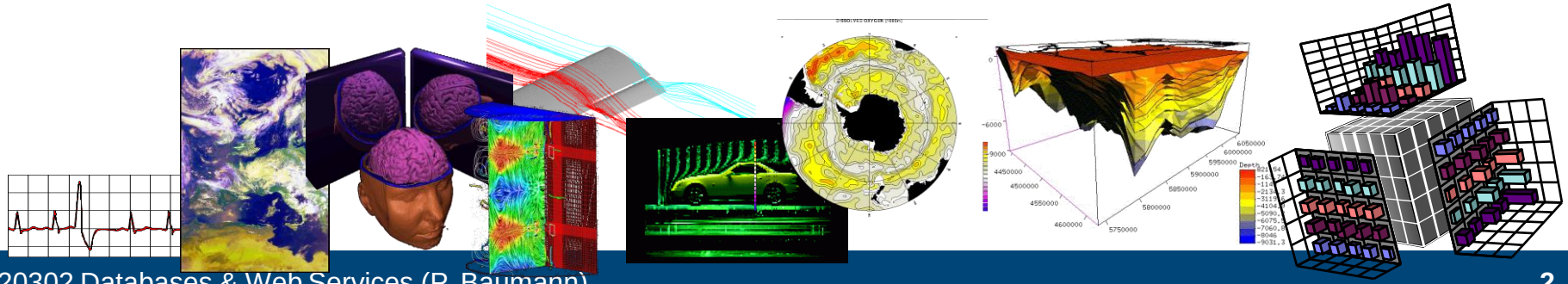
http://www.faculty.jacobs-university.de/pbaumann → publications

http://en.wikipedia.org/wiki/Array_DBMS

[animation: gamingfeeds.com]

Who Needs Arrays?

- Sensor, image, simulation, statistics data
  - **Earth:** Geodesy, geology, hydrology, oceanography, climate, earth system, ...
  - **Space:** optical / radio astronomy, cosmological simulation, planetary science, ...
  - **Life:** Pharma/chem, healthcare / bio research, bio statistics, genetics, ...
  - **Engineering & research:** Simulation & experimental data in automotive/shipbuilding/ aerospace industry, turbines, process industry, ...
  - **Management/Controlling:** Decision Support, OLAP, Data Warehousing, census, statistics in industry and public administration, ...
  - **Multimedia:** distance learning, prepress, ...
- „80% of all data have some spatial connotation“ [C&P Hane, 1992]



Arrays in [Geo] Science & Engineering

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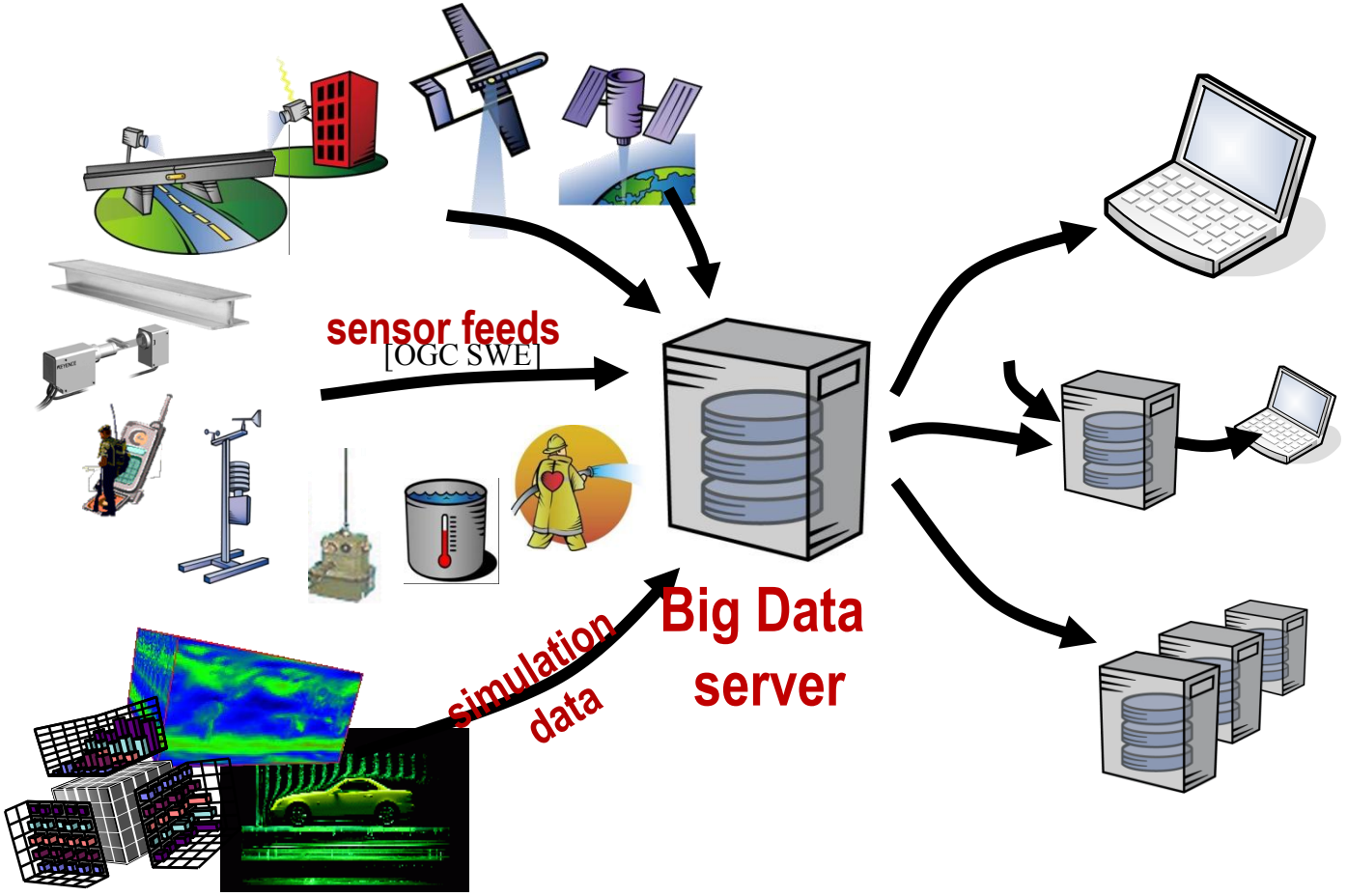
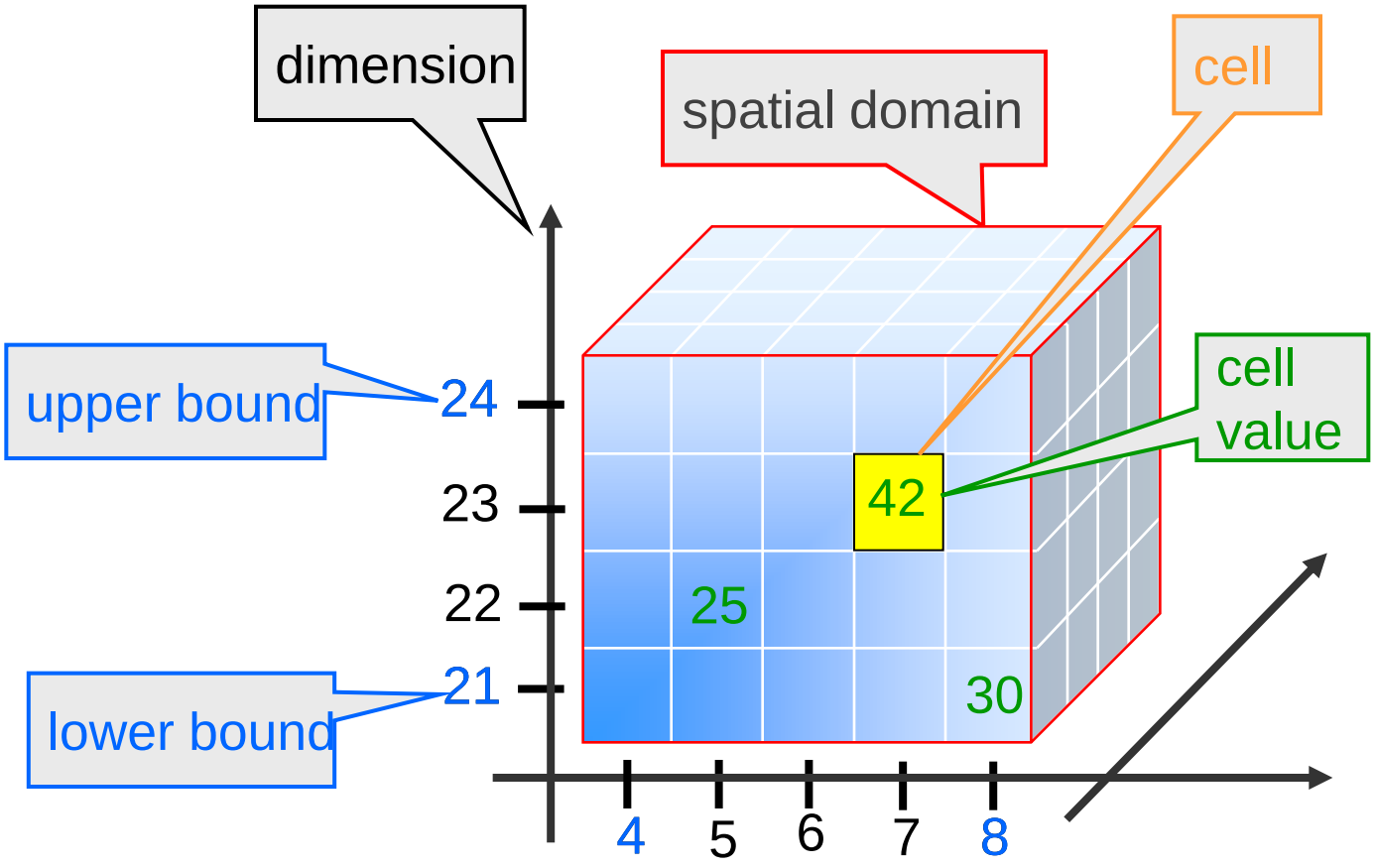
- spatio-temporal sensor, image, simulation, statistics data(cubes)



CONCEPTUAL MODELLING

The Array Data Model



Array Analytics

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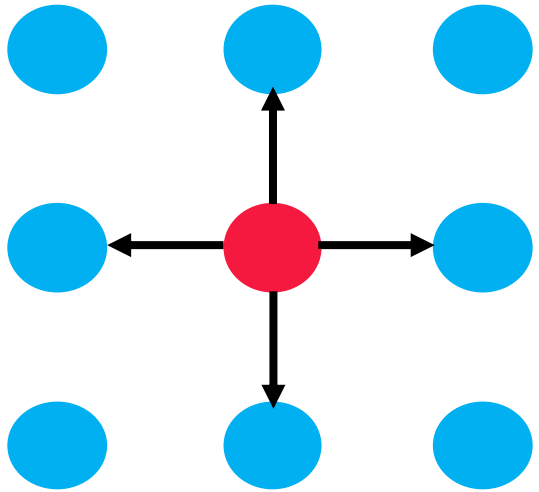
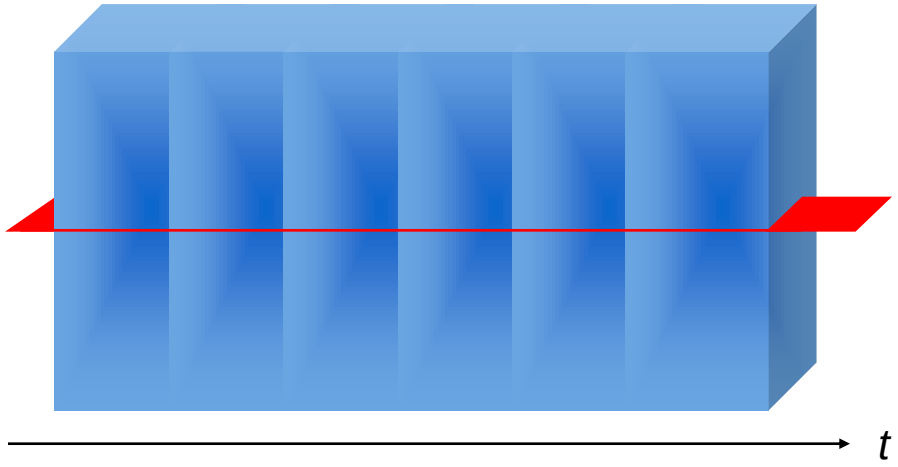
- Array Analytics :=
  Efficient analysis on multi-dimensional arrays of a size several orders of magnitude above evaluation engine's main memory
- Essential data property: n-dimensional Euclidean neighborhood
  - Secondary: #dimensions, density, ...
- Operations: signal/image processing, Linear Algebra [M. Stonebraker], iterations



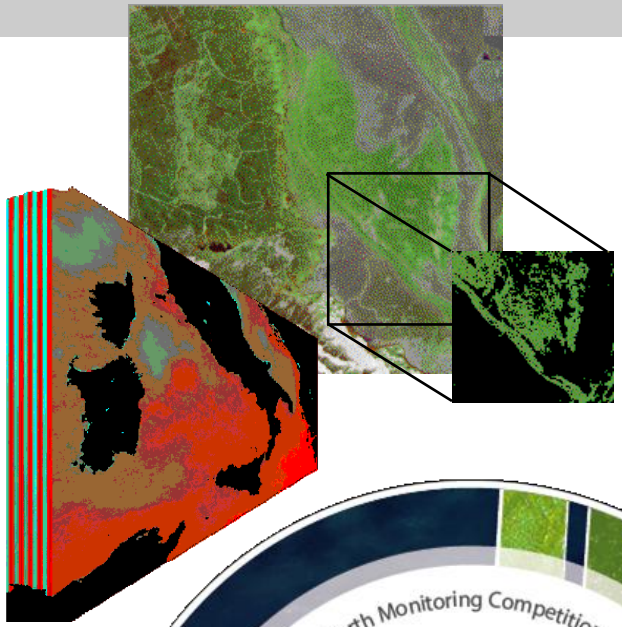
Let's Take a Closer Look...



- Divergent access patterns for ingest and retrieval
- Server must mediate between access patterns

rasdaman

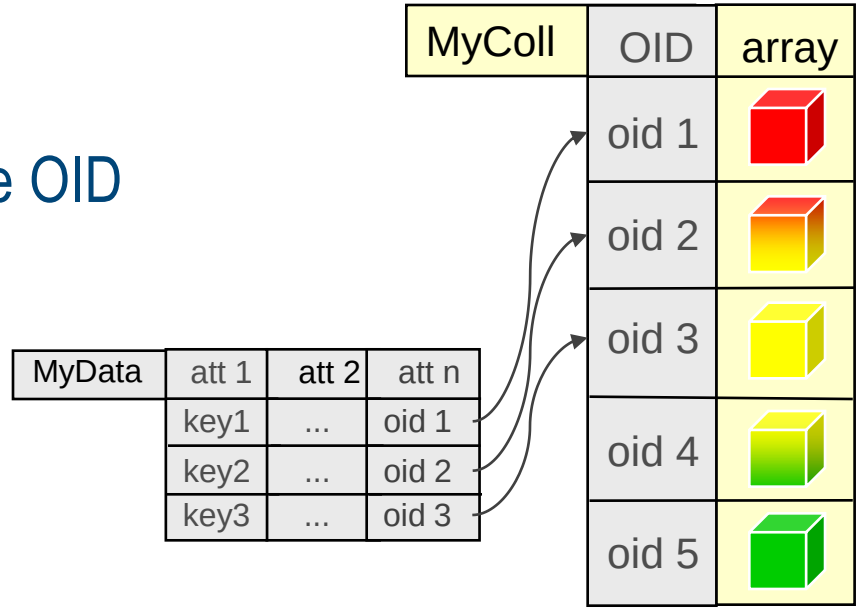
- „raster data manager“: SQL + n-D arrays
  - Scalable parallel “tile streaming” architecture
  - [VLDB 1994, VLDB 1997, SIGMOD 1998, VLDB 2003, …, VLDB 2016]
- Blueprint for stds, in operational use
  - 250 TB →PB



CIO Review 100 MOST PROMISING BIG DATA SOLUTION PROVIDERS 2016

Array Embedding

- Goal: integration of arrays with relational model
  - tables of typed n-D arrays
- Original rasql: Array + system attribute OID
  - „collections“ = binary relations (oid,array)
  - In hindsight, bad tuple access design: array like tuple variable, oid via function
- In future: ISO SQL/MDA (Multi-Dimensional Arrays)
  - Arrays as another „attribute type“
  - Under finalization in ISO




```
select img[ 100:199, 100:199 ]
from   MyColl as m
where  oid(m) = 42
```

The rasql Query Language

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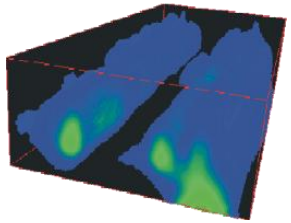
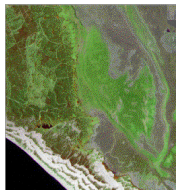
- selection & subsetting

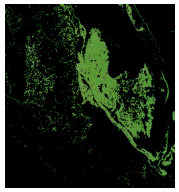
```
select c[ *:*, 100:200, *:*, 42 ]
from   ClimateSimulations as c
```



- result processing

```
select img * (img.green > 130)
from   LandsatArchive as img
```



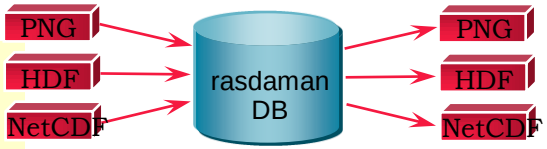


- search & aggregation

```
select mri
from   MRI as img, masks as am
where  some_cells( mri > 250 and m )
```

- data format conversion

```
select encode( c[*:*,*:*,100,42], „png“ )
from   ClimateSimulations as c
```



Visual Database Interaction

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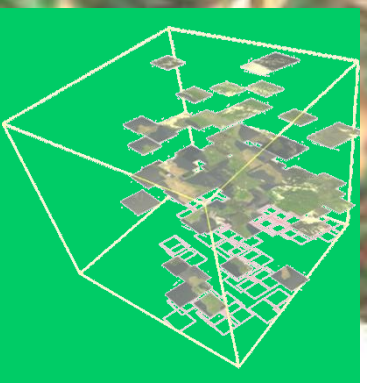
```
select
  encode(
    struct {
      red:    (char) s.image.b7[x0:x1,x0:x1],
      green:  (char) s.image.b5[x0:x1,x0:x1],
      blue:   (char) s.image.b0[x0:x1,x0:x1],
      alpha:  (char) scale( d.elev, 20 )
    },
    "image/png"
  )
from SatImage as s, DEM as d
```



[JacobsU, Fraunhofer; data courtesy BGS, ESA]

Linear Algebra Ops

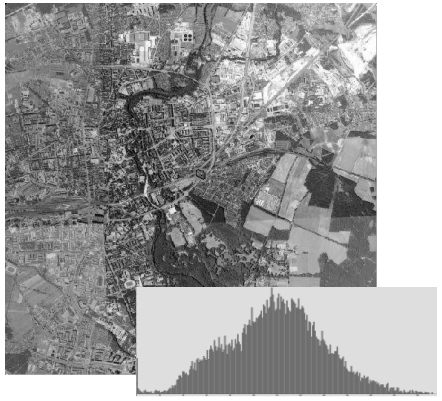
- Matrix multiplication

$$(\mathbf{AB})_{ij} = \sum_{k=1}^{m} A_{ik} B_{kj}$$

```
select marray i in [0:m], j in [0:p]
       values condense +
              over     k in [0:n]
              using    a [ i, k ] * b [ k, j ]
from   matrix as a, matrix as b
```

- Histogram

```
select marray bucket in [0:255]
       values count_cells( img = bucket )
from   img
```



Adding Arrays to ISO SQL

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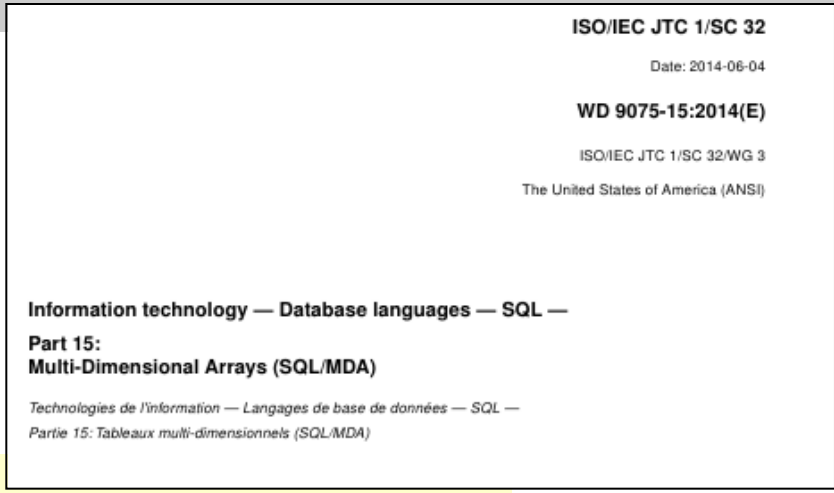
- ISO 9075 Part 15: SQL/MDA
  - resolved by ISO SQL WG in June 2014
  - Based on rasdaman concepts & experience



ISO/IEC JTC 1/SC 32

Date: 2014-06-04

WD 9075-15:2014(E)

ISO/IEC JTC 1/SC 32/WG 3

The United States of America (ANSI)

Information technology — Database languages — SQL —

Part 15:
Multi-Dimensional Arrays (SQL/MDA)

Technologies de l'information — Langages de base de données — SQL —
Partie 15: Tableaux multi-dimensionnels (SQL/MDA)

- n-D arrays as attributes

```
create table LandsatScenes(
    id: integer not null, acquired: date,
    scene: row( band1: integer, ..., band7: integer ) array [ 0:4999,0:4999] )
```

- declarative array operations

```
select  id, encode(scene.band1-scene.band2)/(scene.nband1+scene.band2)), „image/tiff“ )
from    LandsatScenes
where acquired between „1990-06-01“ and „1990-06-30“ and
        avg( scene.band3-scene.band4)/(scene.band3+scene.band4)) > 0
```

ARCHITECTURE

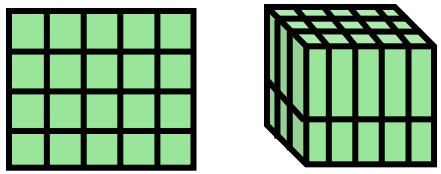
Storage Mapping: Variants

- Coordinate-free sequence
  - BLOB (binary large object)
  - *Costs mainly position/dimension dependent*

- Sequence independent, coordinates explicit

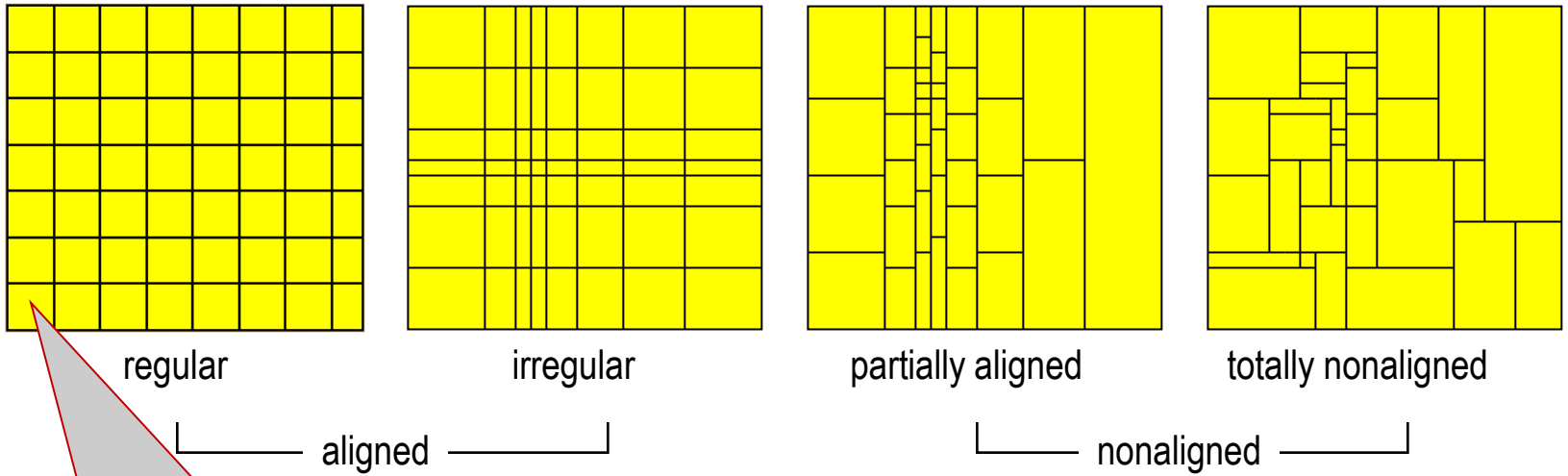
$$\{ (x_1,f_1), (x_2,f_2), ..., (x_n,f_n) \}$$

  - ROLAP
  - *Costs not position correlated, but high*
- Imaging, multidimensional OLAP
  - Partitioning, sequence within partition
  - *Costs low for bulk access, usually not location correlated*



Datacube Partitioning

- Goal: faster tile loading by adapting storage units to access patterns
- Approach: partition n-D array into n-D partitions („tiles“)
- Tiling classification based on degree of alignment [ICDE 1999]

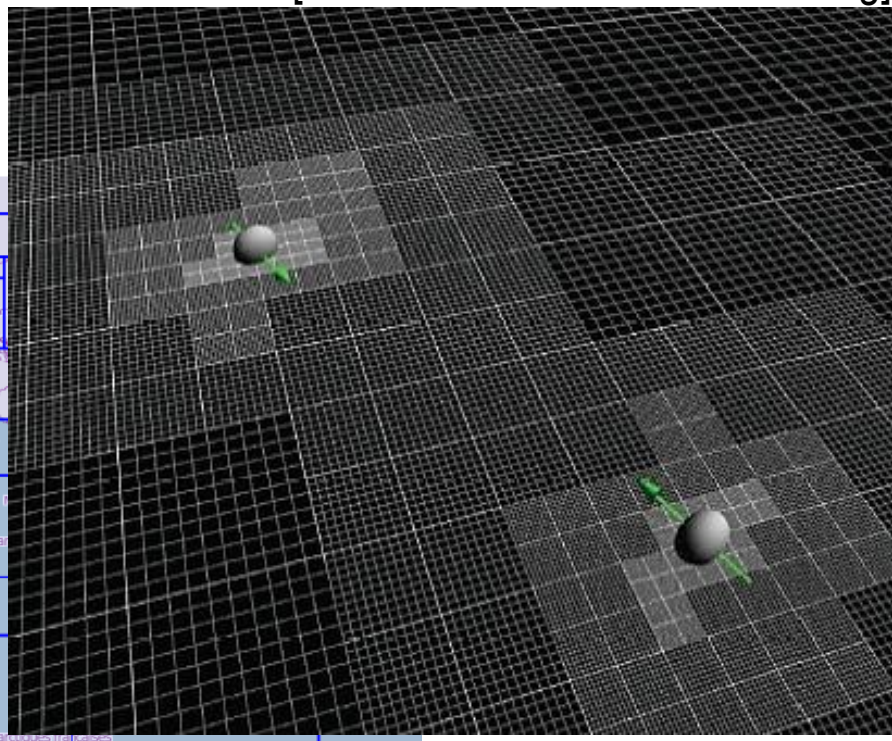


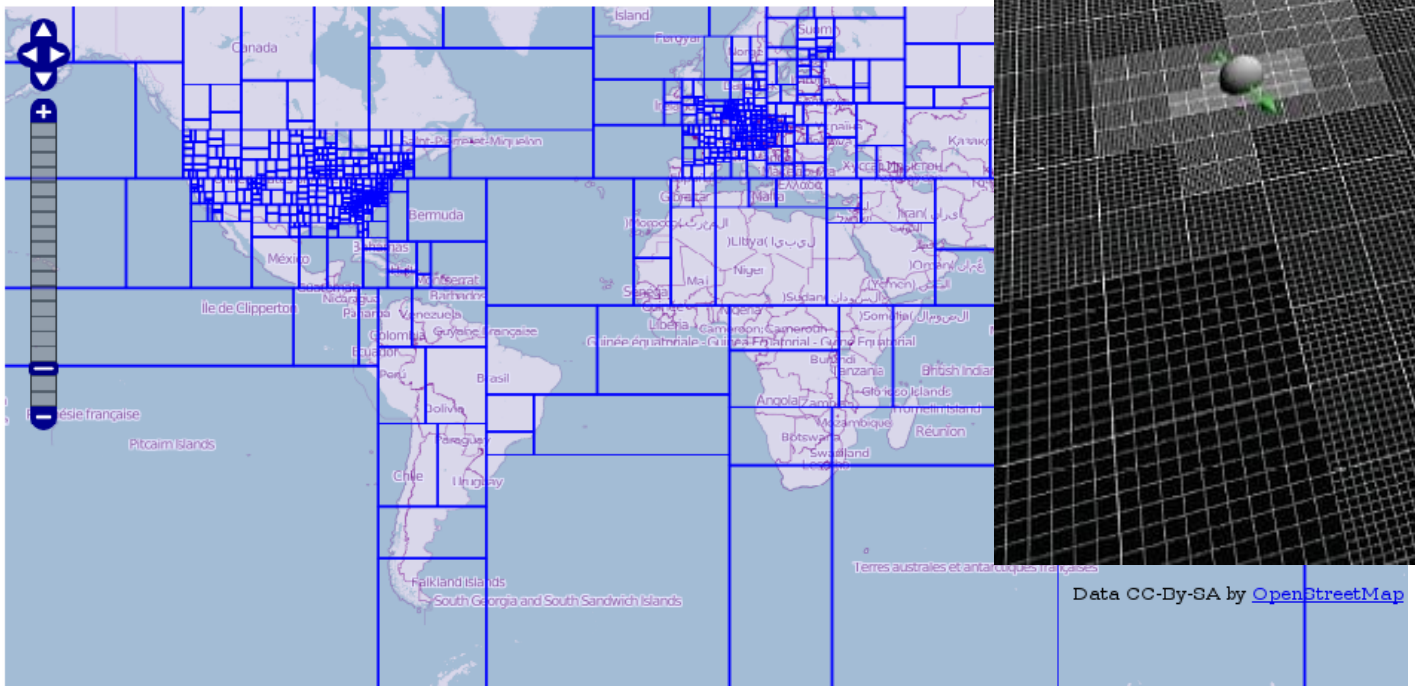
chunking [Sarawagi, Stonebraker, DeWitt, ...]

Why Irregular Tiling?

- e-Science often uses irregular partioning

[Centrella et al: scidacreviews.org]



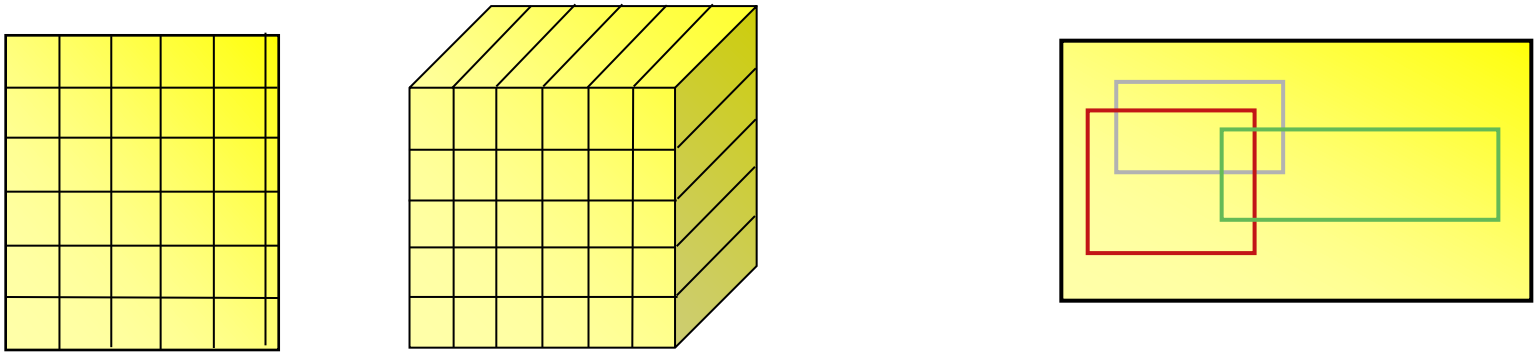


[OpenStreetMap]

Tiling as a Tuning Parameter

- tiling strategies [ICDE 1999]:

regular | directional | ... | area of interest



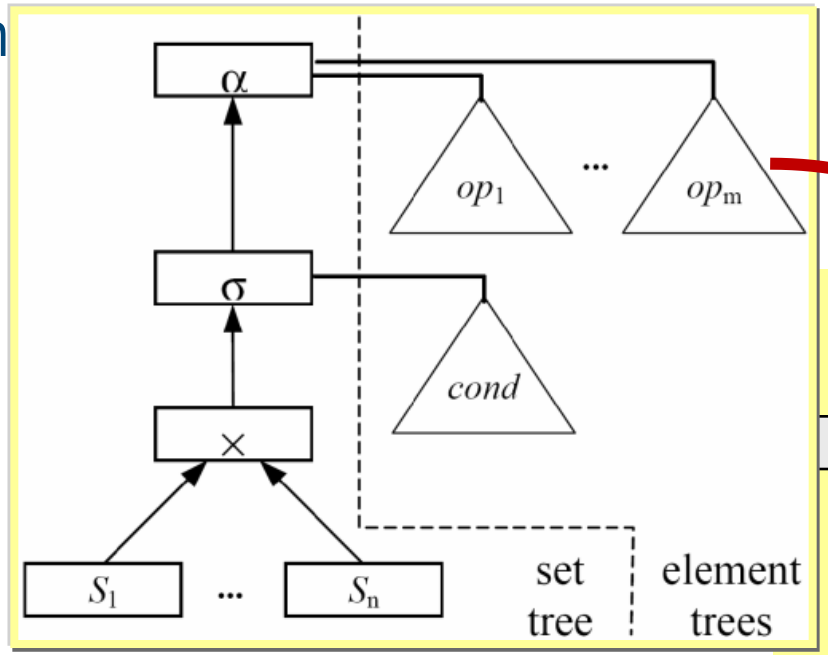
- storage layout language [SSTDM 2010]

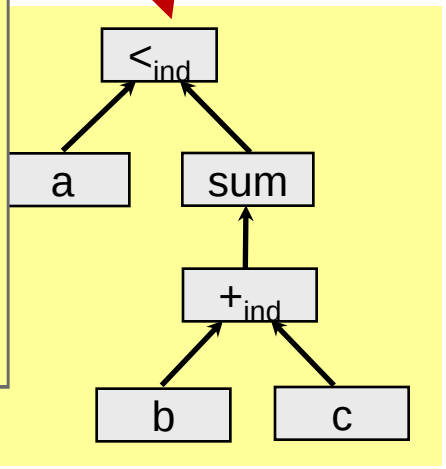
```
insert into MyCollection
  values ...
  tiling
    area of interest [0:20,0:40], [45:80,80:85]
    tile size 1000000
    index d_index storage array compression zlib
```

Query Processing

- Clear separation:
  set vs array trees
  - Arrays as 2nd order attributes
- Extensive optimization
- Tile-based evaluation

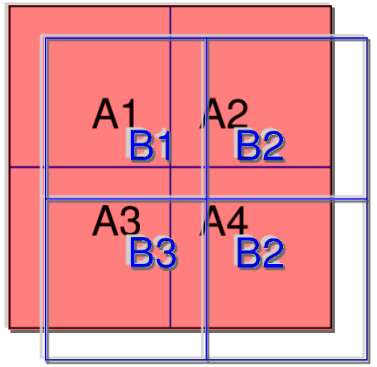
```
select a < sum_cells( b + c )
from   a, b, c
```

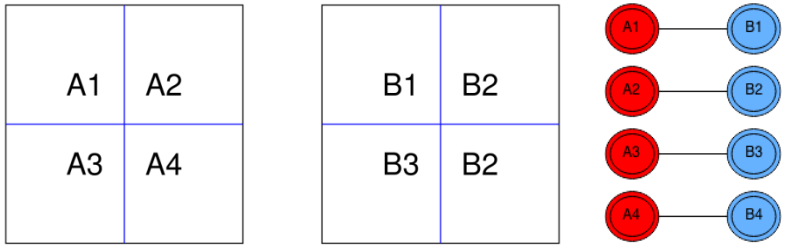


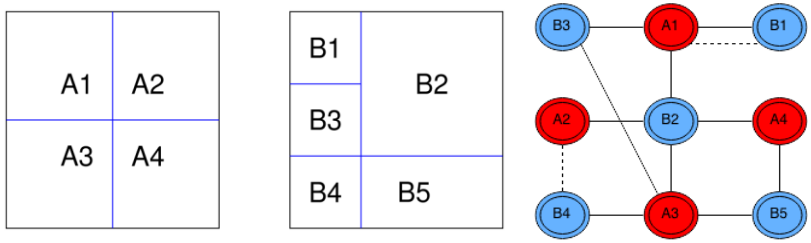


Array Joins

- „A θ B“ in presence of partitioned arrays A, B
  - Challenge: partitions shifted, different size, heterogeneous
  - inefficient multiple reads of sub-arrays
- Goal: optimal partition loading sequence
- Approach: bi-partite graph traversal







- Also useful for buffer mgmt, parallelization

Query Optimization

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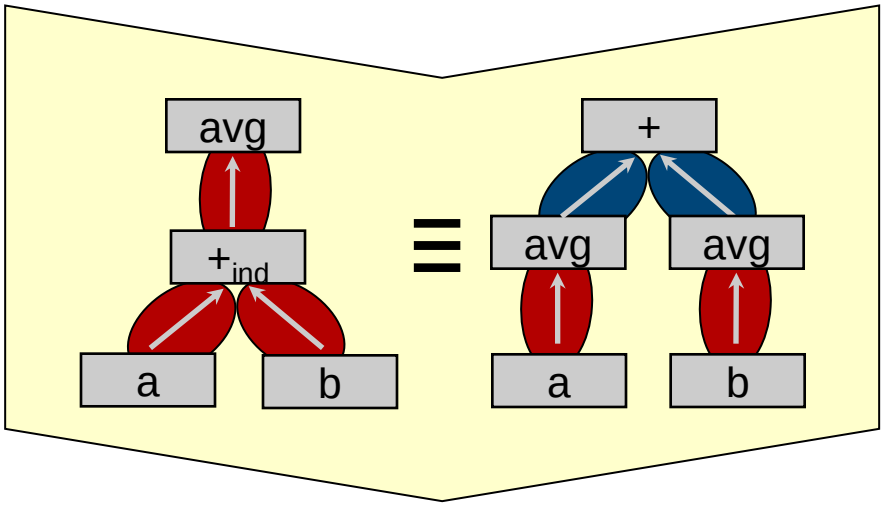
[Ritsch 2000]

```
select avg_cells( a + b )
from   a, b
```

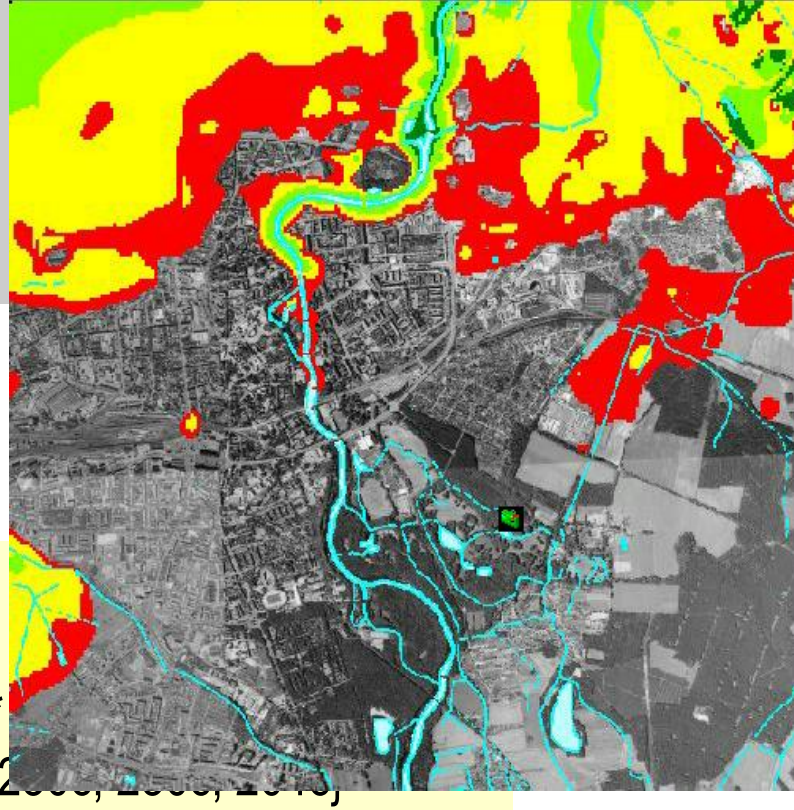


Tile stream
high traffic

Scalar stream
low traffic

```
select avg_cells( a )
     + avg_cells( b )
from   a, b
```

Optimisation Does Pay Off!



- Complex queries give more space to optimizer
- Typical OGC *Web Map Service* query:

```
select jpeg(
                scale(bild0[...],[1:300,1:300])          * {
     overlay ((scale(bild1[...],[1:300,1:300])<71.0)) *
     overlay bit(scale(bild2[...],[1:300,1:300]), 2)  * {
     overlay bit(scale(bild2[...],[1:300,1:300]), 5)  * {1c, 1c, 1c}
     overlay bit(scale(bild2[...],[1:300,1:300]), 7)  * {102c, 102c, 102c}
     overlay bit(scale(bild2[...],[1:300,1:300]), 6)  * {255c, 255c, 0c}
     overlay bit(scale(bild2[...],[1:300,1:300]), 3)  * {191c, 242c, 128c}
     overlay bit(scale(bild2[...],[1:300,1:300]), 4)  * {191c, 255c, 255c}
     overlay bit(scale(bild2[...],[1:300,1:300]), 1)  * {0c, 255c, 255c}
     overlay bit(scale(bild2[...],[1:300,1:300]), 0)  * {102c, 102c, 102c}       )
from ...
```

Parallel / Distributed Query Processing

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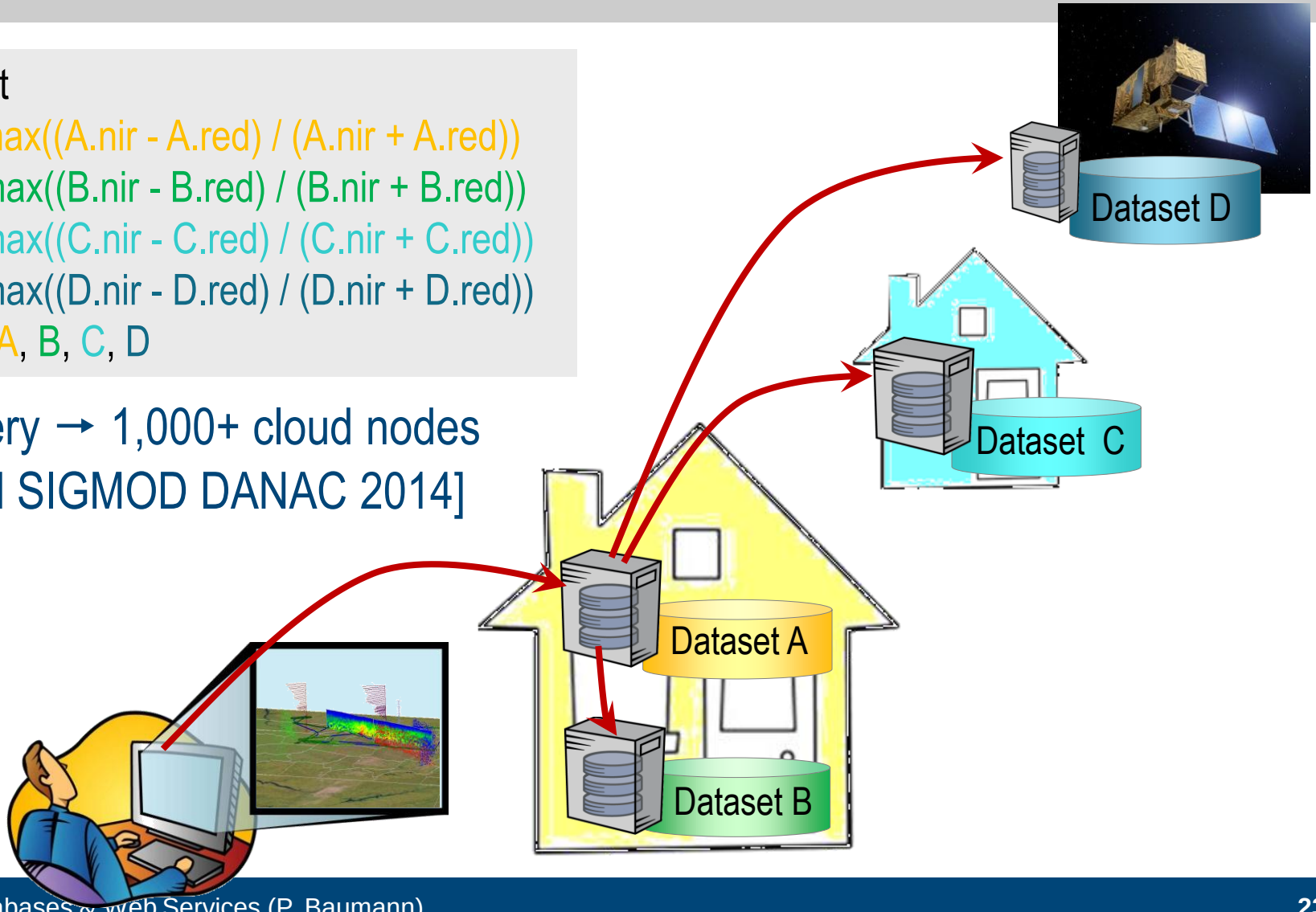
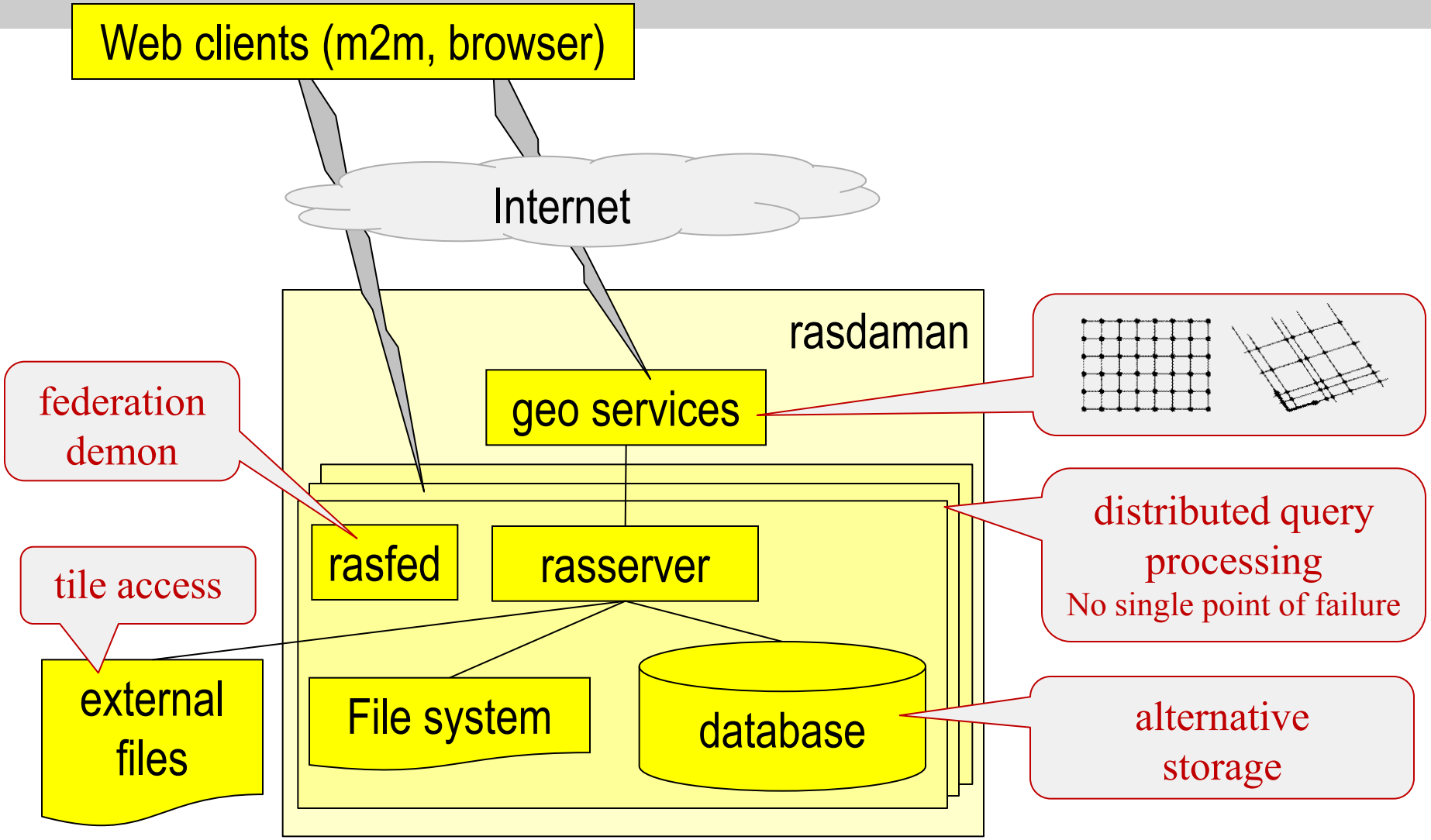
```
select
      max((A.nir - A.red) / (A.nir + A.red))
    - max((B.nir - B.red) / (B.nir + B.red))
    - max((C.nir - C.red) / (C.nir + C.red))
    - max((D.nir - D.red) / (D.nir + D.red))
from A, B, C, D
```

1 query → 1,000+ cloud nodes
[ACM SIGMOD DANAC 2014]



Architecture

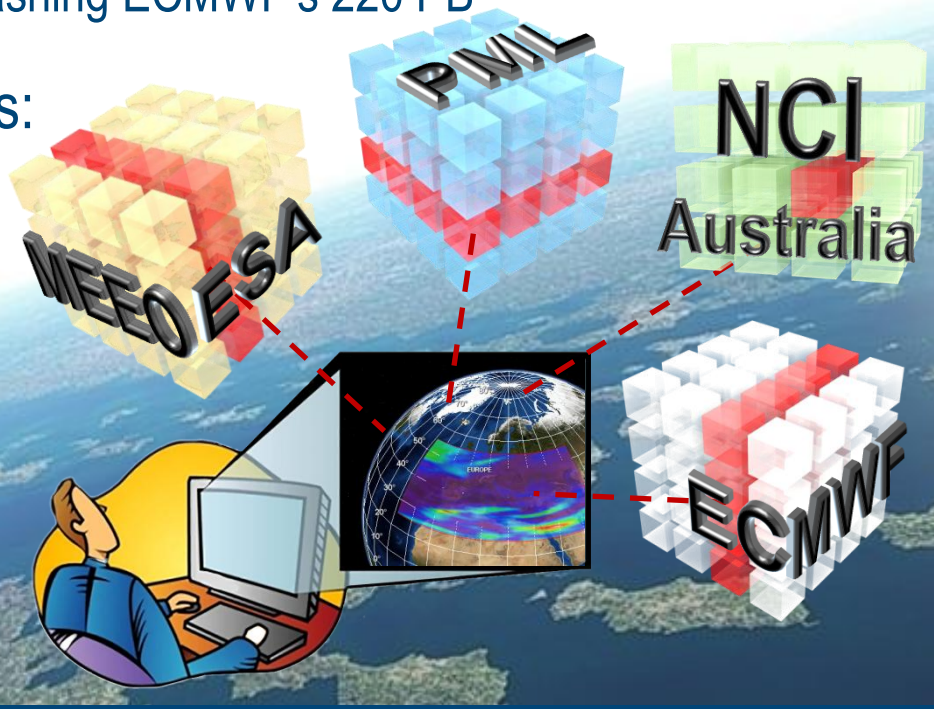


[SSTD 2013]

APPLICATIONS

- Agile Analytics on x/y/t + x/y/z/t Earth & Planetary datacubes
  - EU rasdaman + US NASA WorldWind
  - Rigorously standards as c/s APIs
  - Databases of 1+ Petabyte, now unleashing ECMWF's 220 PB
- Intercontinental initiative, 3+3 years:
  EU + US + AUS

www.earthserver.eu



Co-funded by
the European Union

OGC WCPS: Analyzing Datacubes

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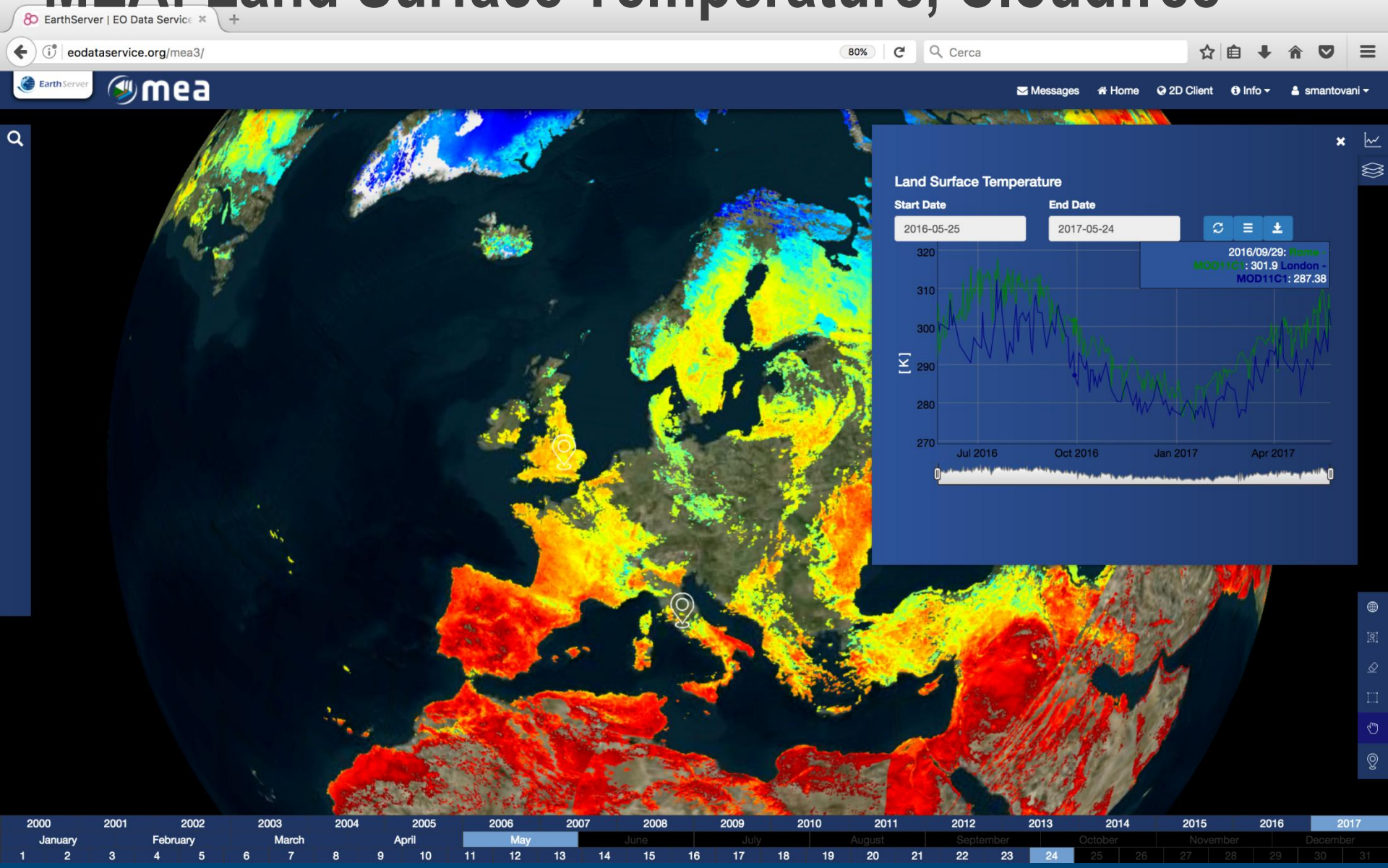
- Web Coverage Processing Service (WCPS)
  - = spatio-temporal datacube analytics language

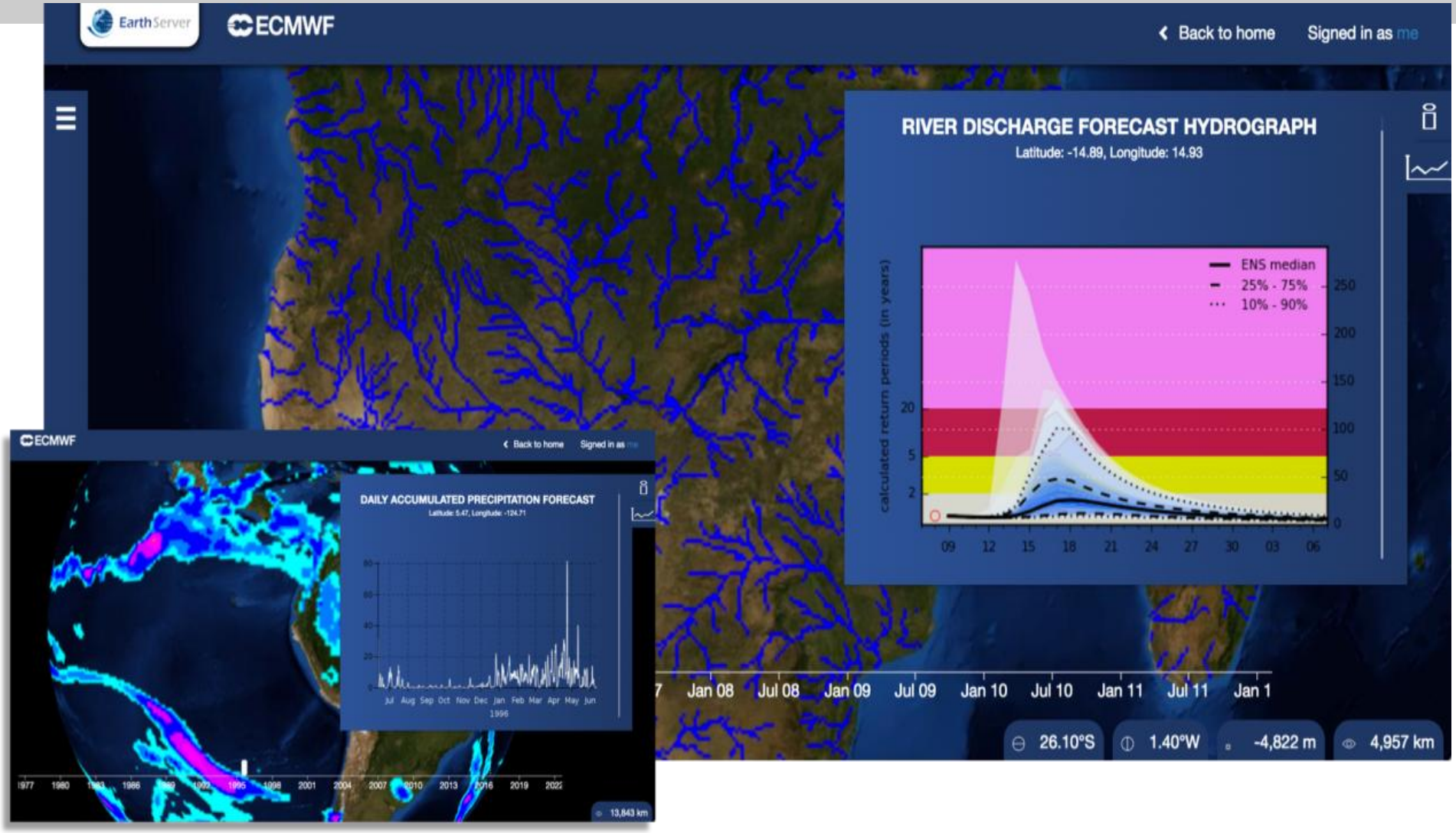
- "From MODIS scenes M1, M2, M3: difference red & nir, as TIFF"
  - "…but only those where nir exceeds 127 somewhere"

```
for $c in ( M1, M2, M3 )
where some( $c.nir > 127 )
return encode( $c.red - $c.nir, "image/tiff" )
```

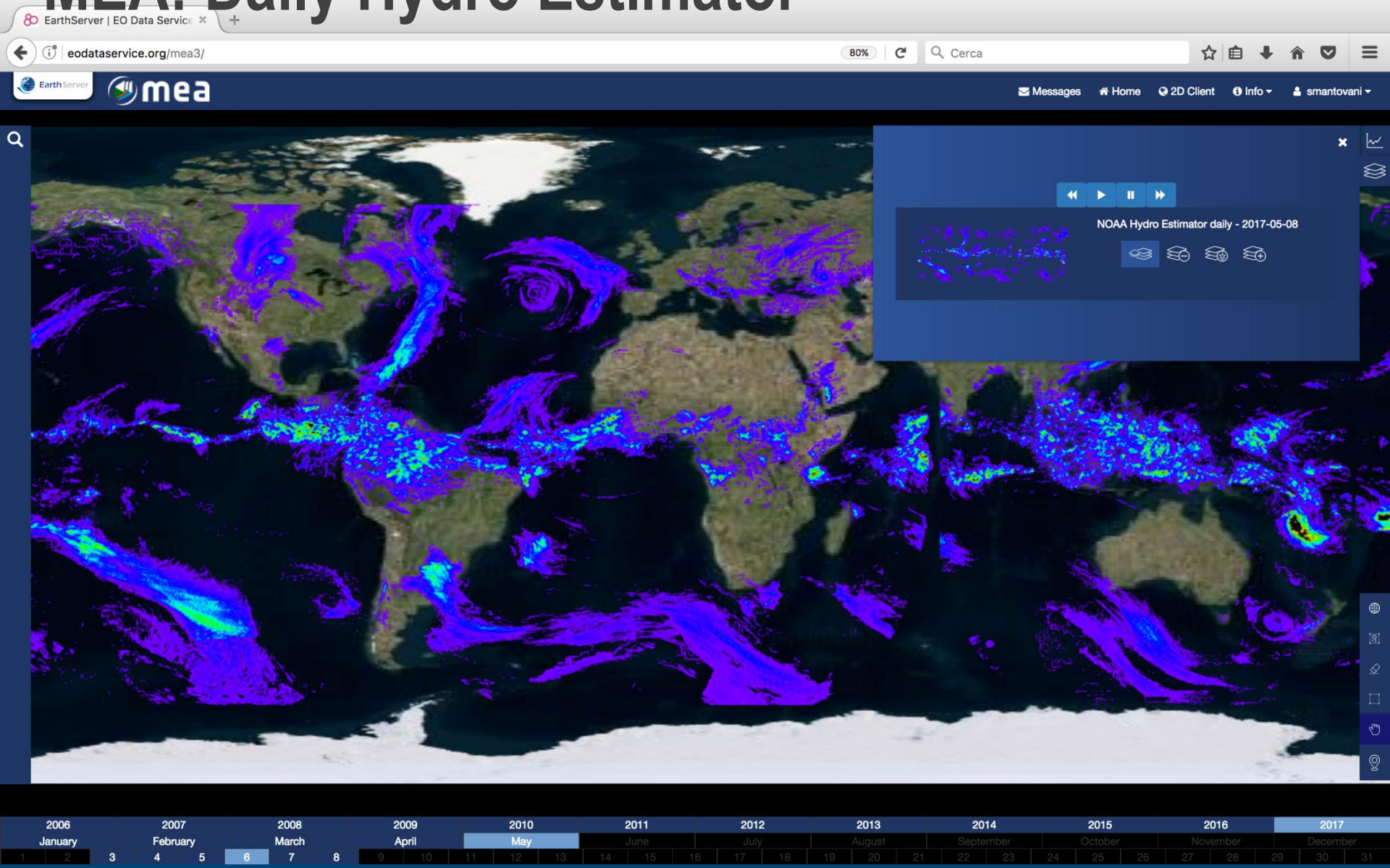
MEA: Land Surface Temperature, Cloudfree



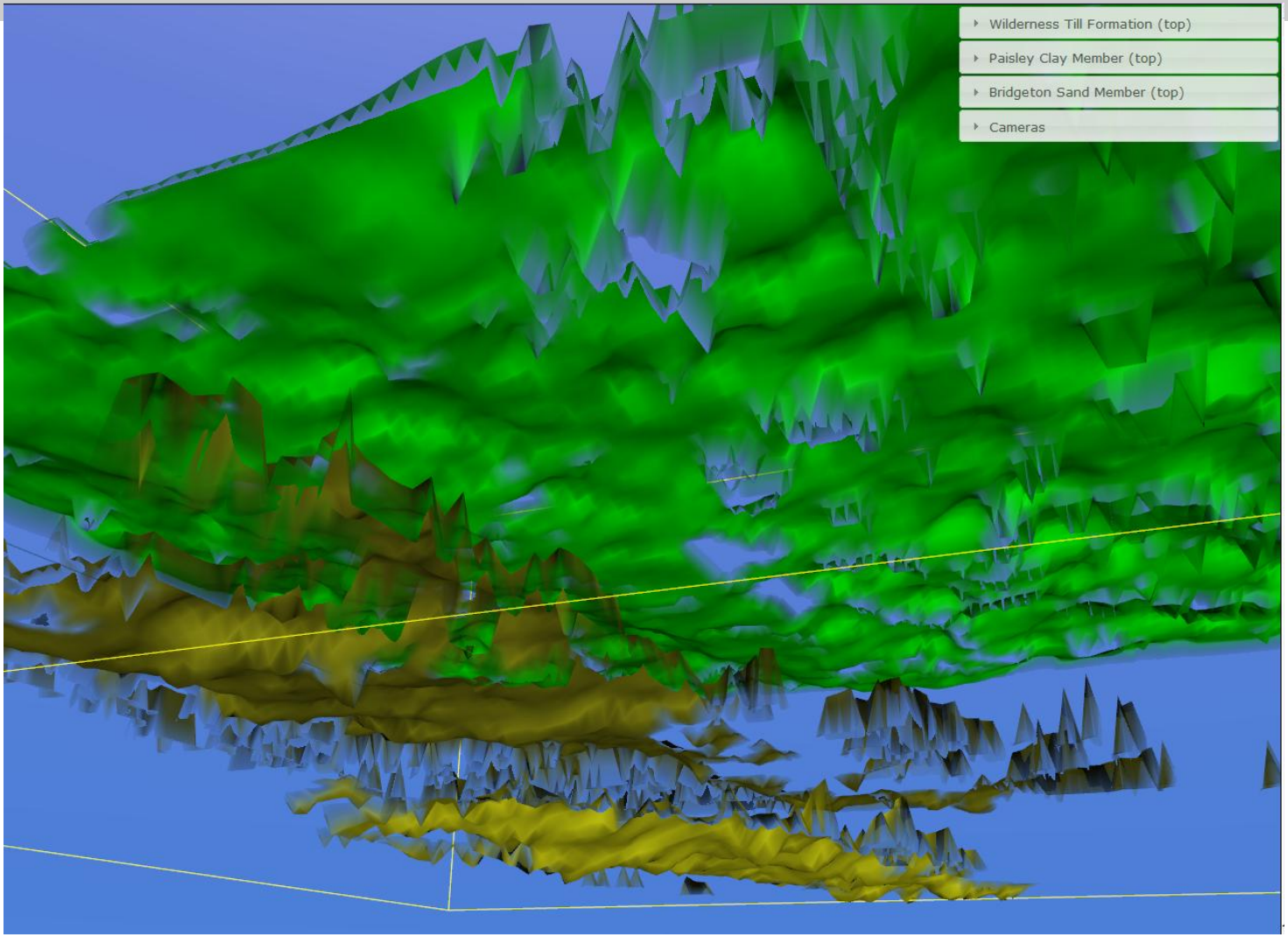
ECMWF: River Discharge



MEA: Daily Hydro Estimator



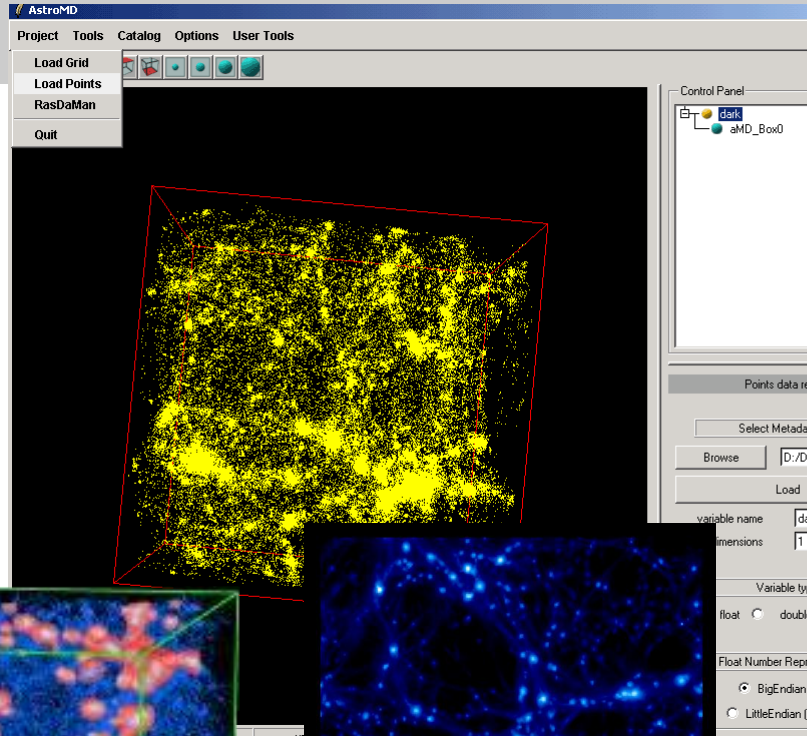
British Geological Service

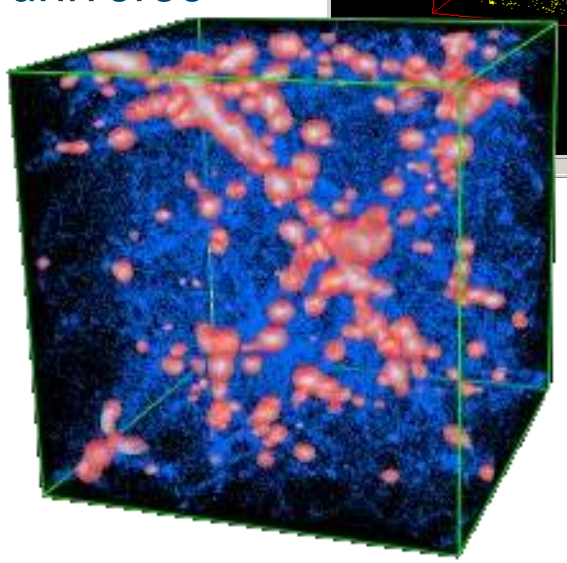


[BGS 2013]

Cosmological Simulation

- Modelling domain: 4D
  - Dark matter (highest mass factor in universe)
  - Baryonic matter (stars, gas, dust, …)
  - → Coupled simulation: particle + fluid
- Results: 3D/4D cutouts from universe
  - Eg, 64 Mpc^3
    (1 pc = 3.27 light years)
- Screenshots: AstroMD
  [Gheller, Rossi 2001]

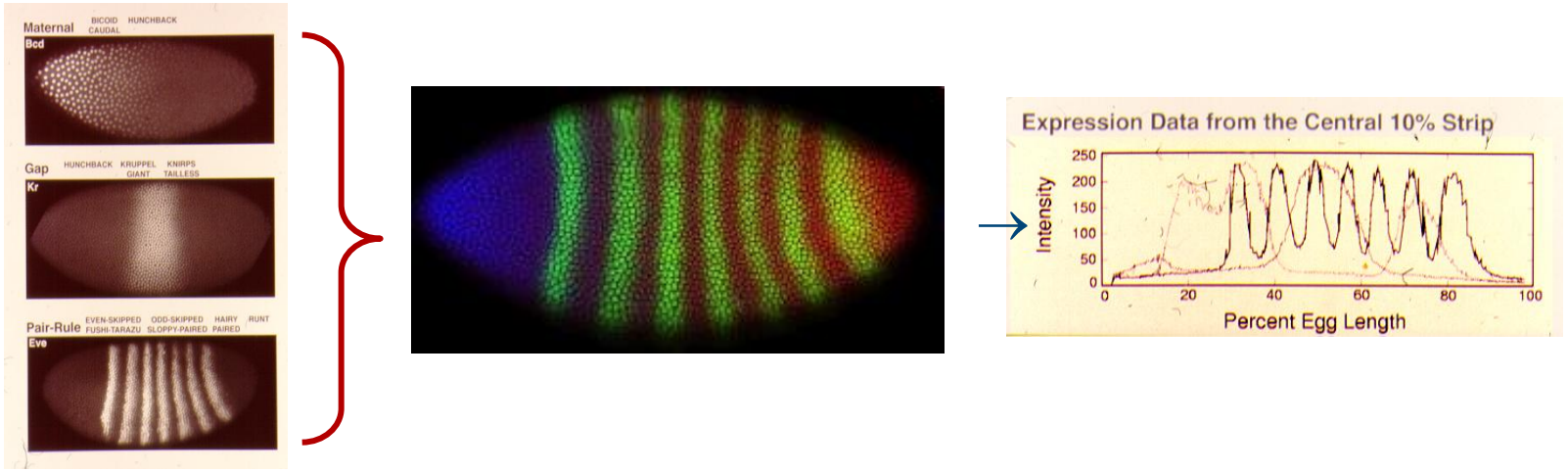




Gene Expression Analysis

http://urchin.spbcas.ru/Mooshka/
[Samsonova et al]

- Gene expression = reading out genes for reproduction
- Research goal: capture spatio-temporal expression patterns in Drosophila




```
select encode( scale( {1c,0c,0c}*e[0,*:*,*:*]
                    +{0c,1c,0c}*e[1,*:*,*:*]
                    +{0c,0c,1c}*e[2,*:*,*:*], 0.2 ), „image/jpeg“ )
from EmbryoImages as e
where oid(e)=193537
```

Human Brain Imaging

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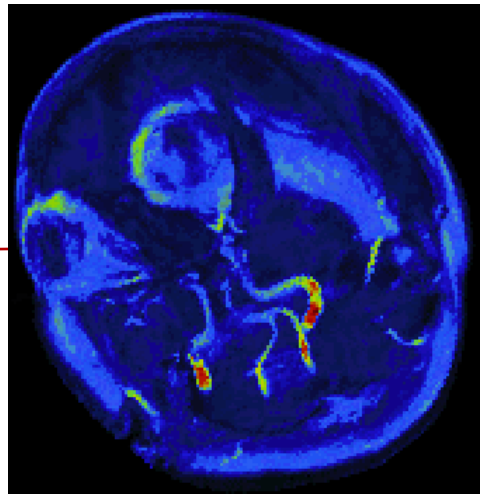
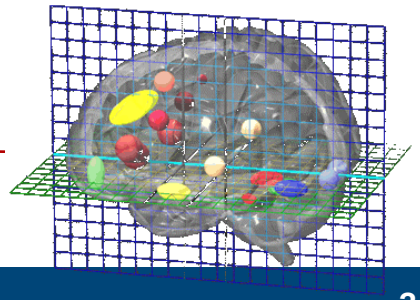
- Research goal: to understand structural-functional relations in human brain
- Experiments capture activity patterns (PET, fMRI)
  - Temperature, electrical, oxygen consumption, ...
  - → lots of computations → „activation maps“
- Example: “*a parasagittal view of all scans containing critical Hippocampus activations, TIFF-coded*.“



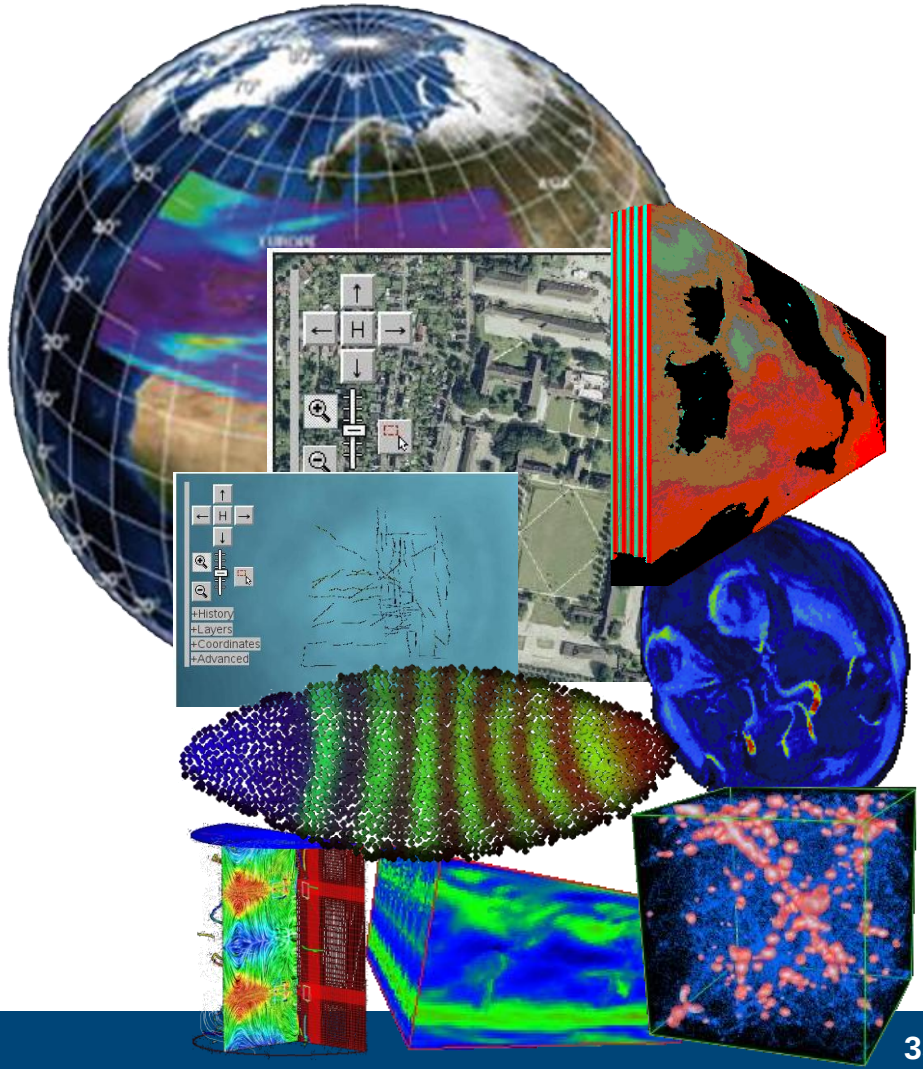


```
select tiff( ht[ $1, *:*, *:* ] )
from   HeadTomograms as ht,
       Hippocampus as mask
where  count_cells( ht > $2 and mask )
       / count_cells( mask )
       > $3
```

`$1` = slicing position, `$2` = intensity threshold value, `$3` = confidence

Domains Investigated

- Geo
  - Environmental sensor data, 1-D
  - Satellite / seafloor maps, 2-D
  - Geophysics (3-D x/y/z)
  - Climate modelling (4-D, x/y/z/t)
- Life science
  - Gene expression simulation (3-D)
  - Human brain imaging (3-D / 4-D)
- Other
  - Computational Fluid Dynamics (3-D)
  - Astrophysics (4-D)
  - Statistics (n-D)

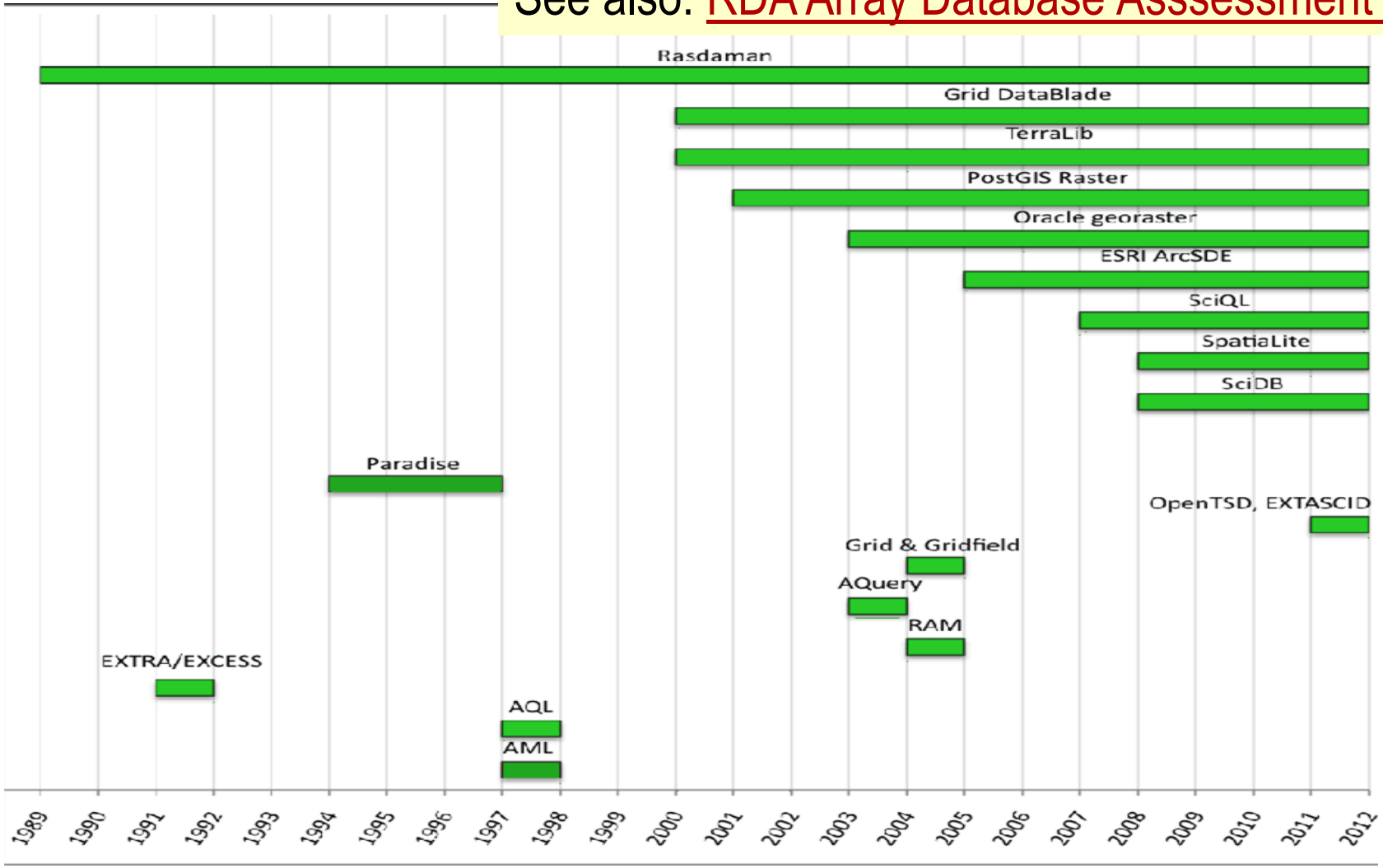


WRAP-UP

Early History of Array Databases

JACOBS UNIVERSITY

See also: RDA Array Database Asssessment WG



Summary

- Arrays are core data structure next to sets, graphs, hierarchies
  - sensor, image, simulation, statistics datacubes
- Array DBMS for declarative queries on massive n-D arrays
  - rasdaman
- Issues:
  - enhancing distributed processing
  - iterative methods
  - ...