Parallel Programming

Cosmic Dark Matter / 2-point Angular Correlation

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Program Design and Implementation

- In this exercise you are asked to
  - *design*
  - *implement*
  - *run* and
  - *report*

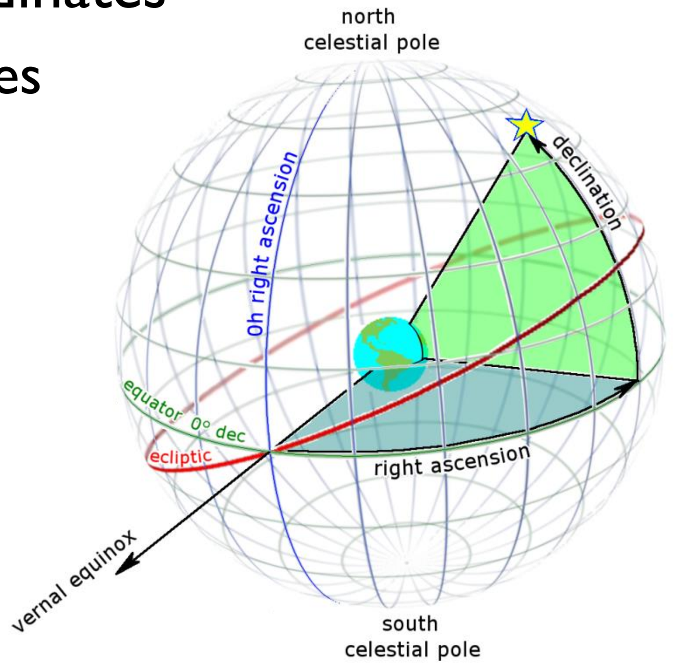
  the calculation of three histograms for the 2-point angular correlation function for two sets of galaxies D and R:
  - D: a measured set of 100 000 galaxies D
  - R: a synthetic random evenly distributed set of 100 000 galaxies

Program Design and Implementation

- Input data
- What needs to be calculated
- Implementation on CPU and GPU
- Output data
- Check points?

Input Data

- Two lists of N galaxy locations: real measured galaxies and synthetic evenly distributed random galaxies
- For each galaxy, real or synthetic, each row in the list contains the two galactic coordinates
  - right ascension α, in arcminutes
  - declination δ, in arcminutes
- Convert from arcminutes to radians by multiplying with $1/60*\pi/180$
- Download lists from moodle



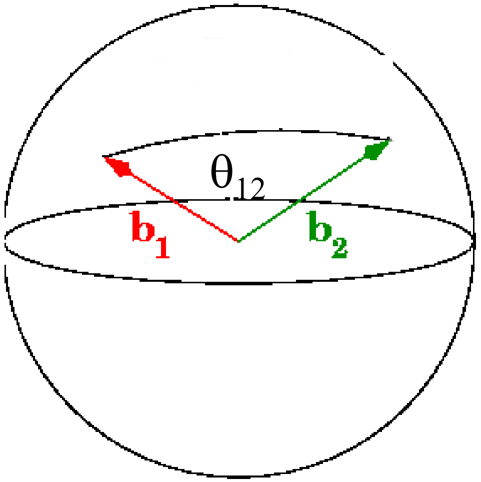
Input Data in moodle

Real data

```
100000
4646.98 3749.51
4644.35 3749.52
4643.24 3748.67
4646.98 3750.89
4641.13 3748.23
4646.75 3750.26
4643.29 3751.99
4640.78 3747
4638.95 3749.74
4647.29 3749.82
4651.65 3749.02
4649.65 3747.16
4646.66 3752.23
4649.38 3749.14
4648.22 3750.32
4639.27 3747.96
4637.3  3749.5
4649.07 3751.94
4640.39 3752.43
```

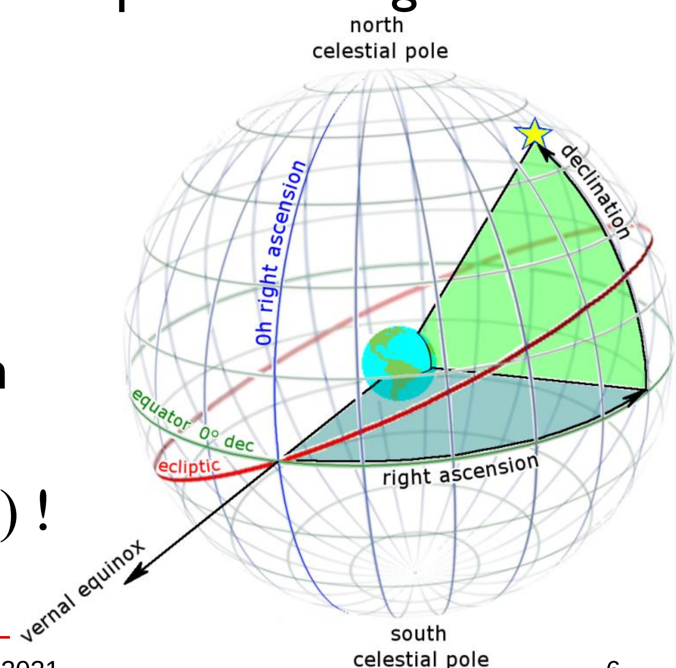
Synthetic data

```
100000
840.961426 387.991697
387.368692 2967.285746
2667.070581 3385.866638
3942.141923 3720.545649
5164.800068 3205.065003
1680.286209 653.214854
3553.889989 152.983872
1011.581615 76.716702
298.341944 3752.723427
4044.605401 2943.458158
1030.720073 2342.109887
54.257097 3769.420145
2478.545632 336.072740
970.044311 3556.987037
840.791266 2610.257310
5272.628047 2441.450374
380.633015 3771.599991
5049.735705 4627.545008
2849.250851 2945.861883
```



What Needs to be Calculated

- Initialize the three histograms DD, DR and RR to zero, covering $0 \rightarrow 180$ degrees, bin width $= 0.25$ degrees: DD[0] covers [0, 0.25), DD[1] covers [0.25,0.5), etc.
  - Hint: $0 \rightarrow 90$ degrees is enough in our case
- Fill DD with the angles between each pair of real galaxies
- Fill DR with the angles between each pair of real-random galaxies
- Fill RR with the angles between each pair of random galaxies
- Check point: how many entries in DR? In DD and RR?
  Answer: 10 billion (10000000000) !



What Needs to be Calculated

- Given two points on the surface of a sphere, how do we calculate the angle between those two points as seen from the center of the sphere?
- Basic idea: represent each point by a unit vector from the center of the sphere to the surface of the sphere, and calculate the dot product of two vectors.
- The dot product $\bullet$ between two 3-D vectors $\mathbf{r}_1$ and $\mathbf{r}_2$ is given by $\mathbf{r}_1 \bullet \mathbf{r}_2 = |\mathbf{r}_1|\,|\mathbf{r}_2| \cos(\theta_{12})$ where $|\mathbf{r}|$ is the length of the vector $\mathbf{r}$, and θ_{12} is the angle between the two vectors.
- Here we have unit vectors, hence $|\mathbf{r}_1| = |\mathbf{r}_2| = 1$

What Needs to be Calculated

- The formula we can use is now

  $$\theta_{12} = \arccos(\mathbf{r}_1 \bullet \mathbf{r}_2)$$

  $$\mathbf{r} = r_x\mathbf{e}_x + r_y\mathbf{e}_y + r_z\mathbf{e}_z$$

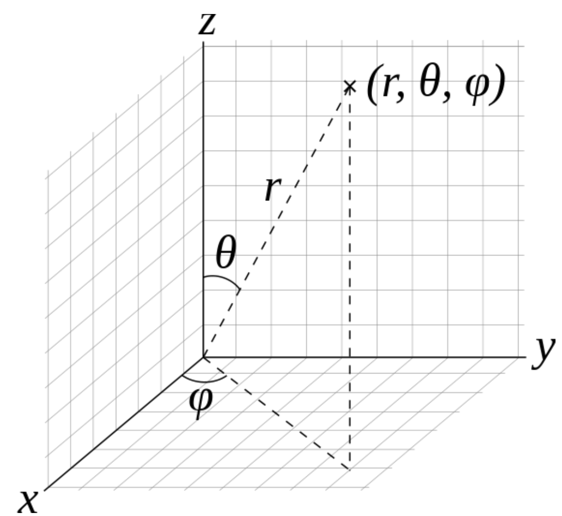
  $$\mathbf{r}_1 \bullet \mathbf{r}_2 = r_{1x}*r_{2x} + r_{1y}*r_{2y} + r_{1z}*r_{2z}$$

- Using spherical coordinates (r,θ,φ), the Cartesian components of **r** are given by

  $$r_x = r*\sin(\theta)*\cos(\varphi)$$

  $$r_y = r*\sin(\theta)*\sin(\varphi)$$

  $$r_z = r*\cos(\theta)$$



Cartesian: x, y, z
Spherical: r, θ, φ

What Needs to be Calculated

- Finally, what is the connection between the spherical coordinates θ, φ and the galactic coordinates, right ascension α and declination δ ?
- Answer: $\varphi = \alpha$ and $\theta = 90 - \delta$
- $r_1 \bullet r_2 = \sin(\theta_1)\cos(\varphi_1)\sin(\theta_2)\cos(\varphi_2) +$
  $\sin(\theta_1)\sin(\varphi_1)\sin(\theta_2)\sin(\varphi_2) + \cos(\theta_1)\cos(\theta_2)$

  $= \cos(\delta_1)\cos(\alpha_1)\cos(\delta_2)\cos(\alpha_2) +$
  $\cos(\delta_1)\sin(\alpha_1)\cos(\delta_2)\sin(\alpha_2) + \sin(\delta_1)\sin(\delta_2)$

  $= \cos(\delta_1)\cos(\delta_2)[\cos(\alpha_1)\cos(\alpha_2) + \sin(\alpha_1)\sin(\alpha_2)]$
  $+ \sin(\delta_1)\sin(\delta_2)$

  $= \cos(\delta_1)\cos(\delta_2)\cos(\alpha_1 - \alpha_2) + \sin(\delta_1)\sin(\delta_2)$

What Needs to be Calculated

- Final result: the angle θ_{12} between two galaxies (α_1, δ_1), (α_2, δ_2) is given by

$$\theta_{12} = \text{arccos}\left(\sin(\delta_1)*\sin(\delta_2)+\cos(\delta_1)*\cos(\delta_2)*\cos(\alpha_1-\alpha_2)\right)$$

- Data type for α_i, δ_i : single or double precision floating point numbers?
- Data layout in memory?

Output Data

- Plot the histograms DD and RR to see if there are any visible differences.
- The scientific measure for differences between the two distributions of galaxies is given by the estimator

  $$\omega_n(\theta) = (DD_n - 2*DR_n + RR_n)/RR_n$$

  DD_n, DR_n, RR_n = value in histogram bin n
- If all ω_n are close to zero, that is, in the range $[-0.5,0.5]$, we have a random distribution of real galaxies (the two distributions are statistically the same)
- If some of the ω_n values are < -1.0 or $> +1.0$, then we have a non-random distribution of real galaxies.

GPU: Threads and Thread Blocks

- Choose your threads and thread blocks
- If you have the time, play around with the size of your thread blocks and the amount of work one thread does.
- Do you need to synchronize your threads?
- Do you need to use atomic operations?
- Is it a good idea to read the galaxy data within a thread block into *shared* memory?

Implementation on CPU and GPU

- Use the very basic program template from the lecture slides
  - read the data from the files, manipulate as needed
  - transfer data to the GPU (or use unified memory)
  - start the kernel(s)
  - transfer result data back to the CPU
  - present your results
- If there are problem, perhaps start out with a small set of galaxies, perhaps with known relative angles?

Short Instructions for dione.abo.fi

- Log on to dione:

```
ssh user_name@dione.abo.fi
```

- Load necessary modules:

```
module load openmpi              // MPI
module load CUDA                 // CUDA
```

- Compile your program

```
mpicc -O3 mpiprog.c -o mpiprog -lm
nvcc gpuprog.cu -o gpuprog -lm
```

- Run your program on the batch system

```
srun -n 40 -o prog.out -e prog.err mpiprog real_data sim_data
srun -p gpu -n 1 gpuprog real_data sim_data
```

Hints and help

- Input data is downloaded from moodle
- Reference results and further explanations available from

  D. Bard, M. Bellis, M.T.Allen, H. Yepremyan, J.M. Kratochvil, "*Cosmological calculations on the GPU*", **Astronomy and Computing**, Vol. 1 (2013) 17–22
- Report the total time for your program to calculate the estimators $\omega_n(\theta)$.