CRPropa observer sphere lensing for forward-tracking studies

Alex Kääpä

CRPropa face-to-face meeting

2nd October 2019

BERGISCHE UNIVERSITÄT WUPPERTAL

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

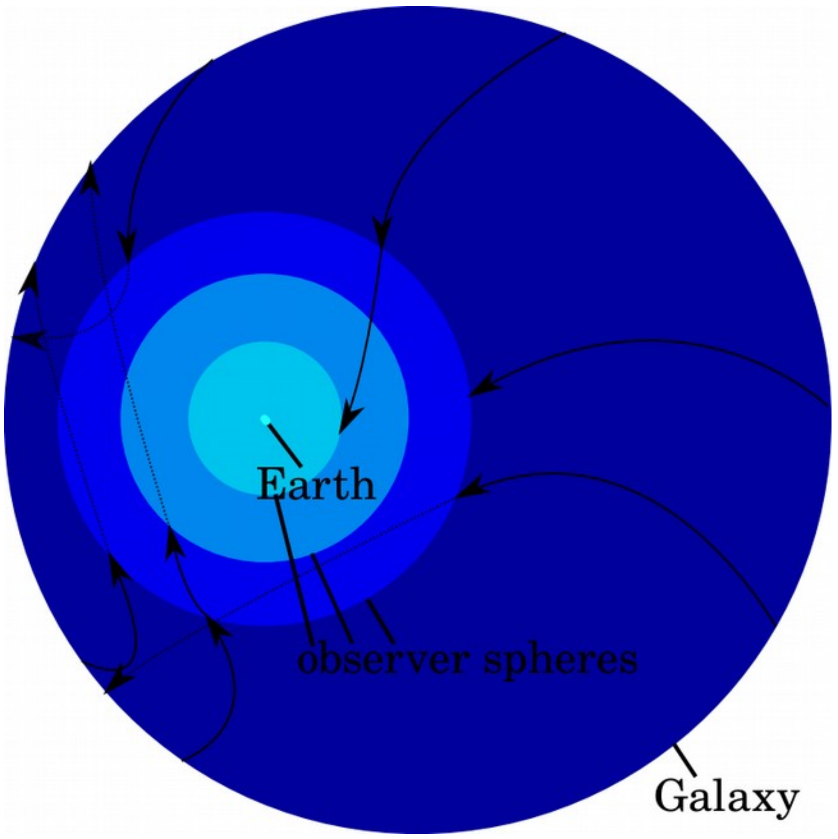
Issues with forward-tracking

Computationally expensive (Earth is hard to hit from large distances)

→ solution: increase size of observer sphere

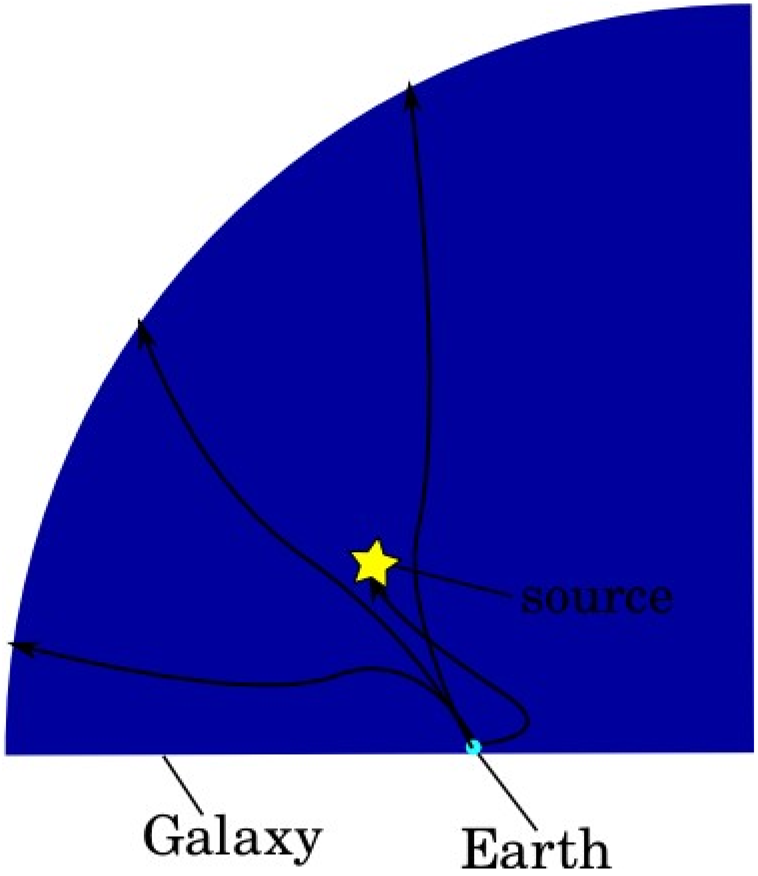
→ problem: larger observer spheres cause distortion in arrival direction

compromise:
efficiency ↔ realism



Backtracking and its drawback

Not well suited for discrete source distributions (e.g. point sources), esp. within Galaxy

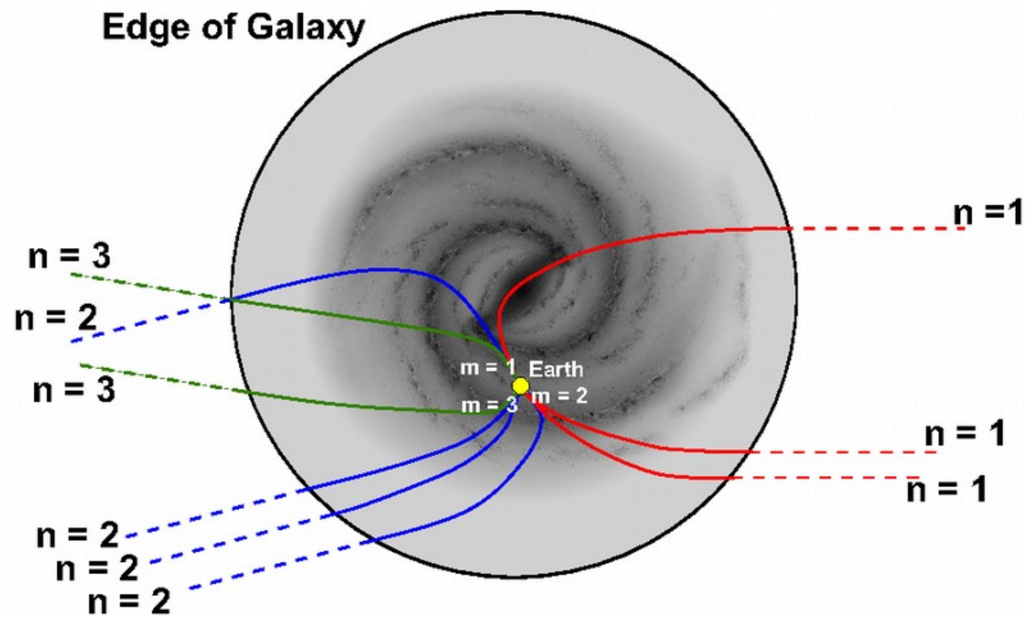


Galactic lensing

Only deflections, no energy losses
→ Galaxy acts as lens:

$$\overrightarrow{p}_{arr} = L \cdot \overrightarrow{p}_{inj}$$

Limitation: lens is model dependent



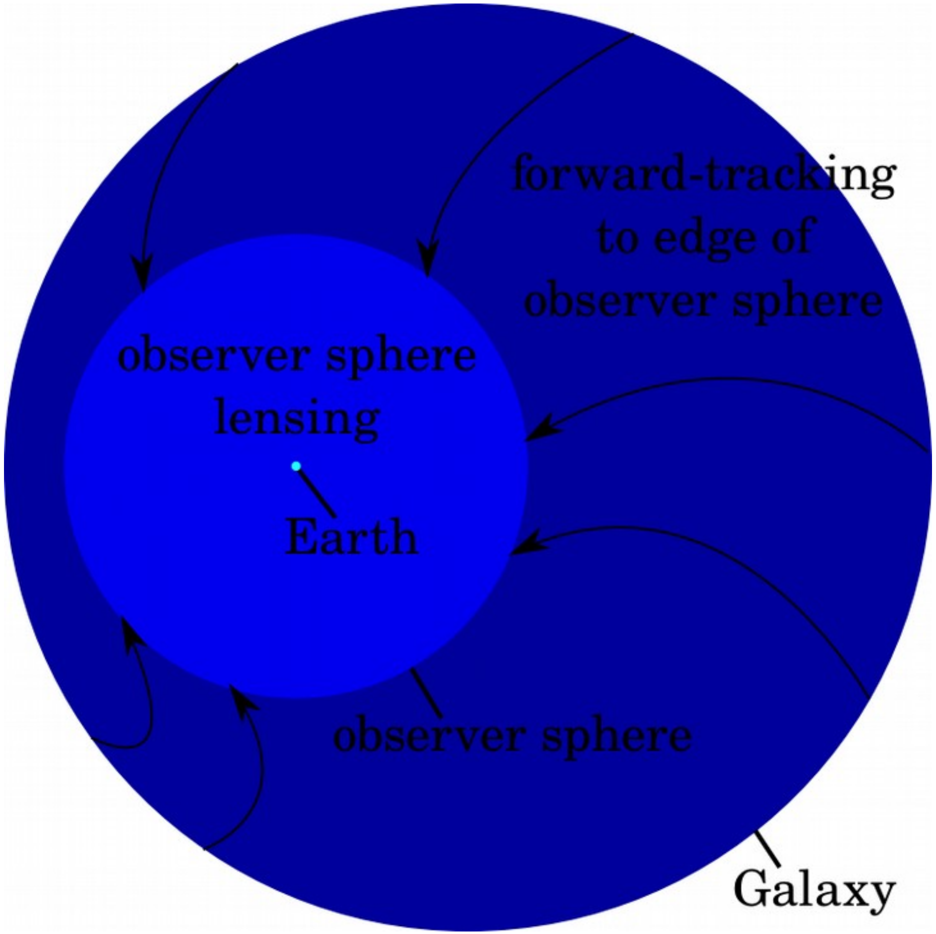
Astropart. Phys. 54 (2014) 110

Observer sphere lensing

GMF is best understood in the vicinity of Earth

→ lensing to edge of volume 'close enough' to Earth

Goal: make forward-tracking studies more efficient AND realistic

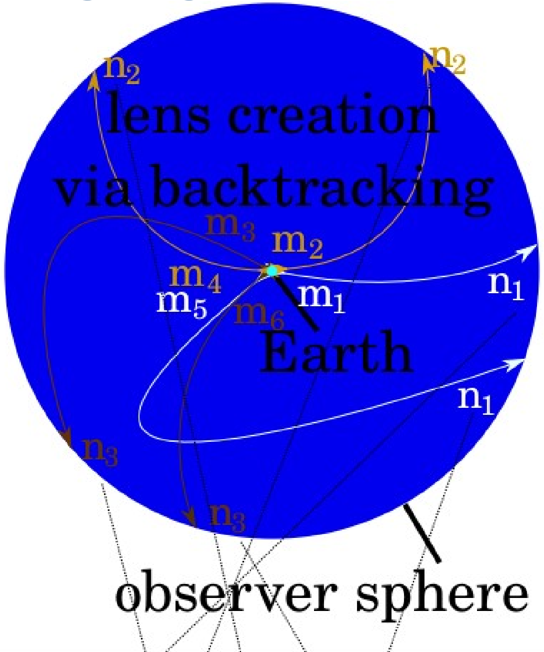


Creation of observer sphere lens:

1. **backtrack** *N* particles from Earth **to observer sphere surface** to get $(\overrightarrow{p}_{inj}, \overrightarrow{p}_{arr})$-pair

2. **discretise solid angle range** and **count occurences** of each pair

3. **Weight** matrix with 1-norm to obtain lens L



1	0	0	0	1	0	...
0	1	0	1	0	0	
0	0	1	0	0	1	
⋮						⋱

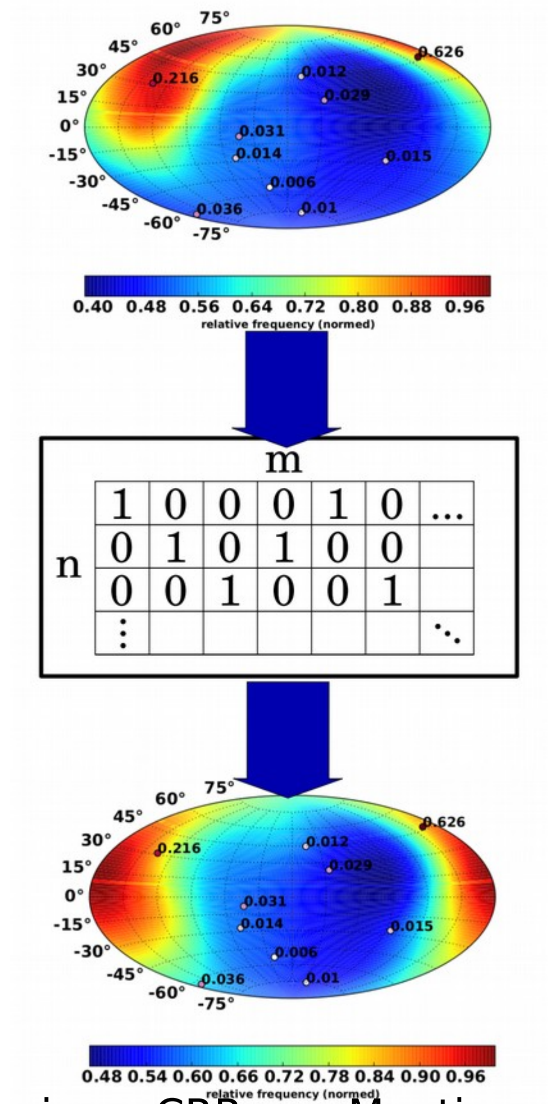
Testing

Forwardtrack from discrete point soruce distribution (here: 10 isotropically distributed sources):

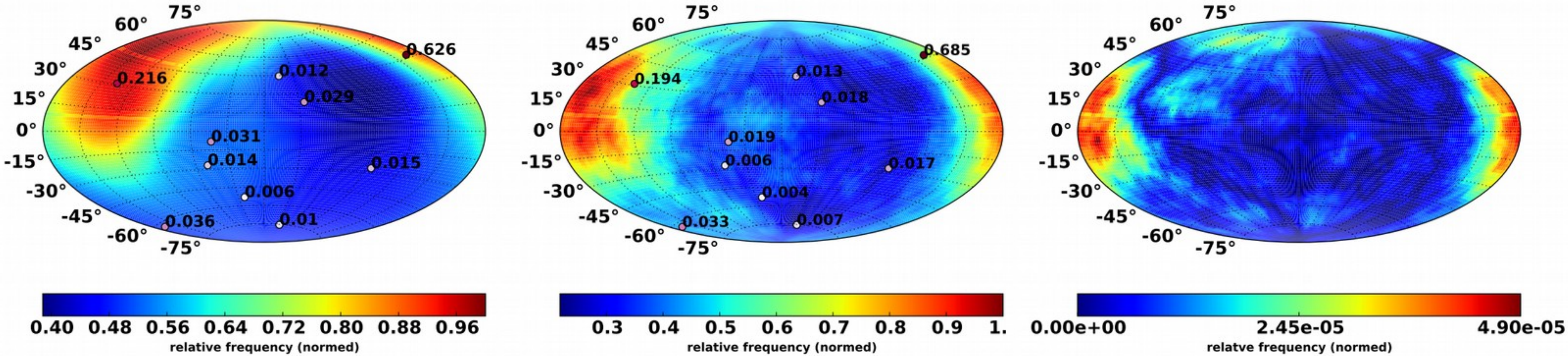
- test for ‘low’ energy (strongest deflections → largest distortion): lg(E/eV) = 18.0
- Protons (all other particles by lensing for $E = Z \cdot E_{proton}$)
- R = 1000 pc (large), 100 pc (small)
- ~5 x 10^9 protons per set

Compare:

- lensed vs. unlensed w.r.t. reference distribution (R = 10 pc)
- effect of granularity



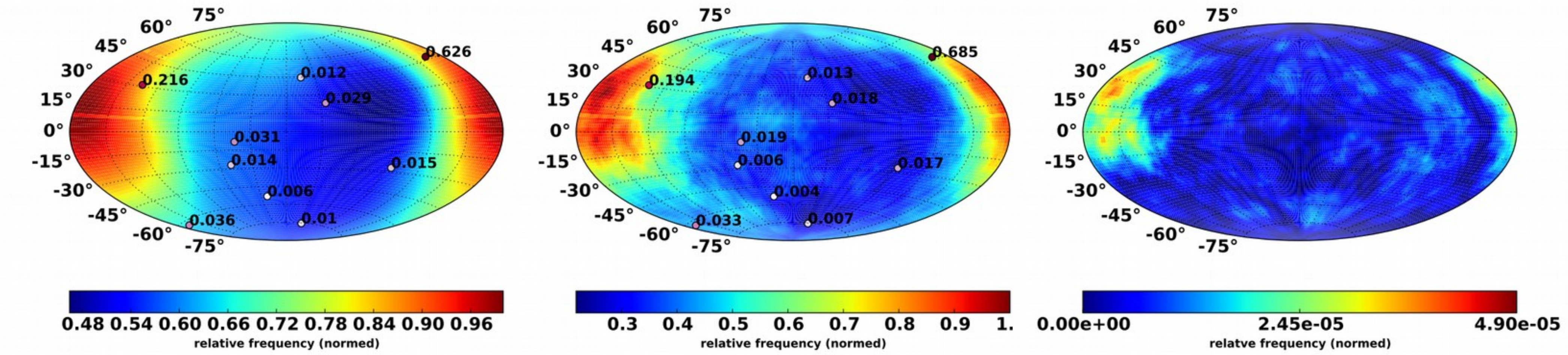
Distribution 1 (large observer, before lensing):



R = 1 kpc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

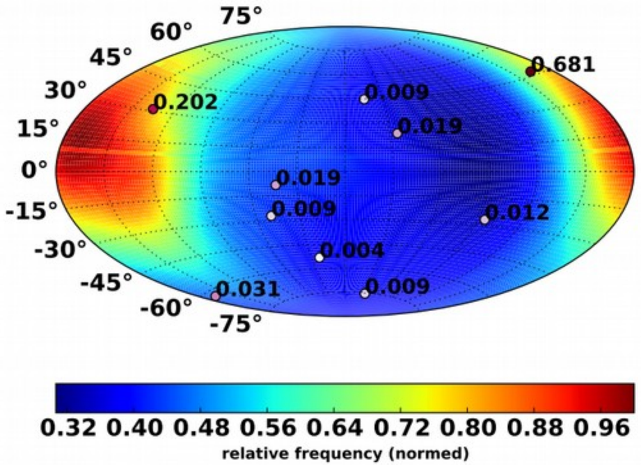
Distribution 1 (large observer, after lensing):



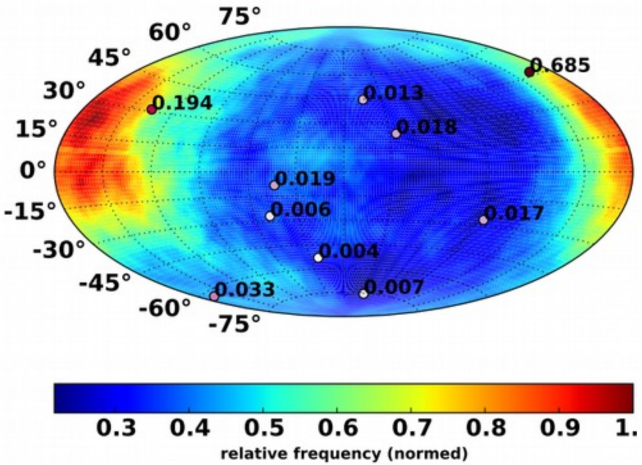
R = 1 kpc | R = 10 pc | Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

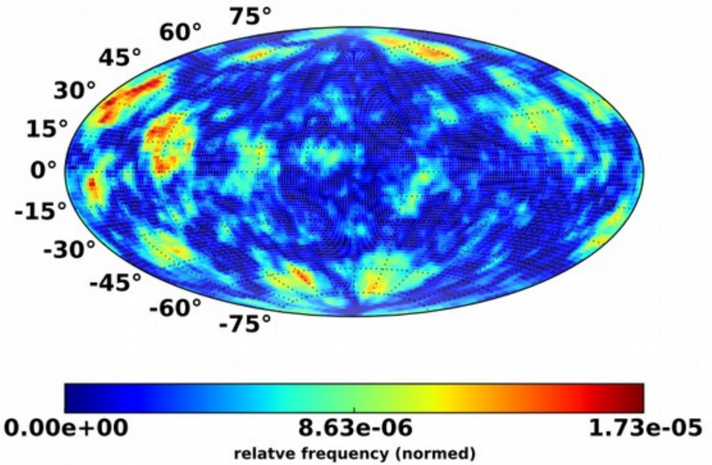
Distribution 1 (small observer, before lensing):



R = 100 pc



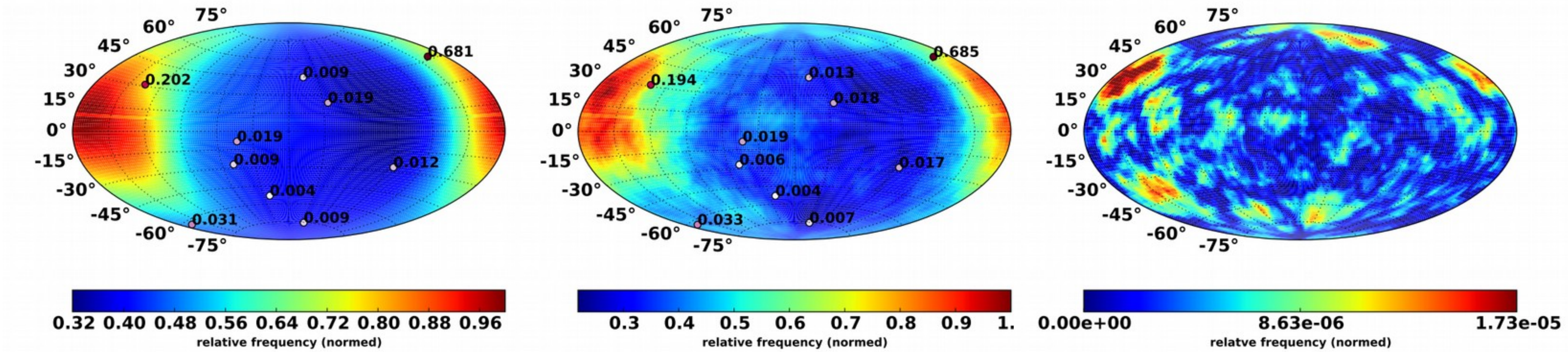
R = 10 pc



Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

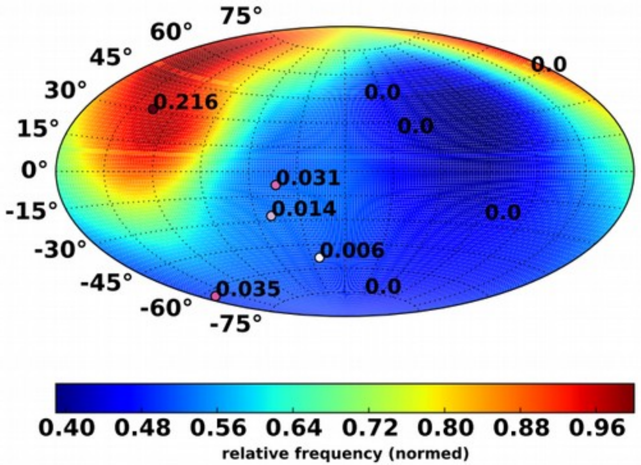
Distribution 1 (small observer, after lensing):



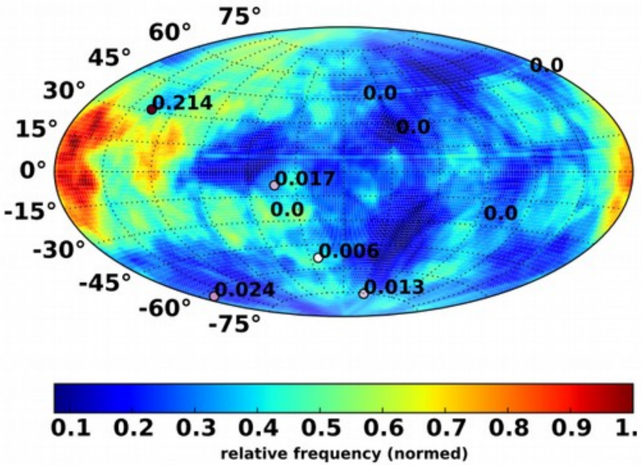
R = 100 pc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

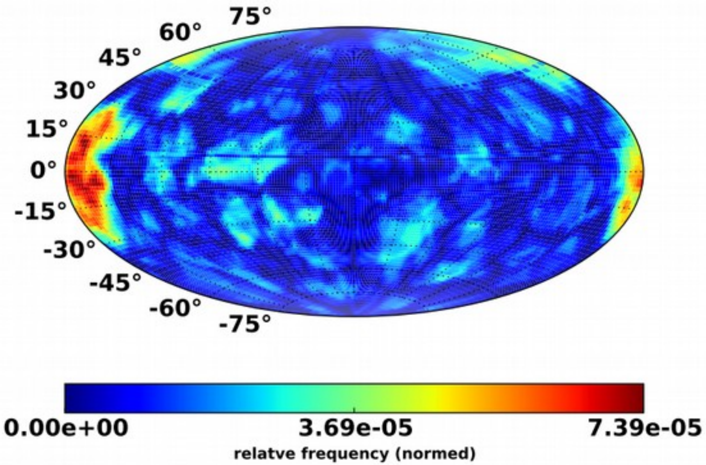
Distribution 1 (finer step size, before lensing):



R = 1 kpc



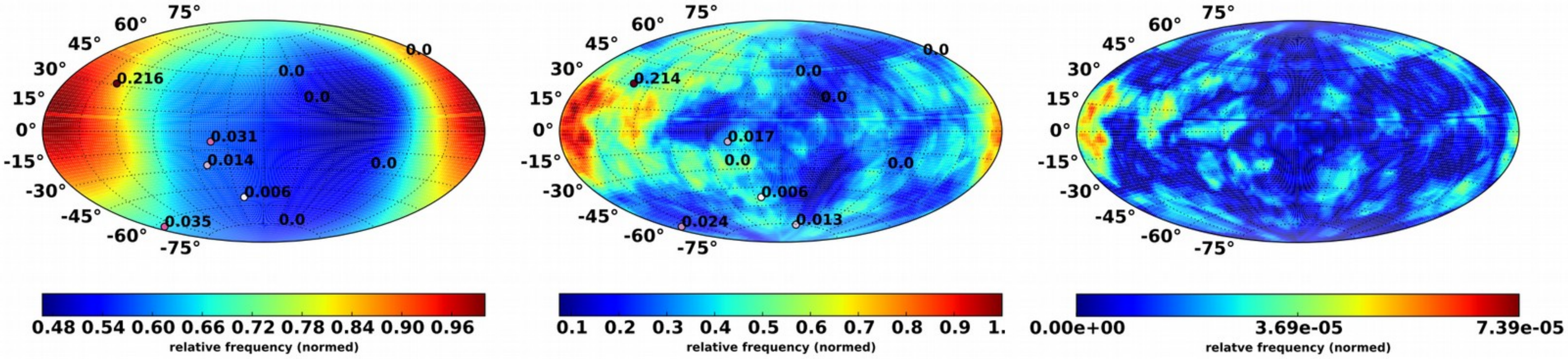
R = 10 pc



Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- same amount of reduction of residuals as for regular granularity

Distribution 1 (finer step size, after lensing):



R = 1 kpc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

Observer sphere lensing - summary

Observer sphere lenses combine strengths of forward- and backtracking simulations:

- forwardtrack to edge of observer sphere
- create lens via backtracking simulations from Earth to edge of sphere
- apply lens to arrival direction distribution (via HEALPix pixelisation)

Observer sphere lensing provides more realistic arrival direction distributions (especially for $\leq$100 pc spheres)

- reduction of residuals by <10 – 30 %
- increase in statistics by factor of 10^2 – 10^4

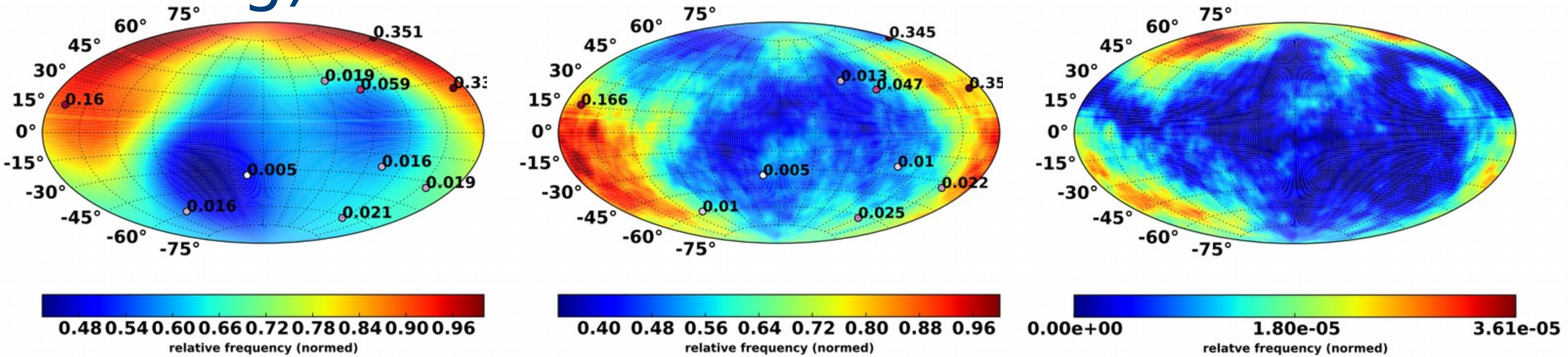
Conclusion and future plans

- Observer sphere lensing has potential to improve forward-tracking analyses
- Publication to introduce principle to community as well as detailing method for purposes of personal application
- If desired: incorporate lenses as a tool into CRPropa framework for quick use

Thank you for your attention!

Questions?

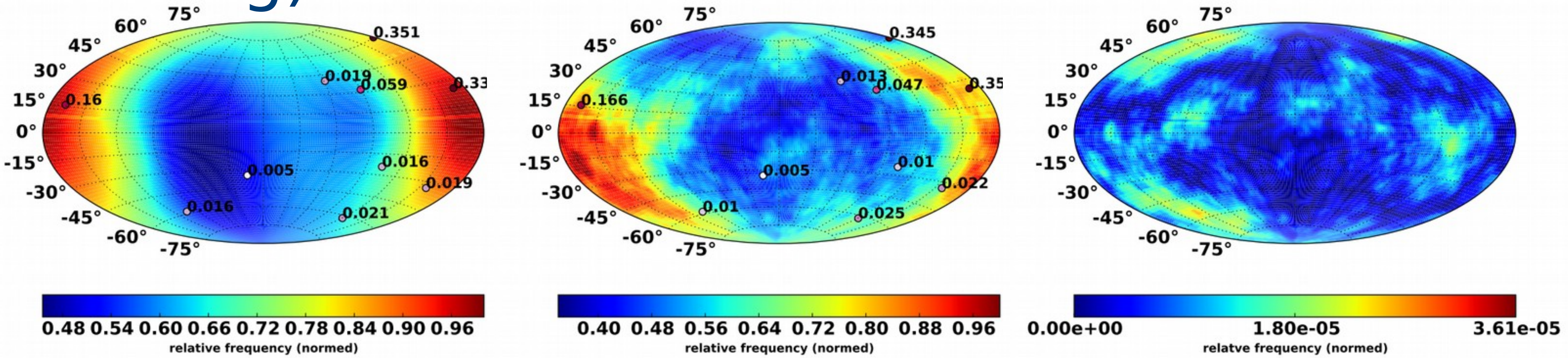
Distribution 2 (large observer, before lensing):



R = 1 kpc | R = 10 pc | Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

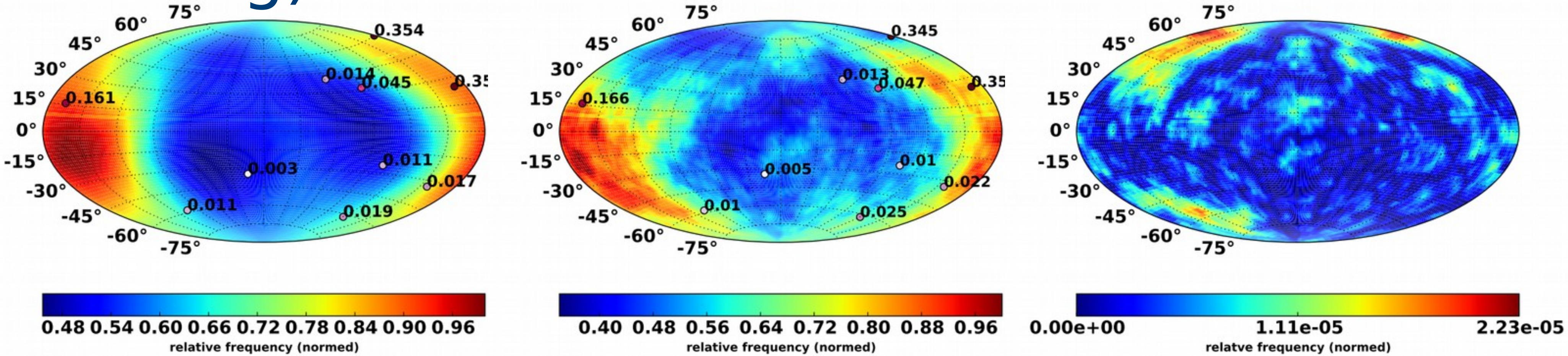
Distribution 2 (large observer, after lensing):



R = 1 kpc   R = 10 pc   Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

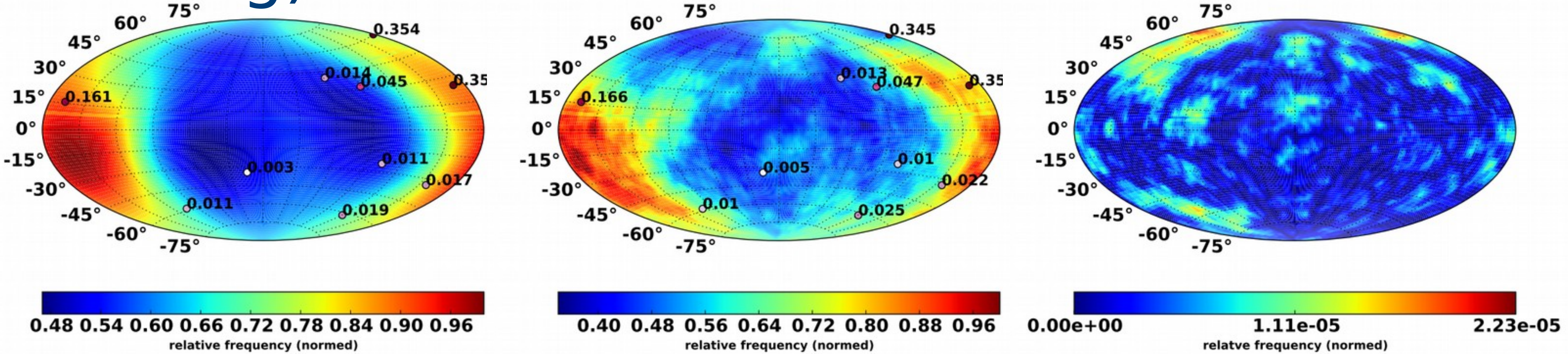
Distribution 2 (small observer, before lensing):



R = 100 pc | R = 10 pc | Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

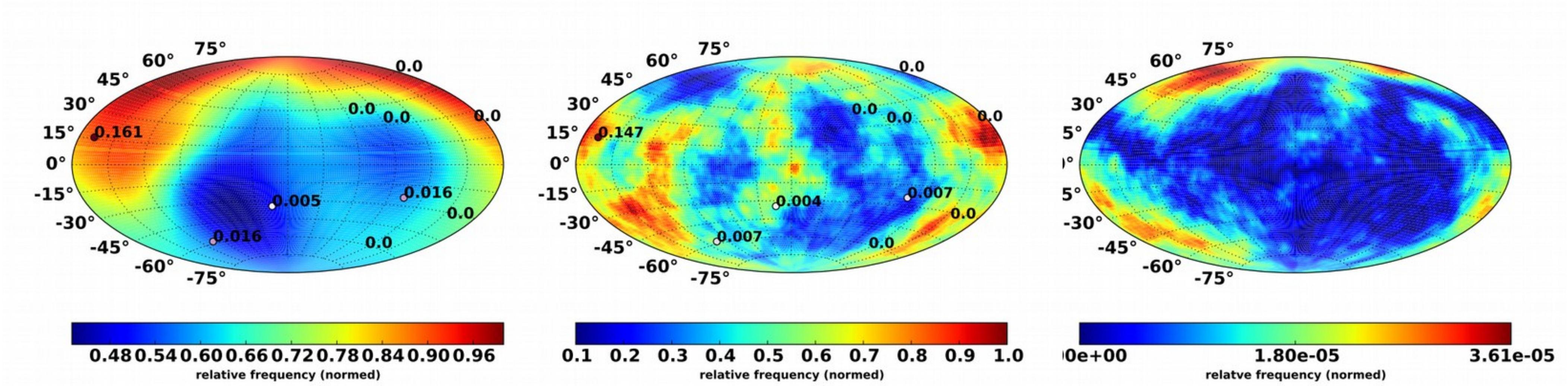
Distribution 2 (small observer, after lensing):



R = 100 pc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

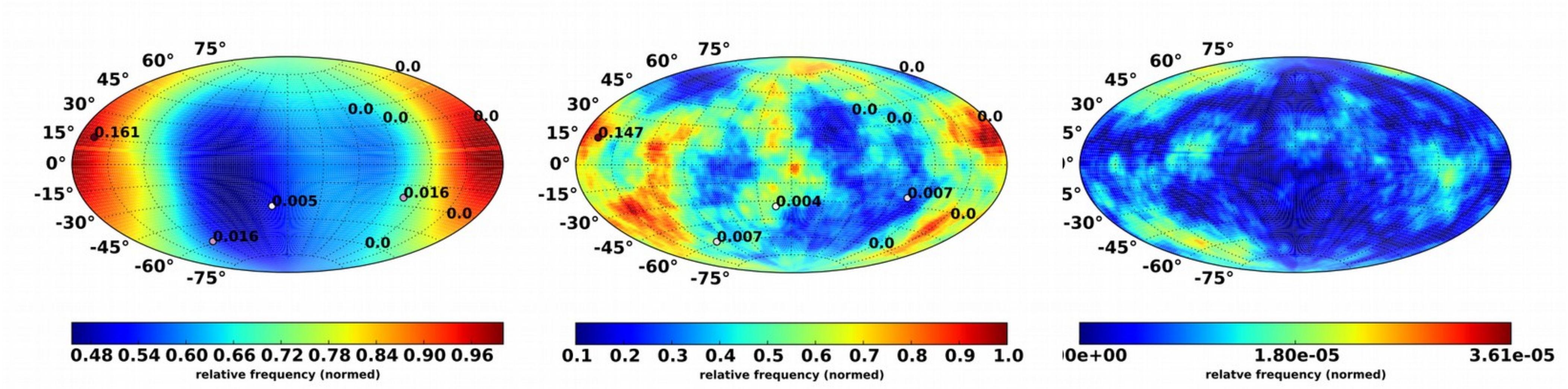
Distribution 2 (finer step size, before



R = 1 kpc   R = 10 pc   Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

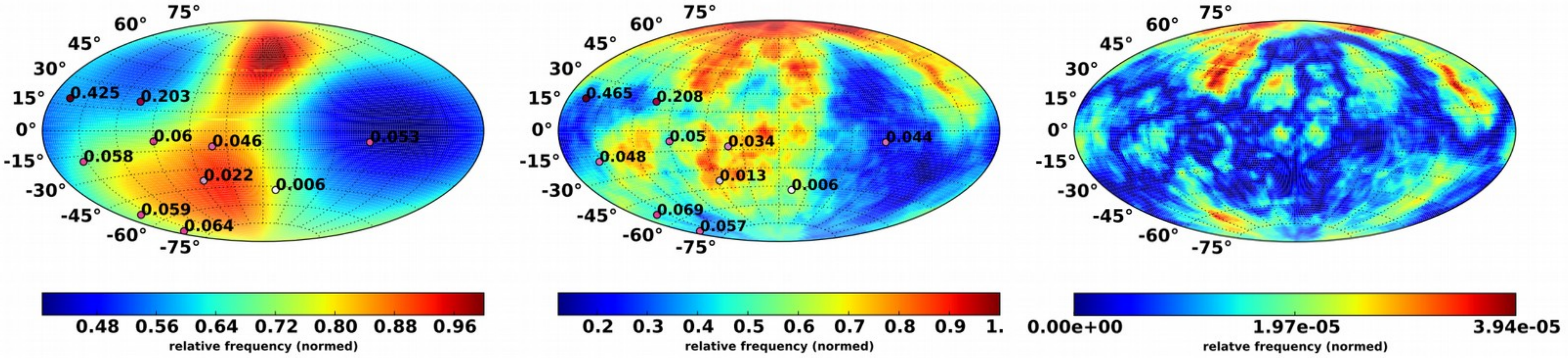
Distribution 2 (finer step size, after lensing)



R = 1 kpc | R = 10 pc | Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

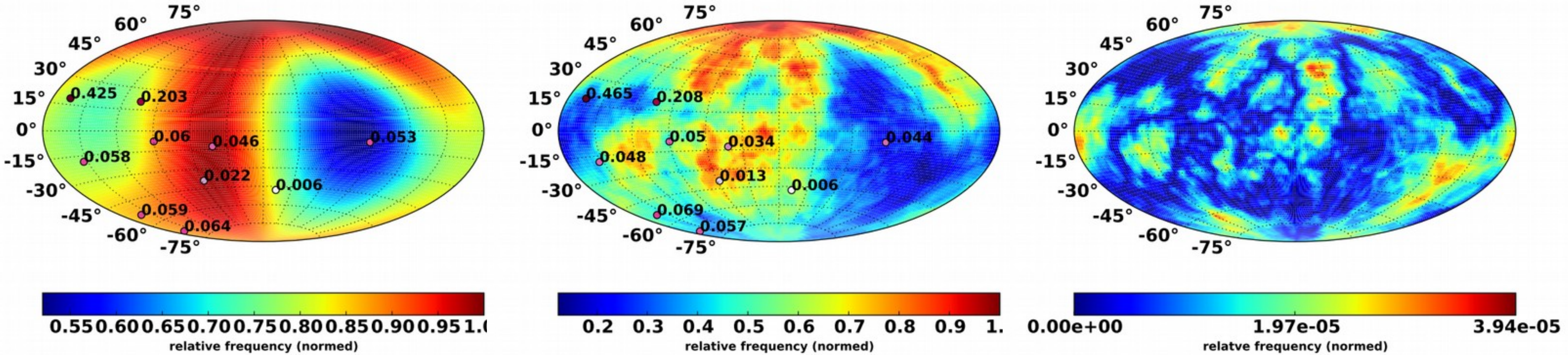
Back-up - Distribution 3 (before lensing):



R = 1 kpc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

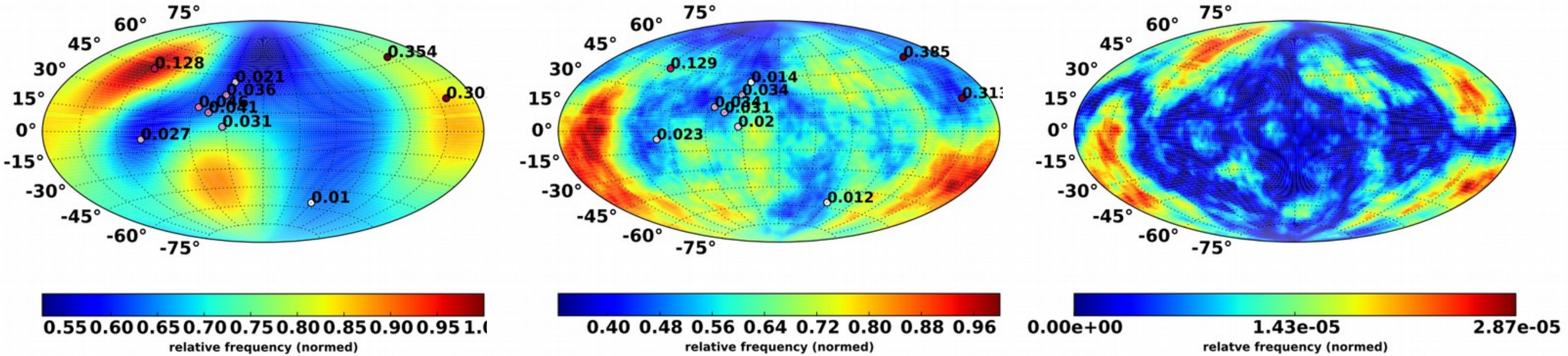
Back-up - Distribution 3 (after lensing):



R = 1 kpc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

Back-up - Distribution 4 (before lensing):



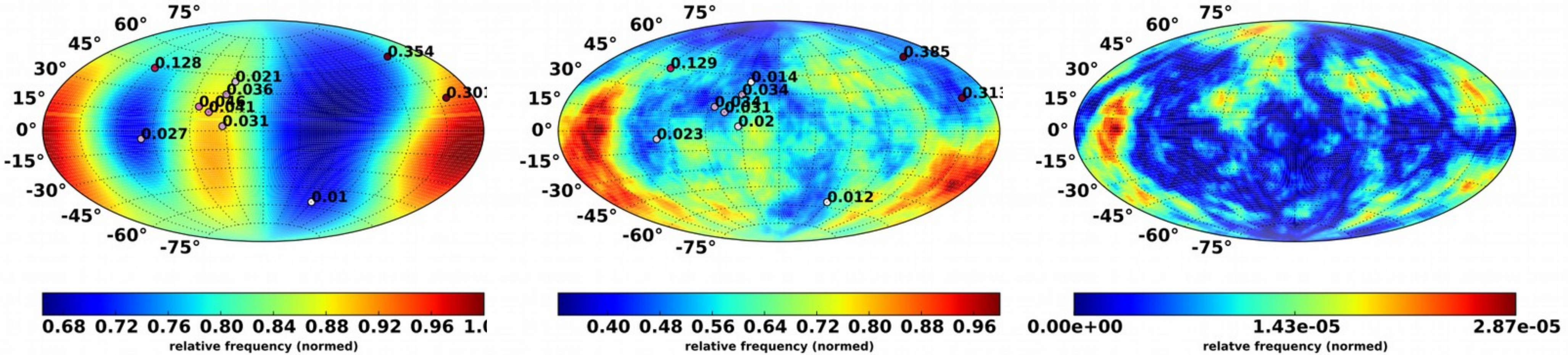
R = 1 kpc

R = 10 pc

Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

Back-up - Distribution 4 (after lensing):



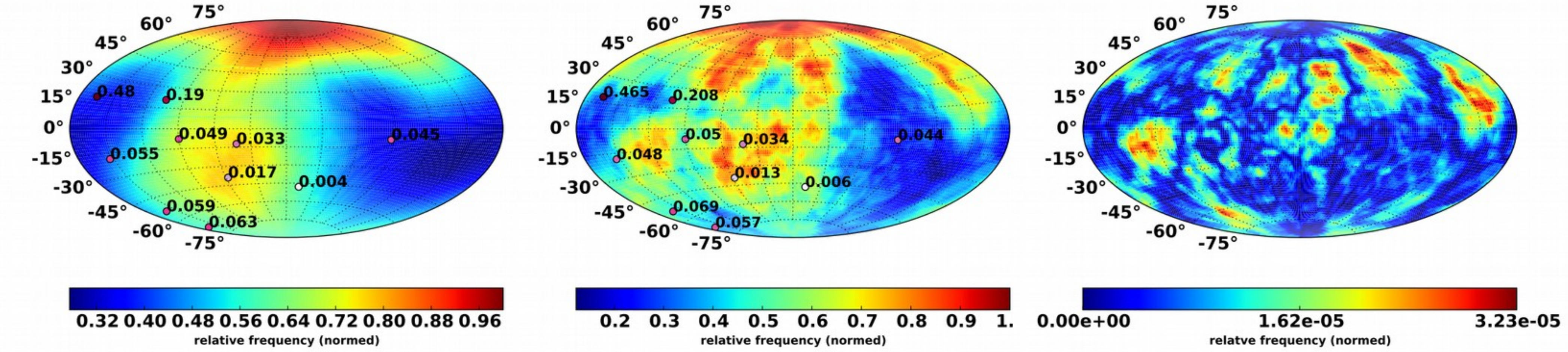
R = 1 kpc

R = 10 pc

Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

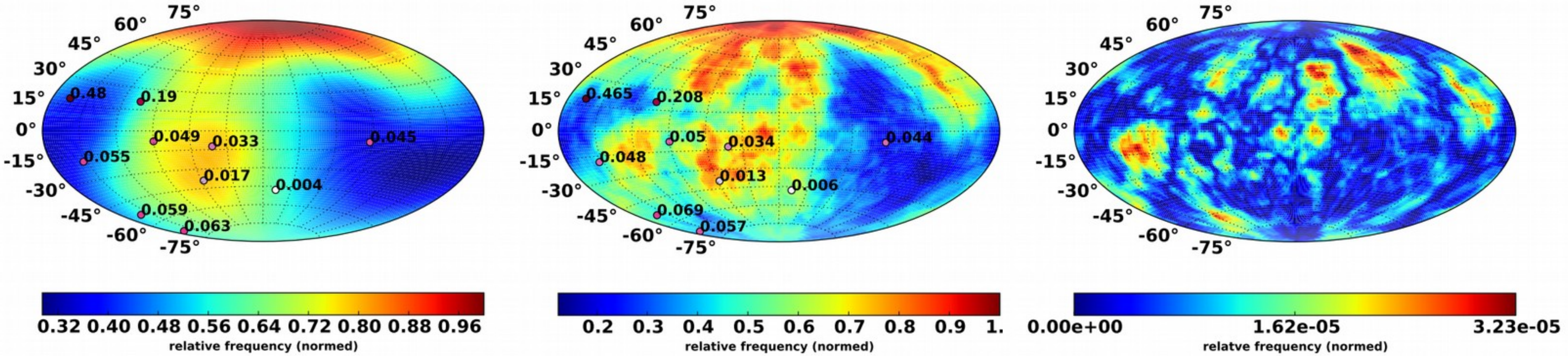
Back-up - Distribution 3 (before lensing):



R = 100 pc   R = 10 pc   Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

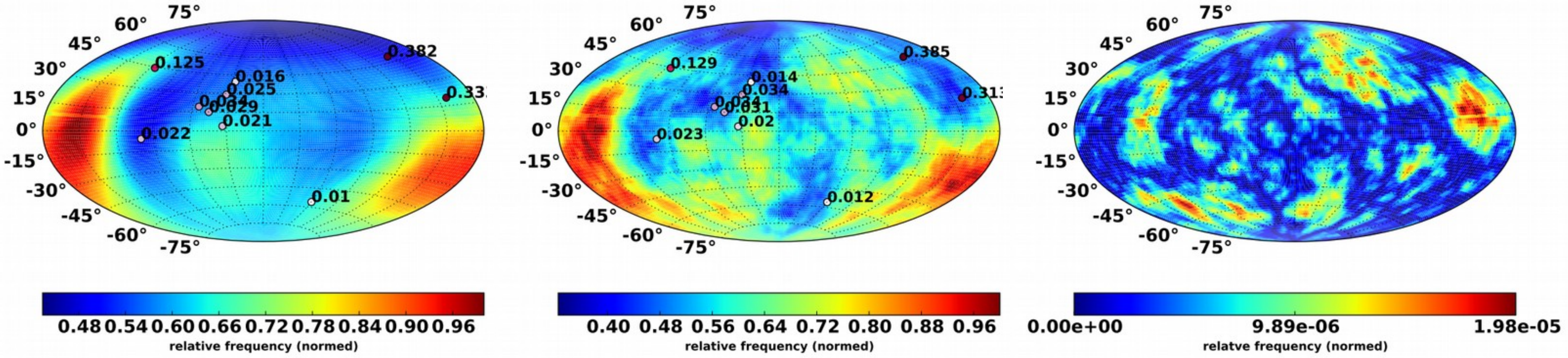
Back-up - Distribution 3 (after lensing):



R = 100 pc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

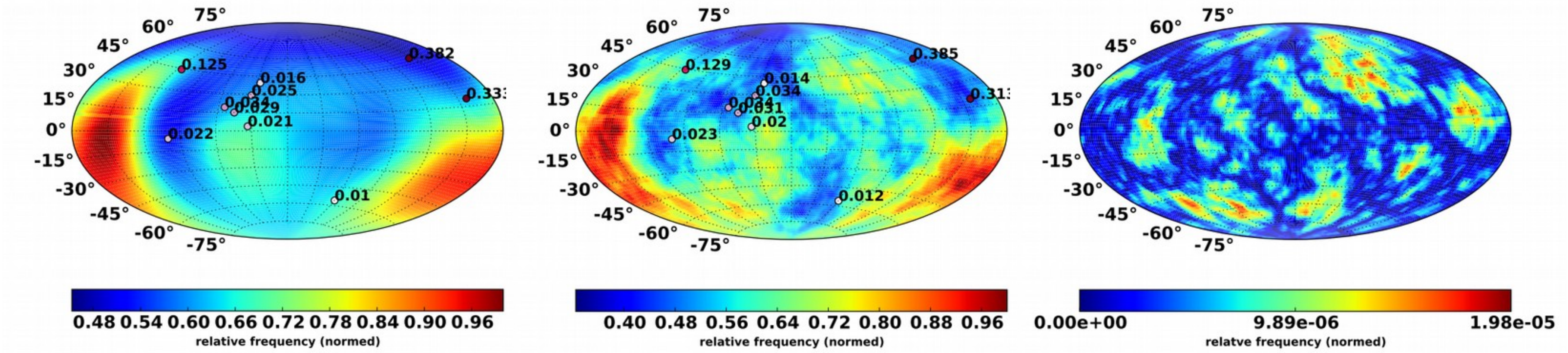
Back-up - Distribution 4 (before lensing):



R = 100 pc | R = 10 pc | Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

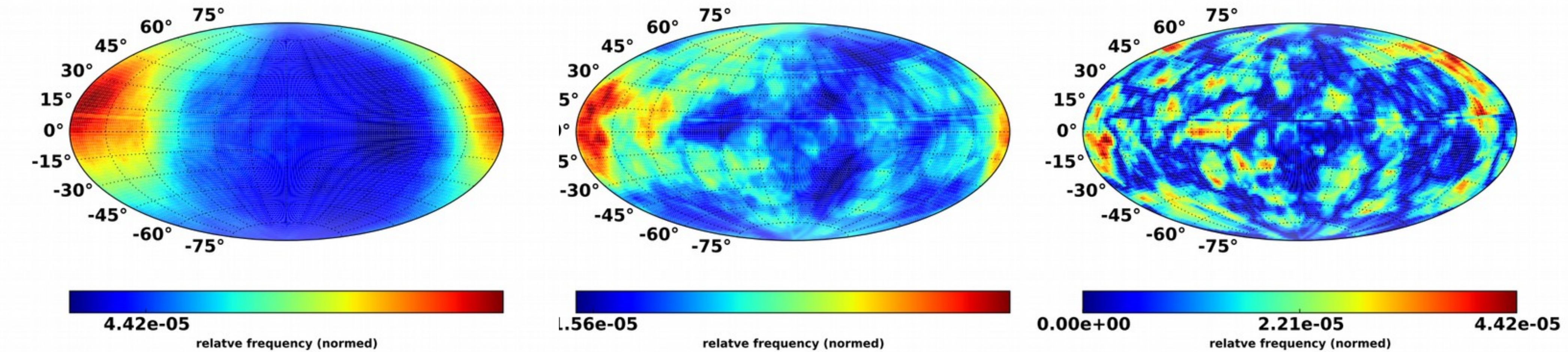
Back-up - Distribution 4 (after lensing):



R = 100 pc　　R = 10 pc　　Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- deviations small for radii ≤100 pc (reduction of residuals by < 10 %)

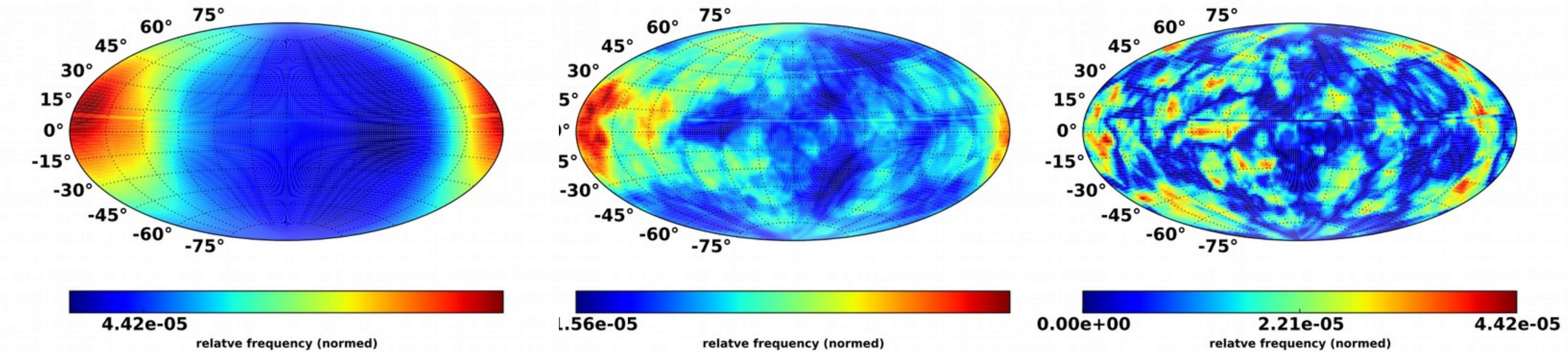
Distribution 1 (finer step size, before lensing)



R = 100 pc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

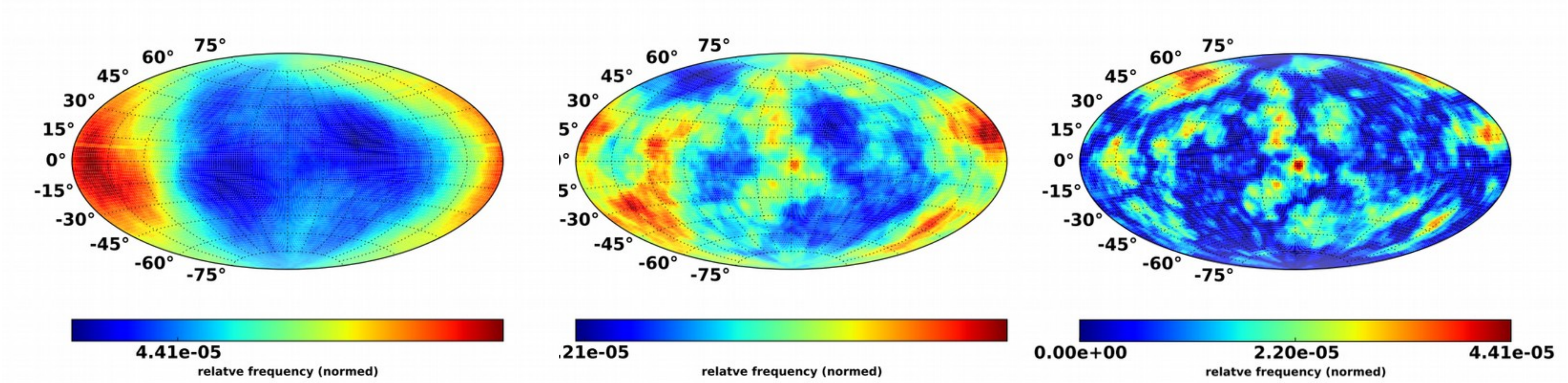
Distribution 1 (finer step size, after



R = 100 pc | R = 10 pc | Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

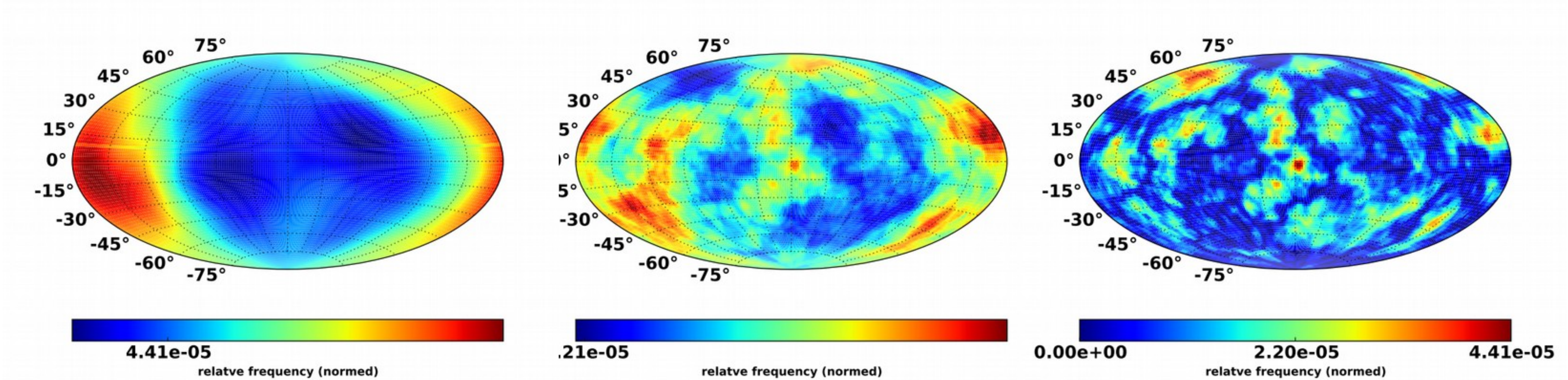
Distribution 2 (finer step size, before



R = 100 pc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

Distribution 2 (finer step size, after



R = 100 pc R = 10 pc Absolute value of residuals

- more realistic arrival direction distribution for all sphere sizes
- reduction of residuals by 20 – 30 %

Results and next steps

- Results:
  - CRs are (strongly) concentrated in the Galactic plane for <10^{19} eV
  - hardly any deflection > $10^{19.5}$ eV
  - track length isotropised < $10^{17.5}$ eV

    → no information on arrival direction/source position from track length for <10^{18} eV
  - “interesting region” inbetween (mainly 10^{18} – $10^{18.5}$ eV for protons)