Caustics* in UHE Cosmic Rays

G. Farrar, NYU

***Rapidly varying magnification and demagnification as a function of direction and rigidity**

GCOS Workshop, Jul 13, 2022

Deflections of UHECRs in the Galactic magnetic field

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The Galactic Magnetic Field and UHECR Optics

Glennys R. Farrar (New York U.), Nafiun Awal (New York U.), Deepak Khurana (New York U.), Michael Sutherland (Ohio State U., CCAPP) (Aug 19, 2015)

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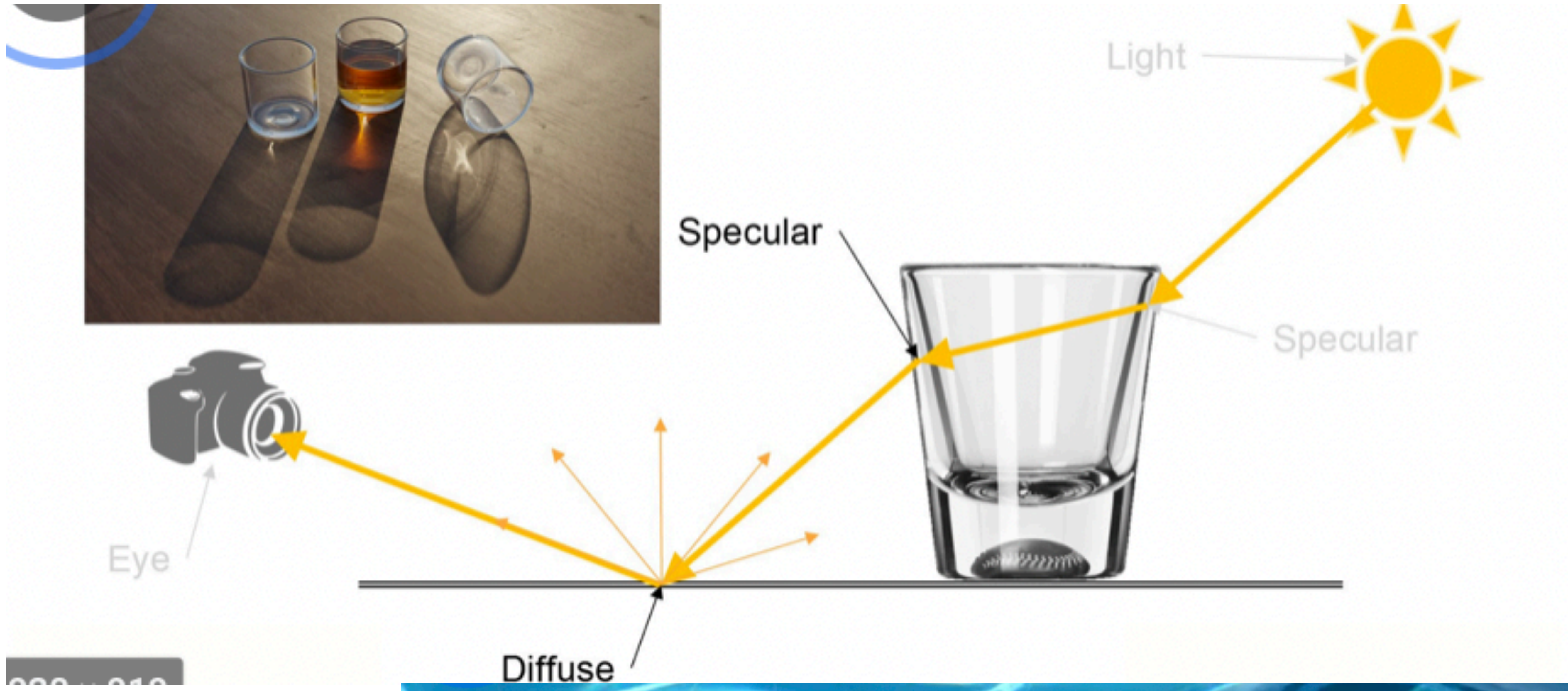
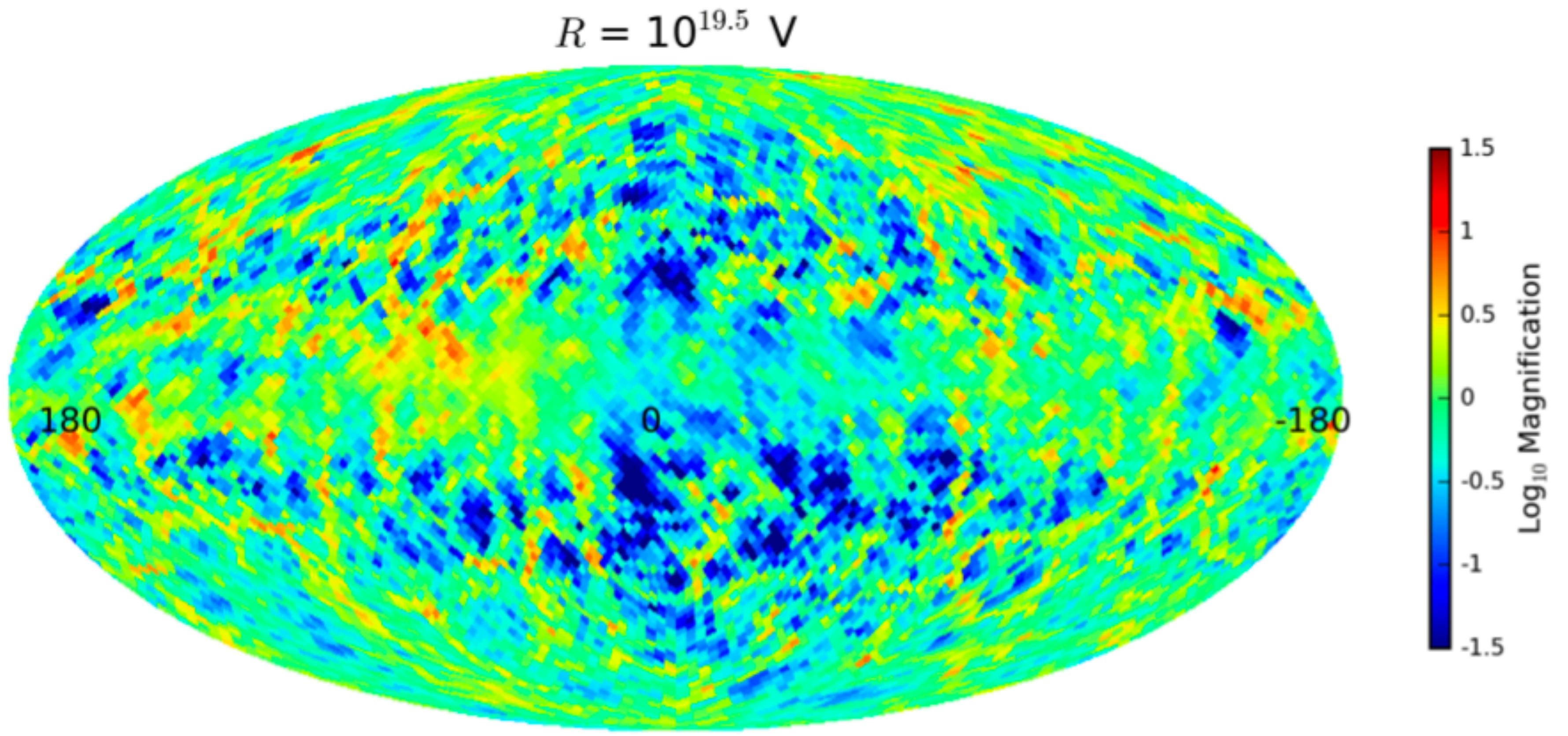
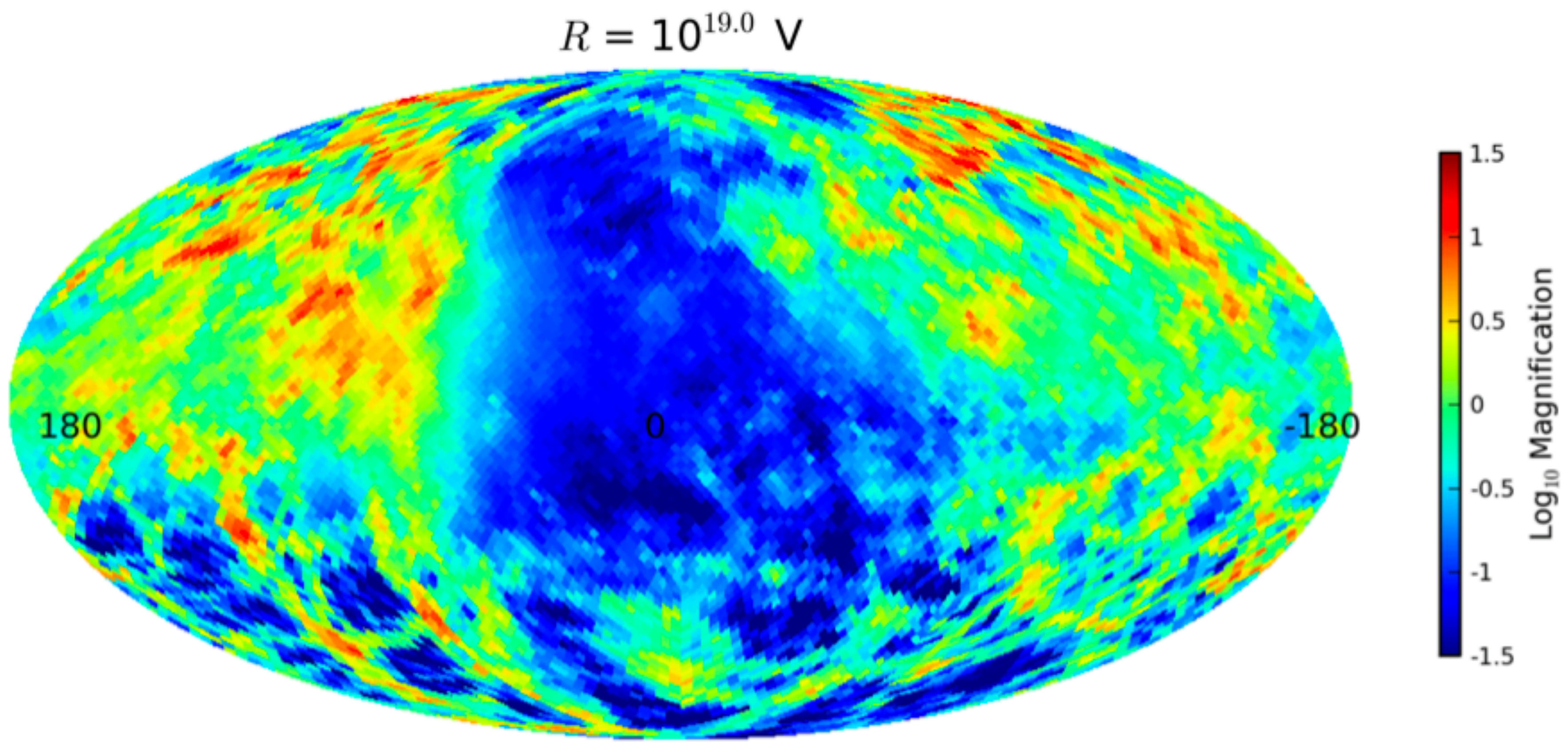
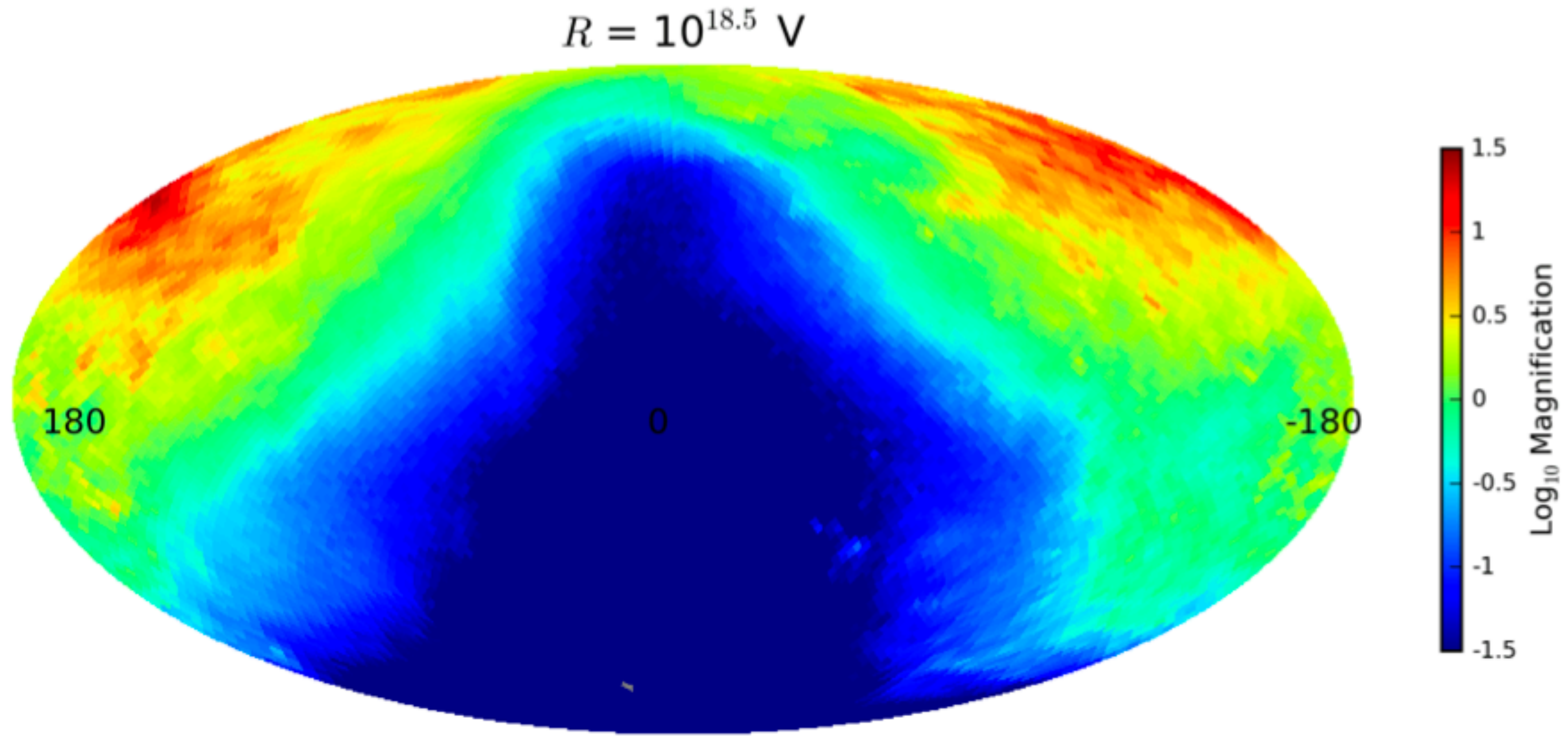

Light
Specular
Specular
Eye
Diffuse

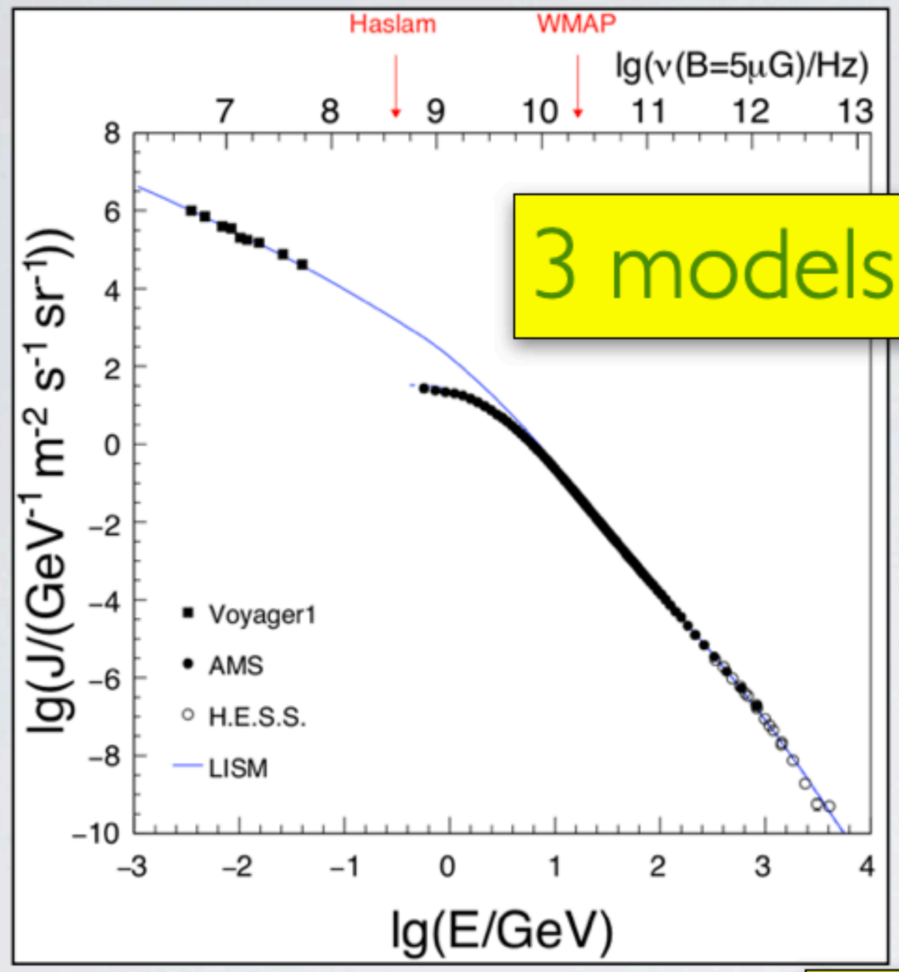

R = $10^{19.5}$ V
180
0
-180
1.5
1
0.5
0
-0.5
-1
-1.5
Log Magnification


R = $10^{19.0}$ V
180
0
-180
1.5
1
0.5
0
-0.5
-1
-1.5
Log Magnification

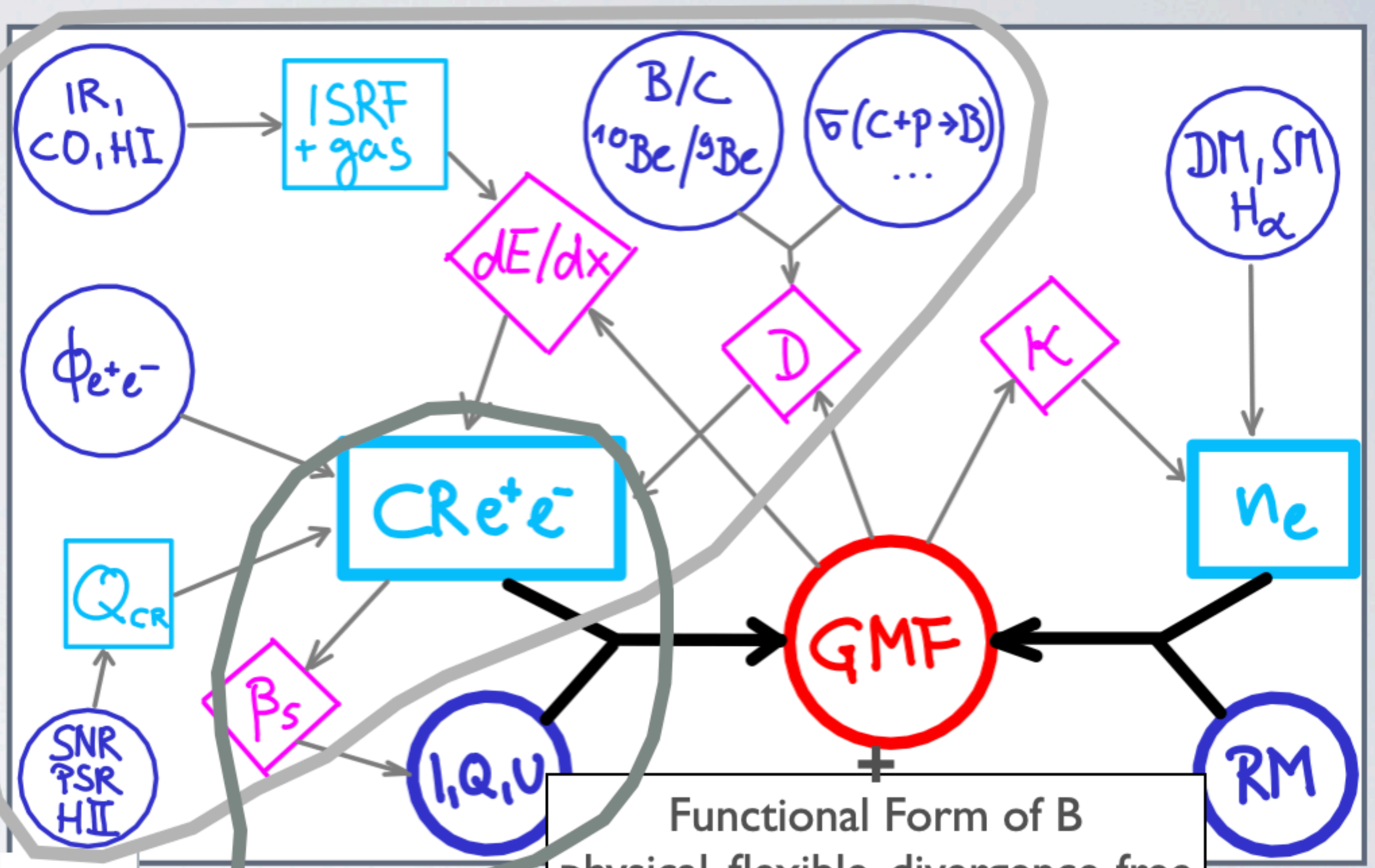

R = $10^{18.5}$ V
180
0
-180
1.5
1
0.5
0
-0.5
-1
-1.5
Log Magnification

PROGRESS MODELING THE GMF

M. Unger
G. Farrar



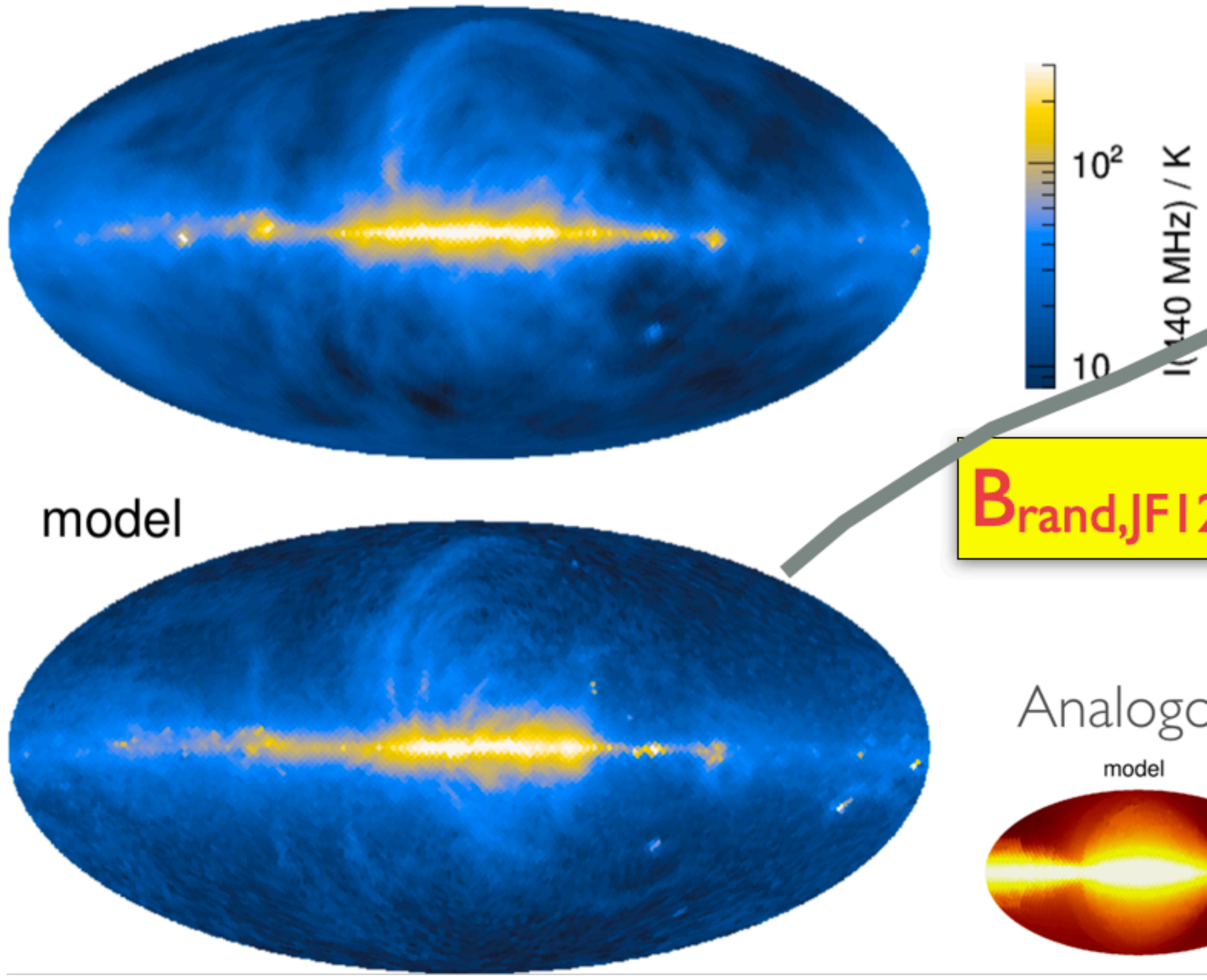
3 models of n_{cre}



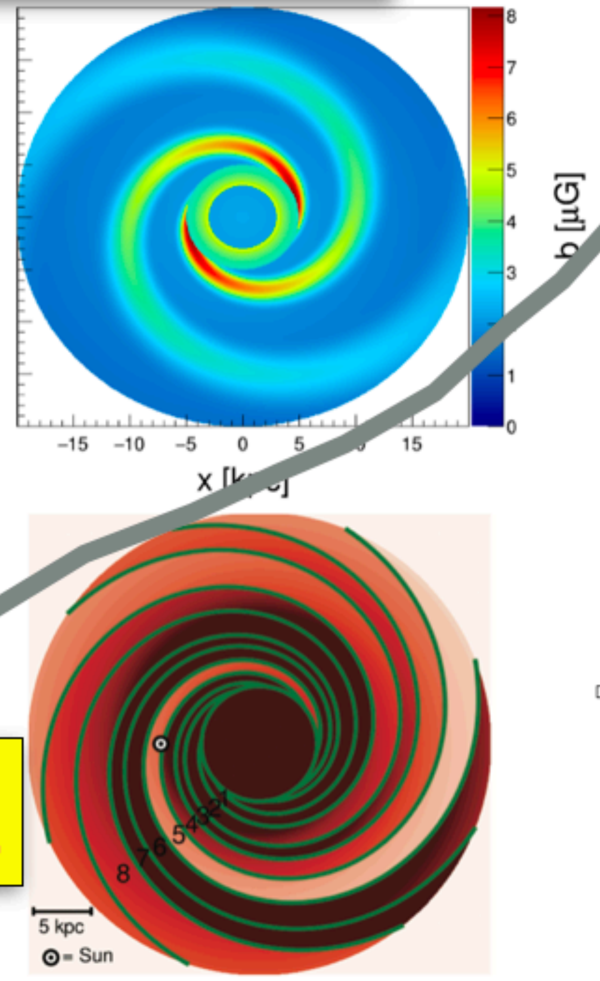
Functional Form of B
physical, flexible, divergence-free

Improved determination of synchrotron emission

Haslam intensity

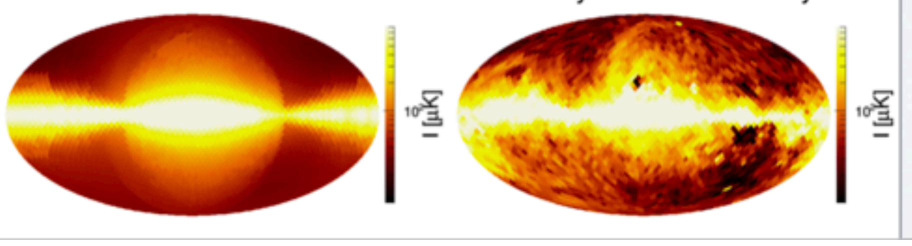


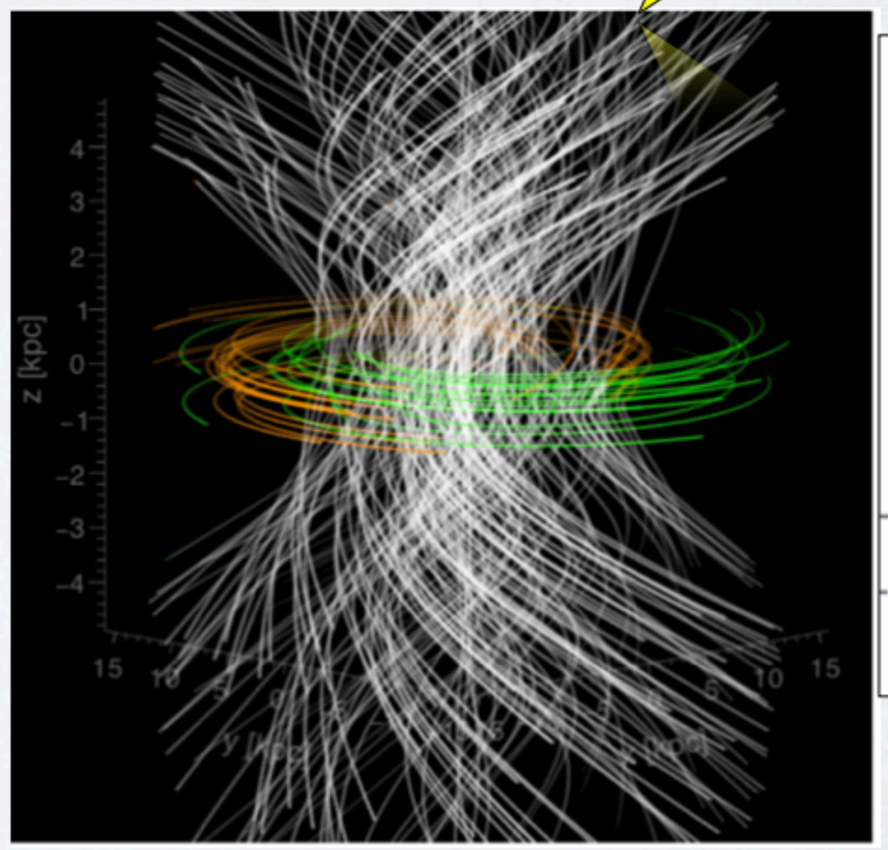
$B_{rand,UF19}$ (prelim)



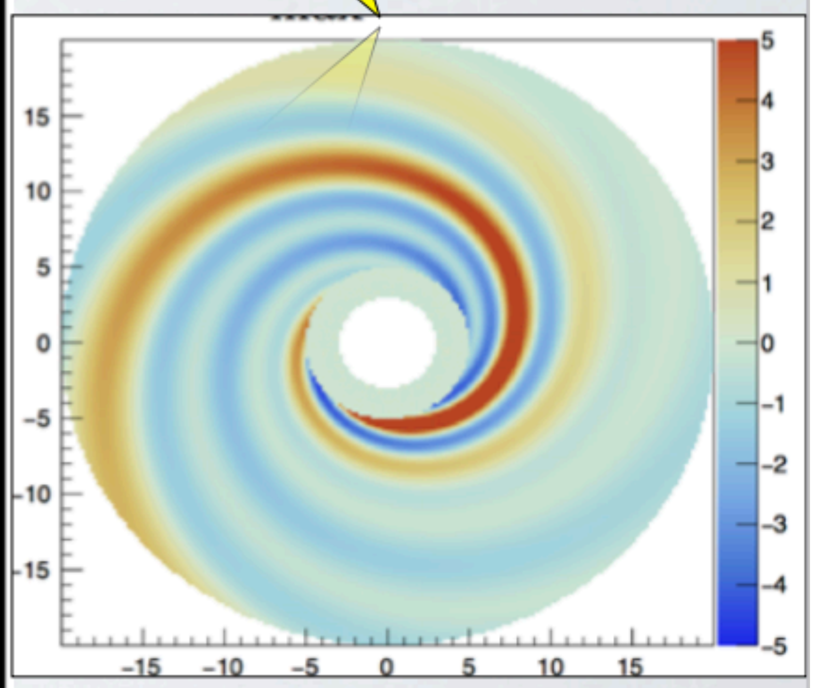
$B_{rand,JF12}$

Analogous comparison JF12

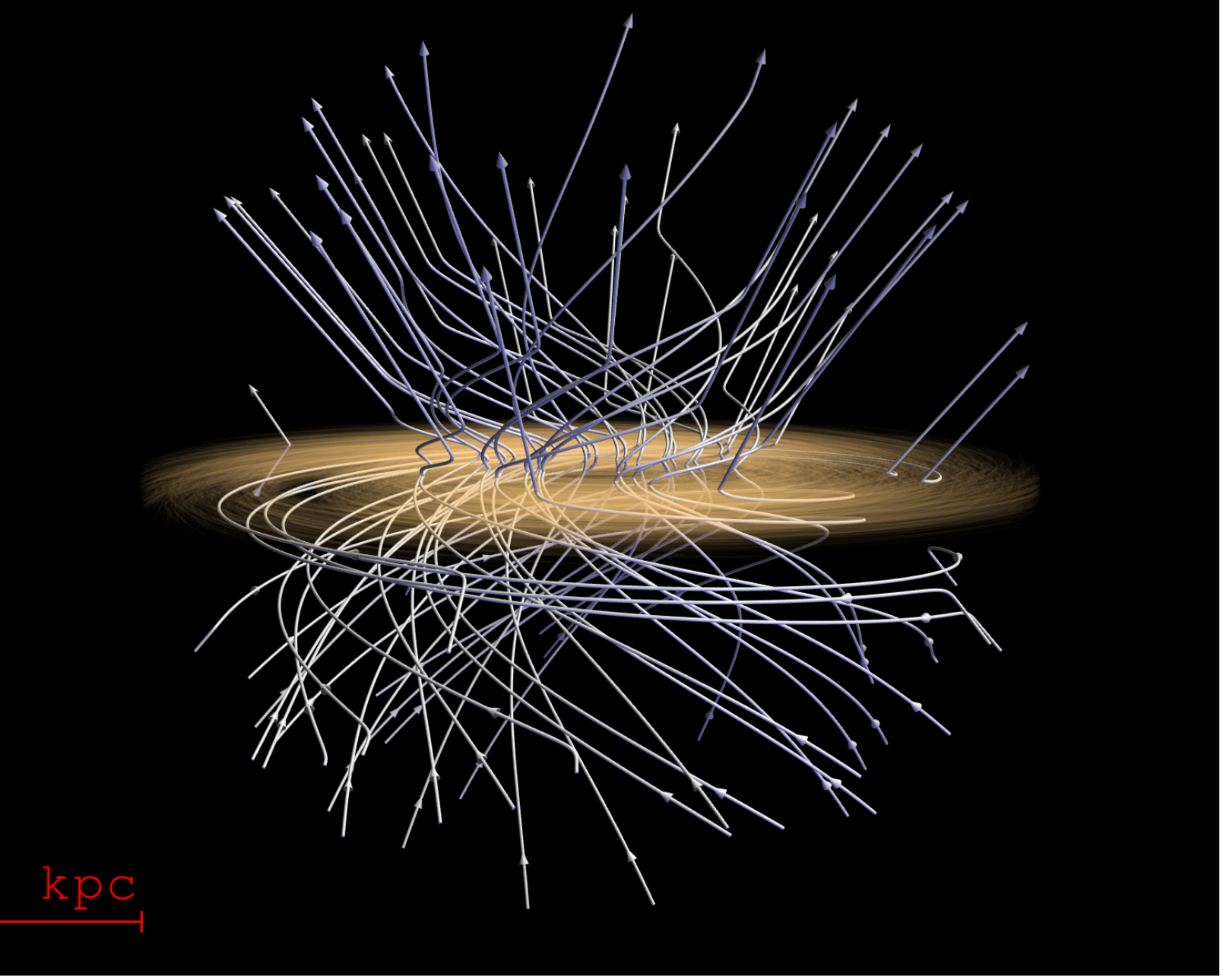




Toroidal field from differential rotation



Fourier spiral



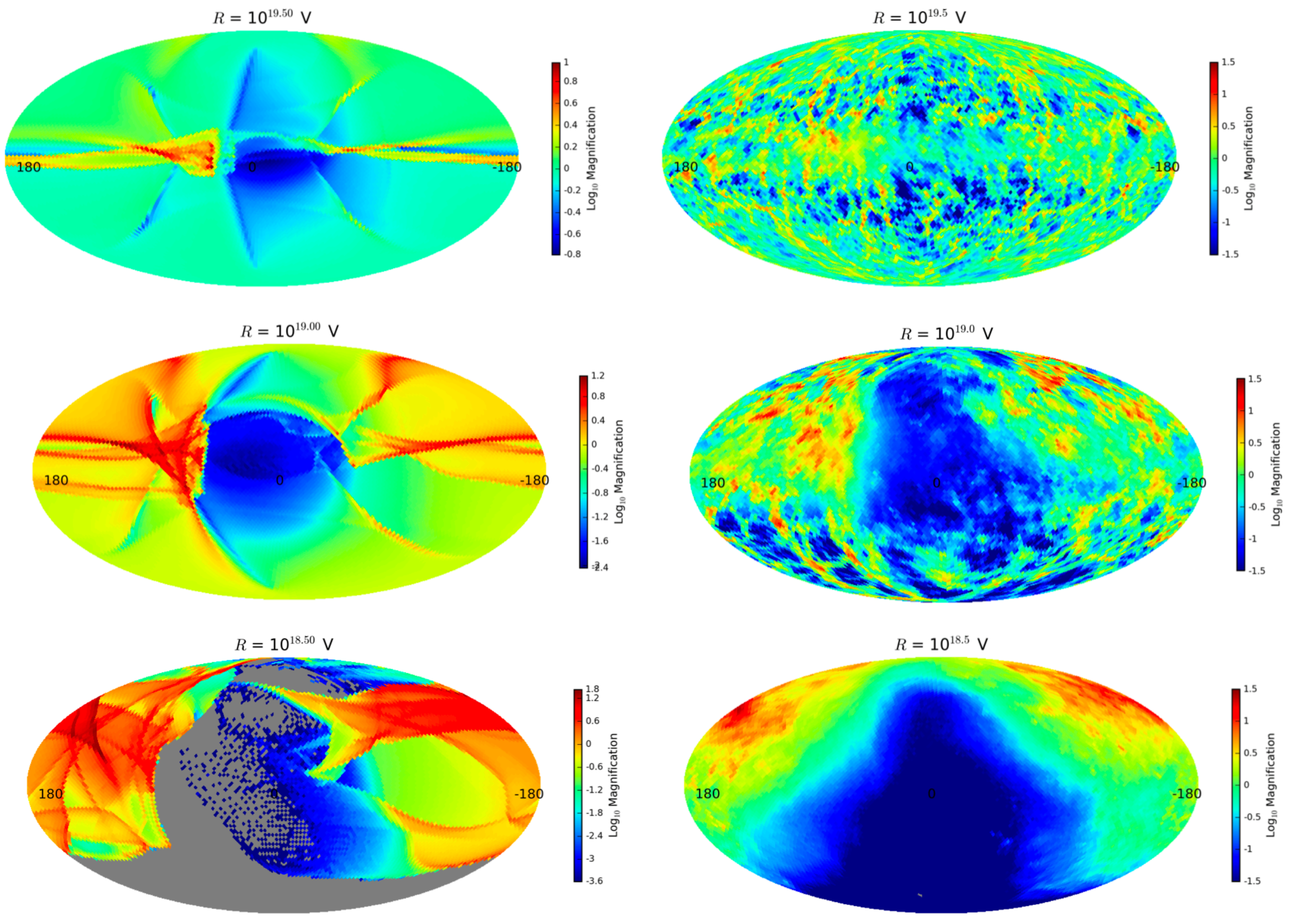
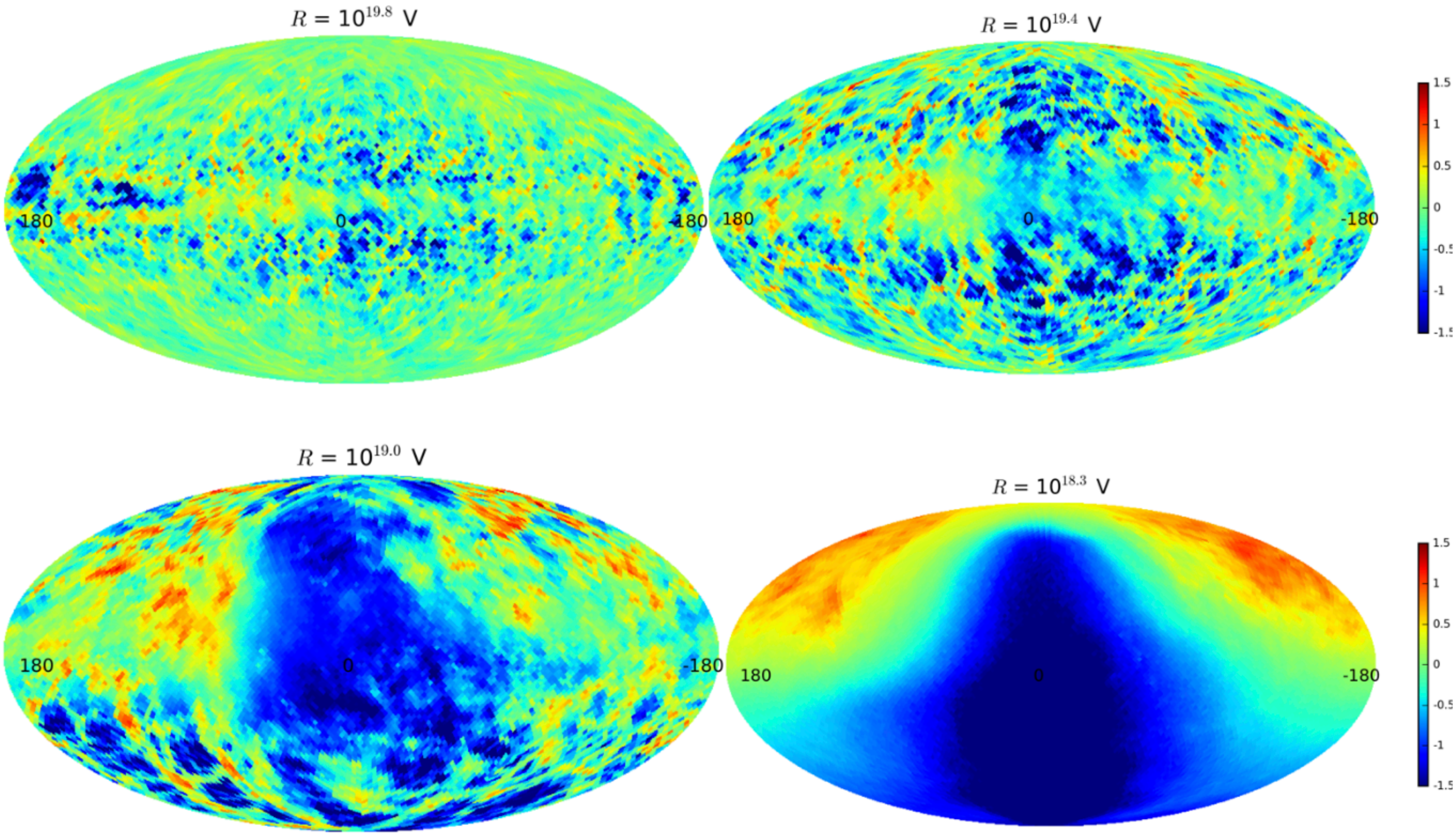


Figure 4. Magnification maps for $\log(R/\mathrm{V})$=19.5, 19.0, and 18.5 from top to bottom. The magnification is defined to be the flux from a standard source in the given direction, summed over its images, relative to the flux in the absence of the GMF. The left column shows the simulation results with only the coherent JF12 component and the right column shows the coherent plus the KRF6 turbulent realization with $L_{\mathrm{coh}} = 100$ pc. The colorbar shows the log10 factor of the magnification of each pixel. The linear features in the coherent-field-only maps on the left result from the abrupt



R = 10^19.8 V
R = 10^19.4 V
R = 10^19.0 V
R = 10^18.3 V
180
0
-180
1.5
1
0.5
0
-0.5
-1
-1.5

Key Features of UHECR Caustics

- Magnification rapidly changing in RIGIDITY
  - structure @ 0.1 in log_10 (E/Z)
  - composition a challenge!
- Present at all rigidities
- Rigidity dependence reveals scale of inhomogeneities
- Opportunity for serendipitous discovery
  - c.f. very high z sources via gravitational lensing

$\log R$	mag	$<\ell>$ (°)	$<b>$ (°)	$<\Delta>, \sigma_\Delta$ (°)
HPX 2: $\ell = 135°$, $b = 41.8103°$				
20.0	1.31 (0.88) {1.05}	132 (135) {135}	42 (42) {42}	2.1, 0.8 (0.5, 0.7) {0.6, 0.7}
19.8	1.18 (0.76) {1.07}	131 (134) {134}	43 (42) {43}	3.4, 0.8 (0.7, 0.6) {0.9, 0.7}
19.6	0.77 (0.71) {1.12}	128 (134) {134}	43 (43) {43}	5.4, 0.6 (1.5, 0.8) {1.5, 0.7}
19.5	0.54 (1.06) {1.16}	126 (133) {134}	43 (44) {43}	6.5, 0.5 (2.1, 0.8) {2.0, 0.8}
19.4	0.39 (1.23) {1.21}	125 (133) {133}	43 (44) {44}	7.8, 0.5 (2.5, 0.8) {2.6, 0.8}
19.2	0.07 (1.71) {1.37}	119 (131) {132}	42 (45) {46}	11.7, 2.2 (4.3, 1.3) {4.5, 0.8}
19.0	3.4 (1.45) {1.76}	146 (128) {128}	25 (49) {49}	19.0, 12.4 (8.4, 1.9) {8.6, 0.9}
18.8	6.64 (3.99) {4.59}	127 (101) {113}	27 (61) {58}	16.4, 23.6 (27.8, 8.1) {21.5, 2.3}
18.6	5.43 (2.37) {1.74}	132 (111) {102}	11 (−34) {−46}	30.8, 29.0 (79.2, 22.0) {92.7, 7.4}
18.5	3.81 (2.72) {2.68}	134 (103) {127}	−6 (−27) {−27}	48.0, 50.5 (74.6, 36.8) {68.9, 7.4}
18.4	4.92 (3.31) {3.01}	157 (99) {106}	−9 (−25) {−28}	54.8, 44.1 (74.9, 40.3) {75.0, 27.0}
18.3	3.24 (5.07) {5.53}	180 (111) {77}	−20 (−25) {−24}	74.8, 69.6 (70.3, 47.5) {85.2, 53.7}
18.2	4.19 (4.36) {1.1}	−167 (91) {11}	−12 (−29) {7}	75.6, 65.3 (81.3, 56.3) {109.4, 46.7}
18.1	7.75 (5.0) {8.01}	−162 (−154) {41}	8 (−26) {−55}	65.1, 49.7 (94.3, 70.9) {125.1, 25.6}
18.0	5.42 (3.53) {2.06}	152 (34) {23}	5 (1) {21}	39.4, 85.0 (97.8, 53.2) {91.2, 34.2}
HPX 3: $\ell = -135°$, $b = 41.8103°$				
20.0	1.14 (1.06) {1.01}	−135 (−135) {−135}	41 (41) {42}	1.3, 0.8 (0.4, 0.7) {0.4, 0.7}
19.8	1.15 (1.17) {1.01}	−136 (−135) {−135}	40 (41) {41}	2.0, 0.8 (0.6, 0.8) {0.6, 0.7}
19.6	1.04 (1.22) {1.02}	−136 (−136) {−136}	39 (41) {41}	3.1, 0.7 (0.9, 0.8) {0.9, 0.7}
19.5	1.26 (1.16) {1.03}	−137 (−136) {−136}	38 (41) {41}	3.6, 0.8 (1.2, 0.8) {1.1, 0.7}
19.4	1.27 (1.09) {1.04}	−137 (−136) {−136}	38 (41) {41}	4.2, 0.9 (1.4, 0.9) {1.4, 0.7}
19.2	3.63 (0.76) {1.06}	−139 (−137) {−137}	38 (40) {40}	4.7, 4.9 (2.2, 1.0) {2.3, 0.7}
19.0	2.9 (0.76) {1.11}	−135 (−138) {−138}	22 (39) {39}	19.9, 11.5 (3.7, 2.1) {3.9, 0.7}
18.8	2.25 (1.65) {1.2}	−141 (−141) {−141}	7 (35) {37}	34.9, 19.3 (8.0, 3.5) {6.5, 0.8}
18.6	2.53 (3.48) {2.07}	−134 (−142) {−140}	6 (7) {11}	36.3, 25.5 (35.4, 28.5) {30.9, 22.8}
18.5	3.73 (4.55) {4.54}	−159 (−136) {−136}	23 (1) {−1}	27.1, 53.4 (41.0, 33.1) {43.2, 32.4}
18.4	3.93 (4.89) {5.33}	−36 (−130) {−136}	11 (4) {5}	89.7, 79.3 (37.7, 37.4) {37.3, 23.6}
18.3	6.24 (5.32) {3.62}	60 (−93) {−38}	32 (4) {−4}	104.4, 57.5 (53.0, 64.0) {98.0, 30.4}
18.2	5.77 (3.82) {1.81}	79 (−109) {−60}	34 (30) {53}	98.1, 44.0 (24.4, 47.3) {49.8, 8.0}
18.1	1.71 (3.24) {2.04}	93 (−118) {−97}	16 (33) {60}	107.4, 75.4 (16.2, 44.3) {29.5, 9.3}
18.0	2.47 (2.89) {2.25}	67 (−123) {−138}	4 (23) {51}	130.2, 83.6 (21.8, 54.8) {9.4, 12.2}

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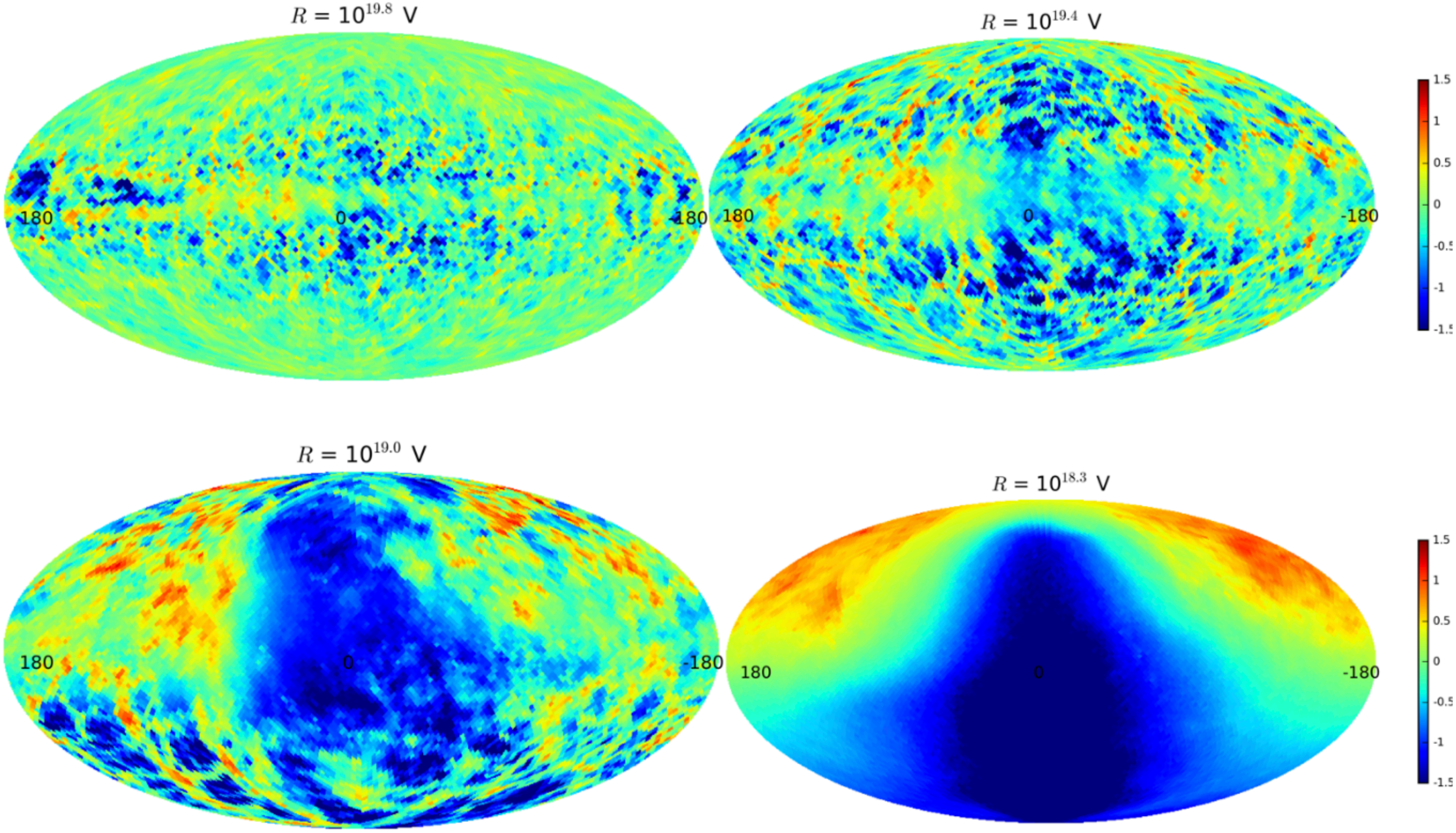

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