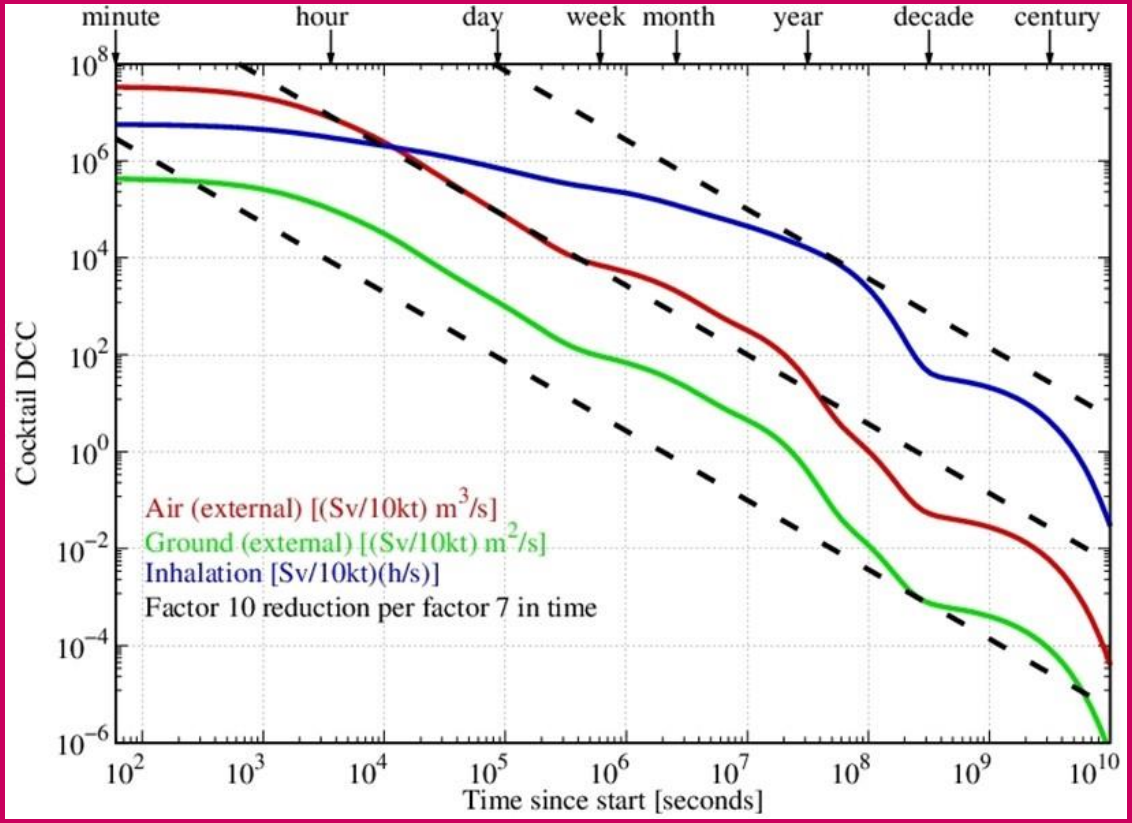

National Institute for Public Health
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Ministry of Health, Welfare and Sport

NOVEL METHOD FOR RADIATION DOSE ESTIMATION APPLIED TO DISPERSION SIMULATIONS OF NUCLEAR DETONATIONS

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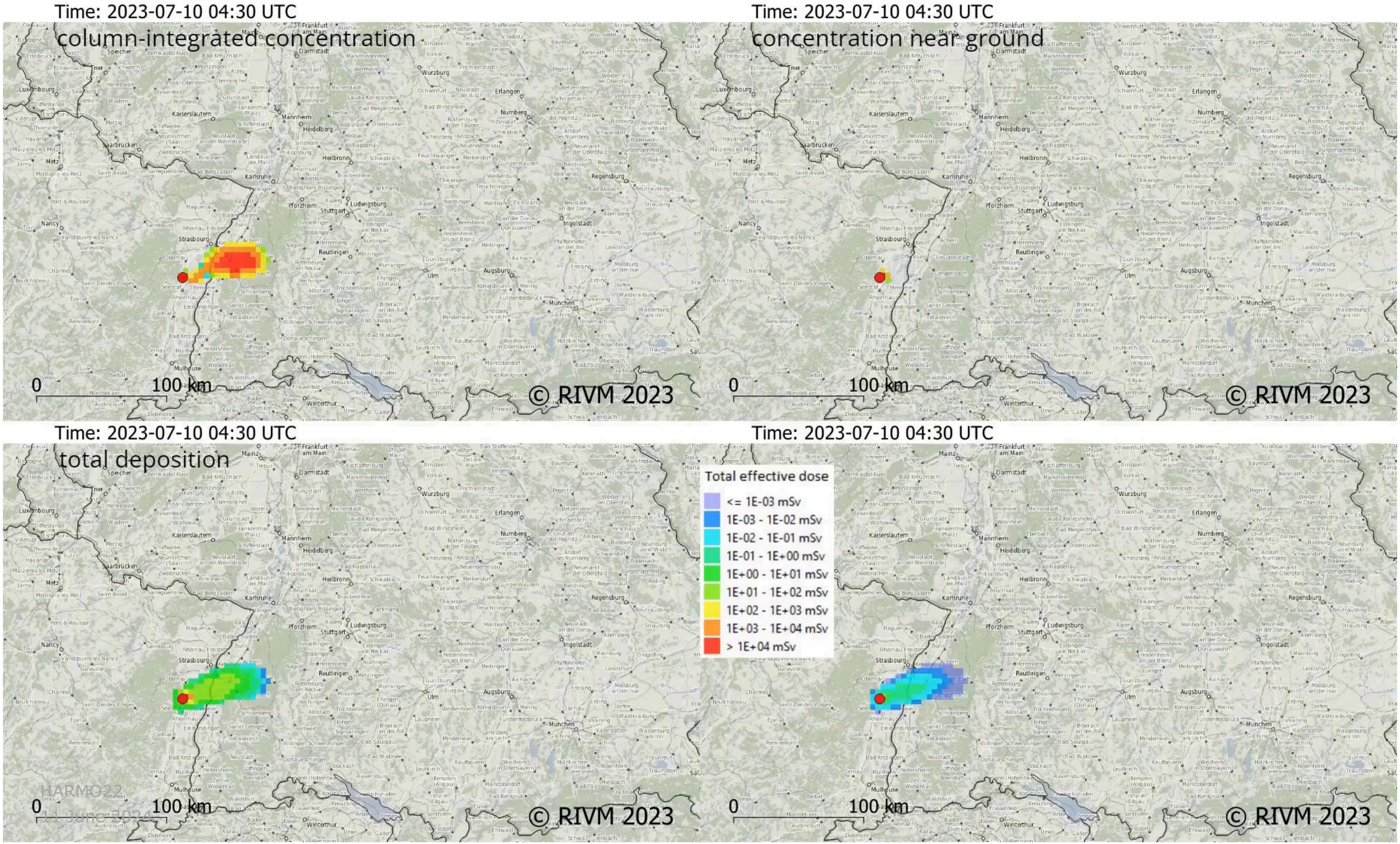
Presentation lay-out

- Example of dispersion of nuclear weapon fall-out
- How do we do the radionuclide decay
  - Application of new decay-method
- Simulation of a nuclear cloud
  - Definition of a nuclear cloud
- Conclusions


Time: 2023-07-10 04:30 UTC
column-integrated concentration
Time: 2023-07-10 04:30 UTC
concentration near ground
Time: 2023-07-10 04:30 UTC
total deposition
Time: 2023-07-10 04:30 UTC
Total effective dose
<= 1E-03 mSv
1E-03 - 1E-02 mSv
1E-02 - 1E-01 mSv
1E-01 - 1E+00 mSv
1E+00 - 1E+01 mSv
1E+01 - 1E+02 mSv
1E+02 - 1E+03 mSv
1E+03 - 1E+04 mSv
> 1E+04 mSv
0
100 km
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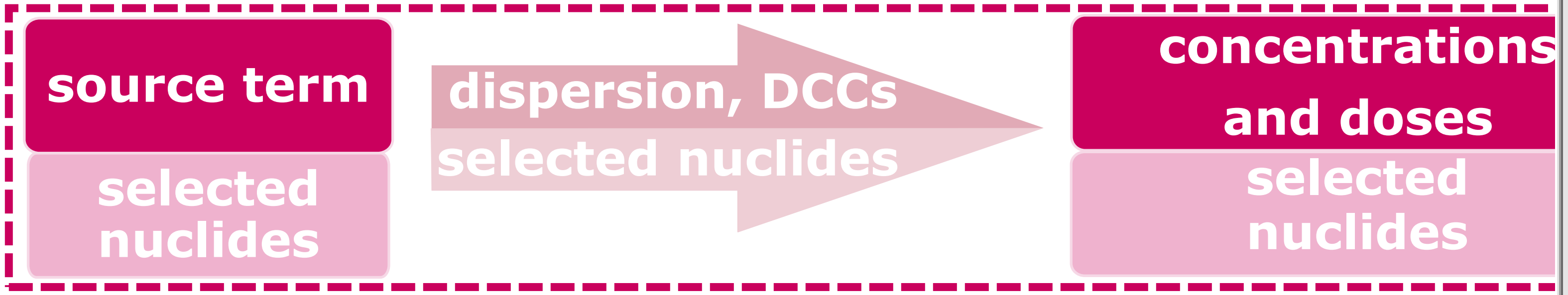
Traditional - radionuclide composi

atmospheric dispersion and dose model chain - *t*

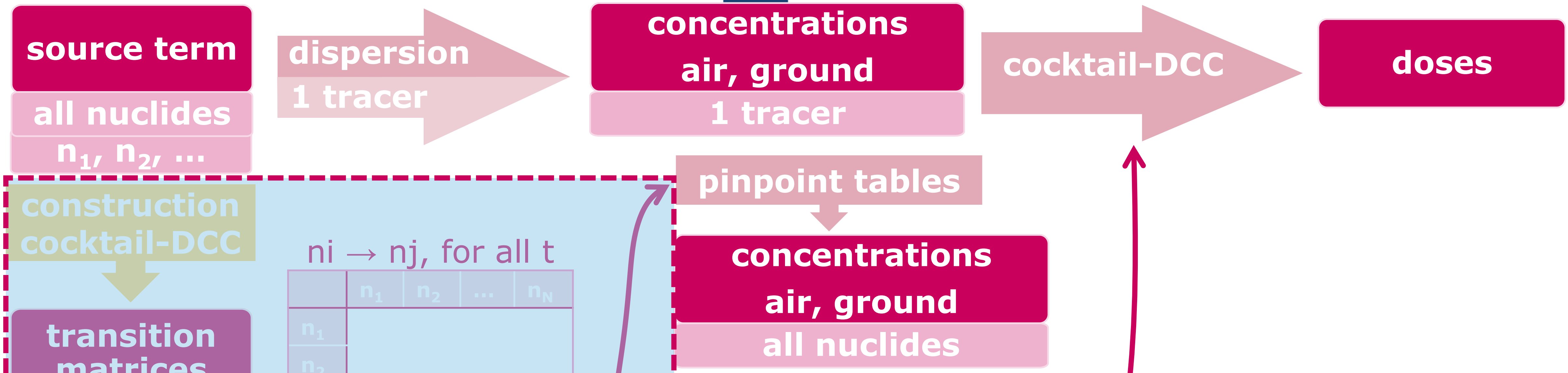


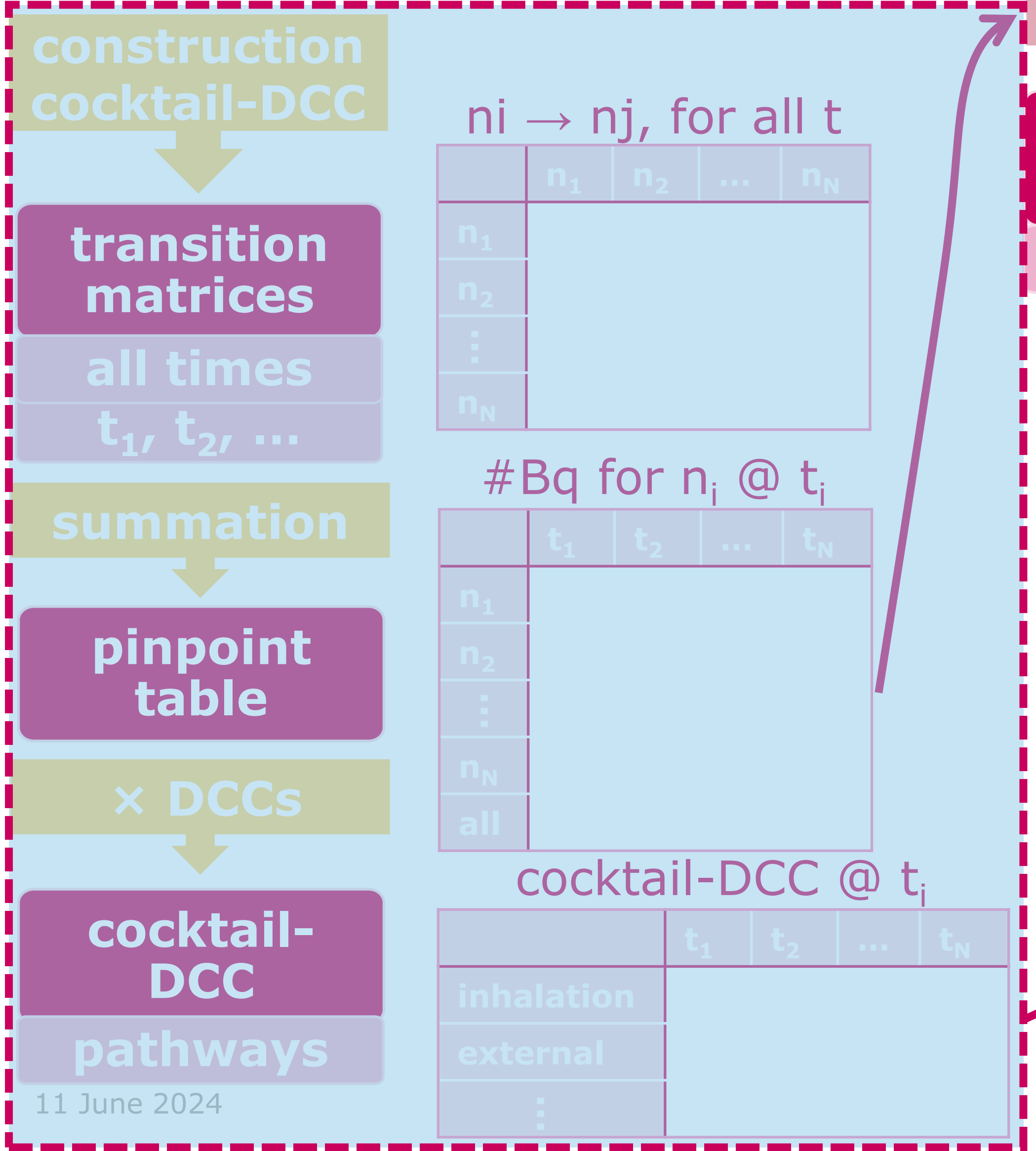
- High computational costs
- Large list of radionuc
- Limit progeny inclusion

I-132	3.38E+17
I-132m	4.34E+17
I-133	6.70E+17
I-134	1.99E+19
I-134m	2.00E+19
I-135	4.98E+18
Xe-131m	6.98E+11
Xe-133	8.32E+14
Xe-133m	2.44E+15
Xe-135	4.48E+17
Xe-135m	1.28E+19
Xe-137	8.68E+19
Xe-138	8.58E+19
Cs-136	2.16E+15
Cs-137	1.09E+14
Cs-138	2.46E+19
Cs-139	1.13E+20
Ba-137m	4.62E+16
Ba-139	1.23E+19
Ba-140	1.07E+17
Ba-141	7.36E+19
Ba-142	9.22E+19
La-140	3.00E+15
La-141	2.44E+18
La-142	9.72E+18
La-143	8.08E+19
Ce-141	1.85E+14
Ce-143	3.48E+17
Ce-144	4.14E+15
Ce-145	4.78E+19
Ce-146	4.36E+19
Pr-144	1.31E+16
Pr-145	3.08E+18
Pr-146	1.38E+19
Pr-147	3.44E+19
Nd-147	1.61E+16
Nd-149	3.94E+18
Nd-151	1.24E+19
Pm-151	6.56E+16
Pb-203	2.16E+17
U-237	6.96E+17
U-239	2.14E+20
Np-239	5.08E+17

New method – Cocktail-DCC

- Separate dispersion from nuclear decay characteristics
- Pre-calculate nuclear decay characteristics
- Pre-calculate time dependent conversion for dose and activity
- Not only applicable to radiological cases but also chemical, biological, or ….





precalculated

accurate:
- including all radionuclides (3821) with progeny
- no nuclide selection (endpoint-dependent)
    - relevant for measurements
- 200 timesteps between 60 sec and 2.6 million year (exponentially distributed)

computationally efficient
- one tracer
- precalculated lookup tables

Pinpoints with logarithmic intervals

FirstDelay: 60.0 DelayGrowthFactor: 1.15000 NStartingTimes: 200

Pinpoint	t[s]	SumDoseRate	Mn-54	Mn-56	Co-58	Co-58m	Sr-89	Sr-90	Sr-91	Sr-92	Y-92	Y-93	Y-94	Y-95
0	0.0000	0.37203E+06	0.43658E-01	7905.0	0.27366	0.42618E-04	0.66867E-05	0.44183E-07	706.33	4769.3	1.1152	1.6240	25657.	65067.
1	60.000	0.35766E+06	0.43658E-01	7869.7	0.27366	0.38752E-03	0.69760E-05	0.44391E-07	709.80	4752.1	1.1116	1.6222	24723.	60832.
2	69.000	0.35557E+06	0.43658E-01	7864.4	0.27366	0.43922E-03	0.69831E-05	0.44422E-07	710.31	4749.5	1.1110	1.6219	24586.	60221.
3	79.350	0.35318E+06	0.43658E-01	7858.3	0.27366	0.49866E-03	0.69885E-05	0.44458E-07	710.90	4746.6	1.1104	1.6216	24429.	59526.
4	91.252	0.35046E+06	0.43658E-01	7851.3	0.27366	0.56700E-03	0.69923E-05	0.44499E-07	711.58	4743.2	1.1097	1.6212	24250.	58737.
5	104.94	0.34736E+06	0.43658E-01	7843.3	0.27366	0.64557E-03	0.69948E-05	0.44546E-07	712.35	4739.2	1.1089	1.6208	24046.	57842.
6	120.68	0.34385E+06	0.43658E-01	7834.1	0.27366	0.73590E-03	0.69963E-05	0.44601E-07	713.24	4734.7	1.1079	1.6203	23813.	56830.
7	138.78	0.33987E+06	0.43658E-01	7823.5	0.27366	0.83974E-03	0.69971E-05	0.44664E-07	714.25	4729.6	1.1068	1.6197	23549.	55688.
8	159.60	0.33536E+06	0.43658E-01	7811.4	0.27366	0.95911E-03	0.69975E-05	0.44736E-07	715.41	4723.6	1.1056	1.6191	23248.	54403.
9	183.54	0.33027E+06	0.43658E-01	7797.4	0.27366	0.10963E-02	0.69976E-05	0.44819E-07	716.74	4716.8	1.1041	1.6184	22906.	52962.
10	211.07	0.32455E+06	0.43658E-01	7781.4	0.27365	0.12540E-02	0.69976E-05	0.44914E-07	718.25	4709.0	1.1025	1.6175	22520.	51352.
11	242.73	0.31812E+06	0.43658E-01	7763.0	0.27365	0.14352E-02	0.69976E-05	0.45024E-07	719.97	4700.0	1.1006	1.6166	22084.	49560.
12	279.14	0.31094E+06	0.43658E-01	7742.0	0.27365	0.16435E-02	0.69976E-05	0.45150E-07	721.92	4689.7	1.0984	1.6154	21593.	47577.
13	321.02	0.30295E+06	0.43658E-01	7717.8	0.27365	0.18828E-02	0.69975E-05	0.45296E-07	724.15	4677.9	1.0959	1.6142	21041.	45395.
14	369.17	0.29410E+06	0.43658E-01	7690.1	0.27365	0.21578E-02	0.69975E-05	0.45462E-07	726.67	4664.3	1.0930	1.6127	20425.	43008.
15	424.54	0.28434E+06	0.43658E-01	7658.4	0.27365	0.24736E-02	0.69974E-05	0.45654E-07	729.52	4648.8	1.0897	1.6110	19738.	40419.
16	488.22	0.27366E+06	0.43658E-01	7622.0	0.27365	0.28364E-02	0.69974E-05	0.45875E-07	732.74	4631.0	1.0860	1.6091	18976.	37633.
17	561.46	0.26204E+06	0.43658E-01	7580.5	0.27364	0.32530E-02	0.69973E-05	0.46129E-07	736.36	4610.6	1.0817	1.6068	18137.	34666.
18	645.68	0.24950E+06	0.43658E-01	7533.0	0.27364	0.37312E-02	0.69972E-05	0.46420E-07	740.42	4587.2	1.0767	1.6043	17217.	31542.
19	742.53	0.23609E+06	0.43657E-01	7478.7	0.27364	0.42802E-02	0.69971E-05	0.46755E-07	744.95	4560.5	1.0711	1.6014	16217.	28295.
20	853.91	0.22190E+06	0.43657E-01	7416.8	0.27363	0.49100E-02	0.69970E-05	0.47141E-07	749.99	4530.0	1.0646	1.5980	15139.	24973.

Dose Conversion Coefficients

ICRP 119

ICRP 144

Radionuclide decay and dose estimation

- Radionuclide decay
  - Matrix exponential
  - Logarithmic steps

- Dose Coefficients
  - ICRP 119
  - ICRP 144

Dose conversion factors (DCCs) from:
<u>Inhalation:</u>
Eckerman et al. (2013) (ICRP 119)
Kawai et al. (2002)
<u>External radiation:</u>
EDC-Viewer, conform ICRP Publication 144 (Petoussi-Henss et al., 2020)

Formulae to solve nuclear decay

- Following van Dillen et al. (2019):

$$A_i(t) = \sum_j H_{ij}(t) A_j(0)$$

- With:

$$H(t) = e^{Mt},$$

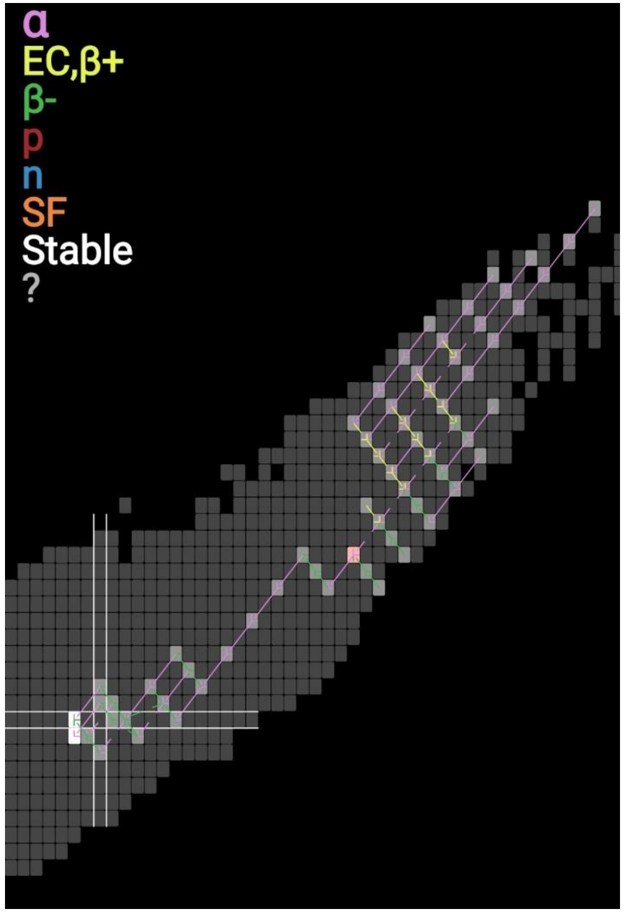
- Where matrix M is defined as:

$$M_{ij} = \nu_{ij}\lambda_i,$$

ν_{ij}=yield if i≠j (production)

ν_{ij}=-1 for i=j (decay)

Full detail: Van Dijk et al. (2024), to be published



Source: IAEA isotope browser

Adding dispersion

$$DCC_{\mathrm{air,cocktail}}(t) = \sum_i DCC_{\mathrm{air},i} \sum_j H_{ij}(t) A_j(0)$$

$$D_{\mathrm{ext,air}}(\boldsymbol{x}, t_1 \to t_2) = \int_{t_1}^{t_2} \sum_i DCC_{\mathrm{ext,air},i}\, \rho_i(\boldsymbol{x}, \tau)\, \mathrm{d}\tau$$

$$T_{\mathrm{air}}(\boldsymbol{x}, \tau) = \rho_{\mathrm{passive}}(\boldsymbol{x}, \tau) / A_{\mathrm{passive}}(0)$$

$$D_{\mathrm{ext,air}}(\boldsymbol{x}, t_1 \to t_2) = \int_{t_1}^{t_2} DCC_{\mathrm{ext,air,cocktail}}(\tau)\, T_{\mathrm{air}}(\boldsymbol{x}, \tau)\, \mathrm{d}\tau$$

- $\rho_i(\boldsymbol{x}, \tau)$ is concentration of a nuclide or tracer

- The dispersion calculation is reduced to a *single* non-decaying tracer to determine ‘thinning coefficients’. $T_{\mathrm{air}}(\boldsymbol{x}, \tau)$ and $T_{\mathrm{ground}}(\boldsymbol{x}, \tau)$.

Radioactivity	1. has same origin in time 2. does not ‘unmix’

Source terms of nuclear detonations

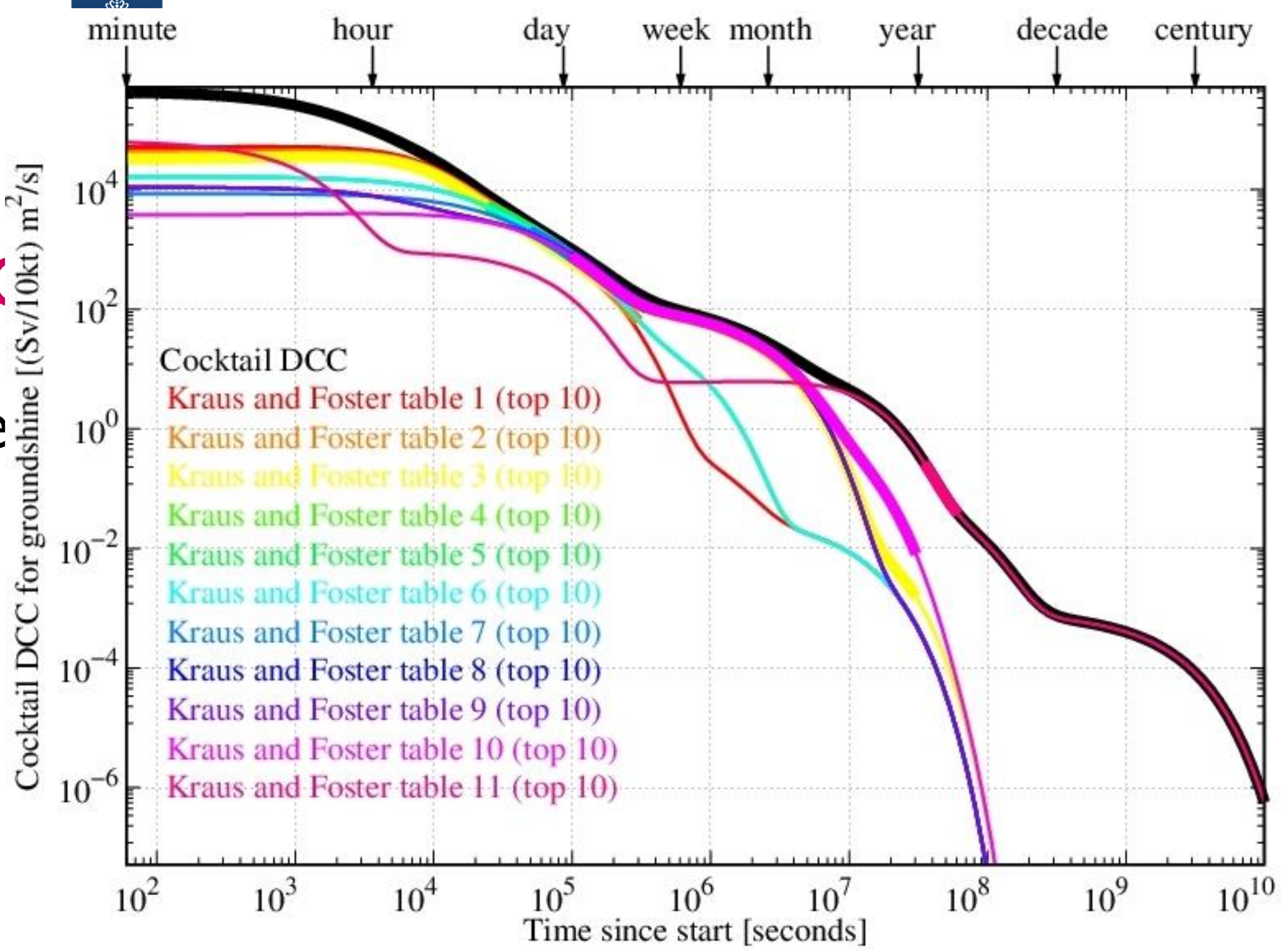
- Kraus and Foster (2014)
  - Selection of 69 nuclides

- Axelsson et al. (2023)
  - Selection of 129 nuclides

- Based on Hicks (1982)

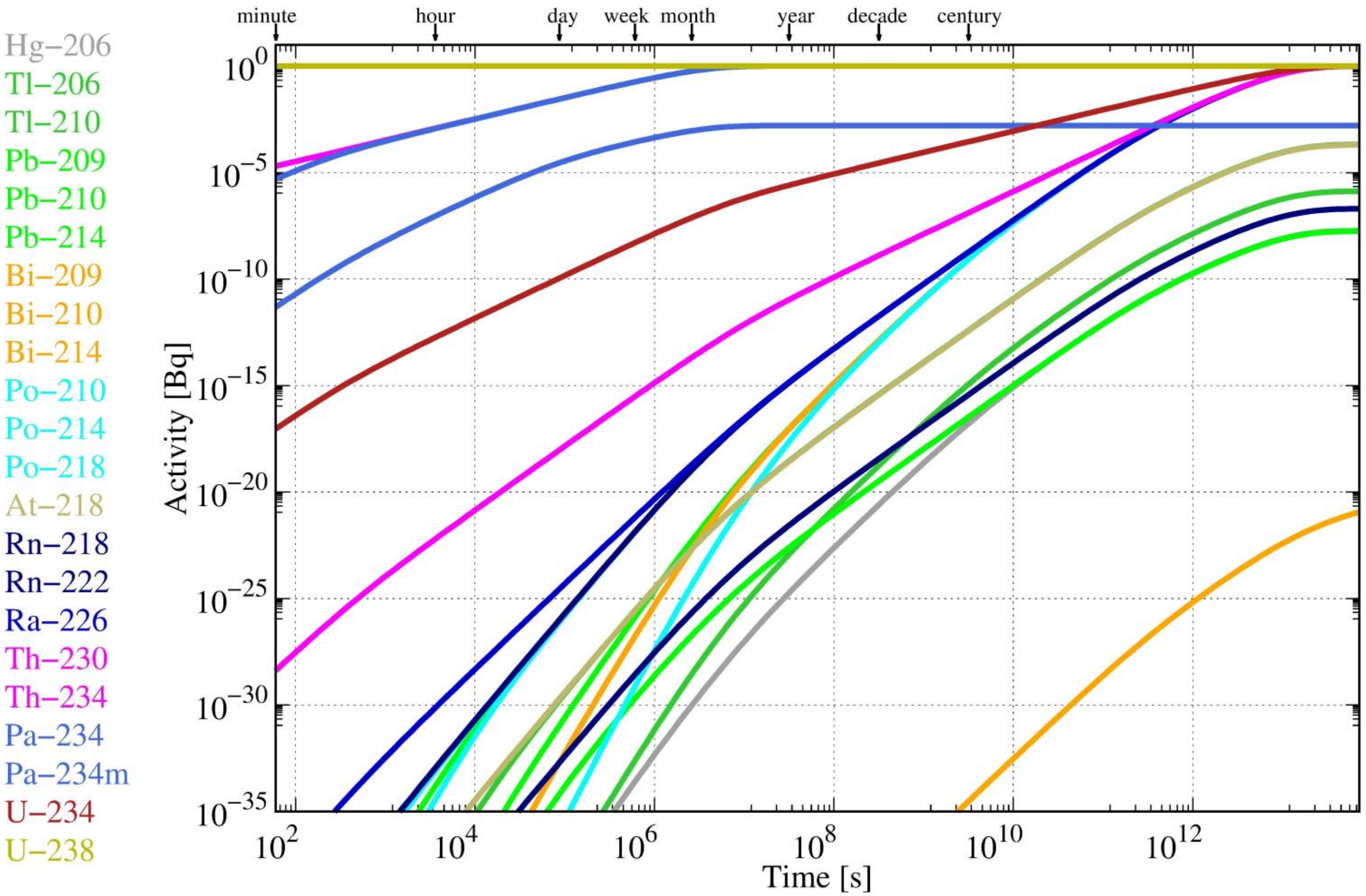
Estimation of accurac

- Sourceterm: Kraus and Foste
(2014)



Examples of applica

- Ingrowth of 1 Bq U-238
- $T_{1/2}^{238U} = 1.41 \cdot 10^{17}$ sec



Modelling dispersion and dose of fallout from nuclear detonation

- **Radionuclide composition**
  - initial composition
  - decay and ingrowth of progeny
  - dose calculation for a large number of radionuclides

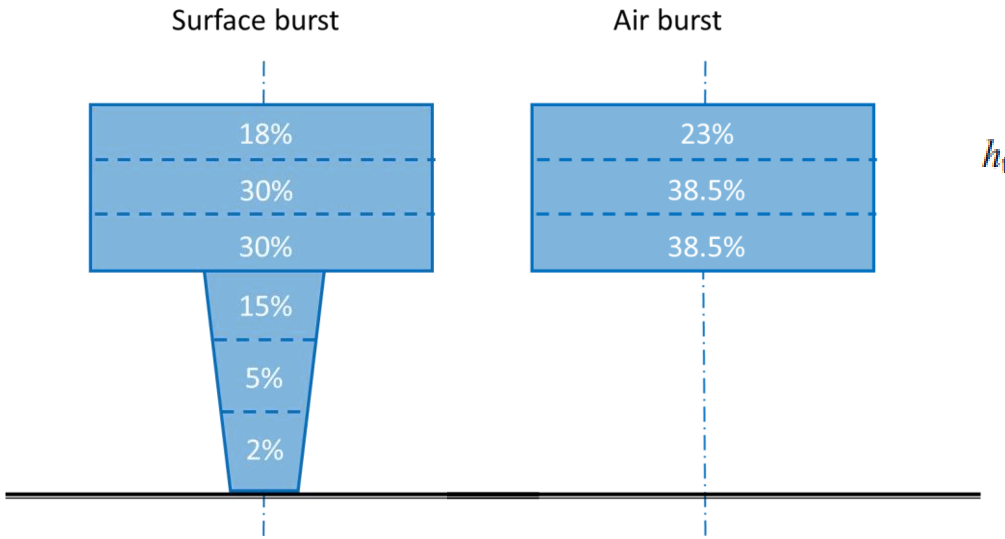
- **Stabilized cloud characteristics**
  - geometry based on yield, height of burst, etc.
  - distribution of radioactivity
  - particle size distribution

Stabilized cloud characteristics

vertical distribution of radioactivity:

Initial cloud geometry:
KDFOC3 – emperical
Harvey (1992)

Distribution:
Heffter (1969)



$$h_{\text{top}} = \begin{cases} 3730\ Y^{0.229} & \text{if } Y \leq 2 \\ 3330\ Y^{0.393} & \text{if } 2 < Y \leq 20\,. \\ 6360\ Y^{0.177} & \text{if } Y > 20. \end{cases}$$

$$\begin{aligned} r_{\text{stem,top}}[m] &= r_{\text{hat}}/3 \\ r_{\text{stem,bottom}}[m] &= 3 r_{\text{fireball}} \end{aligned}$$

Radioactivity normally distributed in layers

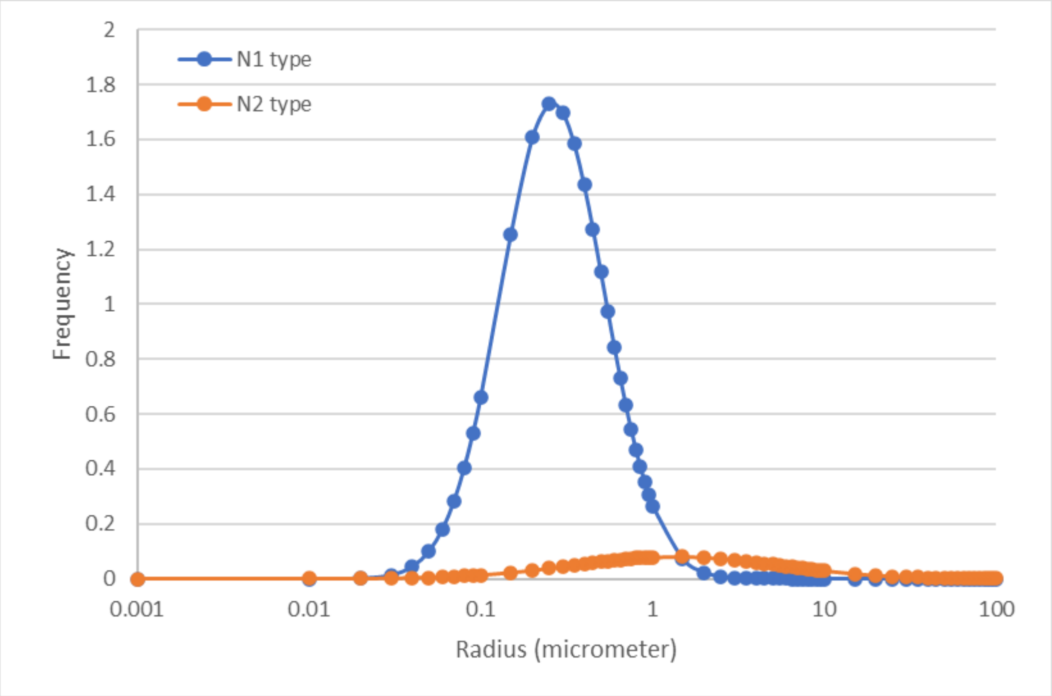
Particle size distribution

- Bi-modal normal log-function
  - N1 is condensed particle
  - N2 is dust particles

particle size distribution:

St Ledger (2015) interpretation of Baker (1987)

Particle radius	Median radius	Surface burst	Air burst
(in µm)		fraction of total activity (in %)	
< 0.1	0.05	0.44	1.63
0.1-1	0.55	22.47	76.05
1-5	3	20.11	9.30
5-10	7.5	12.63	0.02
10-50	30	23.96	0
> 50	100	7.38	0
Gaseous	-	13	13
	Total	100.00	100.00



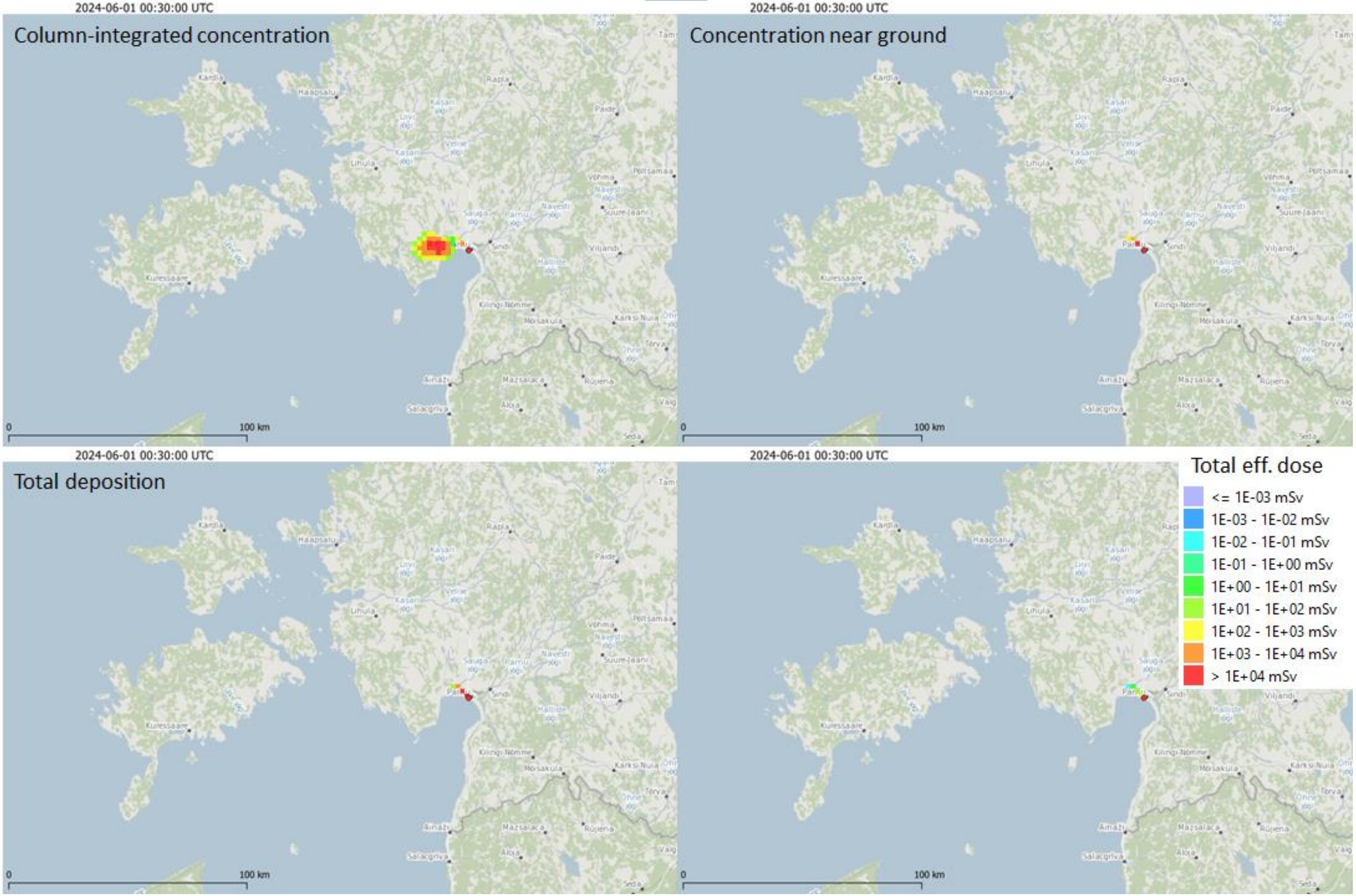
Possible improvements

- Multiple-tracer simulations
- Adding shielding
- Include chemical transitions

Summary

- New method for decay chain calculations
  - Applicable on many different issues

- Extended modelling for nuclear detonations with method for accurate and fast estimation of radiological effects of fallout (accepted for publication - GitHub)
  - https://github.com/rivm-syso/Cocktail-DCC


2024-06-01 00:30:00 UTC
Column-integrated concentration
0
100 km
2024-06-01 00:30:00 UTC
Concentration near ground
0
100 km
2024-06-01 00:30:00 UTC
Total deposition
0
100 km
2024-06-01 00:30:00 UTC
Total eff. dose
<= 1E-03 mSv
1E-03 - 1E-02 mSv
1E-02 - 1E-01 mSv
1E-01 - 1E+00 mSv
1E+00 - 1E+01 mSv
1E+01 - 1E+02 mSv
1E+02 - 1E+03 mSv
1E+03 - 1E+04 mSv
> 1E+04 mSv
0
100 km

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Thank you for your attention

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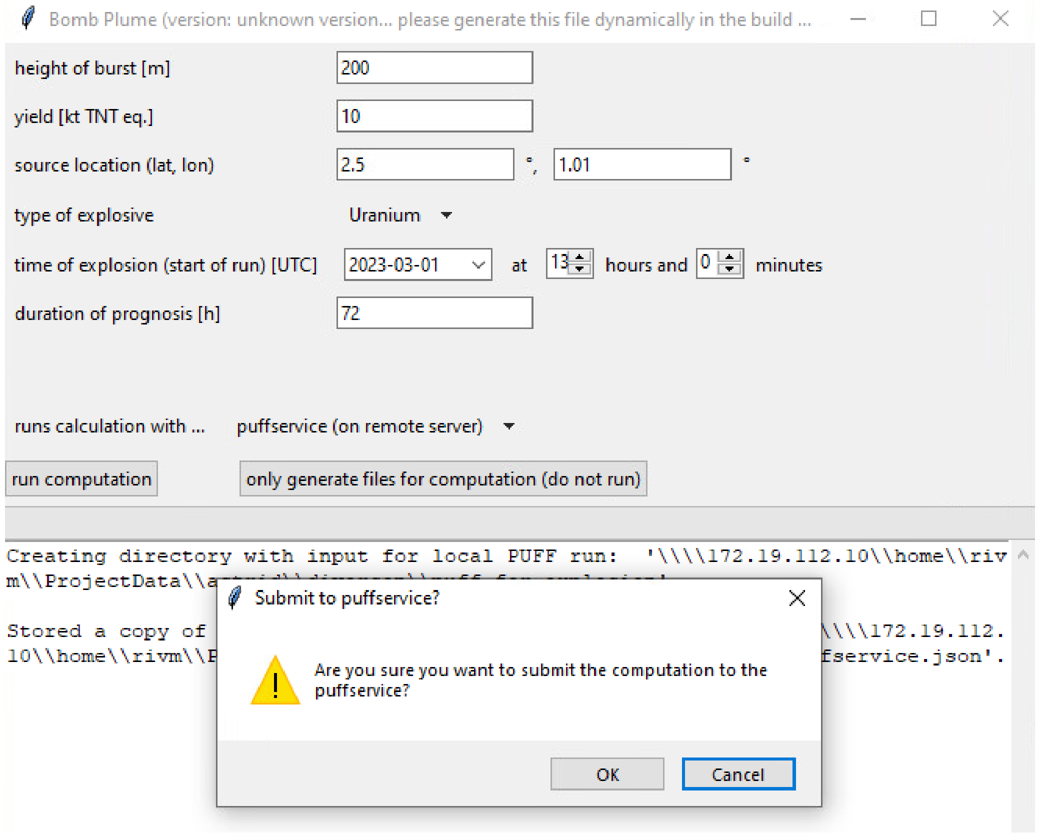
Any questions?

Application in tool IRIS

- 100 kT yield uranium weapon
  - source term Kraus & Foster (2014), 69 initial nuclides
- dispersion model NPK-Puff, 48h prognosis
- instantaneous plume: 1491 puffs
- meteorology: ECMWF-HRES, resolution 0.1°
  - 15 levels up to 11.5 km height

flexible in yield, cocktail, output,…



IRIS: Initial Radiological Interpretation Software

Additional model assumptions

- No shielding (yet), but location and occupancy factor
- In principle every nuclide can be considered from ENDF-database (DCC is needed for dose calculation)
- DCCs for groundshine dose are from Petoussi-Hens and ICRP
- No soil mitigation (with cocktail-DCC), but implicitely in time-integrated DCC’s in traditional dispersion and dose modelling
- Deposition wet: bulk,
- Deposition dry: particle size dependent surface resistance-values combined with other resistances

Outlook: gathering statistics
varying yield, location, and release time