Indoor Environments 2025™
The 39th Annual Radon and Vapor Intrusion Symposium

Domestic radon exposure and cancer risk by site, age group, and sex in Massachusetts, 2001-2020

Presenter: Matt Bozigar

Assistant Professor of Epidemiology at Oregon State University

Coauthors: Garyfallos Konstantinoudis, Ernani Choma, Carolina L. Zilli Vieira, Yazan Alwadi, Longxiang Li, Rena R. Jones, Petros Koutrakis

Oregon State University College of Health

HARVARD T.H. CHAN SCHOOL OF PUBLIC HEALTH

Imperial College London

NIH NATIONAL CANCER INSTITUTE

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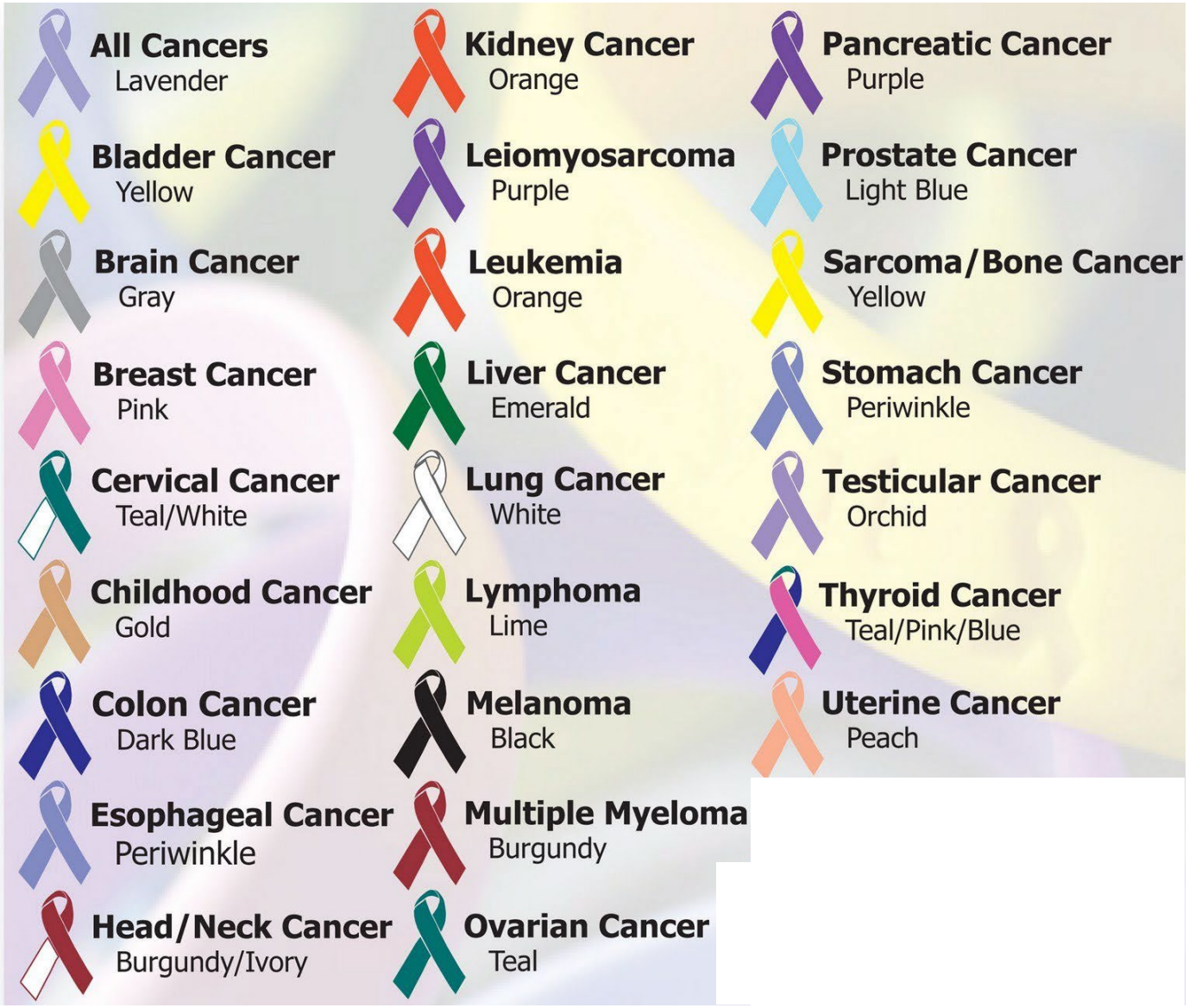
Personal motivation

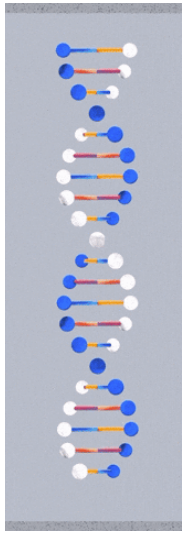
Causes of many cancers are still largely unknown

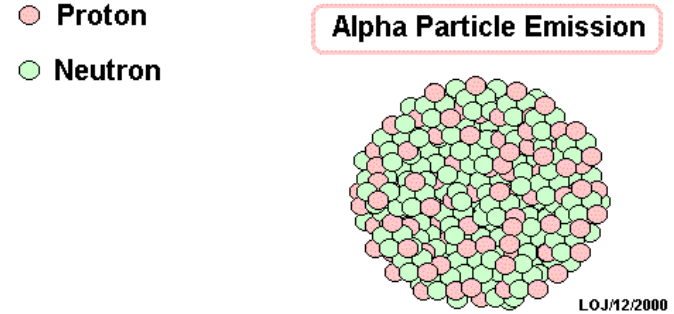
- Known, *general* risk factors:
  - Age, tobacco use, diet and alcohol, physical activity, weight, ultraviolet light and sun exposure, human papillomavirus, chemicals, genetic factors
- Research Question: What role does **radon** play, if any, in **non-lung cancer incidence**, and does the role differ by **subgroups**?



Alpha particle radiation from radon gas decay is one of the most toxic substances known

- Radon gas emits several high-energy, mutagenic alpha particles as it decays
- Disintegration count per unit volume-time (Bq/m^3 or pCi/L per sec)
- Group 1 carcinogen for lung cancer (1988) [1]
- Non-lung tissues are exposed, even the brain [2]





*"The EPA recommends homes be fixed if the radon level is 4 pCi/L (picocuries per liter) or more. Because **there is no known safe level of exposure to radon**, the EPA also recommends that Americans consider fixing their home for radon levels between 2 pCi/L and 4 pCi/L."* [4]

1 International Agency for Research on Cancer, 2018
2 Santos et al., 2020
3 U.S. Environmental Protection Agency, 2019

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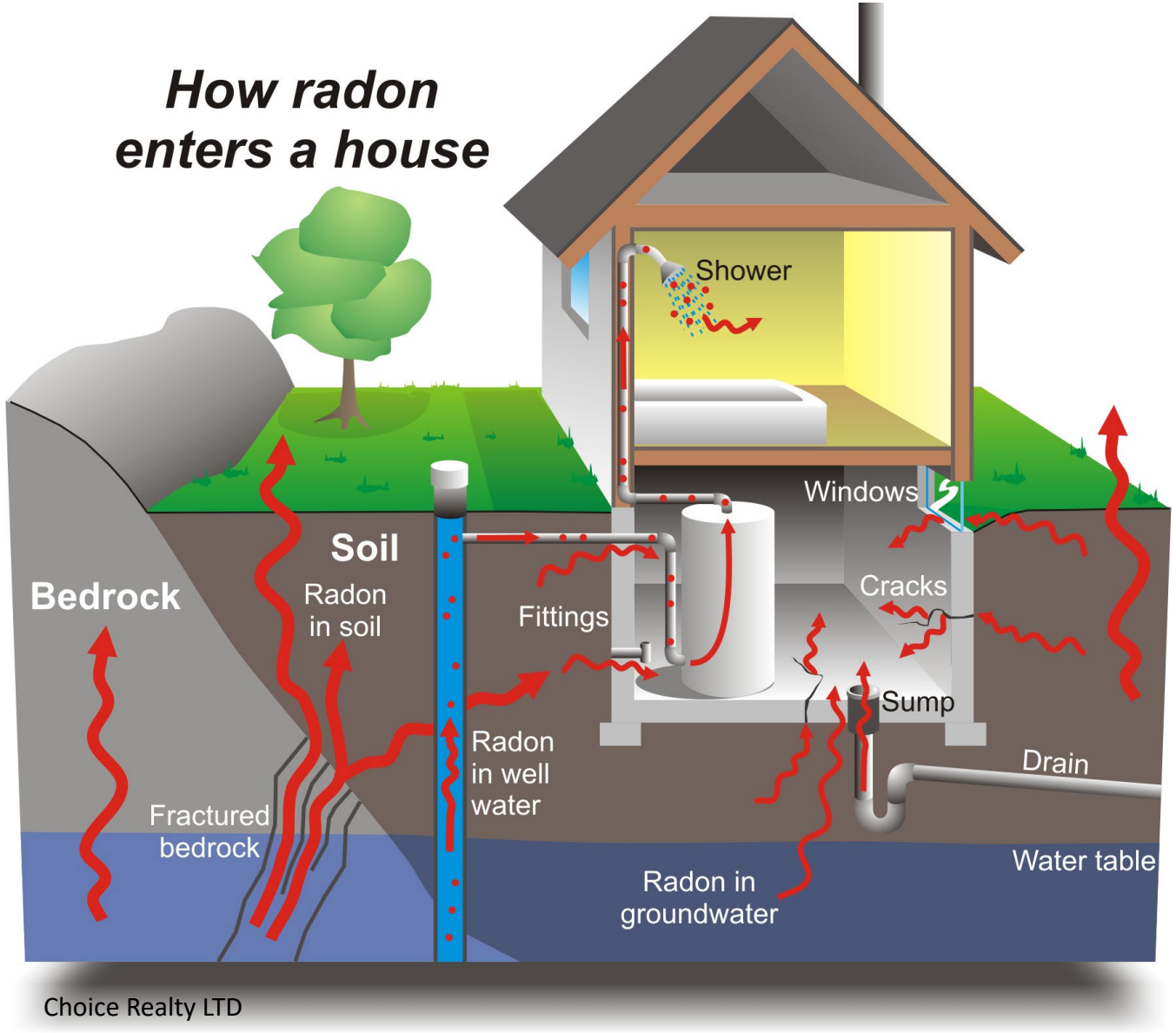
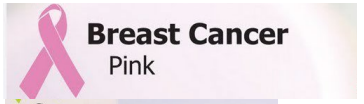
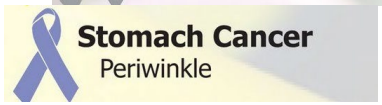


Choice Realty LTD

Limited previous research on radon & non-lung cancers in general adult population

- **Some recent evidence:**
  - ↑ risk: Leukemia[1]
  - ↑ risk in cohort studies: Breast cancer[2,3]
  - ↑ risk (ecologic/cohort): Skin cancer[2,4–6]
- **Inconclusive recent evidence:**
  - Brain/CNS cancer[1,7]
  - Stomach cancer[1]

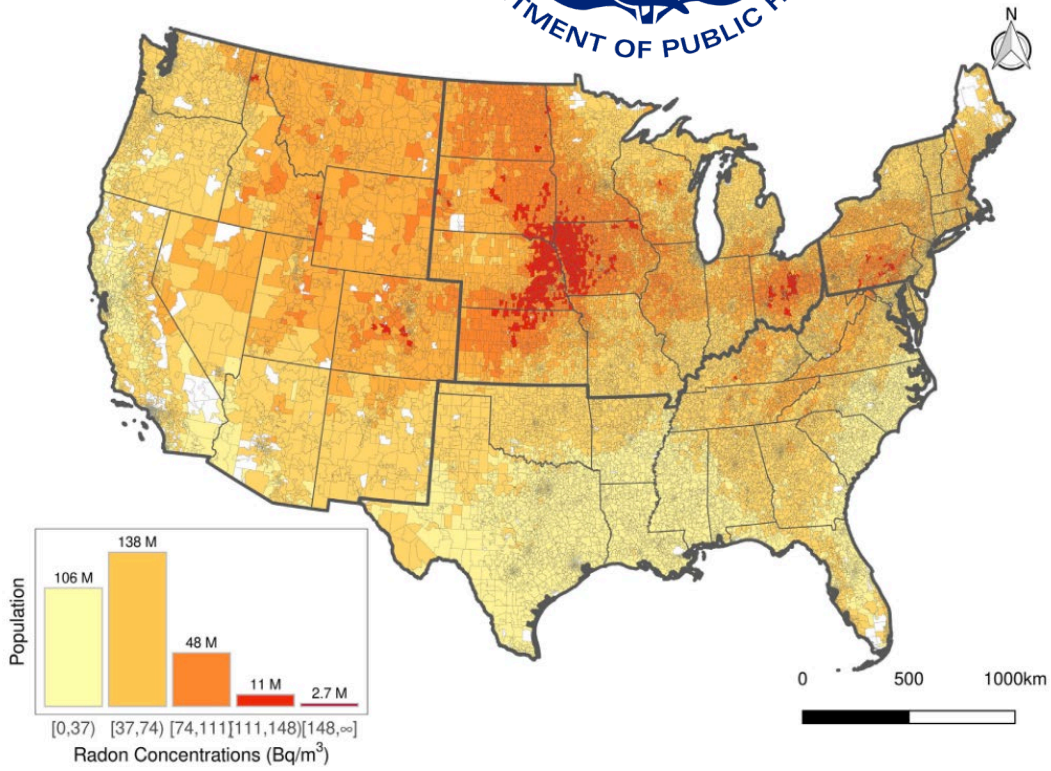




1 Mozzoni et al., 2021
2 Barbosa-Lorenzo et al., 2016
3 Vopham et al., 2017
4 Boz et al., 2024
5 Braüner et al., 2015
6 Wheeler et al., 2012
7 Del Risco Kollerud, 2014

Data linked across many sources

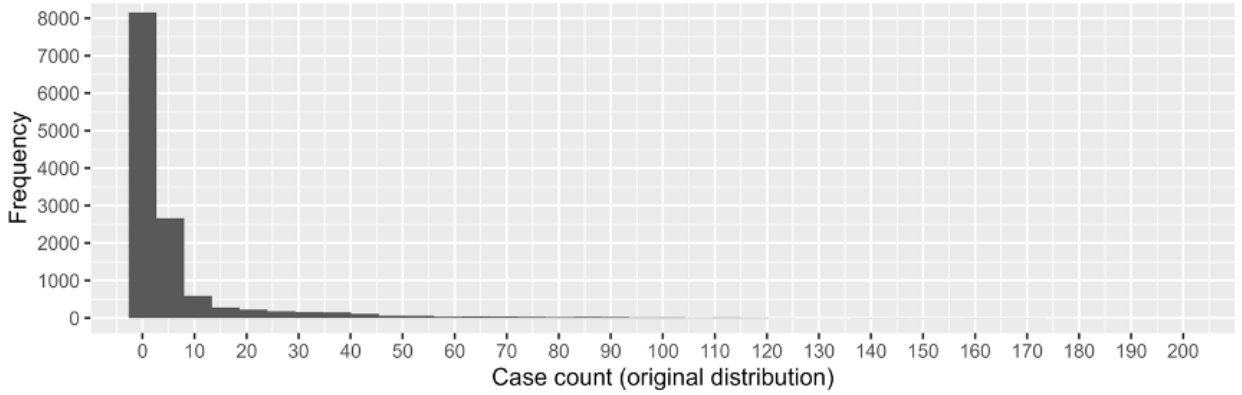
- Registry-derived cancer incidence data
  - Annual diagnosis counts in MA postal codes
- Granular estimated radon concentrations
  - Geographic machine learning model [1]
  - Monthly, postal code resolution
- Few known confounders of radon-cancer
- Study period: 2001-2020



1 Li et al., 2025

Accounting for ”sparse data” (many zero-counts of cancer diagnoses due to rarity) in our statistical methodology

- Zero-inflated (ZI) outcomes
  - Aggregated over moving 5-year windows
- Besag, York, & Mollié (BYM) [1] models by site & sex, sequentially adjusted for random & fixed effects
- Radon exposure: continuous (+50 Bq/m^3 or 1.35 pCi/L)
- Exposures & covariates averaged over previous 5 years, respectively

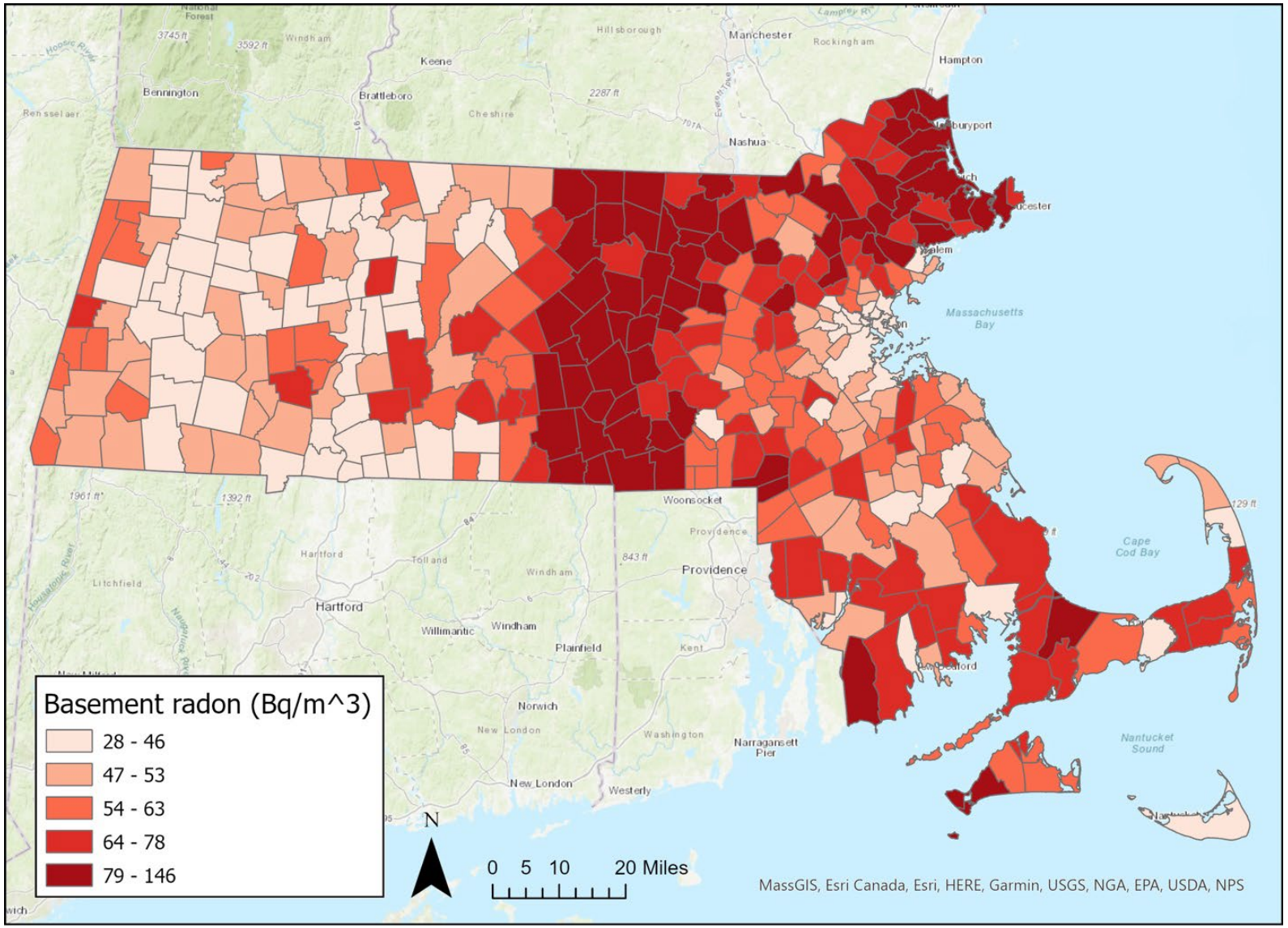


$$Y_{ijk} \sim ZIP(\lambda_{ijk})$$

$$log(\lambda_{ijk}) = \log(Pop_{ijk}) + \beta_0 + \boldsymbol{\beta_1 X_{ijk}} + w_j + v_i + u_i + t_k$$

where: *i=postal codes*
j=counties
k=year after previous 5-year window

1 Besag, York, Mollié, 1991



Geographic distribution of average basement radon levels in 483 Massachusetts postal codes included in the study.

	Overall	Radon (Bq/m³)	
		0-74	≥74
		Radon (pCi/L)	
		0.00-1.99	≥2.00
Characteristic	N = 483	N = 284	N = 199
Average greenness, NDVI (mean (SD))	0.32 (0.06)	0.30 (0.07)	0.34 (0.03)
Average temperature, degrees C (mean (SD))	10.3 (0.9)	10.5 (0.9)	10.0 (0.9)
Average relative humidity, (mean (SD))	78.0 (1.7)	78.0 (1.7)	78.0 (1.7)
Homes built <1950, % (mean, SD))	35.9 (18.0)	40.0 (19.6)	30.4 (13.8)
Homes built 1950-1979, % (mean, SD))	35.1 (12.3)	35.4 (13.7)	34.6 (10.0)
Homes built ≥1980, % (mean, SD))	29.0 (13.8)	24.8 (13.3)	35.0 (12.3)
Single family homes, % (mean, SD))	4.4 (4.5)	4.3 (4.3)	4.4 (4.9)
Current smoking, % (mean (SD))	21.8 (2.8)	21.2 (2.9)	20.2 (2.3)
Average median income, $ (mean (SD))	65,198 (22,982)	62,005 (23,968)	69,753 (20,716)
<Federal poverty level, % (mean (SD))	8.3 (7.0)	10.0 (8.2)	6.0 (3.7)
Less than high school education, % (mean (SD))	11.3 (7.6)	12.5 (8.9)	9.7 (4.8)
Population, ppl (mean (SD))	13,439 (12,197)	16,121 (13,345)	9,612 (9,086)
Female population (mean (SD))	6,941 (6,336)	8,362 (6,936)	4,912 (4,682)
Male population, m (mean (SD))	6,498 (5,875)	7,758 (6,425)	4,670 (4,413)

Exposure patterns

Higher radon postal codes had significantly ($p<0.001$) newer housing

Higher radon postal codes had significantly ($p<0.001$) higher SES

Higher radon postal codes had significantly ($p<0.001$) fewer people

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PRELIMINARY, UNPUBLISHED: Estimated relative risk and 95% credible intervals for continuous (linear) average basement radon exposure (+50 Bq/m³ (1.35 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for ADULTS.

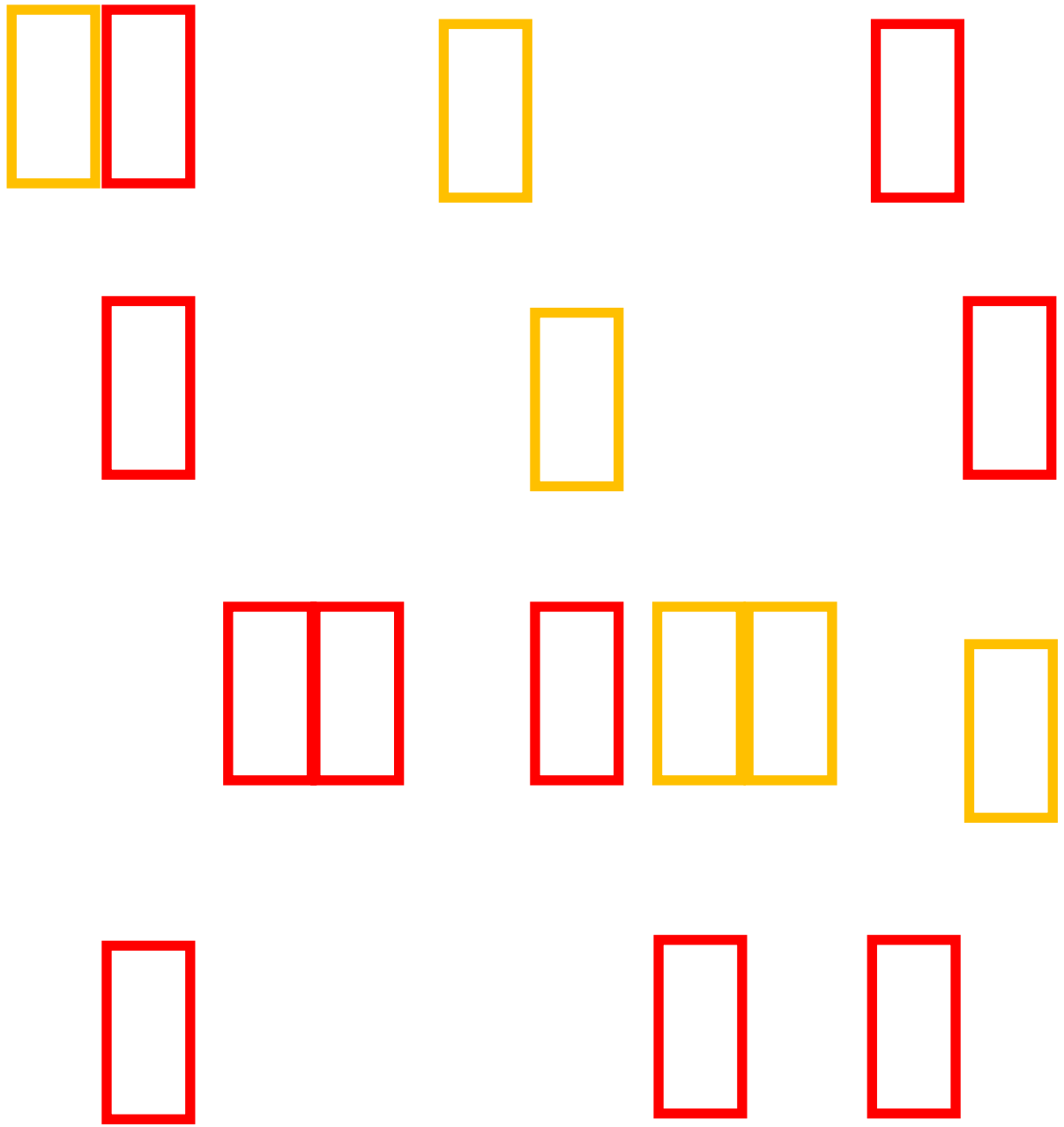
Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.

Statistically Significant ↑RR

Female:	Male:
• Colorectal	• Bladder
• Melanoma	• Esophageal
• Thyroid	• Leukemia
• Uterine	• Melanoma
	• Myeloma
	• Prostate

Marginally Significant ↑RR (CrI includes 1.0; nearest bound ≤10% of CrI width)

Female:	Male:
• Bladder	• Kidney
• Breast	• Oral
• Oral	• Pancreas (inv)



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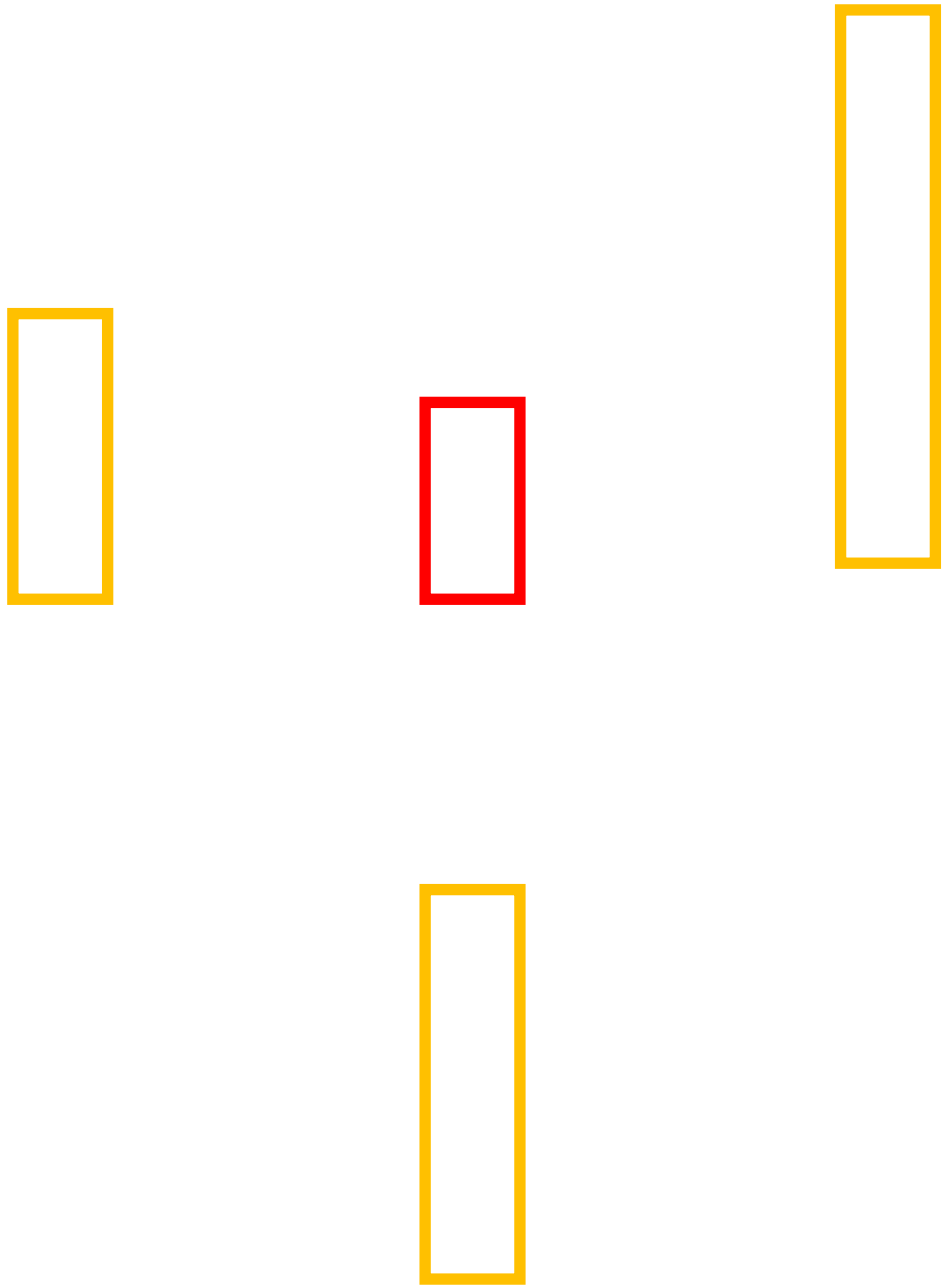
Male:
- **HL** (↓ RR)

Statistically significant

Male:
- **Brain/NS-invasive**
- **Testes**
- **Kidney**

Marginally Significant ↑RR (CrI includes 1.0; nearest bound ≤10% of CrI width)



Our Results *(incl. marginal)*	**Earlier Findings**	**Alignment / Contrast**
Hematologic: ↑**leukemia** (male), ↑**myeloma** (male), ↓**HL** (child)	Weak link in adults, stronger in childhood; inconclusive for other blood cancers [1-3]	Stronger & more consistent links for adults; inverse HL in children potentially explained by high incidence in high SES areas [4]

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Digestive tract: ↑**colorectal** (female), ↑**esophageal** (male), ↑***pancreas*** *(inverse in male)*	Inconclusive for stomach; little evidence on others [1]	Expands to multiple GI sites with plausible exposure pathways; pancreas marginally inverse finding is likely spurious

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Skin: ↑**melanoma** (adult)	Suggestive melanoma links [8-10]	Adds evidence to melanoma link (both sexes), strengthening prior findings

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Other: ↑bladder (adult), ↑*oral (adult),* ↑*kidney (male)*	Little prior evidence for bladder, oral, kidney cancers [1]	Adds potential new associations

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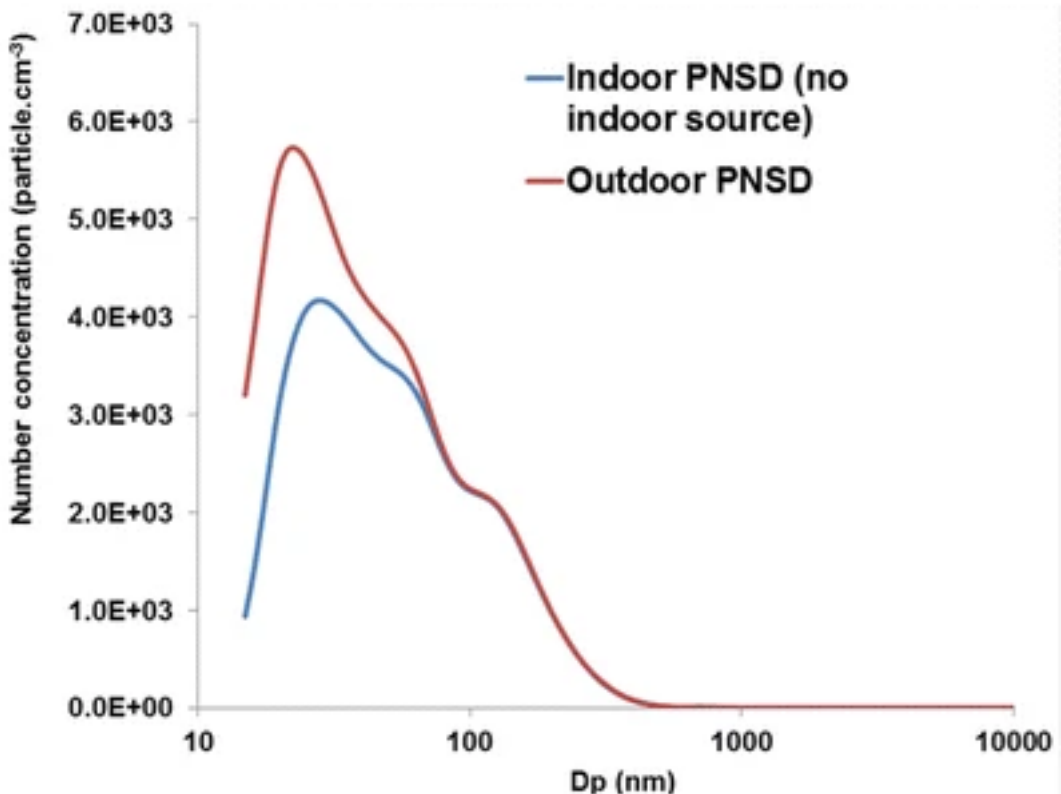
How might radon cause non-lung cancers? (hypotheses generated)

- **DNA damage:** Alpha particles → mutations; fits hematologic and melanoma signals
- Systemic dose: Radon progeny in **blood** → bone marrow, hormone-sensitive tissues (thyroid, uterine, prostate)
- Need to investigate radon **ingestion**? Swallowing saliva? Drinking water?
- Tissue sensitivity: **Rapidly dividing/developing tissues** (blood, GI, pediatric CNS), **urothelial/epithelial** (bladder, oral)
- **Potential modifiers:** Hormones, immune effects, UV (melanoma), smoking

Additional hypotheses generated about particle radioactivity and tissue dose dynamics

- ***Most dosimetric literature previously assumed ~200nm PD for attached fraction***

Fraction	Particle Size	Proportion of Airborne Particles	Proportion of Radioactive Airborne Particles
Unattached fraction	< 1-10 nm (ultrafine)	Very small number fraction (< 10%), but can dominate surface area at low PM levels	Minor when particle counts are high; **increases sharply when air is clean**
Attached fraction (small)	10–200 nm	High number fraction and surface area (see graph →)	**Major carrier of radioactivity under cleaner indoor conditions** (emerging evidence)
Attached fraction (large)	> 0.2–2.5 µm	Dominant by mass; smaller number fraction	Usually contains most total activity mass



Additional hypotheses generated about particle radioactivity and tissue dose dynamics

- ***Most dosimetric literature previously assumed ~200nm PD for attached fraction***

Fraction	Particle Size	Proportion of Airborne Particles	Proportion of Radioactive Airborne Particles	Behavior	Possible Biological Implications
Unattached fraction	< 1-10 nm (ultrafine)	Very small number fraction (< 10%), but can dominate surface area at low PM levels	Minor when particle counts are high; **increases sharply when air is clean**	**Diffuses freely; penetrates deeply** into alveoli and may enter **systemic circulation**	**May irradiate distant or systemic tissues** (e.g., blood, bone marrow, thyroid, skin)
Attached fraction (small)	10–200 nm	High number fraction and surface area (see graph →)	**Major carrier of radioactivity under cleaner indoor conditions** (emerging evidence)	Binds efficiently to ultrafine and fine PM; persists hours to days; **similar/same behavior as unattached fraction**	Sustained local alpha dose to bronchial and bronchiolar epithelium; **potential contributor to systemic exposure like unattached fraction**
Attached fraction (large)	> 0.2–2.5 µm	Dominant by mass; smaller number fraction	Usually contains most total activity mass	Deposits in upper airways and on mucosal surfaces; cleared via mucociliary transport and ingestion	Localized irradiation of upper-airway and digestive-tract tissues (e.g., oral, bladder, stomach)

Limitations and strengths

Limitations:

- Ecologic exposure metric; no individual radon measurements
- Potential residual confounding (other environmental/SES factors)
- Limited power for rare cancers → wide credible intervals
- Multiple comparisons may yield some false positives

Strengths:

- Large, population-based dataset across multiple subgroups (age, sex)
- Ability to detect site-specific and subgroup-specific patterns
- Multi-year, postal code-level radon estimates
- Bayesian modeling captures uncertainty & accommodates small counts

Takeaway messages

- **Radon's impact may extend beyond lung cancer**
  - **Wide carcinogenic signal** – many tissues and cancer types involved
  - Patterns consistent with **plausible systemic mechanisms**
- **No strong ecologic confounders** identified
  - Smoking *may* modify radon-cancer association – need better smoking data
- **Atypical exposure patterns** in terms of environmental justice concerns
  - Higher SES, newer homes, and rural (in MA)
- **Critical future work**: individual-level exposure, mechanistic research (particle dynamics), replication in other populations, pathways (inhalation vs. ingestion)

Other studies happening now

- **Particle radioactivity in Portland homes** (small case study)
  - Measuring radon decay, ultrafine and fine PM, weather, particle radioactivity
  - 3 homes, 3 locations
    - Basement, first floor, outdoor ambient

- **Radon exposure and central nervous system (includes brain) cancer** (national cohort study)
  - Women's Health Initiative cohort(s)
  - Preliminary result: average area-level radon concentration associated with increased individual risk for brain cancer

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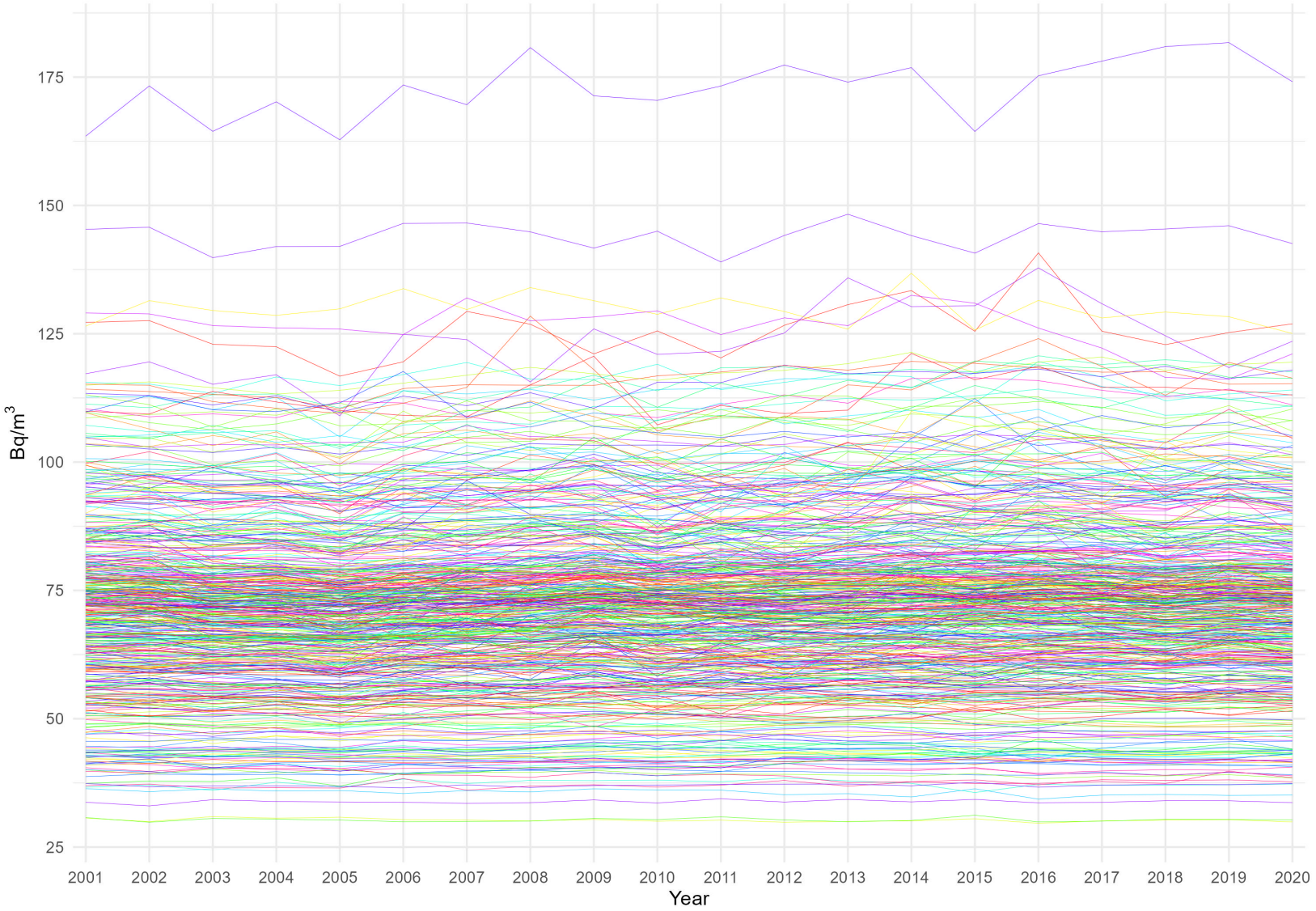
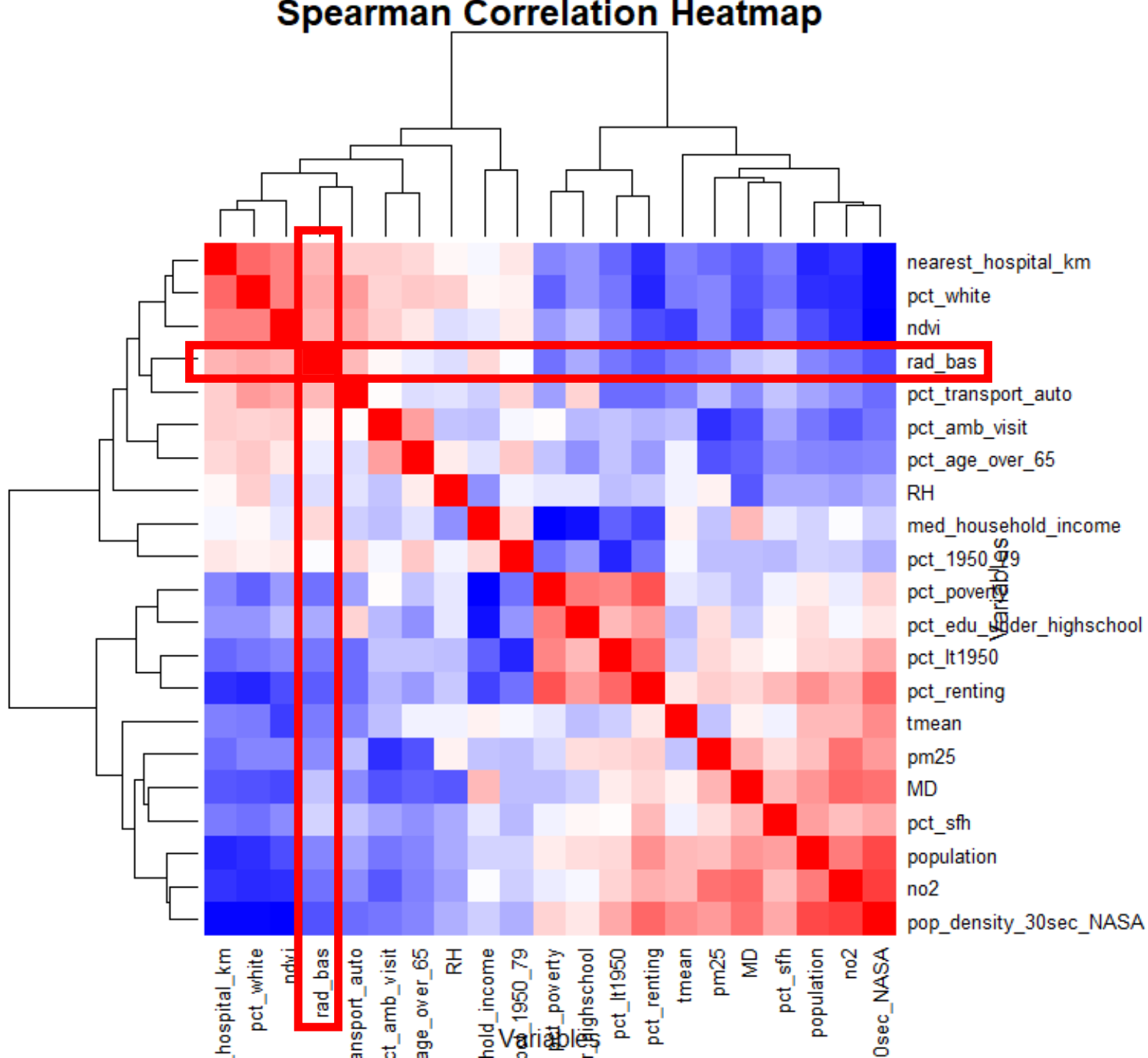
Thank you! Questions?

Appendix



Estimated basement radon levels over time for 483 postal codes included in the study 2001-2020.


Spearman Correlation Heatmap
nearest_hospital_km
pct_white
ndvi
rad_bas
pct_transport_auto
pct_amb_visit
pct_age_over_65
RH
med_household_income
pct_1950_79
pct_poverty
pct_edu_under_highschool
pct_lt1950
pct_renting
tmean
pm25
MD
pct_sfh
population
no2
pop_density_30sec_NASA
Variables
Variables

Directed acyclic graph (DAG) guided confounder identification and adjustment*

- Minimally sufficient adjustment set (often in form of proxies)
- *Other covariates and variables from the literature were considered to improve precision if they did not increase bias (e.g., colliders)
- Still an ecologic study…

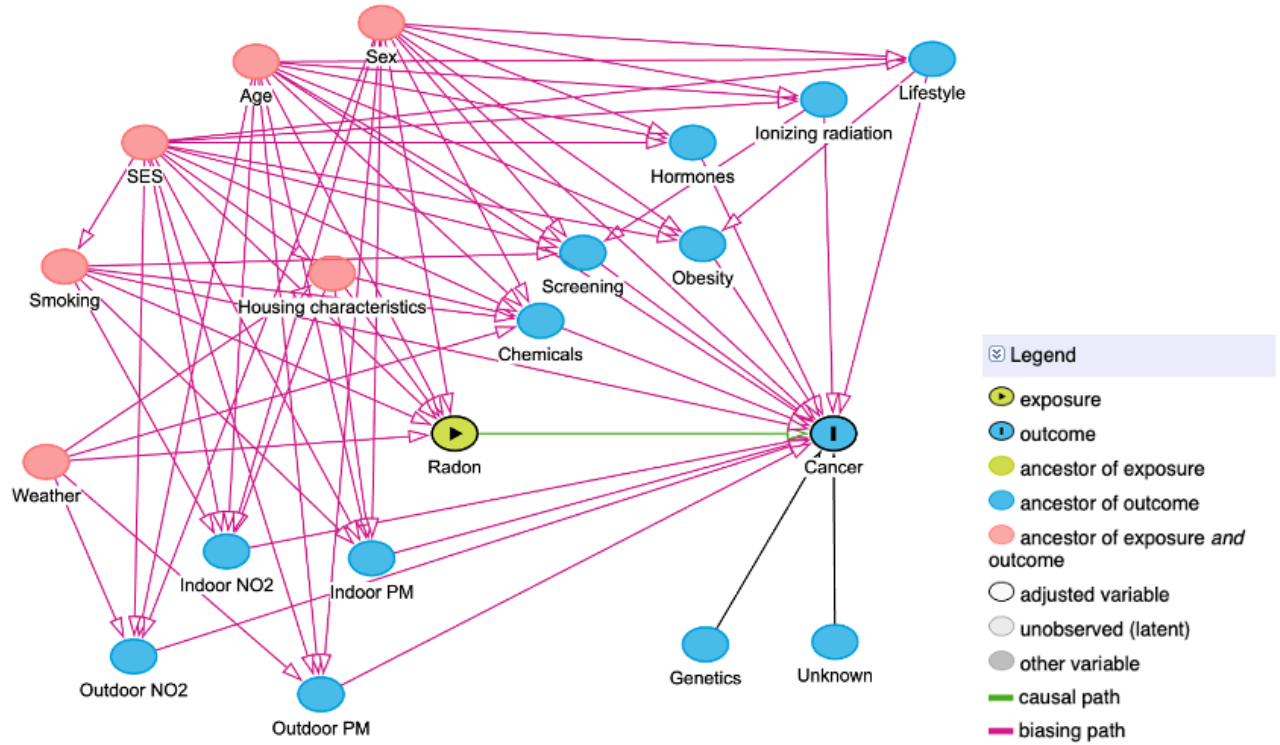


Fig. 1. Directed acyclic graph of the theoretical causal association between radon exposure and cancer diagnosis.

Textor et al, 2017

Numerous sensitivity analyses performed

- **Assessments**
  - Watanabe-Akaike information criterion (**WAIC**)
  - "**Posterior predictive checks**" via summary statistics and histograms
- **Model specifications**
  - Outcome **distributions**
  - Prior distributions (of parameters; "**priors**")
  - Handling of **zero counts** (i.e., ZI)
    - Replacing zero-counts with random numbers
  - **Linearity** of exposure-response
    - Distributed lag linear & nonlinear models (DLM, DLNM) with 2nd order random walks
  - Adjustment for **air pollutants** ($PM_{2.5}$, NO_2, O_3; hypothesized covariates)

Results were robust in sensitivity analyses

- **General assessments:**
  - Prior knowledge and **WAIC** indicated fully-adjusted ZIP model was best
  - **Posterior predictive checks** confirmed
- **Results did not differ by:**
  - Handling of **zero counts** (i.e., ZI)
    - Time-aggregation, replacing zero-counts with random numbers
  - **Non-linearity** of exposure-response
    - Distributed lag linear & nonlinear models (DLM, DLNM) with 2nd order random walks
  - Adjusting for **air pollution**

Indoor Enviro

The 39th Annual Radon and

Estimated relative risk and 95% credible intervals for continuous (linear) average basement radon exposure (+50 Bq/m³ (1.35 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for ADULT NEVER SMOKERS.

Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.

Female:

- **colorectal** (↑RR 1.21 [1.08, 1.36])
- **oral** (↑RR 1.30 [1.03, 1.64])

Male:

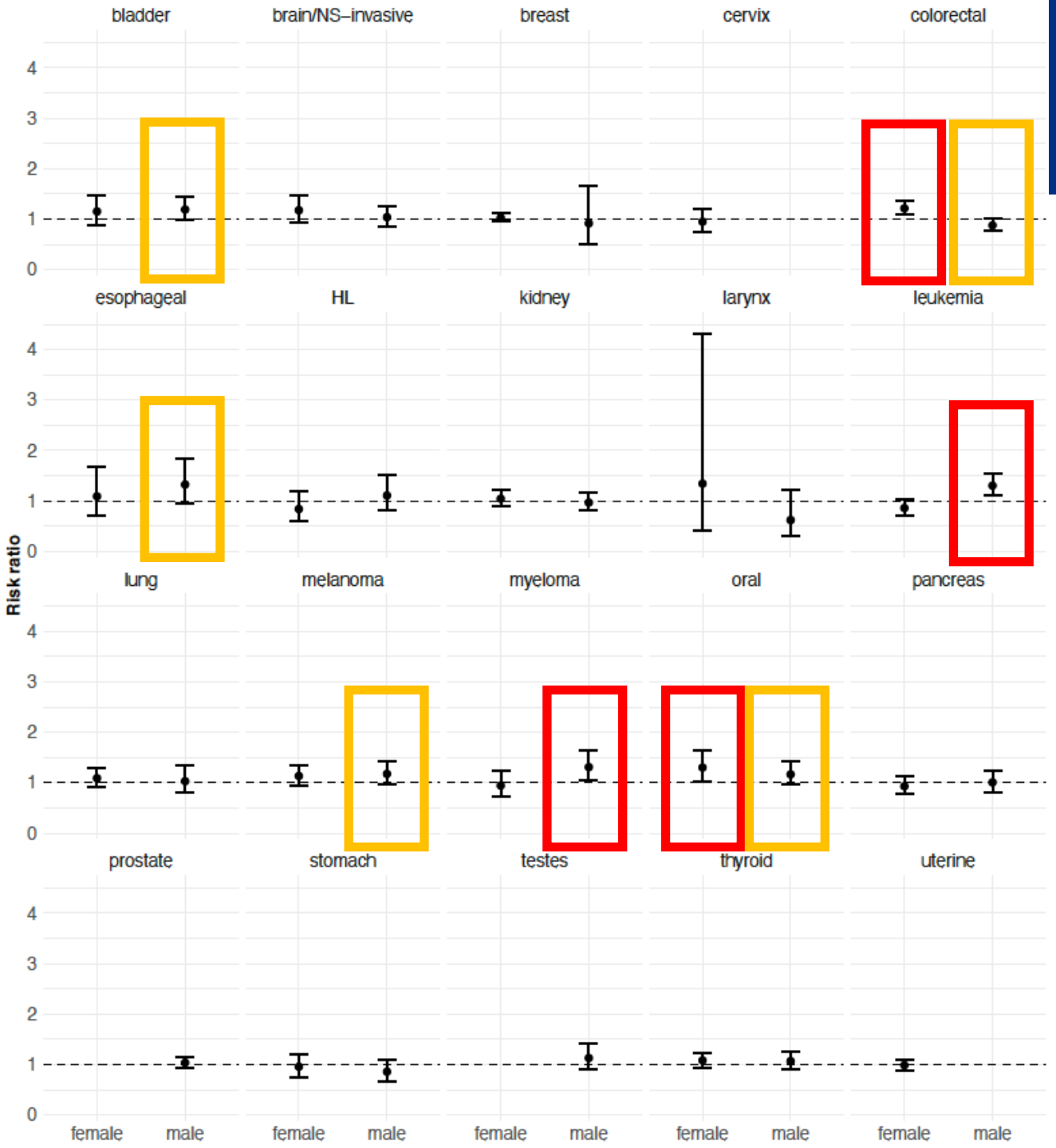
- **leukemia** (↑RR 1.30 [1.10, 1.54])
- **myeloma** (↑RR 1.31 [1.04, 1.64])

Statistically significant

Male:

- **bladder** (RR 1.19 [0.98, 1.45])
- **colorectal** (RR 0.88 [0.77, 1.00])
- **esophageal** (RR 1.33 [0.95, 1.84])
- **melanoma** (RR 1.17 [0.97, 1.42])
- **oral** (RR 1.17 [0.96, 1.41])

Marginally Significant (CrI includes 1.0; nearest bound ≤ 10% of CrI width)



Indoor Environ

The 39th Annual Radon and V

Estimated relative risk and 95% credible intervals for continuous (linear) average basement radon exposure (+50 Bq/m³ (1.35 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for ADULT EVER SMOKERS.

Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.

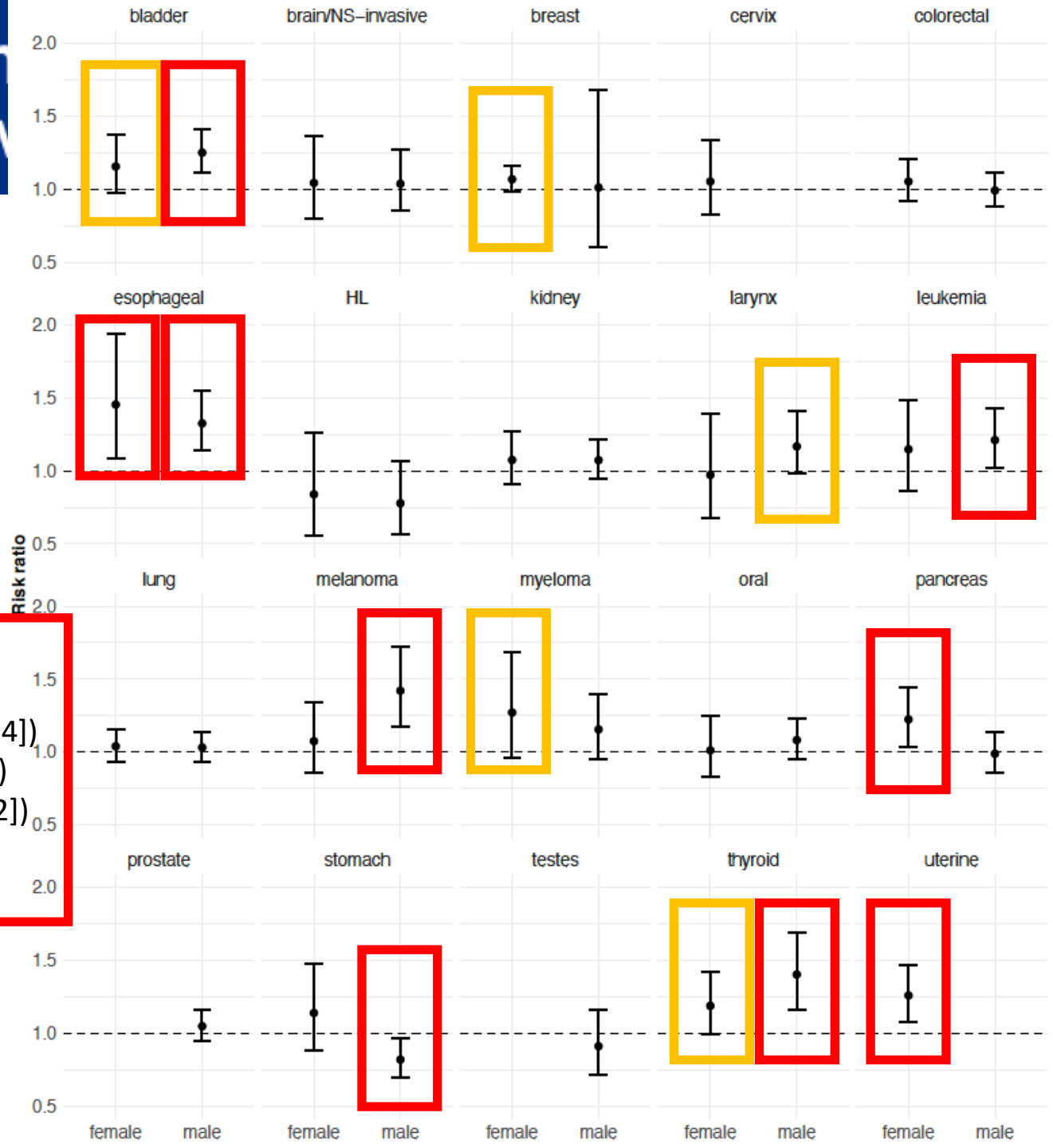
Female:
- **esophageal** (↑ RR 1.45 [1.09, 1.94])
- **pancreas** (↑ RR 1.22 [1.04, 1.45])
- **uterine** (↑ RR 1.26 [1.08, 1.47])

Male:
- **bladder** (↑ RR 1.25 [1.11, 1.41])
- **esophageal** (↑ RR 1.32 [1.14, 1.54])
- **leukemia** (↑ RR 1.21 [1.02, 1.43])
- **melanoma** (↑ RR 1.42 [1.18, 1.72])
- **stomach** (↓ RR 0.82 [0.70, 0.97])
- **thyroid** (↑ RR 1.40 [1.16, 1.69])

Female: bladder (RR 1.16 [0.98, 1.38]); **breast** (RR 1.07 [0.98, 1.17]); **myeloma** (RR 1.27 [0.96, 1.69]); **thyroid** (RR 1.19 [1.00, 1.42])
Male: larynx (RR 1.17 [0.98, 1.40])

Statistically significant

Marginally significant



Estimated relative risk and 95% credible intervals for continuous (linear) average basement radon exposure (+50 Bq/m^3 (1.35 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for ADULTS with MISSING SMOKING STATUS.

Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m^3.

Female:
- **Melanoma**

Male:
- **Pancreas** (↓ RR)

Statistically Significant ↑RR

Female:
- **Oral**
- **Cervix** (↓ RR)

Male:
- **Prostate**
- **Bladder** (↓ RR)
- **Larynx** (↓ RR)

Marginally Significant ↑RR (CrI includes 1.0; nearest bound ≤10% of CrI width)

Indoor Environ

The 39th Annual Radon and V

Estimated relative risk and 95% credible intervals for continuous (linear) average basement radon exposure (+50 Bq/m³ (1.35 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for CHILDREN (NEVER SMOKERS).

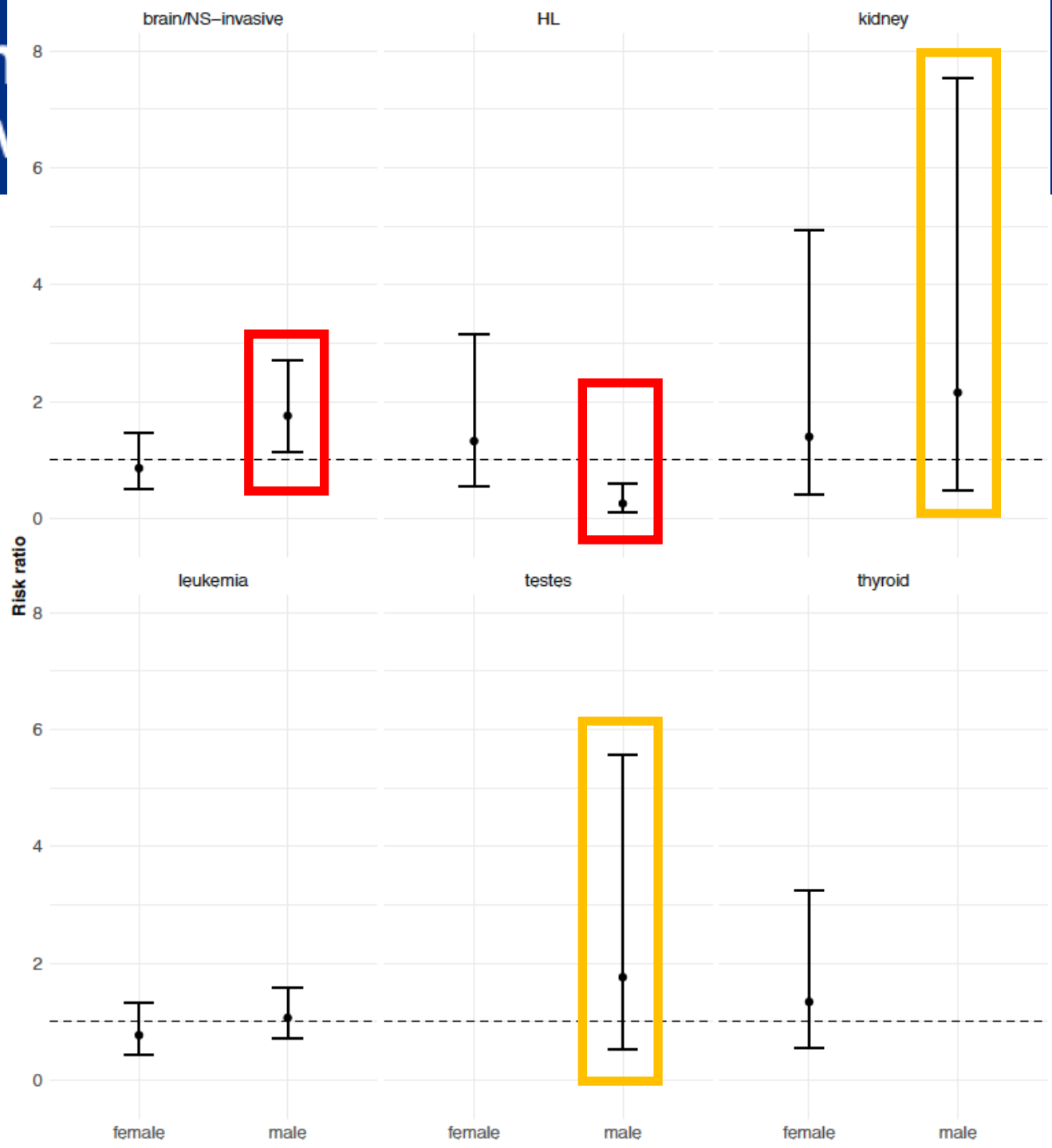
Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.

Male:
- **brain/NS-invasive** (↑ RR 1.76 [1.14, 2.72])
- **HL** (↓ RR 0.25 [0.11, 0.58])

Statistically significant

Male:
- **testes** (RR 1.76 [0.52, 5.57])
- **kidney** (RR 2.15 [0.47, 7.53])

Marginally significant



Indoor Environ

The 39th Annual Radon and V

Estimated relative risk and 95% credible intervals for dichotomized average basement radon exposure (cut point: 74 Bq/m³ (2.00 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for ADULT NEVER SMOKERS.

Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.

Female:
- **breast** (↑ RR 1.04 [1.01, 1.07])
- **colorectal** (↑ RR 1.10 [1.04, 1.16])
- **lung** (↑ RR 1.18 [1.08, 1.29])

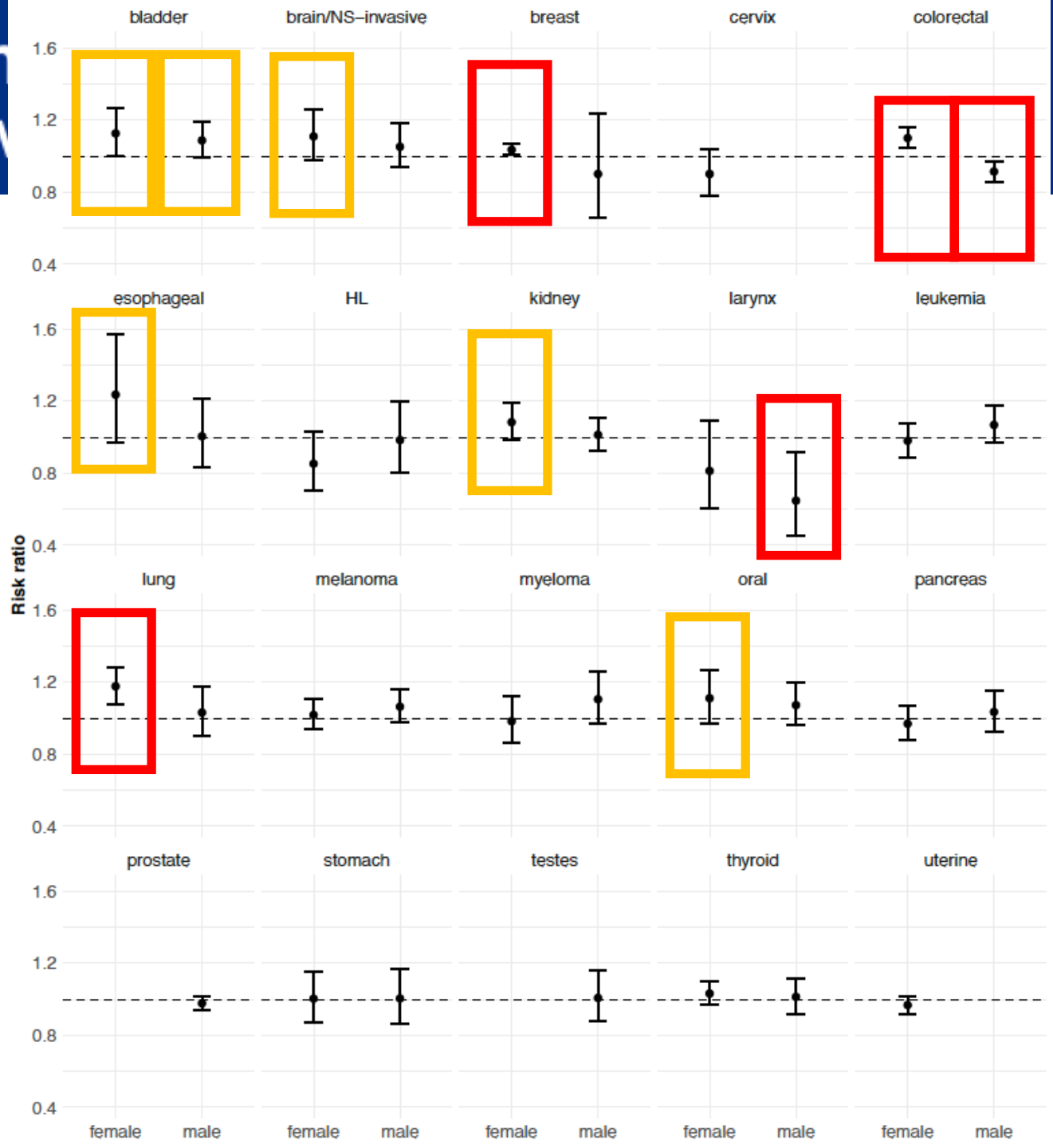
Male:
- **colorectal** (↓ RR 0.91 [0.86, 0.97])
- **larynx** (↓ RR 0.65 [0.46, 0.92])

Statistically significant

Marginally significant

Female: bladder (RR 1.13 [1.00, 1.27]); **brain/NS-invasive** (RR 1.11 [0.98, 1.26]); **esophageal** (RR 1.24 [0.97, 1.57]); **kidney** (RR 1.08 [0.99, 1.19]); **oral** (RR 1.11 [0.97, 1.27])

Male: bladder (RR 1.09 [1.00, 1.19])

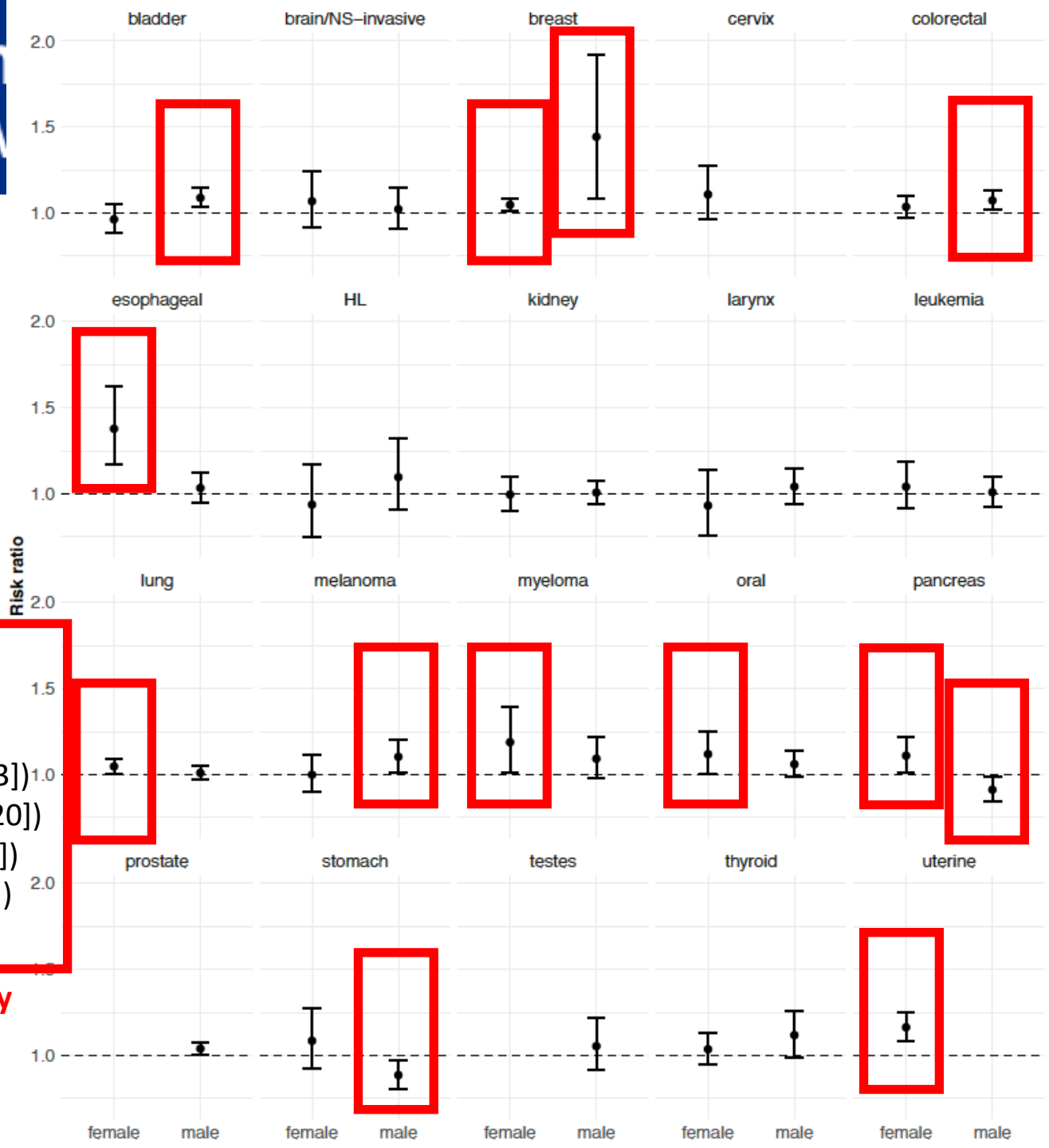


Indoor Environ

The 39th Annual Radon and V

Estimated relative risk and 95% credible intervals for dichotomized average basement radon exposure (cut point: 74 Bq/m³ (2.00 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for ADULT EVER SMOKERS.

Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.



Female:
- **breast** (↑ RR 1.04 [1.01, 1.08])
- **esophageal** (↑ RR 1.40 [1.19, 1.65])
- **lung** (↑ RR 1.05 [1.01, 1.09])
- **myeloma** (↑ RR 1.22 [1.04, 1.43])
- **oral** (↑ RR 1.13 [1.01, 1.27])
- **pancreas** (↑ RR 1.10 [1.00, 1.21])
- **uterine** (↑ RR 1.16 [1.08, 1.25])

Male:
- **bladder** (↑ RR 1.09 [1.03, 1.14])
- **breast** (↑ RR 1.47 [1.10, 1.97])
- **colorectal** (↑ RR 1.07 [1.02, 1.13])
- **melanoma** (↑ RR 1.10 [1.01, 1.20])
- **pancreas** (↓ RR 0.91 [0.84, 0.98])
- **stomach** (↓ RR 0.86 [0.78, 0.95])

Male:
- **prostate** (RR 1.03 [1.00, 1.07])
- **thyroid** (RR 1.13 [1.00, 1.27])

Statistically significant

Marginally significant

Indoor Environ

The 39th Annual Radon and V

Estimated relative risk and 95% credible intervals for dichotomized average basement radon exposure (cut point: 74 Bq/m³ (2.00 pCi/L)) and incident cancer diagnoses over previous 5 years by site and sex for CHILDREN (NEVER SMOKERS).

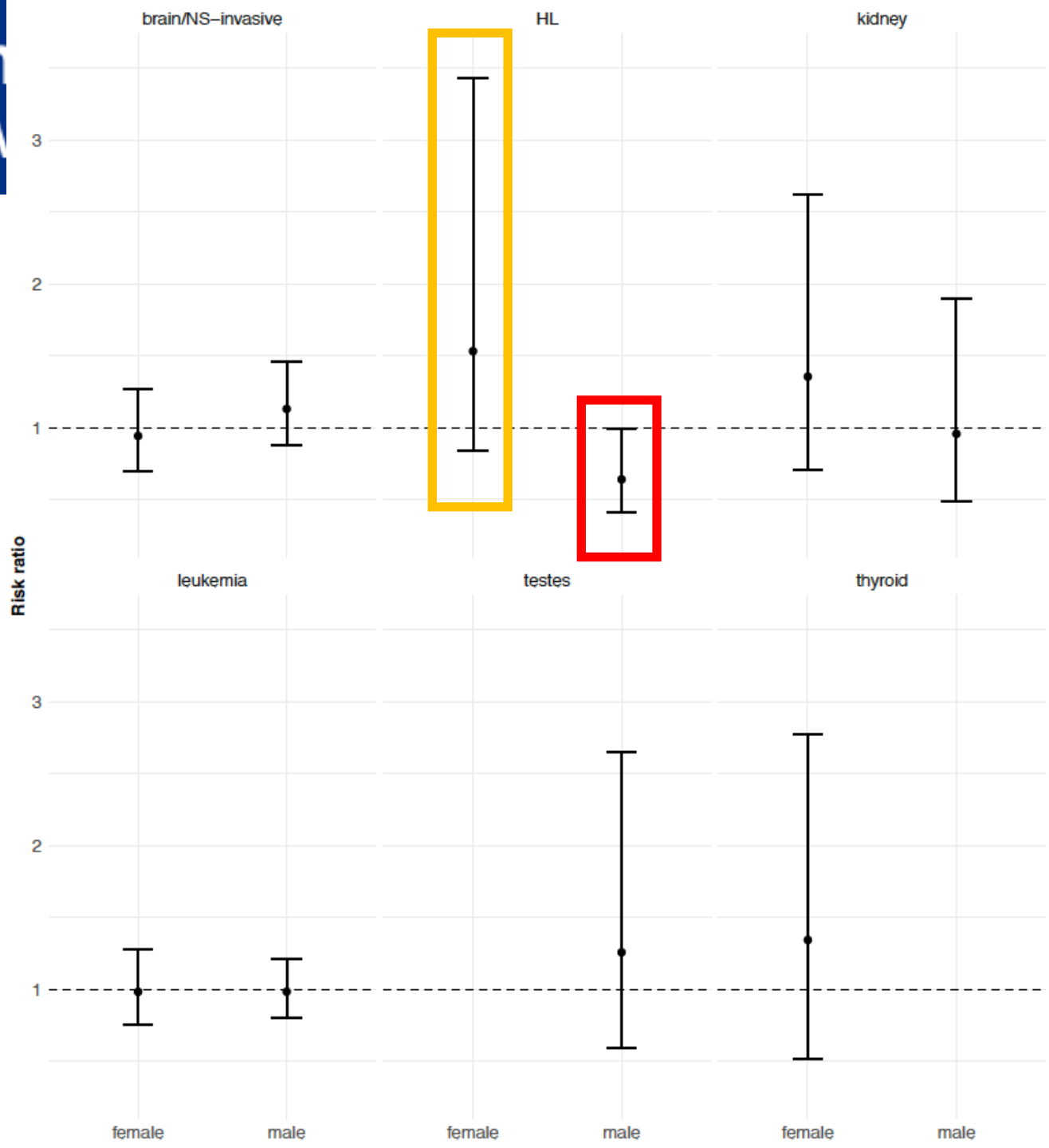
Model adjustments: Random walk within county over time effect, postal code and county spatially correlated and uncorrelated random effects, fixed effects (mean housing age, % single family homes, % poverty, mean of median household income, mean temperature, mean relative humidity, % smokers). Central nervous system: CNS. Becquerels/cubic meter: Bq/m³.

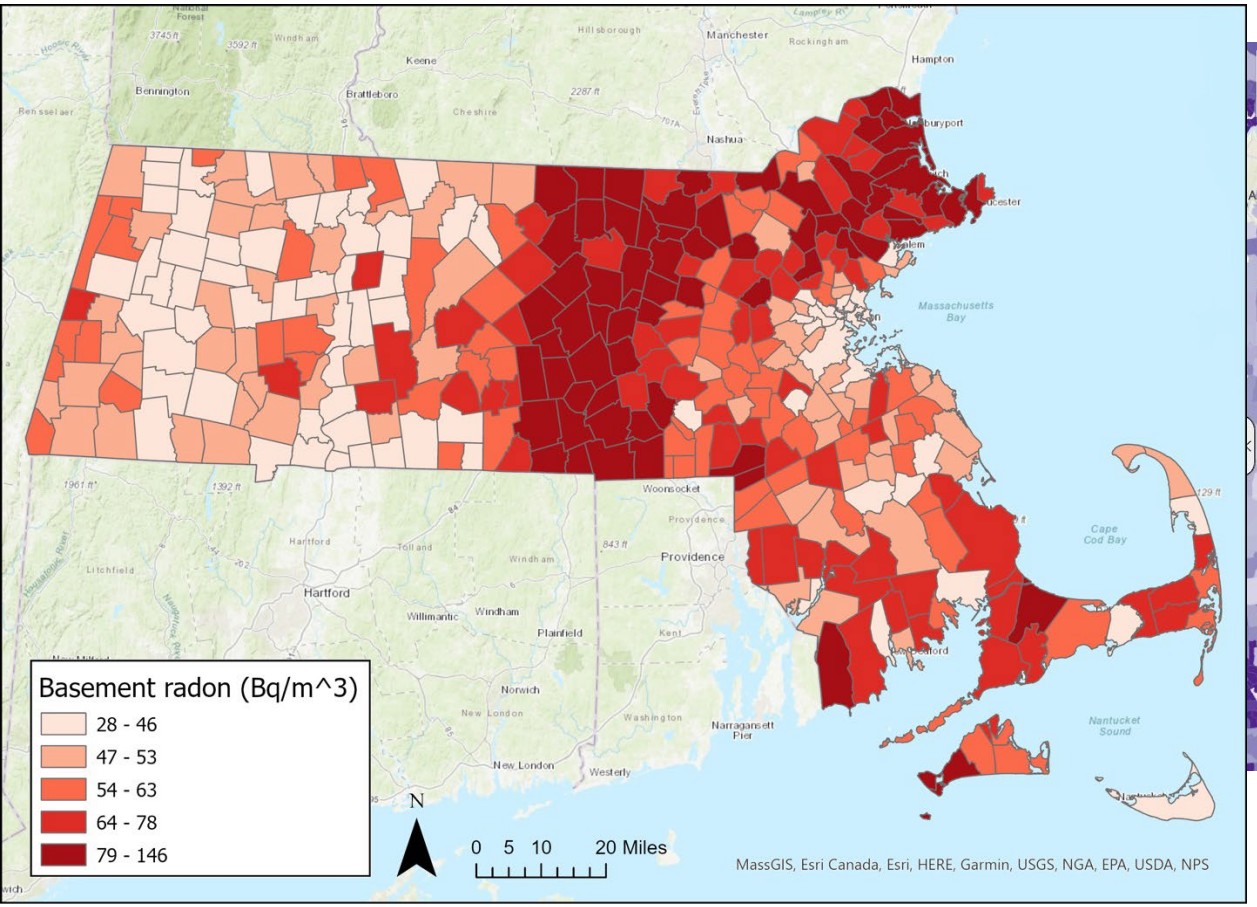
Male:
- **HL** (↓ RR 0.64 [0.41, 1.00])

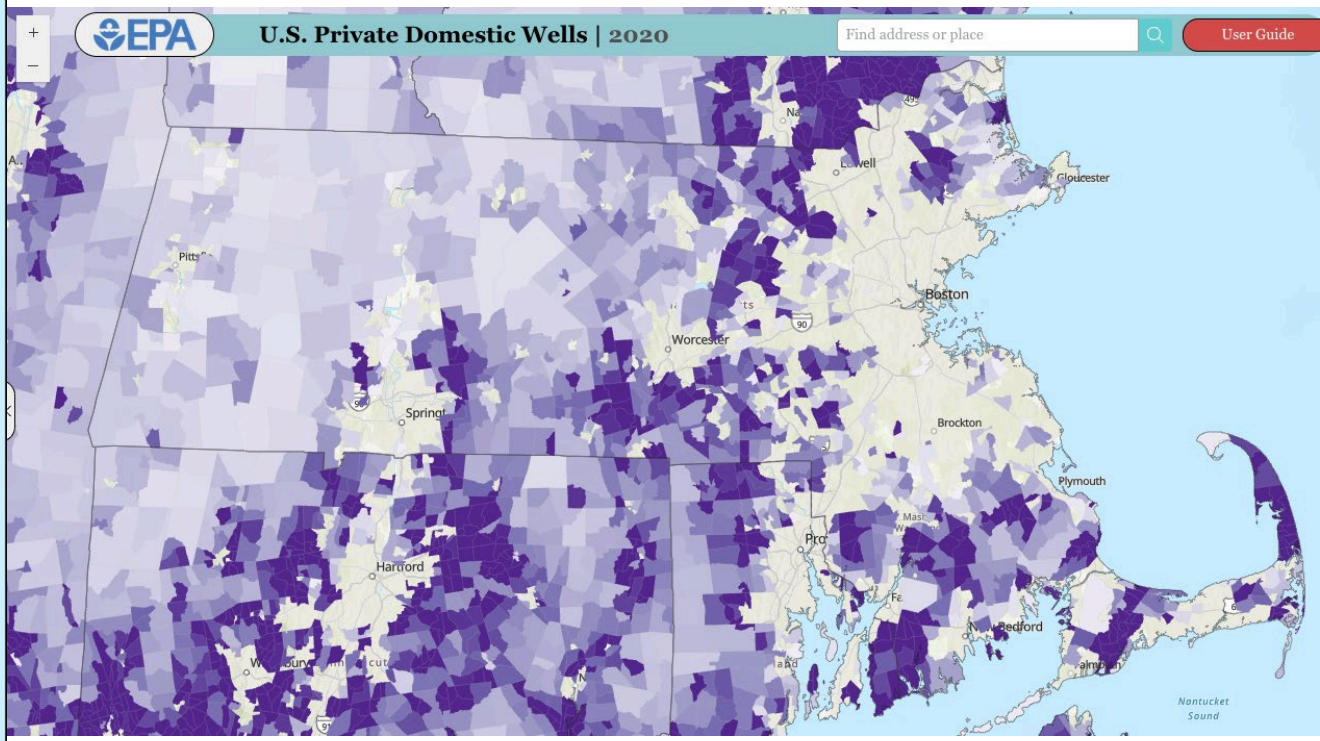
Statistically significant

Female:
- **HL** (RR 1.53 [0.84, 3.43])

Marginally significant




Basement radon (Bq/m^3)
28 - 46
47 - 53
54 - 63
64 - 78
79 - 146
N
0 5 10 20 Miles
MassGIS, Esri Canada, Esri, HERE, Garmin, USGS, NGA, EPA, USDA, NPS
Manchester
Nashua
Hampton
Keene
Brattleboro
Bennington
Worcester
Providence
Hartford
Springfield
Boston
Cape Cod Bay
Massachusetts Bay
Nantucket Sound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U.S. Private Domestic Wells | 2020
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Hartford
Brockton
Plymouth
Gloucester
Bedford
Nantucket Sound