Methane leaks from North American natural gas systems

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Study origins and participants

- Goal: To better understand natural gas leakage rates by critically analyzing available evidence
- Method: Assemble experts to review existing literature
  - Reviewed ~200 scientific and technical references
  - Reviewed studies at all scales: individual devices to continental atmospheric studies
- Organized by Novim (UCSB, Institute for Theoretical Physics)
- Funded by: Cynthia and George Mitchell Foundation and Novim

Background: EPA inventory

- The EPA GHG inventory[1] estimates that ~1.5% of gross methane (CH_4) production leaks from the natural gas (NG) system before it is burned[2]

- Small leakage rates from NG systems can be significant because CH_4 is a potent greenhouse gas (~30x CO_2)[3]

Notes:
[1]Data from EPA 2013 inventory, which assess emissions through 2011.
[2]Percentage computed as a mass fraction of gross CH_4 production from both gas wells and petroleum-associated gas. Stage-specific leakage rates and gas compositions are used from EPA 2013 Inventory. This is equal to ~1.8% of end-use methane consumption.
[3]This study uses IPCC AR4 global warming potentials, as these were the standard potentials at the time calculations were performed

Results: Inventories underestimate CH_4 emissions

- Evidence from numerous studies suggests that total U.S. CH_4 emissions are larger than those estimated by EPA inventory

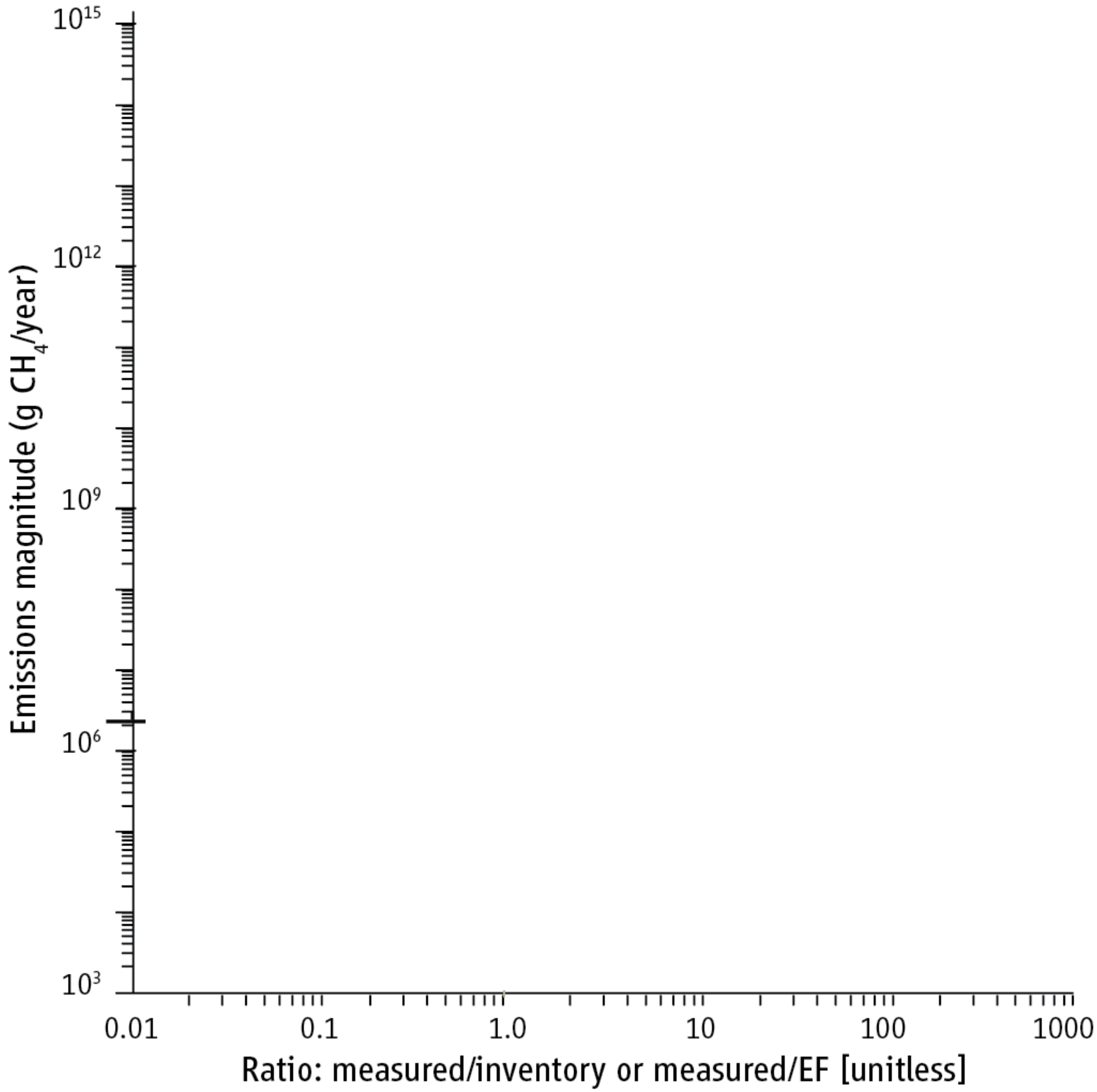
- National-scale atmospheric studies[1] suggest that CH_4 emissions are 50% higher than EPA estimates (uncertainty range = 25 – 75% higher)
  - 14 million tonnes of excess CH_4 per year (range 7 to 21)[2]

- Excess CH_4 emissions from the NG industry are very likely to contribute to this excess, but exact contribution is still uncertain

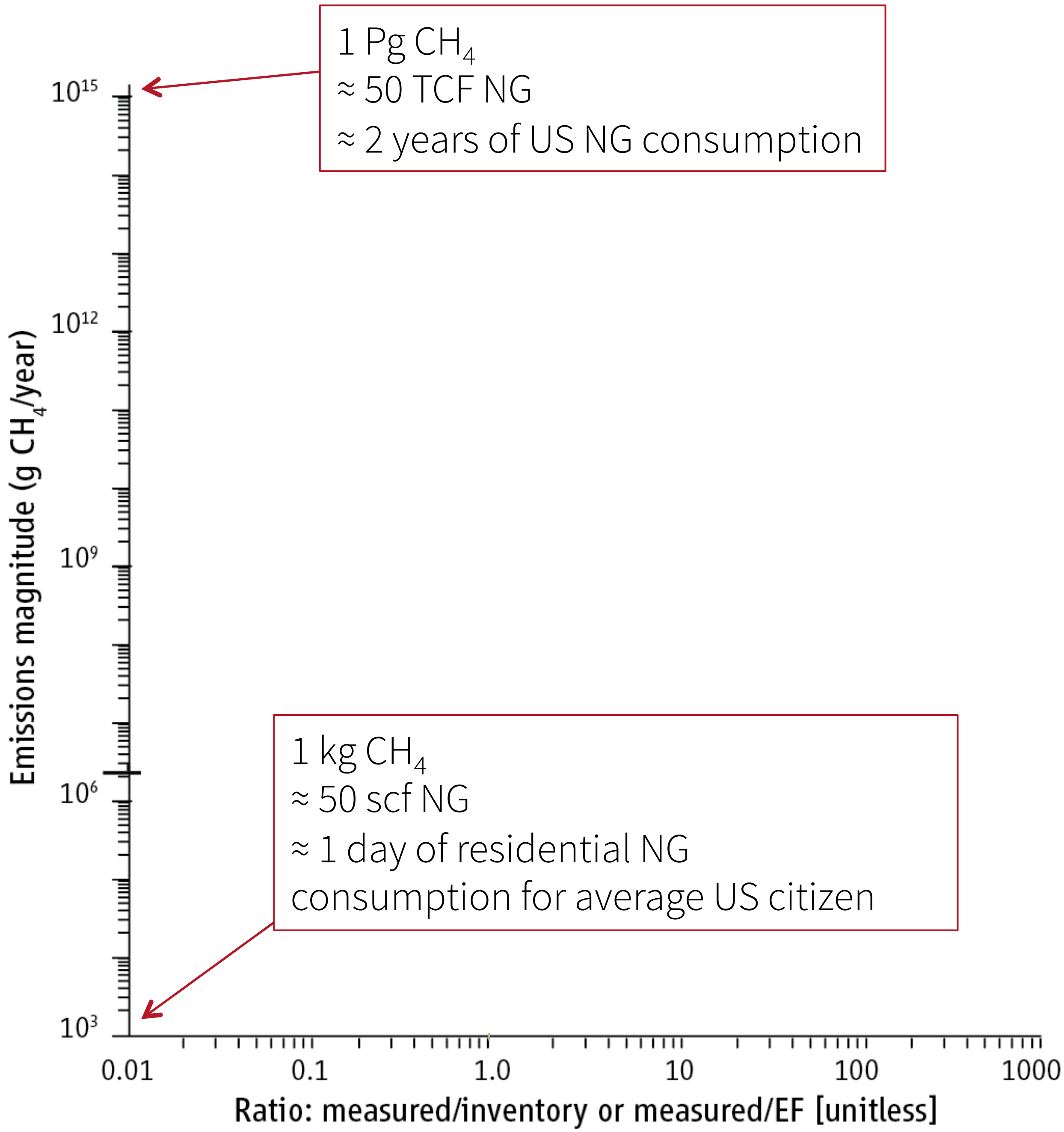
Notes:
[1]National-scale studies include Kort et al. (2008), Xiao et al. (2008), Miller et al. (2013), Wang et al. (2004)
[2]This excess amounts to ~14 Tg (+/- 7 Tg) of excess methane

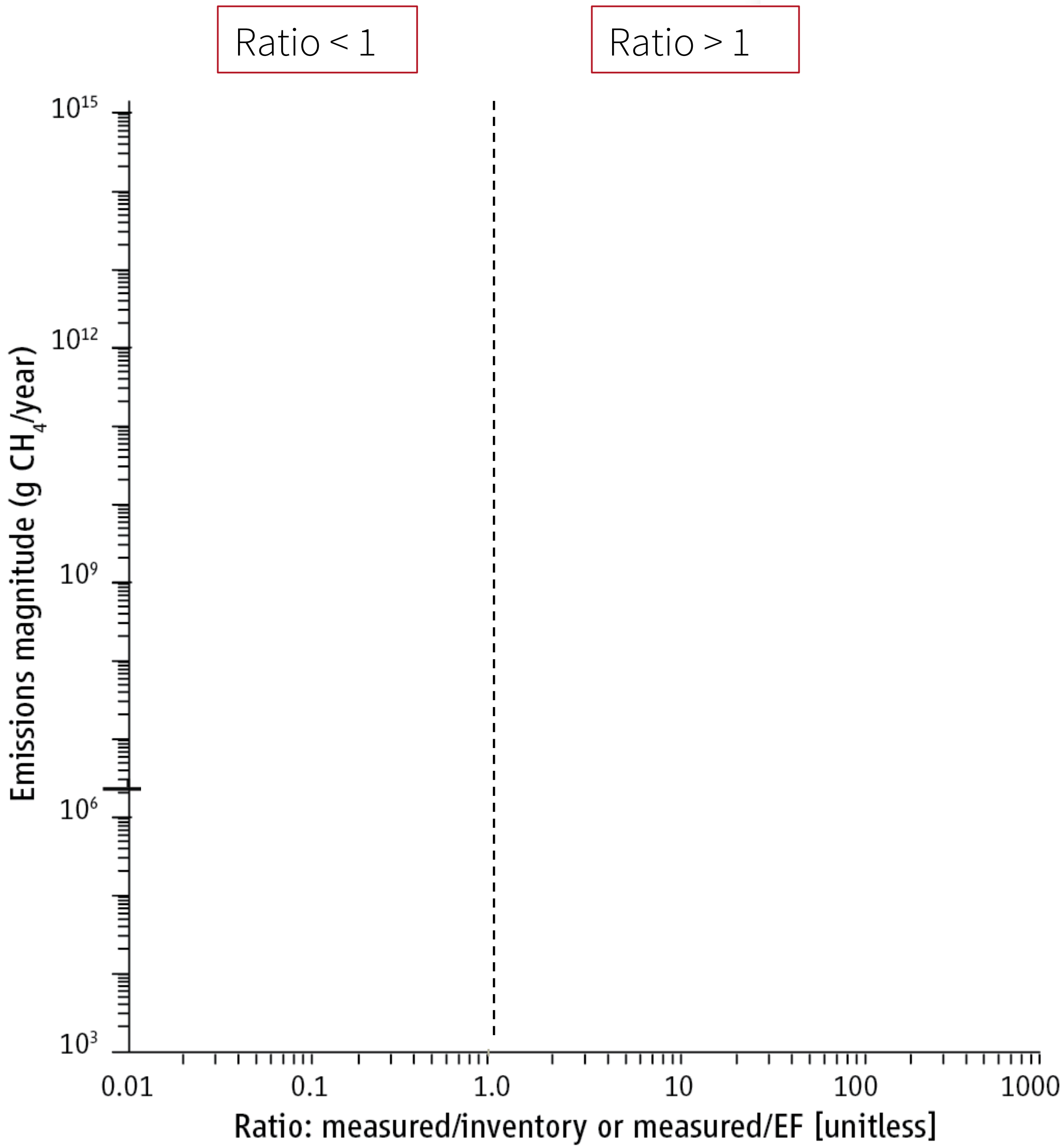
Figure 1: What is evidence for excess CH_4?

- In Figure 1, we collect and compare evidence from all studies we could locate which:
  - Were based on original observations or experimentation
  - Computed an emissions flux and compared their estimate to established emissions factor or inventory

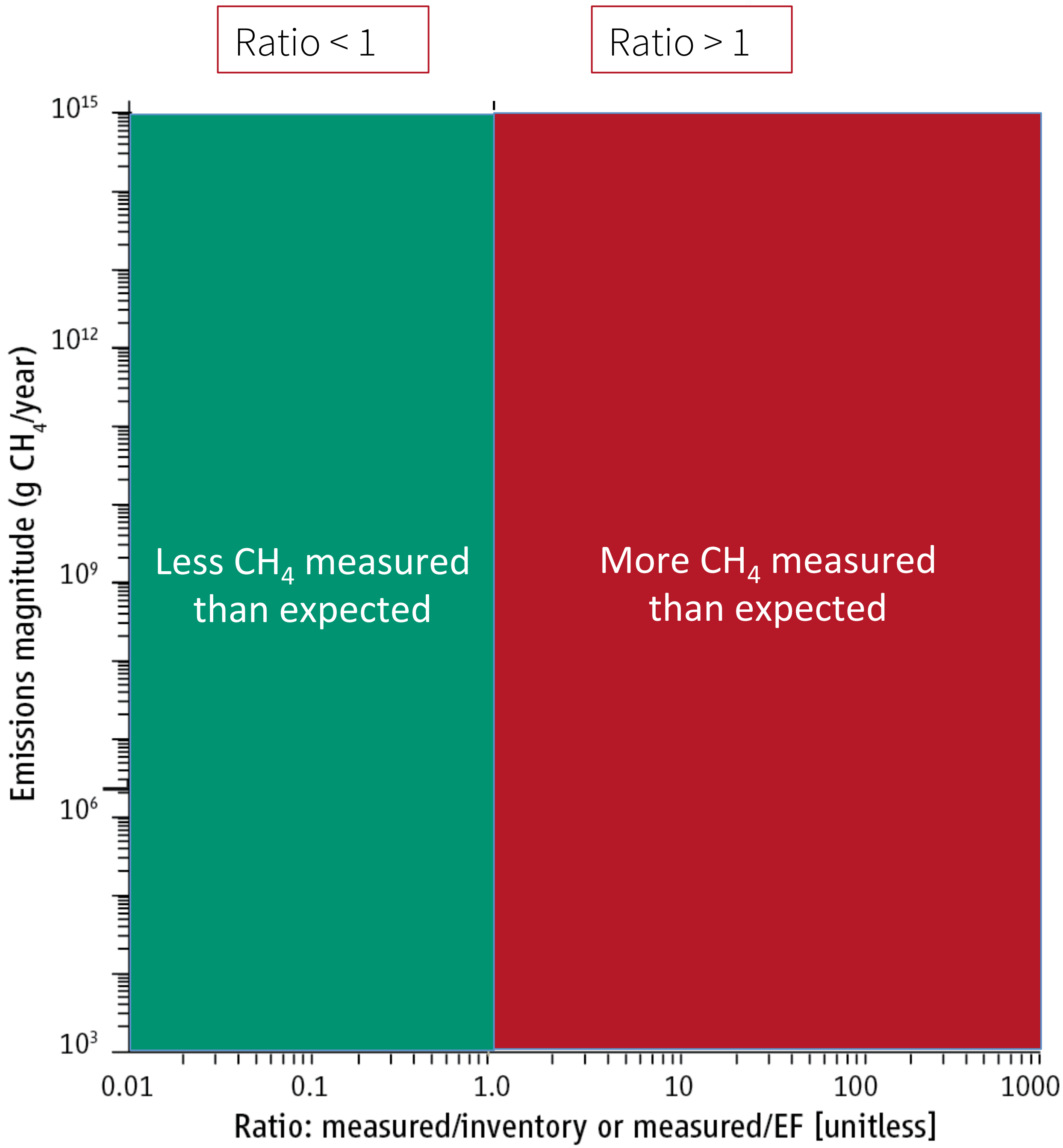


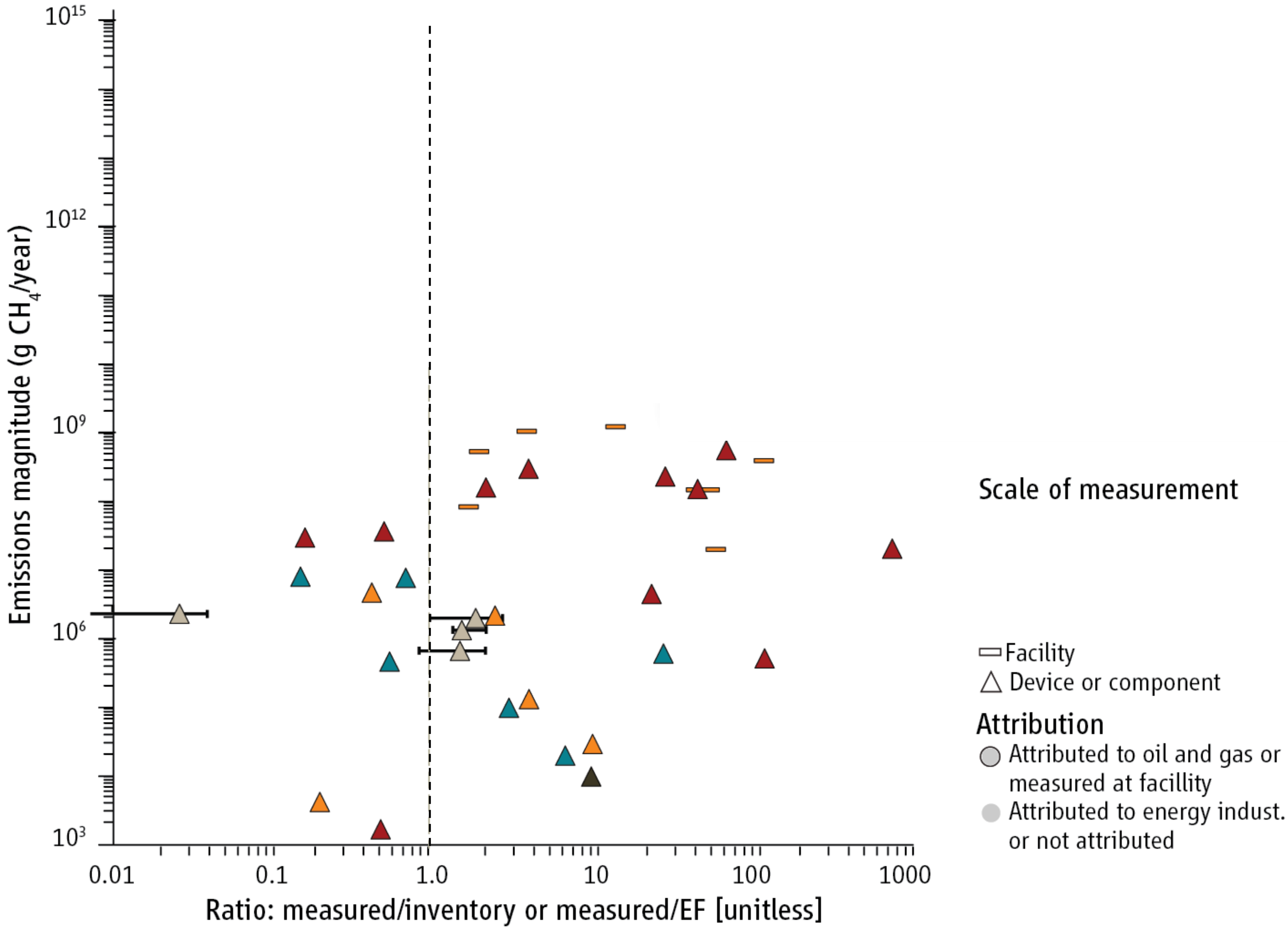
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
Emissions magnitude (g CH_4/year)
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]


1 Pg CH_4
≈ 50 TCF NG
≈ 2 years of US NG consumption
1 kg CH_4
≈ 50 scf NG
≈ 1 day of residential NG
consumption for average US citizen
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]

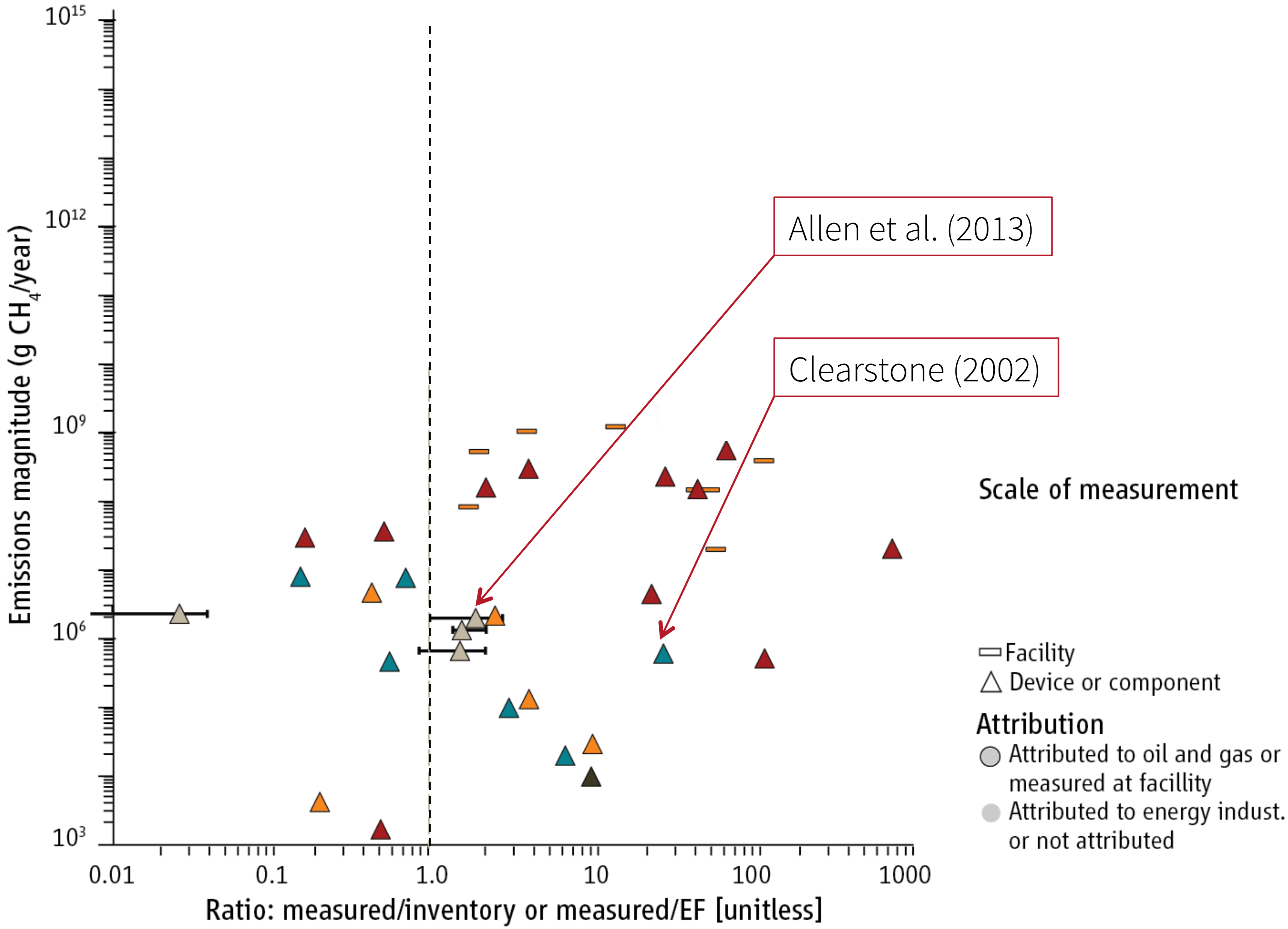


Ratio < 1
Ratio > 1
10^15
10^12
10^9
10^6
10^3
Emissions magnitude (g CH4/year)
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]


Ratio < 1
Ratio > 1
Less CH_4 measured than expected
More CH_4 measured than expected
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]



Emissions magnitude (g CH4/year)
10^15
10^12
10^9
10^6
10^3
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
Scale of measurement
Facility
Device or component
Attribution
Attributed to oil and gas or measured at facillity
Attributed to energy indust. or not attributed



Allen et al. (2013)
Clearstone (2002)
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
Scale of measurement
Facility
Device or component
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Attributed to oil and gas or measured at facillity
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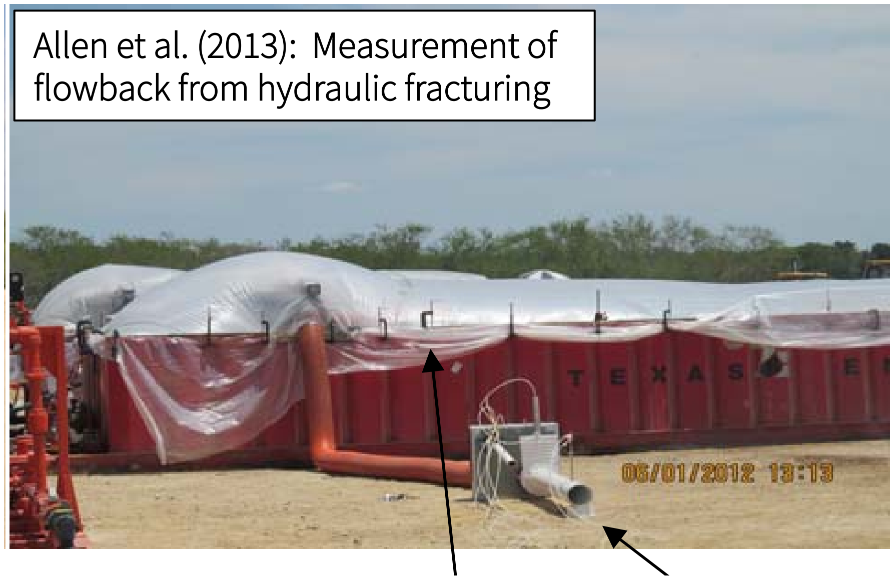
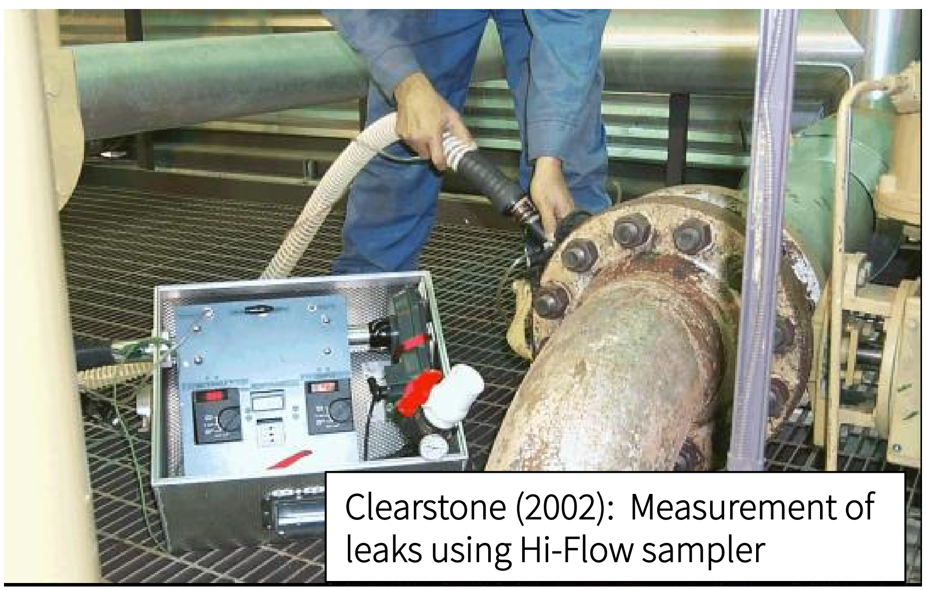
Examples: Bottom-up studies



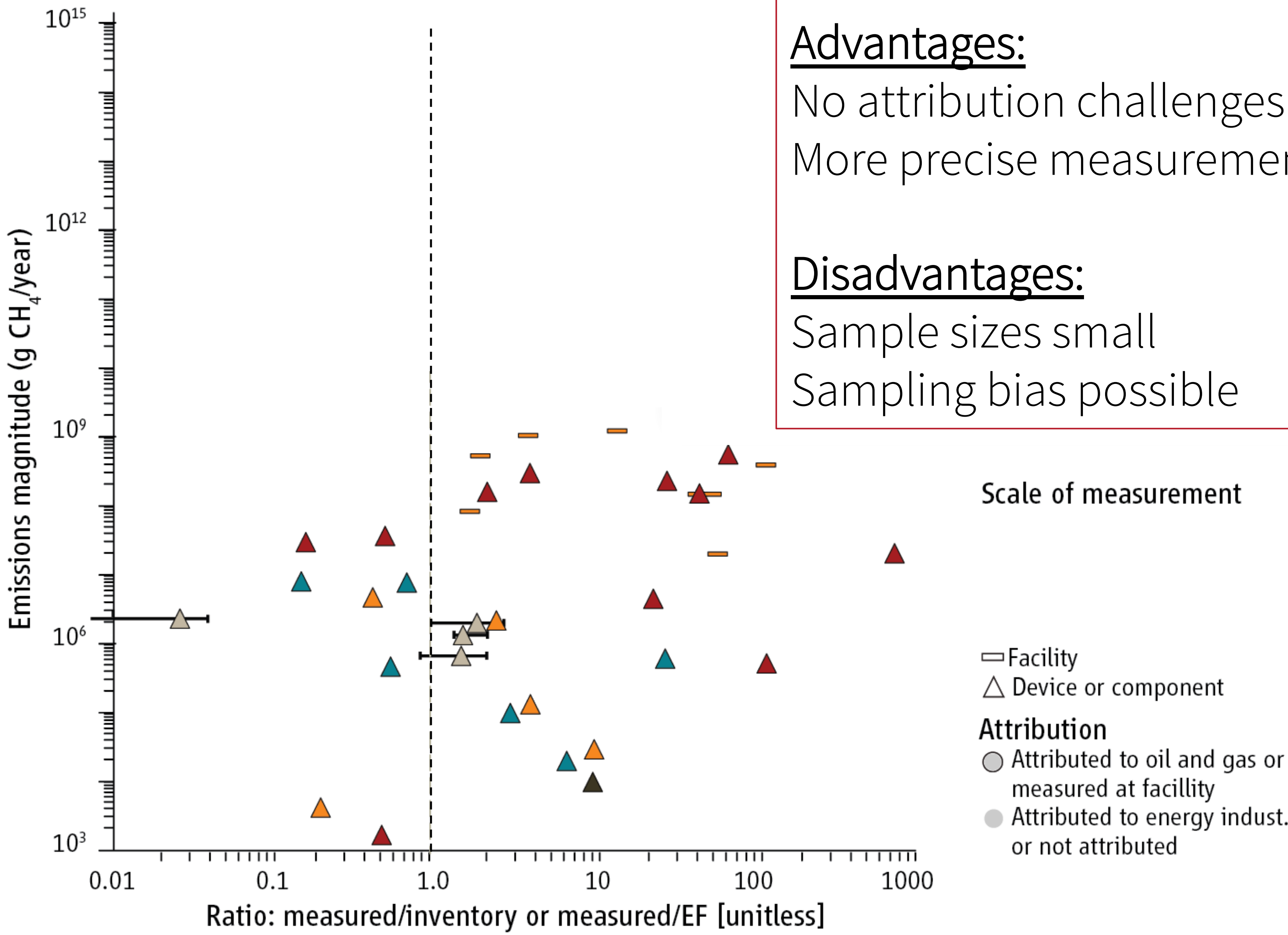
Allen et al. (2013): Measurement of flowback from hydraulic fracturing

Result:
- EPA estimates for hydraulic fracturing flowback far overstated
- Other sources underestimated (chemical pumps, pneumatic controllers, leaks)



Clearstone (2002): Measurement of leaks using Hi-Flow sampler

Result:
- Mixed results: connectors, PRVs larger than EPA, compressor seals smaller than EPA
- Highly heterogeneous leakage rates (top 10 sources at each site (50/100,000) were 35% of leaks



Bottom-up studies

Advantages:

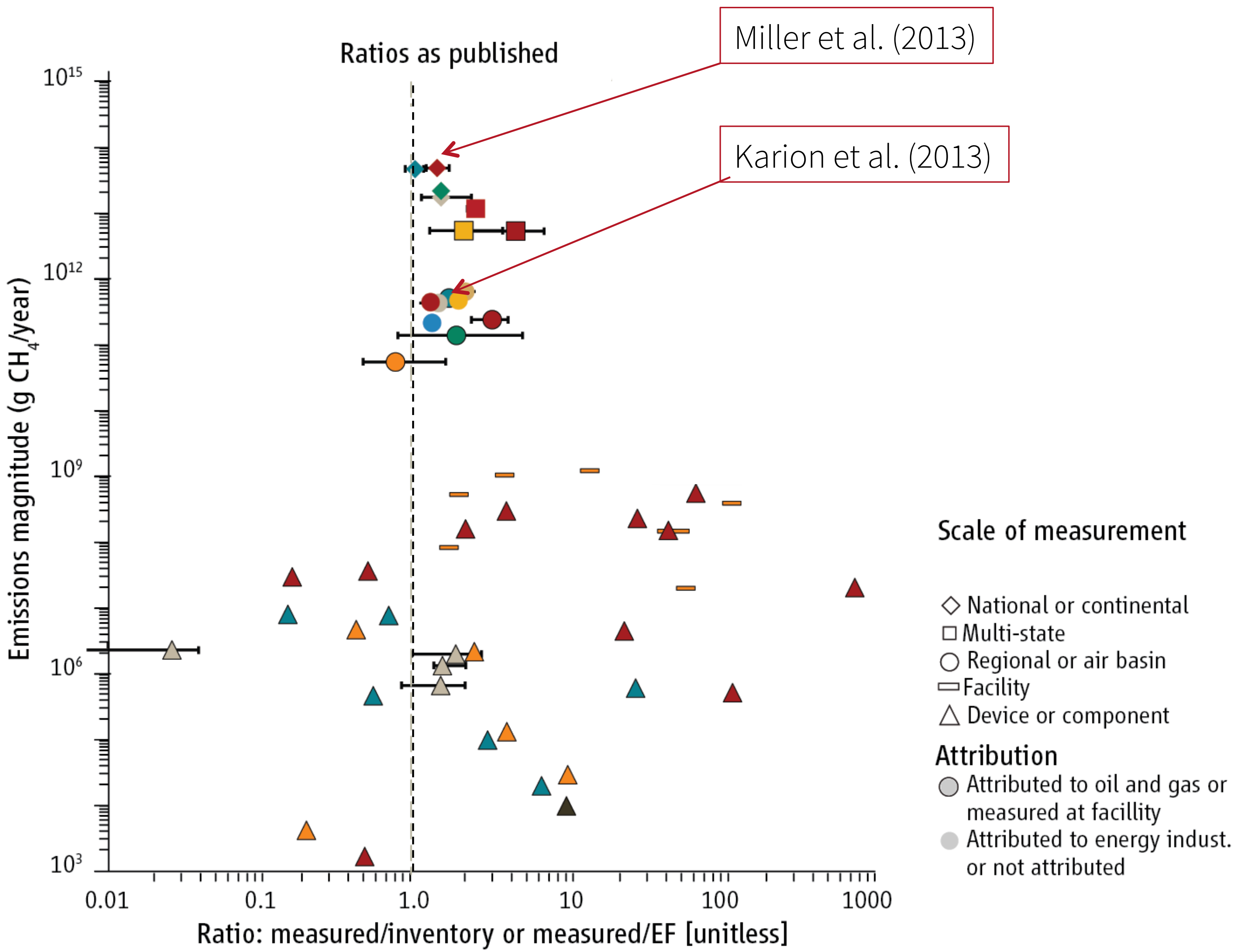
No attribution challenges

More precise measurement

Disadvantages:

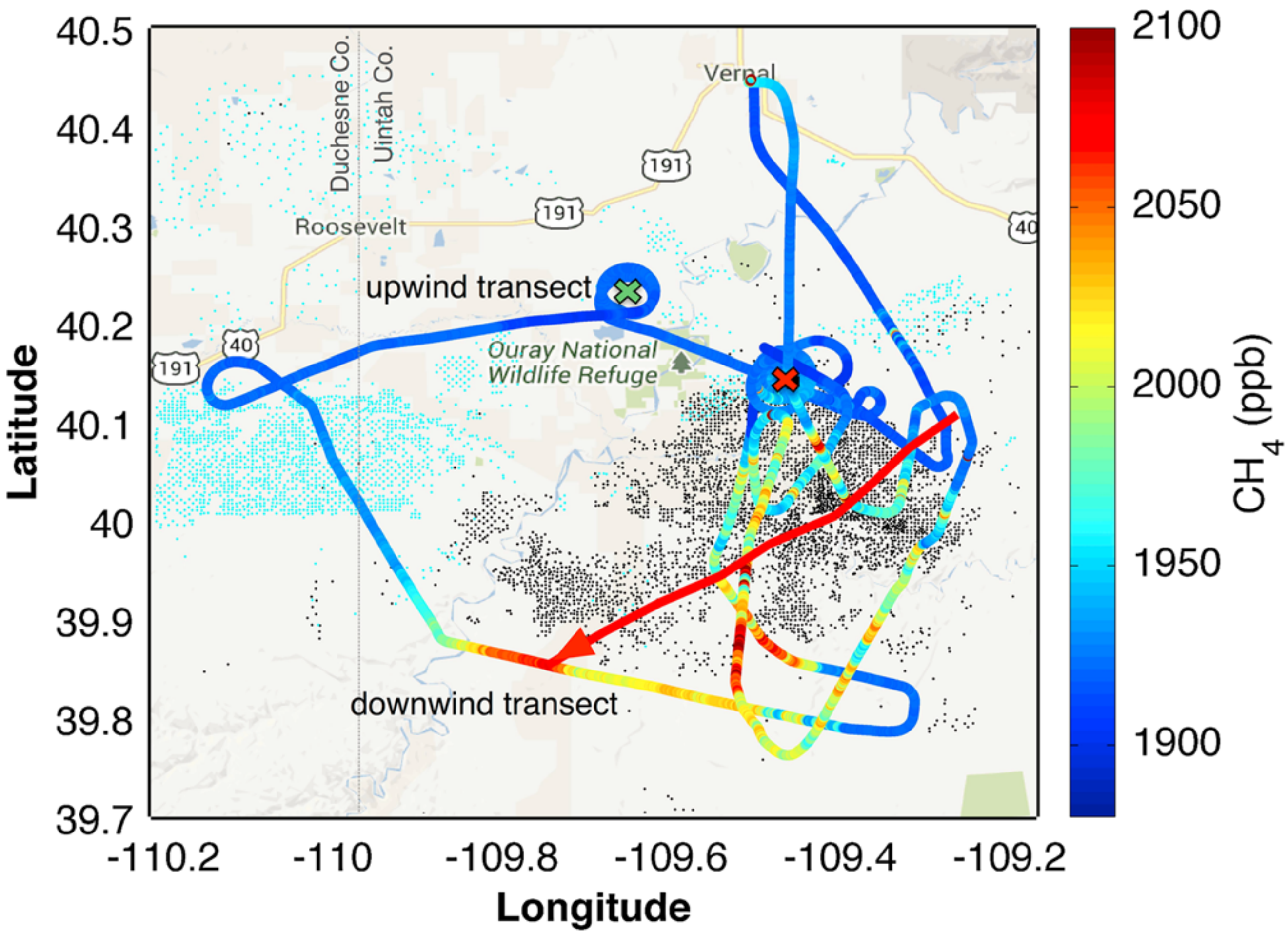
Sample sizes small

Sampling bias possible



Ratios as published
Miller et al. (2013)
Karion et al. (2013)
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
Scale of measurement
National or continental
Multi-state
Regional or air basin
Facility
Device or component
Attribution
Attributed to oil and gas or measured at facillity
Attributed to energy indust. or not attributed

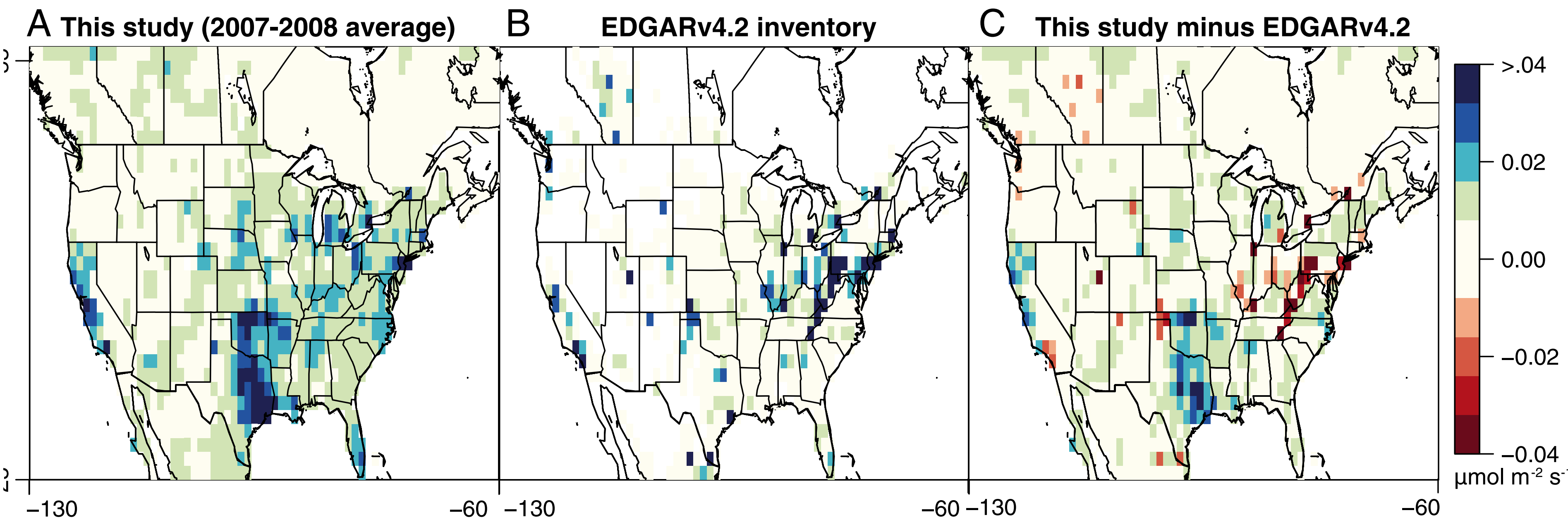
Examples: Top-down studies



Result: Leakage rate of 8.9% (+/- 2.7%) of produced gas

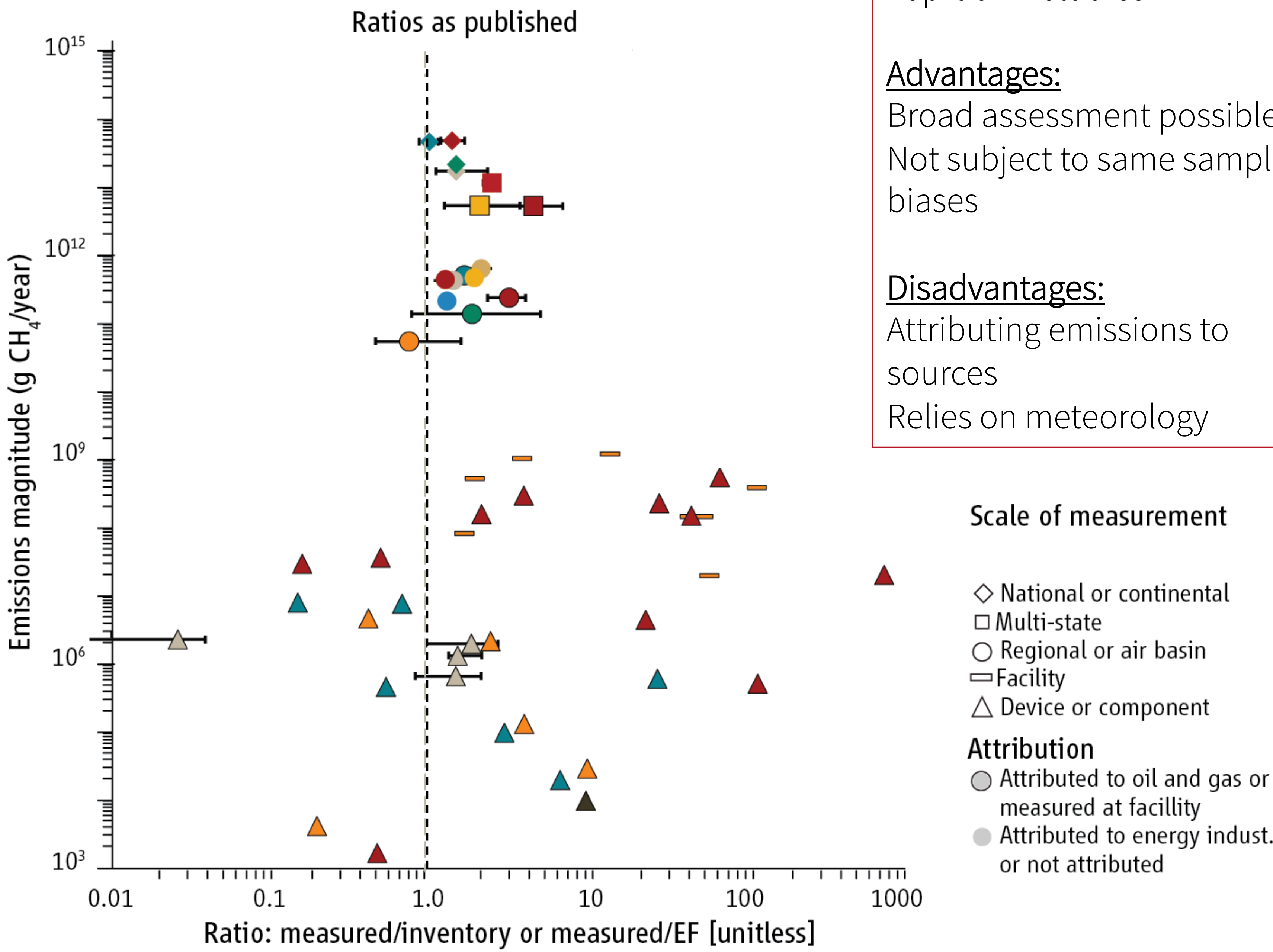
Karion et al. (2013): Upwind and downwind transects of a gas field in rural Utah

Examples: Top-down studies



Miller et al. (2013): 12,000+ measurements underlying atmospheric inverse modeling

Result: Total methane emissions ~1.5 x US EPA GHGI



Top-down studies

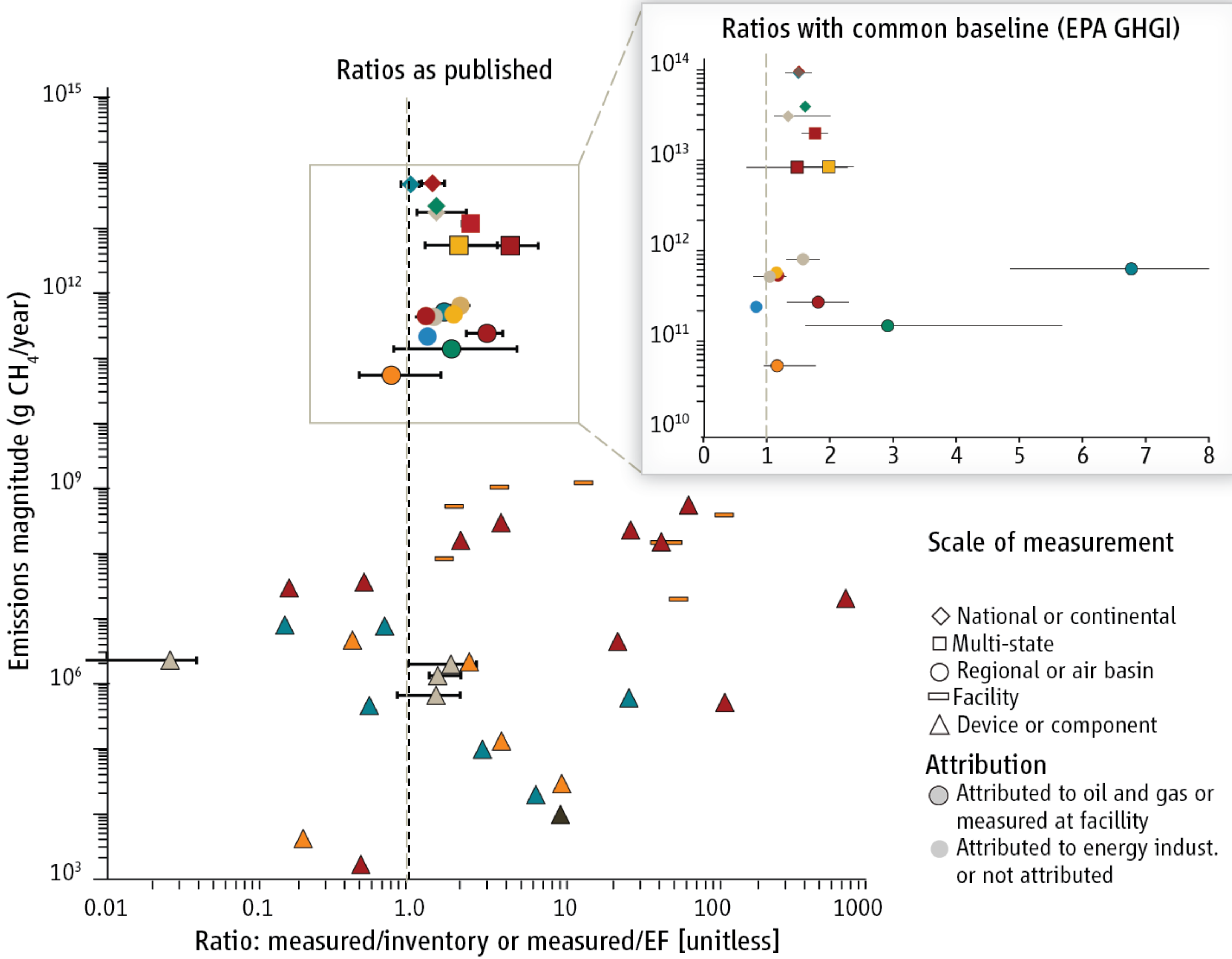
<u>Advantages:</u>
Broad assessment possible
Not subject to same sampling biases

<u>Disadvantages:</u>
Attributing emissions to sources
Relies on meteorology

Challenge of differing baselines

- Nearly all bottom-up studies compare their results to EPA GHGI[1] emissions factors
- Top-down studies compare to a variety of baselines
  - EDGAR
  - National (EPA) or regional inventories (WRAP, CARB)
- Putting studies on consistent basis yields more robust insights
  - For each study, scaled 2013 EPA GHGI to region and sector appropriate for the given study[2]

Additional notes:
[1]One exception: Chambers (2004, 2006) compares his results to CAPP methods
[2]See supplemental worksheet, sheet 'Calc – Figure 1 – Inset' for full computation



Ratios as published
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
Ratios with common baseline (EPA GHGI)
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
0 1 2 3 4 5 6 7 8
Scale of measurement
National or continental
Multi-state
Regional or air basin
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Summary results: Figure 1

- Normalized top-down studies suggest emissions of CH_4 ~1.5X (1.25-1.75) EPA GHGI
- NG-specific studies also find excess
  - Both top-down and bottom-up tend > 1
  - Wider range and more scatter given the smaller emission scale
- We cannot say how much of the overall excess is due to the NG system

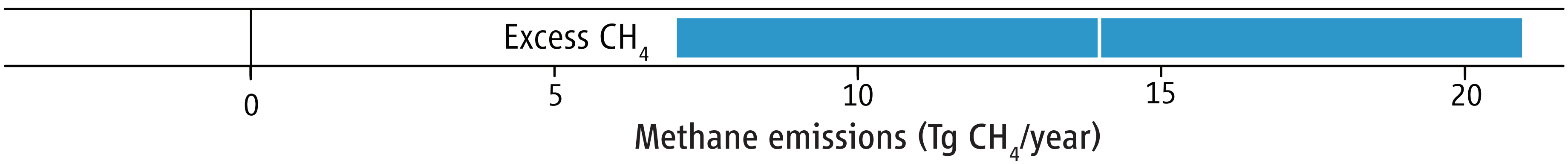
Causes of a methane "gap"

- Why a gap between observations and inventories?
- Inventories rely on a set of key assumptions
    1. Sampled populations are representative
    2. Sample sizes are sufficiently large to characterize variability
    3. Distributions are sufficiently normal for valid extrapolation from sample mean
    4. Activity factors are well characterized
- These assumptions not generally met

Figure 2: What might be causing excess CH_4?

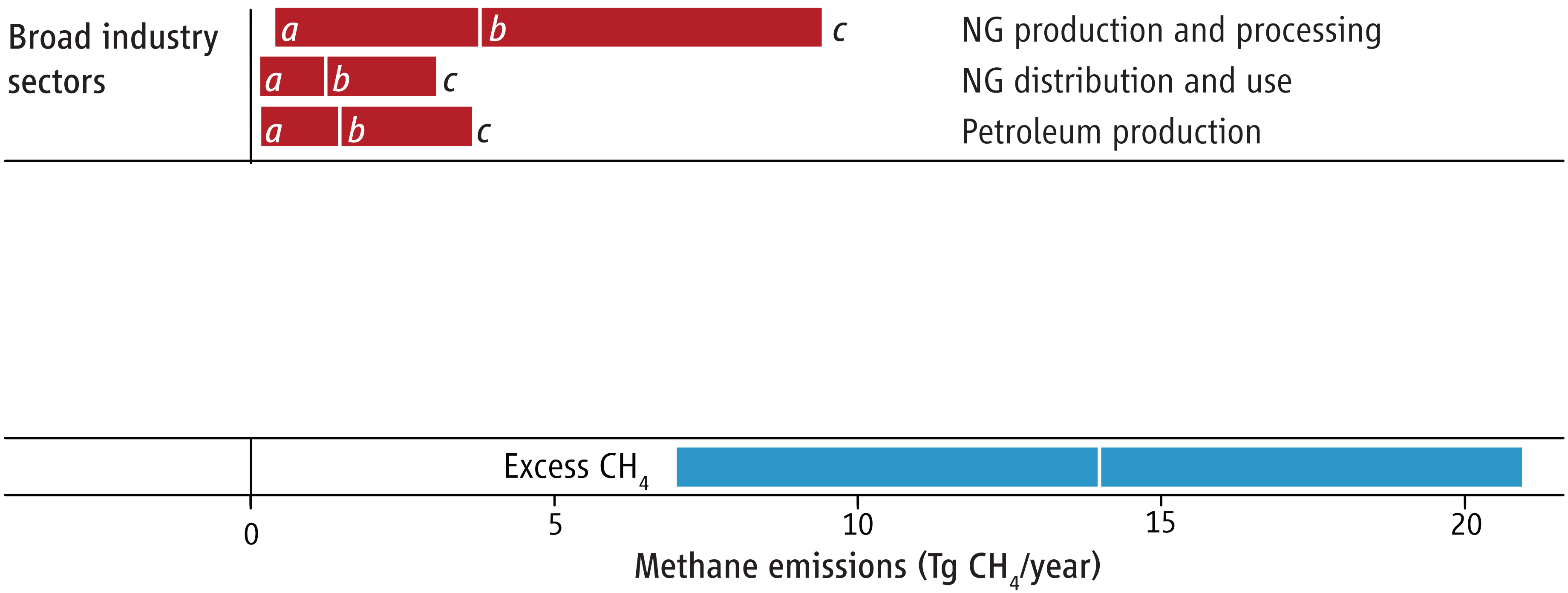
- In Figure 2, we perform a thought experiment on some possible causes of excess CH_4, given evidence available
- Focus on NG sources and sources that might be mistaken for NG
  - "Look like" NG by chemical or isotopic signature


0
5
10
15
20
Methane emissions (Tg CH_4/year)



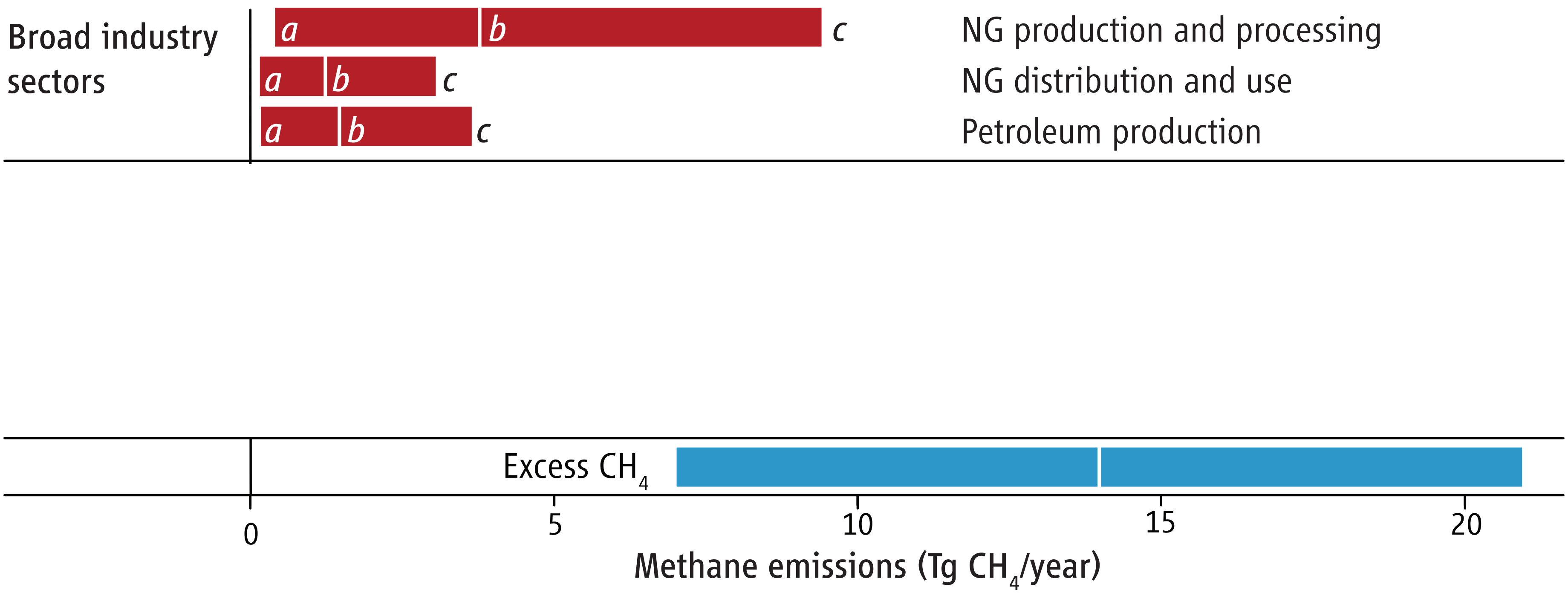
Range of total excess CH_4 (based on normalized Figure 1 results)

= 50% (25-75%) above EPA GHGI
= 14 Tg CH_4/y (7- 21 Tg CH_4/y)



Broad industry sectors

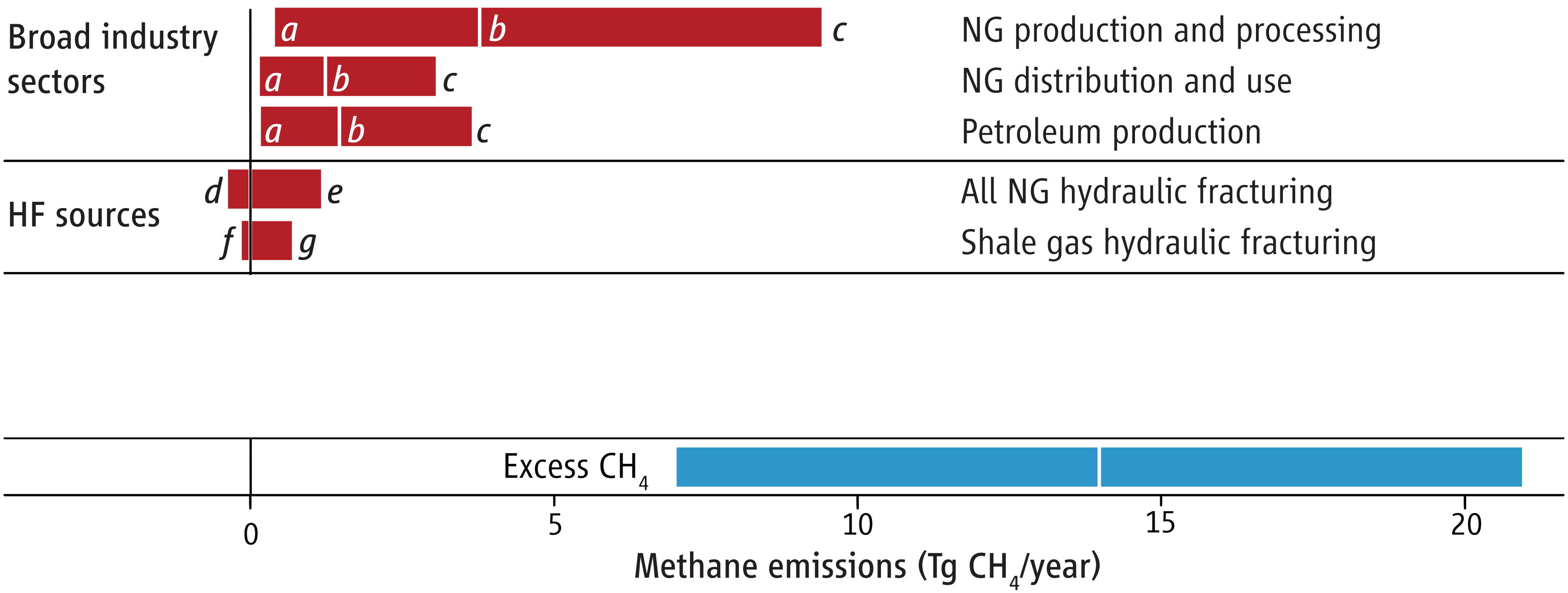
- Top-down studies give us emissions estimates for a region (or NG industry sub-sectors)
- They do not tell us **how common** these emissions rates are
- So we construct "illustrative prevalence scenarios"
  - Take leakage rate observations from the literature
  - Apply these to a set fraction of activity (*a* = 1%, *b* = 10%, *c* = 25%) while the rest of activity remains at EPA average



Broad industry sectors

- Example: NG production and processing:
  - Leakage rate of 9% (Karion et al. (2013) data from Uintah Basin UT)
  - Apply this to 1%, 10% and 25% of US gas production, compute excess

- **Result:** High emissions rates from recent atmospheric studies (UT, LA) are not the norm. If so, we would see more methane from the continental/national atmospheric studies.



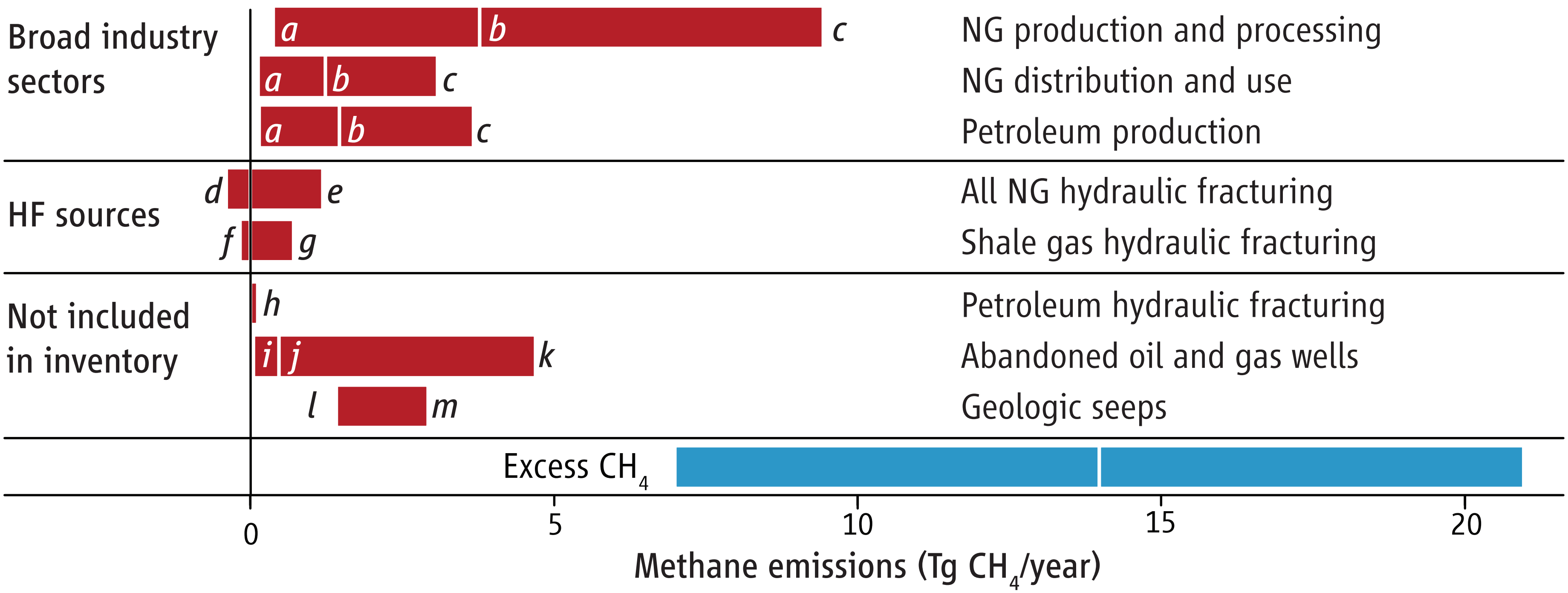
<u>Hydraulic fracturing</u>

Emissions rates during flowback are uncertain

Shale gas HF:

- Examine "Big 5" shale gas plays, use method from O'Sullivan and Paltsev (2012)
- Low (*f*) is "current practice" emissions rate: 56 Mg CH_4/well
- High (*g*) is "all vented" emissions rate: 234 Mg CH_4/well

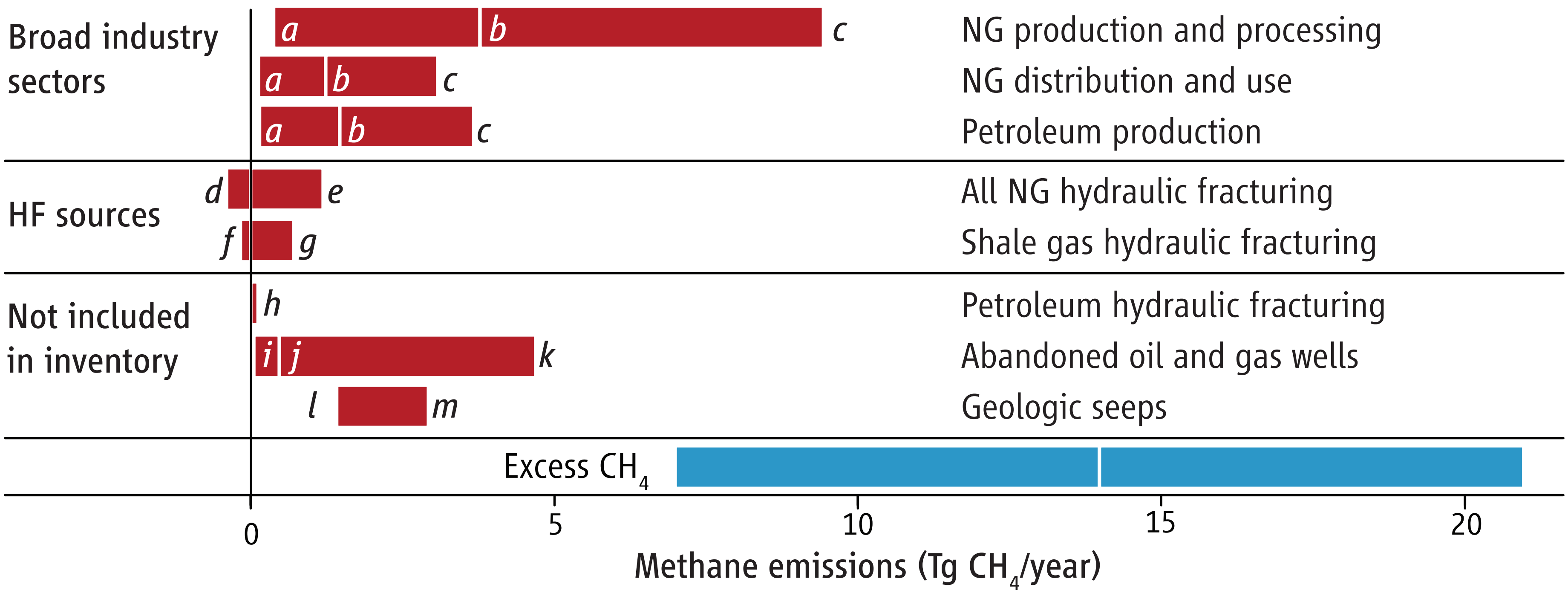
Result: HF may contribute if uncontrolled flowback is the norm. However, results suggests that HF is not the dominant contributor to overall excess CH_4.



Sources not included in inventory

Petroleum hydraulic fracturing:

- Not included in either NG or petroleum inventory
- Applies method of O'Sullivan and Paltsev (2012) to HF wells drilled in tight oil plays
    - Bakken, Eagle Ford, Permian

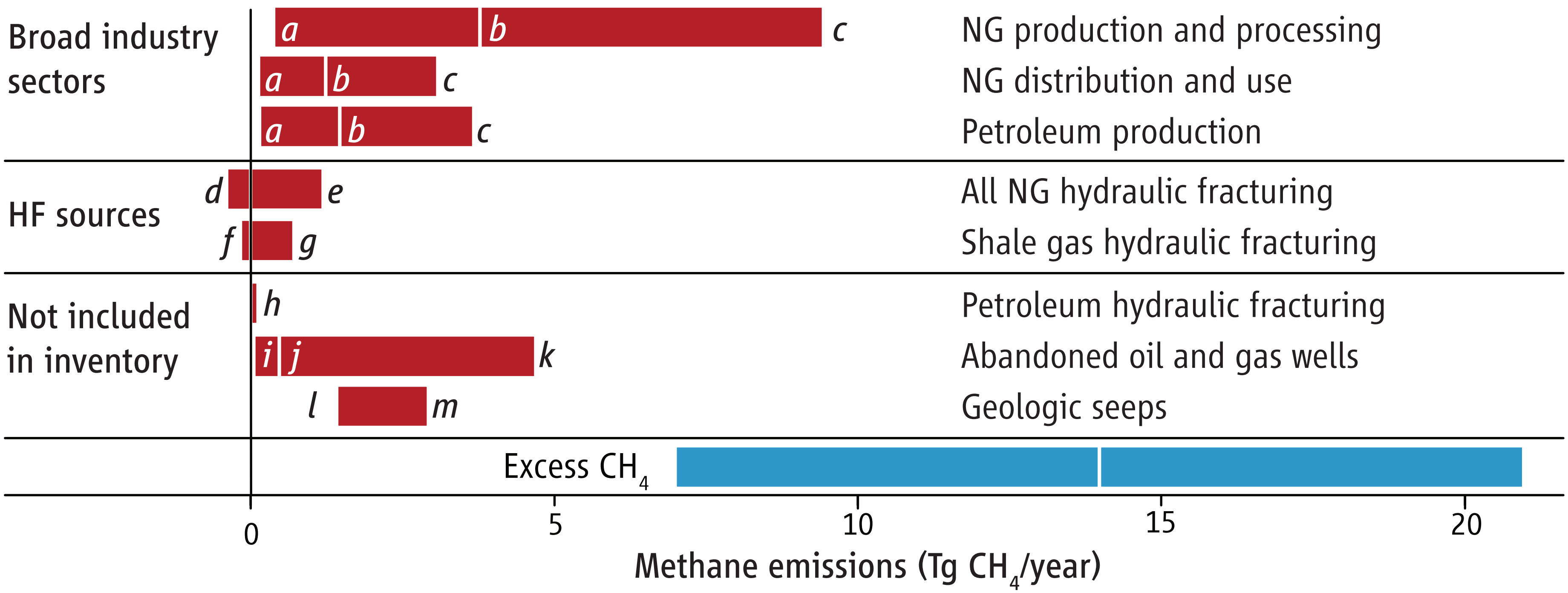


Sources not included in inventory

Abandoned oil and gas wells:

- About 3 million abandoned wells exist in the US, many were abandoned before standards were put into place (see SM worksheet for sources)[1]
- Emissions rates are uncertain, so choose 1, 10, 100 mcf/y per well (*i, j, k*)

[1] http://www.nytimes.com/1992/05/03/us/abandoned-oil-and-gas-wells-become-pollution-portals.html



<u>Sources not included in inventory</u>

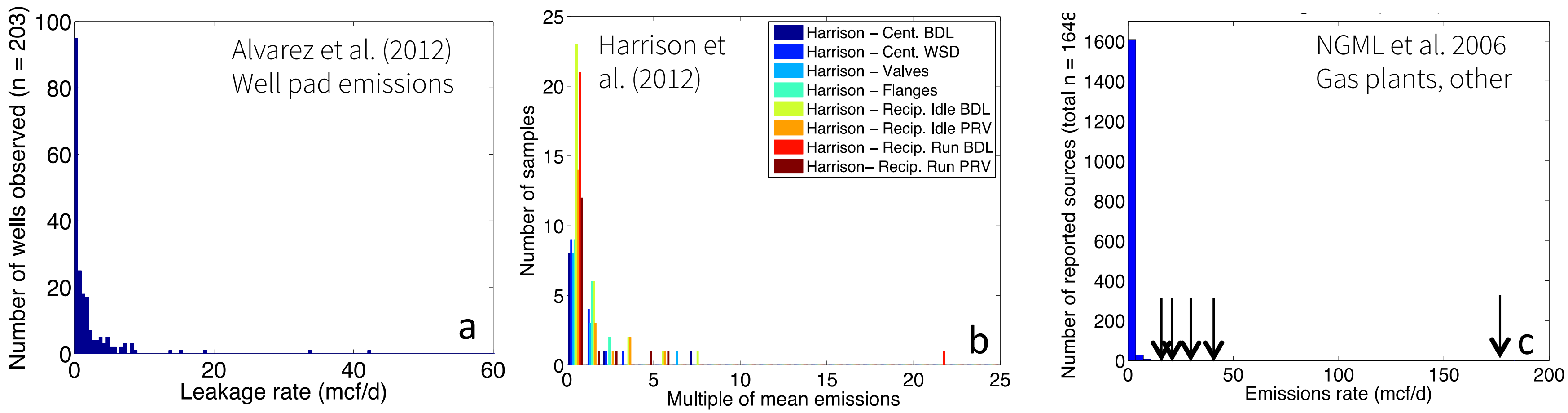
Petroleum HF not likely a major source. Abandoned wells could contribute, but requires assuming high leakage rates. Geologic seeps could confound, but some studies (e.g., Miller et al. 2013) already account for this.

Results: Variability and “super-emitters”

- Bottom-up studies[1] suggest that unintentional leakage rates vary greatly between devices
  - Most devices do not leak
  - A small fraction of devices leak excess gas (1-2 %)
  - A **very** small fraction (<<1%) leak a large amount. These super-emitters often contribute a large fraction of the total leakage

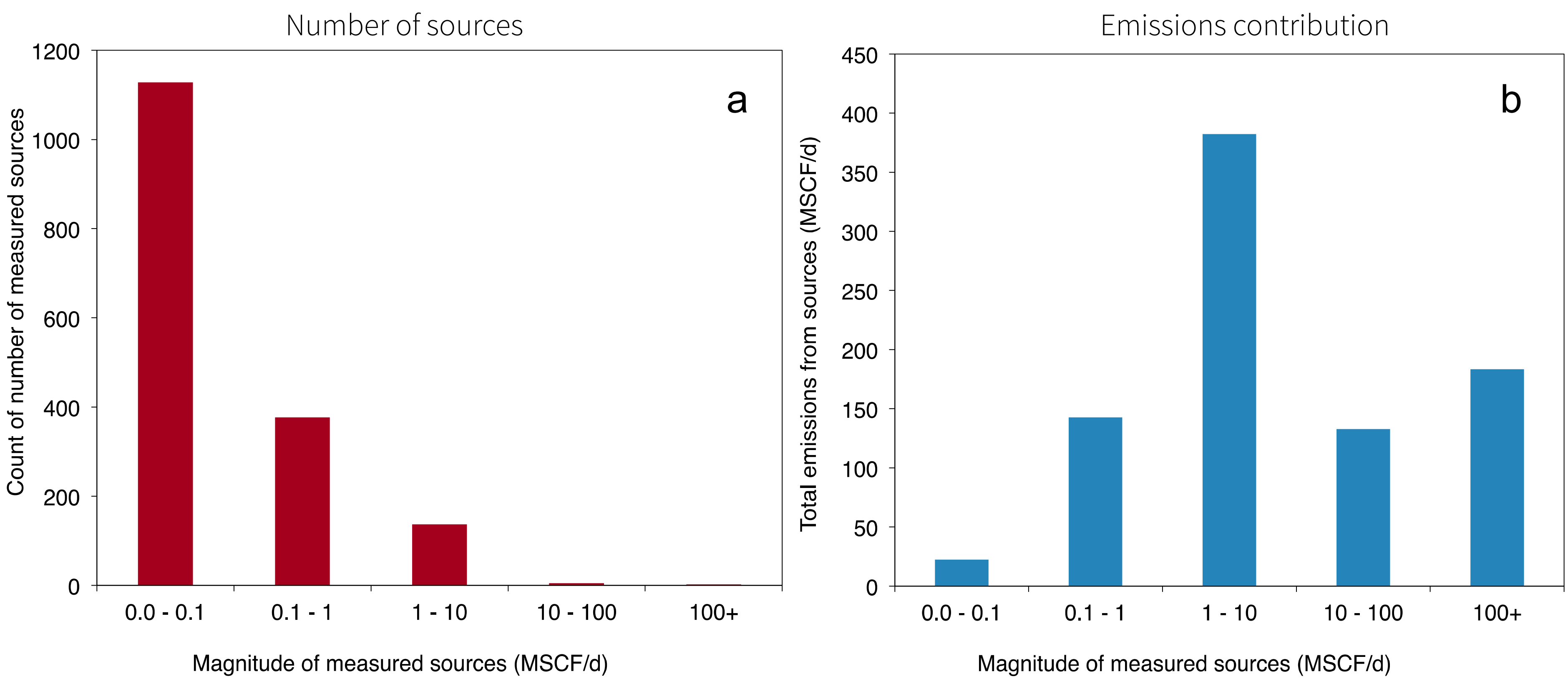
Additional notes:
[1]See Table S6 in paper SM for tabular evidence of “super-emitters”

Distributions of emissions



Footnotes:
[1]Figure S2 in paper SM

Dominance of a few sources



Footnotes:
[1]See Figure S3 in paper SM. Data from NGML, IES, Clearstone (2006) report for EPA. Measurements at gas plants, well pads, other sources.

Misalignment: inventories, LCAs, measurements

- A still-entangled problem: methodologies have different system boundaries
- Comparisons require understanding congruence (or lack thereof) between LCA, inventories, and experimental evidence
- Examples
  - Peischl et al. (2013) gas vs. petroleum
  - EPA GHGI vs. LCA

Results: NG fuel substitution

- Leakage rates from the NG system still favor coal to NG substitution for electricity generation
  - 100 year global warming potentials, life cycle basis
  - To favor coal: high estimate of undercounted emissions (1.75x EPA); all excess CH_4 from NG industry.
  - We know other sources contribute; e.g., livestock

- Climate benefits from using NG in transportation are uncertain (for gasoline cars) or unlikely (for heavy-duty diesel vehicles)

Footnotes:
Fuel switching benefits defined using cutoff percentages from Alvarez et al. (2012)

Fuel switching caveats

- We use 100-year climate assessment period
- We rely on Alvarez et al. (2012) analysis and assumptions
  - Leakage rates for NG vehicle refueling and vehicle efficiencies
  - Global warming potentials for CH_4 have since increased
- System boundary alignment between inventories and LCAs is poor
  - Attributing emissions between oil and gas in co-producing systems
- Does not consider technological change or reductions in leakage

Need for more science

- Atmospheric studies have uncertainty due to challenges inherent in atmospheric modeling
  - More scientific development needed to improve attribution and reduce uncertainty
- Measurements from facilities' current operations are lacking
  - Need much more data from variety of emission sources
  - Need broader participation in studies (e.g., large and small operators) and variety of methods
- Closing the gap between estimates from experiments and invetories is a key challenge
  - Work is ongoing around the country in this area (EDF effort, many national laboratories and universities)

Opportunities to solve the problem

- Leakage detection and repair programs have been shown to be profitable
- Super-emitting sources: if we can find them cheaply and quickly, they are profitable to fix
- EPA Inventory accuracy should be improved to provide better policy guidance