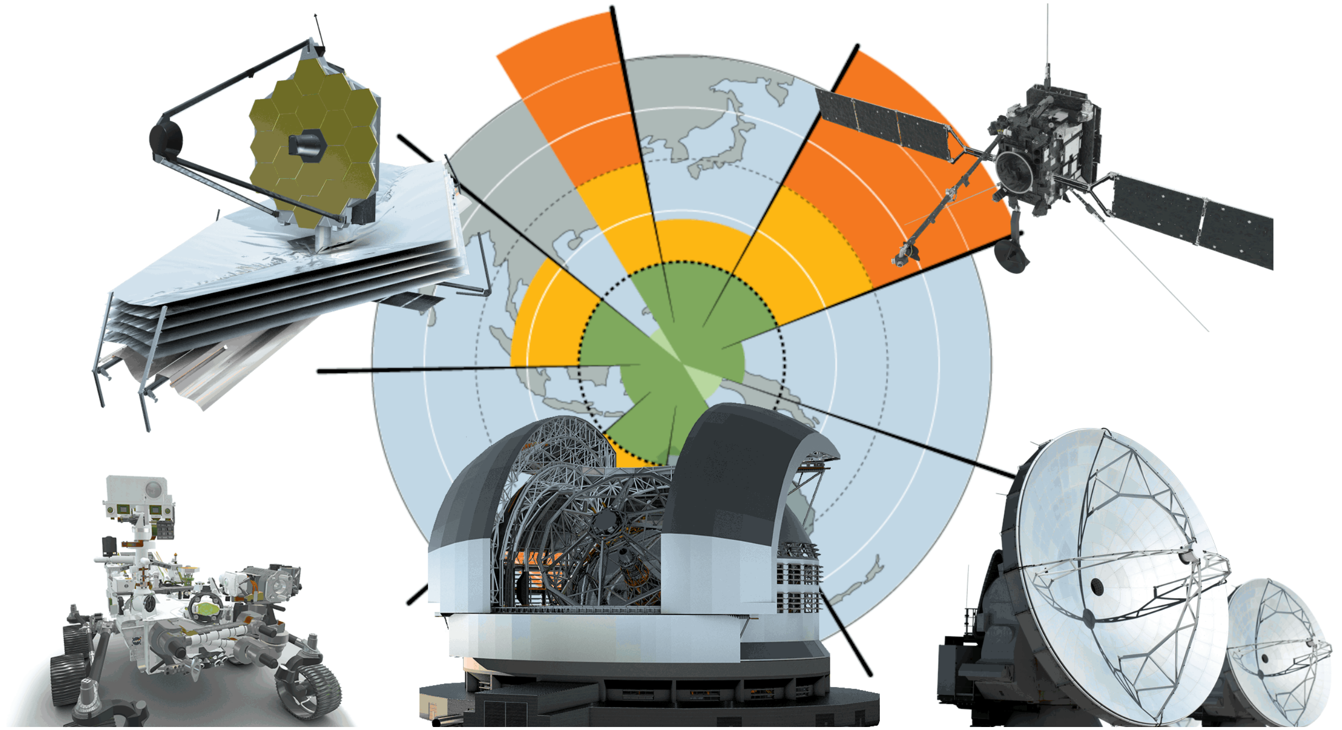
Astronomy in the era of climate change



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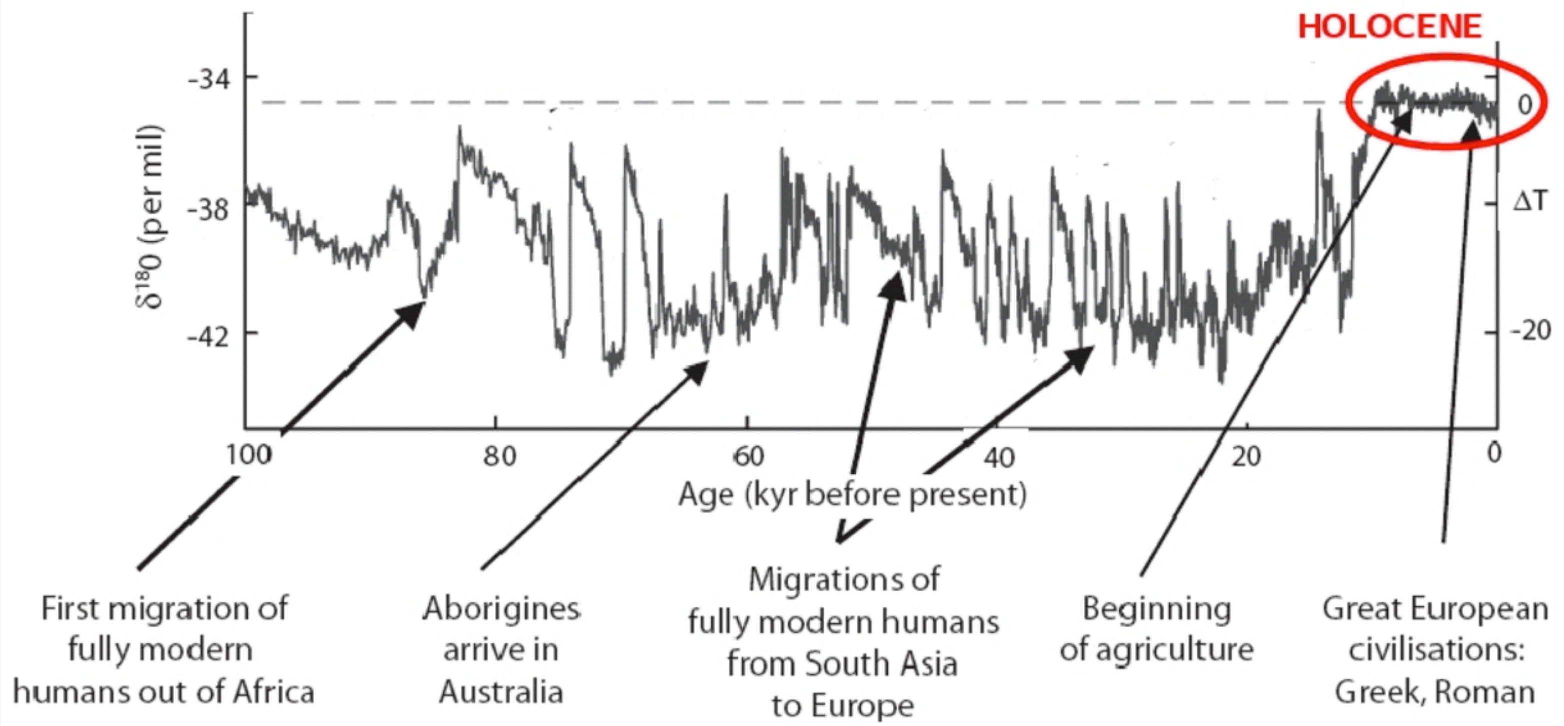
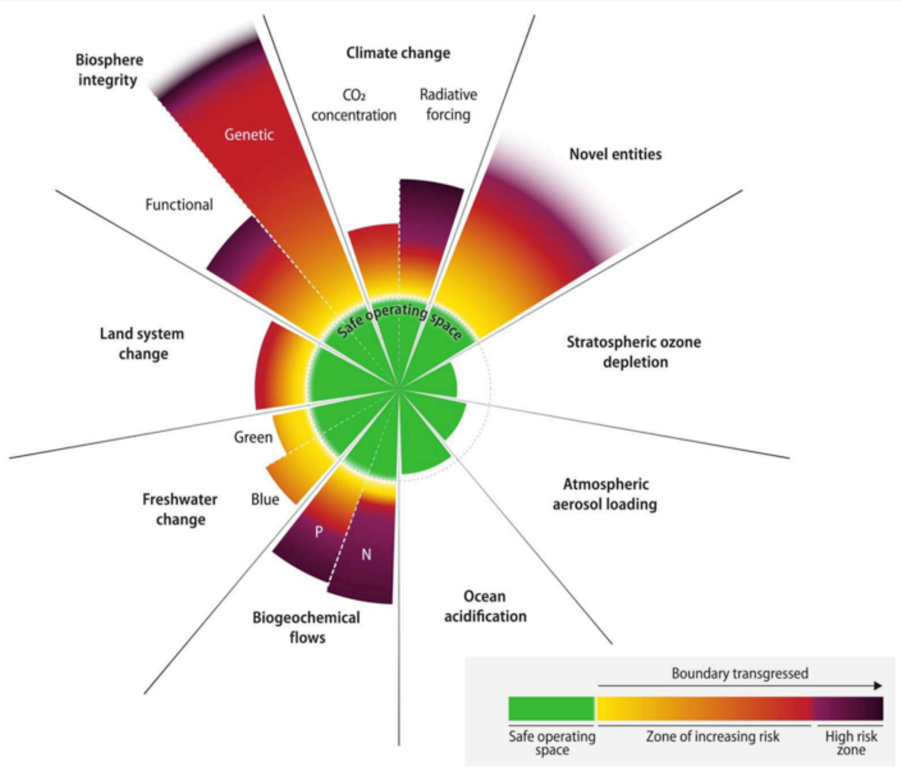
The climate history of Homo Sapiens



Rockström et al. (2009), Ecology and Society, 14, 32

Planetary Boundaries



Richardson et al. (2023), Science Advances, 9, eahd2458

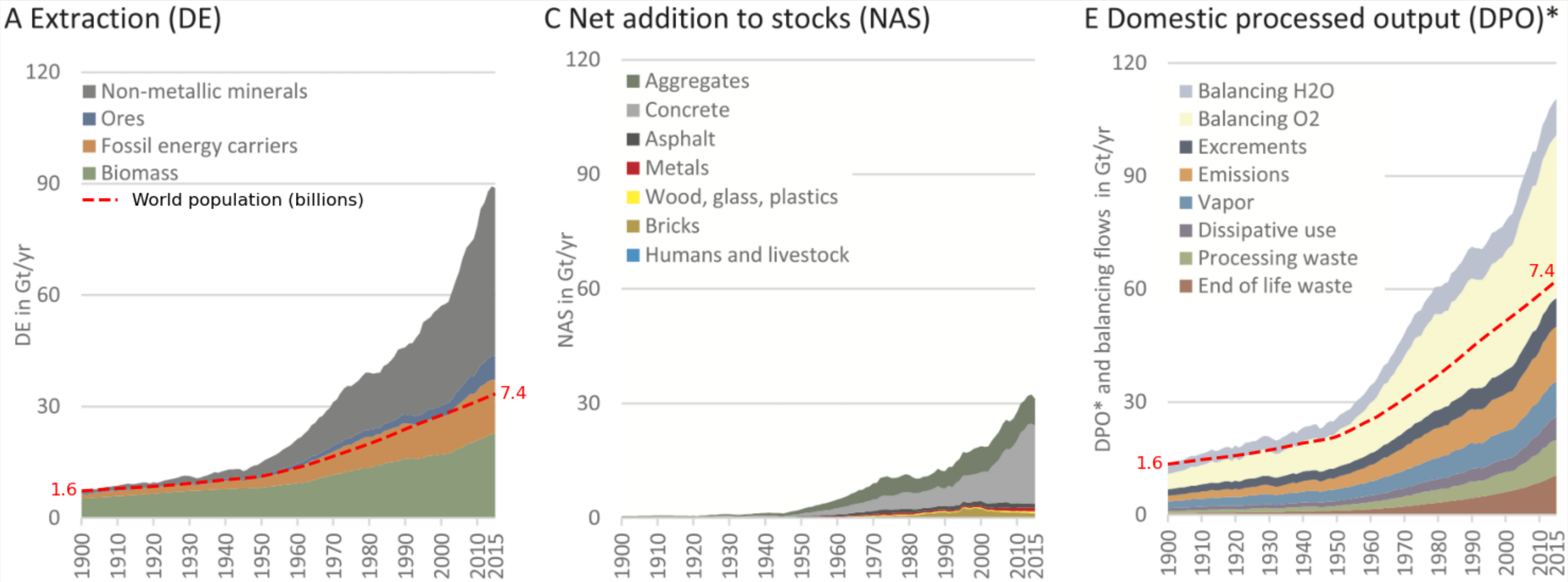
Science-based analysis of the risk that human activities will destabilise the Earth system at the planetary scale

We are no longer in the safe operating zone for
6* out of 9 planetary boundaries

*novel entities, climate change, biosphere integrity, land-system change, freshwater change, biogeochemical flows

Socioeconomic metabolism of the global economy

Extraction | Infrastructures | Waste



Adapted from Krausmann et al. (2018), Global Environmental Change, 52, 131-140

Climate change: the evidence

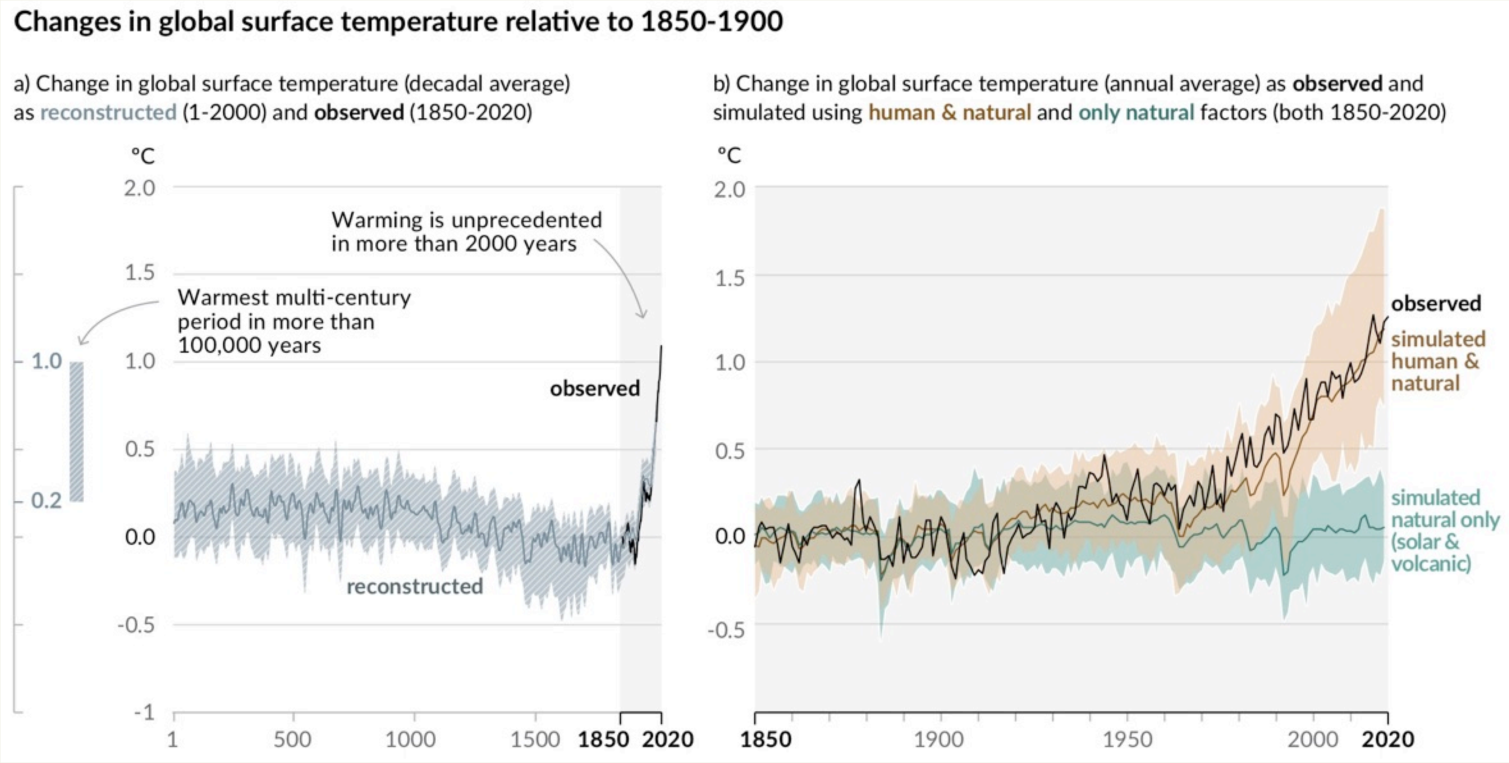


Figure 1 of Summary Report for Policy Makers of the IPCC 6th assessment report of Working Group 1

Climate change: the risks

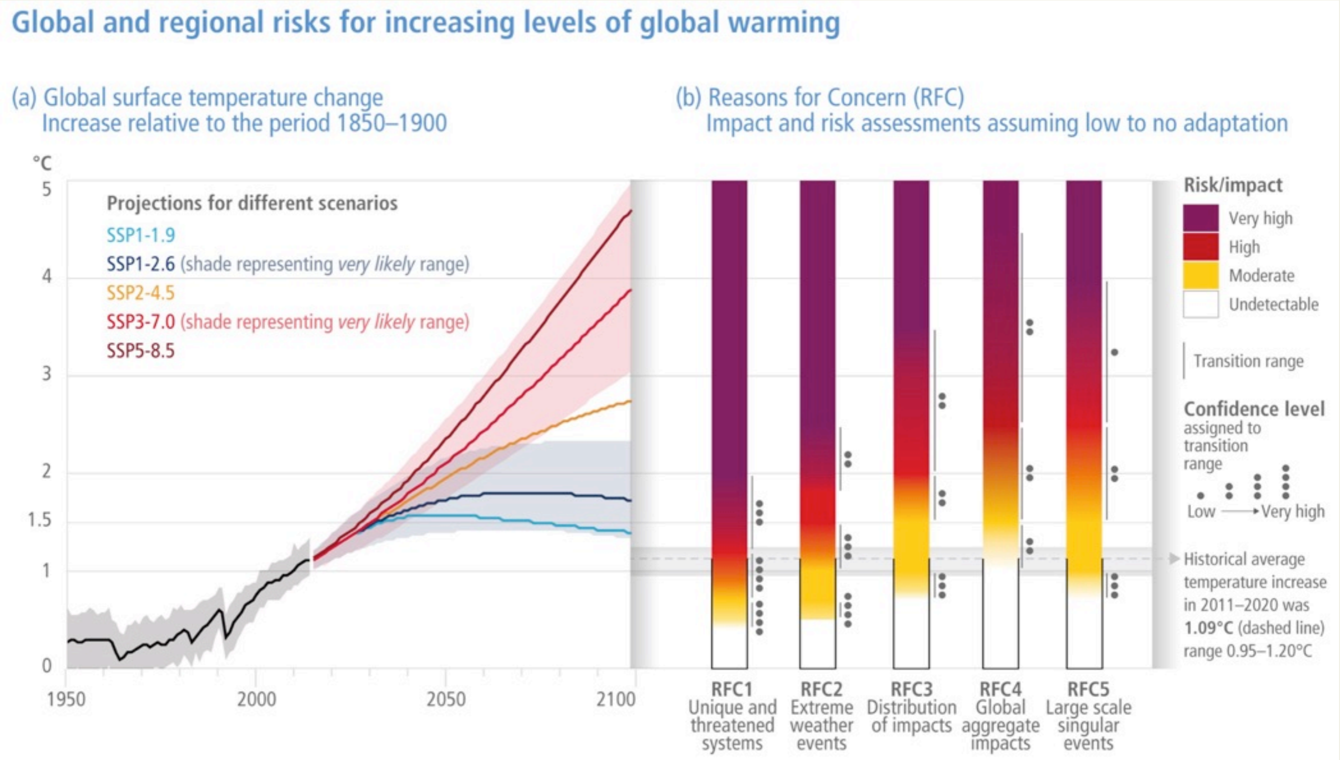
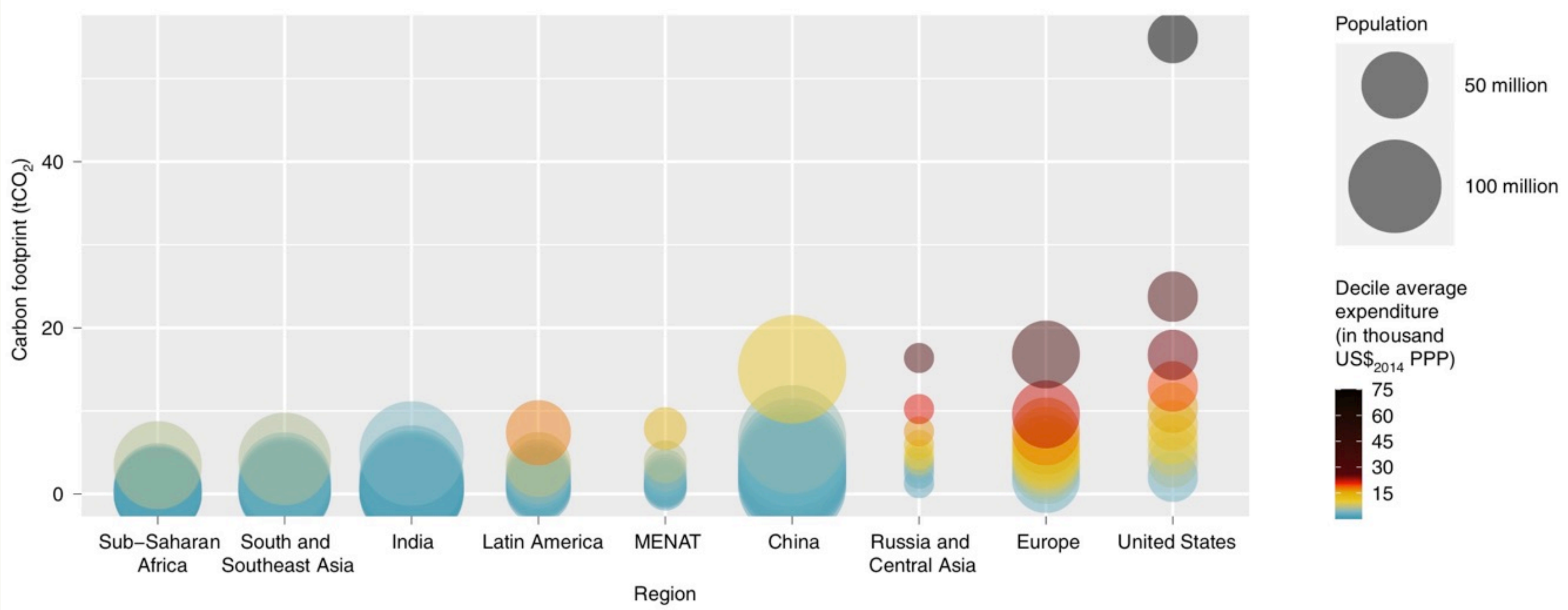


Figure 3 of Summary Report for Policy Makers of the IPCC 6th assessment report of Working Group 2

Climate change: responsibilities

Per capita carbon footprint for each decile of regional populations



Bruckner et al. (2022), Nature Sustainability, 5, 311

Climate change: our responsibility

COMETS
Comité d'éthique du CNRS

AVIS n°2022-43

« Intégrer les enjeux environnementaux à la conduite de la recherche – Une responsabilité éthique »

Approbation en séance plénière le 5 décembre 2022

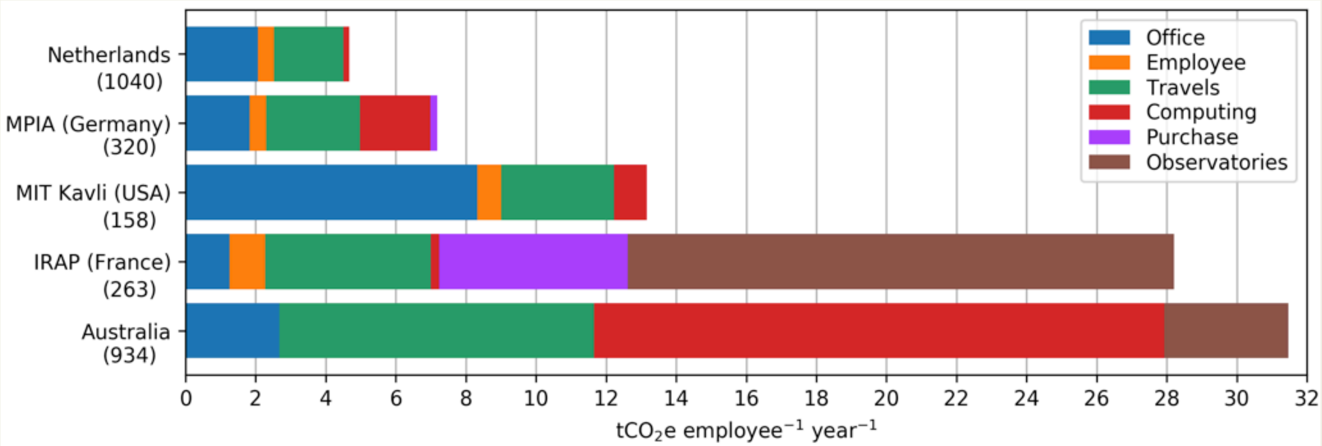
« Un très large accord se fait jour sur la nécessité que la recherche, comme toute activité, participe à l'effort de réduction des émissions de gaz à effet de serre. »

« La prise en compte de l'environnement fait partie intégrante de l'éthique de la recherche »

C'est de « la responsabilité des acteurs et actrices de la recherche de penser leur activité au regard des enjeux environnementaux »

« Cette responsabilité concerne non seulement l'empreinte des pratiques de recherche mais plus généralement l'impact environnemental négatif ou positif que le choix de tel ou tel sujet de recherche et de telle ou telle voie pour le traiter peut engendrer pour l'environnement au sens large, à court, moyen ou long terme. »

The carbon footprint of astronomy



Knödlseder et al. (2023), in: Climate Change for Astronomers (IOP)

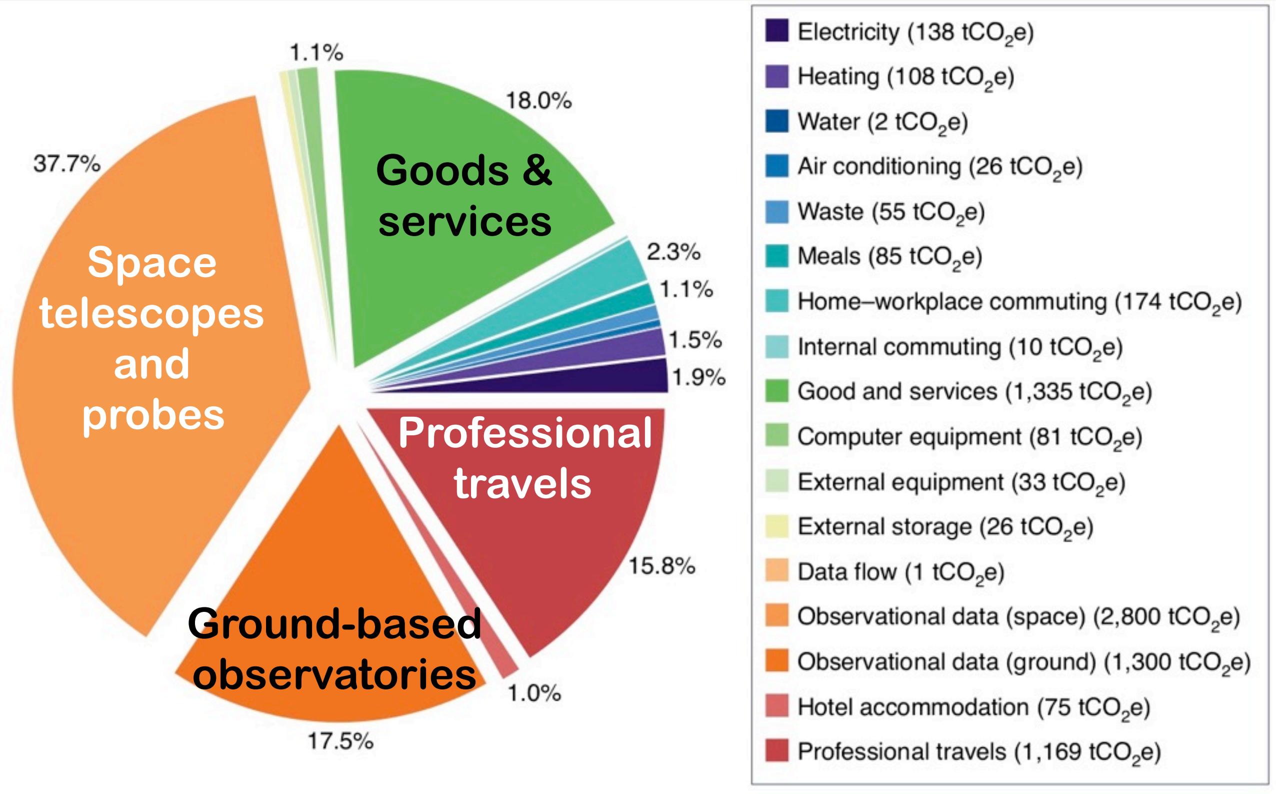
Huge differences among estimates

Strong impact of carbon intensity of electricity production

Based on data from:
Van der Tak et al. (2021) – Netherlands
Jahnke et al. (2020) – MPIA
Simcoe et al. (2022) – MIT Kavli
Martin et al. (2022) – IRAP
Stevens et al. (2020) – Australia

Importance of following standards in carbon accounting and considering all sources of GHG emissions

IRAP carbon footprint



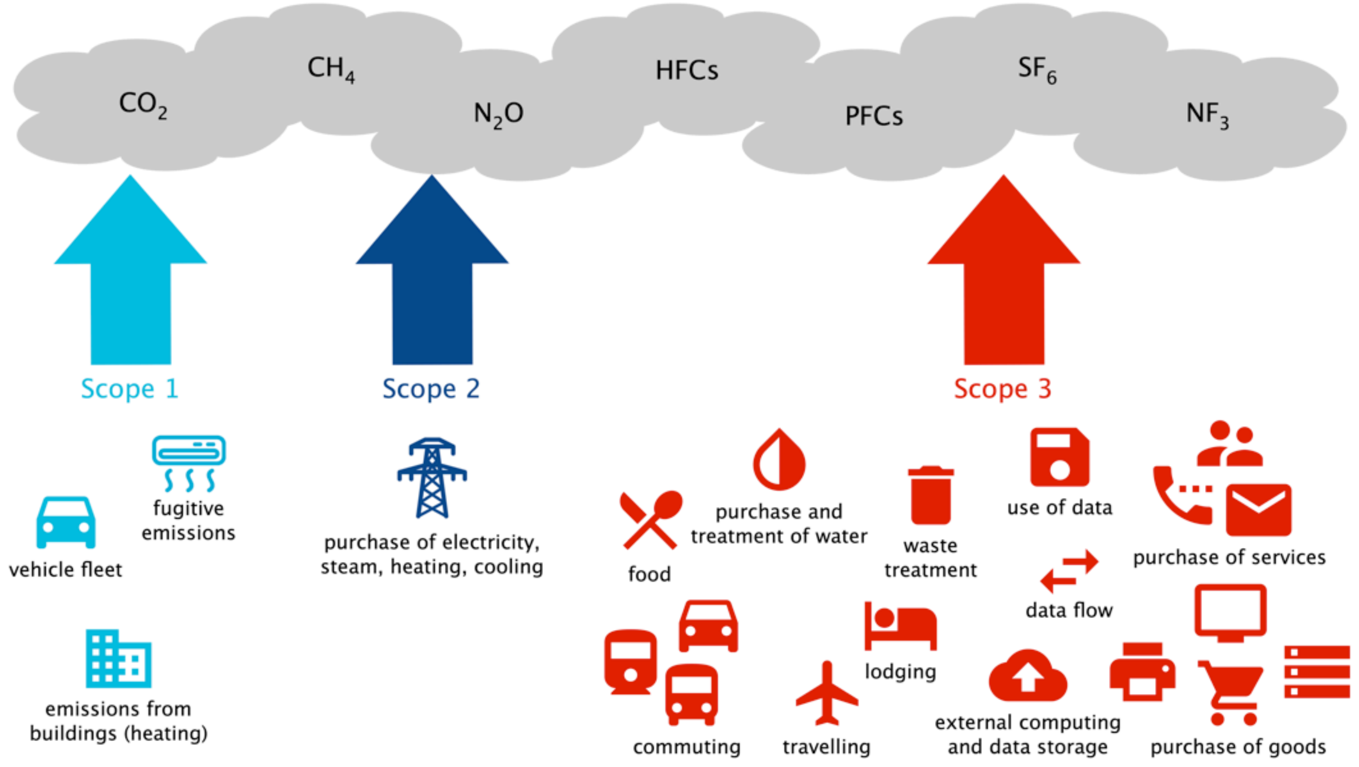
2019 carbon footprint:
7418 ± 860 tCO_2e

Average 2019 carbon footprint:
52 tCO_2e / astronomer*

*144 astronomers
263 employees

Martin et al. (2022), Nature Astronomy, 6, 1219; arXiv:2204.12362

Carbon footprint computation



Knödlseder et al. (2023), in: Climate Change for Astronomers (IOP)

Carbon footprint computation

Boundaries

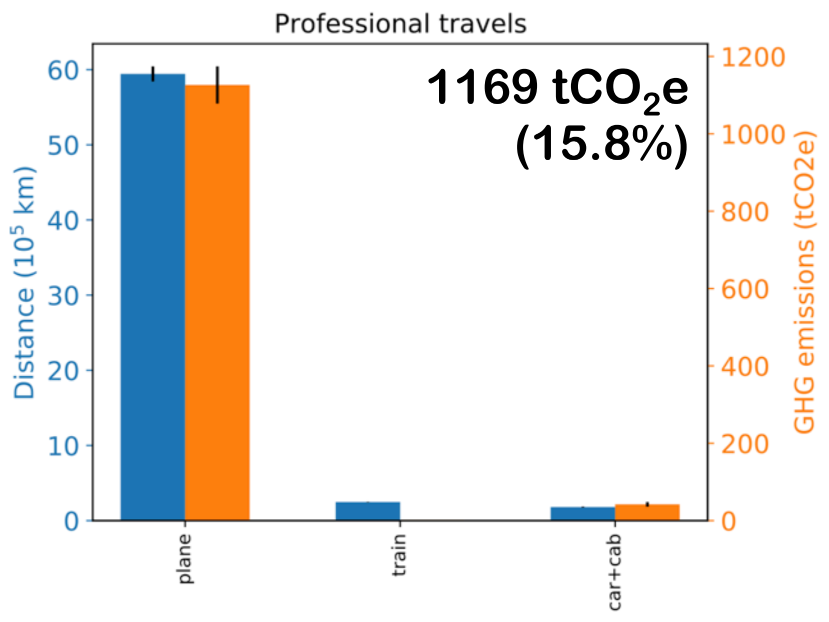
Emission factors
Tonnes of CO_2e per kWh, kg, km, M€ spent

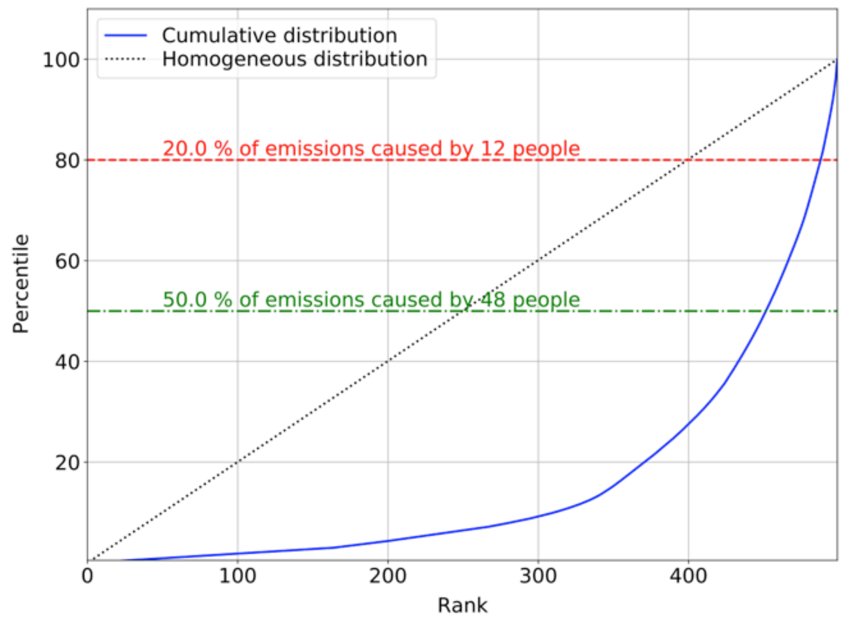
$$\text{Carbon footprint} = \sum_{i=1}^{N} A_i \times EF_i$$

Activity data
Consumption, weight, distance, cost

Professional travels

Martin et al. (2022), arXiv:2204.12362

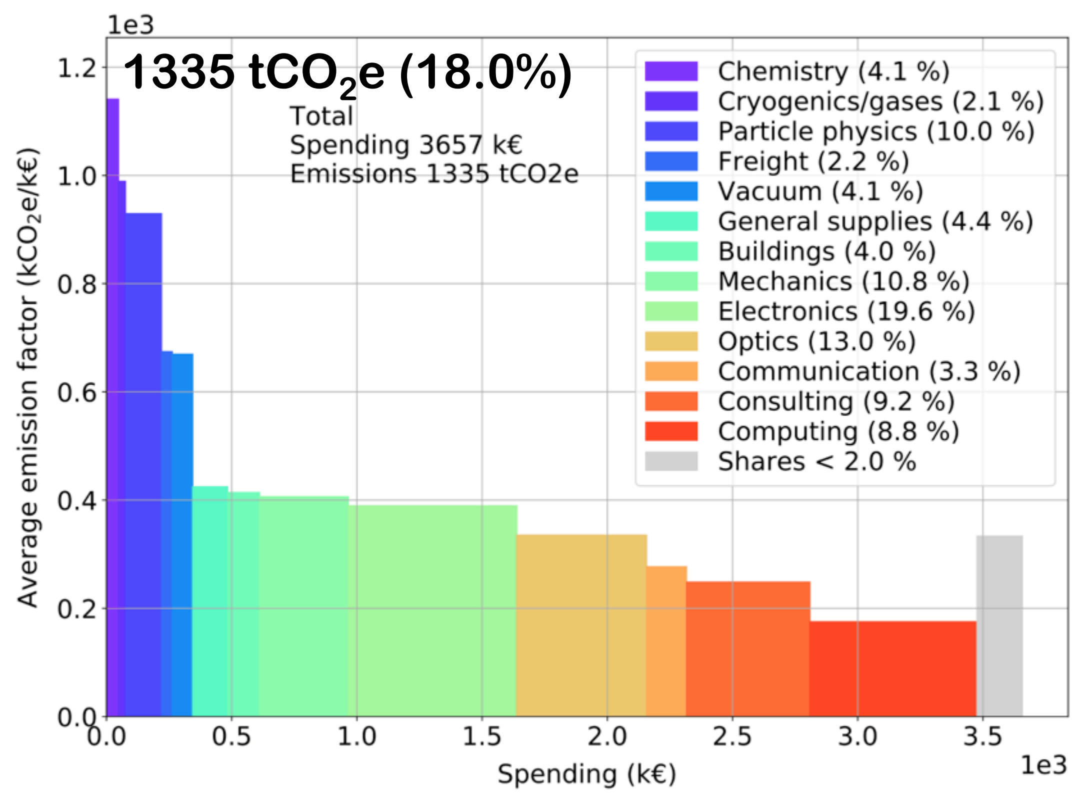




- 96% GHGs due to air travelling
- 15% GHGs attributed to visitors

- very unequal emissions among travellers
- limited relation to seniority
- gender effect (disproportional large fraction of male among high-impact travellers)

Purchase of goods and services



Martin et al. (2022), arXiv:2204.12362

- **Estimated using a monetary method (based on NACRES codes)**
- **Average emission factor: 365 $kgCO_2e/k€$**

Use of observatory data

- Inventory of observatories used in 2019 refereed papers
  - 46 space missions (probes & telescopes)
  - 39 ground-based observatories
- Computation
  - Include construction (amortised) and annual operations
  - Monetary and mass ratios (tCO_2e ~ M€ ; tCO_2e ~ kg)
  - Emission factors from literature survey
  - Activity data from literature and internet
- Attribution
  - Based on the fraction "IRAP authors / all authors" on refereed papers published in 2019 that cite a given facility

Notes:

- Estimations based on the same method have been recently derived for the use of Earth observation satellites (Marc et al. 2023)
- The inclusion of research infrastructures in the GES 1p5 tool is under implementation and will include, for example, the LHC (thanks to work by Mélissa Ridel and colleagues)

Emission factors for observatories

Emission factors derived from existing carbon footprint estimates

Activity	Emission factor
Space missions (based on payload wet mass)	50 tCO_2e / kg
Space missions (based on mission cost)	140 tCO_2e / M€
Construction of ground-based observatories	240 tCO_2e / M€
Operations of ground-based observatories	250 tCO_2e / M€

Selected other activities for comparison

Activity	Emission factor
Insurance, banking and advisory services	110 tCO_2e / M€
Architecture and engineering, building maintenance	170 tCO_2e / M€
Installation and repair of machines and equipment	390 tCO_2e / M€
Metal products (aluminium, cupper, steel, …)	1700 tCO_2e / M€
Mineral products (concrete, glass, …)	1800 tCO_2e / M€

Activity data

Mission	Payload launch mass (kg)	Mission cost (M€)	Reference
HST	11 110	8 037	43
Chandra	5 860	4 114	44
Cassini	5 820	2 806	45
Cluster	4 800	944	46
Fermi	4 303	863	47
INTEGRAL	4 000	419	48
Curiosity	3 893	2 590	45
XMM	3 800	1 113	49
Juno	3 625	1 082	45
Herschel	3 400	1 152	50
RXTE	3 200	360	51
SDO	3 100	865	52
Rosetta	2 900	1 709	53
Galileo	2 560	1 275	45
MAVEN	2 454	638	45
ROSAT	2 421	635	54
MRO	2 180	928	45
GAIA	2 034	1 037	55
Planck	1 900	775	56
SoHO	1 850	1 469	57
Suzaku	1 706		
AstroSat	1 515	27	59
MMS	1 360	1 054	58
Venus Express	1 270	300	61
WIND	1 250		
STEREO	1 238	614	60
Mars Express	1 223	374	62
Dawn	1 218	439	45
Hipparcos	1 140	933	63
Kepler	1 052	636	64
GEOTAIL	1 009		
Akari	952	106	65
Spitzer	950	1 188	66
SWIFT	843	279	67
ACE	752		
InSight	694	714	45
PSP	685	1 310	43
WISE	661	335	68
TIMED	660	259	67
Double Star	560		
IMP-8	410		
NICER	372	53	69
NuSTAR	360	156	70
TESS	325	275	71
GALEX	280	120	67
DEMETER	130	21	72

Observatory	Cost			
	Construction		Operations	
	(M€)	Reference	(M€ / yr)	Reference
VLT (Paranal)	1 384	78	40	79
ALMA	1 248	80	105	81
SOFIA	1 098	58	90	58
AAT	124	82	15	83
VLA	345	75	10	84
VLBA	132	85	15	85
IRAM	51	86	15	87
Gemini-South	135	75	13	75
CFHT	85	78	6.3	88
ESO 3.6m (La Silla)	99	89	5.2	89
GBT	120	90	10	91
LOFAR	200	92	9.2	93
JCMT	38	94	5.5	95
ATCA	95	96	3.5	97
H.E.S.S.	49	(1)	8.8	32
MeerKAT	128	98	13	98
GTC	125	78		
NRO	51	(1)	1.5	(1)
LMT	77	99	3.1	100
MLSO			1.2	101
APEX	20	(1)	2.7	102
SMA	60	103		
EHT	52	104	-	-
Noto Radio Observatory			1.5	105
2m TBL	6.0	(2)	1.0	106
2.16m (Xinglong Station)	7.3	(2)	0.7	(3)
1.93m OHP	5.5	(2)	0.5	(3)
KMTNet	17	(1)	1.7	(1)
THEMIS			1.1	(1)
2.4m LiJiang (YAO)	9.6	(2)	1.0	(3)
2m HCT (IAO)	6.1	(2)	0.6	(3)
1.5m Tillinghast (FLWO)	2.8	(2)	0.3	(3)
1.5m (OAN-SPM)	2.8	(2)	0.3	(3)
1.8m (BOAO)	4.6	(2)	0.5	(3)
1m (Pic-du-Midi)	1.0	(2)	0.1	(3)
1.3m Warsaw (OGLE)	2.0	(2)	0.2	(3)
C2PU	2.0	(2)	0.2	(3)
TAROT	0.9	(1)	0.1	(3)
1m NOWT	1.0	(2)	0.1	(3)

- Collection of cost data was the most time-consuming part of the work
- Collection of payload mass data was easy
- Cost data not always include mission extensions and never include upgrades; if no data were found contribution was skipped (results are lower limits)
- All cost data were inflation corrected to 2019 economic conditions

Knödlseder et al. (2022), Nature Astronomy, 6, 503

Facility carbon footprint

Mission[a]	Years	Papers	Authors	Mass-based				Cost-based[b]			
	(total since launch)			Footprint (tCO_2e)	Annual ($tCO_2e\ yr^{-1}$)	Carbon intensity ($tCO_2e\ paper^{-1}$)	Carbon intensity ($tCO_2e\ author^{-1}$)	Footprint (tCO_2e)	Annual ($tCO2e\ yr^{-1}$)	Carbon intensity ($tCO_2e\ paper^{-1}$)	Carbon intensity ($tCO_2e\ author^{-1}$)
HST	30	52,497	42,315	555,500	18,517	11	13	1,125,197	37,507	21	27
Chandra	21	17,714	23,942	293,000	13,952	17	12	575,955	27,426	33	24
Cassini	22	4,691	9,328	291,000	13,227	62	31	392,902	17,859	84	42
Cluster	20	2,433	2,959	240,000	12,000	99	81	132,207	6,610	54	45
Fermi	12	8,619	19,675	215,150	17,929	25	11	120,881	10,073	14	6
INTEGRAL	18	2,808	10,640	200,000	11,111	71	19	58,720	3,262	21	6
Curiosity	7	1,360	4,393	194,650	19,465	143	44	362,595	36,259	267	83
XMM	21	18,859	23,773	190,000	9,048	10	8	155,845	7,421	8	7
Juno	8	521	1,832	181,250	18,125	348	99	151,547	15,155	291	83
Herschel	11	5,046	11,092	170,000	15,455	34	15	161,238	14,658	32	15
RXTE	24	7,473	11,601	160,000	6,667	21	14	50,438	2,102	7	4
SDO	10	4,189	4,946	155,000	15,500	37	31	121,164	12,116	29	24
Rosetta	16	1,665	4,337	145,000	9,063	87	33	239,316	14,957	144	55
Galileo	30	2,432	4,594	128,000	4,267	53	28	178,503	5,950	73	39
MAVEN	6	672	2,023	122,700	12,270	183	61	89,270	8,927	133	44
ROSAT	30	19,765	23,154	121,050	4,035	6	5	88,844	2,961	4	4
MRO	14	1,927	4,261	109,000	7,786	57	26	129,850	9,275	67	30
Gaia	7	2,550	10,565	101,700	10,170	40	10	145,114	14,511	57	14
Planck	11	5,515	13,388	95,000	8,636	17	7	108,486	9,862	20	8
SoHO	25	12,218	12,955	92,500	3,700	8	7	205,617	8,225	17	16
Suzaku	15	3,869	9,525	85,300	5,687	22	9				
AstroSat	5	313	5,406	75,750	7,575	242	14	3,751	375	12	1
MMS	5	769	1,623	68,000	6,800	88	42	147,501	14,750	192	91
Venus Express	15	1,221	3,394	63,500	4,233	52	19	41,945	2,796	34	12
Wind	26	3,877	8,254	62,500	2,404	16	8				
STEREO	14	3,731	6,768	61,900	4,421	17	9	86,021	6,144	23	13
Mars Express	17	2,969	6,118	61,150	3,597	21	10	52,332	3,078	18	9
Dawn	12	791	2,175	60,885	5,074	77	28	61,409	5,117	78	28
Hipparcos	31	4,743	8,373	57,000	1,839	12	7	130,664	4,215	28	16
Kepler	11	4,306	9,606	52,620	4,784	12	5	89,037	8,094	21	9
Geotail	28	3,288	3,996	50,450	1,802	15	13				
Akari	14	2,037	6,993	47,600	3,400	23	7	14,878	1,063	7	2
Spitzer	17	9,050	15,940	47,500	2,794	5	3	166,333	9,784	18	10
Swift	16	7,397	17,307	42,150	2,634	6	2	39,030	2,439	5	2
ACE	23	4,147	7,560	37,600	1,635	9	5				
InSight	1	58	447	34,700	3,470	598	78	99,922	9,992	1723	224
PSP	2	287	1,075	34,250	3,425	119	32	183,456	18,346	639	171
WISE	11	6,990	18,877	33,050	3,005	5	2	46,855	4,260	7	2
TIMED	18	2,205	3,593	33,000	1,833	15	9	36,196	2,011	16	10
Double Star	16	166	540	28,000	1,750	169	52				
IMP-8	47	2,485	3,835	20,500	436	8	5				
NICER	3	338	2,657	18,600	1,860	55	7	7,374	737	22	3
NuSTAR	8	2,227	9,559	18,000	1,800	8	2	21,799	2,180	10	2

Continued

Knödlseder et al. (2022), Nature Astronomy, 6, 503

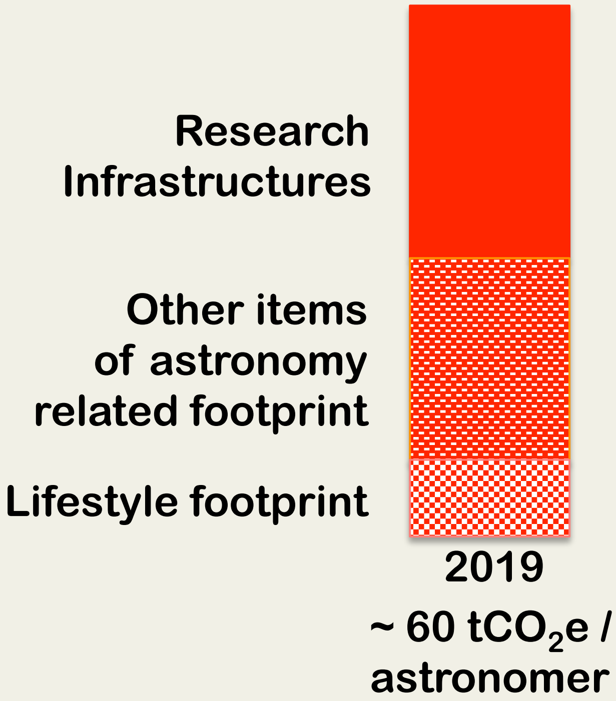
- Order of magnitude estimates of lifecycle carbon footprints for 85 astronomical research infrastructures
- Results of individual infrastructures are uncertain by 80% (recommended uncertainty by French Environmental Agency ADEME for method of monetary ratios)
- Annual footprints by dividing the lifecycle footprint by the mission or observatory lifetime (or ten years, whatever is longer)

Use of observatory data

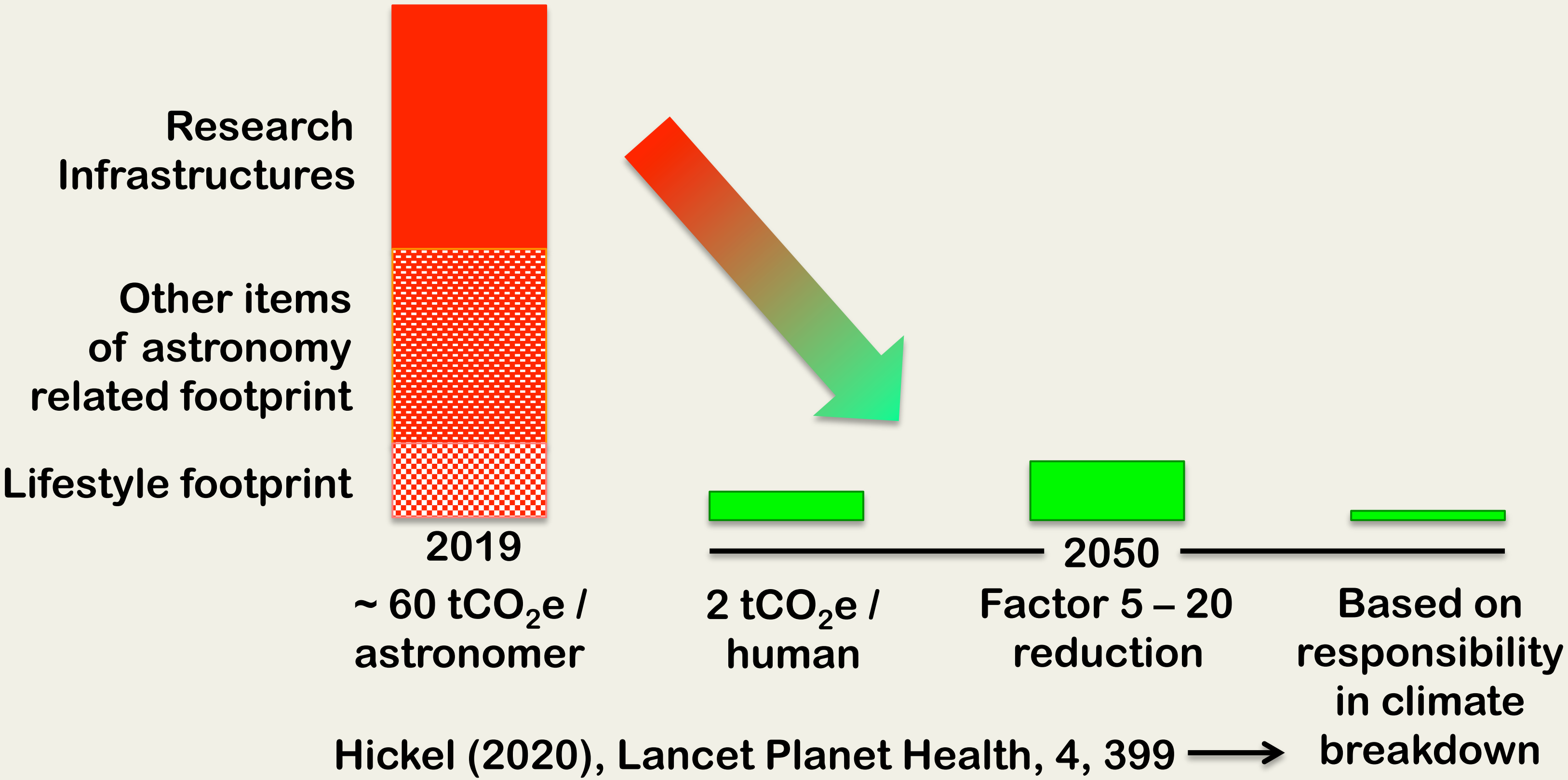
Category	Lifecycle footprint ($MtCO_2e$)	Annual footprint ($ktCO_2e$ / yr)	IRAP attribution (tCO_2e / yr)
Space (cost-based)	5.9 ± 1.2	366 ± 64	2 788 ± 555
Space (mass-based)	4.9 ± 0.8	310 ± 47	2 548 ± 490
Ground-based	3.0 ± 0.8	194 ± 64	1 289 ± 490
Total	7.8 ± 1.4	532 ± 106	3 953 ± 689

- Cost-based and mass-based estimates provide comparable results
- 53% of IRAP's carbon footprint
- Footprint dominated by space-based (IRAP bias)
- Footprint per IRAP astronomer: 27.4 ± 4.8 tCO_2e / yr / astronomer
- Extrapolation to world inventory: 36.6 ± 14.0 tCO_2e / yr / astronomer

Summary of the situation

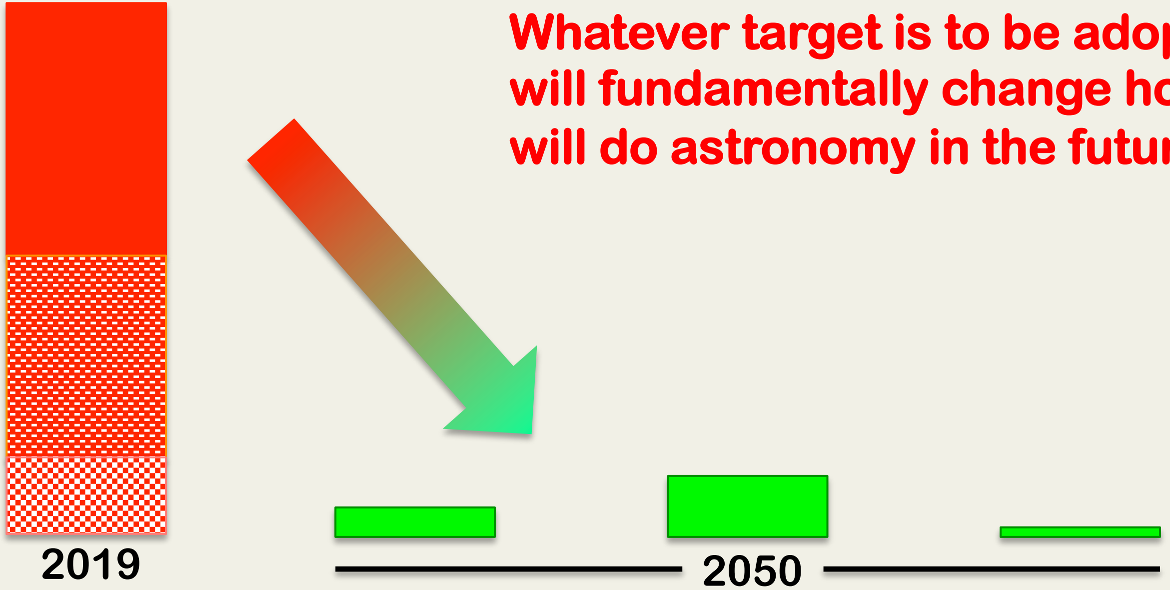


Summary of the situation



Summary of the situation

Whatever target is to be adopted, it will fundamentally change how we will do astronomy in the future



Hickel (2020), Lancet Planet Health, 4, 399 →

Towards an action plan at IRAP

- Hiring of an environmental transition manager
- Working groups to identify potential actions
  - Professional travelling
  - Purchase of goods & services
  - Daily lab life
  - Low carbon science (change of research practices)
- Scenario based action plan (excluding use of observatory data)
  - -2% / yr (minimum requirement by research ministry)
  - -5% / yr (research ministry goal)
  - -7% / yr (compliant with Paris agreement)
- Select / adapt scenario and adopt action plan
  - Discussion forums by employee corps
  - Vote by lab council by the end of the year (current plan)

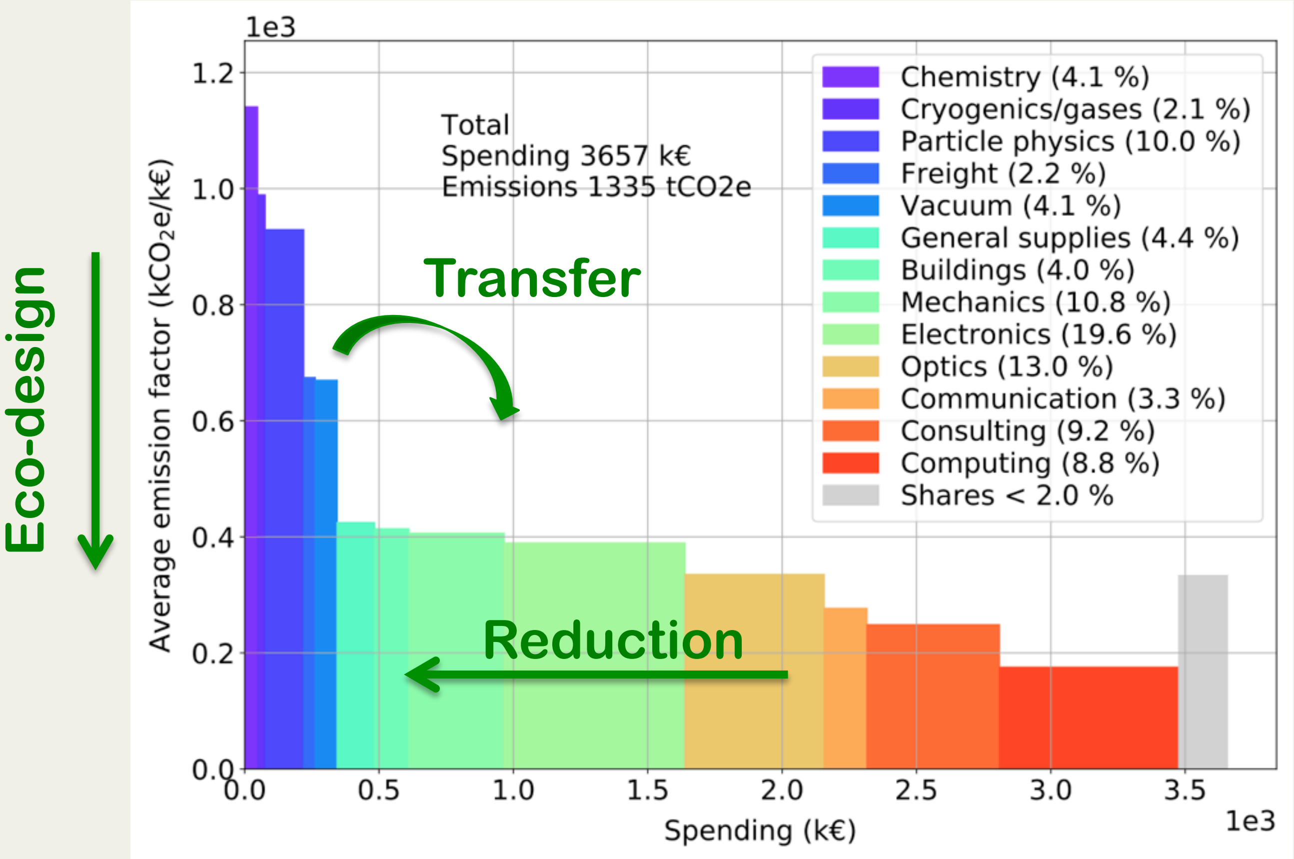
Reducing the travelling footprint

Mouinié (2023), IRAP internal document

- -30% less trips
- -50% CO_2e emissions
- Increased use of train
- Trend confirmed for first semester 2023 (reduction not related to COVID)

A real (voluntary) shift seems to have happened in the lab!

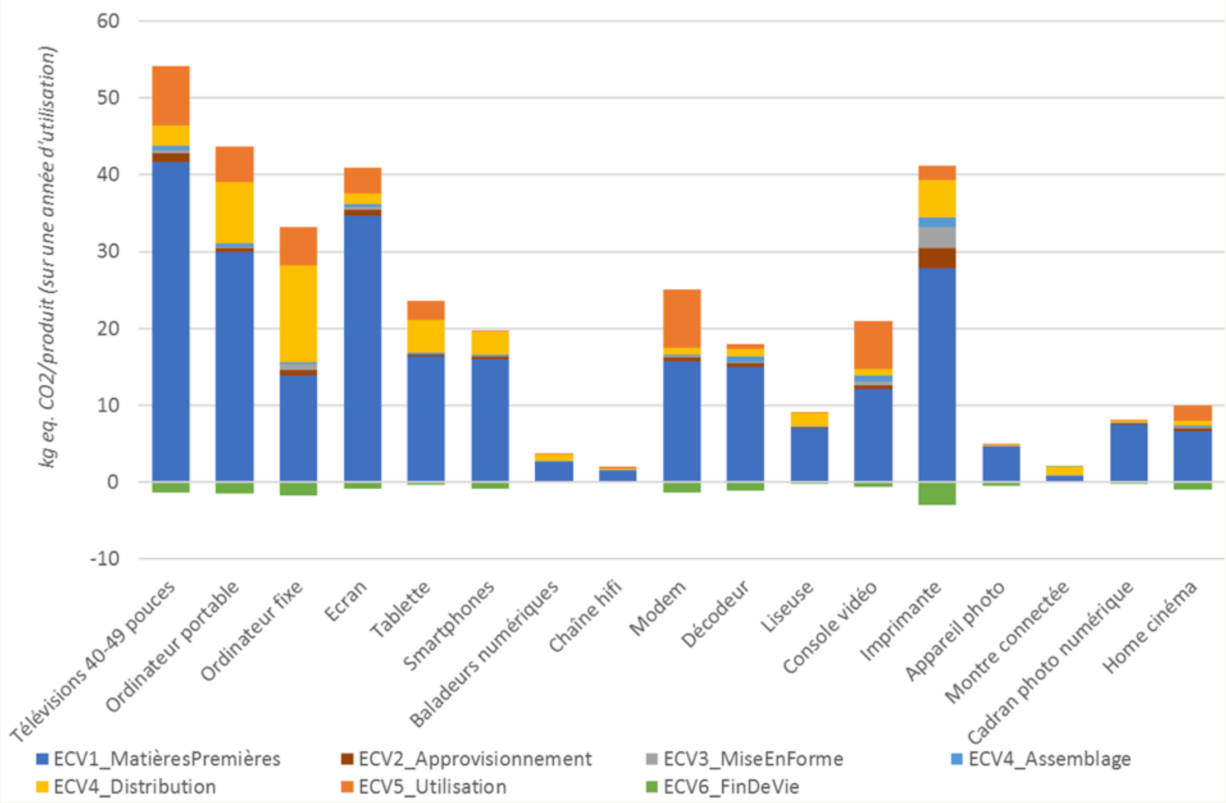
Reducing the purchase footprint



Martin et al. (2022), arXiv:2204.12362

- Easy fixes: mutualise, extend lifetime, repair
- More difficult changes: buy less, buy differently
- Attractive: eco-design

The difficulties of eco-design



Lifecycle footprint of electronic devices (Ademe 2018)

The difficulties of eco-design

> **Norlisk's emissions are more comparable to the passive degassing** that happens at some of the most active effusive volcanoes. Between 2005 and 2017, only one volcano - Ambrym in Vanuatu - emitted more sulfur dioxide through passive degassing than Norilsk. (NASA Earth Observatory, 12/07/2017)

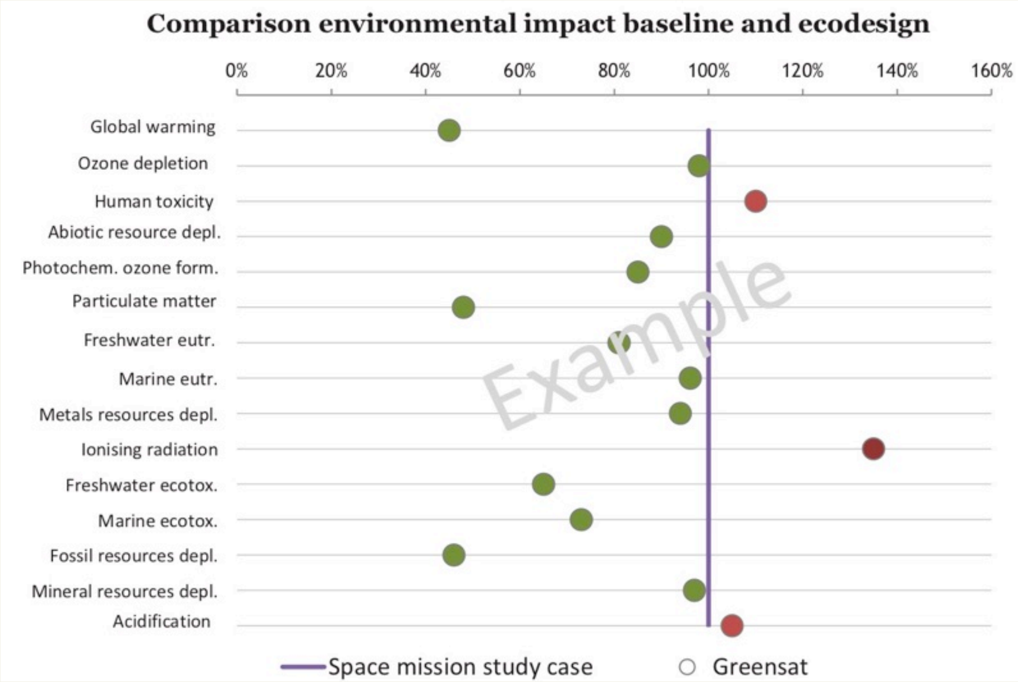
Usines et fonderies de Norilsk| Stanislav Lvovsky · 2008 · cc-by-nc-nd 2.0

Pollution de la rivière Daldykan en septembre 2016 suite au débordement d'un parc à résidus miniers | © Alex Kokcharov 2016 · Twitter

Nickel production in Norilsk mine, Russia (Aurore Stephant)

The difficulties of eco-design

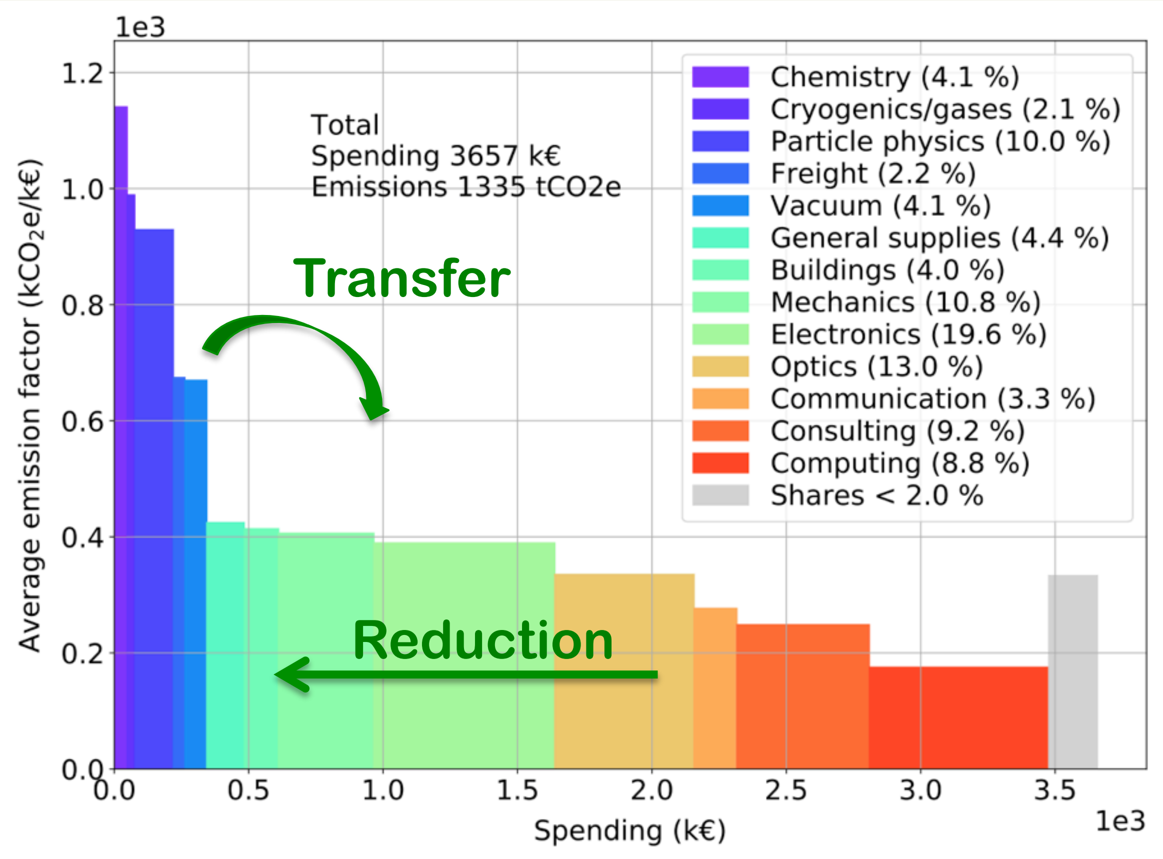
Eco-design – Proba-V satellite



An Vercalsteren et al. (2018), Clean Industry Days

- Perform life cycle analysis (LCA) capturing all environmental impacts (keyword: impact transfers)
- Optimisation is always a trade-off (impossible to win on all impact categories without reducing scope)
- Improvements of typically 20-30% seem feasible

Reducing the purchase footprint

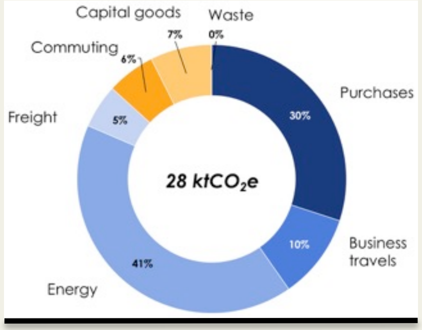


Martin et al. (2022), arXiv:2204.12362

Significant impact reductions likely imply that we have to touch our core business

Reducing the observatory footprint

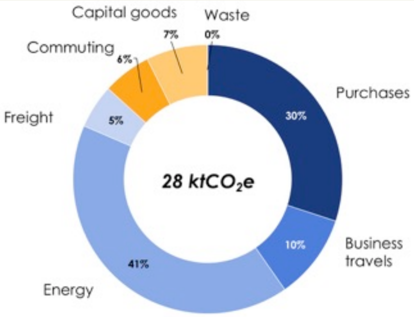
Example of ESO (https://www.eso.org/public/france/about-eso/green/)



2018

Reducing the observatory footprint

Example of ESO (https://www.eso.org/public/france/about-eso/green/)



2018

Next few years

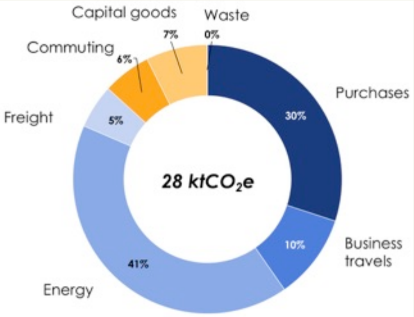
- 15%

- 4.4 $ktCO_2e$ / yr

Running observatory sites using renewable energy (-7.5%)
Preferring sea freight over air (-5.0%)
Reducing business travel (-2.9%)
Extend lifetime of IT equipment (-0.0%)

Reducing the observatory footprint

Example of ESO (https://www.eso.org/public/france/about-eso/green/)



2018

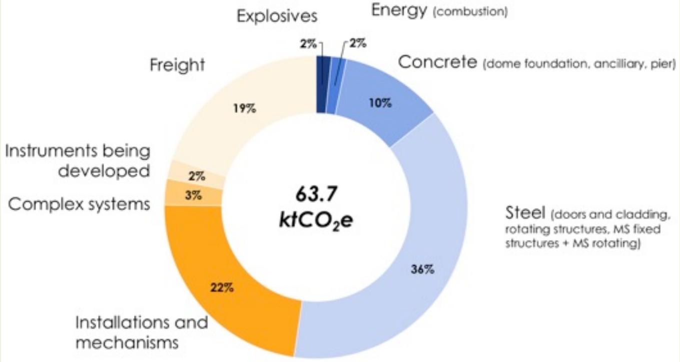
Next few years

- 15%

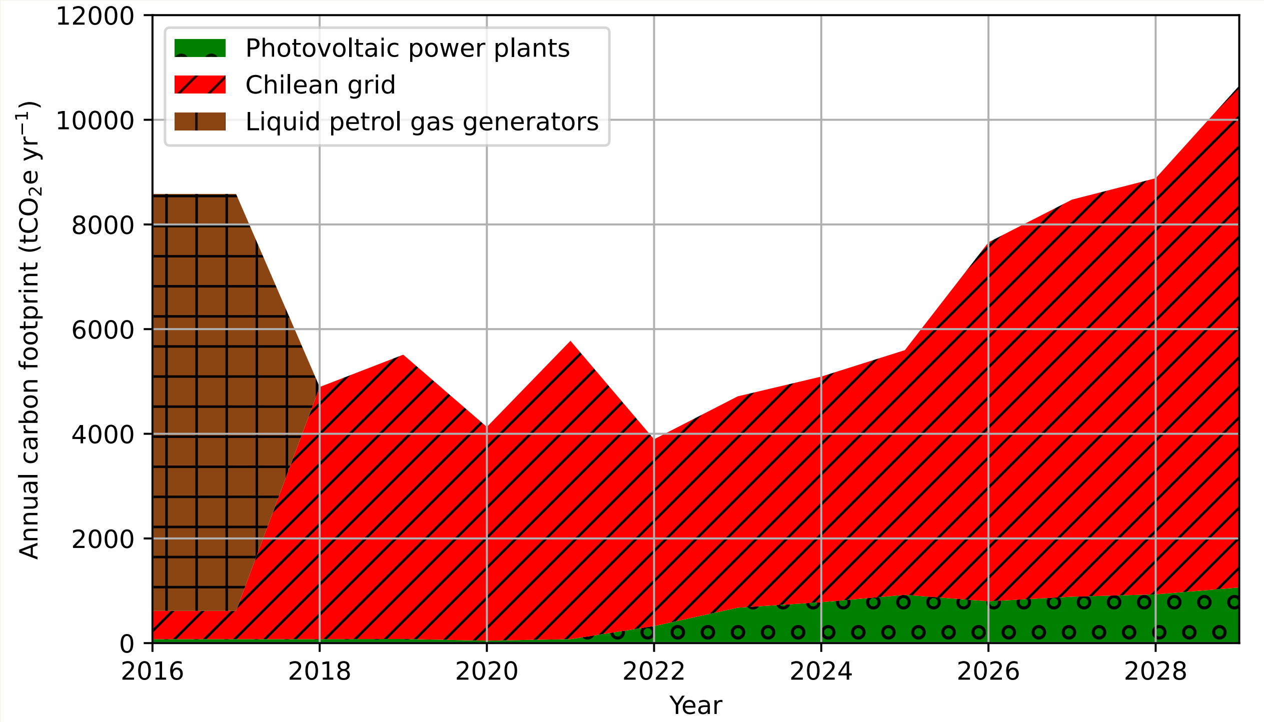
- 4.4 $ktCO_2e$ / yr

ELT
Construction

ELT
Operations



Reducing the observatory footprint



Past and predicted annual carbon footprint of electricity consumption at the ESO observatory sites in La Silla, Paranal and Armazones

Data from Filippi et al. (2022), SPIE, 12182, 3

Reducing the observatory footprint

An inconvenient truth:

It is extremely difficult to decarbonise while ramping up!

We need BOTH carbon footprint reductions AND a reduction of the deployment pace of new observatories

Environmental impact & science roadmaps

Minimiser l'impact environnemental des projets spatiaux scientifiques

Contribution émanant de la communauté scientifique (plus de 240 signataires) au séminaire de prospective du CNES 2024 sur la thématique

"Empreinte environnementale des activités scientifiques spatiales"

Coordination: Didier Barret & Jürgen Knödlseder

Prospective scientifique de l'INP

Intégrer les enjeux environnementaux à la recherche en Physique

COMETS

Comité d'éthique du CNRS

AVIS n°2022-43

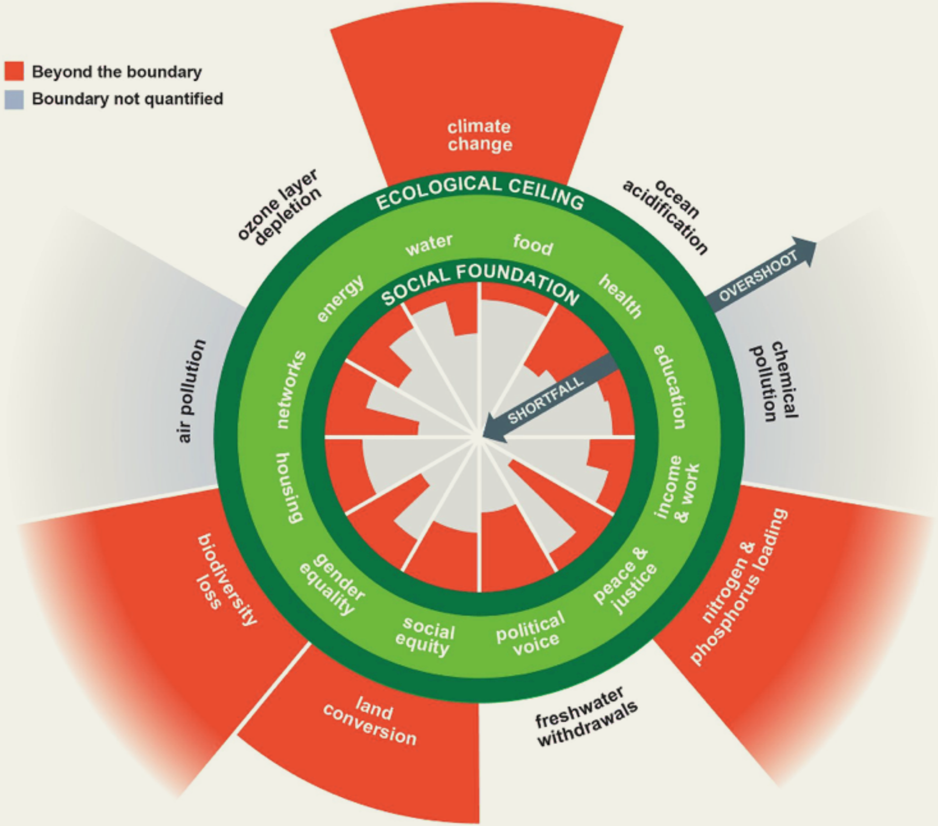
« Intégrer les enjeux environnementaux à la conduite de la recherche – Une responsabilité éthique »

Approbation en séance plénière le 5 décembre 2022

Towards sustainable astronomy

- To keep our planet habitable human societies have to switch to a sustainable socio-economic pathway (cf. IPCC)
- This concerns all human activities, including (astronomical) research (cf. inequalities)
- This (likely) implies that we have to do astronomy differently (cf. previous slides)
  - reduce air travelling
  - rethink our activities (e.g. environmental impact assessment and mitigation, less instrument development, more R&D)
  - deeper use of (abundant) archival data
  - make decarbonisation a funding priority
  - build less new facilities
- This (certainly) implies a systemic change, including individuals, laboratories, research and funding organisation, governments
- As a community, we should recognise our responsibility and be exemplary (cf. credibility)

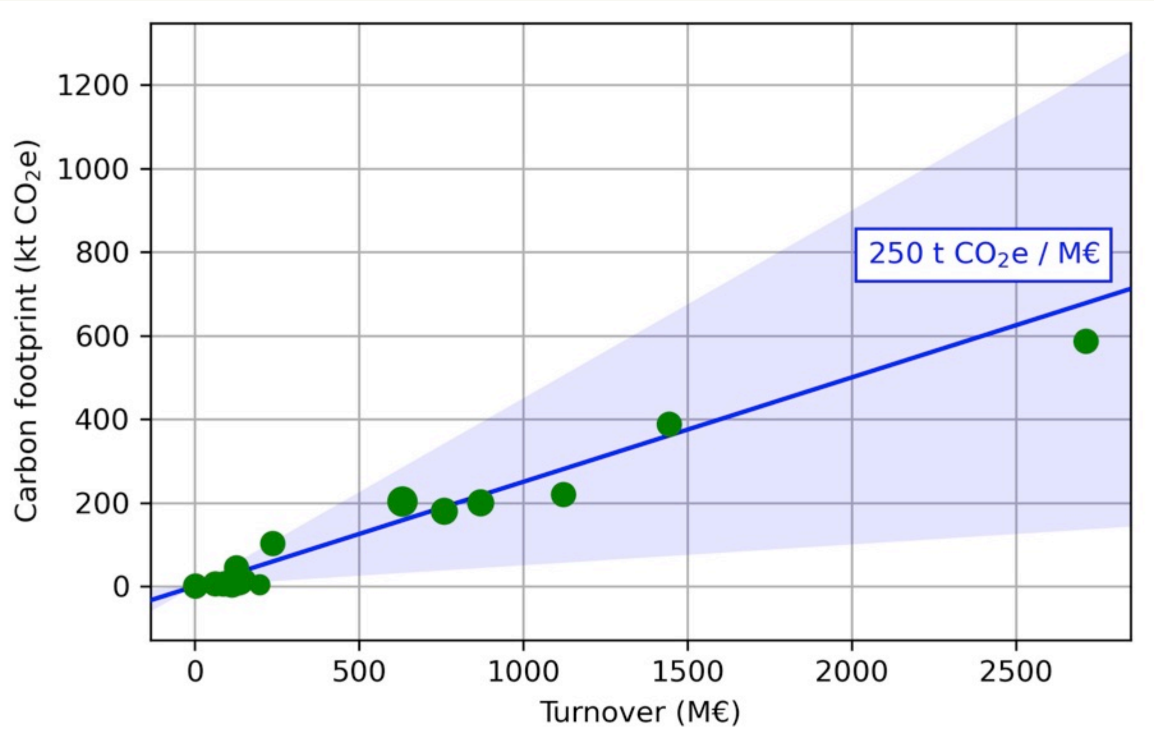
Fitting into the planetary boundaries



Kate Raworth (2018), Doughnut economics

Backup slides

Greenhouse gas emissions versus cost

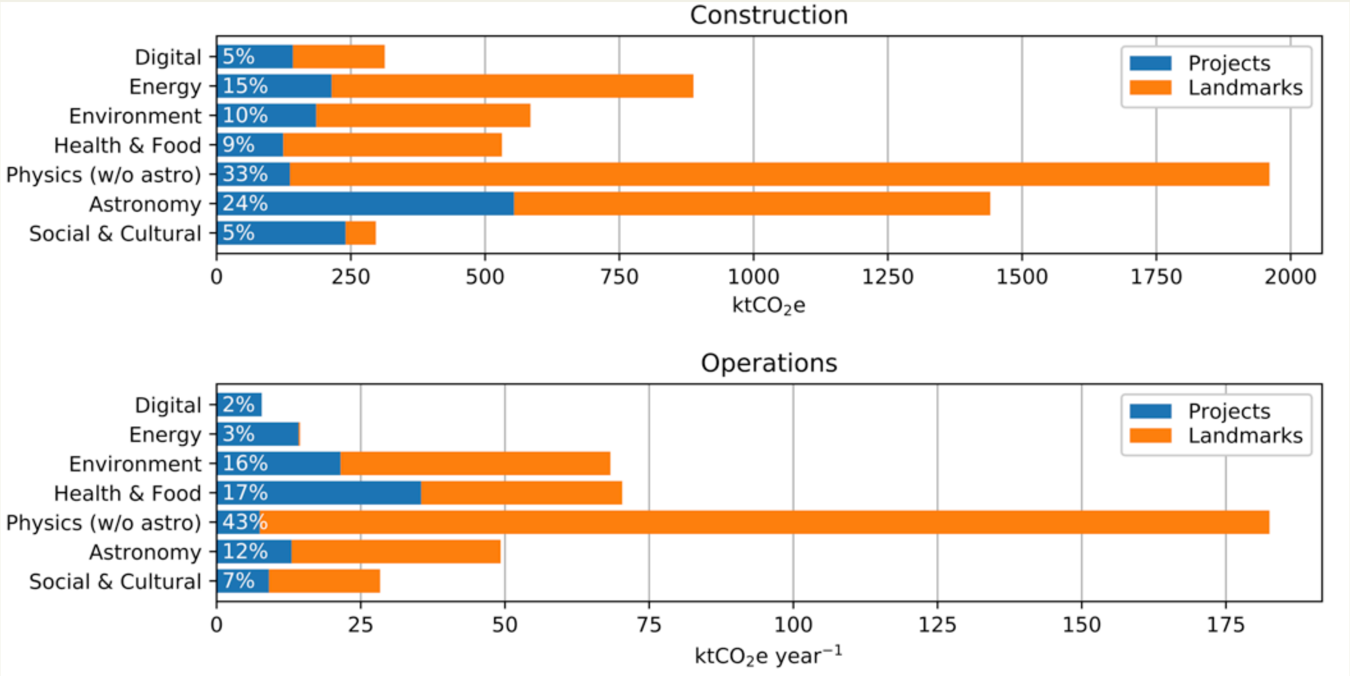


Carbon footprint reports of 19 French companies of the construction sector versus their turnovers (source: Base Carbone ADEME).

The blue line corresponds to a monetary emission factor of 250 tCO_2e / M€, the light blue area indicates an uncertainty of 80%.

Astronomy versus other fields

Based on cost estimates in ESFRI 2021 infrastructure roadmap



Astronomy: 24% (construction)

Other domains (e.g. physics) have an equivalent issue