Scientific resilience: How Italian nuclear physics changed after the Chernobyl disaster *

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March, 2023

Preliminary and Incomplete.
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Abstract

Scientists' human capital is the main factor in the production of knowledge. I study how flexible field-specific human capital is, trying to understand if researchers can bring valuable contributions to innovation out of their main field of studies. I focus on the careers of Italian nuclear scientists before and after the Chernobyl disaster of 1986. In 1987 in Italy a referendum stopped the production of nuclear energy, and strongly reduced fundings to research in that field. Using data from Microsoft Academic Graph, I show that after Chernobyl the amount of Italian papers published in nuclear fission decreased by 50%. Researchers who had already published in fission experienced a reduction of 25% in their citations, and 10% in published papers. Compared to other physicists, they neither moved more frequently, nor contributed permanently to more new fields.

Keywords: Technology policy, Nuclear energy, Human capital

JEL Codes: H54, I23, J24, O31, O33

*I am grateful to Geraud Desazars De Mointgaillhard, Ivan Kim Taveras, Giovanni Morzenti, Alberto Nasi and Julian Streyzcek for their invaluable advice and their careful reviews. Special thanks to my readers Nicolas Serrano Velarde and Carlo Schwarz for their constant guidance and motivation. All errors remain my own.

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1 Introduction

There is no economic growth without innovation (Romer, 1990; Aghion and Howitt, 1992; Akcigit et al., 2020). And there is no innovation without investments in scientific human capital (Barro, 2001; Prato, 2022). However, economists have not fully understood how human capital helps producing new technologies. Capital goods can only perform the limited range of tasks they are designed for. One cannot use an ax to plow or a hoe to cut wood. On the other hand, human capital is generally assumed to be more flexible, although labor economists have debated about its depreciation (Deming and Noray, 2020), specificity with respect to the firm (Becker, 1962; Lazear, 2009), to the team (Chen, 2021) or to the technology (Marx et al., 2009).

In this paper I study how flexible scientific human capital can be. It is flexible when researchers are able to take some scientific principles and apply them out of the fields in which they were discovered. This is the story of many breakthrough innovations, such as penicilline or the X-rays, which are the successful - but unintended - results of projects started with different aims (Nelson, 1959). Yet, there is limited evidence on the transition of scientists to new fields, and their contribution to innovation. One would need to observe a population of scientists who - at some point - were unable to publish in their main field of studies, and had to relocate elsewhere.

In this article I use a rich database provided by Microsoft Academic Graph, which records information on more than 250 billion scientific publications, to study the case of Italian nuclear scientists. A year after the Chernobyl disaster of April 1986, Italy held a referendum that stopped the production of nuclear energy, and rapidly de-funded research in nuclear fission. By its nature, the shock affected only a single sector and a single country. Indeed, every other country involved in a nuclear program neither made such a political decision nor experienced a reduction in the number of publications in nuclear fission.

I document three main findings. First, after Chernobyl Italian nuclear fission lost more than 50% of its potential papers. Second, not only newcomers were kept out of the field, but also incumbent researchers experienced slowdowns in their careers. In particular, I find that authors who had published in fission pre-1986 faced a reduction of 10% in papers produced, and spoke to a narrower audience, being their citations reduced by 25%. Third, Italian fission scientists mainly stayed in Italy, and did not contribute to new fields more than other scientists.

We already know that human capital takes longer to build, and brings much more long-run value to the research output of university departments than physical capital

(Waldinger, 2016). From the findings here presented I argue that scientific human capital has limited flexibility. Scientists' expertise is relatively narrow, as there are significant "losses in translation" in transferring knowledge to new fields.

I contribute to three strands of literature.

Within the field of Economics of Science, the paper that is the closest to mine is Myers (2020), that tries to identify the "elasticity of science". He measures how responsive are biomedical scientists in changing the topics of their research when the National Institutes of Health issue a new grant. However, he only focuses on temporary changes in research topics; indeed, NIH-funded scientists are not required to shift their whole research agenda after receiving the grant. In this paper's setting Italian nuclear scientists cannot go back to nuclear research unless they emigrate (which has not been the case): their field of studies has been permanently shut down.

My work also relates to other articles in the field of Economics of Science, that have analysed collaboration, networks and competition in scientific careers. Collaboration among scientists advances the frontier of knowledge (Iaria et al., 2018; Jia et al., 2022), as they generate spillovers among their peers (Waldinger, 2010; Ductor et al., 2014) and experienced researchers promote the careers of PhD students (Waldinger, 2012). On the other hand, more productive scientists can also slow down their competitors' careers (Borjas and Doran, 2012) or act as gate keepers (Azoulay et al., 2010), steering research towards their interests and blocking unexplored avenues. Such papers have often exploited migration shocks, such as the Jewish diaspora from Nazi Germany (Moser et al., 2014; Becker et al., 2021), the Russian outflow after the collapse of the Soviet Union (Ganguli, 2015; Borjas and Doran, 2015) or US migration policies (Agarwal et al., 2021; Prato, 2022). Compared to previous literature, I consider scientists who switched field, instead of moving abroad. I show that Italian fission scientists became less relevant and did not impact the direction of future research.

Second, this paper speaks to a branch of literature in Labor Economics. Starting from the seminal work by Becker (1962), labor economists have studied how and why human capital can exhibit various degrees of specificity. In some sense, workers are locked to their technology (Neal, 1995), to the task they perform (Gathmann, 2010), to their network (Jäger, 2022) or their education (Aghion et al., 2022). In all those cases, workers' mobility might hurt firm growth, because it would imply some loss of their specific human capital.

A particular case in which human capital specificity can limit firm growth is the case of non-compete agreements, as shown in Marx et al. (2009) and Marx (2011, 2022). In some industries knowledge workers are not allowed to move to competing firms. They are forced to change industry, thus losing a bigger part of their human capital. On the other hand, as Arts and Fleming (2018) argue, those workers may be tempted to explore new areas bringing their past knowledge, which in some cases can lead to innovative activities.

In this paper I consider a particular case of high-skilled workers - i.e. academics - who are forced to exit their field. Results of my analysis show that they did not innovate significantly, but rather they lost human capital.

I also contribute to a third, growing, strand of literature that studies innovation spillovers of large-scale public projects, in defence (Moretti et al., 2019; Bhattacharya, 2021), pharmaceutics (Azoulay et al., 2019), energy (Myers and Lanahan, 2022), or with state nationalisation programs (Akcigit et al., 2021). Recent works have shown positive local spillovers from two large-scale projects conducted by the US government, the Space Race (Kantor and Whalley, n.d.) and the Office of Scientific Research and Development, deployed during WWII (Gross and Sampat, 2020a,b), which also lead to the development of nuclear reactors. I argue that the Italian investment in nuclear fission generated no spillovers in contiguous fields.

The rest of the paper proceeds as follows. Section 2 provides historical background on nuclear research and the Chernobyl disaster. In Section 3, I describe the construction of the sample of Italian fission scientists. In Section 4, I document the aggregate impact of Chernobyl on nuclear fission publications. I report results on individual careers in Section 5. Section 6 concludes.

2 Historical context

During World War II, the Allied countries, and in particular the US, invested in developing a new technology: nuclear fission. While its first scopes were military (the bombs on Hiroshima and Nagasaki), scientists in the Manhattan project already saw its potential as an energy source (Gross and Sampat, 2020b). Research in nuclear physics rapidly grew to be one of the most intriguing scientific fields in the second half of the 20th century.

In the mid 50s, the UK, the Soviet Union and the US built their first nuclear fission power plants. New generations of power plants were built through the 60s, as the number of adopting countries increased (including Italy). When in the 70s the oil crisis caused energy prices to ramp up, most of Western countries decided to expand their nuclear program. Italy already had 4 power plants in its territory, and planned to build 10 more by the end of the 80s.[1]

At the end of 1985 nuclear fission accounted for $5,60\%$ of the world production of energy.[2] The night of April 26th 1986, the fourth reactor of the Chernobyl power plant exploded. Toxic fumes spread all over Europe. Many people got worried and joined anti-nuclear movements, urging governments to stop nuclear programs.[3]

In the first months of 1987, the Italian Radical Party (Partito Radicale) issued a referendum on the use of nuclear power. On Nov. 9th 1987 65% of Italian electorate participated, and with a majority of 80% decided to put an end to the Italian nuclear program.[4]

In a matter of a few months, the Italian authority on nuclear research - ENEA - had to dramatically revise its plans. The composition of its budget rapidly changed. By 1989 all projects on nuclear fission were de-funded. Professors who worked in the nuclear sector had to relocate, either by changing research topics, or by moving abroad.

In Italy, public research on nuclear energy was conducted by universities and, most importantly, by ENEA. Originally founded as a solely-nuclear institution, in 1982 it was reformed in order to include research on renewable sources (mainly solar power). However, before the Chernobyl disaster, the greatest part of its research activity was still in the nuclear sector.

As it can be seen in Figure 1a, in 1985 nuclear fission accounted for 70% of the ENEA budget. Starting in 1986, fundings to projects in nuclear fission were rapidly reduced. In 1989 the share of fundings to nuclear fission dropped to 20% (no new project was financed; money spent on nuclear fission was for maintenance costs).

On the other hand, the overall budget of ENEA neither increased after 1986, nor dropped dramatically. As it can be seen in Figure 1b, the budget reached a peak of around 1020 billion liras[5] in 1985, then it slightly decreased in the following years. Following the red line, it is possible to see that the reduction of fundings to nuclear fission was dramatic both in relative and absolute terms.

[1]For detailed information on Italian nuclear expansion programs, see Appendix C.

[2]See Hannah Ritchie and Rosado (2020).

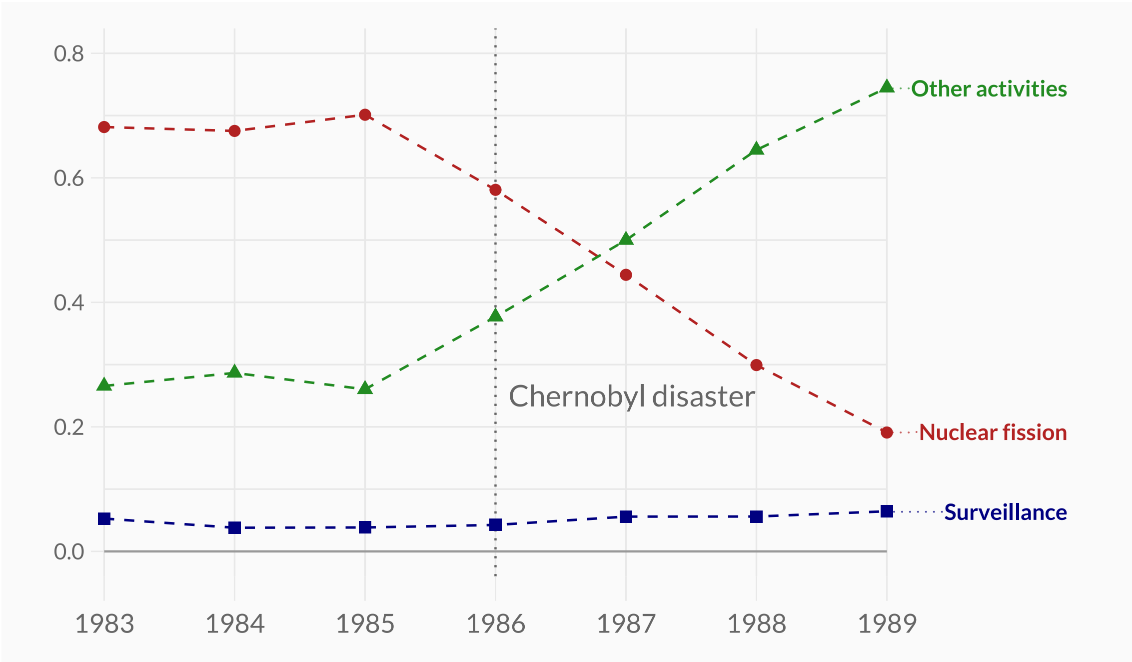
[3]See Bini and Londero (2017).

[4]Italians had to vote on three issues. First, they were asked to repeal a national interest law that allowed the government to overrule local municipalities on the permissions to build a nuclear power plant. Second, they repealed a law that gave municipalities money transfers if they hosted nuclear power plants on their territory. The third vote prohibited Enel - the National Institution for Electric Energy - to build power plants in foreign countries.

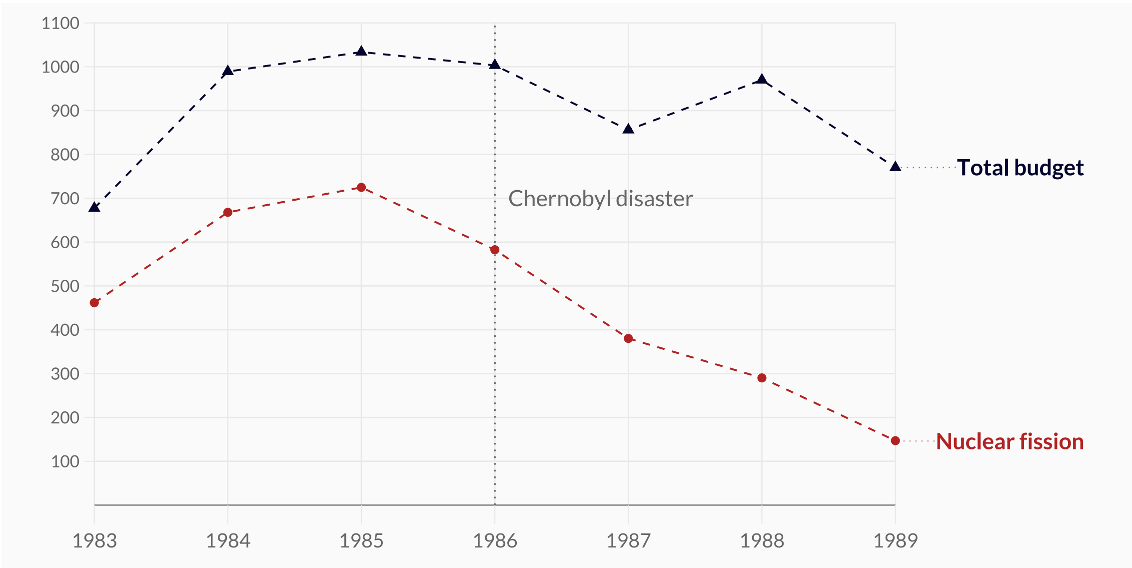
[5]Equivalent to 1,31 billion Euros in 2022.

Figure 1. ENEA budget

(a) Relative shares



(b) Absolute figures



Time series of the three expenditure destination of the ENEA budget in the years 1983-1989. As it may be noticed, right after the Chernobyl disaster, the sector of nuclear fission lost its prominence in the ENEA budget, dropping from 70% of the budget in 1985 to less than 20% in 1989.
After the 1987 referendum investment on new nuclear plants were completely stopped. Still, some maintenance costs on ongoing projects had to be sustained, so figures do not completely drop to 0.

3 Data

The main data source for this article is Microsoft Academic Graph (MAG), a freely-accessible online database on scientific publications. Each entry of the database corresponds to a paper. Every paper is associated to several pieces of information, such as authors (and their affiliations at the time), date of publication, field(s) of studies it belonged to and list of references.[6]

I select 16 fields of studies related to nuclear fission.[7] Papers associated to at least one of them are labelled as "fission papers". I identify Italian authors as being affiliated to universities whose ISO code was "IT" (MAG provides this information for all affiliations).

3.1 Summary statistics

I present some summary statistics about nuclear fission in Italy and in other developed countries.

First, I show that Italy was not on a frontier country in nuclear fission. As the first row of Table 1 shows, in years 1980-1995 in Italy only 67 papers belonging to nuclear fission have been published, by a total number of 126 authors. The country which contributed the most to nuclear research was the US, both in terms of authors and papers. The US led also in number of active institutions (an institution is labelled as active if at least a paper whose authors were affiliated to that institution was published in the considered timespan). Furthermore, in many countries private companies[8] produced around 50% of research in nuclear fission. In Italy the figure was far lower (18%), meaning that a reduction in public funds to nuclear research could have a big impact on the scientific sector.

Second, I show that patenting activity did not rely that much on nuclear research. Using an extension to Microsoft Academic Graph (Marx and Fuegi, 2022), in Table 2 I show that very few (only 3% worldwide) of papers published in nuclear fission were eventually cited in patents. In Italy just a single paper was cited in patents, suggesting that there was little technological transfer from academic research to innovation activity.

Third, I present data on some internal features of Italian fission research. In Table

[6]The project has been last updated in 2021. This article uses the last version of the database, downloaded on 2021-09-13.

[7]Coding methodology and definition of nuclear fission are explained in Appendix D.

[8]See Appendix D for the proper definition.

Table 1. Academic production in nuclear fission

Country	Authors	Papers	Institutions	Private inst.	Private papers
IT	126	67	17	3	12 (18%)
FR	272	158	23	1	86 (54%)
US	3823	2998	278	56	1364 (46%)
JP	1053	594	65	13	157 (26%)
DE	539	335	35	6	200 (60%)
GB	297	194	56	8	35 (18%)
RU	137	60	8	0	0 (0%)

The table reports the number of authors and research institutions that operated in nuclear fission. Years 1980-1995 are considered.
It also reports the number of institutions that were privately funded (i.e. private companies research labs), and the amount of papers that were published by those institutions.
Source: Microsoft Academic Graph database

3 I show that after Chernobyl, Italian research became less relevant worldwide. Italian papers were cited by more articles that had all-Italian authors (moving from 14% to 19%). The share of Italian authors in citing papers increased from 29 to 42 percent, and Italian papers got more intensively cited by papers in the same field rather than out-of-field papers. This preliminary evidence may suggest that the shock restricted the audience Italian scientists spoke to.

4 Aggregate impact on scientific output

In this section I show that after Chernobyl, Italian research in nuclear fission did not keep pace with other fields of studies.

Figure 2 plots the yearly number of publications in two fields of studies: nuclear fission and semiclassical physics. Both fields belong to the general realm of physics, but they are considerably different. Research in nuclear fission is applied, and aims to improve the efficiency of energy production. On the other hand, semiclassical physics mostly deals with theoretical research. Therefore neither the Chernobyl disaster nor the subsequent referendum should have any impact on it.

As it can be seen in the figure, both fields were expanding before 1986. Then, after Chernobyl, the two fields started to diverge. Yearly publications in semiclassical physics continued to grow, while publications in nuclear fission reached their 1985 level only in 1993.

Table 2. Papers cited in patents

Country	Published Papers	Cited in patents	Produced by privates
IT	67	1	0 (0%)
FR	158	3	1 (33%)
US	2998	92	28 (30%)
JP	594	22	10 (45%)
DE	335	4	2 (50%)
GB	194	12	6 (50%)
RU	60	0	0

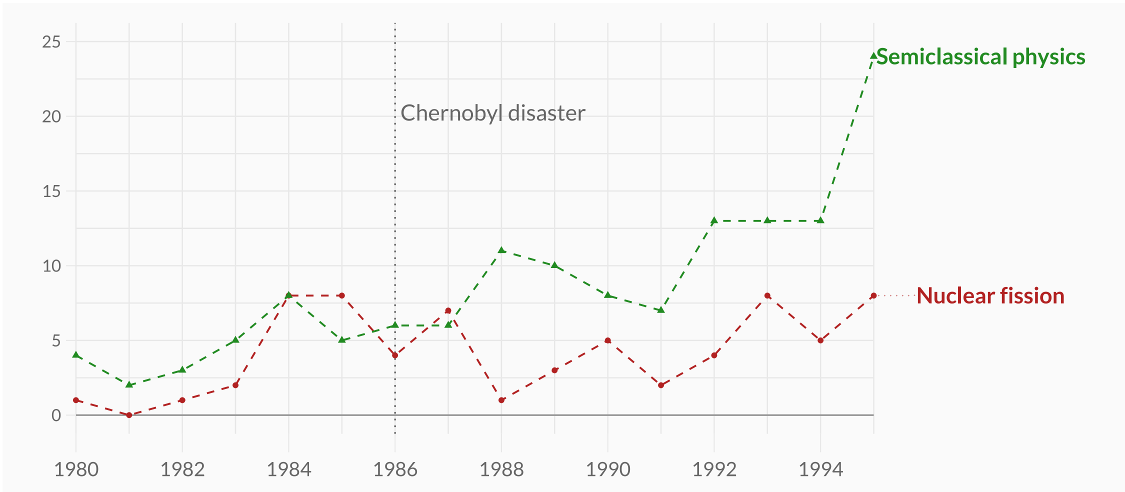
The table reports the number of papers produced in nuclear fission, in every country. It provides also the number of papers that were cited in patents, and the number of papers that - among the ones cited in patents - were produced by private research institutions.
Years 1980-1995 are considered.
Data source: **?**

Table 3. Links to other countries and fields

Period	Published Papers	Citing papers			
		Nr	All-Italian	Share of Italian authors	In-field
1980-1985	20	134	21 (14%)	29%	16 (12%)
1986-1995	47	283	53 (19%)	42%	69 (24%)

The table reports information on the publications of Italian nuclear scientists. It reports the amount of published papers in nuclear fission and the amount of papers that cite them. Among the citing papers, it reports how many where all-Italian (i.e. written only by authors affiliated to Italian universities), what was the average share of Italian authors per paper, and how many of the citing papers belonged to the field itself.
Source: Microsoft Academic Graph database

Figure 2. Time series of scientific publications



Yearly number of academic publications per scientific field. The red line represents nuclear fission. The green line is semiclassical physics. Apparently, the two fields were following a parallel trend before the Chernobyl disaster.
Source: Microsoft Academic Graph database

I test whether the Chernobyl disaster has slowed down Italian research in nuclear fission using a Difference- in-Difference model, as

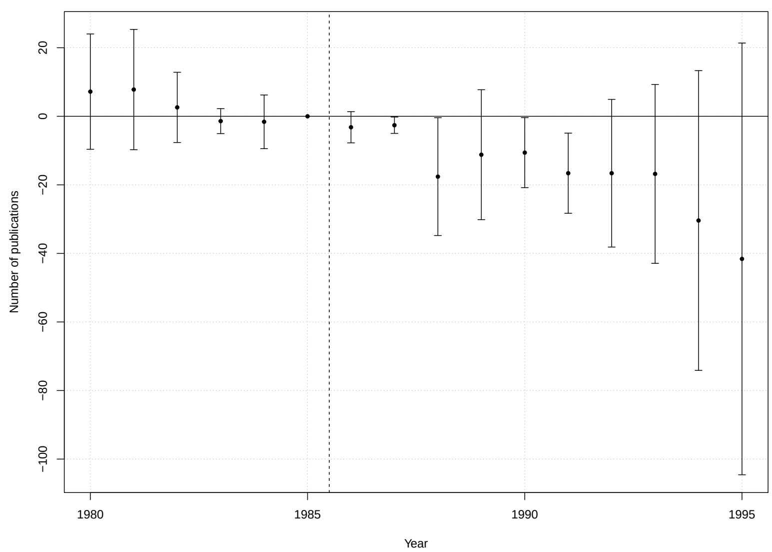
$$y_{ft} = \alpha + \beta Treat_f + \gamma Post_t + \delta Post_t \times Treat_f + \theta_t + \epsilon_{ft} \tag{1}$$

Where y_{ft} is the yearly number of publications in each field (or a function of it), $Treat_f$ is a dummy variable for the treated field (fission), $Post_t$ is a dummy variable being equal to 1 if the observation relates to year 1986 or later, $Post_t \times Treat_f$ is the interaction term in the DiD and θ_t controls for year-specific fixed effects.

Figure 3 shows estimates and 95% confidence intervals of an event study regression, in which the control group is made not only of semiclassical physics, but also of medical physics, engineering physics, theoretical physics and quantum mechanics. I chose this set of fields because all of them have - as semiclassical physics - little relation to the production of energy. As it can be seen in Figure 3, prior to 1986 nuclear fission was following the same trend of all other fields. After Chernobyl, the number of publications started to reduce (in particular, in periods 2, 4 and 5, i.e. years 1988, 1990 and 1991).

I estimate Equation 1, with two separate sets of controls. In the first specification I only use semiclassical physics as control group. In the second I use a synthetic control, created following Abadie et al. (2010), by using all fields considered when producing

Figure 3. Effects of Chernobyl disaster onto the number of publications



Event study plot. Fission is treated, semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics are used as controls. Period 0 is 1986.
Source: Microsoft Academic Graph database

Table 4. Effect of Chernobyl on aggregate publications

	Nr. publications		Log nr. publications		Asinh nr. publications	
	(1)	(2)	(3)	(4)	(5)	(6)
$Post \times Treat$	-5.233^{**}	-7.109^{***}	-0.274	-0.561^{**}	-0.233	-0.604^{*}
	(2.099)	(1.579)	(0.283)	(0.259)	(0.351)	(0.322)
Year F.E.	Yes	Yes	Yes	Yes	Yes	Yes
N	32	32	32	32	32	32
R^2	0.841	0.920	0.859	0.906	0.854	0.902

*p<0.1; **p<0.05; ***p<0.01

Years 1980-1995 are considered.
Cols. (1), (3) and (5) report the estimates for δ in a DiD regression in which semi-classical physics is used as a control.
Cols. (2), (4) and (6) report the estimates for δ in a DiD regression with a synthetic control in the spirit of Abadie et al. (2010).
It consists of a weighted mean of the following fields: semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) and (2) the dependent variable is the yearly number of publications in a scientific field, in (3) and (4) the dependent variable is the log number of publications, in (5) and (6) it is the inverse hyperbolic sine of the number of publications.
All regressions feature the diff-in-diff term δ, a post-treatment dummy $Post1986$, a dummy for the treated field, and year fixed effects.

Figure 3. In both specifications I consider publications in the years 1980-1995.

Table 4 reports the estimates. Every pair of columns is associated to a different outcome. In column (1) and (2) the outcome is just yearly number of publications. In column (1) only semiclassical physics is in the control group, while column (2) uses the synthetic control.

The pattern is repeated for the subsequent pairs , that differ only for the outcome variable. I perform two standard transformations for count data; in column (3) and (4) the yearly number of publications is log-transformed, while in column (5) and (6) I apply the inverse hyperbolic sine.

In columns (1) and (2) both simple and synthetic control show that after Chernobyl yearly publications significantly decreased. In particular, synthetic control estimates suggest that nuclear fission lost more than 7 articles per year. Turning absolute figures in percentage points, estimates in column (4) indicate that yearly publications decreased by more than 50%.

Table A1 in Appendix A completes Table 4, reporting all the coefficients of Equation 1. Furthermore, Appendix A contains also some robustness exercises. I performed the same exercise for other countries, such as the US, Japan and France. Estimates are reported in tables A7 - A12. It appears that some countries even increased their publications in fission (arguably because they decided to invest more on the safety of nuclear power plants). Italy appears the only that faced a significant reduction in the number of nuclear fission publications.

5 Impact of Chernobyl on individual careers

I identify 42 Italian authors that had at least a publication in nuclear fission between 1972 and 1986. Only 24 of them went on publishing in 1986 or later, and only 10 published papers in nuclear fission post-Chernobyl. Out of the 24 that produced publications after the shock, only 2 of them changed affiliation.

In order to understand to what extent those authors were damaged, I focus on two measures: number of publications and number of citations. Equation 2 presents a formal test for this hypothesis.

$$y_{it} = \alpha_i + \beta Treat_i + \gamma Post_t + \delta Post_t \times Treat_i + \theta_t + \epsilon_{ft} \tag{2}$$

Where y_{it} is the yearly number of publications (or citations) per author, α_i is an author-specific fixed effect, $Treat_i$ is a dummy variable that is equal to 1 if the author had published in fission pre-1986, $Post_t$ is a dummy variable being equal to 1 if the observation relates to year 1986 or later, $Post_t \times Treat_i$ is the interaction term in the DiD, and θ_t controls for year-specific fixed effects.

As a control group, I consider all authors who published at least once in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics in the years 1972-1986. Figure 4 in Appendix B shows estimates and confidence interval for an event study regression. Pre-treatment trends are not clearly visible, although there is arguably a slight decrease in publications per author before 1986.

One can think that younger authors can relocate more easily in different fields, while more experienced authors have a harder time in changing the object of their studies. However, given that I introduce author-specific fixed effects, time-invariant features, such as age in 1986 (which can be a proxy for experience at the time of the shock) are already captured. In this design, estimates may be biased only by omitted time-varying variables that affect each author's productivity (such as health, for instance).

5.1 Publications per author

Table 5 reports estimates for Equation 2, where the outcome variable is number of publications per year. Estimates in column (1) show that authors who were active in fission before 1986 faced a reduction in productivity of almost a paper per year.

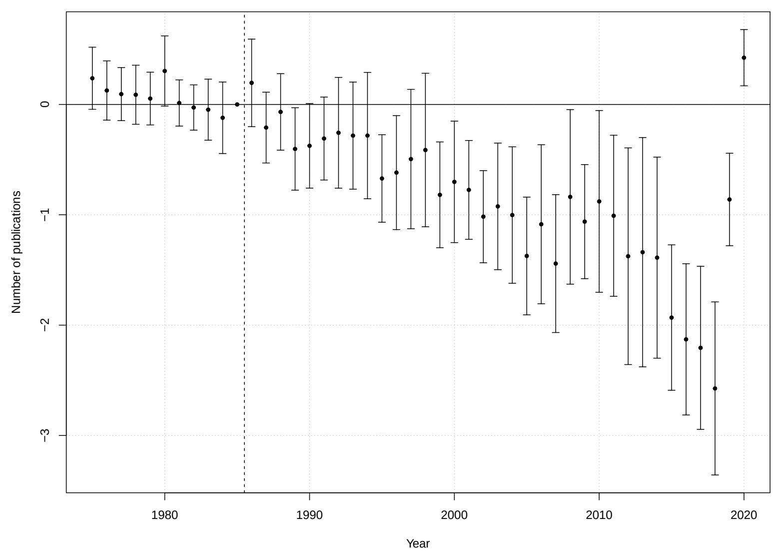
In columns (2) and (3) dependent variables are the log and the inverse hyperbolic sine of yearly number of publications.The DiD estimates suggest that productivity was reduced of almost 10%. However, estimates are significant only at 10% level, with errors clustered at author level. Arguably, with a higher level of clustering (e.g. at field level), estimates would have been more precise. However, there is no unique way to map authors into fields (since authors contributed to several fields), therefore I decided to stick to this more conservative clustering level.

5.2 Citations per author

The second variable of interest is number of citations. Treated and control group are exactly the same as for publications.

Figure 5 shows estimates and confidence intervals for an event study regression. There is no evidence of pre-treatment trends, and the number of publications for fission scientists starts decreasing in the mid-90s.

Figure 4. Event study for number of individual publications



Event study plot. Effects of Chernobyl disaster onto the number of publications of Italian scientists. Scientists who published at least once in 1972-1986 are part of the sample. Scientists who published at least once in fission are treated. Scientists who published in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics are used as controls. Period 0 is 1986.
Source: Microsoft Academic Graph database

Table 5. Effect of Chernobyl on individual publications

	Nr. of publications	Log nr. publications	Asinh nr. publications
	(1)	(2)	(3)
$Post \times Treat$	-0.937***	-0.102*	-0.121*
	(0.184)	(0.054)	(0.070)
Year F.E.	Yes	Yes	Yes
Author F.E.	Yes	Yes	Yes
N	89,240	89,240	89,240
R^2	0.335	0.335	0.572

*p<0.1; **p<0.05; ***p<0.01

Years 1980-2020 are considered.
Every observation is an author-year pair.
Authors who published in nuclear fission before 1986 are considered as treated.
The control group is made of authors who published before 1986 in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) the dependent variable is the number of publications per year.
In (2) the dependent variable is the log number of publications per year.
In (3) the dependent variable is the inverse hyperbolic sine of the number of publications per year.
Every regression features year and author fixed effects, plus the DiD term $Post \times Treat$.
Standard errors are clustered by author.

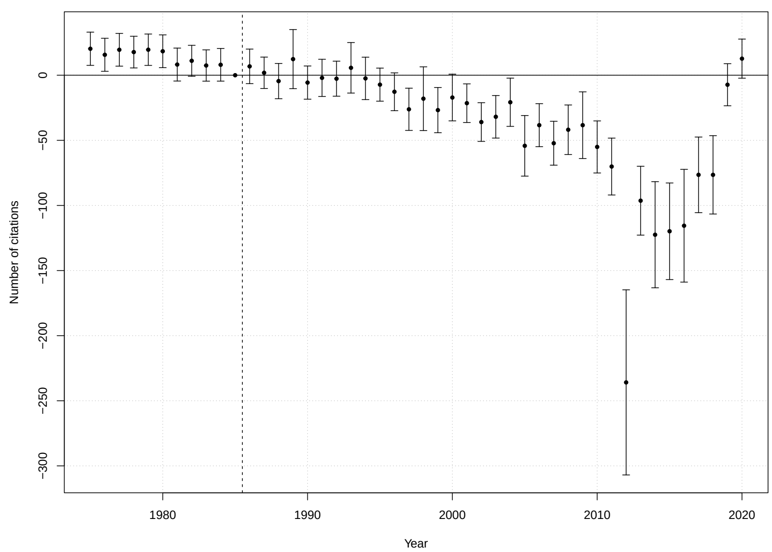
Table 6. Effect of Chernobyl on individual citations

	Nr. of citations	Log nr. citations	Asinh nr. citations
	(1)	(2)	(3)
$Post \times Treat$	-53.186***	-0.253**	-0.276**
	(5.400)	(0.115)	(0.135)
Year F.E	Yes	Yes	Yes
Author F.E.	Yes	Yes	Yes
N	89,240	89,240	89,240
R^2	0.196	0.550	0.553

*p<0.1; **p<0.05; ***p<0.01

Years 1980-2020 are considered.
Every observation is an author-year pair.
Authors who published in nuclear fission before 1986 are considered as treated.
The control group is made of authors who published before 1986 in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) the dependent variable is the number of citations per year.
In (2) the dependent variable is the log number of citations per year.
In (3) the dependent variable is the inverse hyperbolic sine of the number of citations per year.
Every regression features year and author fixed effects, plus the DiD term $Post \times Treat$.
Standard errors are clustered by author.

Figure 5. Event study for number of individual citations



Event study plot. Effects of Chernobyl disaster onto the number of publications of Italian scientists. Scientists who published at least once in 1972-1986 are part of the sample. Scientists who published at least once in fission are treated. Scientists who published in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics are used as controls. Period 0 is 1986.
Source: Microsoft Academic Graph database

Table 6 reports estimates for Equation 2, where the dependent variable is yearly number of citations. Authors who had published in nuclear fission pre Chernobyl lost more than 50 citations per year with respect to their peers (column 1), which accounted for around 25% of their citations (column 2). Not only nuclear fission scientists published fewer papers (10% reduction), but also they became less relevant, speaking to a smaller audience.

So far, I considered the whole career of nuclear fission scientists, taking into account papers published up to 2020. In Appendix A I perform some robustness exercises, considering shorter time periods. Still using 1980 as initial year, I use alternatively 2000 and 2010 as final years. In both cases all point estimates exhibit a negative sign. However, in regressions that use 2000 as a final year point estimates are too small to be significant.

On the other hand, estimates with the 2010 sample are almost identical to the full sample. This is reassuring, because in Figure 5 estimates for years from 2012 on are quite noisy. This implies that the reduction in citations per author is not driven by later years.

6 Conclusions

In this article I argued that Italian nuclear scientists have not been able to successfully relocate after the defunding of their field. They were not able to open the gates of new areas of research, and their careers slowed down. This piece of evidence informs the debate on science funding, showing that - in the absence of pre-designed programs for technological transfer - scientists are not able to smoothly relocate across fields. What is more, their contribution to areas of research they did not initially work on may be less valuable than the work in their original domain.

Further research should quantify the welfare implications of the defunding of a national research area, both at a country-level (i.e. how much research in nuclear fission mattered for Italy) and at a field level (how much Italian scientists mattered for nuclear fission worldwide).

However, this article has two major shortcomings: first, the number of nuclear fission authors is quite small (42 publishing in Italy before 1986). Second, I was not able to access granular budget data and compute any elasticity of academic production with respect to fundings.

Later versions of this article should address those shortcomings, as well as expand the analysis with machine learning techniques. For instance, I did not define any contiguity measure of research areas (i.e. mathematics is relatively closed to physics, while it is far apart from classic literature). Using the tools of network analysis, it would be possible to study the transition to new fields in a richer setting.

Another development of the article would focus on the innovative content of every article. Running text analysis algorithm (both on titles and abstracts), I would be able to estimate whether fission scientists who transitioned to new fields were able to produce more innovative content.

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A Appendix Tables

Appendix Table A1. Aggregate DiD

	Dependent variable:					
	Nr. pub		Log nr. pub		Asinh nr. pub	
	(1)	(2)	(3)	(4)	(5)	(6)
$Post \times Treat$	-5.233^{**}	-7.109^{***}	-0.274	-0.561^{**}	-0.233	-0.604^{*}
	(2.099)	(1.579)	(0.283)	(0.259)	(0.351)	(0.322)
$Treat$	-1.167	-1.305	-0.499^{**}	-0.380^{*}	-0.666^{**}	-0.472^{*}
	(1.659)	(1.248)	(0.224)	(0.204)	(0.277)	(0.255)
$Post$	16.117^{***}	12.950^{***}	1.694^{***}	1.925^{***}	1.952^{***}	2.355^{***}
	(3.059)	(2.302)	(0.413)	(0.377)	(0.511)	(0.470)
Constant	3.083	1.921	1.401^{***}	0.901^{***}	1.821^{***}	1.118^{***}
	(2.195)	(1.651)	(0.296)	(0.270)	(0.367)	(0.337)
Observations	32	32	32	32	32	32
R^2	0.841	0.920	0.859	0.906	0.854	0.902
Adjusted R^2	0.647	0.824	0.688	0.791	0.677	0.782
Note:						*p<0.1; **p<0.05; ***p<0.01

Years 1980-1995 are considered.
In (1) and (2) the dependent variable is the number of publications in a scientific field (in a given year).
In (3) and (4) the dependent variable is the log number of publications in a scientific field (in a given year).
In (5) and (6) the dependent variable is the inverse hyperbolic sine of the number of publications in a scientific field (in a given year).
Nuclear fission is the treated field.
In (1), (3) and (5) the control group is semiclassical physics.
In (2), (4) and (6) the control group is a synthetic control , in the spirit of **?**. It consists of a weighted mean of the following fields: semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
Every regression features year and field fixed effects, a post-treatment dummy *Post*, a dummy for fission and the DiD term δ.

Appendix Table A2. Poisson DiD with semiclassical physics

	Dependent variable:	
	Number of publications	
	(1)	(2)
$Post \times Treat$	-0.559	-0.559
	(0.343)	(0.343)
$Treat$	-0.300	-0.300
	(0.295)	(0.295)
$Post$	0.903^{***}	2.058^{***}
	(0.215)	(0.500)
Constant	1.551^{***}	1.063^{**}
	(0.174)	(0.461)
Year F.E.		YES
Observations	32	32
Log Likelihood	-83.636	-62.473
Akaike Inf. Crit.	175.271	160.946
Note:	*p<0.1; **p<0.05; ***p<0.01	

The dependent variable is the yearly number of publications in a scientific field.
Years 1980-1995 are considered. Fission is considered the treated field.
Semiclassical physics is the control group.
(1) features only the diff-in-diff term, a post-treatment dummy *Post* and a dummy for fission.
(2) features also year-specific fixed effects.

Appendix Table A3. Effect of Chernobyl on individual publications (up to 2000)

	Nr. of publications	Log nr. publications	Asinh nr. publications
	(1)	(2)	(3)
$Post \times Treat$	-0.446**	-0.066	-0.081
	(0.164)	(0.055)	(0.071)
Year F.E.	Yes	Yes	Yes
Author F.E.	Yes	Yes	Yes
N	50,440	50,440	50,440
R^2	0.503	0.570	0.570

*p<0.1; **p<0.05; ***p<0.01

Years 1980-2000 are considered.
Every observation is an author-year pair.
Authors who published in nuclear fission before 1986 are considered as treated.
The control group is made of authors who published before 1986 in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) the dependent variable is the number of publications per year.
In (2) the dependent variable is the log number of publications per year.
In (3) the dependent variable is the inverse hyperbolic sine of the number of publications per year.
Every regression features year and author fixed effects, plus the DiD term $Post \times Treat$.
Standard errors are clustered by author.

Appendix Table A4. Effect of Chernobyl on individual publications (up to 2010)

	Nr. of publications	Log nr. publications	Asinh nr. publications
	(1)	(2)	(3)
$Post \times Treat$	-0.710***	-0.102*	-0.123
	(0.178)	(0.058)	(0.075)
Year F.E.	Yes	Yes	Yes
Author F.E.	Yes	Yes	Yes
N	69,840	69,840	69,840
R^2	0.453	0.598	0.600

*p<0.1; **p<0.05; ***p<0.01

Years 1980-2010 are considered.
Every observation is an author-year pair.
Authors who published in nuclear fission before 1986 are considered as treated.
The control group is made of authors who published before 1986 in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) the dependent variable is the number of publications per year.
In (2) the dependent variable is the log number of publications per year.
In (3) the dependent variable is the inverse hyperbolic sine of the number of publications per year.
Every regression features year and author fixed effects, plus the DiD term $Post \times Treat$.
Standard errors are clustered by author.

Appendix Table A5. Effect of Chernobyl on individual citations (up to 2000)

	Nr. of citations	Log nr. citations	Asinh nr. citations
	(1)	(2)	(3)
$Post \times Treat$	-19.854***	-0.235*	-0.263*
	(3.457)	(0.132)	(0.155)
Year F.E	Yes	Yes	Yes
Author F.E.	Yes	Yes	Yes
N	50,440	50,440	50,440
R^2	0.275	0.539	0.538

*p<0.1; **p<0.05; ***p<0.01

Years 1980-2000 are considered.
Every observation is an author-year pair.
Authors who published in nuclear fission before 1986 are considered as treated.
The control group is made of authors who published before 1986 in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) the dependent variable is the number of citations per year.
In (2) the dependent variable is the log number of citations per year.
In (3) the dependent variable is the inverse hyperbolic sine of the number of citations per year.
Every regression features year and author fixed effects, plus the DiD term $Post \times Treat$.
Standard errors are clustered by author.

Appendix Table A6. Effect of Chernobyl on individual citations (up to 2010)

	Nr. of citations	Log nr. citations	Asinh nr. citations
	(1)	(2)	(3)
$Post \times Treat$	-32.833***	-0.285**	-0.316**
	(3.938)	(0.132)	(0.155)
Year F.E	Yes	Yes	Yes
Author F.E.	Yes	Yes	Yes
N	69,840	69,840	69,840
R^2	0.271	0.568	0.569

*p<0.1; **p<0.05; ***p<0.01

Years 1980-2010 are considered.
Every observation is an author-year pair.
Authors who published in nuclear fission before 1986 are considered as treated.
The control group is made of authors who published before 1986 in semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
In (1) the dependent variable is the number of citations per year.
In (2) the dependent variable is the log number of citations per year.
In (3) the dependent variable is the inverse hyperbolic sine of the number of citations per year.
Every regression features year and author fixed effects, plus the DiD term $Post \times Treat$.
Standard errors are clustered by author.

Appendix Table A7. US: Aggregate DiD

	Dependent variable:					
	Nr. pub		Log nr. pub		Asinh nr. pub	
	(1)	(2)	(3)	(4)	(5)	(6)
Post $\times$ *Treat*	86.033***	66.979**	0.322**	0.330**	0.322**	0.331**
	(25.414)	(22.897)	(0.124)	(0.111)	(0.125)	(0.112)
Treat	46.667**	−5.075	0.506***	−0.055	0.512***	−0.041
	(20.091)	(18.102)	(0.098)	(0.088)	(0.099)	(0.088)
Post	103.483**	118.636***	0.850***	0.683***	0.859***	0.692***
	(37.047)	(33.378)	(0.181)	(0.162)	(0.182)	(0.163)
Constant	47.667*	110.735***	3.959***	4.702***	4.634***	5.367***
	(26.578)	(23.946)	(0.130)	(0.116)	(0.131)	(0.117)
Observations	32	32	32	32	32	32
R^2	0.904	0.876	0.946	0.902	0.946	0.903
Adjusted R^2	0.787	0.725	0.880	0.782	0.881	0.786

Note: *p<0.1; **p<0.05; ***p<0.01

Years 1980-1995 are considered.
In (1) and (2) the dependent variable is the number of publications in a scientific field (in a given year).
In (3) and (4) the dependent variable is the log number of publications in a scientific field (in a given year).
In (5) and (6) the dependent variable is the inverse hyperbolic sine of the number of publications in a scientific field (in a given year).
Nuclear fission is the treated field.
In (1), (3) and (5) the control group is semiclassical physics.
In (2), (4) and (6) the control group is a synthetic control, in the spirit of Abadie et al. (2010). It consists of a weighted mean of the following fields: semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
Every regression features year and field fixed effects, a post-treatment dummy *Post*, a dummy for fission and the DiD term.

Appendix Table A8. US: Poisson DiD with semiclassical physics

	Dependent variable:	
	Number of publications	
	(1)	(2)
$Post \times Treat$	0.356***	0.356***
	(0.073)	(0.073)
$Treat$	0.510***	0.510***
	(0.062)	(0.062)
$Post$	0.317***	0.882***
	(0.058)	(0.107)
Constant	4.251***	3.976***
	(0.049)	(0.092)
Year F.E.	YES	YES
Observations	32	32
Log Likelihood	−227.097	−129.536
Akaike Inf. Crit.	462.194	295.073
Note:	*p<0.1; **p<0.05; ***p<0.01	

The dependent variable is the yearly number of publications in a scientific field.
Years 1980-1995 are considered. Fission is considered the treated field.
Semiclassical physics is the control group.
(1) features only the diff-in-diff term, a post-treatment dummy *Post* and a dummy for fission.
(2) features also year-specific fixed effects.

Appendix Table A9. JP: Aggregate DiD

	Dependent variable:					
	Nr. pub		Log nr. pub		Asinh nr. pub	
	(1)	(2)	(3)	(4)	(5)	(6)
Post × *Treat*	21.833**	19.650**	0.292	0.445*	0.256	0.231
	(8.886)	(8.132)	(0.229)	(0.221)	(0.242)	(0.219)
Treat	14.667*	7.559	1.076***	0.246	1.183***	0.443**
	(7.025)	(6.429)	(0.181)	(0.174)	(0.191)	(0.173)
Post	26.083*	30.925**	1.587***	1.363***	1.743***	1.716***
	(12.954)	(11.855)	(0.335)	(0.322)	(0.353)	(0.319)
Constant	−2.333	4.735	1.240***	2.094***	1.702***	2.472***
	(9.294)	(8.505)	(0.240)	(0.231)	(0.253)	(0.229)
Observations	32	32	32	32	32	32
R^2	0.855	0.849	0.937	0.875	0.938	0.900
Adjusted R^2	0.680	0.665	0.860	0.724	0.864	0.779

Note: *p<0.1; **p<0.05; ***p<0.01

Years 1980-1995 are considered.
In (1) and (2) the dependent variable is the number of publications in a scientific field (in a given year).
In (3) and (4) the dependent variable is the log number of publications in a scientific field (in a given year).
In (5) and (6) the dependent variable is the inverse hyperbolic sine of the number of publications in a scientific field (in a given year).
Nuclear fission is the treated field.
In (1), (3) and (5) the control group is semiclassical physics.
In (2), (4) and (6) the control group is a synthetic control, in the spirit of Abadie et al. (2010). It consists of a weighted mean of the following fields: semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
Every regression features year and field fixed effects, a post-treatment dummy *Post*, a dummy for fission and the DiD term.

Appendix Table A10. JP: Poisson DiD with semiclassical physics

	Dependent variable:	
	Number of publications	
	(1)	(2)
Post × *Treat*	0.257	0.257
	(0.220)	(0.220)
Treat	1.257***	1.257***
	(0.192)	(0.192)
Post	0.569***	1.923***
	(0.196)	(0.377)
Constant	1.764***	0.795**
	(0.169)	(0.350)
Year F.E.	YES	YES
Observations	32	32
Log Likelihood	−147.007	−81.576
Akaike Inf. Crit.	302.014	199.153
Note:	*p<0.1; **p<0.05; ***p<0.01	

The dependent variable is the yearly number of publications in a scientific field.
Years 1980-1995 are considered. Fission is considered the treated field.
Semiclassical physics is the control group.
(1) features only the diff-in-diff term, a post-treatment dummy *Post* and a dummy for fission.
(2) features also year-specific fixed effects.

Appendix Table A11. FR: Aggregate DiD

	Dependent variable:					
	Nr. pub		Log nr. pub		Asinh nr. pub	
	(1)	(2)	(3)	(4)	(5)	(6)
Post × *Treat*	−2.700	−5.098*	−0.038	−0.152	−0.010	−0.147
	(2.367)	(2.499)	(0.215)	(0.191)	(0.246)	(0.220)
Treat	−1.000	−1.878	−0.189	0.059	−0.233	0.053
	(1.871)	(1.976)	(0.170)	(0.151)	(0.195)	(0.174)
Post	13.850***	17.382***	1.141***	1.357***	1.248***	1.509***
	(3.450)	(3.643)	(0.313)	(0.278)	(0.359)	(0.320)
Constant	5.500**	6.153**	1.872***	1.519***	2.410***	2.001***
	(2.475)	(2.614)	(0.224)	(0.200)	(0.258)	(0.230)
Observations	32	32	32	32	32	32
R^2	0.838	0.865	0.828	0.864	0.820	0.859
Adjusted R^2	0.642	0.700	0.618	0.700	0.601	0.689

Note: *p<0.1; **p<0.05; ***p<0.01

Years 1980-1995 are considered.
In (1) and (2) the dependent variable is the number of publications in a scientific field (in a given year).
In (3) and (4) the dependent variable is the log number of publications in a scientific field (in a given year).
In (5) and (6) the dependent variable is the inverse hyperbolic sine of the number of publications in a scientific field (in a given year).
Nuclear fission is the treated field.
In (1), (3) and (5) the control group is semiclassical physics.
In (2), (4) and (6) the control group is a synthetic control, in the spirit of Abadie et al. (2010). It consists of a weighted mean of the following fields: semiclassical physics, medical physics, engineering physics, theoretical physics and quantum mechanics.
Every regression features year and field fixed effects, a post-treatment dummy *Post*1986, a dummy for fission and the DiD term δ.

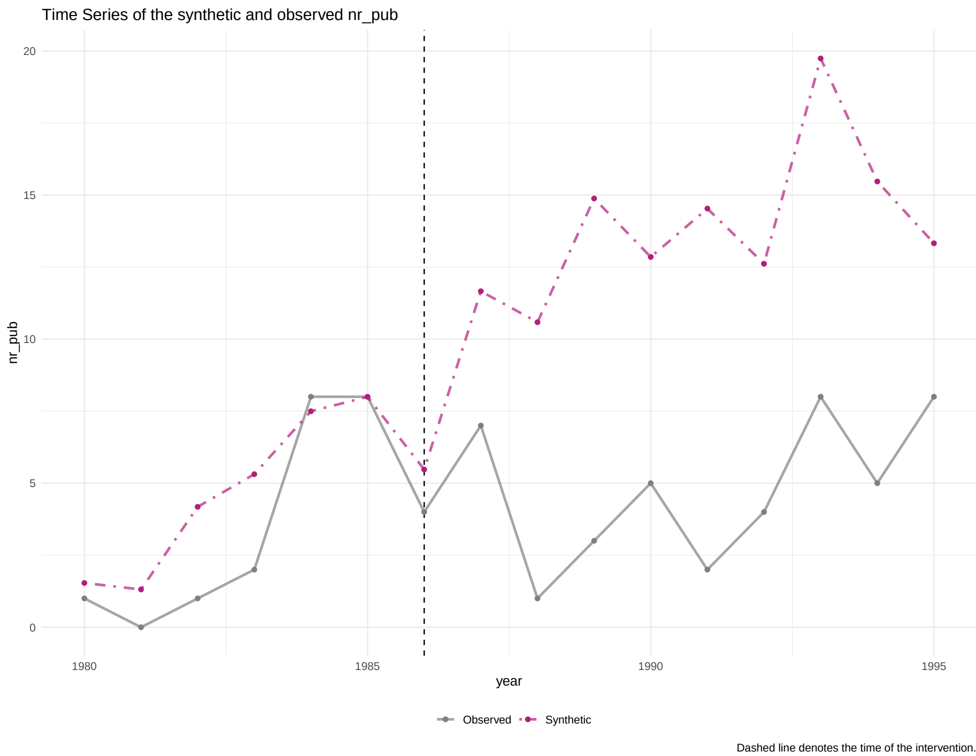
Appendix Table A12. FR: Poisson DiD with semiclassical physics

	Dependent variable:	
	Number of publications	
	(1)	(2)
$Post \times Treat$	-0.145	-0.145
	(0.245)	(0.245)
$Treat$	-0.134	-0.134
	(0.211)	(0.211)
$Post$	0.642^{***}	1.318^{***}
	(0.166)	(0.376)
Constant	2.079^{***}	1.674^{***}
	(0.144)	(0.331)
Year F.E.	YES	YES
Observations	32	32
Log Likelihood	-91.431	-72.426
Akaike Inf. Crit.	190.862	180.852
Note:	*p<0.1; **p<0.05; ***p<0.01	

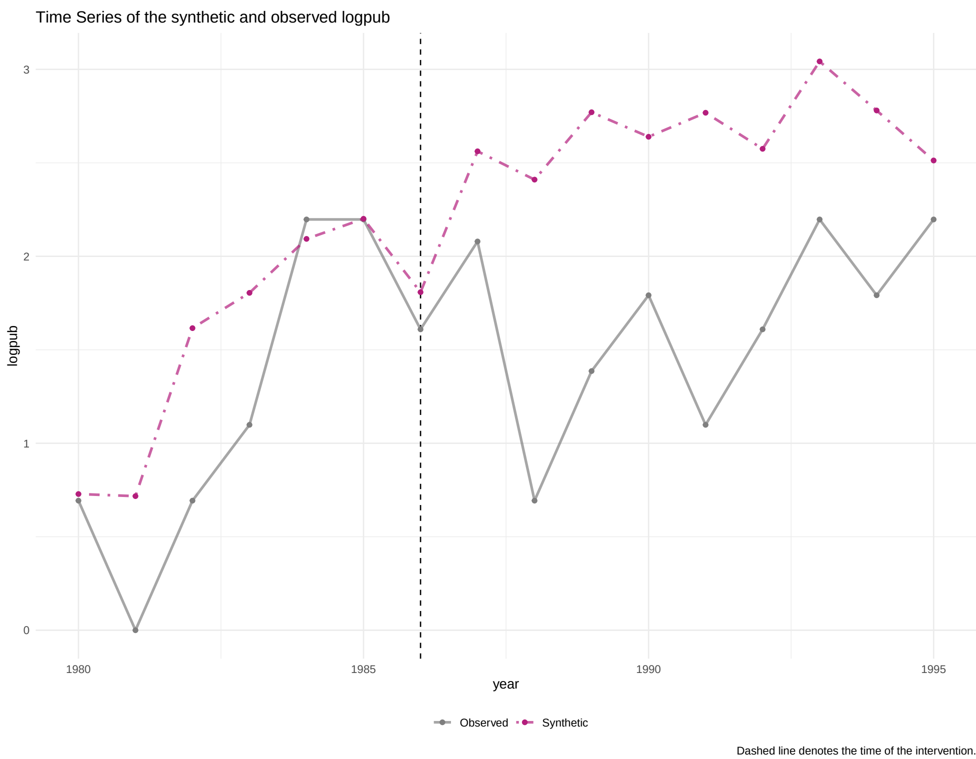
The dependent variable is the yearly number of publications in a scientific field.
Years 1980-1995 are considered. Fission is considered the treated field.
Semiclassical physics is the control group.
(1) features only the diff-in-diff term, a post-treatment dummy *Post* and a dummy for fission.
(2) features also year-specific fixed effects.

B Appendix Figures

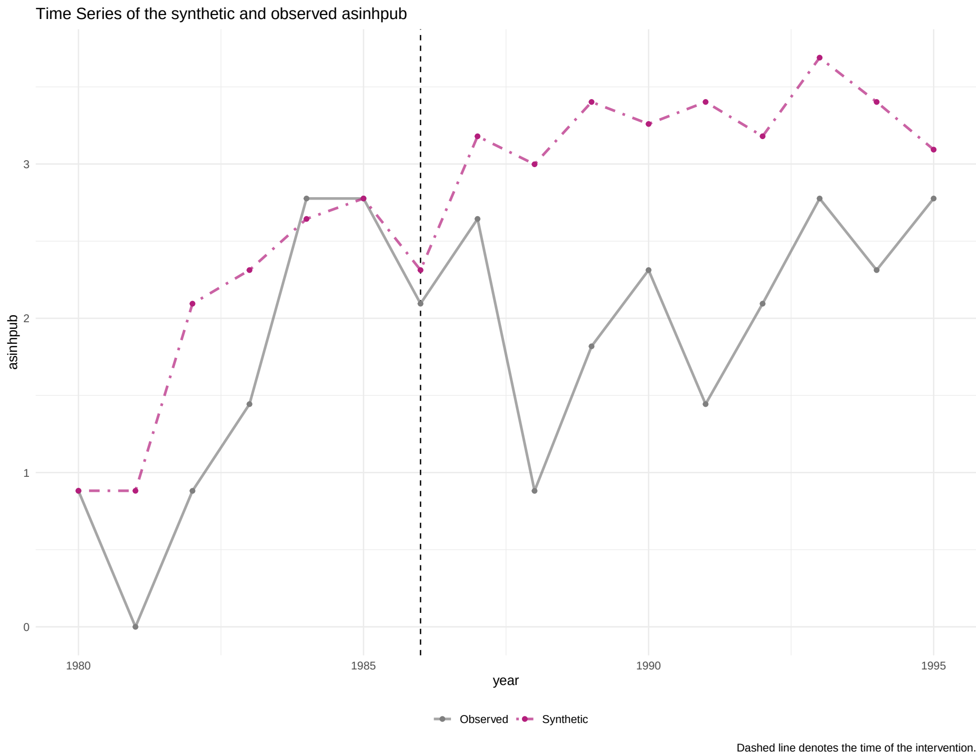
Appendix Figures B1. Time series of scientific publications



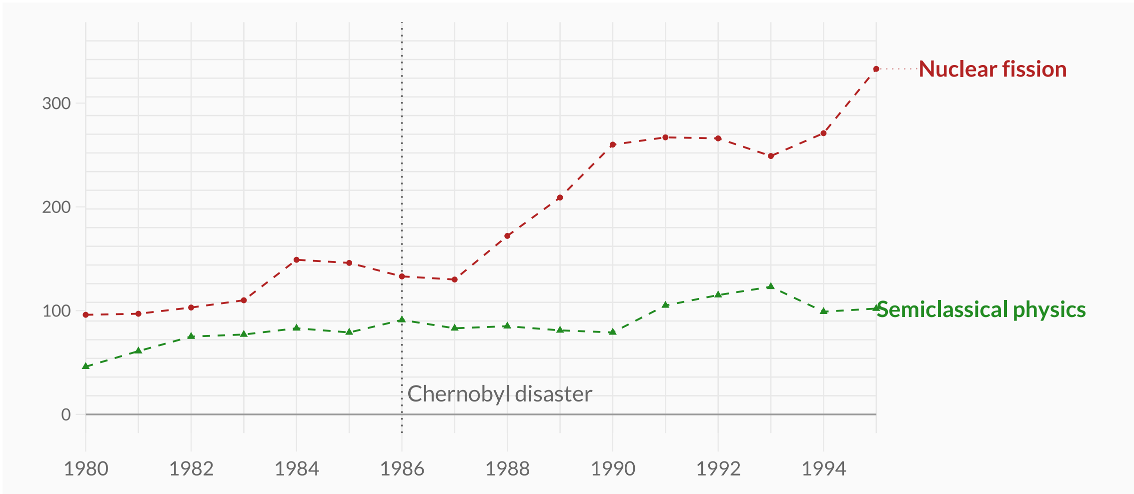
Appendix Figures B2. Time series of log of scientific publications



Appendix Figures B3. Time series of hyperbolic transformation of scientific publications

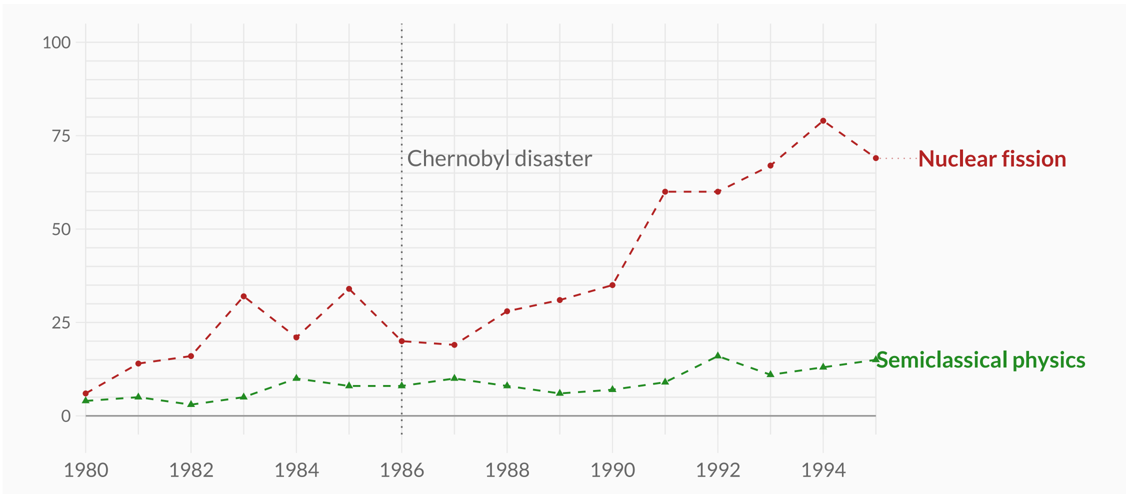


Appendix Figures B4. US: Time series of scientific publications



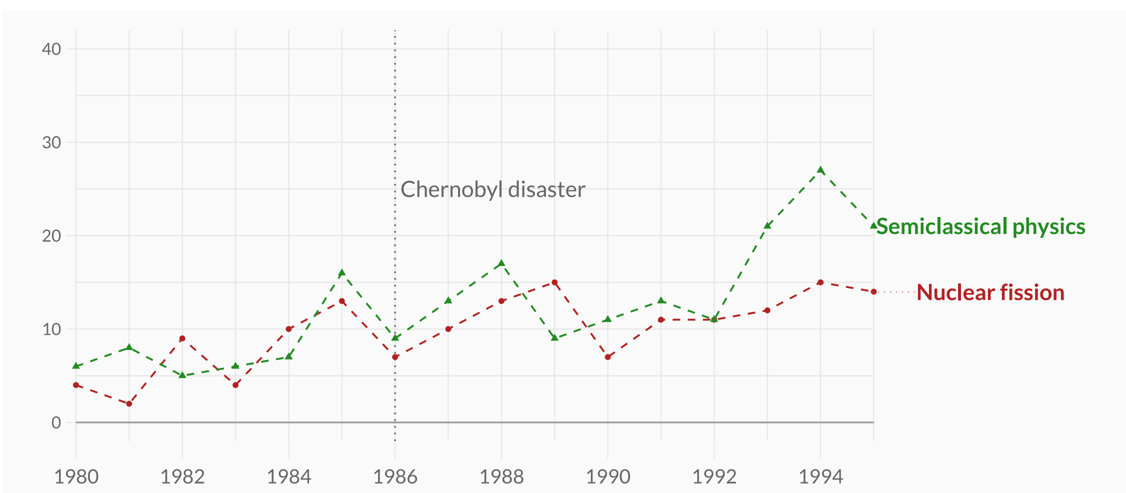
Yearly number of academic publications per scientific field by US authors. The red line is nuclear fission. The green line is semiclassical physics.
Source: Microsoft Academic Graph database

Appendix Figures B5. JP: Time series of scientific publications



Yearly number of academic publications per scientific field by Japanese authors. The red line is nuclear fission. The green line is semiclassical physics.
Source: Microsoft Academic Graph database

Appendix Figures B6. FR: Time series of scientific publications



Yearly number of academic publications per scientific field by French authors. The red line is nuclear fission. The green line is semiclassical physics.
Source: Microsoft Academic Graph database

C Non-anticipation of the shock

The event of the Chernobyl disaster (and the subsequent referendum) is here interpreted as a sudden shock to the fundings for nuclear research. In order for this claim to be true, it has to be proved that Italian authorities were not already planning to reduce the contributions to nuclear fission and increase the amount of resources spent in fusion and renewables. Two documents support this claim:

1. **?**. It is a report presented to the Italian parliament documenting what ENEA has done in the years 1980-84, and describing the program for the following 5 years. The report for the 1980-84 years describes all the activities and the projects, including also detailed tables on the allocation of resources (p.59) and a long list of suppliers. In the part that explains the objectives for the 1985-89 period, most of the attention is devoted to nuclear fission. When listing the objectives of the plan (p.233), the extenders of the document put as the priority the realisation of new nuclear plants in Italy and the completion of the CIRENE reactor.

   The comment on the priorities is "the program is now at the apex of its effort, which is forecasted to last until the first nuclear plants of the National Electric Plan will start functioning. The current collaboration system features a whole bunch of big, small and medium enterprises, mostly belonging to the mechanical, electric and electronic sector."

2. **?**. This document is a biennial report written by the ENEA president. It covers the activities carried on by the institution in the years 1985-86. With respect to the previous one, it contains more technical pieces of information. It covers the first two years of the 1985-89 plan, and presents updates on the realisation of the most important projects. Moreover, the report has been completed after the Chernobyl incident (but before the referendum).

   In its introductory pages, the president clearly states that "The irreplaceable role of this source [*nuclear*] has been firmly reaffirmed in every occasion, especially after the Chernobyl accident. [...] At the Tokyo G7 summit, held between the 4th and the 6th of May 1986, to which the Italian government took part, the participants agreed on the importance of the nuclear development in the industrialised countries, in order not to put excessive pressure on the costs of the fuel, which is crucial for economic growth in developing countries.(p.22)"

Then the document proceeds in analysing ENEA's major projects, saying that the CIRENE reactor had reached a completion percentage of "more than 90% at the end of 1985", while the PEC plant was "above 65% at the end of 1985". Both projects were suddenly interrupted in 1987.

D Coding of the variables

I list here some technical notes on the way I defined variables.

Fission fields Every entry in the MAG database is associated to one or more fields of studies. I define an indicator "fission indicator" equal to 1 if any paper is associated to one of the following fields : "nuclear fission", "nuclear reactor", "nuclear power plant", "nuclear reactor safety systems", "nuclear reactor core", "nuclear material", "special nuclear material", "nuclear fission product", "nuclear reactor physics", "nuclear fuel cycle", "nuclear reactor coolant", "ford nuclear reactor", "economics of nuclear power plants", "convention on the physical protection of nuclear material", "weapons grade nuclear material"

Private institutions In the MAG database, universities and research centres are often associated to their website. I use this information in order to establish whether a research institution is public or not. In particular, I define an indicator being equal to 1 if any institutions has its website terminating with ".com" or having the string ".co." (typical in some countries such as the United Kingdom, where companies have often websites terminating in ".co.uk").