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Supplementary Materials for

Ryugu's nucleosynthetic heritage from the outskirts of the Solar System

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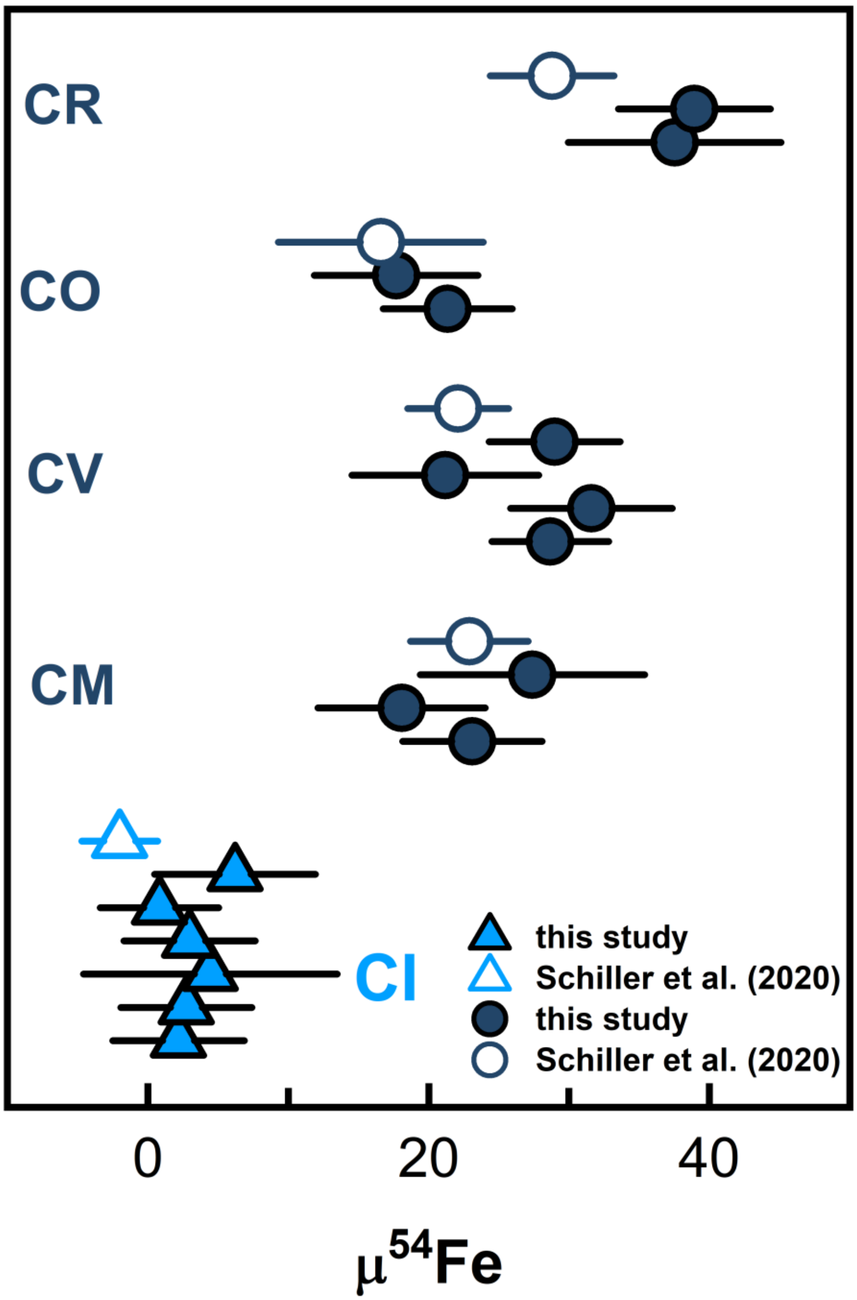

Fig. S1. Comparison of μ^{54}Fe values of carbonaceous chondrites determined in this study with literature data of (*22*). The data from this study agree with previous studies. Uncertainties of individual samples are 95% confidence intervals calculated from replicate analysis (N=14-30).

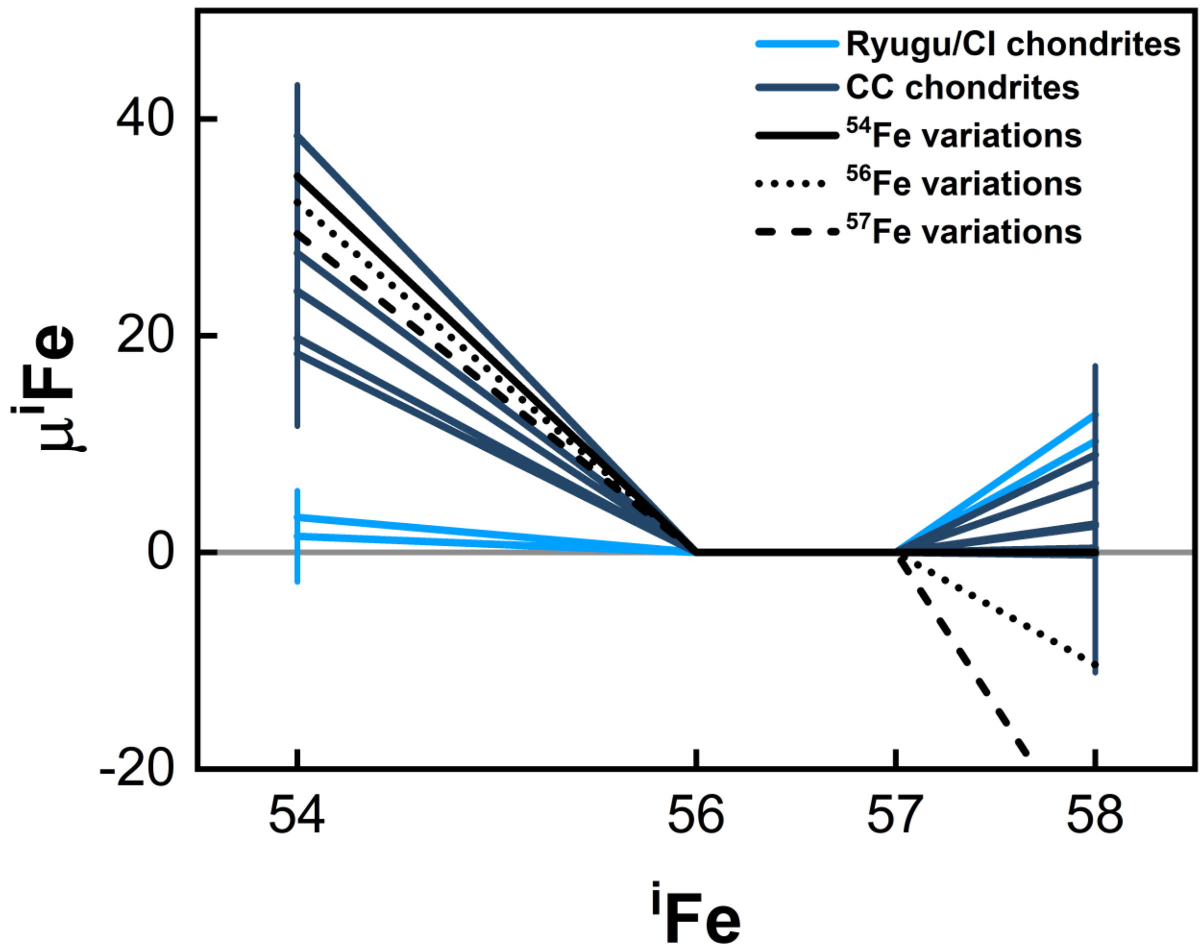

Fig. S2. Average nucleosynthetic isotopic anomalies of carbonaceous chondrites and Ryugu samples normalized to $^{57}Fe/^{56}Fe$. All carbonaceous chondrites except CI chondrites and Ryugu display resolvable $\mu^{54}Fe$ (dark blue lines). The $\mu^{58}Fe$ values of most carbonaceous chondrites are not resolvable from the terrestrial standard. While the calculated averages of CI chondrites and Ryugu display excesses in $\mu^{58}Fe$ resolvable from the standard, these are not resolvable from the other carbonaceous chondrites. Comparison with expected anomalies produced by individual variations in ^{54}Fe, ^{56}Fe, and ^{57}Fe (black lines) reveals that the observed $\mu^{54}Fe$ anomalies are best explained by ^{54}Fe variations (*24*). Exposure to galactic cosmic rays induces positive shifts in $\mu^{54}Fe$ that correlate with negative shifts in $\mu^{58}Fe$ (*24*, *26*). If Fe isotopic compositions of CI chondrites and Ryugu had been affected by exposure to galactic cosmic rays, their primary Fe isotopic compositions would be even more distinct from other carbonaceous chondrites than they are because the pre-exposure $\mu^{54}Fe$ and $\mu^{58}Fe$ values would shift towards more negative and positive values, respectively.

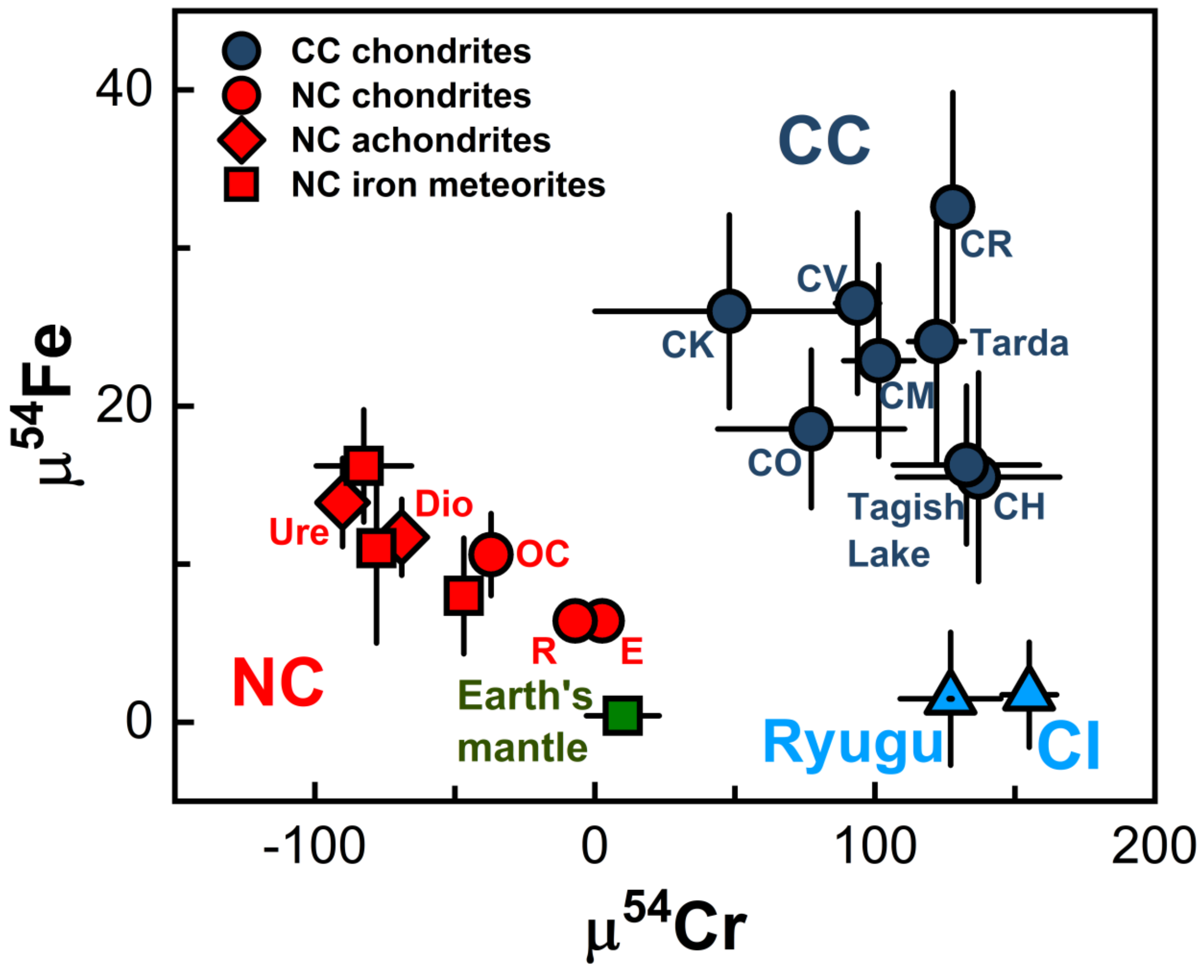

Fig. S3. Isotopic anomalies of Fe and Cr in Ryugu and other Solar System materials. The average μ^{54}Fe and μ^{54}Cr data of Ryugu samples are from this study and (*6*). The average compositions of non-carbonaceous (NC) and carbonaceous (CC) meteorite groups and Earth's mantle (BSE) are given in the data compilation Table S1 and are calculated using data from this study and the data compilation of (*64*). Uncertainties for individual groups are the 95% confidence interval of the mean. E-enstatite; R-rumuruti; OC-ordinary chondrites; Ure=ureilites; Dio=diogeneites. Error bars that are not visible smaller than symbols.

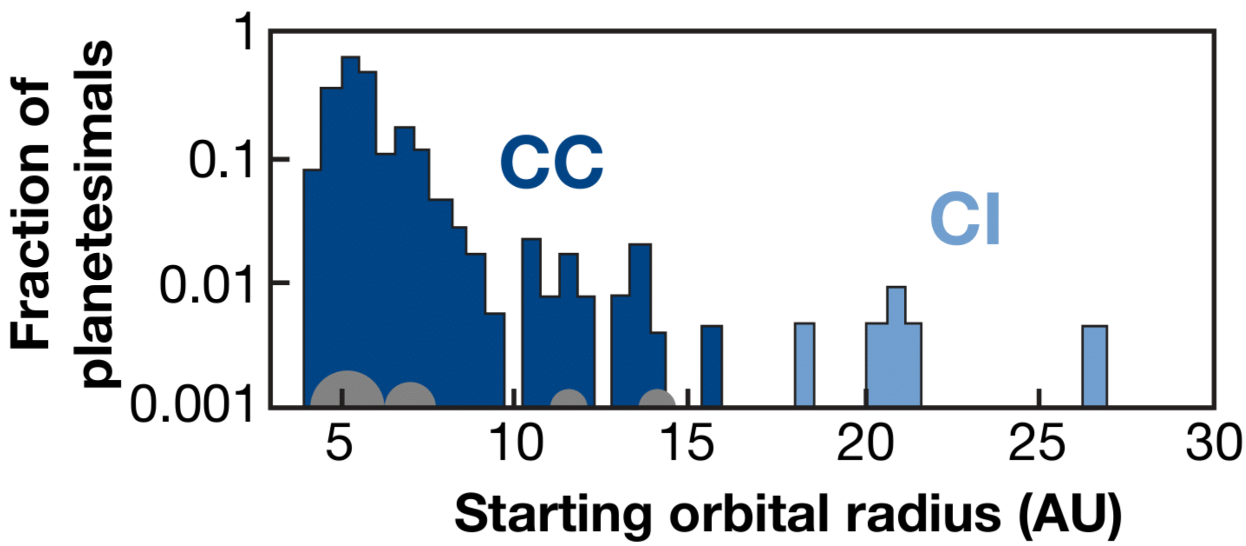

Fig. S4. Example of possible source regions for CC and CI asteroids in the Main Belt [modified from Fig. 12 of (*39*)**].** This figure depicts the fractions of asteroids from different starting orbital radii that are implanted into the Main Belt in a simulation involving the growth and migration of the gas and ice giant planets. In that simulation, Jupiter, Saturn, Uranus, and Neptune start with initial orbital radii of 10, 15, 20, and 25 AU and grow and migrate inwards on a timescale of ~2.5 Myr (*39*). As shown, the processes of planetesimal excitation by the giant planets and interaction with nebular gas leads to a far-reaching and uneven sampling of planetesimals. We speculate that CC chondrites could have formed in the birth region of Jupiter and Saturn while CI chondrites and Ryugu derived from planetesimals that could have been implanted into the Main Belt by the growth and migration of Uranus and Neptune, explaining their distinct isotopic and chemical heritage. While the fraction of planetesimals implanted into the Main Belt from the outskirts of the Solar System (e.g., CI) is small (~1% of the planetesimals located in these regions are implanted into the Main Belt), the total number of planetesimals from these regions implanted into the Main Belt can be significant if the total mass in that source region is higher. This could explain why up to 20% of carbonaceous (C-type) asteroids are of Cb-type.

Table S1: Average O, Ti, Cr, and Fe isotopic anomalies of Ryugu, meteorites, and Earth's mantle. Averages adopted from the data compilation of (*65*) and (*64*) and updated with more recently published data.

Samples	Reservoir	$\Delta^{17}O$	±	95% CI	$\mu^{50}Ti$	±	95% CI	$\mu^{54}Cr$	±	95% CI	$\mu^{54}Fe$	±	95% CI	$\mu^{58}Fe$	±	95% CI
Hayabusa2																
Ryugu A	CC		±		163	±	20	135	±	21	0	±	4	12	±	4
Ryugu C	CC		±		202	±	19	125	±	10	3	±	3	13	±	4
Ryugu Mean	CC	0.61	±	0.08	183	±	27	127	±	18	1	±	4	13	±	4
Chondrites																
CI	CC	0.39	±	0.10	189	±	15	155	±	10	2	±	3	10	±	7
CM	CC	-2.92	±	0.44	301	±	10	101	±	13	23	±	6	5	±	6
CV	CC	3.62	±	0.48	345	±	19	94	±	8	27	±	6	0	±	7
CO	CC	-4.32	±	0.26	377	±	99	77	±	33	19	±	5	1	±	2
CK	CC	-4.47	±	0.21	342	±	105	48	±	42	26	±	6		±	
CR	CC	-1.48	±	0.55	251	±	45	128	±	7	33	±	7		±	
CH	CC	-1.55		0.27				137	±	29	16	±	7	9	±	0
CB	CC				204		7	120		9						
Tagish Lake	CC	-0.91	±	0.53	276	±	26	133	±	26	16	±	5	2	±	12
Tarda	CC							122	±	10	24	±	8	3	±	12
EC	NC	-0.02	±	0.05	-20	±	8	3	±	3	6	±	1			
OC	NC	0.98	±	0.48	-66	±	6	-37	±	6	11	±	3			
R	NC	2.64	±	0.15		±		-7	±	3	6	±	1			
Achondrites/ Iron meteorites																
Diogenites	NC	-0.29	±	0.08	-123	±	5	-69	±	8	14	±	3			
Ureilites	NC	-1.16	±	0.15	-200	±	32	-90	±	4	12	±	2			
IIAB	NC							-83		17	16	±	4			
IIIAB	NC							-78		6	11	±	6			
IVA	NC							-47		6	8	±	4			
Earth's mantle		0	±	0	-2	±	3	10	±	13	0	±	1	1	±	5

Data sources: O – Data compilation of (*65*) and (*6*); Ti – (*6*, *10*, *66–70*); Cr - (*6*, *11*, *29*, *30*, *66*, *67*, *69–85*); Fe – (*22–24*, *26*).

Table S2: Fe isotopic data of samples investigated in this study. Calculated mass-independent ($\mu^{54}Fe$, $\mu^{58}Fe$) and mass-dependent ($\delta^{5X}Fe$) Fe isotopic compositions in Ryugu samples, carbonaceous chondrites, and geostandards. Uncertainties of individual samples are 95% confidence intervals of the mean of standard-sample-standard bracketing analyses (N). The chemical procedure used at Tokyo Institute of Technology is described in the Methods and (*6*). Samples processed at the University of Chicago (UofC) were digestion aliquots taken after digestion with $HF\text{-}HNO_3\text{-}HCl\text{-}HClO_4$ mixtures. Matrix aliquots containing the bulk Fe of samples processed at the Institut für Planetologie Münster (IfP) were digested $HF\text{-}HNO_3\text{-}HCl\text{-}HClO_4$ mixtures and then separated from Sr using cation exchange resin (AG50W-X8). All samples, regardless of their processing at the Tokyo Institute of Technology or Institut für Planetologie, Münster were further processed at the University of Chicago to purify Fe.*Samples for which soluble organic matter was extracted prior digestion. †Sample analyzed with XRF before digestion.

Sample	Mass digested (g)	Mass homogenized (g)	Processed?	N	$\mu^{54}Fe$	$\mu^{58}Fe$	$\delta^{56}Fe$	$\delta^{57}Fe$	$\delta^{58}Fe$
Ryugu									
A0106*	0.0146	0.0175	Fe, U (Tokyo Tech)	30	-2±5	14±14	-0.01±0.02	-0.01±0.02	0.00±0.05
A0106-A0107	0.0239	0.0289	Fe, U (Tokyo Tech)	30	2±5	10±10	-0.01±0.02	-0.02±0.03	-0.08±0.05
C0107*	0.0128	0.0174	Fe, U (Tokyo Tech)	25	4±4	15±17	-0.02±0.02	-0.03±0.03	-0.02±0.05
C0108†	0.0222	0.0333	Fe, U (Tokyo Tech)	25	2±5	11±7	0.01±0.02	0.02±0.03	0.03±0.05
CI									
Orgueil-1	0.401	1.12	Sr matrix cut (IfP)	30	2±5	12±8	-0.02±0.02	-0.02±0.03	-0.02±0.05
Orgueil-2	0.012	~0.1	Fe (UofC)	30	3±5	2±11	0.01±0.02	0.02±0.03	0.02±0.05
Orgueil-3	0.010	~0.1	Fe (UofC)	14	4±9	3±12	0.00±0.02	0.00±0.03	0.00±0.05
Orgueil-4	0.020	0.050	Fe, U (Tokyo Tech)	30	3±5	12±8	0.06±0.02	0.09±0.03	0.13±0.05
Ivuna	0.099	~0.1	Fe (UofC)	30	1±4	16±11	0.00±0.02	0.00±0.03	0.01±0.05
Alais	0.022	0.051	Fe, U (Tokyo Tech)	28	6±6	17±12	-0.02±0.02	-0.02±0.03	-0.01±0.05
CM									
Murchison-1	0.010	~0.3	Fe (UofC)	14	23±5	6±7	0.00±0.02	0.01±0.03	0.03±0.05
Murchison-2	0.025	1.65	Fe, U (Tokyo Tech)	15	18±6	2±9	0.01±0.02	0.03±0.03	0.05±0.05
Mighei	0.011	~0.1	Fe (UofC)	14	27±8	7±9	-0.01±0.02	0.00±0.03	0.01±0.05
CV									
Allende-1	0.012	~4000 (USNM)	Fe (UofC)	15	29±4	2±9	-0.02±0.02	-0.02±0.03	-0.01±0.05
Allende-2	0.514	~100 g (MS-A)	Sr matrix cut (IfP)	15	32±6	2±9	-0.05±0.02	-0.06±0.03	-0.07±0.05
Allende-3	0.025	~4000 (USNM)	Fe, U (Tokyo Tech)	15	21±7	3±12	0.08±0.02	0.13±0.03	0.18±0.05
Vigarano	0.014	~0.3	Fe (UofC)	15	29±5	-7±13	0.02±0.02	0.05±0.03	0.07±0.05
CO									
Ornans	0.041	~0.3	Fe (UofC)	15	21±5	0±8	-0.03±0.02	-0.03±0.03	-0.04±0.05
Lance	0.092	~0.5	Fe (UofC)	15	18±5	1±10	0.01±0.02	0.03±0.03	0.04±0.05
CR									
Acfer 139	0.525	0.525	Mo matrix cut (IfP)	14	38±8	9±11	-0.11±0.02	-0.15±0.03	-0.17±0.05
GRA 06100	0.281	0.281	Sr matrix cut (IfP)	15	39±5	9±6	0.00±0.02	0.02±0.03	0.04±0.05
Ungrouped									
Tagish Lake-1	0.486	1.5	Sr matrix cut (IfP)	15	18±7	2±14	-0.03±0.02	-0.04±0.03	-0.04±0.05
Tagish Lake-2	0.025	1.06	Fe, U (Tokyo Tech)	15	15±6	2±22	0.05±0.02	0.08±0.03	0.11±0.05
Tarda	0.025	0.212	Fe, U (Tokyo Tech)	30	24±8	3±12	-0.01±0.02	0.00±0.03	0.01±0.05
Geostandard									
BHVO-2-1	0.012	-	Fe (UofC)	15	1±7	-9±8	0.09±0.02	0.14±0.03	0.18±0.05
BHVO-2-2	0.010	-	Fe (UofC)	15	1±7	-1±11	0.06±0.02	0.10±0.03	0.13±0.05
AGV-2	0.012	-	Fe (UofC)	30	2±4	1±6	0.08±0.02	0.13±0.03	0.16±0.05

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