

Genome of Melody: Applying bioinformatics to study the evolution of Gregorian chant

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Abstract

Gregorian chant was a central musical tradition in Medieval Latin Europe and one of the expressions of its cultural unity: any Latin Christian liturgy, such as the weekly Sunday mass, would have involved Gregorian chant as a major part of the prescribed ritual. The Gregorian legend of chant melodies’ divine origin required the practitioners to conserve them, to the extent that this requirement motivated the development of exact pitch notation. Nevertheless, surviving written sources document a considerable melodic diversity. Some systematic patterns within this melodic diversity have previously been observed in chant scholarship, especially during efforts to build a critical edition reconstructing the earliest possible forms of chant melodies with philological approaches. Taking an evolutionary perspective, we notice analogies between biological evolution and processes of chant transmission, which lead us to suggest recovering these “melodic dialects” using phylogenetic methods instead. In this paper, we show that phylogenetic models recover historically plausible patterns of chant melody evolution. We observe that some, but not all, institutional networks play a more important role than geographic proximity. Phylogeny is shown to be a viable class of methods for studying chant melody, and we discuss next steps for a more comprehensive evolutionary approach to chant.

1 Introduction

Gregorian chant is the universal liturgical vocal monody¹ of the Latin church,² an essential part of Western music history, and a dominant musical tradition in Latin Europe, as well as an expression of its religious and political unity. It is a musical tradition that is highly regulated by the institutions of the Roman Church: each day of the year has an assigned set of chants to be sung at specific points of the liturgies of that day. The Roman rite (and its variants in the Latin church) defines positions in liturgy for more than 3,000 such units of chant repertoire in the liturgical calendar.

The moniker “Gregorian” comes from the legend of pope Gregory I., who supposedly dictated Gregorian repertoire as sung to him by a dove of the Holy Spirit. Current historical understanding is that Gregory I. had little to do with this music: rather, its origins and rise have to do with the establishment of the Frankish empire under Pepin III. and especially Charlemagne, in the late 8th and early 9th century (1; 2, pp.514-520). The legend of the divine origin of Gregorian chant, including its melodies, obligated practitioners to perform chant faithfully to this implied “original” (2, pp.510-511).³ A significant effort was expended to conserve chant: both in rules for the institutional practice of the *schola cantorum* model, where a selected member of the given community had the responsibility to teach new members the repertoire and correct deviations (2, pp.39-40),⁴ and in the production

¹Music written for only a single voice.

²Today specifically the Roman Catholic church, after the differentiation of Christian churches through various reform movements.

³This differentiates the Gregorian tradition from many other liturgical monodies: e.g., from Greek Catholic chant, which allows for matching melodic patterns more closely to different pronunciations of its language, Church Slavonic, depending on the native language of the singers. (From personal communication with Greek Catholic chant singers.)

⁴For instance, the abbot William of Dijon (961–1031 AD) is reported by his biographer Rodulphus Glaber to have “corrected and emended all that was sung by his choirs during the night or the day...” (3).

of liturgical books with notated melodies, at significant expense (4, p.412). Conserving Gregorian melodies in fact even motivated development of a major feature of modern music notation: the staff, an 11th-century innovation of Guido of Arezzo, which allowed notating pitches exactly and thus enabled learning the melodies without a teacher present (5, p.228).

Yet in this era of chant manuscript tradition between approx. 800 and 1600 AD, one rarely finds the melody of a chant recorded as exactly the same sequence of pitches in any two different sources. The Gregorian melodies spanning all of Latin Europe for the better part of a millennium were – despite the conservation pressure and resources allocated for conservation – diverse. This diversification of chant (together with the diversification of liturgy) went so far that the Council of Trent (1545–1563) decided to drastically limit permissible local liturgical specifics, and a major part of this effort was creating a new edition of Gregorian chant for this (re-)unified Roman rite: the so-called ‘Medicean Gradual’ (1608-1614) (2, pp.614-618), printed and massively distributed, ending the dominance of manuscripts for transmitting and conserving chant.

There are long-open questions in chant scholarship about the nature of this diversity within the medieval Gregorian melodies (6; 7; 8; 9; 10; 2; 11). It could be an effect of randomness in the imperfect transmission processes (memorization, manuscript copying, as well as musical dictation (12)), especially as memorization was key to transmitting Gregorian chant at least until the invention of exact pitch notation on the staff in the 11th century (2, pp.466-470). Scribal errors did happen, and given the authority of written sources and their use in learning chant, such error could propagate. However, one should not underestimate capacity of medieval memorization practices (13; 14) to retain and transmit a fixed melody, especially with adialematic notation (neumes, see 1a) serving as mnemonic signs. Froger argues that outright mistakes would likely be corrected by later scribes (15); the lessons from building a large-scale critical edition of chant at the Solesmes monastery indicate that the stemmatological perspective of “mistakes” should be superseded by a perspective of “acceptable variants” (15; 16, p.54).

What, then, are these “acceptable variants”? Traditions have been observed in *repertoire* choices for individual feasts (17; 18), but in melodies, this has not been systematically reported so far beyond strong (though not quantitative) evidence of a split between “Germanic” or “East Frankish” vs. “French” or “West Frankish” melodies (8). The adoption of repertoire from a different community of practitioners does not necessarily imply the adoption of corresponding melodies in the dialect of that source community: this can be a complicated, diverse relationship.⁵

This is our central research question: did “melodic dialects” of Gregorian chant exist? Are the observed differences between melodies of the multiple written versions of same chants systematic? That is, has Gregorian melody diversified in the period of manuscript chant culture in ways that have correlates in chronology, geography, or the specific institutional contexts (individual monastic orders, dioceses and their cathedrals, and other ecclesiastical communities)? Then, if significant melodic dialects are observed, they can inform us about relative significance of the factors shaping chant transmission.

Addressing such questions with computational models at scale is possible using digital chant scholarship resources, most notably the Cantus database, Cantus Index (20; 21), and its broader digital ecosystem (i.e., the DACT project⁶, SIMSSA Cantus Ultim⁷), as well as other digital chant scholarship projects (Corpus Monodicum⁸, ECHOES⁹). These databases contain more than 20,000 fully transcribed chant melodies, and thus seem promising for quantitative approaches. Descriptive statistics have of course been extracted from the Cantus Database (20), including dendrograms for visualizing the relationship between sources in terms of repertoire, but not yet for melodies (and in any case, hierarchical clustering methods merely aggregate by some distance without explicitly determining which clusters are in fact meaningfully different from each other). While multiple works have focused on computational investigation of chant modality (22; 23; 24; 25; 26), and on relating Gregorian chant to other European liturgical monodies (27; 28), these have not yet addressed the question of multiple Gregorian versions of one melody ((22) acknowledges it as an issue).

We notice that Gregorian chant and its history have some properties remarkably analogous to building blocks of evolutionary genetics.

- **Sequences.** Melodies are sequences of pitches from a limited alphabet (ca. 20 elements) defined by medieval music theory and remaining stable over the applicable time period (5).
- **Homology.** The tradition of Gregorian chant is organized into several thousand units of repertoire, each

⁵This is documented for example by the reception of Easton’s version of a new office for the 14th century feast Visitation of Mary (19). The new chant was a (complex) contrafact of an existing Franciscan office, and different communities used different underlying Franciscan office melodies with the text.

⁶<https://dact-chant.ca/>

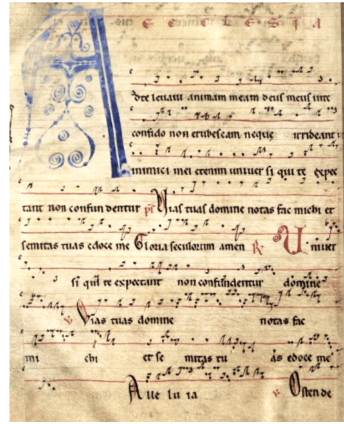
⁷<https://cantus.simssa.ca/>

⁸<https://corpus-monodicum.de/>

⁹<https://echoes.fcsh.unl.pt/>



(a) Liber passionalis, D-B. Ms. Phill. 1790, f.92v. The leaf may be an insert from a graduale, since there are no other chants recorded within the manuscript.



(b) Cistercian graduale from the diocese of Milan, F-Pn : NAL 01414, f.1v.



(c) Graduale des Johannes von Valkenburg, D-KNd Ms 1001b, f.3r.

Figure 1: Homology in chant. Three instances of the mass introit *Ad te levavi animam meam*, which the Roman rite assigns for the mass on the first day of the liturgical year: the first Sunday of Advent. Thus its initial “A” is often heavily ornamented. After the introit are written the chants that follow in the mass. Example (a) is earliest, from the 9th or 10th century, and uses adiastematic notation that records only the approximate contour of the melody, and is thus just a memory aid. Example (b) is from the 12th century, already with an earlier form of diastematic notation that uses the staff to record pitch exactly. Example (c) is a late medieval source, with yet more readable square notation. In the Cantus database, the catalogues for all three sources would contain a record with the Cantus ID g00489, corresponding to instances of the *Ad te levavi* “gene of chant”.

defined by both its fixed text and melody (2, pp.1–45). This allows identifying homology between chants in different chant books. An example of one chant written in three different books is given in Fig. 1.

- **Fixity.** The Gregorian legend of the divine origin of chant obligated practitioners to *not* innovate (2, p.628). Compared to other oral traditions, both musical and e.g. storytelling (11), the desirable level of variation in the sequence of pitches sung in Gregorian chant was zero. This still allowed for variation in performance practices, most importantly timing and improvised polyphony, but the melodies themselves were supposed to be kept exactly as one received them from a teacher (and as one could verify against a liturgical book, once diastematic notation became available).¹⁰
- **Inheritance** was the predominant transmission mechanism. As chant was sung by the clerical class (who were bound to celibacy and thus not able to raise children), it was transmitted obliquely: taught in highly formalized hierarchical institutions (schools or monasteries), with one *cantor* in charge of teaching and enforcing the correct melodies, texts, and their placement in liturgy (2, pp.39-40). Chant books were either copied from an exemplar, written from expert memory, dictated – sung – by an expert singer for an expert scribe, or a combination thereof. While the personal histories of cantors may lead to some reticulation, and travel was not rare for members the clerical class, to re-learn the melodies from one’s original environment would require a serious commitment to a new ecclesiastical community, which seems to have been rare enough to not undermine the predominance of inheritance-like transmission of chant melody. (2; 12; 19; 1; 30; 31; 32; 13; 14)
- **Differentiation.** Europe’s population grew until the Black Death in the 14th century, which is reflected also in the production of manuscripts (33). Church structures had an organisational capacity for how many people they could serve at each level of the hierarchy (parish, diocese, archdiocese). Hence, these levels of hierarchy would be split: new parishes with smaller areas of responsibility created from bigger ones, dioceses being split into several new ones, with the original perhaps being elevated to arch-bishopric; monasteries would “spin off” daughter houses. Each new site where liturgy was performed required chant books. Thus, there was opportunity for speciation – within a hierarchical framework that assigned a clear “ancestral environment” to the new organisational unit (2, p.564).

¹⁰Even the early 15th century Hussite reformers, who translated liturgy into vernacular in the Jistebnice Cantional (Cz-Pn II C 7), maintained melodies without modification, at the cost of unwieldy lexical and text underlay choices (29).

- **Common ancestor.** There is a known community of practitioners that would serve as a historical common ancestor to Gregorian chant sources: the city of Metz in the Carolingian period (ca. 800 AD), where chant practices from Rome were brought, adapted for the needs of the new Frankish empire, codified, and transmitted outwards to the rest of the empire (34; 15; 1; 16; 2, p.513).

Given these conditions, we attempt to address the research question with a phylogenetic model.

Furthermore, using Divergence Time Estimation (DTE), one can advance past the description of melodic dialects within “clades” of a tree into modelling their *history*, with probability distributions over dates for the inferred ancestral sources (or, more accurately, ancestral communities of chant practitioners that produced these written sources). This would allow for cross-referencing predicted points of melodic divergence against specific historical environments, also to assess the plausibility of the inferred phylogeny.

A phylogenetic model of course oversimplifies actual history. The role of horizontal transmission in the evolution of culture is generally established (35). Reticulate evolution did happen, to some extent: scribes could work from multiple exemplars, or sources could have been brought to a different place and “hybridized” by some editorial process. However, based on existing chant scholarship, we believe inheritance is *predominant*, and phylogenies can be reconstructed even with significant rates of reticulation (36).

In the taxonomy of CE and the humanities of (37), our work falls into the category of using models and methods from evolutionary biology to understand culture, in this case specifically the tradition of Gregorian chant melodies. By extrapolating from processes of transmission and selection at the individual level to “population-wide models of cultural diversity and change” (38), CE informs the choice of model based on existing music-historical knowledge. In the absence – or abundance that is overwhelming for music-historical methods (16) – of material evidence, one has nothing but a guess: CE is a principled framework for designing a *best* guess (and, with probabilistic models, one that transparently quantifies its uncertainty).

The evolutionary perspective is not new in music (39). There was the Cantometrics project (40; 41), which proposed a high-level evolutionary tree of folk music worldwide. Bioinformatics tools have been used to characterize diversity in Japanese vs. English and US folk melodies directly (42), or in electronic music (43), Billboard-100 songs have been studied using methods from evolutionary cancer genomics reformulated as a variational autoencoder (44). A phylogeny of Gabon musical patrimonies has been proposed (45), which highlighted the role of vertical transmission, compared to the importance of lateral transmission in evolutionary linguistics (35), though phylogenetic models have been found to be resistant to some levels of borrowing (36) and remain prominent in linguistics (46). However, the focus has been living musical practices (39; 42; 45) and ethnographic records (47). An analogous ethnomusicological perspective can justifiably be applied to chant (48), but as the material is historical, it requires a different combination of methods, perhaps closer to CE applications on archaeological data, such as Palaeolithic artifacts (49). Instead of field research and recording, we draw on synthesis of source criticism from historical musicology to inform our understanding of chant practices and transmission patterns. CE theory then translates this knowledge into a model of chant melody development, implemented with computational biology tools, and to interpret the results, historical disciplines – codicology, musicology and history more broadly – are applied again.¹¹ The closest computational humanities work in spirit, analogous in going where philological methods cannot by reasoning about unavailable sources with computational models, is using an ecological model estimating to estimate loss of diversity in Arthurian romances (50).

This paper is an exploratory study of whether the analogies between chant and biological evolution can be operationalised using phylogenetics at all. Is there phylogenetic signal, and does it have interpretable historical correlates? We do not (yet) aim to explain *why* melodies differentiated, if they did. It may reflect regional musical aesthetics, but an imperfect process of correcting scribal errors may lead to “accidental” melodic dialects taking hold as well. However, regardless of the mechanism by which melodic dialects arise, identifying and modelling their development is already a valuable contribution of CE to musicology.

¹¹Our research is not entirely without a link to the present. Gregorian chant is still a living practice – besides monastic communities, many parishes have a *schola* of the laity (non-clerics) performing chant for liturgy even though it is no longer actively promoted by the Roman Catholic church, and this application of CE can help such communities of practitioners understand their specific, local musical heritage within the context of the “global” practice, e.g. by contributing transcriptions of manuscripts coming from their particular church. This promotes survival of chant as an element of cultural diversity underneath a dominant layer of globalised popular culture. Some examples of communities in the present that are singing from their local sources are in Kiedrich, Germany (<https://www.kiedricher-chorbuben.de/index.php/musik/choral>), and at the Fu Jen University in Taiwan (<https://www.youtube.com/@vincentlebbechants>).

2 Materials and Methods

We use two datasets of chant melodies: the **Christmas** dataset, and the **Introits** dataset. Both datasets were manually transcribed by experts according to Cantus rules (51) from scans of the liturgical books. Historical metadata for the liturgical books – century of origin, place of origin (provenance), and *cursus* (the institutional context within the church) – were available through Cantus Index. In both cases, quality assurance was performed: a second expert checked all transcriptions. Details on the data acquisition process are given in supplementary materials.

The larger CantusCorpus v0.2 dataset (23) was found unsuitable for this study. While it contains over 20,000 melodies for the divine office and over 2000 for mass, these come from complete transcriptions of all melodies in only a few sources, and we found the office repertoire in its selected sources so diverse that no significant set of antiphons was homologous across the sources with melodies transcribed. In contrast, we need only a small selection of melodies per source, but coming from as diverse a selection of sources as possible.

2.1 The Christmas Eve Vespers Dataset

The Christmas dataset consists of 72 melodies for the liturgy of Christmas Eve vespers, part of the divine office, across 14 sources¹² with six (in some cases five) homologous melodies each. There are 5367 transcribed pitches in total, for an average of 383,4 per source. This was a pre-existing dataset and the largest available dataset of fully transcribed homologous melodies, and has already been introduced in pilot experiments with chant phylogeny (52).

The selection of sources is, fortunately, diverse: two secular French, three Cistercian, three Benedictine, one Augustinian, a secular source from the Low Countries, and a set of later secular sources from Bohemia. For each source, we briefly report its century of origin, its provenance, and which ecclesiastical institution it belonged to, as well as on the level of uncertainty associated with these properties in current chant scholarship, in supplementary materials.

2.2 The Introits dataset

The Introit is the first chant of mass. Its typical structure is an antiphonal part, a verse intoned on a simple psalmodic tone, a doxology on the same tone, and the antiphonal part is then repeated. Being the first part of mass, introits are prominent markers of the ritual identity of their assigned days and feasts: many Sundays of the year would be referred to according to the first words of their assigned introit (the “Estomihi” Sunday before the start of Lent, or the “Gaudete” Sunday in Advent that is further unique by use of pink as the colour of liturgical vestments). The introits are a “public face of chant”.

Furthermore, mass repertoire is less varied than office repertoire. This improves the chance of finding among the catalogued sources a sufficiently large set of sources with homologues that is at the same time sufficiently diverse to address our research questions. Furthermore, introit repertoire is known to have been stable since the Carolingian transmission (2, p. 518), so we can assume that homologues of introits would have existed at each of the inferred ancestral nodes.

The Introits dataset contains melodies of the leading antiphonal part of the introit. We restrict ourselves to sources that have already been catalogued in the Cantus network, with homology thus already resolved via the assignment of Cantus IDs to chants. The melodies were then transcribed by chant specialists. The dataset consists of 560 melodies across 28 sources, with 56011 transcribed pitches in total (an average of 2000,4 positions per source). More detailed information is again given in supplementary materials.

2.3 Methods

With the exception of (42), works on musical phylogenies extract features from their melodies that are known from other literature to be salient for the research questions posed. However, for chant melody (as opposed to later European tonal music), such features are not known yet. Computational work on chant melody has so far tried finding as features some building blocks of melody (22; 23; 53; 25; 24), but despite indications of the formulaic nature of parts of chant repertoire (54; 55), these experiments have not yet led to a satisfactory theory of chant

¹²As is usual in historical scholarship, we identify sources by their *siglum*: a unique identifier according to the RISM standard (<https://rism.online>), for example: A-VOR Cod. 259/I. The first part of the siglum is the country and holding institution: “A” stands for Austria, “VOR” is the code of the Vorau monastery library. The second part identifies the source within the collections of that institution, according to their own cataloguing system: “Cod. 259/I” identifies the source as codex (implying the bound manuscripts collection of the library) number 259, part 1.

melody. Thus, we use the chant melodies directly. Fortunately, this is feasible for Gregorian chant, as opposed to e.g. a cross-cultural comparison of folksong: the rigidity of chant repertoire means sets of homologous melodies can be clearly identified, and this has already been done for many sources by assigning Cantus IDs through Cantus Index (21).

We treat melody as a sequence of pitches. We retain absolute pitch values rather than transposing everything to start from the same tone. This retains modal quality (placement of semitones relative to reciting tone/final/initial), and in any case homologous melodies are overwhelmingly in the same mode. Based on the findings of (15), we decided to not differentiate between B and B flat for now, because of the ambiguities involved. We also do not retain neume, syllable, and word separators, even though they are encoded in the Volpiano standard (51), because the extent to which text and melody interact is not at all clear (16; 24, pp.43–48).

Previous contributions have provided us with both tools and approaches for applying Bayesian phylogenetics to chant data (52; 56). We follow the analytical strategy of (56), adding a larger datasets of introits. The analytical procedure involves using multiple sequence alignment with MAFFT v7.505 (57) for generating data matrices to be used in inference of Bayesian phylogenetic trees. The posterior sample of trees calculated with `mrBayes_volpiano` (52) is then used to generate a summary maximum credibility tree with `treeannotator` (58). Tree formatting is carried out with `phyx` (59).

While tree topology already provides some insight into the development of chant melody, it has no chronology and therefore no music-historical interpretation. But, we assign to all inferred internal nodes a distribution in time, therefore making predictions that can then be verified against music-historical knowledge and provide new insights as well. First, iterative rerooting generates a collection of rooted trees, which are used in Bayesian model selection to recover the most reasonable positions for the root. Once with a rooted topology, we use divergence time estimation for converting the branches from conflation of rate and time into time and evolutionary rate.

There is no obvious way to root a Gregorian chant phylogeny as it appeared as a unique event in time with no sisters that we can explicitly use in phylogenetic analysis. A good choice would be Old Roman chant, but its evolutionary relationship to Gregorian repertoire is unclear (2, pp.530-539) – the Old Roman melodies, which we have from 11th-century and later sources, may in fact result from an imposition of Gregorian tradition on top of an earlier Roman one (60; 1; 61), and while this is disputed (62), the relative history of Old Roman and Gregorian is not clear enough to use Old Roman melodies simply as an outgroup. Without an outgroup, we can at least consider the root position as a fixed model and then calculate the marginal likelihood using stepping stones under a Bayesian framework (63). Generation of all possible rooted trees on the MCC tree was carried out using `ape` (64) and `phytools` (65) in R v.4.3 (66). We applied stepping stones in `mrBayes_volpiano` with 50 stones and 1,000,000 generations sampling every 100th generation. The marginal likelihood was then used for calculating BF and model PP in R.

Divergence time estimation was carried out with `mrBayes_volpiano` using the Mk model with inverse-gamma rates (67). The rooted tree topology was fixed. The clock model was set to independent gamma rates (68) and an Exponential(2) prior used for the variance whereas an Exponential(5) prior was used for the clock rate. The FBD parameter priors were set to uniform(0,10) for the speciation rate, and Beta(1,1) for both the extinction and fossilisation rates. Calibration densities were specified as in Table 5. Parallel-tempering MCMC (69) was used with eight chains, one cold and seven hot, with a temperature of 0.001. MCMC sampling was carried out with 10,000,000 generations, sampling every 1,000. Posterior summarisation used a burn-in of 10%. All parameters attained effective sample size (ESS) > 500, indicating an appropriate sampling of the parameter posterior distributions. Time tree plotting (Figure 6) was carried out in `figtree` (70). The pipeline is shown in Fig. 2.

2.4 Code and data availability

All code and data necessary for reproducing the results are available on GitHub (https://github.com/Genome-of-Melody/divtime_christmas and https://github.com/Genome-of-Melody/genome_of_melody_paper) as well as on Zenodo (DOIs <https://doi.org/10.5281/zenodo.13344525> and <https://doi.org/10.5281/zenodo.14768498>). The `mrBayes_volpiano` software is available at https://github.com/gaballench/mrBayes_volpiano.

3 Results

3.1 Phylogenetic tree topology

What chant sources are grouped together, and how strongly? If there were no systematic melodic dialects, or if horizontal transmission had an effect as strong or stronger than “melody inheritance” via the mechanisms discussed

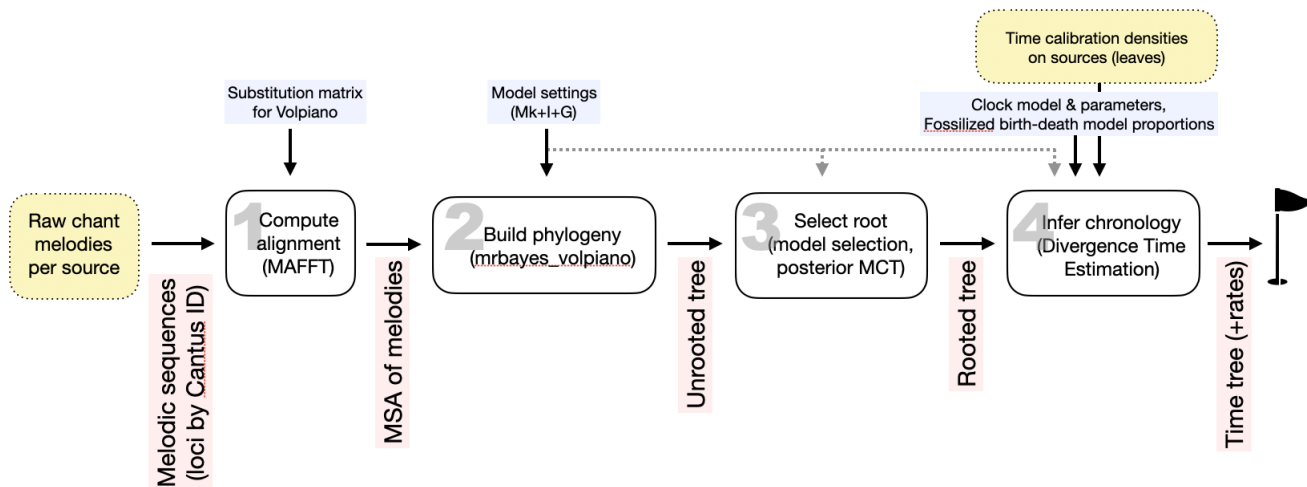


Figure 2: Overview of the methods, from alignment to a time tree. Externally provided data is highlighted in yellow, parameters in blue, artefacts at intermediate steps in red. These steps start from several sets of homologous melodies, proceed through alignment to unrooted phylogeny, and root selection and divergence time estimation assign a distribution in time to inferred nodes, therefore making it possible to interpret the tree against specific music-historical knowledge.

in 1, we would expect a poorly resolved tree, with clades not corresponding to discernible historical patterns. On the other hand, if significant melodic dialects do exist, we should see clades that have a clear interpretation – whether geographical, institutional, or other types of shared histories.

3.1.1 Christmas Dataset

The topology of the phylogeny on the Christmas dataset follows the same contours of geography and *cursus* as the phylogeny of (52). This is expected, as the alignment is similar and the tree inference methods are same. There is a distinct French and Cistercian branch (given that the Cistercians originated in France, this is not surprising), then a geographical gradient towards the group of secular Bohemian sources (CZ and A-VOR), with a monastic group of Benedictine and Augustinian sources (CZ-Pu I D 20, D-KA Aug. LX, and CH-E 611). However, as the dataset has been cleaned better, there are a few changes in the topology and the historical Augustinian link from (52) between CZ-Pu I D 20 and A-VOR 259 I is not replicated.

3.1.2 Introits dataset

On the Introits dataset, a clear “German” clade of the tree east of the Rhine is inferred, a different clade consists exclusively of Cistercian sources, and within the “non-German” portion of the tree two Italian and one German Franciscan source are in a common clade. Sources in the north of France and south of France are also in separate clades, though one internal node of the southern branch only has a posterior probability of 0.64, and the small “Parisian” (?) clade in the middle is connected with the Italian/Franciscan branch. The internal nodes that separate these clades have posterior probabilities significantly lower than 1, so a different sampling of French sources would likely produce a different sub-structure for the region.

Note that this is *not* a time tree: one cannot interpret the pattern from the “most internal node” towards the tips as the flow of differentiation in time until a root is selected.

3.2 Evolution of melodies in time: DTE

3.2.1 Christmas dataset

Root position. A single rooted tree was found to be the best one (model PP = 0.75) and used for subsequent analysis. Model selection recovered the root position so that the highest-level clades correspond to French and Cistercian sources, and (non-Cistercian) sources coming from east of the river Rhine in the other clade (Figure 5a). The Cistercian order was founded at Citeaux, in France, and the order was strict about maintaining this lineage

also for chant books (71). This corresponds exactly to existing hypotheses about the distinct “west Frankish” and “east Frankish” chant melodic dialects (8).

Temporal information. The inferred times for ancestral nodes are shown in Fig. 6. The speciation times are generally historically plausible.

3.2.2 Introits dataset

Root position. Two possible root positions with similar likelihoods were found: nodes 18 and 24 (see Fig. 5b). Both lie in the “French” part of the tree, and both are unsatisfactory from a musicological perspective: Branch 24 (the 2nd most likely, at approx. $P = 0.42$) separates two sources (Paris and Chartres, both 13th century); no explanation for why these sources should have lineage distinct from all others exists in current chant scholarship. Branch 18, which is most likely (at $P = 0.52$), separates the tree into one high-level clade that combines this pair of sources with the Italian/Franciscan clade. This would be interpreted either analogously to Branch 24 as the sources from Brescia being copied from an early Metz exemplar but with the same reading of the melody as the small “Parisian” clade, or one would have to accept the existence of a Roman source of chant that pre-dates all known notated sources that had retained a notated Gregorian repertoire, a descendant of this source being brought to Metz as part of the Carolingian transmission event, and the Paris and Chartres sources being copied rather from some previous source, perhaps descended from this hypothetical exemplar still in Italy. This construction would again contradict what is known about the process of Gregorian chant creation (2; 1). Hence, we believe these root positions to be implausible. It is possible that these issues are a result of over-resolution among branches 7, 17–19, 24, and 27–29. This is the only part of the tree where posterior probabilities of the internal nodes are below 0.9.

The choice that would best fit historically would again be the Rhine. In this case, the Dutch source NL-Uu Hs.415 lies in the western part: it is from the French-speaking diocese of Liège. This is congruent with the evolutionary distance being greater from the ancestor of NL-Uu Hs.415 to the German clade node than to the French clade node. For DTE, we therefore also root at edge 4 instead, with the knowledge that on the Introits dataset, as opposed to Christmas, model selection method behaved in a faulty manner.

Temporal information. The DTE result for both the automatic and musicological root position have, again, issues. The automatic root position leads to a tree that compresses the available time range for the branch that “crosses the Rhine” (between NL-Uu Ms. 0415 and eastern sources to just 100-150 years, while this branch has the greatest evolutionary distance in the topology, leading to an exceptionally high rate of change (over 8.6; the highest observed rate of change on Christmas was below 2.0) and to placing the time of transmission of Gregorian melodies to German-speaking lands after the year 1000 (see Fig. 7a). This is highly unlikely, as it would imply that the earlier adiastematic sources east of the Rhine recorded a melodic dialect that was supplanted with a new one coming over the Rhine after 1000 – which was nevertheless subsequently modified so strongly that the branch exhibits this extreme rate of change; there is currently no historical evidence for this.

The musicologically motivated root placement onto the Rhine-crossing branch avoids this particular issue (see fig. 7b), but introduces another extreme rate of change, this time on the Italian/Franciscan clade. The “middle source” in terms of time (N19) has an earlier common ancestor with the much *later* source N5, rather than the *earlier* N20 (note that all the nodes in the topology were resolved with a probability of 1, and the evolutionary distances on this clade are above-average). Why would an early source be so heavily modified for the city, but in a direction that does not match anything else in the dataset closer than the much later Franciscan source?

The time distributions for individual nodes also come with higher variances than for Christmas.

4 Discussion

The experiments on the Christmas and Introits dataset provide predictions that can be directly verified against musicological, codicological, or historical knowledge. In this section, we discuss a selection of these predictions in light of what is known from music history.

Geography as the most influential factor. Out of the three expected major factors along which melodic dialects might form (chronology, geography, and *cursus*), geography exerted the greatest influence. This agrees with observations from the critical edition of chant built at Solesmes, which observed geographical groups (15), finer-grained than the East Frankish – West Frankish split (8), though it is partly based on visual properties of various adiastematic notations rather than on the (ambiguous) melodies written as such. The hierarchical structure of geographically defined parishes, dioceses, and archdioceses does imply inheritance along geographical lines, and except for the Cistercians, the melodies of other continent-spanning institutions (Canons Regular and Augustinians,

who both follow the rule of St. Augustine, and Benedictines) also do not exhibit melodic identity that would overcome the influence of physical distance.

Cistercians sources. For Cistercians, their institutional identity dominates physical proximity. The order maintained strict discipline in copying liturgical books (34, p.69), mandating that all monasteries’ books must be identical (71, p. 99). A part of the Cistercian “master exemplar” survives (2, p. 322).¹³ This institutional focus is already reflected in the topology inferred in (52) on the Christmas dataset, and it is replicated in our topologies as well in both Christmas and Introits data. Additionally, the DTE step of our pipeline provides an explicit time for the common ancestor of Cistercian sources: the median falls on the year 1150 (see Fig. 6), which coincides with the reform of the antiphonary initiated by St. Bernard of Clairvaux before 1147 (72). Drafts of the Bernardine liturgy are found in the 12A-B Westmalle Antiphonary, dating from 1140-1143 (73). This agreement between the estimated median age of the common ancestor of Cistercian sources in the tree and the historical record is notable, though the 95 % credibility interval covers a broad range of 1075–1210.

In the Introits data, the Cistercian root is estimated earlier, around 1050 in tree 18 (Fig. 7a) and 1100 in tree 4 (Fig. 7b). The date 1050 is implausible because the Cistercian order was not founded until 1098. The first edition of a Cistercian graduale was completed in the first years of Stephen Harding as abbot of Citeaux (1109–1133) by copying an exemplar from the abbey of St. Vincent or St. Arnault of Metz (74; 71, p.37–38). However, this was superseded by Bernard’s reform that involved the graduale as well as the antiphoner and focused on melodies (71, p. 73). This is the clearest signal that even with the root selected musicologically, the clock model needs more experiments for calibration. It is possible that the office and mass liturgies will require different priors each.

In comparison, the sources of the earlier Benedictine order, which did not mandate such strict procedures for copying chant books (34, p.69), are distributed in the phylogeny according to geography, rather than showing institutional melodic identity.

Aquileia is legitimately East Frankish. V-CBav Ross.0076, an Italian source in the Introits dataset, is in the “German” part of the tree, while the two other Italian sources, from Brescia, are not (see Fig. 4). This does have a historical correlate: throughout the 13th century, Aquileia, the provenance of V-CBav Ross.0076, was ruled by a dynasty from Bavaria, and already in the 11th century clerics from Augsburg were appointed to leadership positions (2, p.585). Even though it is across the Alps from southern Germany to Aquileia, the power structure is more influential than relative ease of travel to e.g. Venice. This suggests one can perhaps use chant melody – a remarkably homogeneous tradition across all of the Middle Ages in Latin Europe – to also study medieval power structures, corroborating previous results on early trope repertoire (75).

The lively history of Brescia. The Italian/Franciscan clade in the Introits dataset shows a tree structure not easily reconciled with the temporal order of the tips. The three sources on this clade are ordered N20--N19--N5 from oldest to youngest, but its topology is (N19, (N20, N5)), placing the middle source “out of order” and leaving a large gap in time between adjacent N20 and N5 (see Fig. 7b). The topology inference step does not take temporal information into account – it is driven purely by the melodies themselves – and it is entirely possible that N20 and N5 are indeed melodically related closer. A look at the city’s history, however, reveals that in the early 12th century the city was site of a major conflict with an ecclesiastical dimension: the revolt of Arnold of Brescia, of the Canons Regular at San Pietro in the Italian city.¹⁴ It is not entirely implausible that afterwards, the Canons Regular community would undergo some reorganization that may have involved obtaining new liturgical books from elsewhere — or that conversely Arnold himself brought some from his stay in France around 1115: he was a colleague and supporter of the 12th century intellectual Abelard, who was active in the St. Victor house of Canons Regular (which is the provenance of source N10, sharing a common ancestor – albeit with the lowest posterior probability in the tree, of only 0.54 (see Fig. 4 – with the Italian/Franciscan clade). It is thus possible that there were two different transmission of Gregorian melody from France to Brescia, but because the presumably later Canons Regular book was likely transmitted with fewer opportunities for modification, speculatively thanks to the personal travels of Arnold providing an exemplar, and in any case likely made smoother by the institutional network of the Canons Regular, its melodies are closer to those of the French environment, and thus its common ancestor with the other Italian/Franciscan sources is “higher up” the topology even though it was transmitted later than N20. While speculative, this does show a limit of the non-reticulate phylogenetic tree model in relation already to medieval society.

However, it also indicates¹⁵ that unexpected phenomena in the phylogenetic model correlate with stand-out

¹³France, Dijon, Bibliothèque municipale 114 (0082). See: <https://arca.irht.cnrs.fr/ark:/63955/md88cf95jn5g>.

¹⁴The full story of Arnold of Brescia ((76); for a summary, see e.g. <https://www.newadvent.org/cathen/01747b.htm>) is a fascinating tale that, while hitting the limits of 12th century source material from conflict-prone Northern Italy, would easily make for multiple seasons of a TV series. It includes Arnold’s revolt in Brescia, exile across France, Bohemia, and a penitent return to Italy – and then one-upping the Brescia revolt by blocking the Pope himself from accessing Rome in the 1150s.

¹⁵As was also the case of A-VOR Cod. 259/I (56).

historical events even though perhaps not as straightforwardly as the phylogenetic model would itself indicate. Not only does the model seem useful despite being wrong; to our considerable surprise, it is apparently useful by *where* it is wrong.

4.1 Future work

The time tree results on Introits have shown limitations of the method. The issues with recovering plausible ancestor times may indicate that the DTE priors we used are not suitable for chant transmission patterns. Simulation studies will be needed to determine what models of variation in the rate of change correspond to observed data, and what the appropriate priors for the birth/death process are. And while recovering a historically plausible model with just phylogenetic trees on the Christmas dataset hints that horizontal transmission is not necessarily a defining feature of evolution of *all* cultural traditions, the timeline discrepancies in the Introits dataset shows that reticulations perhaps cannot be ignored entirely. Further historical study is needed to understand the extent of reticulations in the manuscripts' histories before an appropriate model and hyperparameters can be found, in combination with simulations as in (77). On the musicological side, possible differences in transmission behaviours between office and mass chants should be investigated.

Once conditions are known under which plausible – and, when verifiable, accurate – histories are recovered, the method could be applied to existing open problems in chant transmission, such as the issue of transmission of the “Germanic” melodic dialect (10, pp.116-117). The fact that DTE predict a slightly earlier common ancestor for the east Frankish sources on Christmas may be a part of the discussion, although more sources in the dataset are needed to try and narrow the time ranges down. Similarly, given an encoding of melodies from Old Roman sources, this method could provide additional empirical evidence of its chronology in relation to Gregorian chant, which is still an open problem (1; 62; 16).

If one added Ancestral State Reconstruction to model how likely a melody is at a given ancestral node, further options for validating the method would open. Given that the phylogeny seems to predict ancestral nodes that do have some relation to the material circumstances of extant sources (provenance, time, *cursus*, etc.), we can use melodies from sources that are sufficiently close to the inferred time and place of an ancestral node and check whether ASR truly assign a higher probability to melodies from the sources closer to the node's inferred historical circumstances than to melodies with circumstances closer to other nodes. In rare cases (such as Montpellier H.159), there are even melodies recorded exactly with letter notation from before the invention of staff notation. While there is likely no single “original chant” that a dove sang to Gregory I, the ability to predict an earlier melody, such as those recorded before precise pitch notation, would again be a significant new capability for chant scholarship. A brief pilot study (56) has shown that ASR of melodies is indeed possible; the results have hinted, however, that it may be more difficult to define what features are in fact characteristic for the individual melodic dialects.

We also suggest including non-Latin, vernacular Gregorian chant traditions, such as the early 15th century Jistebnice Cationale (78) and later utraquist liturgical books in Bohemia (79), editions of Chinese vernacular chant (80; 81), Korean chant (82), or Mi'kmaq chant (83). These repertoires might offer insight into how language interacts with melody under a very strict conservation pressure, and in turn reveal the role of regional pronunciations of Latin in the differentiation of chant melody.

The advantage of computational methods in scaling to large datasets applies to chant. Past the 10th century, there are more sources of Gregorian chant that musicology can handle under its predominant “close reading” paradigm (16). However, as Optical Music Recognition (OMR) for chant notations improves (84; 85; 86), it may be possible to process the considerable digitized collections and obtain catalogues and transcriptions automatically. Though OMR systems will not be perfect, phylogenetic methods have some resistance to sequencing errors. With automated data acquisition, one can imagine building a truly large-scale, dynamic *paleobiogeography* of chant.

5 Conclusion

In terms of the goal of CE “to understand how processes of transmission and selection at the individual level lead to population-wide patterns of cultural diversity and change” (38), we have shown that Gregorian chant melodies indeed do exhibit population-wide patterns of diversity and change that follow from the processes of transmission and selection of chant practitioners, and these patterns have plausible historical and geographical correlates.

The indicated patterns of chant geography are not necessarily surprising for chant scholarship itself. More significant is the fact these patterns were recoverable *from raw melodies* with a straightforward standard phylogenetic model: despite the conservation pressure of its “divine origin”, and institutions to enforce fixity, chant melody evolved. (The observed rates of evolution could perhaps serve as a lower bound on rate of cultural change in the

absence of print technology.) While minor differences have been called “surface detail, not basic structure” in musicology (2, p.371), we showed that computational models did discover patterns in how these seemingly minor differences compound across sets of melodies. This result establishes, in our view, that the geographic patterns of chant melody with phylogenetic methods is a topic worthy of further study and scaling: this “surface detail” may reveal as-of-yet unknown chant transmission patterns. (However, while the inheritance-based model has been able to find this structure, more experimental work must be carried out to improve the model’s ability to estimate the specific histories of how these patterns have developed.)

This paper is merely a first step towards unveiling geographic and institutional patterns in chant transmission, but it has already brought surprising insight, especially in how peculiarities in the model have pointed to significant local historical events.¹⁶ There is perhaps educational value in such a dynamic map of chant as a proxy for medieval history. We are looking forward how the CE perspective on this musical tradition will help integrate the fragments of knowledge we have into an understanding of how chant worked as a cultural system, and how its melodies perhaps provide a uniquely homogeneous domain for the study of the diverse histories of its practitioners.

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¹⁶Specifically, we did not learn about the Arnold of Brescia before investigating the peculiar relationship between inheritance and time of source origin on the Italian/Franciscan branch of the Introits phylogeny.

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Supplementary material for Genome of Melody: applying bioinformatics to study the evolution of Gregorian chant

In these supplementary materials, we provide detailed descriptions of the Christmas and Introids datasets, and all the tip calibration densities for divergence time estimation.

5.1 Christmas dataset comprehensive description

Data selection and acquisition process. The dataset was created from two components: melodies transcribed for a previous study of late medieval Bohemian sources related to the Hussite reformation,¹⁷ and then all sources with homologous transcribed melodies within the Cantus network of databases. The resulting dataset contained 14 sources.

Some sources contained multiple instances of chants of one Cantus ID: In that case, we retained the version with the most complete version of the melody (as repeated instances of the same chant are sometimes only written as incipits in the sources), and if multiple full melodies were available, we selected the melody that was directly in the Vig. Nat. Dom. section (Table 2).

Furthermore, as noted by (24), *differentiae* (see <https://differentiaedatabase.ca/about> for details) tend to be encoded together with antiphon melodies and must be removed. Furthermore, in the Cistercian sources, some melodies had been recorded transposed a fifth up. This was a scribal practice based in the Cistercian reform of chant theory which has no implication on performance (73), so we transpose these melodies back by a fifth down, in order to not introduce spurious differences.

Basic information about individual sources. Here we give for each source of the Christmas dataset a brief overview of its basic metadata: century of origin, provenance, and the ecclesiastical environment it belonged to. For most sources, there is significant uncertainty in at least one of these parameters. We therefore also report on the level of uncertainty in chant literature pertaining to individual sources.

- C1 **A-VOR Cod. 259/I.** A 14th century antiphoner of the collegiate chapter church of Vyšehrad, Prague. In the early 15th century, it was moved to Voraú because of Hussite wars. In 1490-1500, it was adapted for Salzburg liturgy. Available at https://manuscripta.at/hs_detail.php?ID=6267.
- C2 **A-Wn 1799**.** A 13th century Cistercian antiphoner from the Rein monastery in Austria. Available at <https://differentiaedatabase.ca/manuscripts/wn-1799>.
- C3 **CDN-Hsmu M2149.L4.** Cistercian antiphoner from the Abbey of Salzinnes, Namur, in the Diocese of Liège, central Belgium, completed in 1554-1555. Available at <https://cantusdatabase.org//source/123723>.
- C4 **CH-E 611.** A 14th-century antiphoner from the Benedictine monastery of Einsiedeln, central Switzerland. Available at <https://cantus.simssa.ca/manuscript/123606/>.
- C5 **CZ-HKm II A 4.** An antiphoner from the 1470s, belonging to the municipal Church of the Holy Spirit in Hradec Králové, eastern Czechia. Available at <http://hun-chant.eu/source/1481?page=1>.
- C6 **CZ-PLm 504 C 004.** A late antiphony from the St. Bartholomew municipal church in Pilsen, western Czechia, from 1616. Available at <https://rukopisy.zcm.cz/view.php?ID=504C004>.
- C7 **CZ-Pn XV A 10.** Late 15th century notated breviary from the cathedral cursus in Prague, Czechia. Available at <http://hymnologica.cz/source/47>.
- C8 **CZ-Pu I D 20.** An antiphony from the Augustinian monastery in Třeboň, southern Czechia, created in the 2nd half of the 14th century. Available at <http://hymnologica.cz/source/10721>.
- C9 **CZ-Pu XVII E 1.** A mixed Latin and Czech antiphony from the early 16th century, of Czech (but further unspecified) provenance. Available at <http://hymnologica.cz/source/10664>.
- C10 **D-KA Aug. LX.** A complex 12th-century antiphoner, of which the musical notation was almost completely rewritten in the 13th or 14th centuries. From the Zwiefalten Benedictine monastery in southwestern Germany, moved to the abbey of Reichenau in the 15th century. Available at: <https://cantusdatabase.org//source/123612>.

¹⁷<http://hymnologica.cz/jistebnice>

- C11 **D-KNd 1161**. A late 12th- and early 13th-century Cistercian antiphoner, possibly written for use by the female abbey of Saint Mechtern in Cologne, western Germany, renamed Saint Apern in 1477. Available at: <https://cantusdatabase.org/source/601861>.
- C12 **F-Pn lat. 12044**. An early 12th-century antiphoner from the Benedictine abbey of St.-Maur-de-Fossés, close to Paris, France. Available at: <https://cantusdatabase.org/source/123628>.
- C13 **F-Pn lat. 15181**. An early 14th-century notated breviary belonging to the Notre Dame cathedral in Paris, France. Available at: <https://cantusdatabase.org/source/123631/>
- C14 **NL-Uu 406**. A 12th-century antiphonary from St. Mary’s church in Utrecht, Netherlands. Later 13th-15th-century changes. Complex source that has multiple versions of some melodies. Available at: <https://cantusdatabase.org/source/123641>.

Dataset content details. The Cantus IDs (not in liturgical order) with melodies per source transcribed in the Christmas dataset are listed in Tab. 1.

Cantus ID	Incipit	Genre	URL
001737	Orietur sicut sol	antiphon	https://cantusindex.org/id/001737
002000	Cum esset desponsata	antiphon for Magnificat	https://cantusindex.org/id/002000
003511	Judaea et Jerusalem	antiphon	https://cantusindex.org/id/003511
004195	Bethleem non ese minima	antiphon	https://cantusindex.org/id/004195
007040	Judaea et Jerusalem	responsory	https://cantusindex.org/id/007040
007040a	Constantes estote videbitis	responsory verse	https://cantusindex.org/id/007040a

Table 1: The chants with melodies per source transcribed in the Christmas dataset.

Note that the responsory Judaea et Jerusalem been misreported in (52) as Cantus ID 605019, which refers to a shorter version of the responsory which uses the text ”*Cras egrediemini...*” as a verse instead of respond, while 007040 uses ”*Constantes estote...*” as the verse (Cantus ID 007040a).

A full listing of which Cantus ID is present in which source is given in Tab. 2.

Source	Provenance	Date	Cursus	007040	001737	002000	003511	004195	007040a
A-Wn 1799**	Rein	1200s	Cistercian	1	0	1	1	1	1
A-VOR Cod. 259/I	Prague	1360	Secular	1	2	1	1	1	1
CDN-Hsmu M2149.L4	Salzannes	1554	Cistercian	1	0	1	1	1	1
CH-E 611	Einsiedeln	1300s	Benedictine	1	3	1	1	1	1
CZ-HKm II A 4	Hr. Král.	1400s	Secular	1	1	1	1	1	1
CZ-PLm 504 C 004	Pilsen	1616	Secular	1	1	1	1	1	1
CZ-Pu XVII E 1	Bohemia	1516	Unknown	1	0	1	1	0	1
CZ-Pn XV A 10	Prague	1300s	Secular	1	1	1	1	1	1
CZ-Pu I D 20	Passau	1300s	Augustinian	1	1	1	1	1	1
D-KA Aug. LX	Zwiefalten	1100s	Benedictine	1	1	1	1	1	1
D-KNd 1161	Köln	1200s	Cistercian	1	0	1	1	1	1
F-Pn lat. 12044	Paris	1100s	Benedictine	1	1	1	1	2	1
F-Pn lat. 15181	Paris	1300s	Secular	1	0	1	1	2	1
NL-Uu 406	Utrecht	1150	Secular	1	2	1	3	2	1

Table 2: Sources of the Christmas Vespers dataset with their provenance, approximate date, cursus, and presence of the chant in each source (1 or more instances per source).

5.2 Introit dataset comprehensive description

Data selection and acquisition process. The introits were chosen to maximize the number of comparable sources. We started by downloading all cataloged introit records from the Cantus Index JSON endpoint, yielding 24993. As the selected melodies had to be manually transcribed, we only retained those that had the URL of the digitized source, and we also filtered out legacy records assigned to no source or no Cantus ID. This left 21219 chants. We set the target number of introits per source to 20 (with an average introit length in CantusCorpus of roughly 100 positions, this translates to approx. 2000 position per sequence). This implied we could filter out any

source with fewer than 20 introits (which discards mainly fragments of liturgical books, or small supplementary books that added repertoire e.g. for feasts instituted after the main gradual of the given community was already written). Also, we filtered out any introit that any introit appearing in fewer than 20 sources, as these had no hope of containing any homologous set of chants of the target size. This left an incidence matrix of 155 sources times 124 Cantus IDs.

Then, we performed a greedy search for the maximal subset of sources with at least 20 introits homologous among all of them. We started with the most frequent introit (g00331), retained only sources that contained it, and then looked for the next most frequent introit within the retained subset of sources. Iterating this process 20 times, we found a set of 71 sources that contained this “greedy” subset of introits, for a total of 1420 melodies.

Next, a team of four annotators (students of musicology with previous exposure to chant notation) were contracted to transcribe the melodies. The sources were assigned in a random order, and each annotator had to complete all melodies from a source before being assigned a new source, to ensure that whenever the annotations had to be stopped, the maximum number of fully comparable sources would be available. Within the available timeframe, the annotators only managed to complete 587 melodies. of which 28 were fragmentary. The resulting 559 melodies were further filtered for incompletely processed sources (of which fortunately there was only one), and checked for catalogization noise (some sources do not fully write out every introit, only an incipit – the first few words and notes, just to remind a reader what chant it is) which caused in some cases more than 2 of the selected 20 homologous chants in fact missing. We filtered out these sources as well.

All the retained melodies were then re-checked by an expert for quality control.

Afterwards, when collecting metadata for the retained sources, we found that there were three sources with homologous introits that belonged to the Old Roman tradition rather than Gregorian. Because of the unclear evolutionary relationship of this tradition to Gregorian chant (60; 1; 62), we excluded these sources from experiments: CH-Cobodmer C 0074, V-CVbav Archivio di San Pietro F.22, and V-CVbav Vat.lat.05319. Addressing the uncertainty of the evolutionary relationship between extant Old Roman melodies and Gregorian melodies may be possible, but current scholarship posits a high likelihood of reticulation events between the two repertoires, necessitating methods that models reticulations and thus beyond the scope of our work.

Dataset content details. The Cantus IDs (not in liturgical order) with melodies per source transcribed in the Introits dataset are listed in Tab. 3. (Since all these chants are of the introit genre, we omit the genre column.)

Cantus ID	Incipit	URL
g00331	Confessio et pulchritudo in conspectu ejus	https://cantusindex.org/id/g00331
g00625	Adorate Deum omnes Angeli ejus	https://cantusindex.org/id/g00625
g00631	Circumdederunt me gemitus mortis	https://cantusindex.org/id/g00631
g00640	Exsurge quare obdormis Domine	https://cantusindex.org/id/g00640
g00648	Esto mihi in Deum protectorem	https://cantusindex.org/id/g00648
g00662	Misereris omnium domine et nihil odisti	https://cantusindex.org/id/g00662
g00670	Audivit dominus et misertus est mihi	https://cantusindex.org/id/g00670
g00675	Invocavit me et ego exaudiam eum	https://cantusindex.org/id/g00675
g00728	Redime me domine et miserere mei	https://cantusindex.org/id/g00728
g00733	Tibi dixit cor meum quaesivi vultum	https://cantusindex.org/id/g00733
g00742	Lex domini irreprehensibilis convertens animas	https://cantusindex.org/id/g00742
g00768	Fac mecum domine signum in bonum	https://cantusindex.org/id/g00768
g00771	Verba mea auribus percipe domine	https://cantusindex.org/id/g00771
g00776	Laetare Jerusalem et conventum facite	https://cantusindex.org/id/g00776
g00783	Deus in nomine tuo salvum me	https://cantusindex.org/id/g00783
g00785	Exaudi deus orationem meam	https://cantusindex.org/id/g00785
g00789	Dum sanctificatus fuero in vobis congregabo	https://cantusindex.org/id/g00789
g00793	Meditatio cordis mei in conspectu tuo	https://cantusindex.org/id/g00793
g00800	Judica me deus et discerne causam	https://cantusindex.org/id/g00800
g01178	Dum clamarem ad dominum exaudivit vocem	https://cantusindex.org/id/g01178

Table 3: The chants with melodies per source transcribed in the Introits dataset.

A full listing of which Cantus ID is present how many times in which source is given in Tab. 4. In case multiple versions of the same Cantus ID are present in a source, typically the first occurrence has melody written out in full, and the subsequent occurrences have only the beginning of the melody (melodic incipit) or nothing (textual incipit only).

Basic information about individual sources. Here we give for each source of the Introits dataset a brief overview of its basic metadata: century of origin, provenance, and the ecclesiastical environment it belonged to.

Source	Provenance	Date	Cursus	g00331	g00625	g00631	g00640	g00648	g00662	g00670	g00675	g00728	g00733	g00742	g00768	g00771	g00776	g00783	g00785	g00789	g00793	g00800	g01178
A-Gu Ms 0807	Austria	1100s	Benedict.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
CH-ROM Ms. liturg. FiD 5	Switzerland	1200s	Cist.	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
D-B Ms mus 40078	Quedlinburg	1100s	unknown	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
D-HEu Cod. Sal. X,007	Salem (Ger.)	1200s	Cist.	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1
D-KNd Ms 1001b	Cologne	1299	Franc.	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
D-LEu Ms Thomas 391	Leipzig	1200s	August.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-CA Ms 0061 (62)	Lille	1100s	Canons	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-G Ms 0084 (Ms. 395 Rés.)	Écoudes	1100s	Carthus.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-NS Ms 0004	Valence	1100s	Carthus.?	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-Pa Ms 0197	Paris	1280s	Canons	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2
F-Pn NAL 01235	Nevers	1100s	unknown	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-Pn NAL 01414	Milan	1100s	Cist.	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1
F-Pn Ms Lat 00833	Reims	1175+	unknown	2	1	1	1	2	1	1	1	1	1	1	1	1	1	1	2	1	1	2	2
<i>F-Pn Ms Lat 00904</i>	<i>Rouen</i>	<i>1200s</i>	<i>secular</i>	2	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	2
F-Pn Ms Lat 17307	Compiègne	1100s	Benedict.	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-PR Ms 0012	Charters	1200s	secular	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
F-SEm Ms 018	Sens	1200s	Benedict.	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	2
NL-Uu Hs. 0415	Maastricht	1400s	August.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
I-BGc MA 150 (Ψ III.8)	Brescia	1100s	Canons	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
I-BGc MA 239 (Γ III.18)	Brescia	1190+	unknown	2	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
PL-WRu I F 414	Lubiąż	1200s	Cist.	1	1	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	0	0
PL-WRu I F 416	Henryków	1300s	Cist.	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
PL-Wn rps 12722 V	Tyniec	1300s	Benedict.	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V-CVbav Ross.0076	Aquileia	1200s	unknown	1	1	1	1	0	0	1	0	1	1	1	1	1	1	1	1	1	1	0	0
<i>F-Pn Ms Lat 00903</i>	<i>St. Yrieux</i>	<i>1000s</i>	<i>Benedict.</i>	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>CH-Cobodmer C 0074</i>	<i>Rome</i>	<i>1200s</i>	<i>Old Rom.</i>	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>V-CVbav Arch. S. Pietro F.22</i>	<i>Rome</i>	<i>1100s</i>	<i>Old Rom.</i>	1	1	1	0	1	1	0	0	1	1	0	1	1	1	0	1	1	1	0	0
<i>V-CVbav Vat.lat.05319</i>	<i>Rome</i>	<i>1100s</i>	<i>Old Rom.</i>	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 4: Sources of the Christmas Vespers dataset with their provenance, approximate date, cursus, and number of occurrences of each in each source.

For most sources, there is significant uncertainty in at least one of these parameters; we therefore also report on the level of uncertainty in chant literature pertaining to individual sources.

- N1 **A-Gu Ms 0807** A 12th century graduale of Austrian provenance, from the environment of the semi-monastic Canons Regular of St. Augustine (87), specifically canonesses of Klosterneuburg (88), with partial concordances to its peculiarities found in Seckau (southeastern Austria), Kremsmünster (northwestern Austria), and Seon (southeastern Bavaria). Available at: <https://musmed.eu/source/10059>.
- N2 **CH-ROM Ms. liturg. FiD 5** A 13th century graduale and kyriale of the Cistercian order. Likely originated at Abbaye de Haut-Crêt in Switzerland (north of Lake Geneva in the Vaud canton), which was the motherhouse of its current location, Abbaye de la Fille-Dieu Romont (less than 100 kilometers away), until 1536. Faithful copy of an older Cistercian graduale from 1140-1143.¹⁸ Available at: <https://www.musmed.eu/source/97795>.
- N3 **D-B Ms mus 40078** A 12th century graduale from the city of Quedlinburg, in north-central Germany. Possibly secular cursus, from the Quedlinburg church of St. Servatius. One of the earliest diastematic sources from Germany. Available at: <https://musmed.eu/source/8817>.
- N4 **D-HEu Cod. Sal. X,007** A 13th century graduale of the Cistercian order, originating from Salem in southwestern Germany, very close to Switzerland. Likely from before 1230, according to codicological analysis.¹⁹ Available at: <https://musmed.eu/source/17266>.

¹⁸<https://www.e-codices.unifr.ch/en/list/one/fdr/0005#details>

¹⁹<https://www.ub.uni-heidelberg.de/digi-pdf-katalogisate/sammlung29/werk/pdf/salX7.pdf>

- N5 **D-KNd Ms 1001b** A graduale from the year 1299, belonging to the Franciscan (Minorite) order in Cologne, Germany.²⁰ Available at: <https://musmed.eu/source/11493>.
- N6 **D-LEu Ms Thomas 391** A combined 13th-century chant book for mass (graduale, kyriale for the ordinary, a sequentiary, and even a tonary and a music-theoretical treatise), from to the Augustinians at St. Thomas in Leipzig, eastern Germany. Available at: <https://musmed.eu/source/138221>.
- N7 **F-CA Ms 0061 (62)** A graduale from the 12th century (likely around the middle of the century), from the collegiate church of St. Pierre in Lille, northern France. The “collegiate” moniker implies these were likely Canons Regular. Available at: <https://musmed.eu/source/9071>.
- N8 **F-G Ms 0084 (Ms. 395 Rés.)** A 12th century graduale of the Carthusian monastic order from the monastery of Écogues in southeastern France. The Carthusians follow the rule of St. Augustine rather than St. Benedict, but the implications for chant melody are not clear. They are example of an order that would merit further investigation: a stemmatology of Carthusian sources has been suggested on the basis of repertoire (89), as a lot is known about the order’s early history, but the extent to which Carthusians would have a melodic identity is not clear. Available at: <https://musmed.eu/source/10075>.
- N9 **F-NS Ms 0004** A graduale from the 12th century, from the city of Valence in southeastern France. Some signs of a relationship to the Carthusian order in corrections of textual choices made in the margins. Available at: <https://www.musmed.eu/source/12600>.
- N10 **F-Pa Ms 0197** A graduale dated between 1270 and 1297, placed in the St. Victor Abbey in Paris, France. The abbey followed Augustinian rule, as Canons Regular. It was a intellectual center since its founding in the 12th century, with notable persons documented to have spent time there being i.a. Abelard and Thomas Beckett, and it exerted significant influence over other houses of the Canons Regular. Available at: <https://musmed.eu/source/98760>.
- N11 **F-Pn NAL 01235** A 12th-century combined liturgical book for mass that includes the graduale. Originates in the central French city of Nevers, which shared a cultural milieu with other cathedral cities around Paris (90). Contains some polyphony in a later layer (outside of the graduale). Cursus is unclear. Available at: <https://musmed.eu/source/13534>.
- N12 **F-Pn NAL 01414** A 12th century graduale belonging to the Cistercian monastery Sancte Marie de Morimundo in the Italian diocese of Milan. Its founding house was the French abbey of Morimond. Available at: <https://musmed.eu/source/28426>.
- N13 **F-Pn Ms Lat 00833** A kyriale and notated missal²¹ from the last quarter of the 12th century. The manuscript can be placed into the area of Reims, northeastern France, thanks to a separate rubric on f.230v (in the original 12th century hand) for a certain Helanus, priest who lived near Reims. Named Missale Premonstratense but only adapted for the use of the Premonstratense monastic order during the 15th century by way of substituting repertoire; the melodies show no signs of palimpsest or other modifications. On the other hand, the formulae for the canon of mass are recorded to follow Premonstratense use,²² and the founding abbey of the order is in the same area, leaving cursus uncertain. Available at: <https://musmed.eu/source/13007>.
- N14 **F-Pn Ms Lat 00904 (Excluded.)** A 13th-century graduale from the cathedral of Rouen (thus unambiguously secular cursus), northern France. During experiments, we found that two melodies from the source are incomplete despite passing length checks, and thus in addition to the two missing introits, the source is missing more than 10 % of the 20 introits, and thus we excluded it; however, it may be useful in the future. Available at: <https://musmed.eu/source/13023>.
- N15 **F-Pn Ms Lat 17307** A 12th-century notated missal, likely from the abbey of S. Corneille de Compiègne, north of Paris, of the Benedictine order. Probably from after the year 1170, because the feast of St. Thomas Beckett, canonized in 1173, is part of its calendar. Available at: <https://musmed.eu/source/13489>.

²⁰<https://digital.dombibliothek-koeln.de/hs/content/titleinfo/311427>

²¹The missal is a type of liturgical book that includes all the liturgical formulas said or chanted throughout the yearly cycle of masses. This includes the texts of the propers of mass. A notated missal records, for the propers, also the melody in whatever notation is applicable at the given time and place of the manuscript’s origin. Thus, a notated missal is a superset of the graduale.

²²<https://iif.bibliissima.fr/collections/manifest/d6b20dac99977edd39e1d75ada166e5ad931429e>

- N16 **F-PR Ms 0012** A graduale from the 13th century, originating in the city of Chartres, close to Paris. It belongs to the secular cursus, as it is associated directly with its cathedral (91). Available at: <https://www.musmed.eu/source/14008>.
- N17 **F-SEm Ms 018** A graduale from the 13th century that belonged to the Benedictine monastery of St. Colombe in the city of Sens, close to the northerwestern boundary of the Burgundy region in central France. Available at: <https://www.musmed.eu/source/20281>.
- N18 **NL-Uu Hs. 0415** A gradual from the the 15th century (likely its 2nd half) that originates from Maastricht, in the south of the Netherlands, part of the diocese of Liège. Likely from an Augustinian environment. The latest manuscript in the dataset. Available at: <https://musmed.eu/source/15626>.
- N19 **I-BGc MA 150 (Psi III.8)** A graduale from the 12th century, likely 1st half, originating from the city of Brescia in northern Italy. Possibly connected to the community of canons regular at the St. John Evangelist church, but the cursus is unclear. Available at: <https://musmed.eu/source/41838>.
- N20 **I-BGc MA 239 (Gamma III.18)** Another graduale from the city of Brescia, earlier, from the end of the 11th century. Cursus unknown. Available at: <https://musmed.eu/source/8805>.
- N21 **PL-WRu I F 414** A 13th-century graduale belonging to the Cistercian monastery in Lubiaż, western Silesia (southwestern Poland). Available at: <http://cantusplanus.pl/source/36027>.
- N22 **PL-WRu I F 416** A later, 14th -entury Cistercian graduale, this time from the Henryków (Heinrichau) monastery, one of the daughter houses of Lubiaż in central Silesia. Available at: <http://cantusplanus.pl/source/41816>.
- N23 **PL-Wn rps 12722 V** A 14th-century (likely late 14th century, but unproven) graduale from a Benedictine monastery, St. Peter's abbey in Tyniec, in southeastern Poland close to Krakow. Available at: <http://cantusplanus.pl/source/4559>.
- N24 **V-CVbav Ross.0076** A 13th-century composite manuscript for mass – graduale, kyriale, and sequentiary – from the northeastern Italian city of Aquileia. The repertoire shows evidence of contact with the transalpine German-speaking areas.²³ Cursus is unknown. Available at: <https://musmed.eu/source/98746/>
- N25 **F-Pn Ms Lat 00903 (Excluded.)** A graduale from the first half of the 11th century. from the Benedictine Abbey of St. Yrieux (Aredius) in Limoges. The monastery (founded already in the 6th century) was secularised in the second half of the 11th century (likely 1059 or 1060) and administered by Canons Regular, but at the time this gradual was created, it was still probably a Benedictine monastery, due to its selected textual variants (92), hence the earlier date. The entire source is very early, with 5-line Aquitanian staff notation that predates the Guidonian standard (one of the attempts to notate exact pitch that was not as successful as the Guidonian 4-line staff), which makes it an outlier by nearly 100 years. Due to the way ages of tips may interact with the root selection and DTE steps of the pipeline, we decided to exclude this source from experiments; this does not discard much useful information in terms of the research questions, since we already have two French Benedictine sources in the dataset. Available at: <https://musmed.eu/source/13022?page=161>.
- N26 **CH-Cobodmer C 0074 (Excluded.)** A graduale from the year 1071, from the Roman church of S. Cecilia in Trastevere. Old Roman chant, hence excluded. Available at: <https://musmed.eu/source/9492>.
- N27 **V-CVbav Archivio di San Pietro F.22 (Excluded.)** A 13th-century Graduale from the St. Peter basilica in Rome. Old Roman chant, hence excluded. Available at: <https://musmed.eu/source/14749>.
- N28 **V-CVbav Vat.lat.05319 (Excluded.)** A 12th-century Graduale from the basilica of St. John of Lateran in Rome. Old Roman chant, hence excluded. Available at: <https://musmed.eu/source/14915>.

²³See source description at <https://www.librideipatriarchi.it/en/books/aquileian-gradual/#tab1>

5.3 DTE tip calibration densities

The DTE calibration densities for tips are derived from information about the sources' times of origin according to their source description entry in the Cantus network of databases. Sometimes, musicological literature suggest more exact dates (esp. for the Introits dataset), but we opted to systematically rely on the database as the authority (and submitted requests for making the database data more accurate in the future when applicable, but subject to a more systematic review of the proposed dates by database curators). The time range for the root is set permissively as well, between 700 and 900 AD. The values and references for where they are taken from are given in Tab. 5.

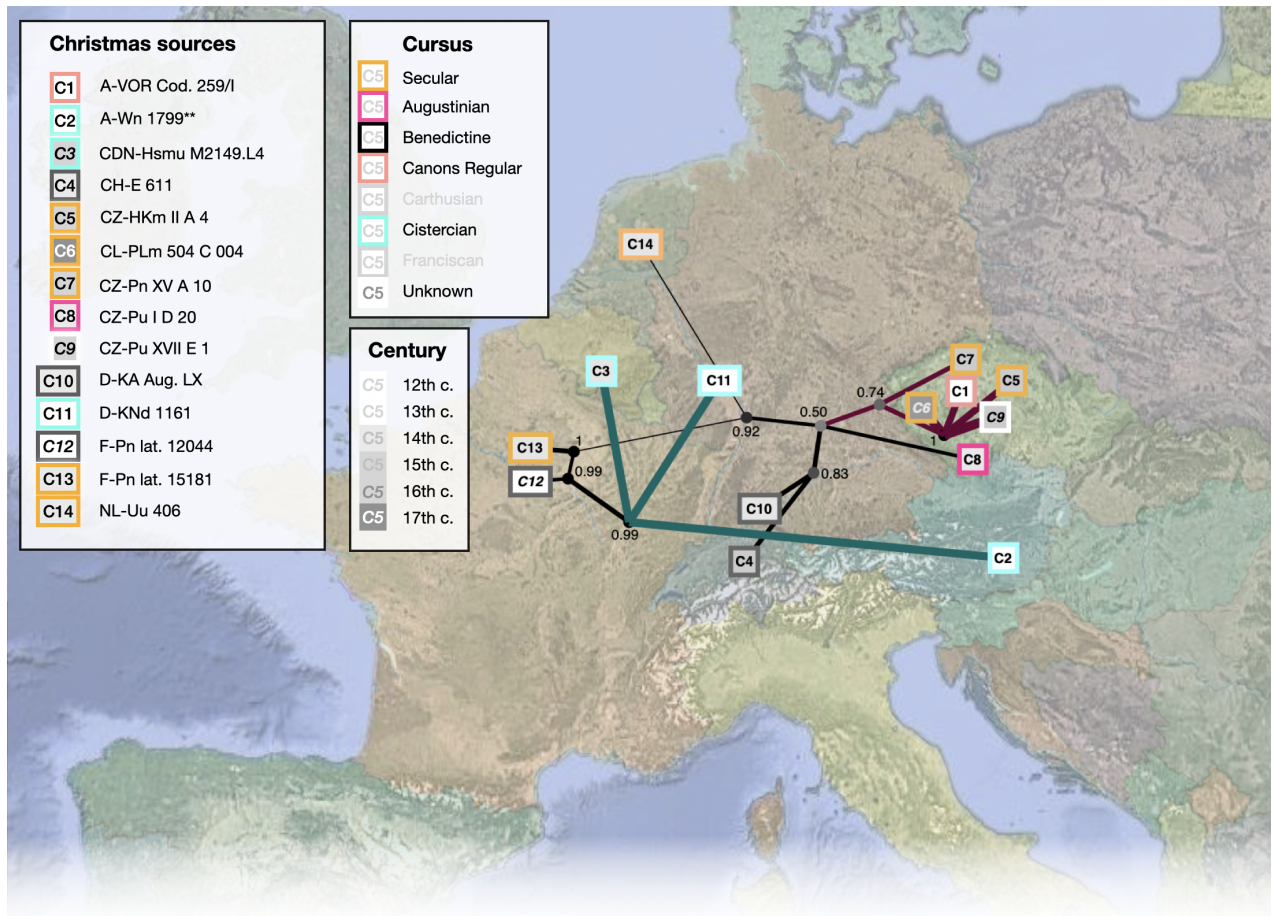


Figure 3: The summary phylogenetic tree (topology and evolutionary distances only, unrooted, not oriented in time) of the Introits dataset. Because the datasets span centuries, no single political map of Europe applies; thus we opted to show current political entities, merely as a readability aid. Branch thickness is inversely proportional to branch length (as shorter branches indicate a closer relationship). Sources – tips – numbered; border colour corresponds to *cursus*, shade corresponds to age (brighter = older). Tip locations on maps correspond to real places of origin (provenance) of the sources, but the locations of internal nodes were placed manually, with figure readability as the main criterion. Numbers and shades of internal nodes correspond to their sampled posterior probability (the summary tree includes nodes that appear in more than 50 % of samples). Branches of some inferred clades coloured, again for readability: Cistercian sources – teal, clade of sources east of the Rhine – dark red, north French clade – purple, south French clade – dark green, Italian/Franciscan clade – olive.

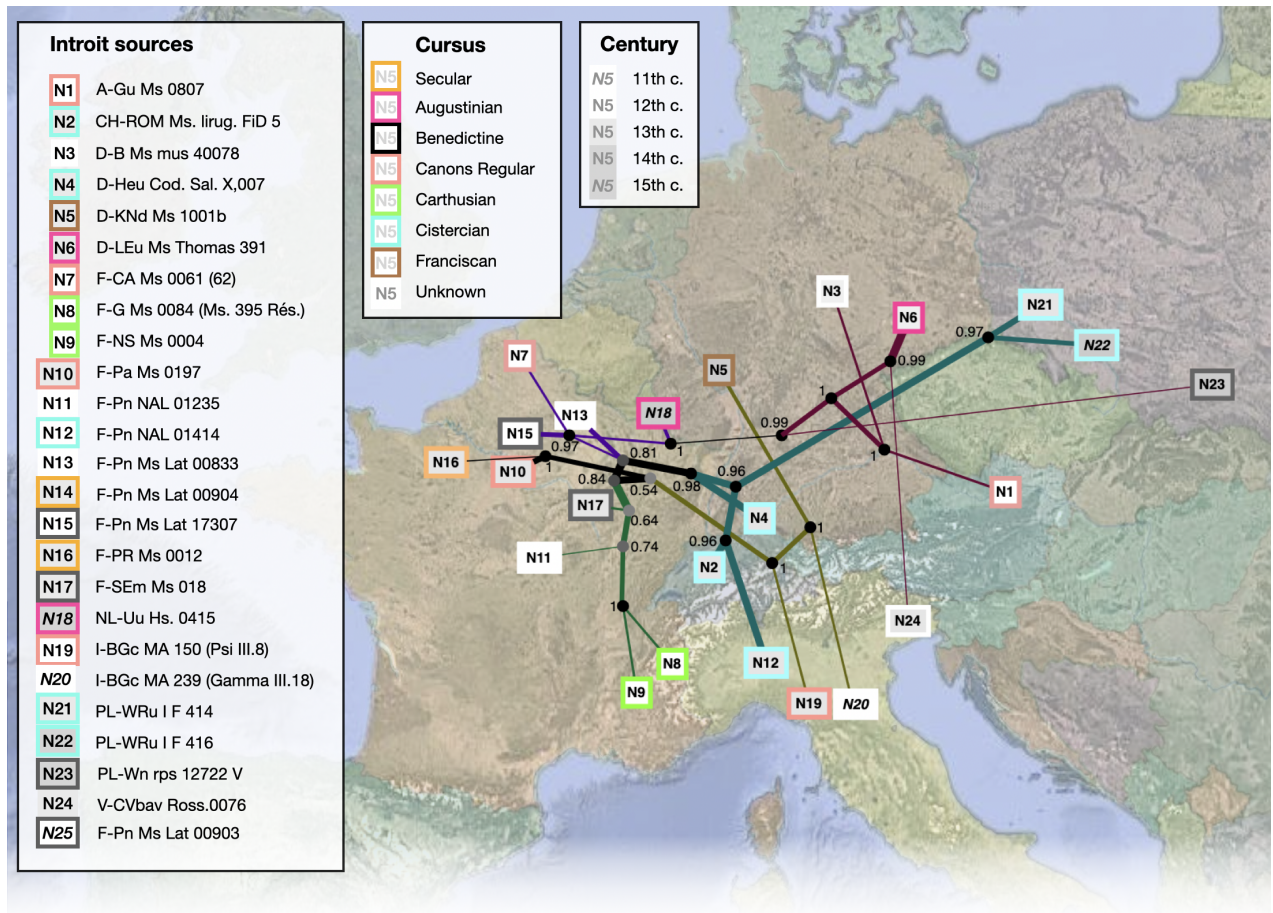
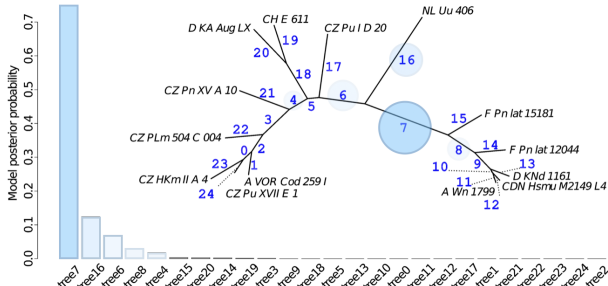
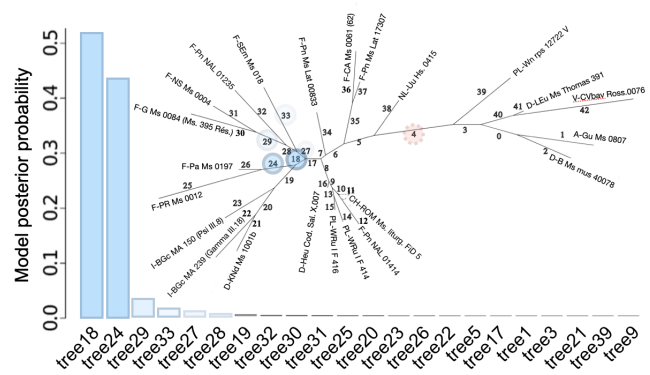


Figure 4: The summary phylogenetic tree (topology and evolutionary distances only, unrooted, not oriented in time) of the Introits dataset. Again, borders of current political entities provided only to aid readability, as there is no single applicable set of historical borders. Branch thickness inversely proportional to branch length (as shorter branches indicate a closer relationship). Sources – tips – numbered; shade corresponds to age (brighter = older); border colour corresponds to *cursus*, with additional colours for Carthusians (green) and Franciscans (brown) compared to the Christmas data. Source locations on maps correspond to their real places of origin, but the locations of internal nodes were placed manually, with figure readability as the main criterion. Numbers and shades of internal nodes correspond to their sampled posterior probability (the summary tree includes nodes that appear in more than 50 % of samples). Branches of some inferred clades coloured, again for readability: Cistercian sources – teal, clade of sources east of the Rhine – dark red, north French clade – purple, south French clade – dark green, Italian/Franciscan clade – olive.



(a) Root position marginal likelihoods for the Christmas datasets. The best rooting position was found to be the branch labelled as 7 with model posterior probability 0.750, whereas the second best rooting position is branch 16 with posterior model probability 0.124. This root position for Christmas is highly plausible, as it separates the tree into a west Frankish vs. east Frankish top-level clade, in accordance with (8).



(b) Root position marginal likelihoods for the Introits dataset. The best rooting position was found to be the branch labelled as 18 with model posterior probability 0.520, and a close second best on branch 16 with posterior model probability 0.420. However, neither of these is musicologically plausible. The most plausible root position would have been branch 4 (red).

Figure 5: Model selection for the position of the root. Bar height represents posterior model probability, each bar is a topology resulting from rooting at a given branch in the maximum credibility tree. Such trees labelled tree0 through tree24 were the varying element of the Bayesian phylogenetic model for which the marginal likelihood was calculated using the stepping stones method.

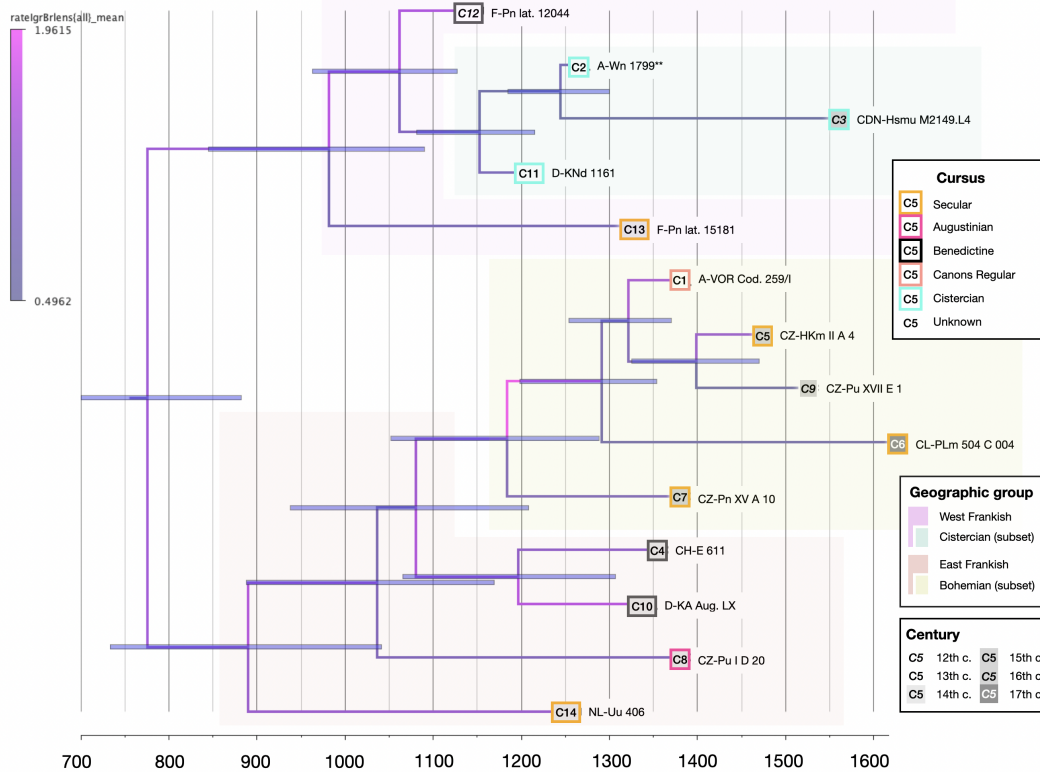
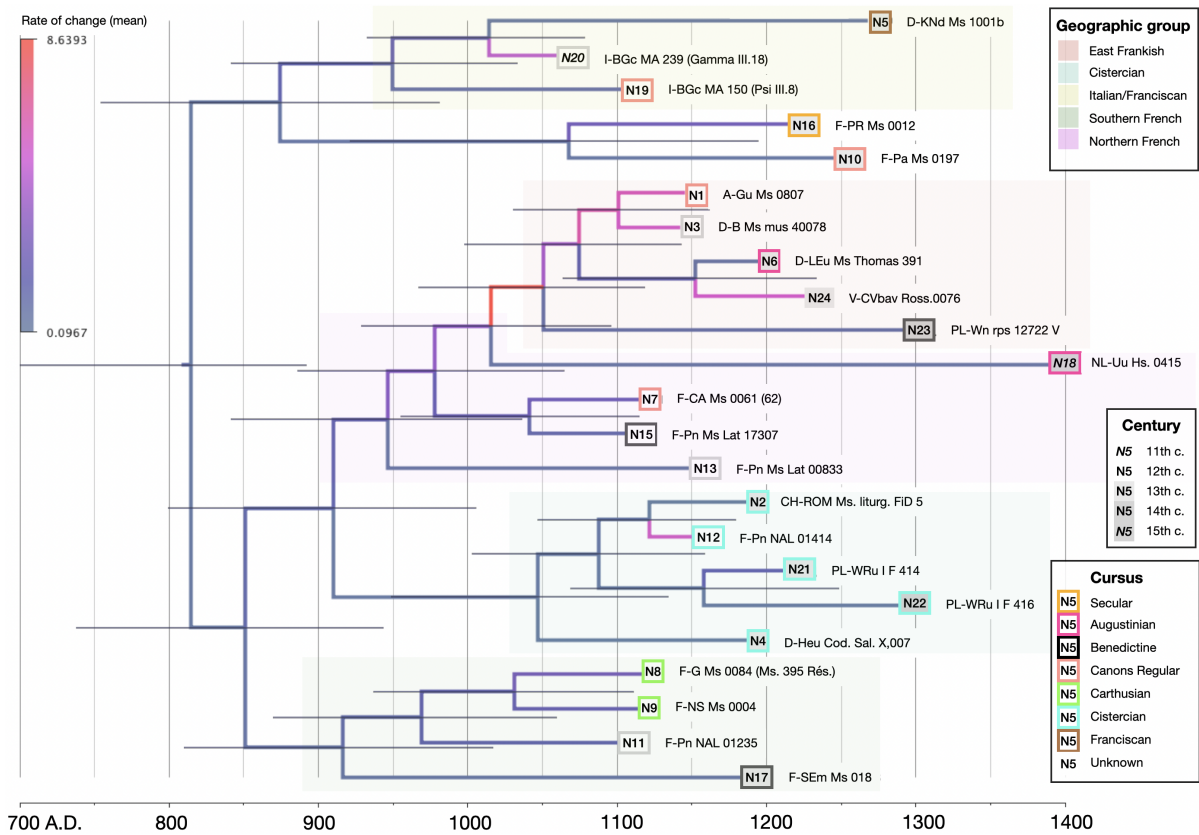
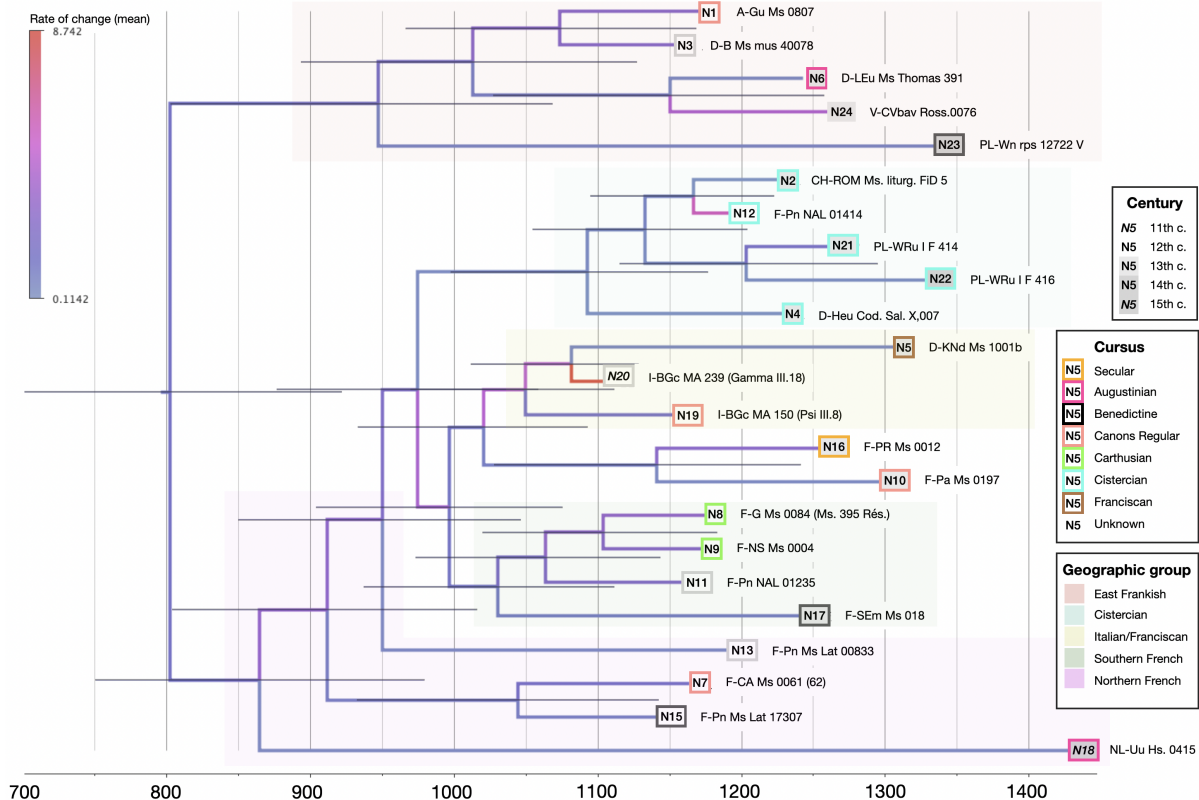


Figure 6: Result of Divergence Time Estimation algorithm over the Maximum Credibility Tree (MCT) obtained from phylogeny inference and rooted using model selection on the Christmas dataset. The horizontal axis is historical time in years (A.D.), the vertical axis has no meaning. Internal nodes positioned at median estimate of the year of divergence. Horizontal bars at the nodes indicate 95% credibility intervals for its estimated age. Branch colour indicates rate of change; tips positioned in the middle of their time ranges. The model selection chose as root the node which separates the tree into a west Frankish and east Frankish top-level clade, in accordance with (8).



(a) DTE result when the tree is rooted using model selection.



(b) DTE result when the tree is manually rooted "on the Rhine", to produce the expected east-west Frankish split.

Figure 7: Results of Divergence Time Estimation algorithm over the Maximum Credibility Tree (MCT) obtained from phylogeny inference on the Introits dataset, with rooting both automatic (7a) and a musicologically motivated selection (7b). Both trees are historically implausible.

Source: Christmas	CD (YBP)	CD (AD)	Ref
A-VOR Cod 259/I	654	1370	https://manuscripta.at/hs_detail.php?ID=6267
A-Wn 1799**	724–824	1200–1300	https://cantusdatabase.org/source/123667
CDN-Hsmu M2149 L4	474	1550	https://cantusdatabase.org//source/123723
CH-E 611	624–724	1300–1400	https://cantus.simssa.ca/manuscript/123606/
CZ-HKm II A 4	554	1470	http://hun-chant.eu/source/1481?page=1
CZ-PLm 504 C 004	408	1616	https://rukopisy.zcm.cz/view.php?ID=504C004
CZ-Pn XV A 10	624–674	1350–1400	http://hymnologica.cz/source/47
CZ-Pu I D 20	624–674	1350–1400	http://hymnologica.cz/source/10721
CZ-Pu XVII E 1	474–524	1500–1550	http://hymnologica.cz/source/10664
D-KA Aug LX	624–924	1100–1400	https://cantusdatabase.org//source/123612
D-KNd 1161	799–849	1175–1225	https://cantusdatabase.org//source/601861
F-Pn lat 12044	874–924	1100–1150	https://cantusdatabase.org//source/123628
F-Pn lat 15181	674–724	1300–1350	https://cantusdatabase.org//source/123631
NL-Uu 406	624–924	1100–1400	https://cantusdatabase.org//source/123641
Source: Introids	CD (YBP)	CD (AD)	Ref
A-Gu Ms 0807	825–924	1100–1199	https://cantusdatabase.org//source/123641
CH-ROM Ms. liturg. FiD 5	725–824	1200–1299	https://www.musmed.eu/source/97795
D-B Ms mus 40078	825–924	1100–1199	https://musmed.eu/source/8817
D-HEu Cod. Sal. X,007	725–824	1200–1299	https://musmed.eu/source/17266
D-KNd Ms 1001b	725	1299	https://musmed.eu/source/11493
D-LEu Ms Thomas 391	725–824	1200–1299	https://musmed.eu/source/138221
F-CA Ms 0061 (62)	858–891	1133–1166	https://musmed.eu/source/9071
F-G Ms 0084 (Ms. 395 Rés.)	825–924	1100–1199	https://musmed.eu/source/10075
F-NS Ms 0004	825–924	1100–1199	https://www.musmed.eu/source/12600
F-Pa Ms 0197	727–754	1270–1297	https://musmed.eu/source/98760
F-Pn NAL 01235	825–924	1100–1199	https://musmed.eu/source/13534
F-Pn NAL 01414	825–924	1100–1199	https://musmed.eu/source/28426
F-Pn Ms Lat 00833	824–849	1175–1200	https://musmed.eu/source/13007
<i>F-Pn Ms Lat 00904</i>	<i>725–824</i>	<i>1200–1299</i>	https://musmed.eu/source/13023
F-Pn Ms Lat 17307	825–924	1100–1199	https://musmed.eu/source/13489
F-PR Ms 0012	725–824	1200–1299	https://www.musmed.eu/source/14008
F-SEm Ms 018	725–824	1200–1299	https://www.musmed.eu/source/20281
NL-Uu Hs. 0415	525–624	1400–1499	https://musmed.eu/source/15626
I-BGc MA 150 (Psi III.8)	825–924	1100–1199	https://musmed.eu/source/41838
I-BGc MA 239 (Gamma III.18)	924–933	1091–1100	https://musmed.eu/source/8805
PL-WRu I F 414	725–824	1200–1299	http://cantusplanus.pl/source/36027
PL-WRu I F 416	625–724	1300–1399	http://cantusplanus.pl/source/4559
V-CVbav Ross.0076	725–824	1200–1299	https://musmed.eu/source/98746
<i>F-Pn Ms Lat 00903</i>	<i>974–1024</i>	<i>1000–1050</i>	https://musmed.eu/source/13022?page=161
<i>CH-Cobodmer C 0074</i>	<i>953</i>	<i>1071</i>	https://musmed.eu/source/9492
<i>V-CVbav Archivio di San Pietro F.22</i>	<i>774–823</i>	<i>1201–1250</i>	https://musmed.eu/source/14749
<i>V-CVbav Vat.lat.05319</i>	<i>825–924</i>	<i>1100–1199</i>	https://musmed.eu/source/14915
Root	1124–1324	700–900	(2)

Table 5: Calibration densities (CD) used in DTE on the Christmas and Introids datasets. Time scale is in both years before the present (YBP, as used by `mrBayes_volpiano`) as well as in anno Domini (AD). Single time values represent fixed values whereas intervals represent Uniform(min,max) calibration densities. Sources excluded in our experiments in italics.