Article

Unlocking carbene reactivity by metallaphotoredox α-elimination

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The ability to tame high-energy intermediates is important for synthetic chemistry, enabling the construction of complex molecules and propelling advances in the field of synthesis. Along these lines, carbenes and carbenoid intermediates are particularly attractive, but often unknown, high-energy intermediates[1,2]. Classical methods to access metal carbene intermediates exploit two-electron chemistry to form the carbon–metal bond. However, these methods are usually prohibitive because of reagent safety concerns, limiting their broad implementation in synthesis[3–6]. Mechanistically, an alternative approach to carbene intermediates that could circumvent these pitfalls would involve two single-electron steps: radical addition to metal to forge the initial carbon–metal bond followed by redox-promoted α-elimination to yield the desired metal carbene intermediate. Here we realize this strategy through a metallaphotoredox platform that exploits iron carbene reactivity using readily available chemical feedstocks as radical sources and α-elimination from six classes of previously underexploited leaving groups. These discoveries permit cyclopropanation and σ-bond insertion into N–H, S–H and P–H bonds from abundant and bench-stable carboxylic acids, amino acids and alcohols, thereby providing a general solution to the challenge of carbene-mediated chemical diversification.

Controlled access to high-energy chemical intermediates, such as carbanions, carbocations, radicals and carbenes, is a key step in many important bond-forming processes[7–10]. Accessing these intermediates requires reactive starting materials that possess high-energy ground states, which results in limited functional group compatibility, particularly in the context of complex synthetic targets. Modern advances in organic chemistry have enabled controlled access to some synthetically useful high-energy species, most notably, radical intermediates[11–14]. Photoredox catalysis harnesses the energy of visible light for reactivity up-conversion, turning inert and stable starting materials into reactive radical species. The extension to metallaphotoredox catalysis, which merges transition metal cross-coupling with these radical intermediates, provides opportunities to explore previously inaccessible chemical space[8]. By contrast, broad access to carbenes and carbenoids remains unknown, despite their similar transformative potential in a wide range of bond formations[2,15]. Traditional methods for accessing carbene intermediates rely on high-energy, bifunctional or pseudo-bifunctional precursors, such as diazo (or pro-diazo) compounds, polyhalogenated precursors or sulfonium ylides[3,5,16]. Ultimately, the reactivity and structural specificity of these starting materials limit utility and, in some cases, raise safety concerns, such as the need for high temperatures and/or explosive reagents. Although recent studies have demonstrated that carbonyl intermediates can serve as carbene precursors through pre-generated zinc carbenoids[17–21], there remains no general strategy to access carbene intermediates from other naturally occurring and abundant starting materials, such as carboxylic acids, amino acids and alcohols. To address these limitations in carbene chemistry, we proposed separating the process of carbene generation into two sequential single-electron operations, exploiting the potential of visible-light photocatalysts to control radical formation and manipulate the oxidation state of metal catalysts. Here we report a general visible-light-mediated strategy to access iron carbenes from abundant precursors by sequences of radical addition and reduction-induced α-elimination operating across six distinct types of non-traditional leaving groups. This approach enables cyclopropanation and X–H insertion reactions under mild conditions with broad functional group tolerance. More generally, this approach introduces the carbene equivalent of radical metallaphotoredox chemistry and overcomes many of the drawbacks of traditional strategies for carbene formation.

To develop a single-electron approach to carbene formation, we first examined existing strategies to identify important design aspects. The most common methods to access carbene intermediates involve starting materials with ylide-type characters, such as diazo-type compounds with a negative charge next to a diazonium ion[22,23]. The bifunctional nature of these species allows for the rapid formation of a metal carbene complex by nucleophilic attack on the metal centre followed by heterolytic α-elimination (which is contingent on the appropriate metal oxidation state) to forge the second metal–carbon bond. The requirement

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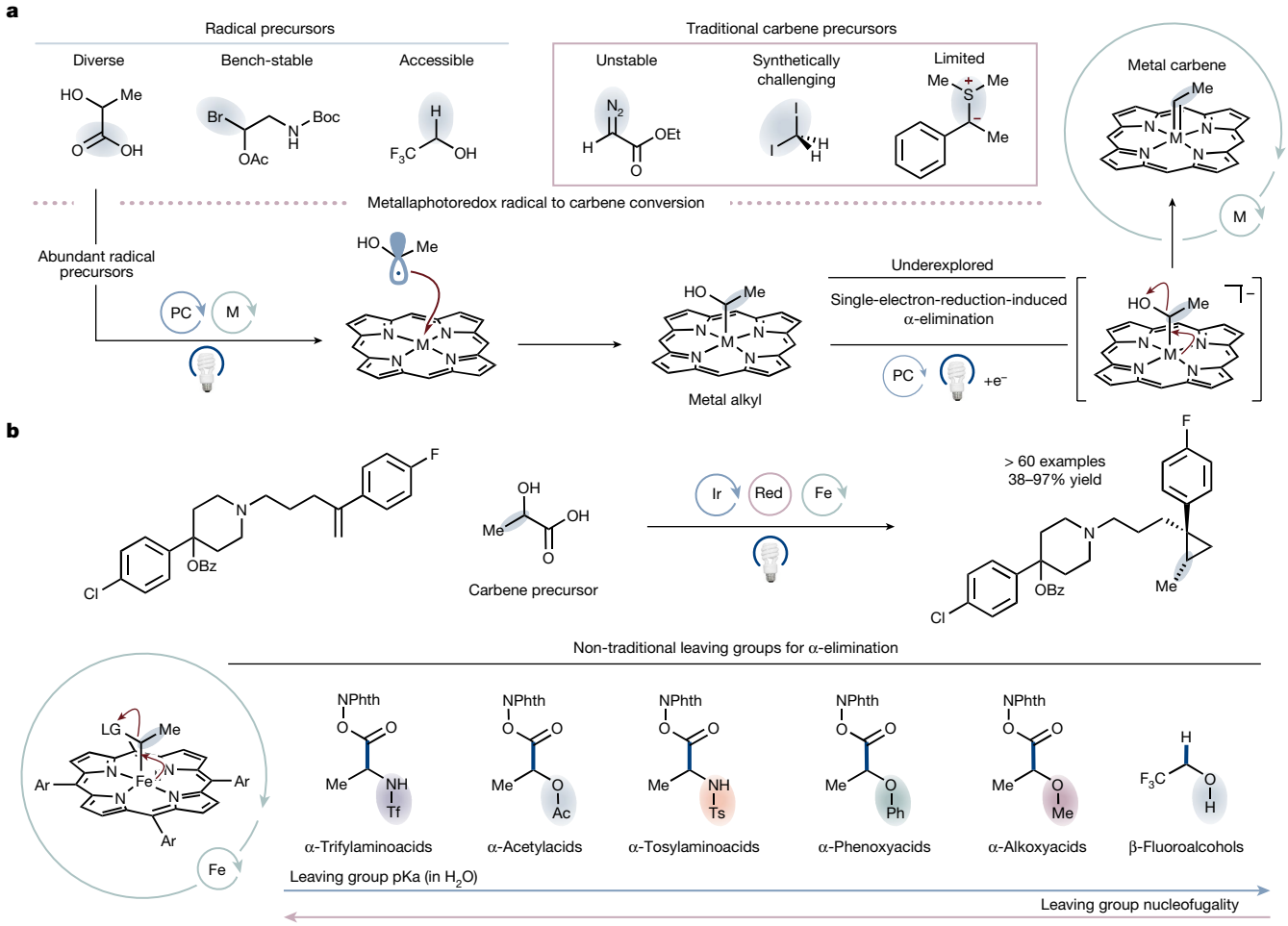

Fig. 1 | Enabling carbene reactivity by radical intermediates. a, Radical starting materials as alternatives to hazardous and limiting traditional carbene precursors. **b**, General approach to iron carbene reactivity through carboxylic acids, amino acids and alcohol precursors using metallaphotoredox for cyclopropanation and σ-bond insertion. Me, methyl; Boc, *tert*-butyloxycarbonyl; Et, ethyl; Bz, benzoyl; NPhth, phthalimide; Ar, 4-methoxyphenyl; Ac, acetyl; Tf, trifluoromethylsulfonyl; Ts, 4-toluenesulfonyl; Ph, phenyl. LG corresponds to the α-elimination leaving group and varies based on the radical precursor used.

for ylide-type reactivity limits the pool of potential starting materials for carbene reactivity and the general functional group tolerance of any method developed with this chemistry. We questioned whether it would be possible to mimic ylide-type reactivity by using single-electron intermediates bearing a leaving group at the incipient radical centre. To generate a carbenoid equivalent, radical metalation would yield the first metal–carbon bond, precluding the requirement for nucleophilic reactivity[8]. Because of the low energy barrier for radical metalation, the event would occur at or close to the rate of diffusion, limiting off-cycle radical coupling or addition-type processes[24,25]. Single-electron reduction of the metal centre would then trigger α-elimination, ejecting the leaving group and furnishing the desired metal carbene species. The timing of radical generation and manipulation of the redox state of the metal is important to success here and, as such, photocatalysis was pursued as a means to orchestrate these events[8] (Fig. 1a). Although radical addition to metal centres is well-established in photocatalytic regimes[8], there are few reports of single-electron reduction-induced α-elimination, resulting in poor understanding of the leaving groups, and by extension carbene precursors, that would be tolerated within this step[26–29]. Realization of this proposed reaction archetype would enable access to various modes of radical generation, expanding the limited palette of metal carbenes and, in turn, the types of transformations enabled by these organometallic complexes. As such, achieving the desired carbene reactivity from radical precursors necessitated an investigation into the proposed redox-induced α-elimination.

Probing radical approach to carbene intermediates

To realize this new carbene model, three components need to be addressed: (1) radical generation from the appropriate precursor; (2) identification of an appropriate metal for radical binding and redox window for controlled oxidation state changes; and (3) establishment of the ability of that metal to engage in α-elimination with synthetically convenient leaving groups on oxidation state change. To evaluate the viability of our proposed sequence, α-acetoxy carboxylic acids were chosen because of the ease of radical formation from carboxylic acids, a benefit amplified by the nucleofugality of the acetate group and the synthetic accessibility of this motif from biologically abundant 2-hydroxyacids[19,30]. We selected iron porphyrins as the metal scaffold for the evaluation of radical binding and α-elimination. Iron has demonstrated metalation reactivity with alkyl radicals and has a rich history of carbene reactivity[28,31–39]. Furthermore, iron can readily facilitate α-elimination when in the appropriate oxidation state, and such states can be controlled with photocatalysts[28,29]. Cyclopropanation was selected as a model reaction to capture evidence of putative carbene intermediates. This choice was motivated, in part, by the established reactivity of iron-mediated carbene insertion across olefins. Further motivation for using cyclopropanation was derived from the value of the resulting cyclopropane products to the industrial and academic communities[40–43]. In evaluating our proposed reaction sequence, we observed the successful cyclopropanation of 2-(prop-1-en-2-yl)naphthalene by

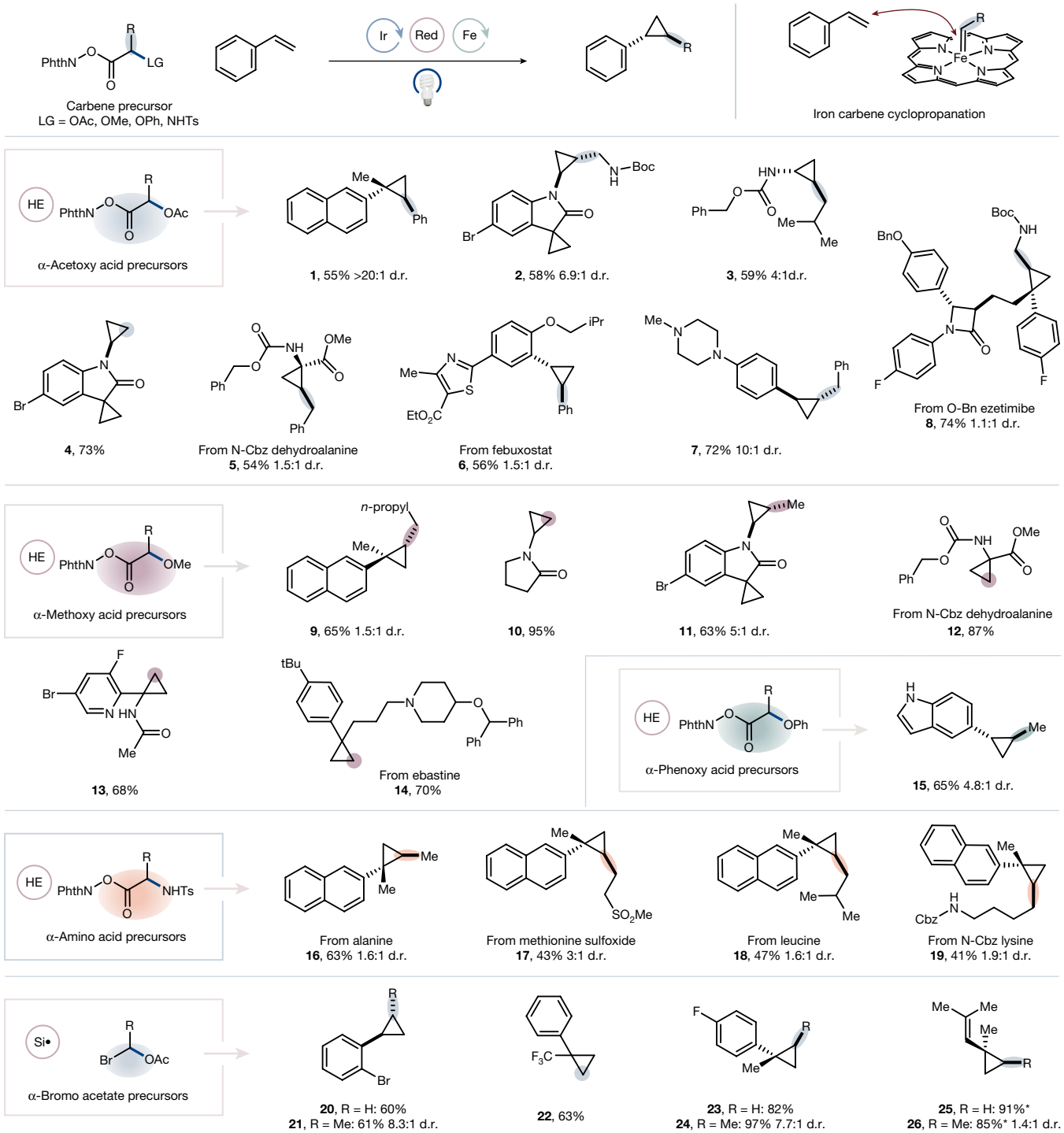

Fig. 2 | Scope of photoredox-enabled iron carbene cyclopropanation using carboxylic acids as precursors. α-Acetoxy, α-methoxy and α-phenoxy carboxylic acids, α-amino acids and α-bromo acetates can be used as carbene precursors. Experiments run with 1.0 equiv. of olefin, 2.0 equiv. carbene precursor, 3.0 equiv. Hantzsch ester or 3.5 equiv. $AdNHSi(TMS)_3$, 7.5 mol% iron catalyst and 2 mol% Ir photocatalyst irradiating using a Penn integrated photoreactor with 450-nm plates for 12 h. For amine-containing substrates, 1.0 equiv. trifluoromethanesulfonic acid (TfOH) was added to the reaction before irradiation. Isolated yields are shown except where noted. Major diastereomer shown (diastereomeric ratio (d.r.) reported from crude reaction mixtures and is relative stereochemistry around cyclopropane). The asterisk indicates ^{1}H NMR yield using 1,3,5-trimethoxybenzene as an internal standard. See Supplementary Information for experimental details. LG, leaving group; HE, Hantzsch ester; Si•, $AdNHSi(TMS)_3$; Boc, *tert*-butyloxycarbonyl; Bn, benzyl; Et, ethyl; Ph, phenyl; Me, methyl; Cbz, benzyl oxycarbonyl; PhthN, phthalimide; Ts, 4-toluenesulfonyl; Ac, acetyl; tBu, *tert*-butyl; iPr, isopropyl.

acetate-protected lactic acid (activated as an *N*-hydroxyphthalimide [NHPI] ester), using diethyl 1,4-dihydro-2,6-dimethyl-3,5-pyridinedicarboxylate (Hantzsch ester) as a sacrificial reductant, with catalytic 5,10,15,20-tetrakis(4-methoxyphenyl)-21H,23H-porphine iron(III) chloride (Fe(TMPP)Cl) and $Ir(dFCF_3ppy)_2dttbpyPF_6$ under blue-light irradiation. This initial reaction provided a proof of concept that a radical approach to carbene intermediates was a viable strategy. On optimization, the desired cyclopropanated product was obtained in 95% yield (see Supplementary Information for further details). Control experiments showed the necessity of all reaction components; no product was formed

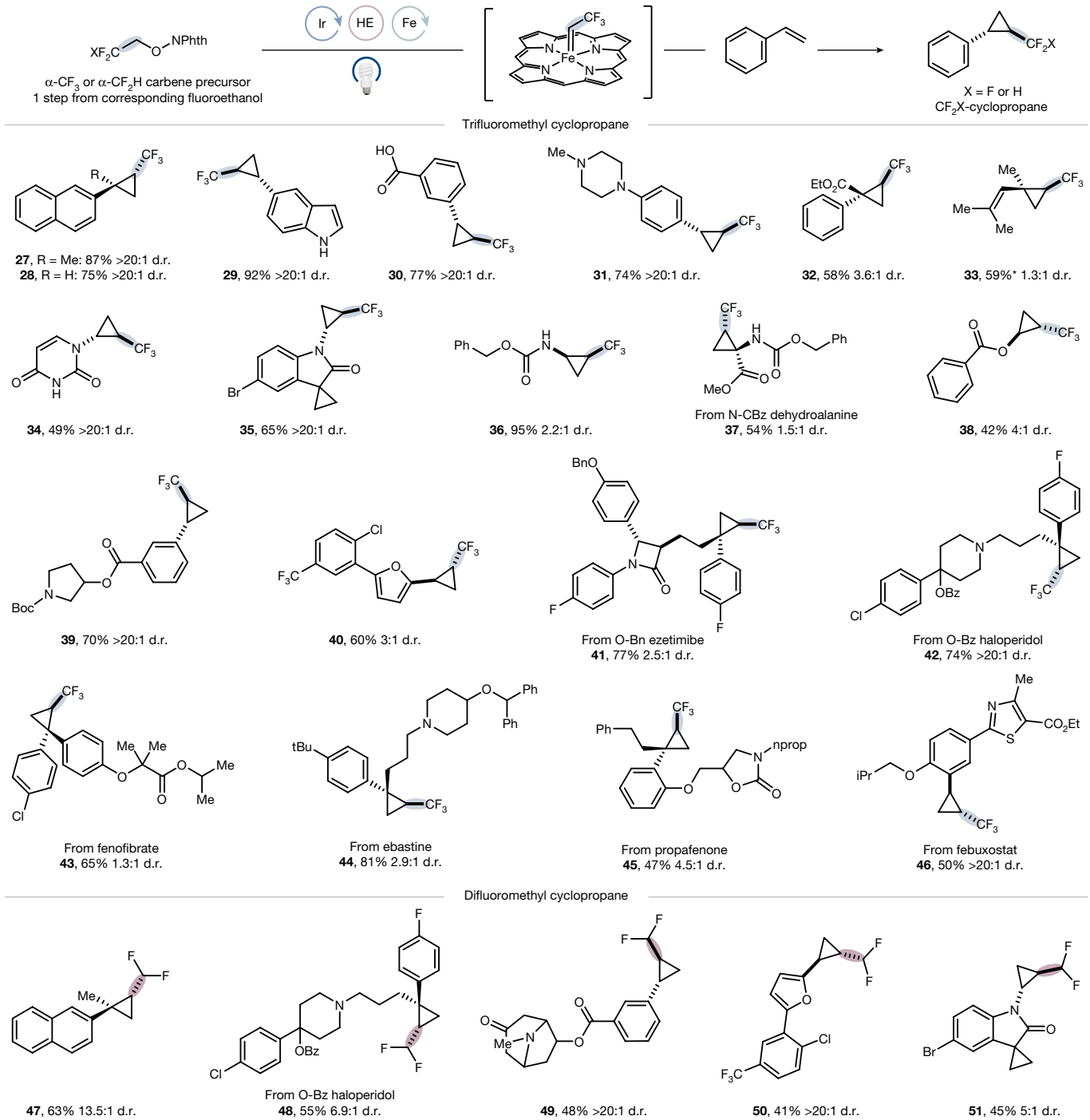

Fig. 3 | Scope of tri- and difluoromethyl cyclopropanation through carbene metallaphotoredox. Formal 1,2-HAT ketyl radical generation for carbene reactivity from β-fluoro alcohols. Experiments run with 1.0 equiv. of olefin, 2.0 equiv. carbene precursor, 3.0 equiv. Hantzsch ester, 7.5 mol% iron catalyst and 2 mol% Ir photocatalyst irradiating using a Penn integrated photoreactor with 450-nm plates for 12 h. For amine-containing substrates, 1.0 equiv. TfOH was added to the reaction before irradiation. Isolated yields are shown except where noted. Major diastereomer shown (diastereomeric ratio (d.r.) reported from crude reaction mixtures and is relative stereochemistry around cyclopropane). See Supplementary Information for experimental details. The asterisk indicates ^{19}F NMR yield using 4-fluoro methylbenzoate as an internal standard. Boc, *tert*-butyloxycarbonyl; Bn, benzyl; Et, ethyl; Ph, phenyl; Me, methyl; Cbz, benzyl oxycarbonyl; NPhth, phthalimide; Ac, acetyl; Bz, benzoyl; nProp, normal propyl; tBu; *tert*-butyl; iPr, isopropyl.

in the absence of the iron catalyst, light or Hantzsch ester. Diminished efficiency (36%) was observed in the absence of the iridium photocatalyst, consistent with a Hantzsch-ester-mediated electron donor–acceptor complex for radical generation[44] (see Extended Data Fig. 1 for proposed catalytic cycle and Supplementary Fig. 1 for further discussion). Taken together, these initial experiments support the viability of our new metallaphotoredox-mediated carbene generation and capture model.

Having established the viability of this process for cyclopropanation, and with the initial optimal conditions, we explored the scope of leaving groups viable for iron carbene formation. We synthesized NHPI esters of lactic acid derivatives possessing a range of non-traditional α-oxygenated leaving groups: α-phenoxy, α-methoxy and α-hydroxy. Under the optimized conditions identified for the α-acetoxy system, all of these substrates were effective in cyclopropanation (77–95% yield)

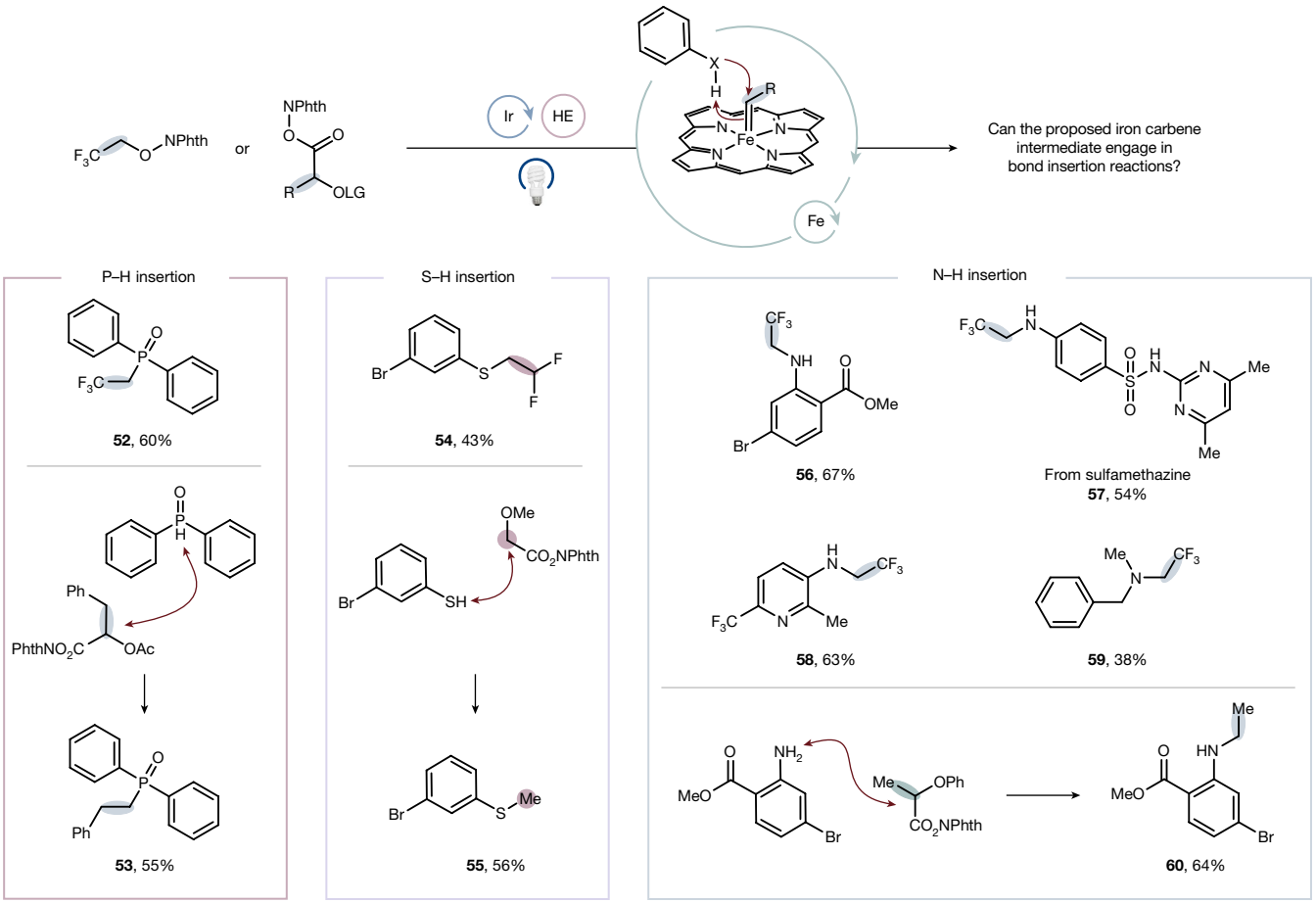

Fig. 4 | Insertions of σ-bond through metallaphotoredox carbene formation. P–H, S–H and N–H insertions are viable using carboxylic acid and alcohol-derived precursors through iron carbene intermediates. Experiments run with 1.0 equiv. of olefin, 2.0 equiv. carbene precursor, 3.0 equiv. Hantzsch ester, 7.5 mol% iron catalyst and 2 mol% Ir photocatalyst irradiating using a Penn integrated photoreactor with 450-nm plates for 12 h. Isolated yields are shown. See Supplementary Information for experimental details. Ac, acetyl; Ph, phenyl; Me, methyl; NPhth, phthalimide.

(Supplementary Fig. 5). This tolerance led us to question whether leaving groups beyond oxygen-based systems would be viable. We investigated α-amino acids as precursors for iron carbenes using our net reductive reaction conditions. Using a range of amine-protecting groups, we systematically evaluated the α-elimination step. Although most protecting groups were ineffective, including those within the expected nucleofugality range[45–47] (see Supplementary Fig. 8 for full list), we observed that tosyl- and trifyl-protected α-amino acids provided the desired cyclopropanated products in good yields. The extension to tosyl- and trifyl-amine leaving groups is a rare example of nitrogen-based leaving groups participating in substitution- and elimination-type reactivity and an underexplored strategy for deaminative functionalization[48–50]. Reaction development resulted in the identification of six distinct leaving groups capable of serving as carbene precursors, demonstrating the tolerance of iron porphyrin α-elimination to a wide range of leaving group abilities (a range of more than 10 pK_a (acid dissociation constant)units) and offering a modular strategy to access carbene intermediates (Fig. 1b).

Cyclopropanation using iron carbene intermediates

With optimized cyclopropanation conditions, we explored the scope of carboxylic acids and alkenes. We found both benzyl and alkyl carbenes, generated from α-acetoxy carboxylic acids, to be effective partners (Fig. 2). Styrenes (**1**) and electron-rich alkenes (**2**–**4**) smoothly underwent cyclopropanation, consistent with the well-established electrophilic reactivity of our proposed iron porphyrin carbene intermediate[33]. Benzyl carbamate (CBz)-protected dehydroalanine was cyclopropanated in moderate yield (**5**), indicating a mild and facile approach to peptide backbone modification. Importantly, complex scaffolds bearing a range of functional groups were found to undergo efficient metallaphotoredox cyclopropanation, demonstrating the amenability of this method to late-state functionalization (**6**–**8**). Tertiary amines, traditionally problematic under photoredox conditions because of competitive oxidation[51,52], were well tolerated under a modified protocol involving the addition of one equivalent of triflic acid to protonate the amine (**7**). An exploration of the scope of α-methoxy and α-phenoxy carboxylic acids again demonstrated that a range of substituted carbenes and alkenes perform well under the reaction conditions, including those containing medicinally relevant heteroaromatic rings[53] (**9**–**15**). Several amino acids underwent carbene formation, albeit with diminished reactivity and yields; tosyl-protected alanine, methionine sulfoxide, leucine and lysine served as viable carbene precursors (**16**–**19**). We found that a diverse array of cyclopropanated scaffolds could be accessed using multiple variations of both the radical precursor and olefin coupling partners (see Supplementary Fig. 14 for more examples).

Beyond carboxylic acids as carbene precursors

Given that the binding of a radical to a metal centre is disconnected from the origin of that radical, we wondered whether this model could

be extended to alternate radical precursors beyond those derived from carboxylic acids. Early studies supported the generality of this approach; α-bromo acetates that are either commercially available or easily generated from the corresponding aldehydes can be engaged by silyl radical-mediated halogen atom abstraction (XAT)[54,55]. On metalation of this alkyl radical species, controlled α-elimination generates the carbene intermediate, which in turn readily undergoes cyclopropanation[19] (**20**–**26**) (Fig. 2, bottom). This finding encouraged us to explore other precursors of carbenes that would be arduous or even dangerous to make by other means. We turned our attention to accessing fluoroalkyl carbenes en route to high-value fluoroalkyl cyclopropanes. Fluoromethylated cyclopropanes have emerged as valuable motifs in pharmaceuticals because of their metabolic stability and beneficial effect on pharmacokinetic and pharmacodynamic profiles[56,57]. Despite growing interest in these small carbocycles, fluoromethylated cyclopropanes are particularly challenging to access as they must currently be synthesized through diazo species, which pose substantial safety concerns[58,59]. Recently, *N*-hydroxyphthalimide-activated β-fluoro alcohols have been shown to fragment to generate ketyl intermediates through a formal 1,2-hydrogen atom transfer (HAT) process (see Supplementary Fig. 9 for proposed mechanism)[60,61]. Owing to the presence of the hydroxy motif geminal to a C(sp^3)-radical, we proposed that these alcohol-derived ketyl intermediates could serve as effective precursors to deliver fluoro-alkylated cyclopropane products through the metallaphotoredox carbene protocol described here. Using a readily accessible 2,2,2-trifluoroethylated NHPI ether, cyclopropanation proceeds smoothly when using styryl derivatives (**27**, **28**), including those with unprotected indoles (**29**) and carboxylic acids (**30**) (Fig. 3), demonstrating tolerance for acidic functionality that would be problematic using traditional carbene precursors because of their ylide-type character. Free amines are tolerated (**31**) under the acidic protonation strategy described earlier. Electron-deficient styrenes containing α-ester functionality undergo cyclopropanation in reasonable yield (**32**), and dienes are successfully converted to allylic trifluoromethylated cyclopropanes (**33**). An enamide derived from uracil exclusively reacts at the more electron-rich olefin (**34**), consistent with electrophilic iron porphyrin carbene reactivity[33]. Anilines and Cbz-protected amines are well tolerated in the reaction, providing amino cyclopropane products (**35**–**37**). Less synthetically accessible cyclopropanes, such as a hydroxycyclopropane equivalent, can also be accessed by vinyl benzoate (**38**). Pharmaceutical compounds and complex drug-like scaffolds are cyclopropanated in high yields, demonstrating the high functional group tolerance of the method and the potential for application to late-stage functionalization (**39**–**46**). The use of 2,2-difluoroethanol as the starting material proved similarly effective, furnishing difluoromethyl-substituted cyclopropanes in moderate yields (**47**–**51**). By exploiting the ketyl-type fragmentation of β-fluoro NHPI-activated alcohols under reductive conditions, we obtained elusive di- and tri-fluoromethylated cyclopropanes under our mild reaction conditions.

σ-Bond insertion reactions

Beyond cyclopropanation, iron carbenes are known to undergo σ-bond insertion reactions because of their Fischer-type carbene character[62]. This reactivity provides another potential avenue to harness the transient carbenes generated by metallaphotoredox, while concurrently verifying the intermediacy of iron carbenes in this platform. Our efforts to achieve σ-bond insertion using our newly developed carbene platform proved successful. We observed the successful insertion of β-fluoro alcohol and carboxylic acid-based systems into P–H bonds (Fig. 4; **52** and **53**). Extending this reactivity to thiophenol starting materials enabled the synthesis of (difluoro)alkylated thioether products (**54** and **55**). Furthermore, N–H alkylation of both anilines and amines proceeded smoothly, including on scaffolds containing medicinally important electron-deficient heteroarenes[53] (**56**–**59**). Monoalkylated amine products were obtained by reaction with NHPI-activated α-phenoxy propanoic acid, bypassing the conventional reactivity of amide bond formation (**60**). The successful demonstration of σ-bond insertion in these diverse settings further shows the ability of carbene intermediates to engage in useful bond formations beyond annulation and establishes their power as reactive intermediates that may be effectively harnessed through our radical approach.

Outlook

In summary, we have proposed a conceptually new platform that effectively accesses high-energy carbenes using the merger of iron catalysis with photoredox catalysis. Bench-stable and ubiquitous starting materials, such as carboxylic acids, amino acids and alcohols, are readily converted to iron carbene intermediates through the energy of visible light. This approach overcomes the inherent limitations associated with accessing carbene reactivity using conventional methods and unlocks their potential as reactive intermediates under metallaphotoredox conditions from bench-stable starting materials using six types of underexplored leaving groups in reduction α-elimination steps. The use of this method is explained by the variety of scaffolds that can be accessed by cyclopropanation and σ-bond insertion. The process described here shows the broad tolerance for complexity that is characteristic of photochemical reactions. We believe that this approach will appeal to academic and industrial practitioners alike as a mechanistic approach for carbene generation and a powerful synthetic tool for exploiting carbene reactivity to enhance molecular complexity.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-024-07628-1.

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Methods

General procedure for cyclopropanation using α-oxy carboxylic acid precursors

An oven-dried 4 ml (≤0.5 mmol scale) or 40 ml (>0.5 mmol scale) vial equipped with a stir bar was charged with the $Ir(dFCF_3ppy)_2dttbpyPF_6$ (2 mol%), Fe(TMPP)Cl (7.5 mol%), Hantzsch ester (3.0 equiv.), alkene/styrene (1.0 equiv.) and redox-active ester (2.0 equiv.). *N*,*N*-dimethylacetamide (DMA) (0.1 M) was then added, and the vial was sealed with a cap. The reaction solution was sparged with N_2 for 2 min followed by an 8-min sparge of the vial headspace (as a precaution for volatile substrates). Following sparging, the vial was sealed with parafilm and placed in a Penn integrated photoreactor and irradiated for 12 h at 450 nm (100% light intensity, max fans (5,200 rpm) and 500 rpm stir rate). After irradiation, the reaction was diluted with H_2O and Et_2O and the organic layer was extracted (Et_2O extraction typically performed 3×). The combined organic layers were then washed with brine, dried ($MgSO_4$ or $NaSO_4$) and filtered over Celite. The filtrate was then concentrated under a reduced vacuum and the resulting residue was purified using flash column chromatography (SiO_2) to afford the cyclopropanated product.

General procedure for cyclopropanation using α-amino acid precursors

An oven-dried 4 ml (≤0.5 mmol scale) or 40 ml (>0.5 mmol scale) vial equipped with a stir bar was charged with the $Ir(ppy)_2dttbpyPF_6$ (2 mol%), Fe(TPP)Cl (5.0 mol%), tBuHantzsch ester (3.75 equiv.), alkene/styrene (1.00 equiv.) and redox-active ester (2.50 equiv.). Acetone (0.1 M) was then added, and the vial was sealed with a cap. The reaction solution was sparged with N_2 for 2 min followed by an 8 min sparge of the vial headspace (as a precaution for volatile substrates). Following sparging, the vial was sealed with parafilm and placed in a Penn integrated photoreactor and irradiated for 12 h at 450 nm (10% light intensity, max fans (5,200 rpm) and 500 rpm stir rate). After irradiation, the reaction was diluted with H_2O and Et_2O and the organic layer was extracted (Et_2O extraction typically performed 3×). The combined organic layers were then washed with brine, dried ($MgSO_4$ or $NaSO_4$), and filtered over Celite. The filtrate was then concentrated under a reduced vacuum and the resulting residue was purified using flash column chromatography (SiO_2) to afford the cyclopropanated product.

General procedure for cyclopropanation using α-bromo acetate precursors

An oven-dried 4 ml (≤0.5 mmol scale) or 40 ml (>0.5 mmol scale) vial equipped with a stir bar was charged with the $Ir(ppy)_2dttbpyPF_6$ (1.5 mol%), Fe(OEP)Cl (5.0 mol%), adamantyl aminosilane (4.50 equiv.), alkene/styrene (1.00 equiv.) and bromoacetate (3.50 equiv.). Dichloroethane (0.1 M) was then added, and the was vial sealed with a cap. The reaction solution was sparged with N_2 for 2 min followed by an 8-min sparge of the vial headspace (as a precaution for volatile substrates). Following sparging, the vial was sealed with parafilm and placed in a Penn integrated photoreactor and irradiated for 12 h at 450 nm (100% light intensity, max fans (5,200 rpm) and 500 rpm stir rate). After irradiation, the reaction was diluted with H_2O and Et_2O and the organic layer was extracted (Et_2O extraction typically performed 3×). The combined organic layers were then washed with brine, dried ($MgSO_4$ or $NaSO_4$) and filtered over Celite. The filtrate was then concentrated under a reduced vacuum and the resulting residue was purified using flash column chromatography (SiO_2) to afford the cyclopropanated product.

General procedure for cyclopropanation using β-trifluoromethyl alcohol precursors

An oven-dried 4 ml (≤0.5 mmol scale) or 40 ml (>0.5 mmol scale) vial equipped with a stir bar was charged with the $Ir(dFCF_3ppy)_2dttbpyPF_6$ (2 mol%), Fe(TMPP)Cl (7.5 mol%), Hantzsch ester (3.0 equiv.), alkene/styrene (1.0 equiv.) and 2-(2,2,2-trifluoroethoxy)isoindoline-1,3-dione (2.0 equiv.). DMA (0.1 M) was then added, and the vial was sealed with a cap. The reaction solution was sparged with N_2 for 2 min followed by an 8-min sparge of the vial headspace (as a precaution for volatile substrates). Following sparging, the vial was sealed with parafilm and placed in a Penn integrated photoreactor and irradiated for 12 h at 450 nm (100% light intensity, max fans (5,200 rpm) and 500 rpm stir rate). After irradiation, the reaction was diluted with H_2O and Et_2O and the organic layer was extracted (Et_2O extraction typically performed 3×). The combined organic layers were then washed with brine, dried ($MgSO_4$ or $NaSO_4$) and filtered over Celite. The filtrate was then concentrated under a reduced vacuum and the resulting residue was purified using flash column chromatography (SiO_2) to afford the cyclopropanated product.

General procedure for cyclopropanation using β-difluoromethyl alcohol precursors

An oven-dried 4 ml (≤0.5 mmol scale) or 40 ml (>0.5 mmol scale) vial equipped with a stir bar was charged with the $Ir(dFCF_3ppy)_2dttbpyPF_6$ (2 mol%), Fe(TMPP)Cl (15 mol%), Hantzsch ester (3.0 equiv.), alkene/styrene (1.0 equiv) and 2-(2,2,2-trifluoroethoxy)isoindoline-1,3-dione (2.0 equiv.). DMA (0.1 M) was then added, and the vial was sealed with a cap. The reaction solution was sparged with N_2 for 2 min followed by an 8-min sparge of the vial headspace (as a precaution for volatile substrates). Following sparging, the vial was sealed with parafilm and placed in a Penn integrated photoreactor and irradiated for 12 h at 450 nm (10% light intensity, max fans (5,200 rpm) and 500 rpm stir rate). After irradiation, the reaction was diluted with H_2O and Et_2O and the organic layer was extracted (Et_2O extraction typically performed 3×). The combined organic layers were then washed with brine, dried ($MgSO_4$ or $NaSO_4$) and filtered over Celite. The filtrate was then concentrated under a reduced vacuum and the resulting residue was purified using flash column chromatography (SiO_2) to afford the cyclopropanated product.

General procedure for X–H bond insertions

An oven-dried 4 ml (≤0.5 mmol scale) or 40 ml (>0.5 mmol scale) vial equipped with a stir bar was charged with the $Ir(dFCF_3ppy)_2dttbpyPF_6$ (2 mol%), Fe(TMPP)Cl (7.5 mol%), Hantzsch ester (3.0 equiv.), nucleophile (1.0 equiv.) and redox-active ester (2.0 equiv). DMA (0.1 M) was then added, and the vial was sealed with a cap. The reaction solution was sparged with N_2 for 2 min followed by an 8-min sparge of the vial headspace (as a precaution for volatile substrates). Following sparging, the vial was sealed with parafilm and placed in a Penn integrated photoreactor and irradiated for 12 h at 450 nm (100% light intensity, max fans (5,200 rpm) and 500 rpm stir rate). After irradiation, the reaction was diluted with H_2O and Et_2O and the organic layer was extracted (Et_2O extraction typically performed 3×). The combined organic layers were then washed with brine, dried ($MgSO_4$ or $NaSO_4$) and filtered over Celite. The filtrate was then concentrated under a reduced vacuum and the resulting residue was purified using flash column chromatography (SiO_2) to afford the σ-bond insertion product.

Data availability

All data supporting the findings of this study are available in the main text or in the Supplementary Information.

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Author contributions D.W.C.M., N.W.D. and B.T.B. conceptualized the radical approach to carbenes. B.T.B., N.W.D., C.B.K. and M.C.B. designed the experiments. B.T.B. and N.W.D. performed and analysed the experiments. B.T.B., C.B.K., M.C.B., N.W.D. and D.W.C.M. prepared the Article. D.W.C.M. directed the project.

Competing interests D.W.C.M. declares an ownership interest in Penn PhD photoreactor, which is used to irradiate reactions in this work. The other authors declare no competing interests.

Additional information

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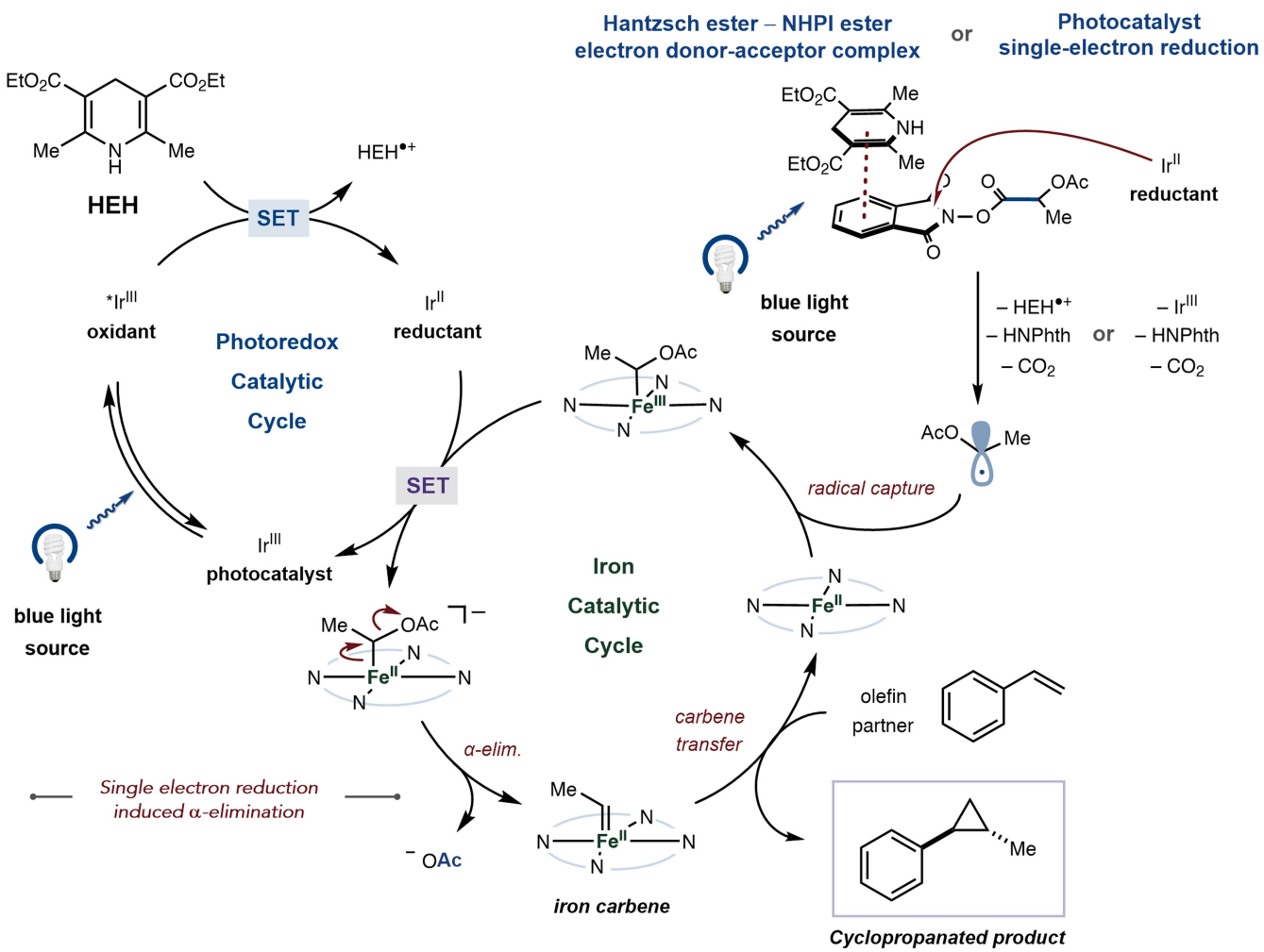

Extended Data Fig. 1 | Proposed mechanism for iron porphyrin carbene formation through metallaphotoredox catalysis. Metallaphotoredox-mediated formation of iron porphyrin carbene intermediates exploiting a single-electron reduction mediated α-elimination. Me, methyl; Et, ethyl, Ac, acetyl; Phth, phthalimide; $HEH^{+\bullet}$, oxidized Hantzsch ester; Ir, $Ir(dFCF_3ppy)_2dttbpy$; Fe, iron porphyrin. For further commentary and discussion see Supplementary Fig. 1.