Upgrading NHC by Structure Modification

Reporter: Xingyuan Gao

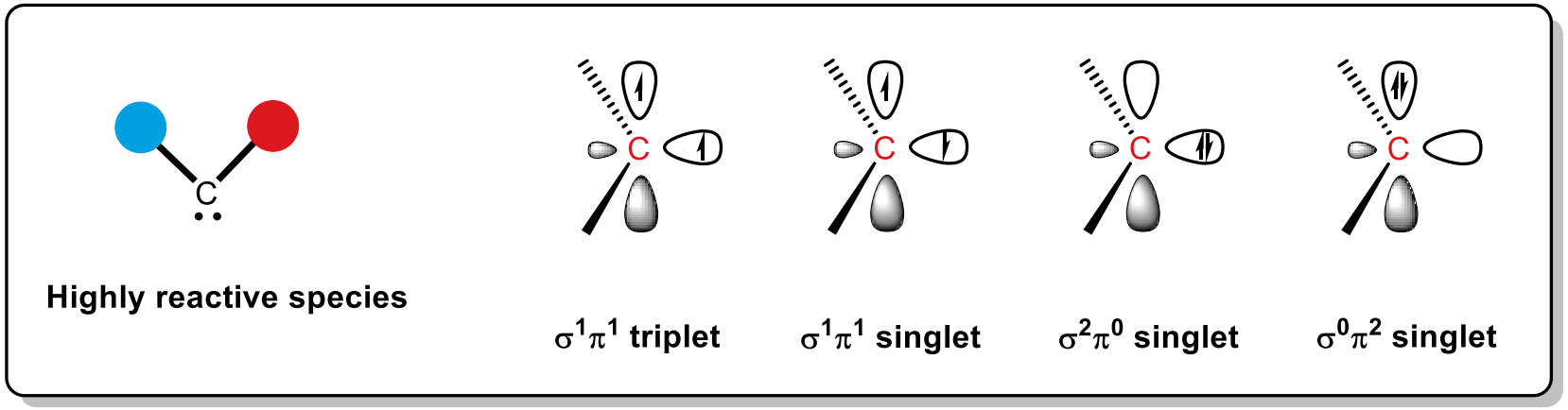
Supervisor: Prof. Zhang-Jie Shi

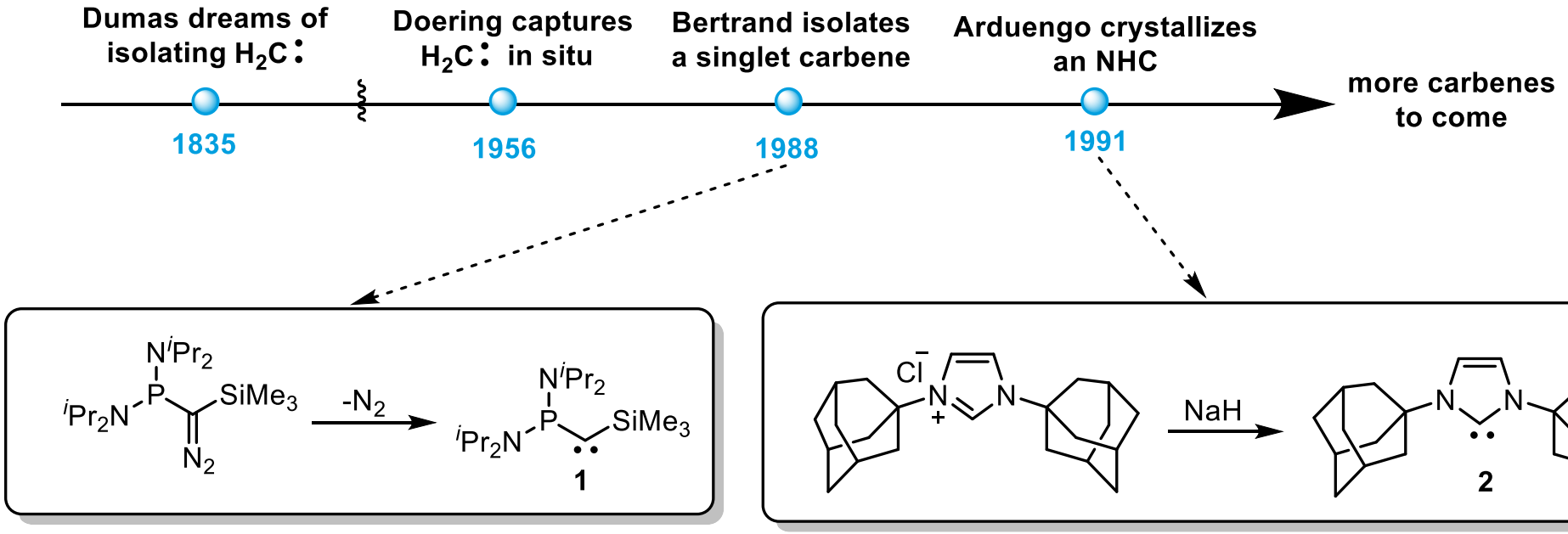
2025-11-7

Content

Content

Introduction

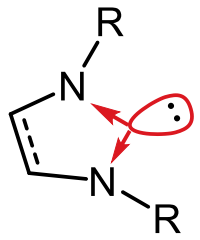




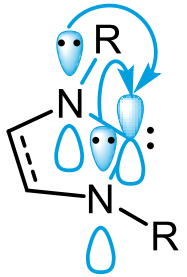
a) G. Bertrand, *J. Am. Chem. Soc.*, **1988**, 110, 19, 6463-6466; b) A. G. Arduengo, *J. Am. Chem. Soc.*, **1991**, 113, 361-363; c) L. L. Liu, *Science*, **2024**, 383, 81–85.

Introduction

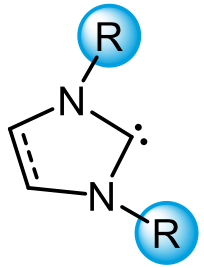
Electronic properties of NHC



σ-accepting N



π-donating N



Steric hindrance

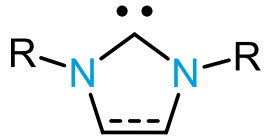
LUMO - 0.46 eV

HOMO - 5.97 eV

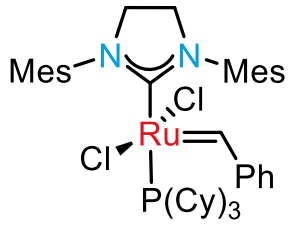
$\Delta E_{S/T}$ 81.4 kcal/mol

Strong stable σ-donor !

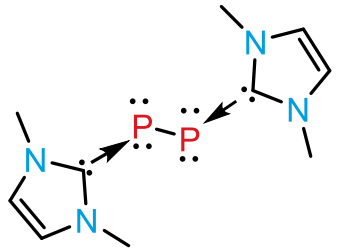
Major applications of NHC



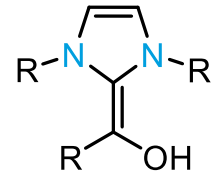
Coordinated to transition metals



Coordinated to p-block elements



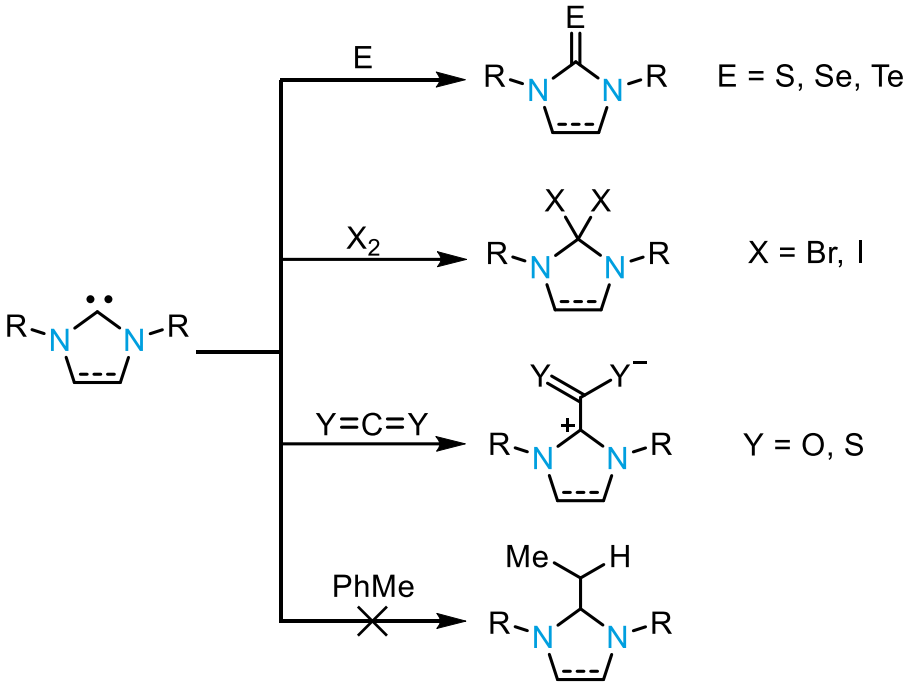
As Organocatalysts



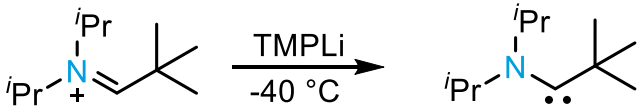
a)) F. Glorius, *Nat. Rev. Chem.*, **2021**, 5, 711-725; b) F. Glorius, *Nature*, **2014**, 510, 485-496.

Introduction

N Stabilize carbene center but sacrifices reactivity

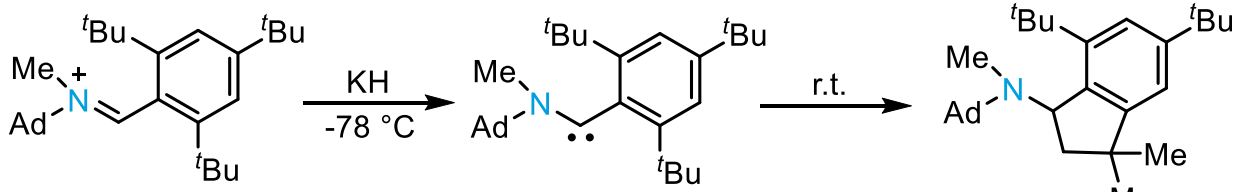


Only one N is necessary to isolate carbene



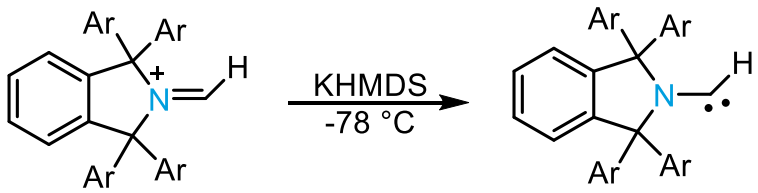
3

not stable in solution



4

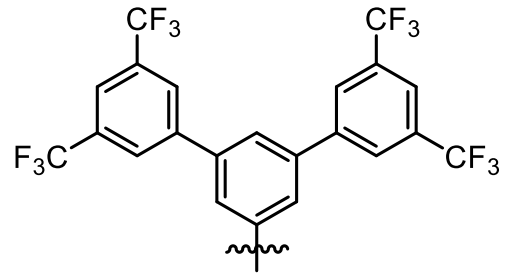
stable at -50 °C



5

not stable in solution

Ar =



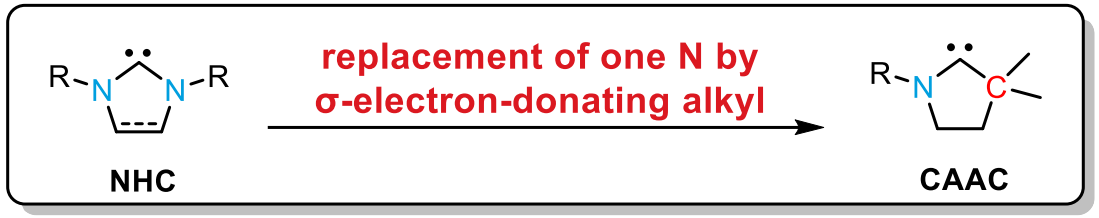
High stability → **High reactivity**

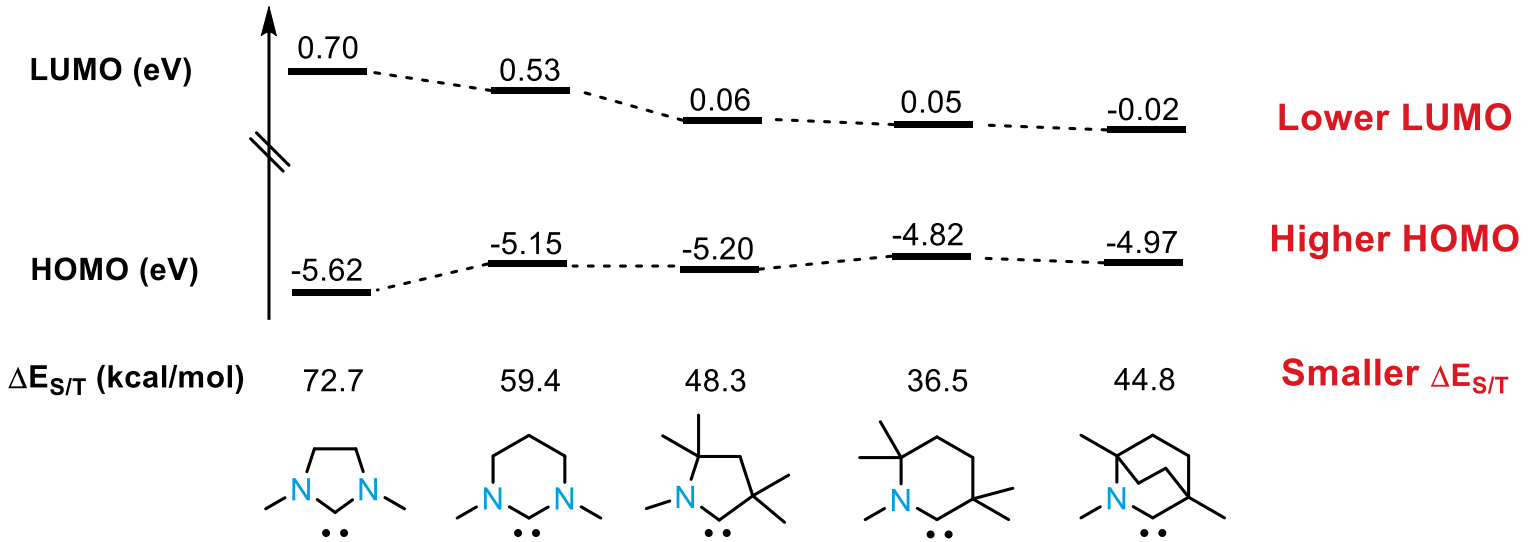
a) G. Bertrand, *Science*, **2001**, 292, 1901-1903; b) G. Bertrand, *J. Am. Chem. Soc.*, **2004**, 126, 8670-8671; c**)** G. Bertrand, *Nat. Chem.*, **2018**, 10, 1196-1200**.**

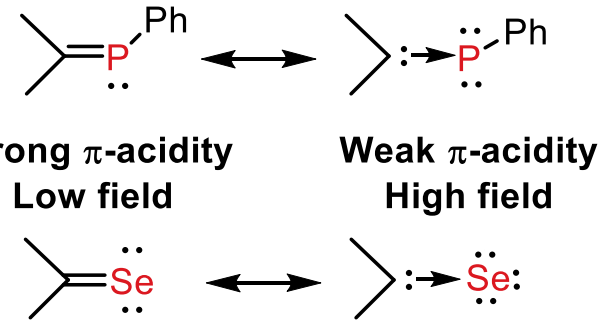
Content

Replace N by C

Electronic properties of CAACs





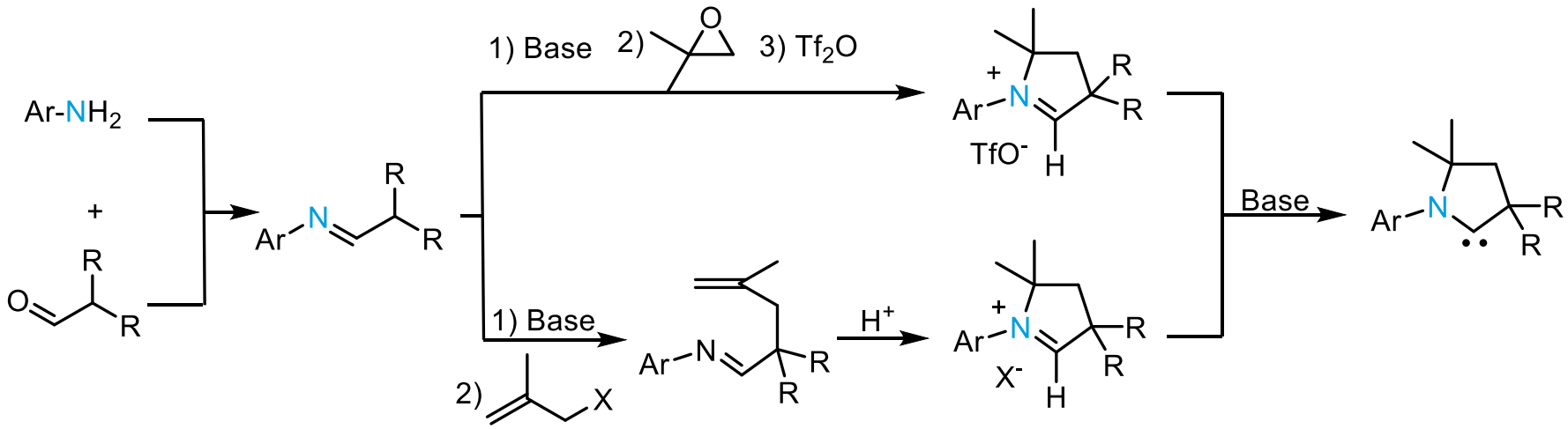


Compound	NHC	^{Me}CAAC-5	^{Et}CAAC-6	BICAAC
^{31}P (ppm)	< 40	69	103	90
^{77}Se (ppm)	< 200	481	715	645

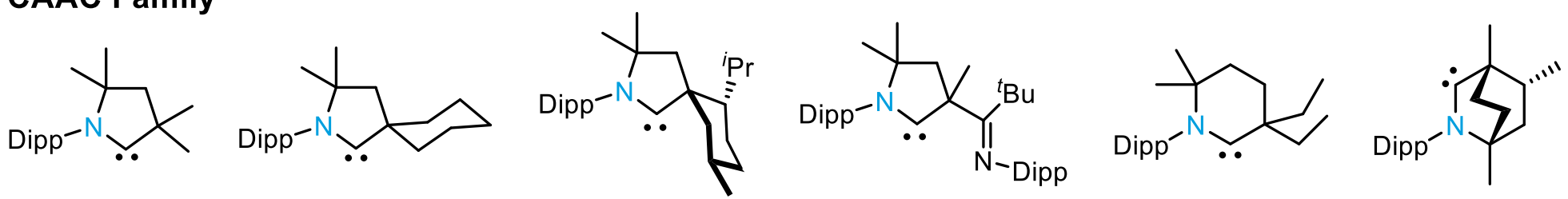
a) G. Bertrand, *Angew. Chem. Int. Ed.*, **2013**, 52, 2939-2943; b) C. W. Bielawski, *Acc. Chem. Res.*, **2016**, 49, 1458-1468; c) U. Radius, *Chem. Eur. J.*, **2016**, 22, 11005-11014; d) G. Bertrand, *Angew. Chem. Int. Ed.*, **2017**, 56, 10046-10068; d) G. Bertrand, *Angew. Chem., Int. Ed.*, **2020**, 59, 22028-22033.

Replace N by C

Synthesis of CAAC



CAAC Family

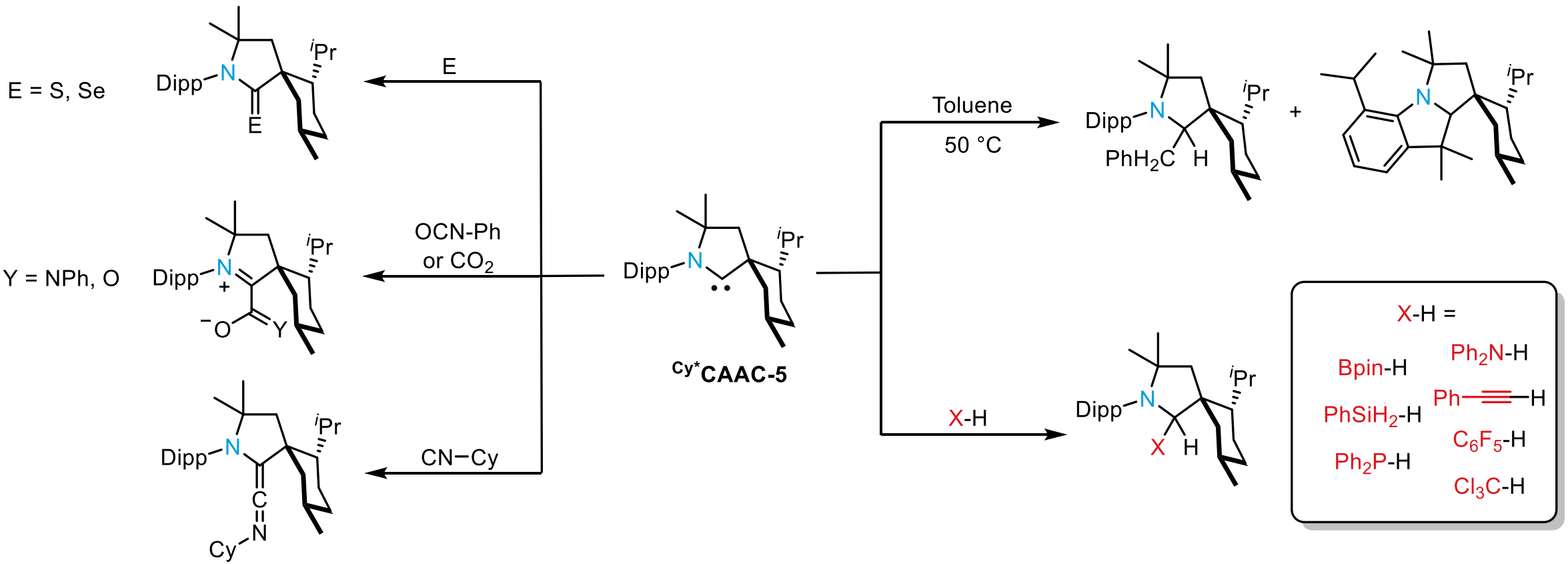


MeCAAC-5 CyCAAC-5 Cy*CAAC-5 FunCAAC-5 EtCAAC-6 BICAAC

a) G. Bertrand, *Angew. Chem. Int. Ed.*, **2005**, 44, 5705-5709; b) G. Bertrand, *J. Am. Chem. Soc.*, **2017**, 139, 7753-7756 ; c) G. Bertrand, *J. Am. Chem. Soc.*, **2018**, 140, 9255-9260.

Replace N by C

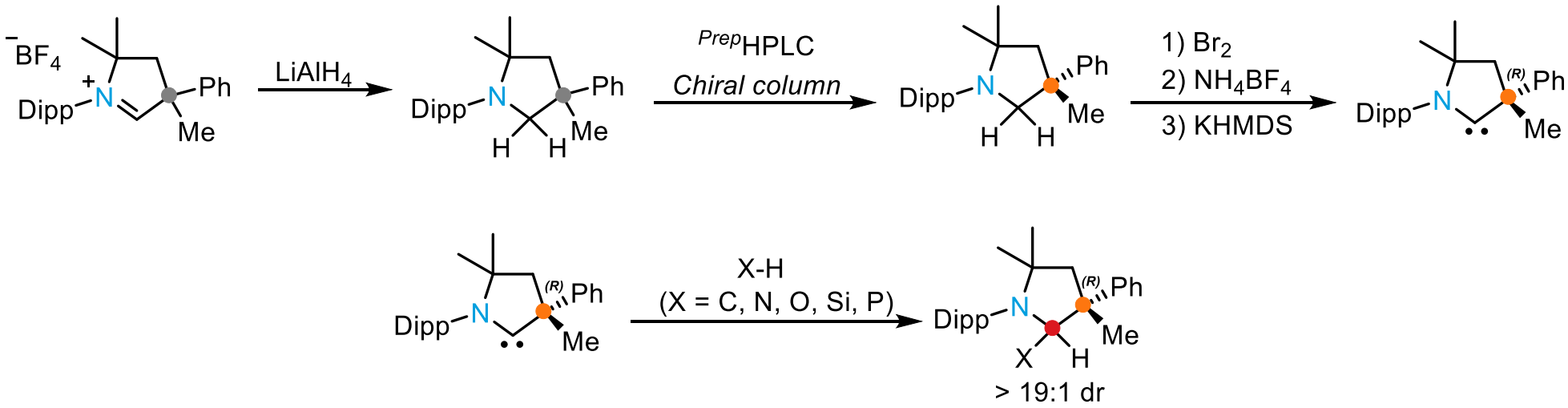
Reactivity of CAACs

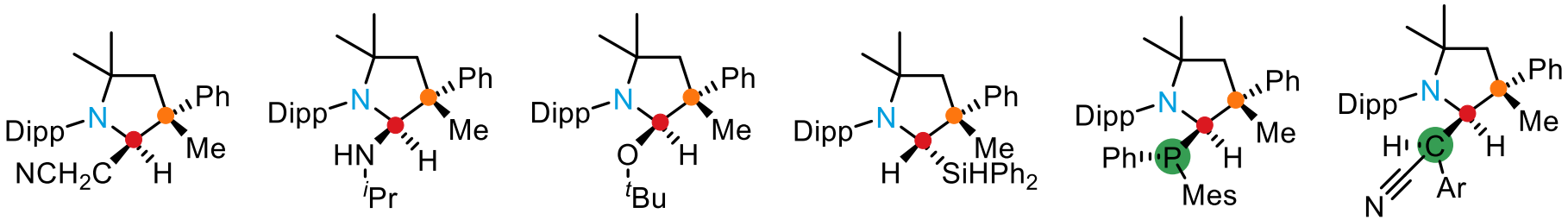


a) G. Bertrand, *Angew. Chem. Int. Ed.*, **2006**, 45, 3488-3491; b) G. Bertrand, *Science*, **2007**, 316, 439-441; c) Z. R. Turner, *Chem. Eur. J.*, **2016**, 22, 11461-11468; d) U. Radius, *Chem. Eur. J.*, **2016**, 22, 13032–13036; e) G. Bertrand, *Angew. Chem. Int. Ed.*, **2010**, 49, 9444-9447; f) U. Radius, *Chem. Eur. J.* **2016**, 22, 13032-13036.

Replace N by C

Reactivity of CAACs





(R,R)
> 19:1 dr

(R,S)
> 19:1 dr

(R,R)
> 19:1 dr

(R,S)
> 19:1 dr

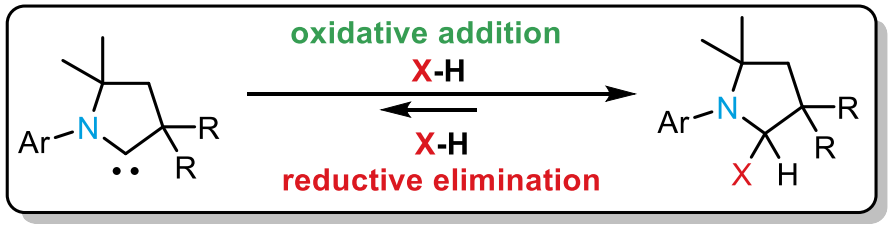
(R,R,S)
> 19:1 dr

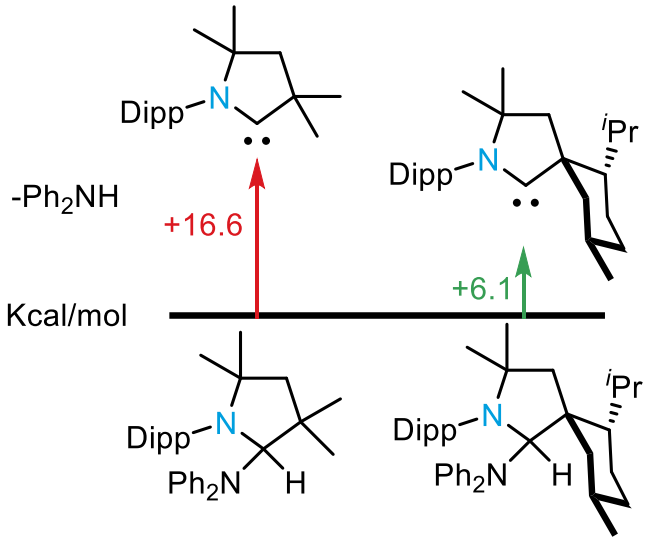
(R,R,R)
> 19:1 dr
Ar = *p*-tolyl

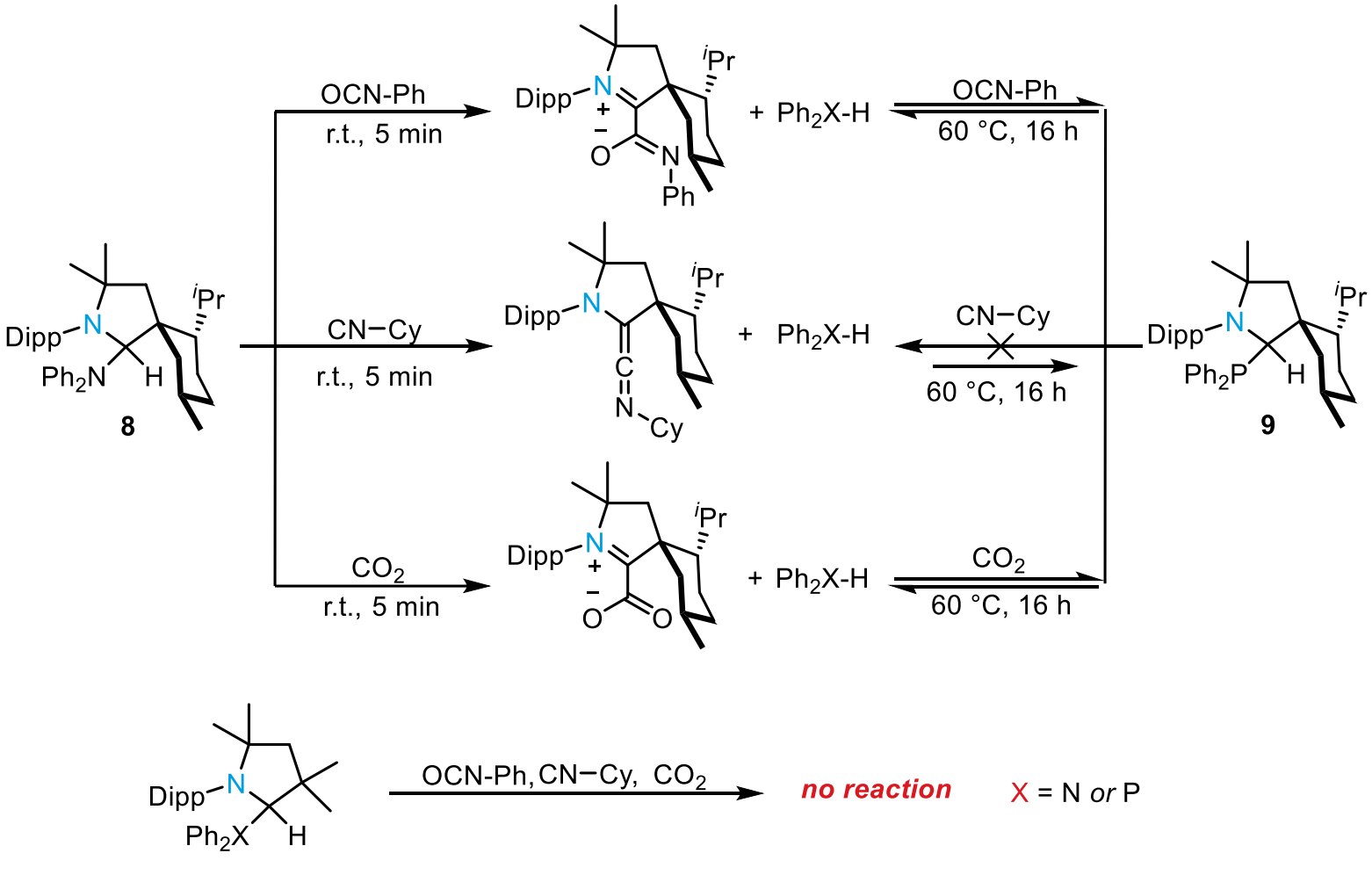
G. Bertrand, *J. Am. Chem. Soc.*, **2025**, 147, 17, 14777-14784.

Replace N by C

Reductive elimination on carbene center



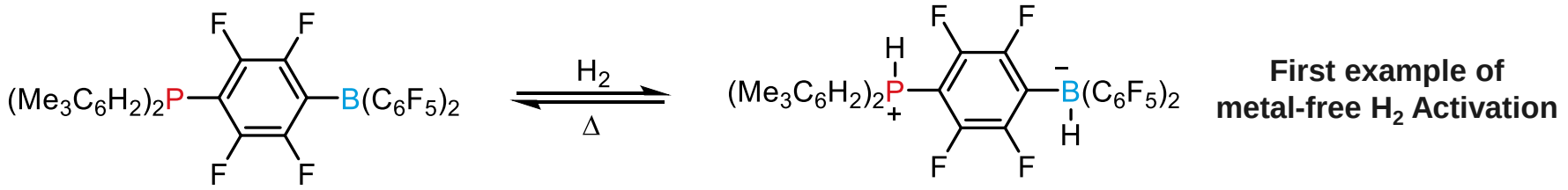




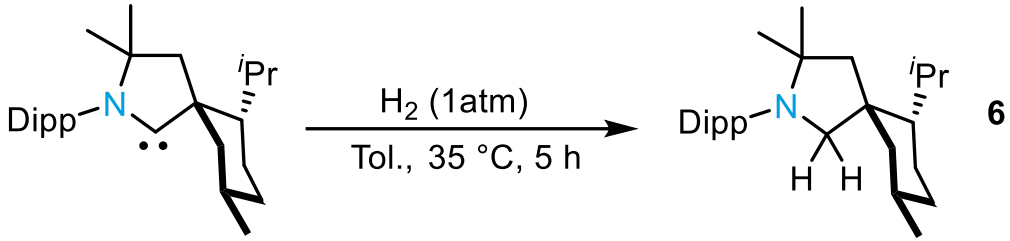
G. Bertrand, *J. Am. Chem. Soc.*, **2019**, 141, 9823-9826.

Replace N by C

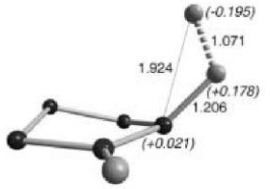
Activation of H_2 and NH_3 by CAAC

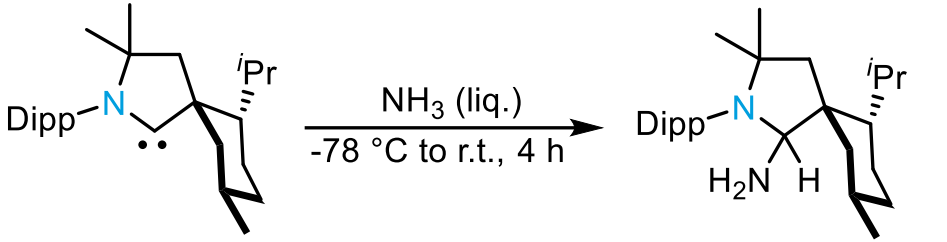


First example of metal-free H_2 Activation

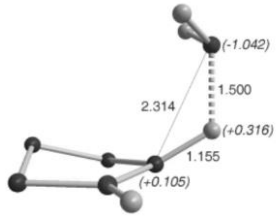


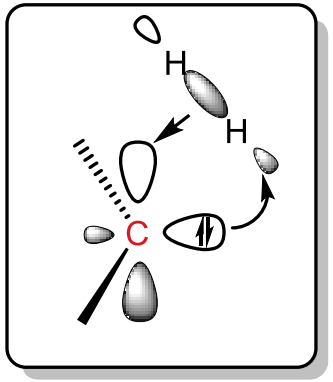
6

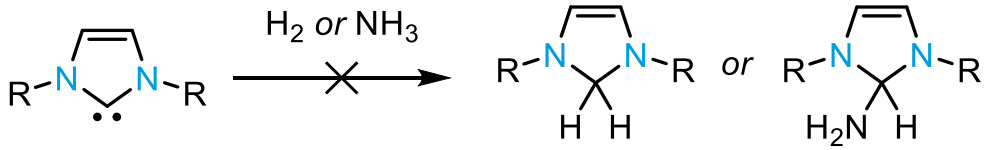




7



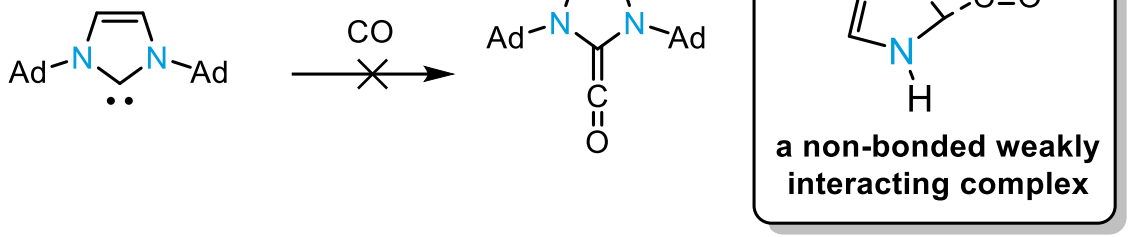


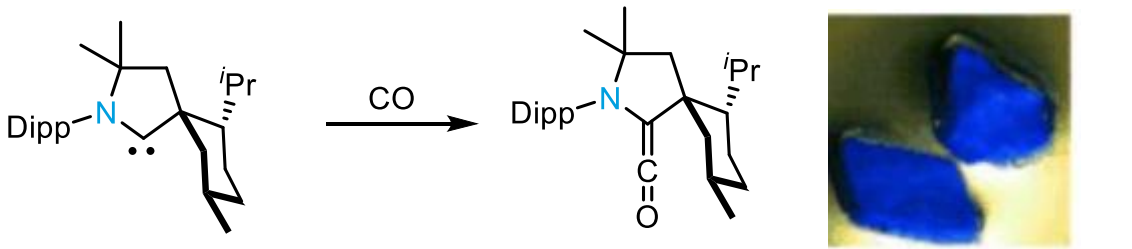


a) D. W. Stephan, *Science*, **2006**, 314, 1124-1126; b) G. Bertrand, *Science*, **2007**, 316, 439-441.

Replace N by C

Activation of CO by CAAC

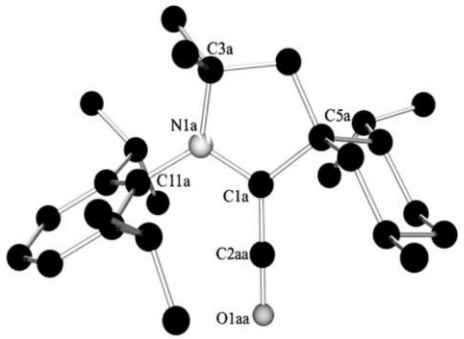




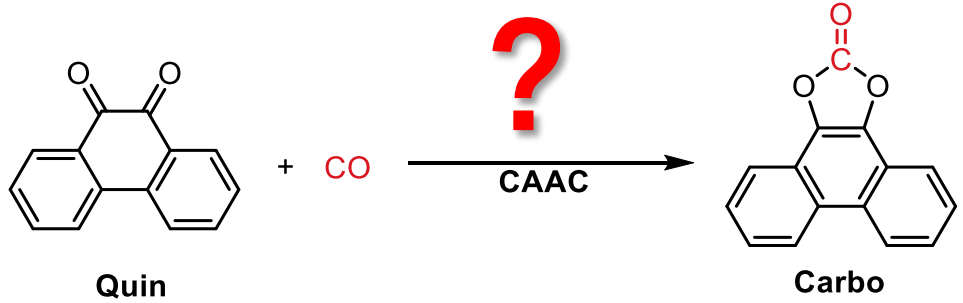
^{13}C C*C*O = 278 ppm

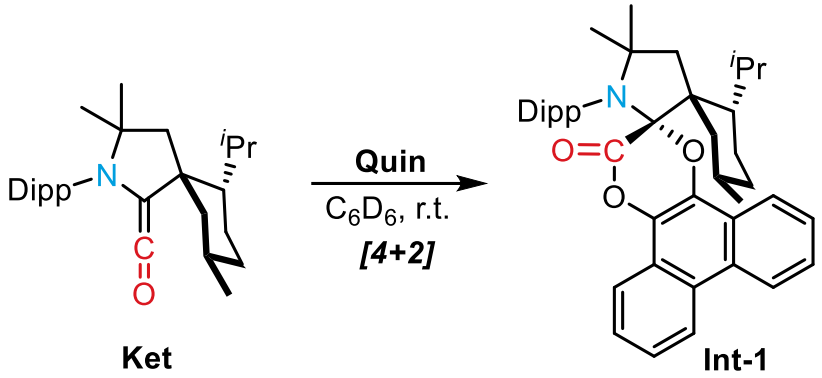
ν_{CCO} = 2073 cm^{-1}

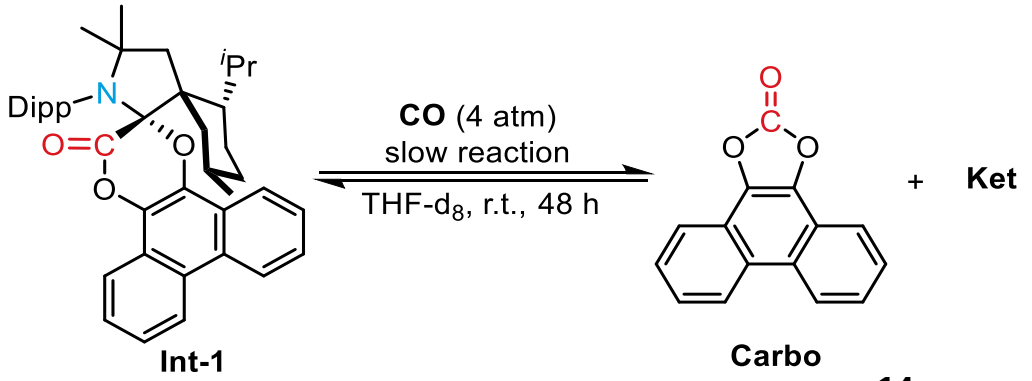
λ_{max} = 598 nm



First ketenes prepared from CO fixation to stable carbene



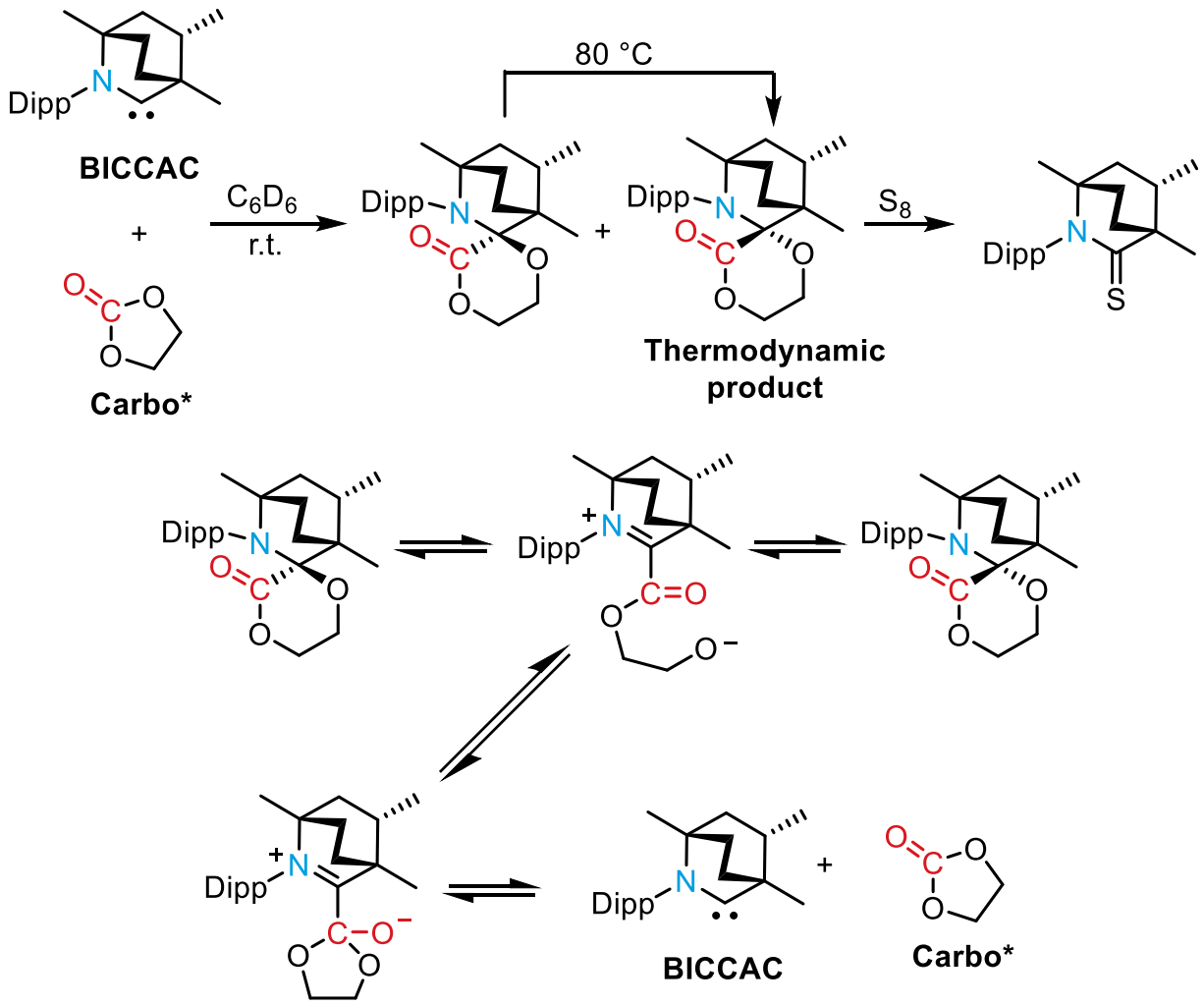


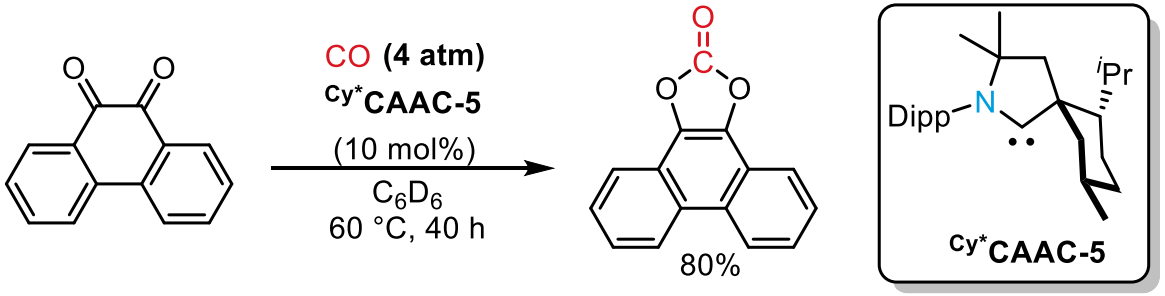


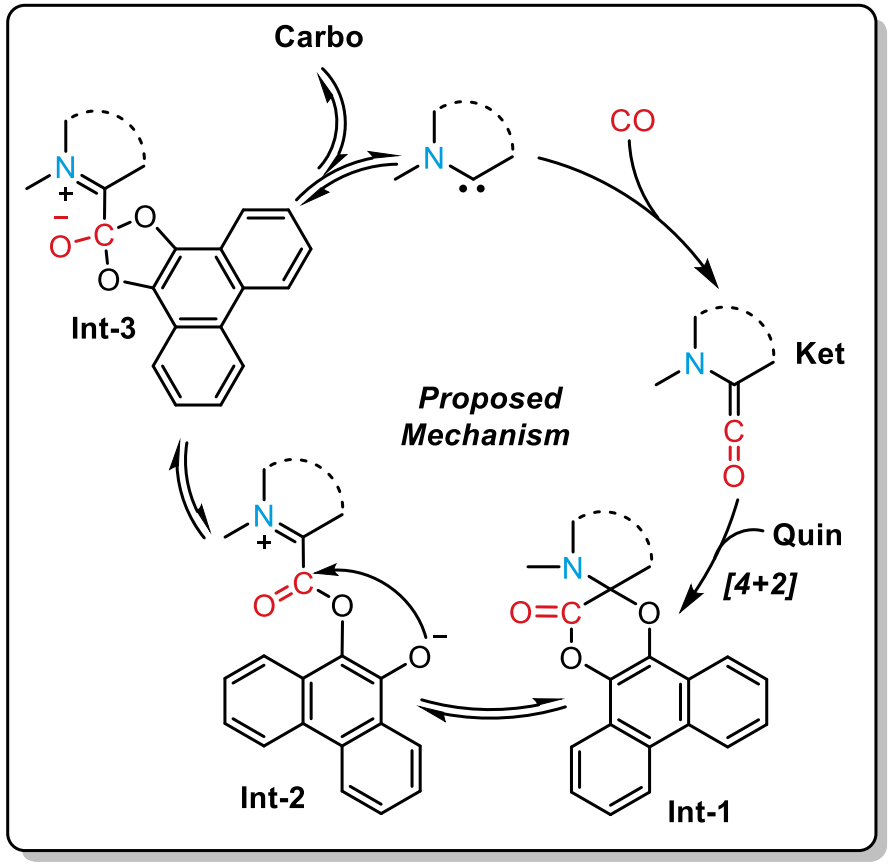
a) G. Bertrand, *Angew. Chem. Int. Ed.*, **2006**, 45, 3488-3491; b) G. Bertrand, *J. Am. Chem. Soc.*, **2020**, 142, 18336-18340.

Replace N by C

Activation of CO by CAAC





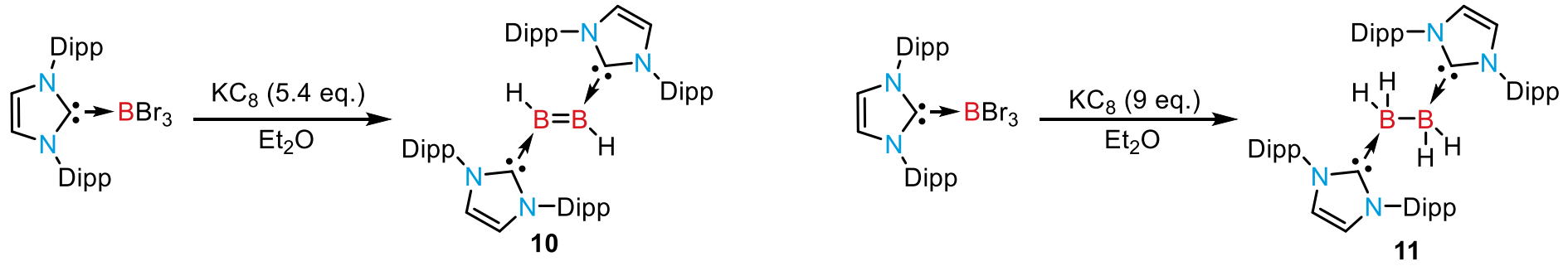


G. Bertrand, *J. Am. Chem. Soc.*, **2020**, 142, 18336-18340.

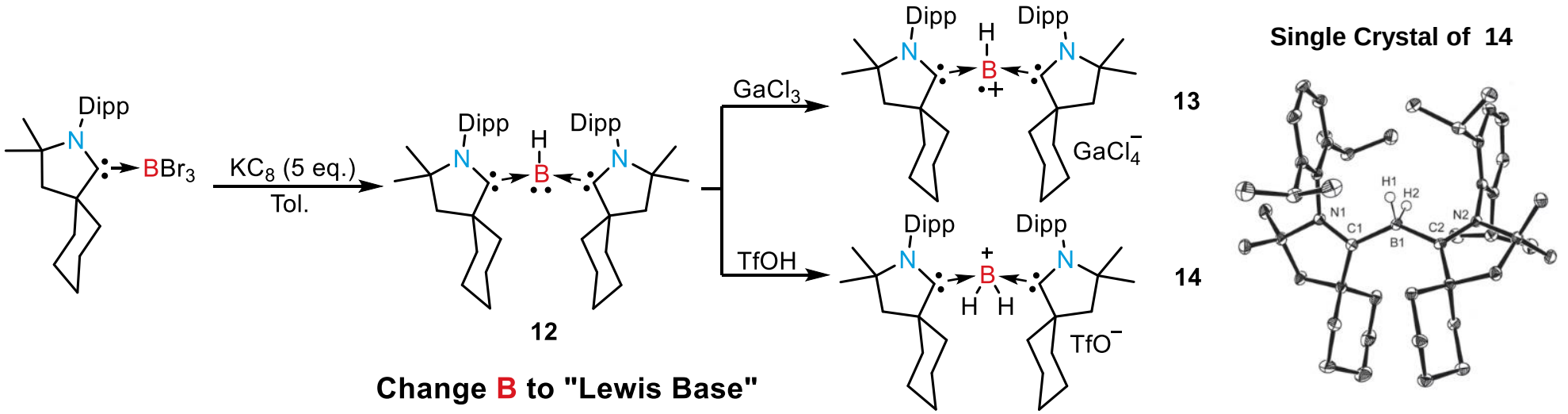
Replace N by C

Low-valence element supported by CAAC

NHC-B_2-NHC



CAAC-BH-CAAC

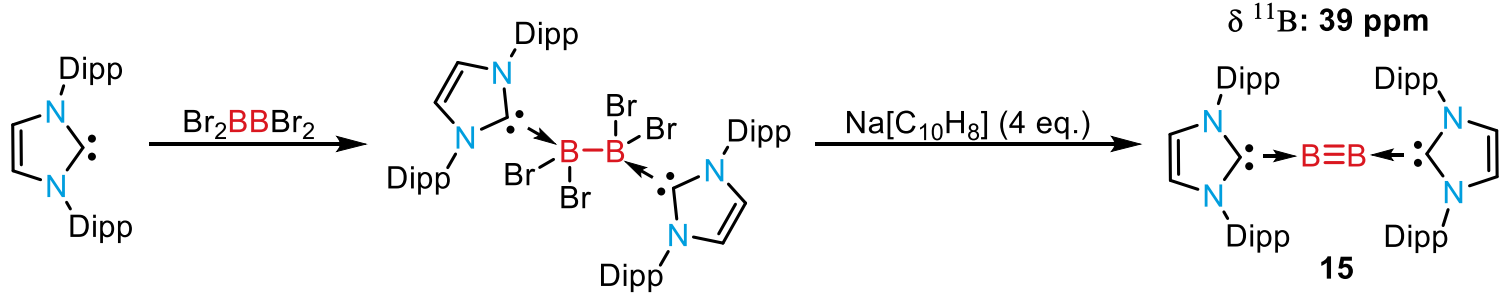


a) G. H. Roninson, *J. Am. Chem. Soc.*, **2007**, 129, 12412-12413; b) G. Bertrand, *Science*, **2011**, 333, 610-613.

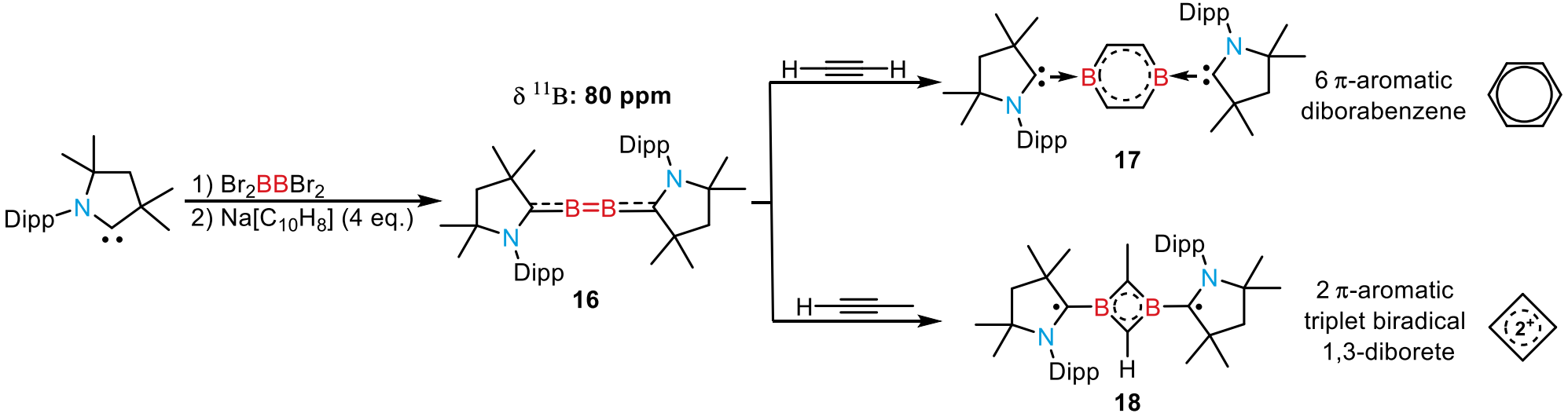
Replace N by C

Low-valence element supported by CAAC

NHC-B_2-NHC



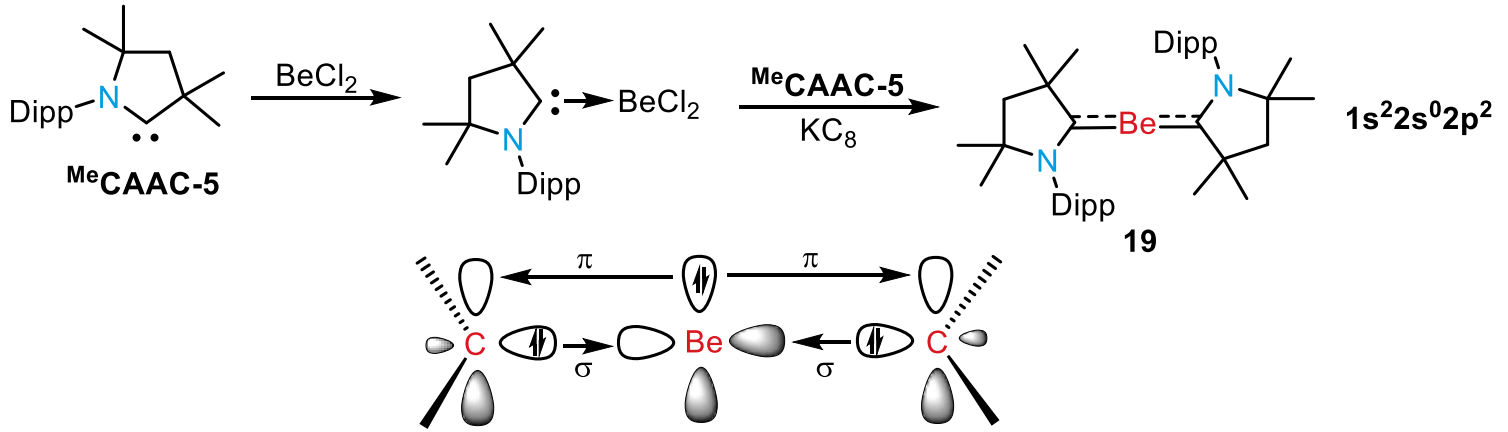
CAAC-B_2-CAAC



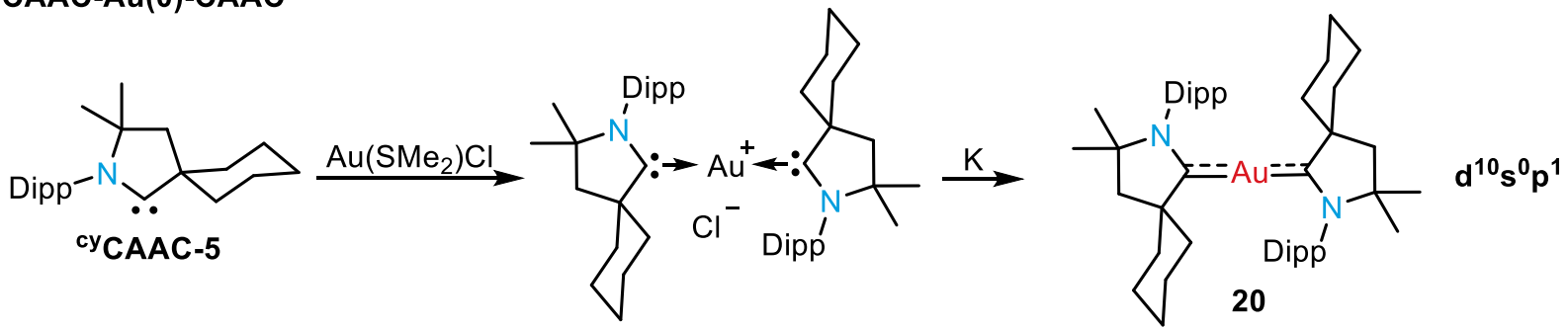
a) H. Braunschweig, *Angew. Chem. Int. Ed.*, **2014**, 53, 9082-9085; b) H. Braunschweig, , *Angew. Chem. Int. Ed.*, **2016**, 55, 11271-11275

Replace N by C

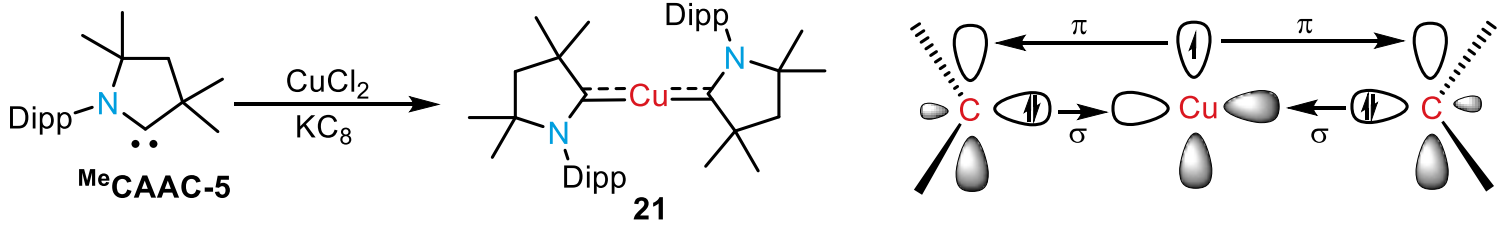
CAAC-Be(0)-CAAC



CAAC-Au(0)-CAAC



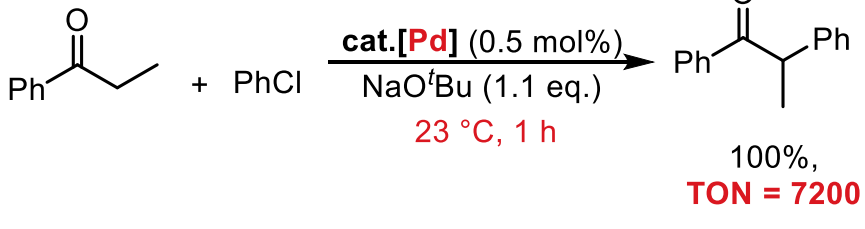
CAAC-Cu(0)-CAAC

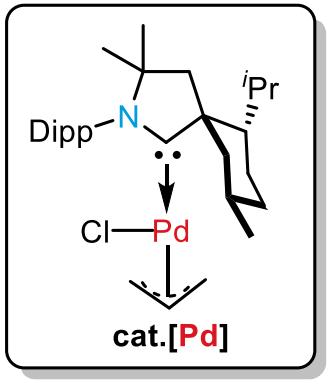


a) H. Braunschweig, *Nat. Chem.*, **2016**, 8, 890-894; b) G. Bertrand, *J. Am. Chem. Soc.*, **2014**, 136, 6235-6238; c) ; G. Bertrand, *Angew. Chem. Int. Ed.*, **2013**, 52, 8964-8967.

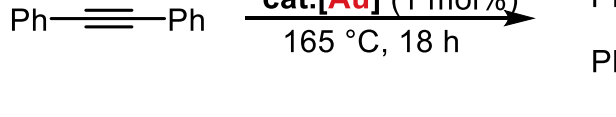
Replace N by C

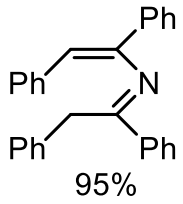
CAAC as ligand improved catalytic efficiency

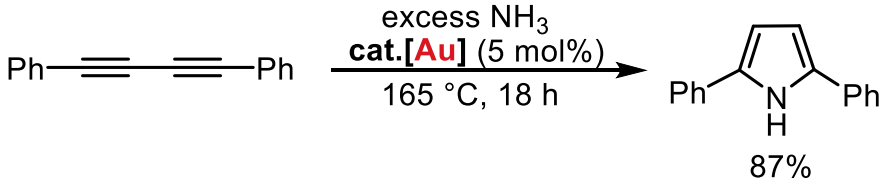


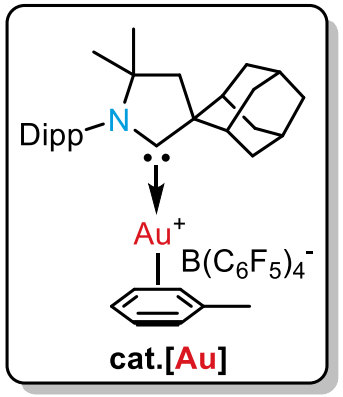


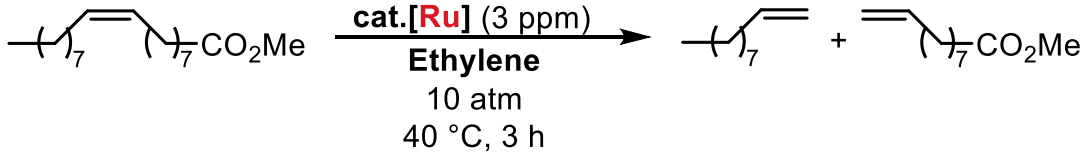
Best TON by NHC or PR_3 : 4200 at 120 °C

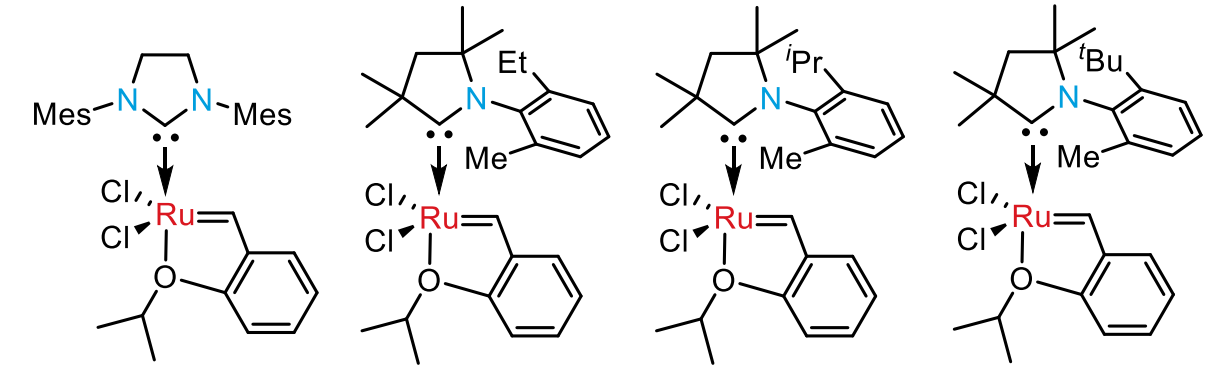










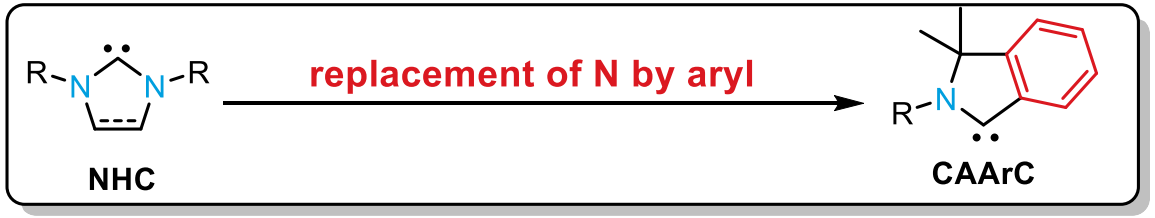


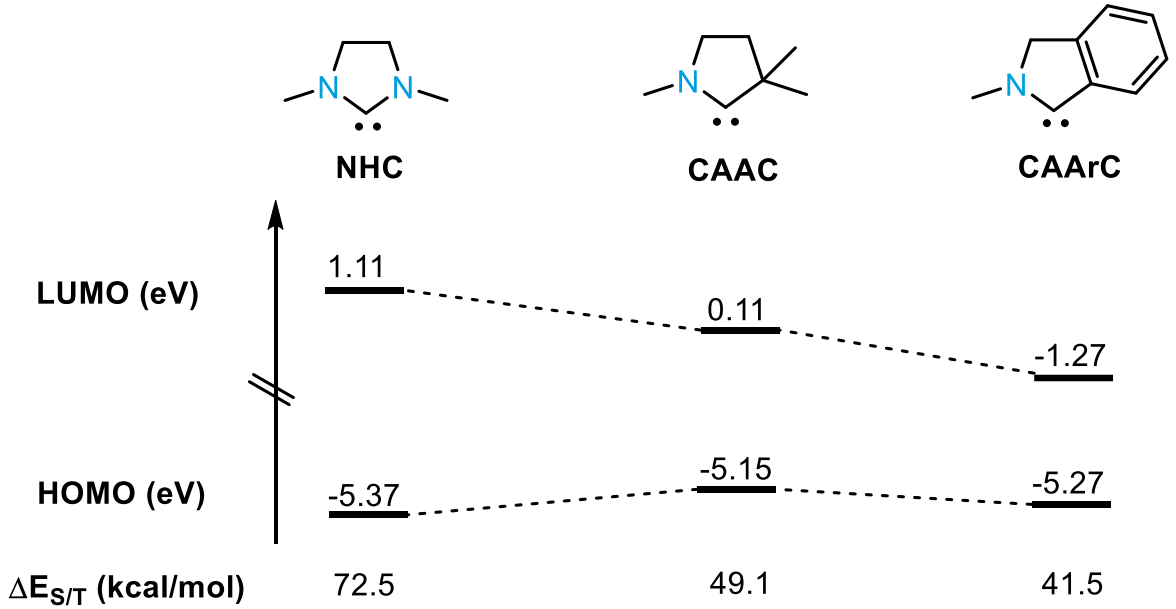
More electron donating than NHC stabilize the methylidene intermediate

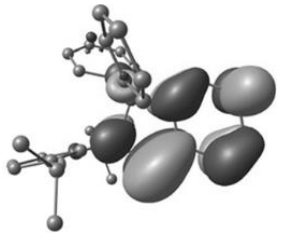
a) G. Bertrand, *Angew. Chem. Int. Ed.*, **2005**, 44, 5705-5709; b) G. Bertrand, *Angew. Chem. Int. Ed.*, **2008**, 47, 5224-5228; c) R. H. Grubbs, *Angew. Chem. Int. Ed.*, **2015**, 54, 1919-1923.

Replace N by C

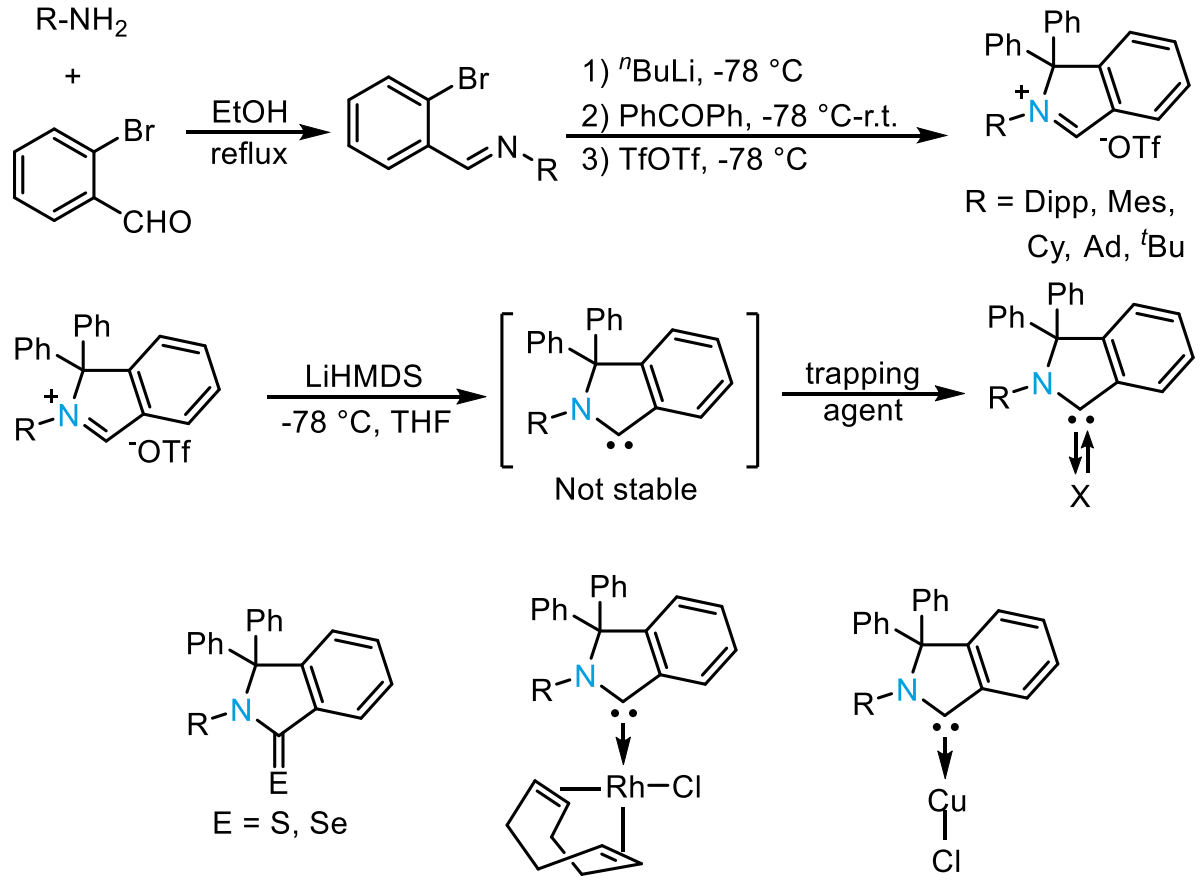
Synthesis, reactivity and electronic properties of CAArC







Aryl substituent serves as a π-acceptor increasing the electrophilicity



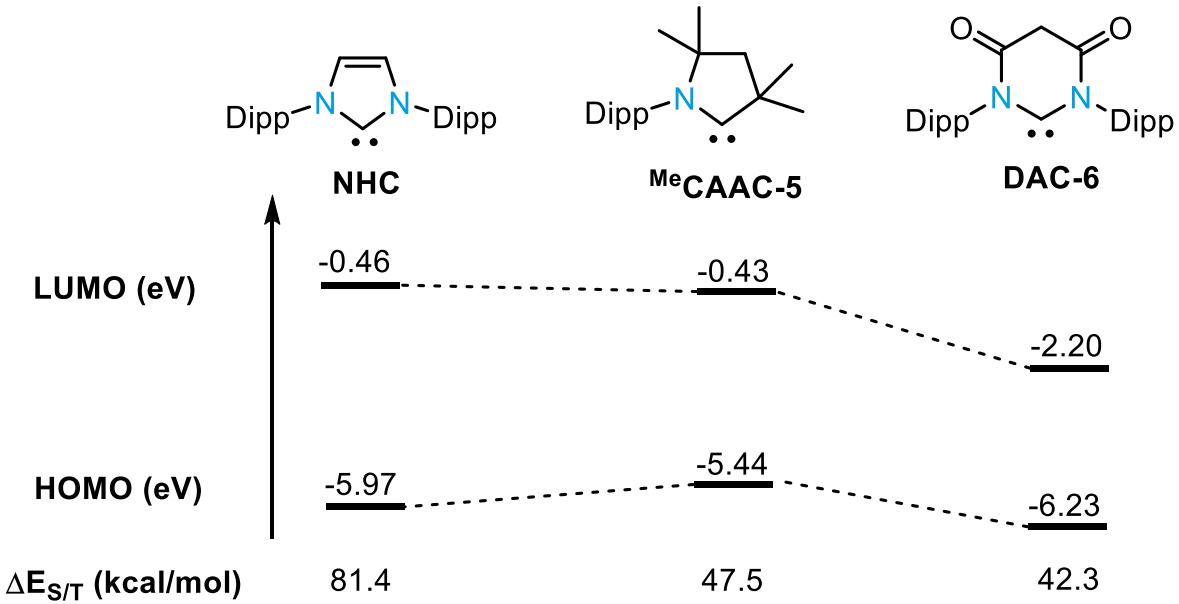
Ligand	NHC	CAAC	CAArC
^{77}Se (ppm)	≈ 200	≈ 480	≈ 590

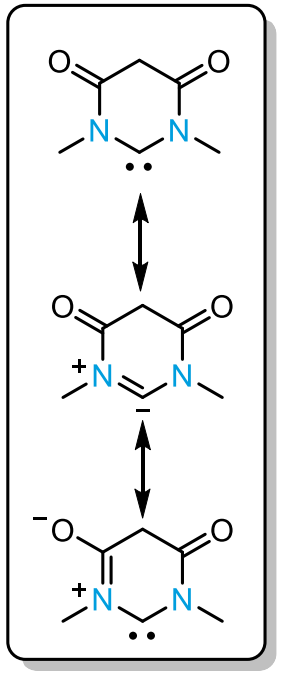
G. Bertrand, *Angew. Chem. Int. Ed.*, **2015,** 54, 14915-14919.

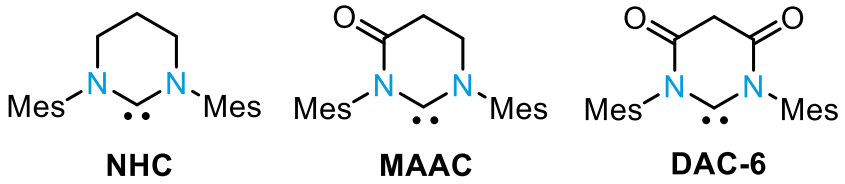
Content

Replace Amino by Amido

Electronic properties of DACs





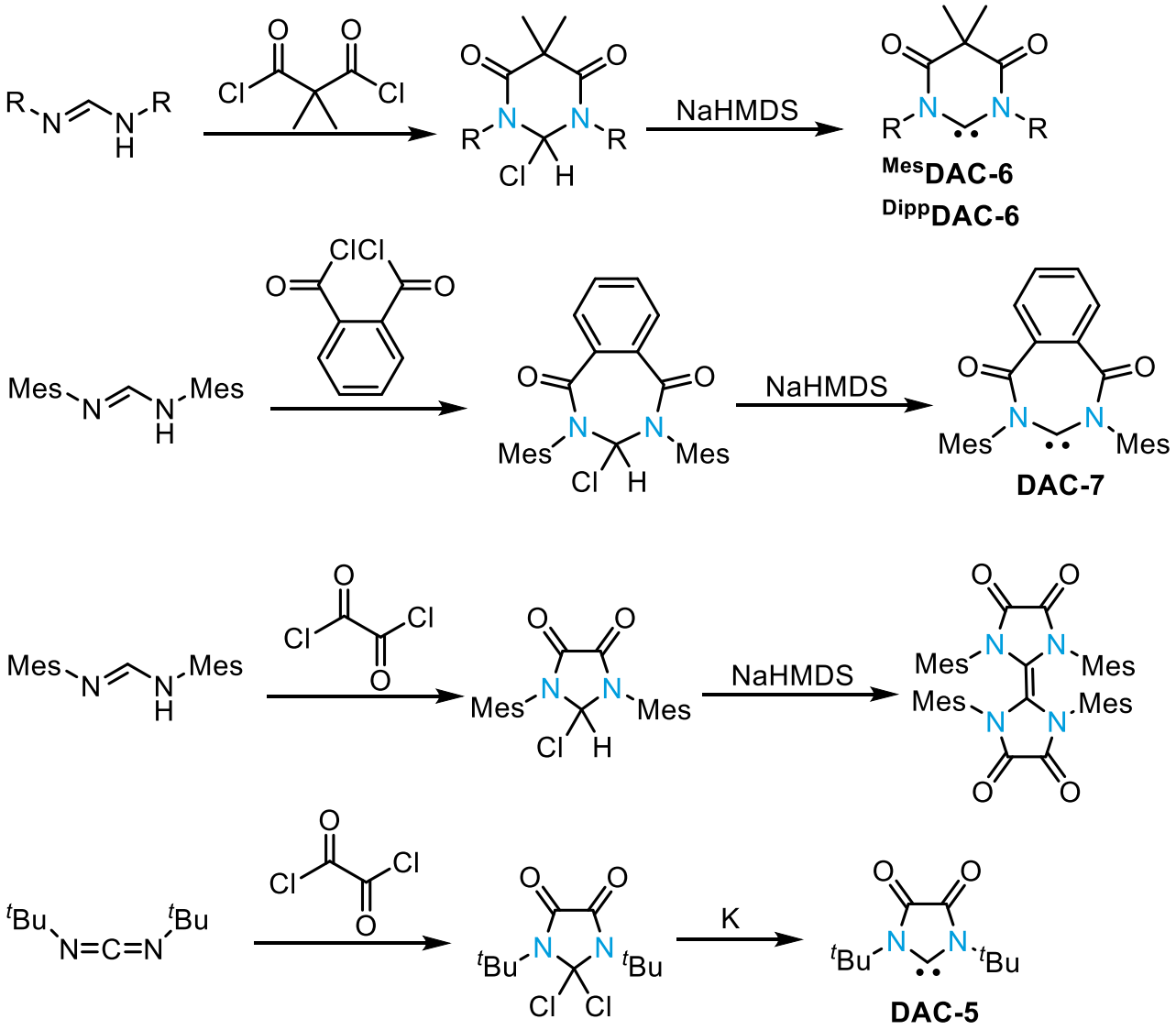


Compound	NHC	MAAC	DAC-6
TEP, **L**Ir(CO)$_2$Cl (cm^{-1})	2042	2050	2056
^{13}C (ppm)	242.7	260.6	277.7

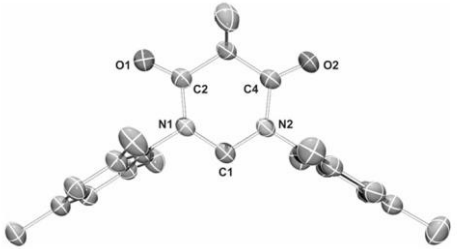
C. W. Bielawski, *Acc. Chem. Res.*, **2016**, 49, 1458-1468.

Replace Amino by Amido

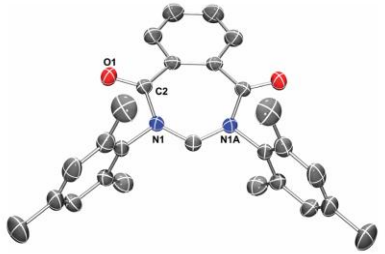
Synthesis of DACs



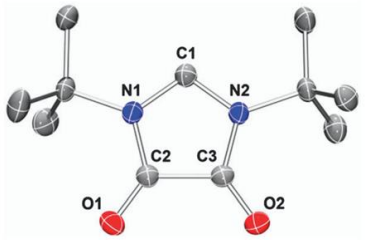
Single Crystal of ^{Mes}DAC-6



Single Crystal of DAC-7



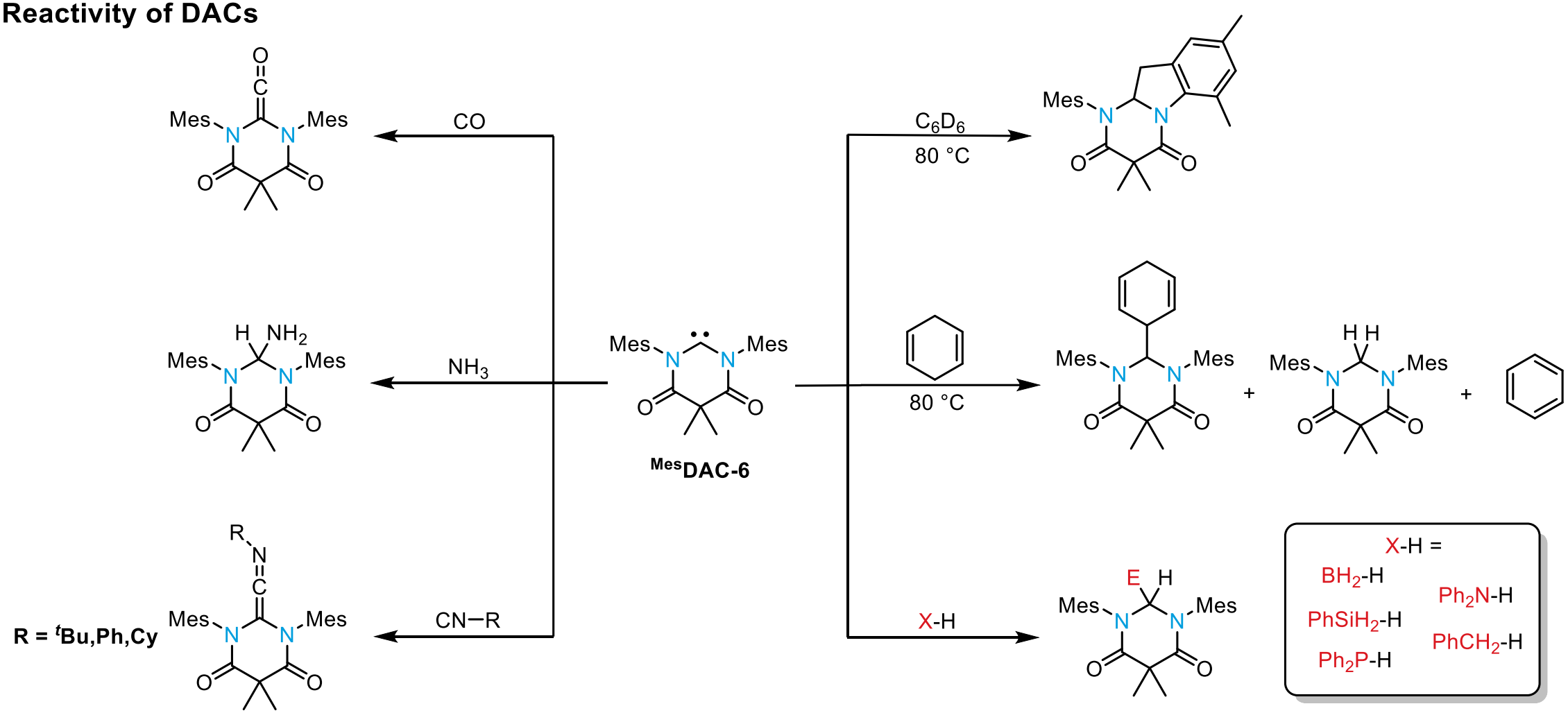
Single Crystal of DAC-5



a) C. W. Bielawski, *J. Am. Chem. Soc.* **2009**, 131, 16039-16041; b) G. Lavigne, *Eur. J. Inorg. Chem.*, **2010**, 2010, 361-365; c) C. W. Bielawski, *Organometallics*, **2010**, 29, 4569-4578; d) C. Ganter, *Organometallics*, **2010**, 29, 4418-4420; e) C. W. Bielawski, *Chem. Commun.*, **2014**, 50, 4551-4553.

Replace Amino by Amido

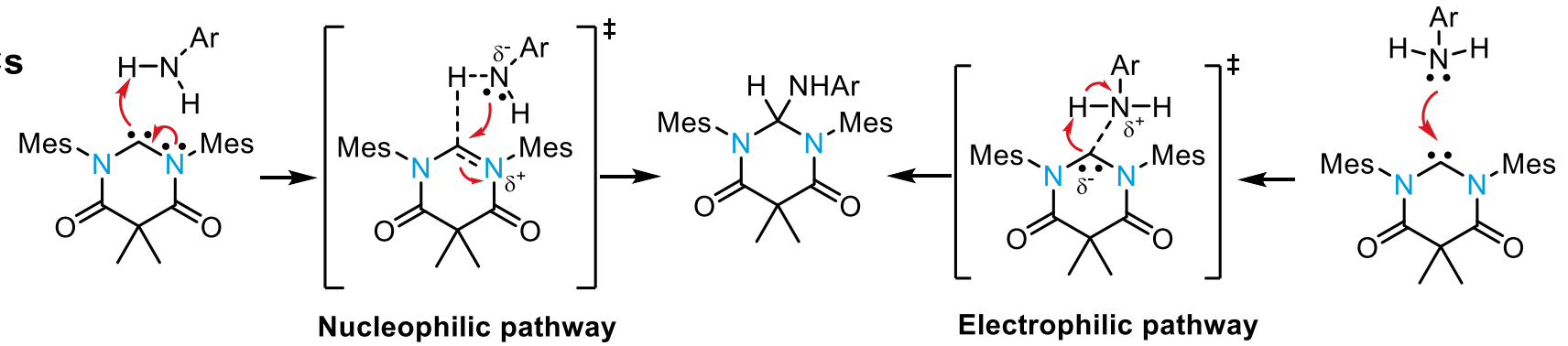
Reactivity of DACs

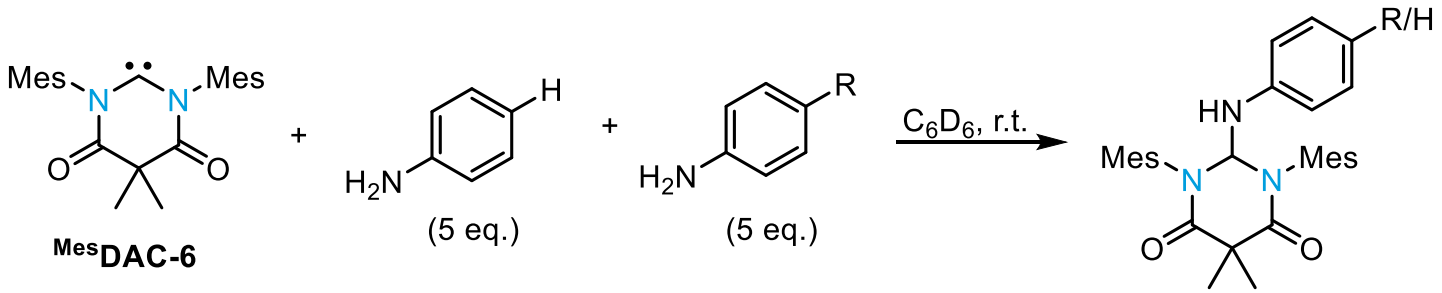


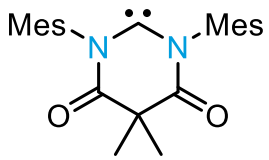
a) C. W. Bielawski, *J. Am. Chem. Soc.*, **2009**, 131, 16039-16041.; b) C. W. Bielawski, *Chem. Commun.*, **2010**, 46, 4288-4290; c) C. W. Bielawski, *J. Am. Chem. Soc.*, **2013**, 135,18798-18801; d) C. W. Bielawski, *Org. Lett*. **2014**, 16, 812-815; e) C. W. Bielawski, *Chem. Commun.*, **2014**, 50, 4551-4553; f) C. W. Bielawski *J. Phys. Org. Chem*. **2015**, 28 75-78; g) C. W. Bielawski, *Organometallics*, **2016**, 35, 706-712.

Replace Amino by Amido

Reactivity of DACs

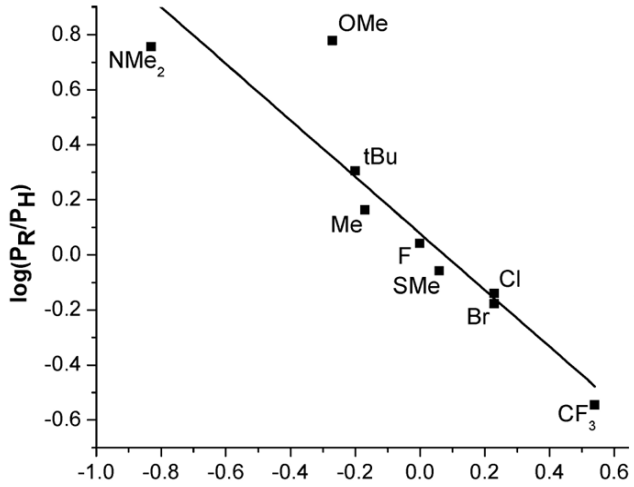


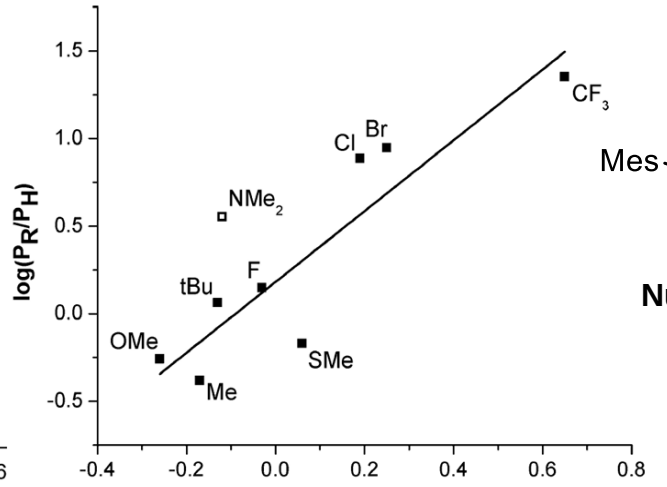




MesDAC-6

Electrophilic





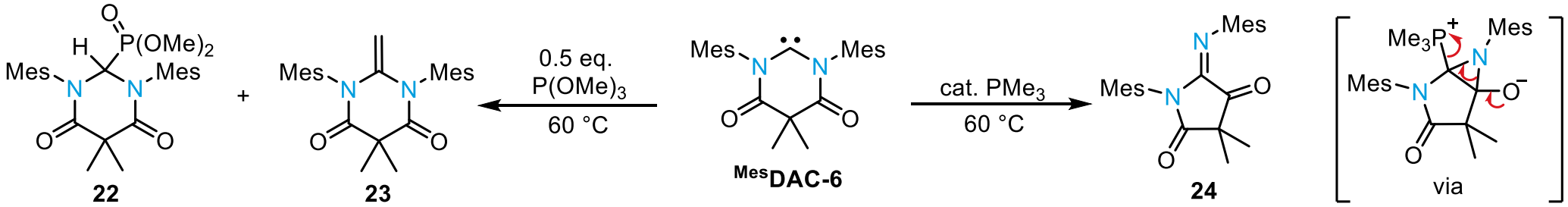
SIMes

Nucleophilic

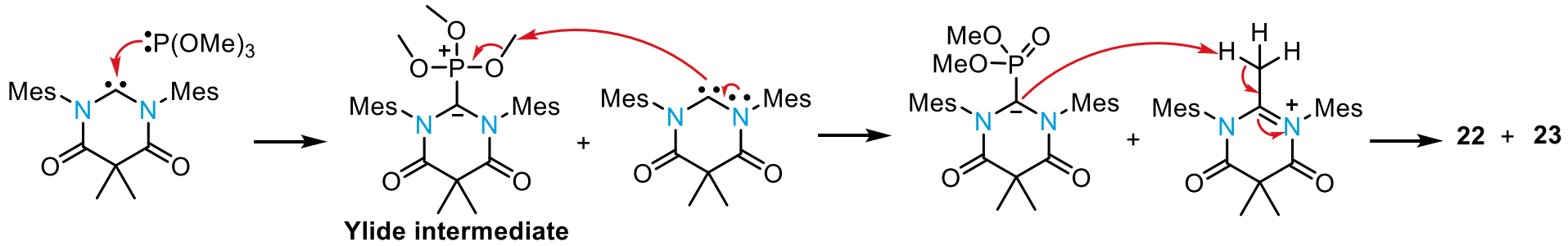
C. W. Bielawski, *J. Am. Chem. Soc.*, **2013**, 135,18798-18801.

Replace Amino by Amido

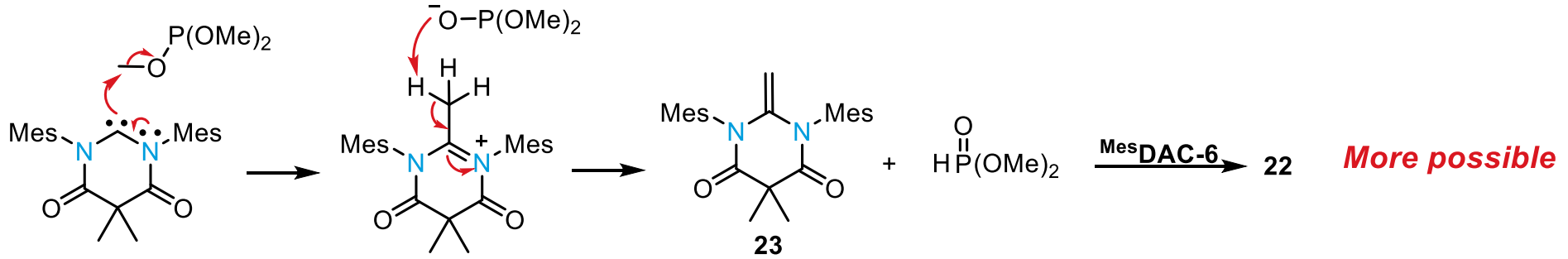
Reactivity of DACs



Arbuzov-type Pathway
Electrophilic



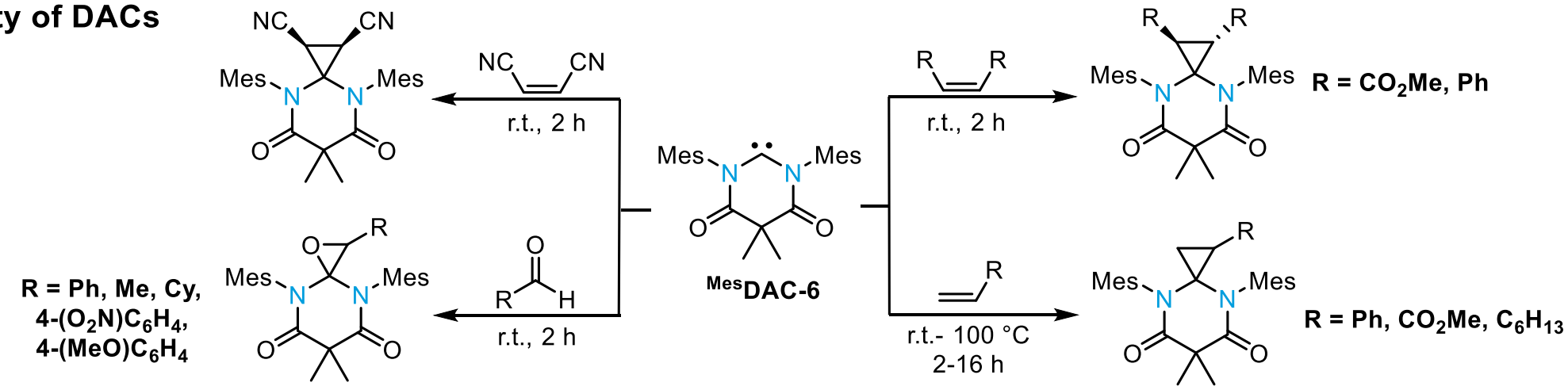
Direct Methylation Pathway
Nucleophilic

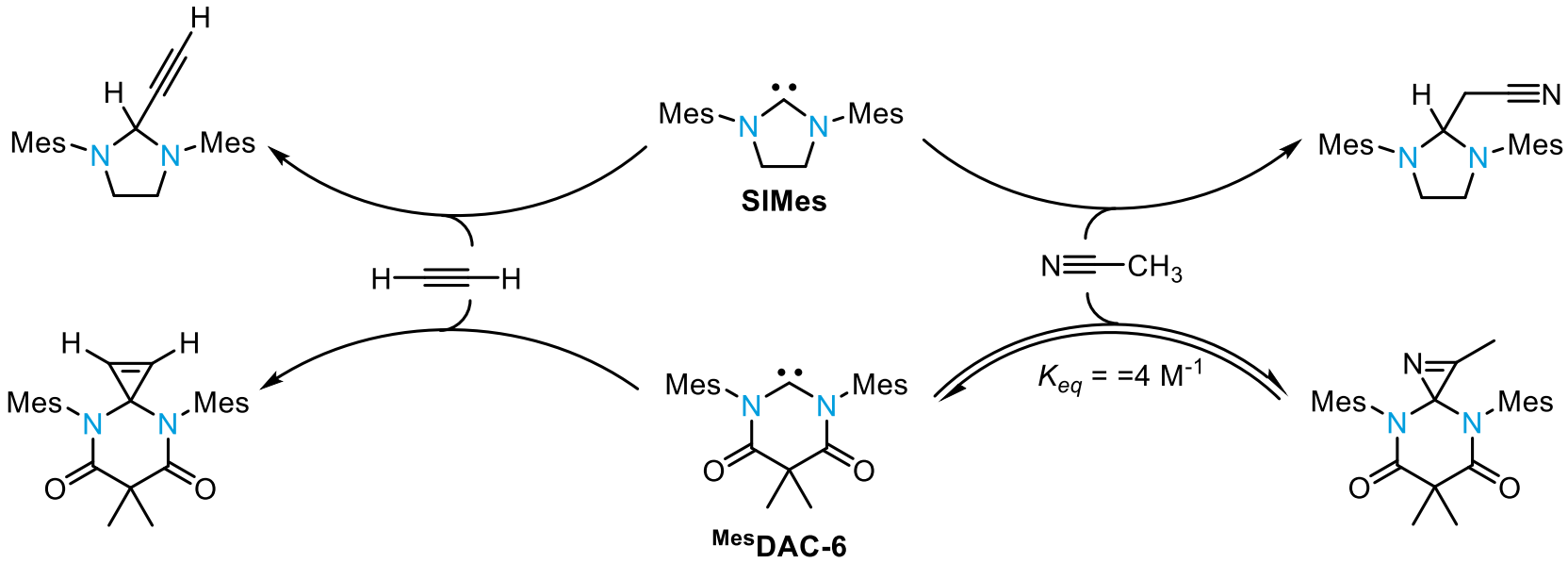


C. W. Bielawski, *Org. Lett.* **2014**, 16, 812-815.

Replace Amino by Amido

Reactivity of DACs

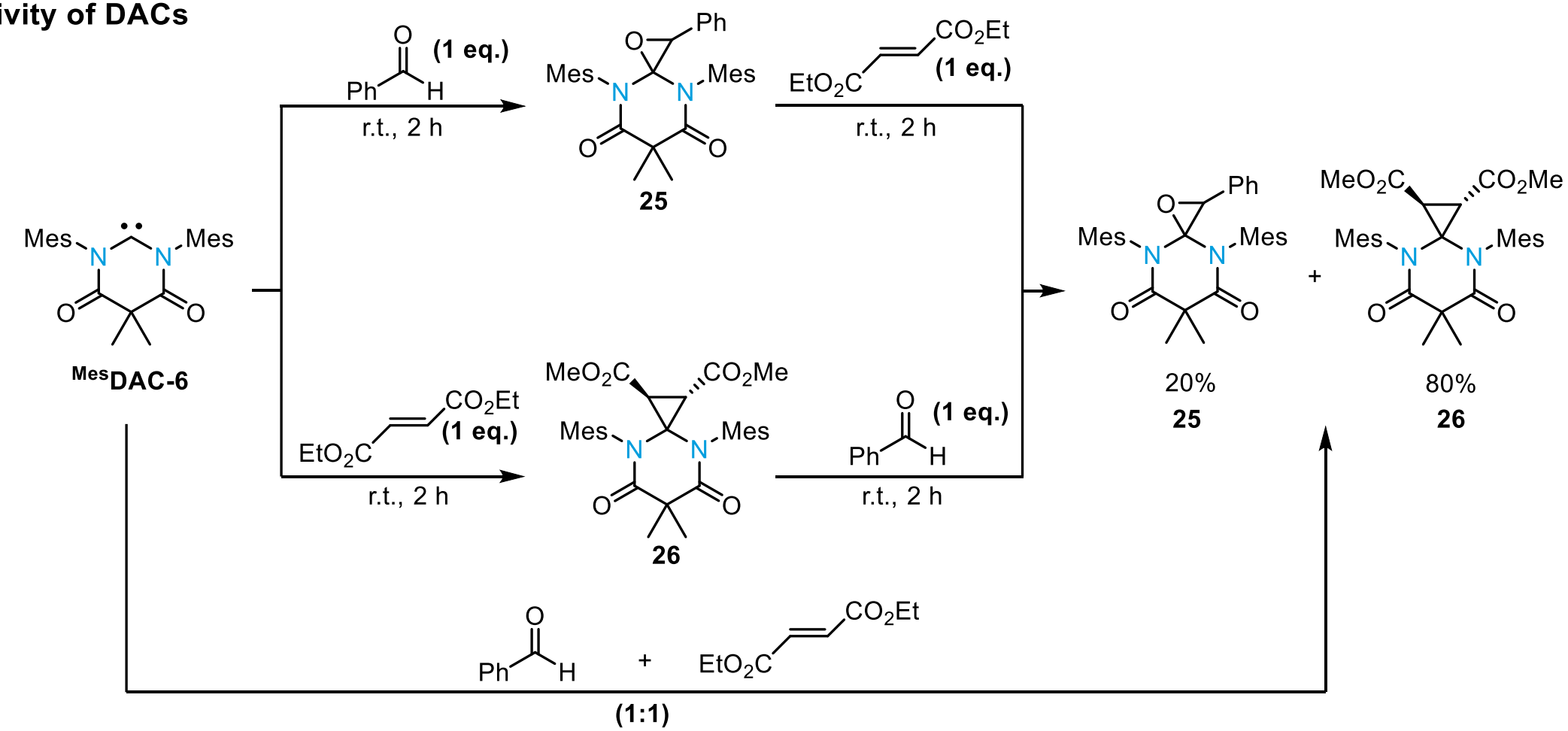




a) C. W. Bielawski, *Nat. Chem.*, **2012**, 4, 275-280; b) C. W. Bielawski, *J. Am. Chem. Soc.*, **2012**, 134, 6116-6119.

Replace Amino by Amido

Reactivity of DACs

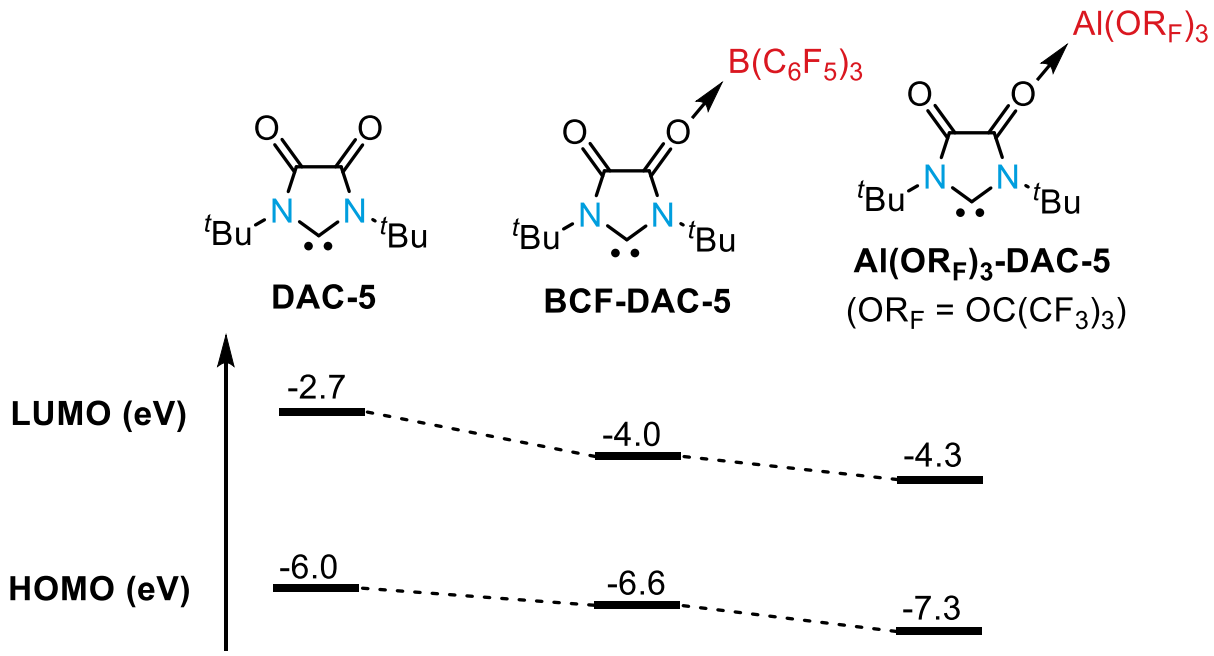


The first example of thermally reversible [2 + 1] cycloadditions that involve an isolable carbene

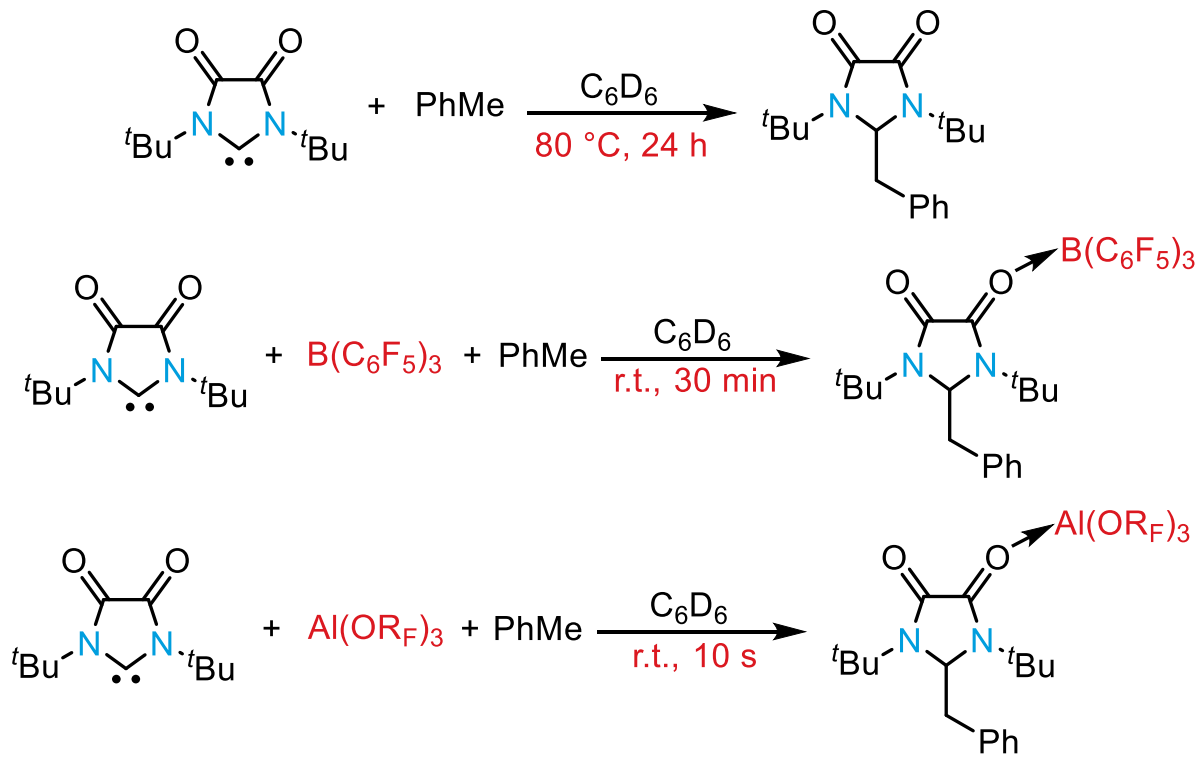
C. W. Bielawski, *Nat. Chem.*, **2012**, 4, 275-280.

Replace Amino by Amido

Lewis acid−DAC adduct



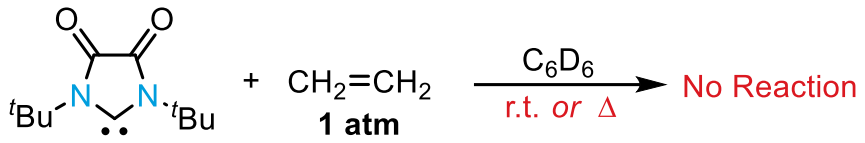
Pushing the Electrophilicity of Carbenes to the Limit

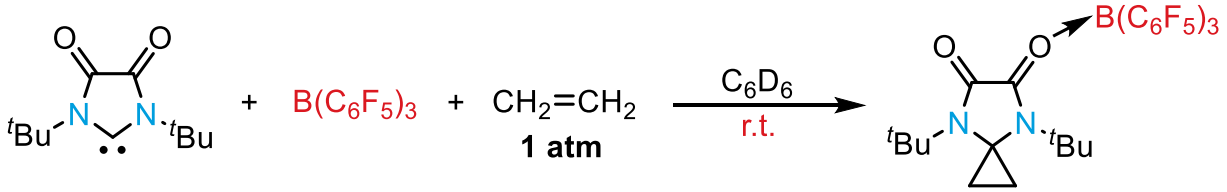


a) X. Wang, *J. Am. Chem. Soc.*, **2023**, 145, 21733-21737; b) X. Wang, *Nat. Commun.*, **2024**, 15, 7943.

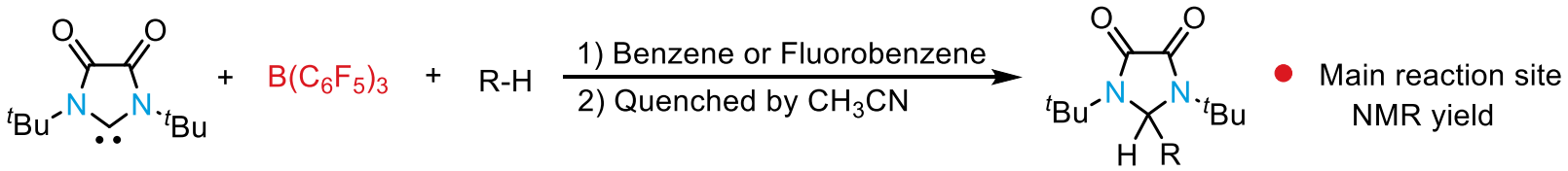
Replace Amino by Amido

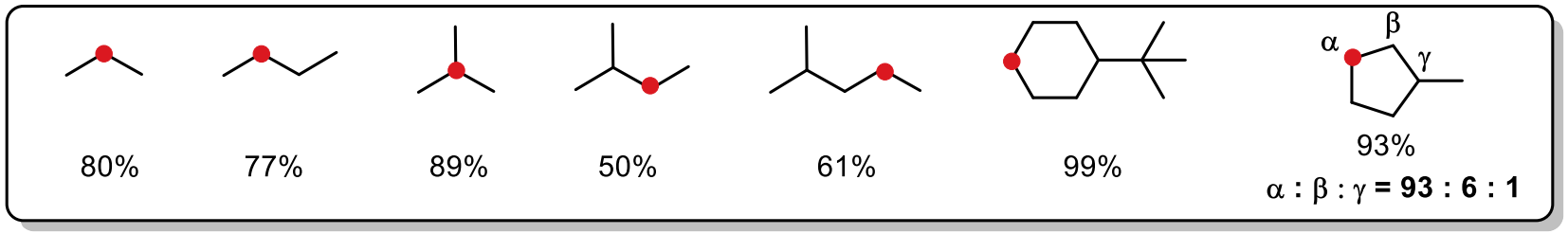
Lewis acid−DAC adduct

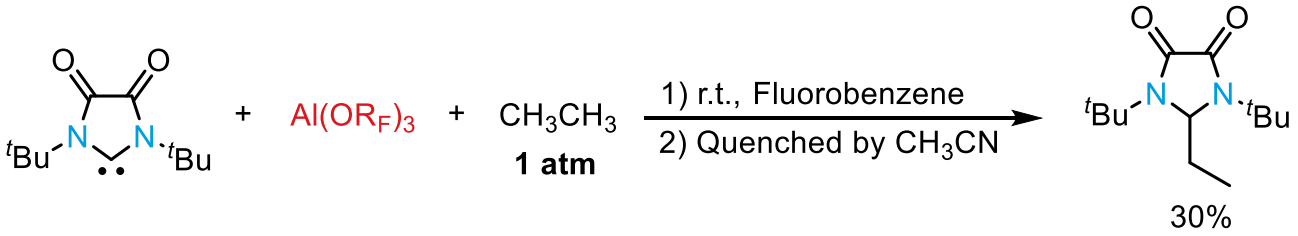




The first example



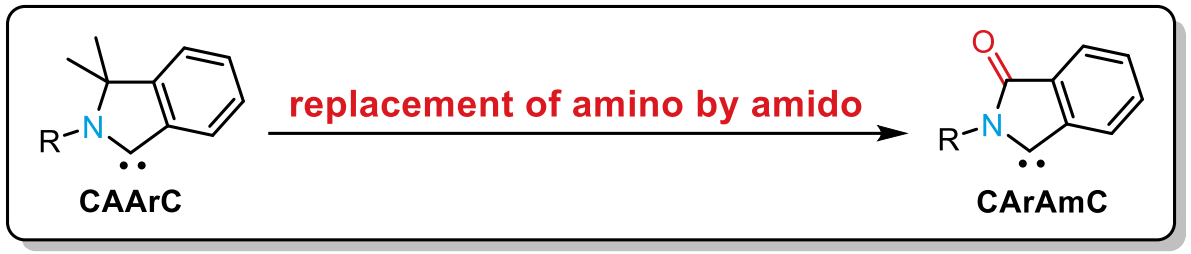


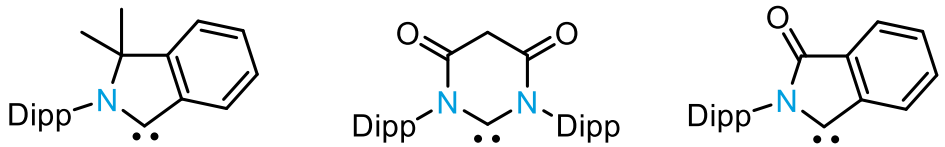


a) X. Wang, *J. Am. Chem. Soc.*, **2023**, 145, 21733-21737; b) X. Wang, *Nat. Commun.*, **2024**, 15, 7943.

Replace Amino by Amido

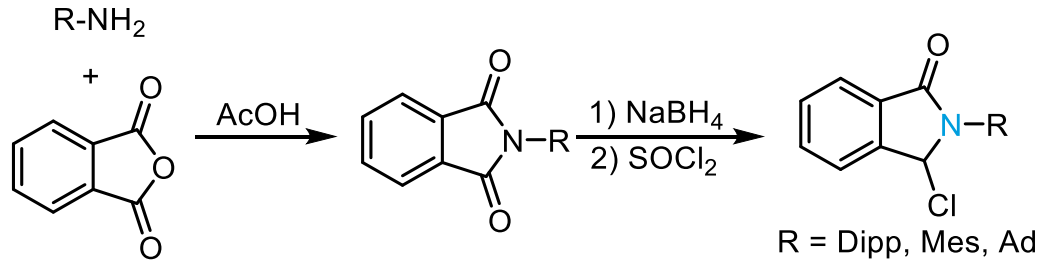
Synthesis, reactivity and electronic properties of CArAmC

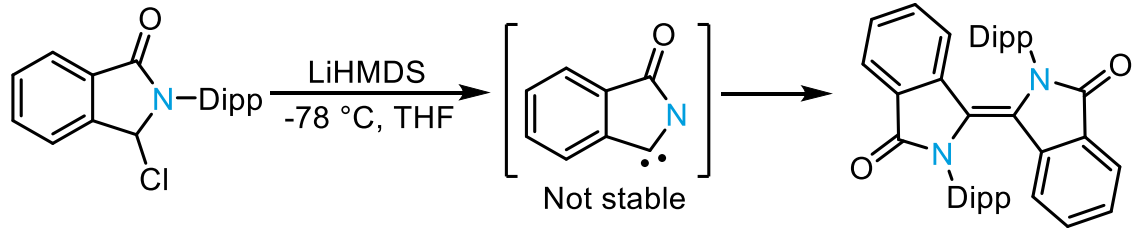


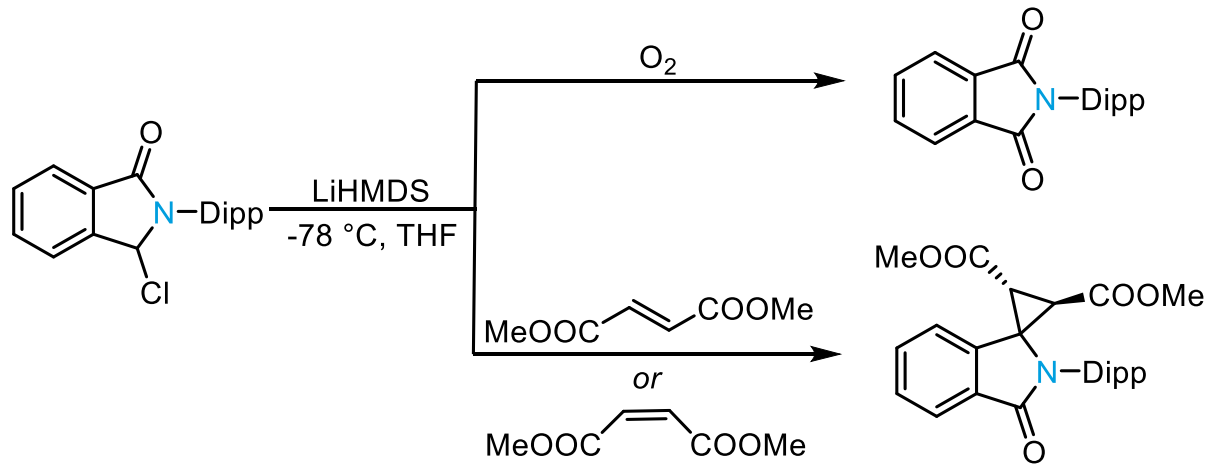


	CAArC	DAC-6	CArAmC
LUMO (eV)	-1.47	-2.20	-3.02
$\Delta E_{S/T}$ (kcal/mol)	39.5	42.3	19.9

Aryl and amido reduce the $\Delta E_{S/T}$ significantly







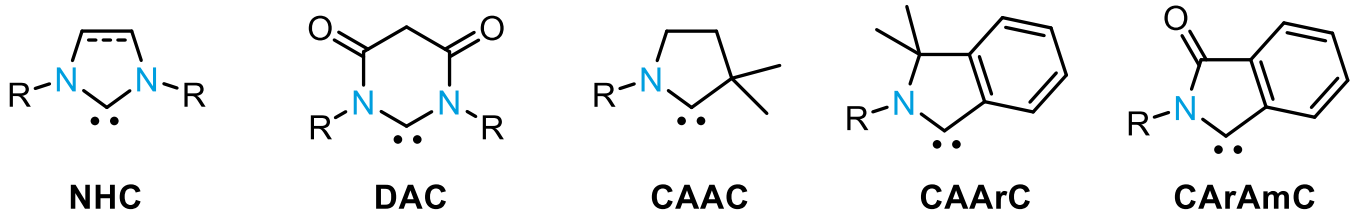
Triplet-like reactivity

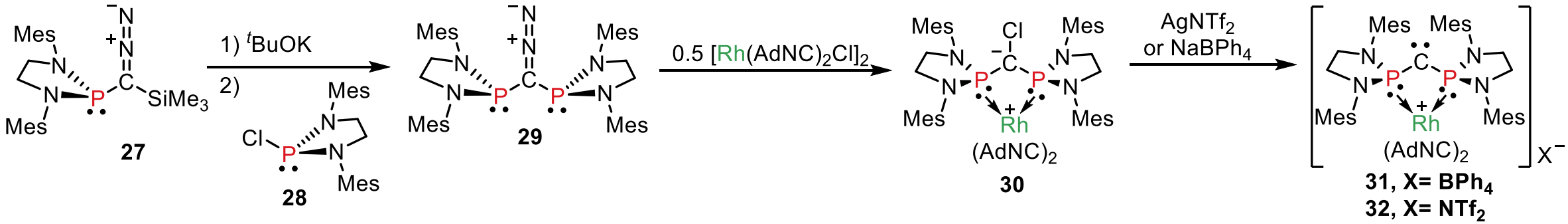
C. W. Bielawski, *Angew. Chem. Int. Ed.*, **2019**, 58, 16320-16325.

Content

Stable $\sigma^0\pi^2$ Carbene

Systhesis stable $\sigma^0\pi^2$ carbene



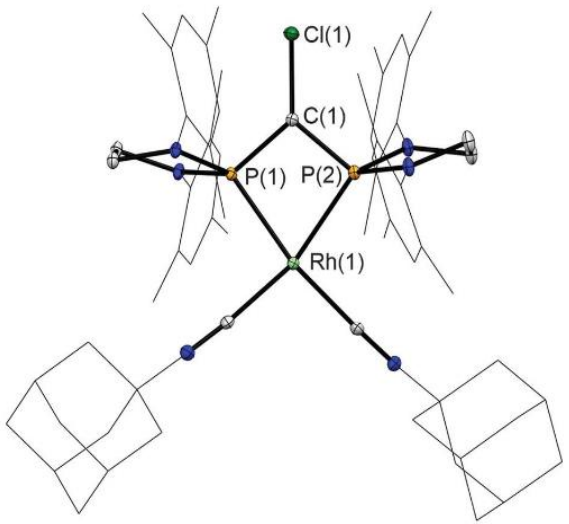


L. L. Liu, *Science*, **2024**, 383, 81–85.

Stable $\sigma^0\pi^2$ Carbene

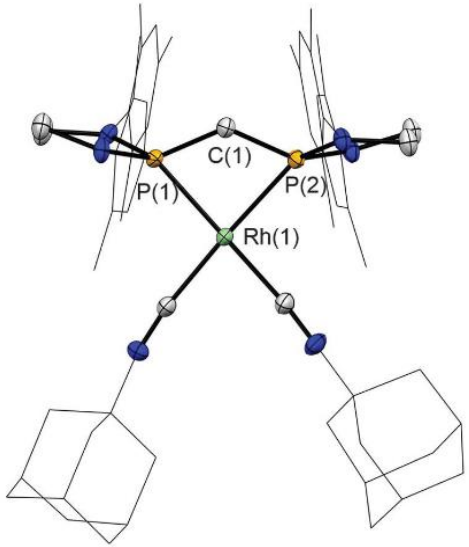
Solid-state structures and energy diagram for the frontier orbitals

Single Crystal of 30

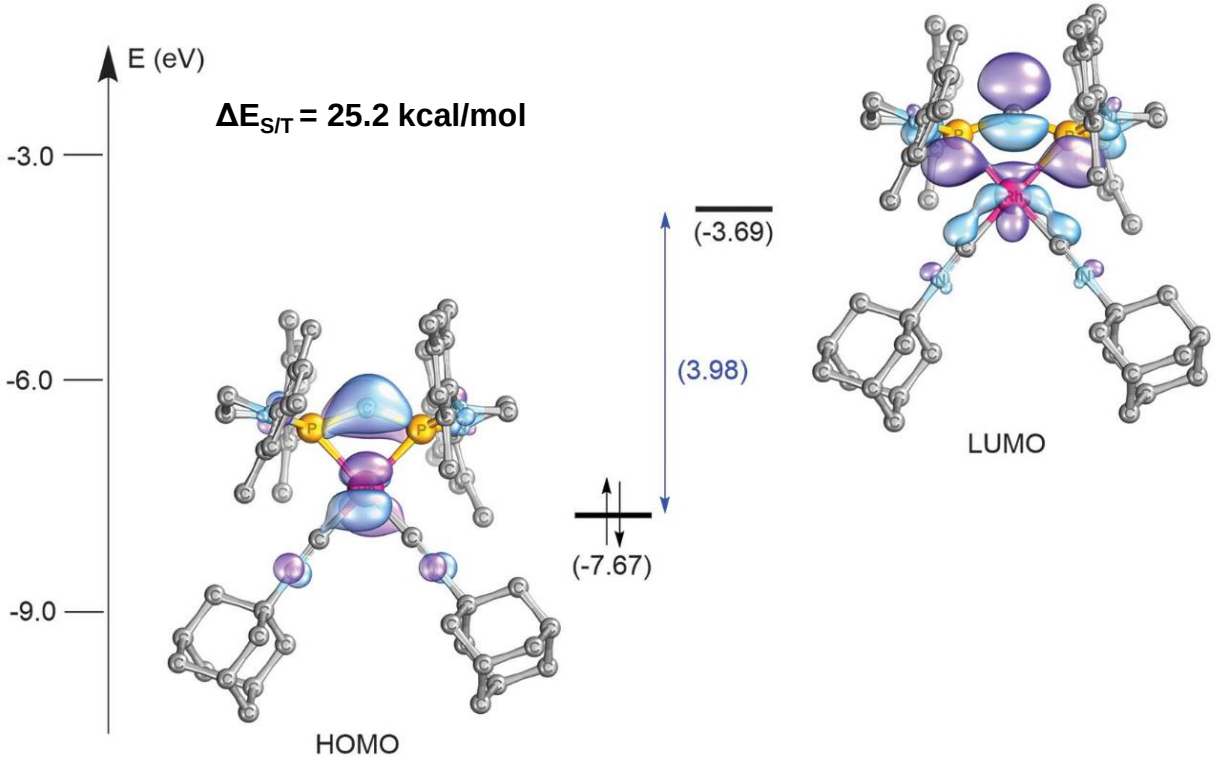


$\angle_{PCP}$ = 101.04(9)°
$d_{C\text{-}Rh}$ = 2.9551(18) Å
$d_{C\text{-}P}$ = 1.7316(18) Å

Single Crystal of 31



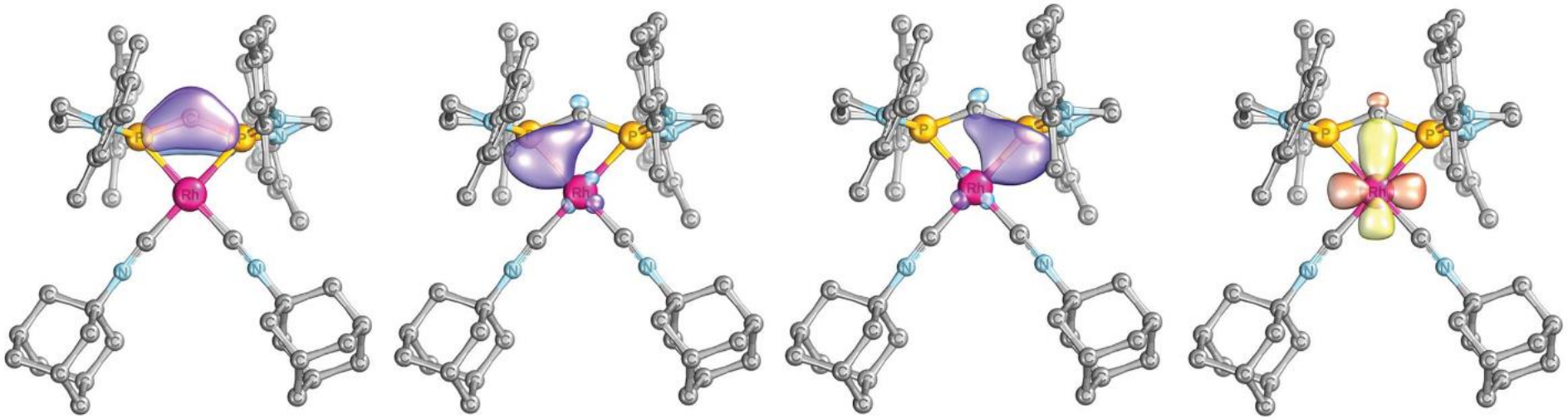
$\angle_{PCP}$ = 133.42(17)°
$d_{C\text{-}Rh}$ = 2.316(3) Å
$d_{C\text{-}P}$ = 1.6672(2) Å



L. L. Liu, *Science*, **2024**, 383, 81–85.

Stable $\sigma^0\pi^2$ Carbene

Intrinsic Bond Orbitals analysis



IBO1

C(1) lone-pair orbital
C(1): 75.2%
P(1): 9.5%
P(2): 9.5%

IBO2

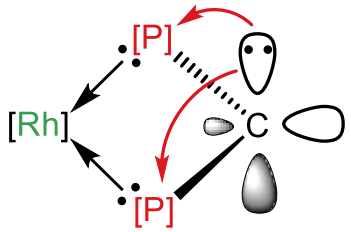
P(1)-Rh(1) σ-bonding orbital
P(1): 62.7%
Rh(1): 20.1%
C(1): 14.4%

IBO3

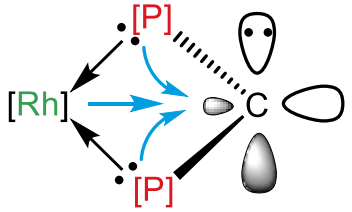
P(2)-Rh(1) σ-bonding orbital
P(1): 62.6%
Rh(1): 20.1%
C(1): 14.5%

IBO4

Rh(1) lone-pair orbital
Rh(1): 78.6%
C(1): 10.5%



out-of-plane elelctron pull effect

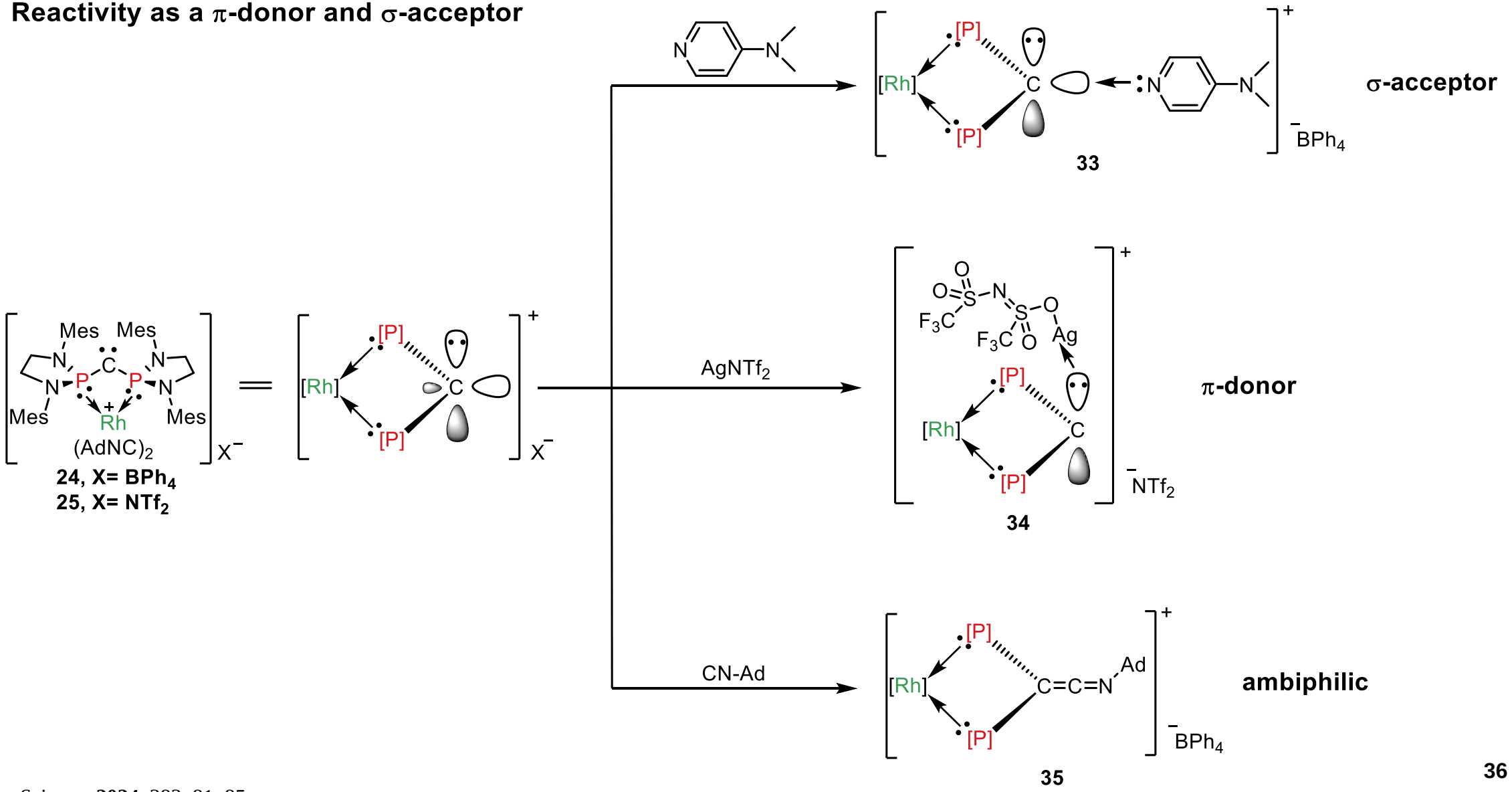


in-plane elelctron push effect

L. L. Liu, *Science*, **2024**, 383, 81–85.

Stable $\sigma^0\pi^2$ Carbene

Reactivity as a π-donor and σ-acceptor

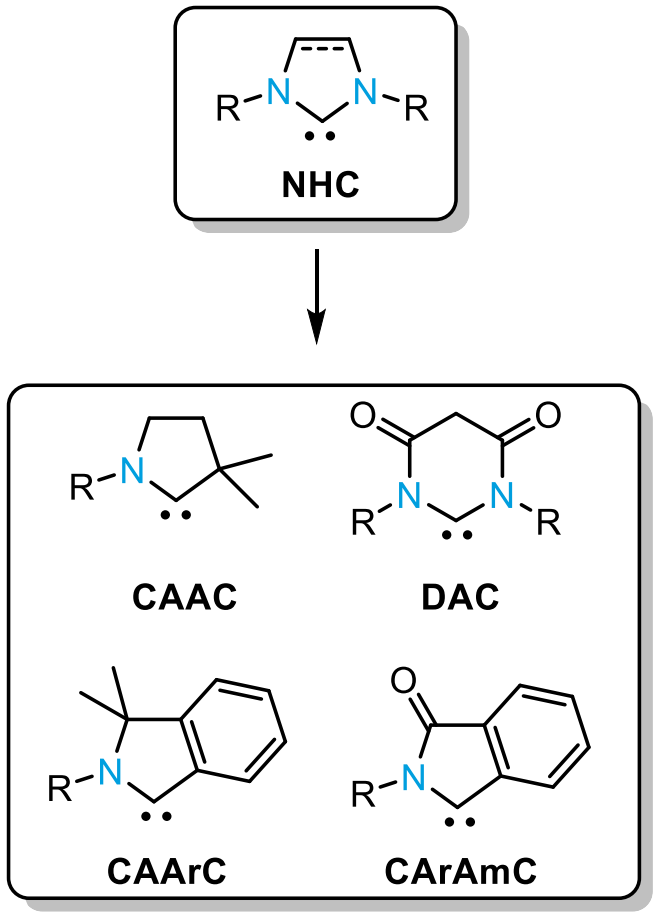


L. L. Liu, *Science*, **2024**, 383, 81–85.

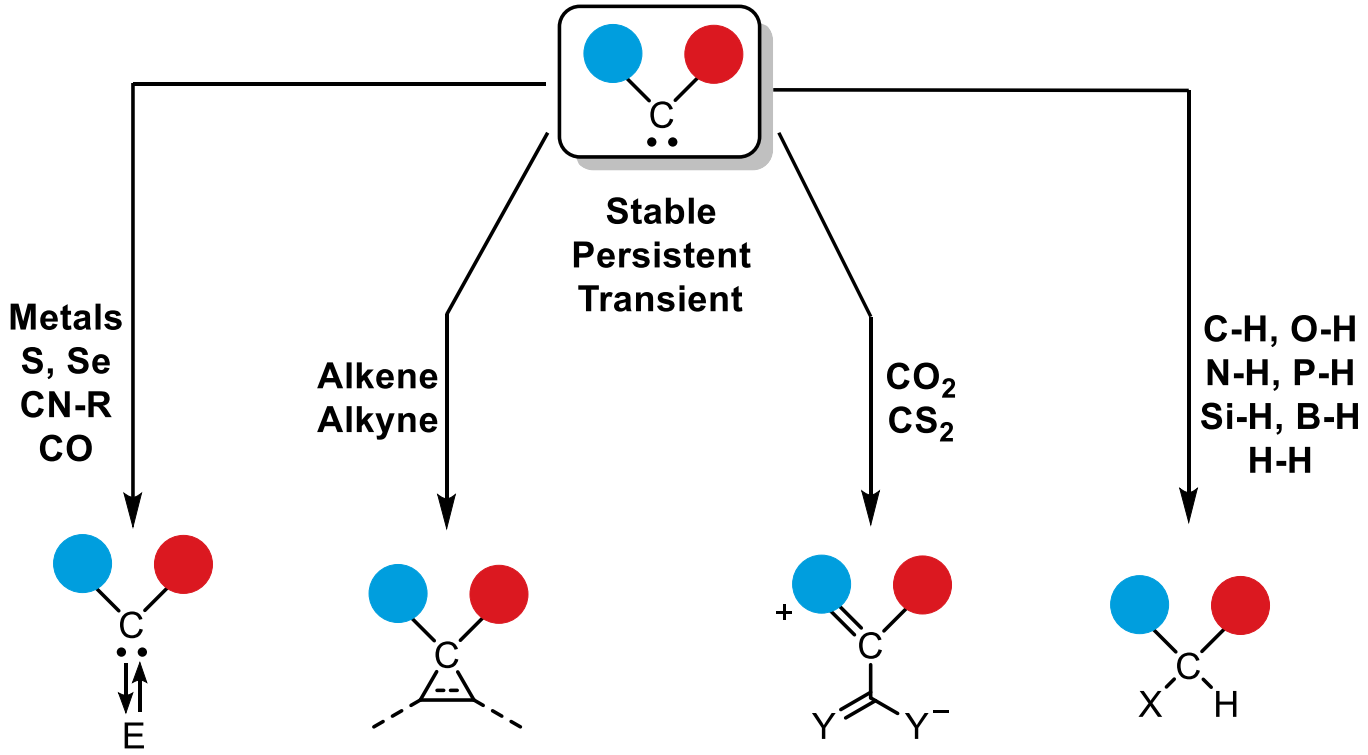
Content

Summary and Outlook

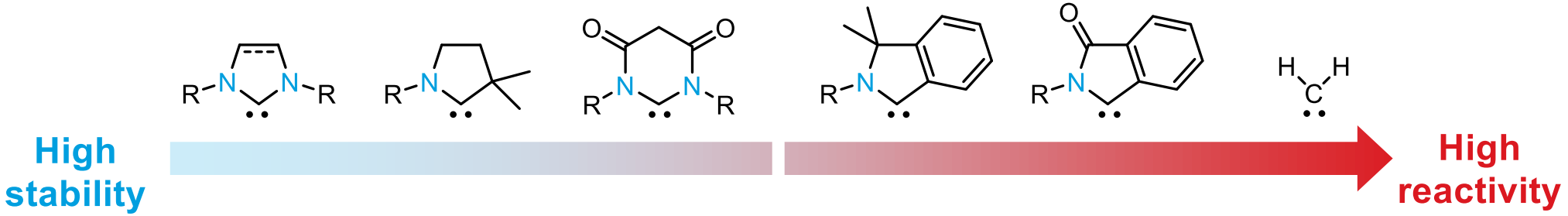
Structure modification



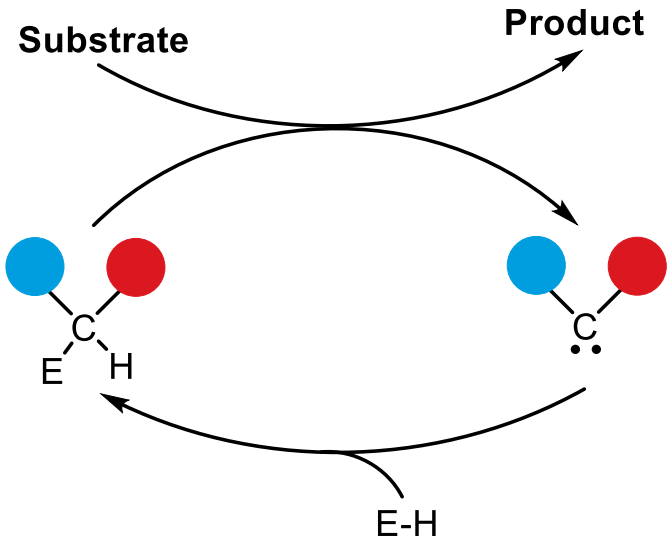
More reactivity than NHC



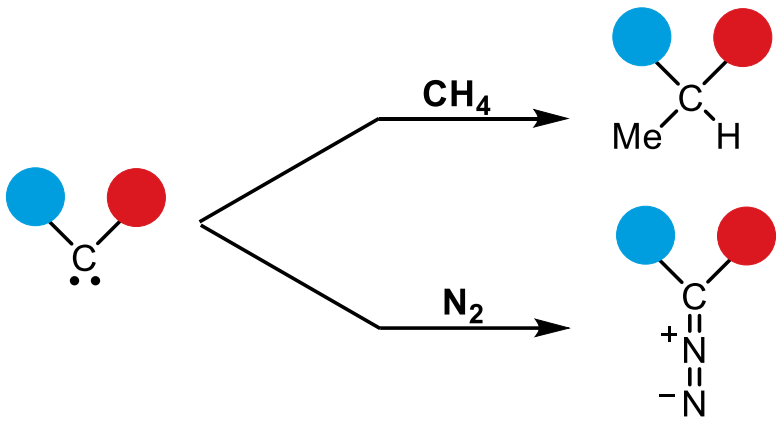
Summary and Outlook



Metal-like catalysis



Activation of inert gas molecule



感谢倾听

请各位老师同学批评指正